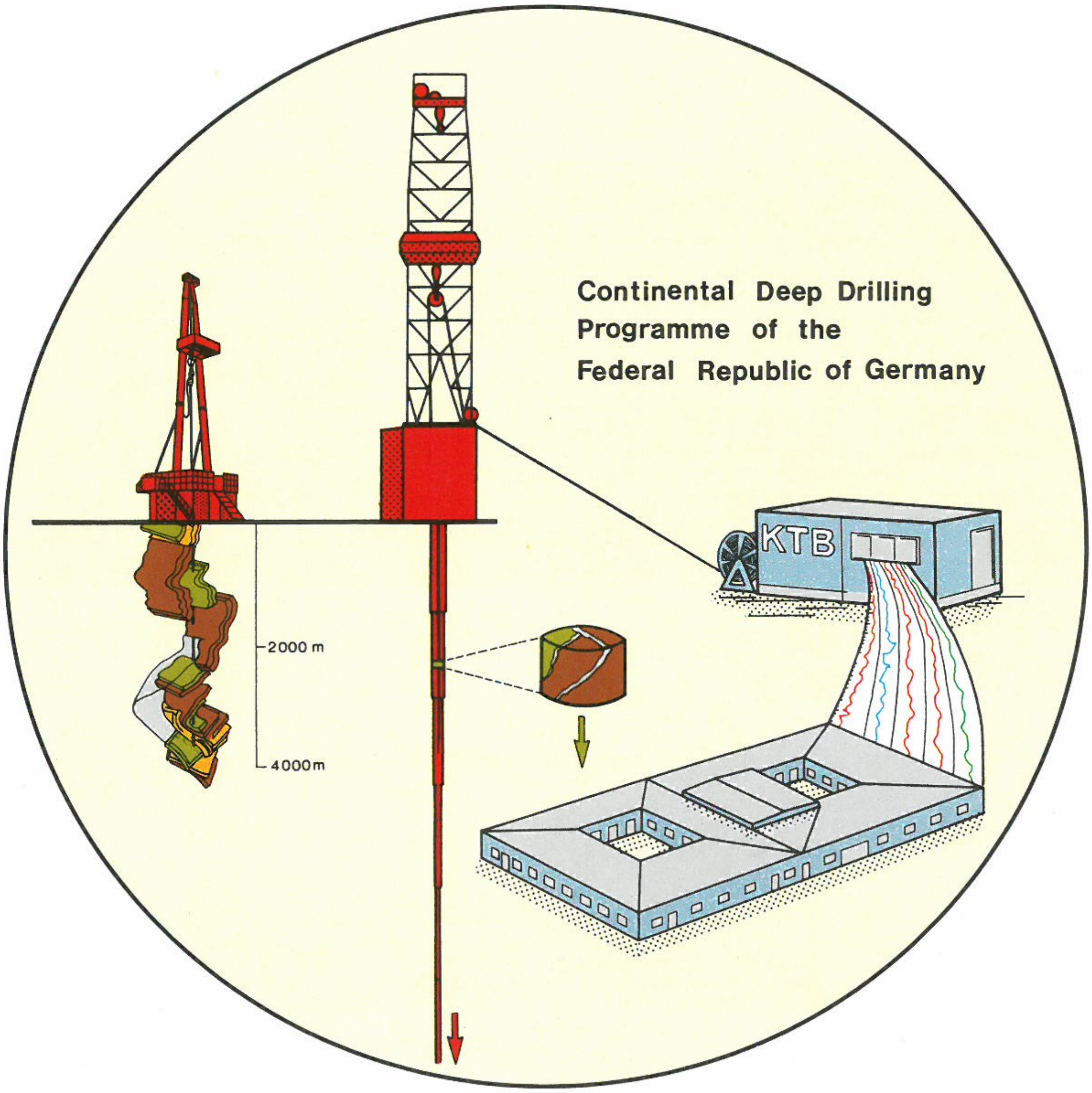
KTB REPORT 90-7

THE CONTINENTAL DEEP DRILLING PROGRAM OF THE FEDERAL REPUBLIC OF GERMANY (KTB)

Selected papers
August 1988 – July 1989



Edited by
the Project Management of the
Continental Deep Drilling Program of the Federal Republic
of Germany in the Geological Survey of Lower Saxony

Redaktion: Prof. Dr. H. Rischmüller

Druck: Wittmann & Wäsch, 3007 Gehrden

Titelbild: Umgezeichnet nach einem Poster von G. Zoth
(KTB-Projektgruppe)

Die diesem Bericht zugrundeliegenden Vorhaben wurden mit Mitteln des Bundesministeriums für Forschung und Technologie (Forschungskennzeichen: RG 8604-0) gefördert. Die Verantwortung für den Inhalt dieser Veröffentlichung liegt bei den Autoren.

Anschrift des Herausgebers: Projektleitung KTB im Niedersächsischen Landesamt für Bodenforschung, Postfach 51 01 53, D-3000 Hannover 51. Telefon: (05 11) 643-2675.

PREFACE

The German Continental Deep Drilling Project is a project of basic geoscientific research of both, national and international importance. Since the actual start of the project, a remarkable number of papers dealing with its results, have been published, most of them written in German.

The necessity of informing the international geoscientific community by English language publications has been recognized from the beginning, therefore, the papers of the Inter-Union Commission on the Lithosphere Conferences and some outstanding articles have been published in this language.

This KTB report is the first in English language, containing a representative number of reports and contributions distributed, so far, only within KTB. Of course, R & D and planning have proceeded, and the actual state at the start of the ultradeep borehole will be presented on September 10 and 11, 1990, at the Fifth Conference on International Lithosphere Research in Regensburg.

TABLE OF CONTENTS

Page

C TECHNICS

PRELIMINARY RESULTS OF THE KTB PILOT HOLE

R. Emmermann

Paper presented at the International Seminar on
"Superdeep Drilling and Deep Geophysical Sounding"
Yaroslawl (USSR)
August, 1988

MAJOR SCIENTIFIC OBJECTIVES OF THE KTB

The Continental Deep Drilling Program of the Federal Republic of Germany (Kontinentales Tiefbohrprogramm der Bundesrepublik Deutschland, KTB) and the closely associated German Continental Seismic Reflection Program (Deutsches Kontinentales Reflexionsseismisches Programm, DEKORP) are major German contributions to the understanding of the Central European crust. This crustal region is distinguished by its position between three Precambrian continental blocks of Pangea, namely Eurasia, North America-Greenland and Africa, and despite its relatively young age of about 500 Ma has a rather complex history. Formation of the Central European crust started in the early Paleozoic during an important rifting episode in Cambro-Ordovician time which resulted in the break-up of Gondwana, development of Variscan microplates and opening of at least some of the Variscan basins. Rifting dismembered an old continental crust previously generated in the course of several Precambrian orogenies. In the subsequent collision between Gondwana and Laurentia/Baltica the Variscan belt of Europe was formed by welding together the Variscan microplates and by incorporation of proto-oceanic basins, shelf areas, accretionary wedges, island arcs and back-arc troughs through compressive, subduction-related processes. This period of plate convergence and crustal shortening began in late Ordovician and continued until Upper Carboniferous. It was followed by a phase of renewed crustal thinning accompanied by intense rhyolitic volcanism in connection with extensional, wrench- and shear tectonics that generated intramontanous basins, graben structures and pull-apart basins. During the Alpine orogeny, the region was subjected to compressional and transpressional tectonics which were followed by another stage of rifting and graben formation in the Tertiary.

This repeatedly reactivated Central European crust is relatively thin (25-30 km) and is extremely heterogeneous both laterally and vertically. It is characterized by regionally variable, but generally high heatflow, pronounced seismic reflection patterns with lamination structures in the lower crust (especially in the young rift regions), the occurrence of high- and low-velocity layers and zones of high electrical conductivity at different depths, penetrative deformation, impregnation with numerous late-Variscan granites and an abundance of late- to post-Variscan hydrothermal mineralizations.

The joint effort of KTB and DEKORP, is to systematically investigate this crustal type which differs fundamentally from those sampled by the research boreholes of Kola (USSR) and Gravberg (Sweden). The main task of DEKORP is to acquire and interpret carefully selected seismic reflection profiles and to reconstruct major geological structures in three dimensions. The aim of the KTB is to sink a superdeep borehole in a geologically and geophysically distinct segment of the Variscan basement in order to:

- investigate the structure, composition, physical properties and thermodynamic state of a representative portion of this crustal type and the processes presently operating in it
- determine the nature of geophysical structures and heterogeneities
- probe the deep crustal stress field and the brittle-ductile transition
- interpret geochemical and geophysical gradients and discontinuities in terms of paleoconditions and paleoprocesses
- decipher the crustal architecture and reconstruct its geological-geodynamic evolution.

The scientific rationale for the KTB and the major questions to be tackled by a superdeep borehole were outlined by Emmermann (1986) and Behr and Emmermann (1987). After the major objectives of the KTB had been agreed upon, two basement regions, the Oberpfalz and the Schwarzwald, were selected as potential drilling targets. Operational considerations played a major role in the final choice of the Oberpfalz as the drill site (Emmermann and Behr, 1987). Of particular significance were the high temperature gradients and near-surface heatflow values of the Schwarzwald, which suggested that temperatures of around 300°C might be reached at a depth of only 7 - 8 km. Such high temperatures would make both drilling and logging of the hole very difficult and would have a considerable impact on the budget provided for the project.

LOCATION AND TECTONIC SETTING OF THE KTB DRILL SITE

The Oberpfalz is situated at the western margin of the Bohemian Massif, the largest coherent surface exposure of basement rocks in Central Europe (Fig. 1). The actual drill site was chosen close to the intersection of KTB reflection profile 8502 and the DEKORP 4 line, a few kilometres south of the boundary between the Saxothuringian and Moldanubian, the two major basement units of the internal zone of the Variscan fold belt. In the Oberpfalz this boundary is called Erbendorf line and according to the results of the pre-site investigations is interpreted as a prominent thrust plane within a broad suture zone formed by the closure of an early Palezoic, probably oceanic rift basin.

In the Oberpfalz region three tectono-metamorphic units can be distinguished which are separated from Permo-Mesozoic sediments in the west by the Franconian line, a steeply northeastward-dipping wrench fault. The Moldanubian (MO) represents a typical basement complex and is made up chiefly of high-grade polymetamorphic gneisses that were reactivated during the Variscan orogeny. The Saxothuringian (ST) predominantly consists of lower Paleozoic metasediments and metavolcanics that were only affected by a monophase metamorphism with the metamorphic grade of the rocks increasing from lower greenschist-facies in the north to upper amphibolite-facies at the contact with the Moldanubian basement. The Zone of Erbendorf-Vohenstrauss, abbreviated as ZEV, where the drill site is located, is a medium-pressure metamorphic basement unit that is made up chiefly of paragneisses with intercalations of metabasic rocks (see also Fig. 1). The drill site lies some 3 km east of the town of Windischeschenbach in a segment of the ZEV which is bordered to the southwest by the Franconian line and to the northeast by the Fichtelnaab fault, two elements of a prominent fault system that are responsible for considerable down-

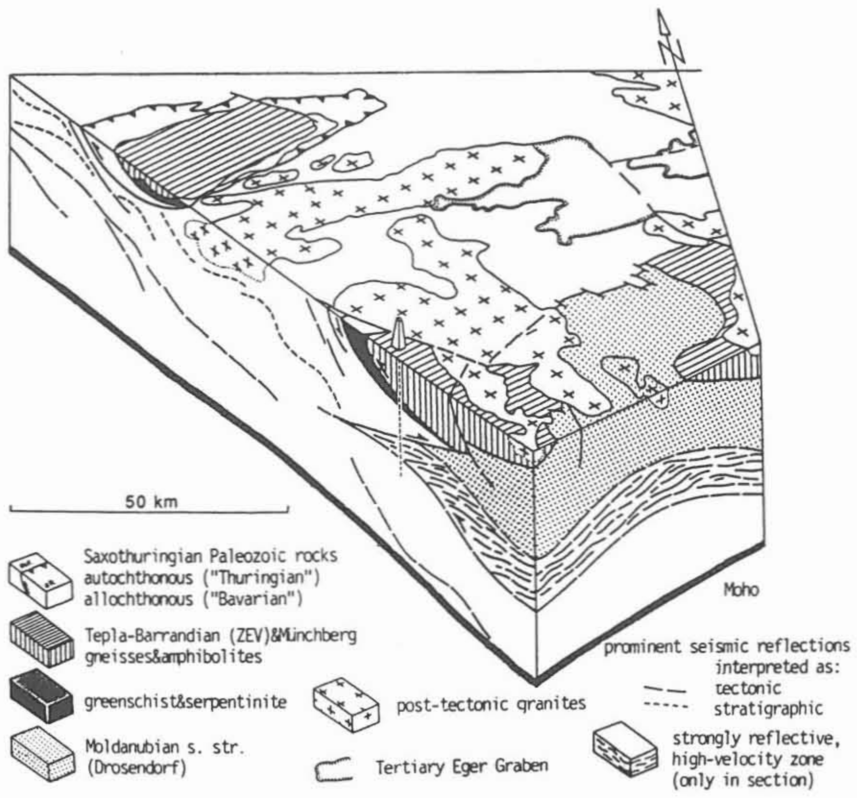


Fig. 3. Three-dimensional geotectonic model of the crustal structure in the Oberpfalz region (Franke 1989)

The drill site is located above a crustal segment of unusually high seismic reflectivity with a number of prominent seismic reflectors between a depth of 8 and 12 km (Figs. 3 and 4). The bottom of this highly reflective zone is marked by a high-velocity body (vp 7 km/sec) which appears to coincide with a zone of high electrical conductivity. The opportunity to drill into this structure, to reveal the nature of seismic reflectors and to test the model of crustal architecture outlined above are the major attractions of the Oberpfalz location.

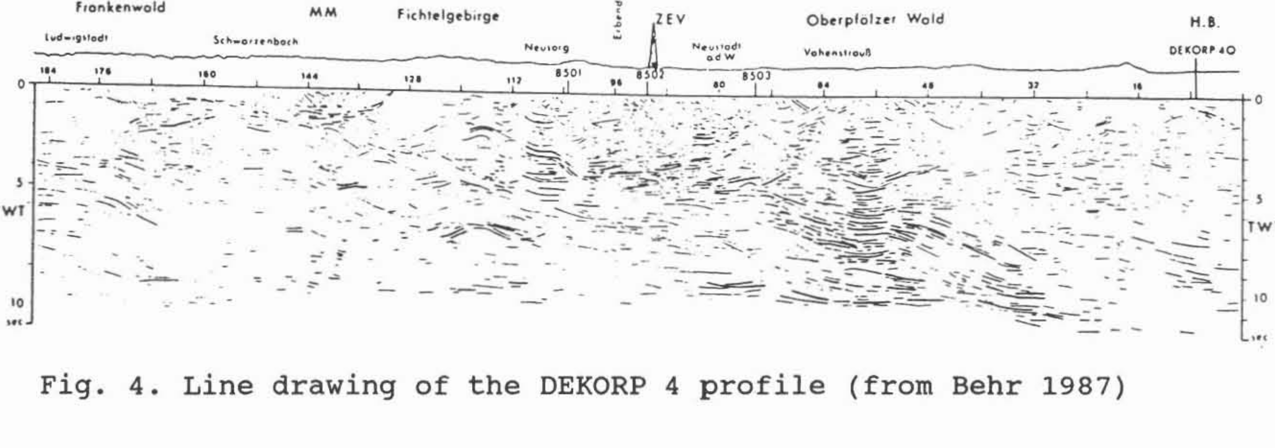


Fig. 4. Line drawing of the DEKORP 4 profile (from Behr 1987)

SCIENTIFIC PROGRAM AND TASKS OF THE FIELD LABORATORY

The drilling strategy of the KTB calls for completion of a pilot hole before starting the main borehole which is planned to reach a final depth of at least 10 km. The pilot hole was spudded on September 22, 1987 and was terminated on April 4, 1989 at a depth of 4000.1 m. The main borehole, located some 200 m E of the pilot hole, will be started in summer 1990 and is scheduled to reach 10 km by the end of 1994.

The aims of the pilot hole were to:

- gather extensive geoscientific data by means of continuous coring, downhole logging, tests and analyses of core material, cuttings and drilling fluid
- collect information about problem sections and technically critical horizons
- investigate the temperature field and improve predictions of expected temperatures at depth
- minimize coring and borehole measurements in the main borehole
- test drilling and logging tools to be used in the main borehole.

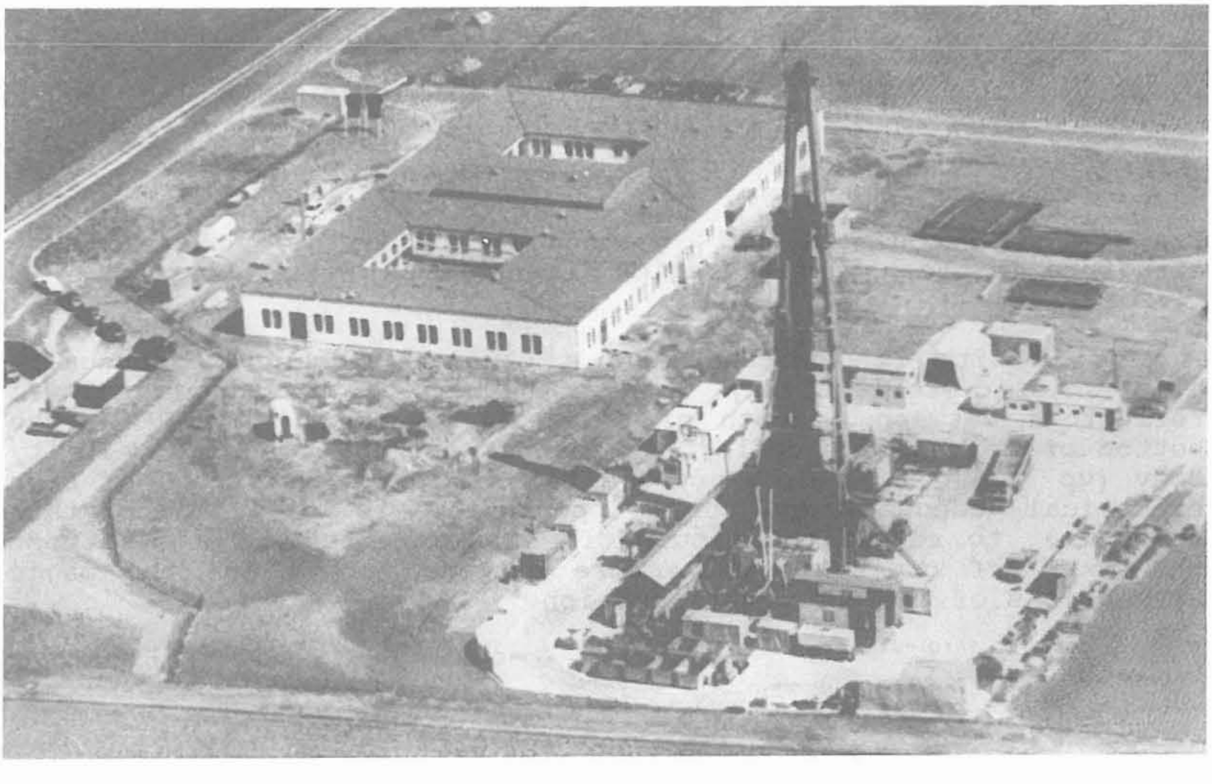


Fig.5. KTB drilling rig and field laboratory

To accomplish these goals, it was decided to drill a 6-inch-diameter hole to a depth of at least 3000 m using a combination of rotary and mining drilling techniques (Rischmüller and Chur 1987; Chur and Sperber 1988). Mining drilling technique involves drilling at high rotational speeds with a double tube wireline core barrel system and thin-kerf diamond core bits. This technique allows wireline retrieval of the inner core barrel and core. Recovery during all phases of wireline coring was excellent and exceeded 97 %.

Scientific evaluation of the pilot hole is based on gathering extensive geoscientific data in a field laboratory (Fig. 5) at the drill site and from accompanying special investigations at universities and other research institutions. The Deutsche Forschungsgemeinschaft (DFG) currently funds some 92 KTB-related research projects with a budget of about 7 million DM per year. This money is provided by the Federal Minister of Research and Technology (Bundesminister für Forschung und Technologie, BMFT) who also funds 15 research and development projects (F+E-Projekte) in the field of engineering and drilling technology. Altogether, about 300 scientists from 64 institutes are presently involved in the KTB.

Establishment of a field laboratory at the drill site had a high priority since the very first KTB discussions. During the preparatory phase of the program, a working group organized under the direction of this author defined the tasks to be accomplished in the lab and determined the equipment and personnel necessary to carry out the work. It was agreed that the main purpose of the field laboratory is to collect extensive geoscientific data on cores, cuttings, drilling muds, drilling fluids and gases recovered from both the pilot hole and the main borehole. In particular properties should be measured which:

- are necessary for quick operational decisions concerning drilling, sampling and testing
- have to be determined on a quasi-continuous scale as a function of depth
- are time-dependent and have to be recorded as soon as possible
- are necessary for correlation with data obtained by borehole measurements
- are needed for proper sample selection and serve as basic information for all individual research projects.

To meet these requirements a comprehensive scientific program is carried out on-site which includes:

- structural, petrographical and mineralogical investigations on cores and cuttings
- preparation of a lithologic log and a first interpretation of geological structures
- determination of major and trace elements on core material, cuttings, drilling mud and drilling fluid
- on-line analysis of gases dissolved in the drilling fluid
- measurements of physical properties of cores, cuttings and drilling muds.

Figure 6 summarizes the tasks of the field laboratory and its organizational structure. In addition to the specified investigations the field laboratory is responsible for distribution, management and archiving of samples, and for regular publication of all scientific results. Progress reports are published every three months and cover borehole sections of 500 m length (Emmermann et al. 1988, 1989). Thus far, seven "Sampling Parties" have been held and over 5000 samples have been prepared and distributed. The staff of the field laboratory currently includes 3 permanently employed assistants of the Project Management, 18 scientists and 16 technicians. These personnel are assigned to four working groups: geology/petrology, geochemistry, geophysics, and data processing.

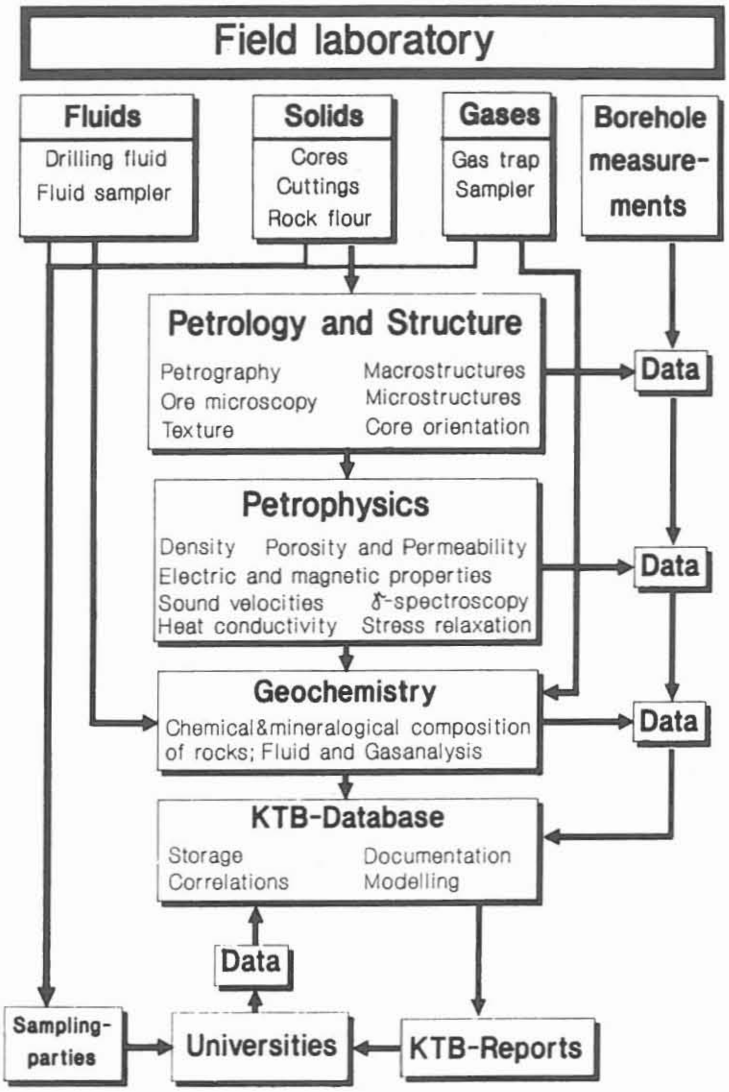


Fig. 6. Sampling and working scheme of the KTB field laboratory

The petrophysical investigations performed at the drilling site include determination of density, seismic velocity (vp), natural remanent magnetization, susceptibility, electrical resistivity, thermal conductivity, porosity and permeability. An important experiment carried out immediately after core retrieval is the measurement of anelastic strain recovery using a specially designed strain measurement apparatus.

A new X-ray diffraction technique is used to qualitatively and quantitatively determine the mineral composition of cores, cuttings and drilling mud separated from the drilling fluid by means of a centrifuge (Emmermann et al. 1989). X-ray fluorescence analysis using a fully automated and computerized XRF spectrometer (Siemens SRS 303) is used for determination of major oxides and selected trace elements on core samples, cuttings and drilling mud.

A new type of drilling fluid was successfully used for the first time in the pilot hole (Herold et al. 1988). This drilling fluid consists of water with about 2 wt. % Dehydril HT, a lithium, sodium, magnesium silicate with a clay mineral-like structure, which yields a solid-free, thixotropic fluid with a high carrying capacity. An extensive analytical program for a quasi-continuous fluid investigation has been developed and up to 12 cations are analyzed at intervals from 1 to 3 m using an ICP atomic emission spectrometer (ARL 3580). Additionally, Cl^- and SO_4^{2-} are determined with a chromatography system. The results obtained show that continuous fluid analysis allows immediate and reliable detection of inflow horizons and even provides qualitative information as to the composition of the waters (see below).

A specially designed gas mass-spectrometer (Vacuum Generators) is used for the qualitative and quantitative determination of gases released from the drilling fluid. Using an on-line technique, 10 gas components (N_2, O_2, Ar, CO_2, H_2, CH_4, C_2H_6, C_3H_8, He and H_2S) are determined routinely by this fully automatic system which operates round the clock. Despite a relatively complex interpretation of the gas data, the "gas logs" have been very sensitive indicators of problem horizons and permeable zones. The on-line gas data, therefore, proved to be very useful for quick operational decisions concerning positioning of drill-stem tests and fluid sampling.

FIRST RESULTS

As was expected from surface geology the two dominant rock types recovered by the pilot hole are paragneisses and amphibolites. Granites, which are widespread in the target area and which crop out north and east of the drill site, have not been encountered. This confirms the interpretations based on geochemical investigations and detailed gravimetric and magnetic surveys, that the granite bodies are flat, tabular intrusions with eastward dipping contacts (Fig.7). The drill site itself is located near the centre

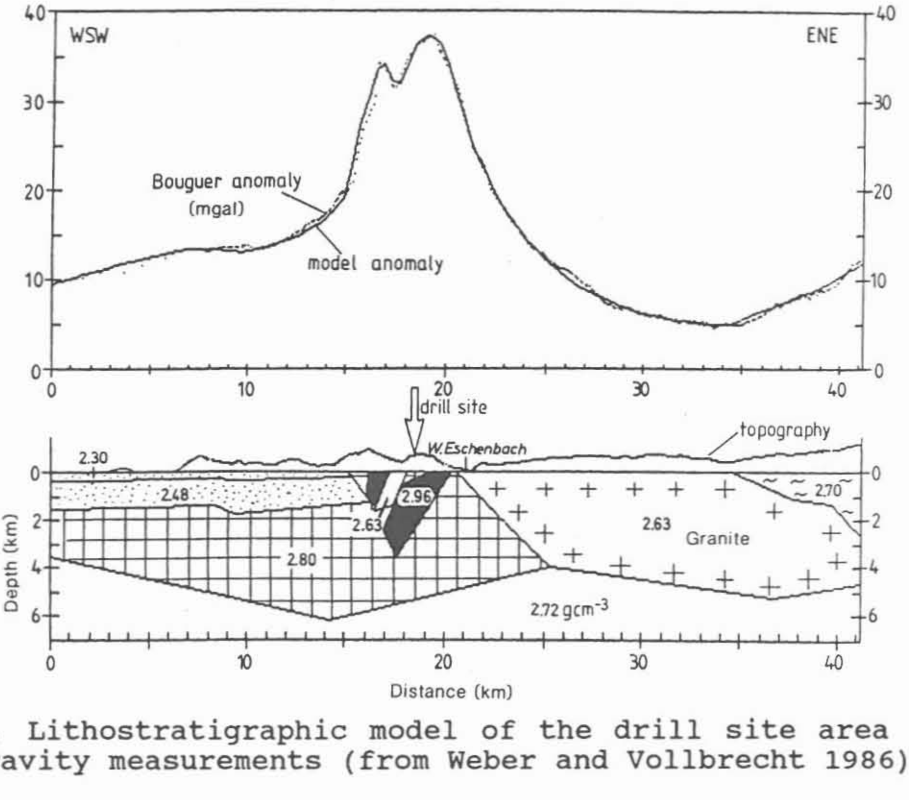


Fig. 7. Lithostratigraphic model of the drill site area resulting from gravity measurements (from Weber and Vollbrecht 1986)

of strong positive magnetic and gravimetric anomalies which are, as has been confirmed by the pilot hole, produced by underlying amphibolite bodies.

The lithostratigraphic profile of the penetrated basement section is characterized by a succession of paragneisses and intercalated metabasic rocks with paragneisses making up about 70% of the entire drilled sequence (Fig. 8). Small lamprophyric and aplitic intrusions, which belong to the dyke sequence of the late-Variscan granites, cut the sequence at various depths.

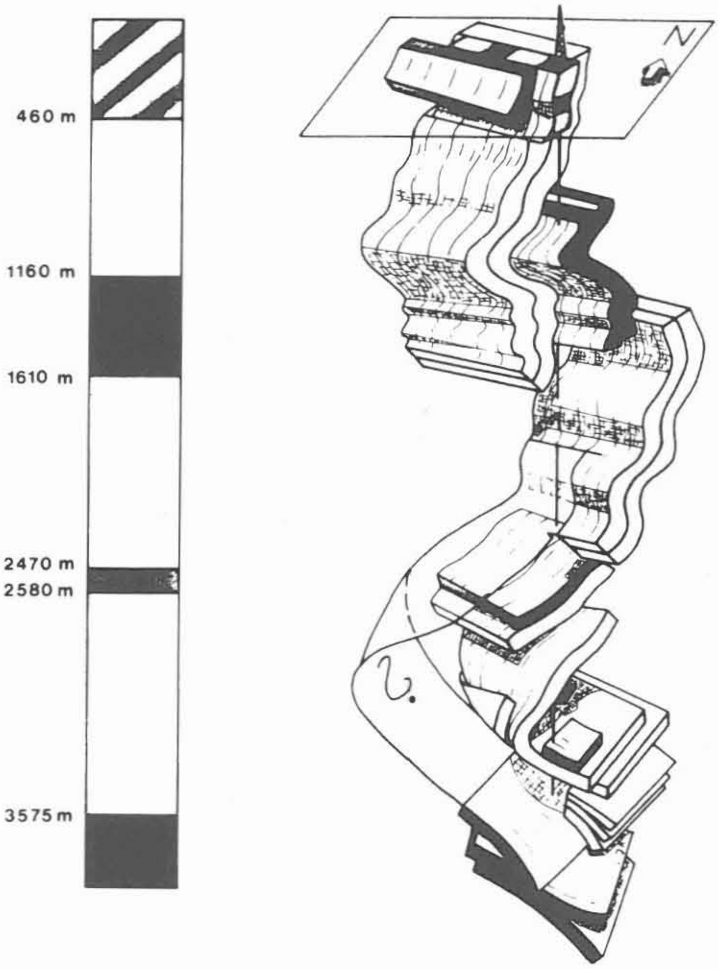


Fig. 8. Lithostratigraphy and structural interpretation of the penetrated basement section (0 - 4000 m)

Seven lithologic units can be distinguished in the drilled sequence (see also Fig. 8):

Unit 1. Above 460 m the borehole penetrated a variegated sequence of garnet-bearing biotite-plagioclase gneisses (sometimes containing K-feldspar and hornblende) and garnet amphibolites intercalated with calcsilicates and a marble horizon. This unit which is strongly affected by retrograde alteration under greenschist-facies conditions, represents a former volcano-sedimentary succession.

Unit 2. Between 460 and 1160 m a sequence of rather uniform garnet-biotite-plagioclase gneisses with varying amounts of kyanite and/or sillimanite was penetrated. Locally, these rocks contain small amounts of K-feldspar and muscovite. Accessories are zircon, monazite, apatite (sometimes accumulated in layers), tourmaline and graphite.

Unit 3. In the interval between 1160 and 1610 m, a sequence of metabasic rocks consisting of garnet amphibolites and metagabbros with subordinate intercalations of meta-ultramafic rocks was recovered. These meta-ultramafic rocks are invariably associated with the metagabbroic portions and occur as irregular fragments or layers of up to 6 m thick.

Unit 4. Between 1610 and 2470 m, another sequence of kyanite- and/or sillimanite-bearing garnet-biotite-plagioclase gneisses was penetrated which are very similar to those of Unit 2. These rocks are cross-cut by lamprophyric and aplitic dykes at various intervals, particularly between 2040 and 2350 m.

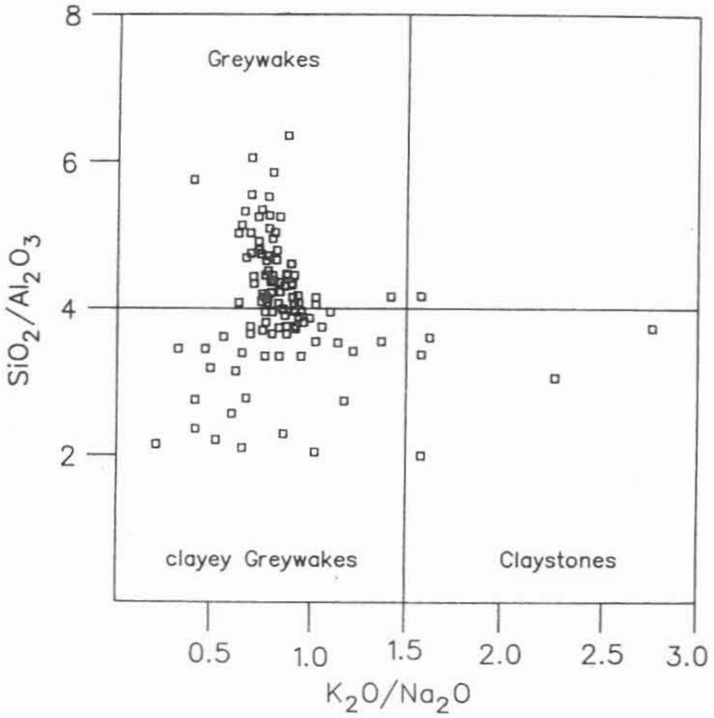


Fig. 9. Major oxide ratios of the paragneisses as indicators of the sedimentary starting material (Müller et al. 1989)

Unit 5. From 2470 to 2580 m, a succession of garnet-bearing hornblende-biotite gneisses grading into garnet amphibolites was penetrated. Petrographically, these rocks resemble the amphibolites recovered from Unit 1. This is also supported by the occurrence of frequent intercalations of small layers of calcsilicates.

Unit 6. A third sequence of uniform kyanite- and/or sillimanite-bearing garnet-biotite-plagioclase gneisses identical to those of Units 2 and 4 was penetrated between 2580 and 3570 m.

Unit 7. Below 3575 m, a metabasic rock series similar to that of

Unit 3 was recovered. This series includes garnet amphibolites, metagabbros and small amounts of meta-ultramafic rocks.

Aluminosilicate-bearing garnet-biotite-plagioclase gneisses constitute the dominant rock type drilled so far. Application of the garnet-biotite geothermometer to these rocks yielded temperatures of formation between 660°and 710°C and pressures in the range of 6 to 8 kbars (Reinhardt et al. 1989).

Chemically, these paragneisses are relatively uniform and, on the basis of their SiO_2/Al_2O_3-and K_2O/Na_2O-ratios, were derived from (clayey) greywackes (Fig. 9). Their chondrite-normalized REE distribution patterns show only a rather limited variation and are distinguished by small negative Eu anomalies and relatively low HREE abundances (Fig. 10).

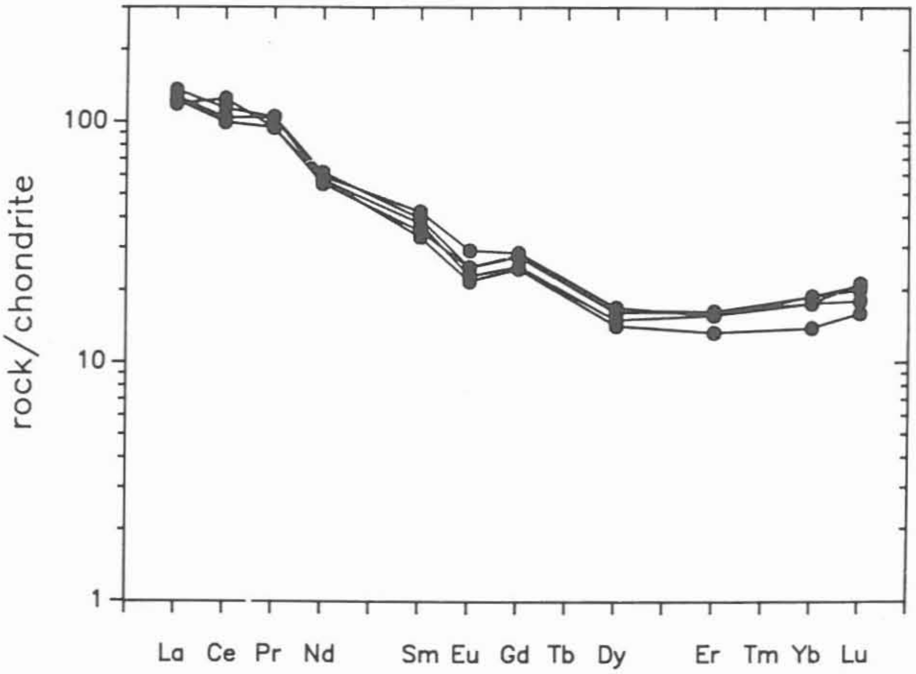


Fig. 10. Chondrite-normalized REE distribution patterns of paragneisses from the KTB pilot hole

The metabasic rocks include amphibolites and metagabbros. The amphibolites are often rich in garnet and display variable textures from massive to strongly foliated. They frequently contain layers or lenses of calcsilicates and grade into paragneisses (Units 1 and 5). These rocks are composed of plagioclase, hornblende and unzoned garnet and occasionally clinopyroxene, biotite and quartz. Typical accessories are ilmenite, rutile, sphene, pyrite and chalcopyrite. All observations indicate that the amphibolites represent basaltic lavas or tuffs erupted contemporaneously with the rapid sedimentation of the greywackes.

The metagabbros are massive medium- to coarse-grained rocks which are distinguished from the amphibolites by relict magmatic textures. These textures and the intimate association of the metagabbros with meta-ultramafic rocks suggest mafic layered intrusions as protoliths. These rocks obviously experienced an early granulite-facies metamorphism under static conditions as is indicated by the development of garnet corona reaction textures around clinopyroxene and by symplectic intergrowths of clinopyroxene + plagioclase after probable omphacitic clinopyroxene. This high-pressure paragenesis was transformed by a later amphibolite-facies metamorphism which led to replacement of clinopyroxene by green hornblende and formation of plagioclase rims by decomposition of garnet in contact with hornblende. Chemically, the metagabbros differ from the amphibolites by having higher Cr and Ni and lower Zr, P and alkali contents.

The meta-ultramafic rocks occasionally recovered from Units 3 and 7 are mostly hornblendites with highly varying contents of talc, chlorite and phlogopite. These rocks, interpreted as former cumulates of layered gabbroic intrusions, were presumably derived from olivine pyroxenites as is suggested by relict diopsidic pyroxene and rare pseudomorphs after olivine.

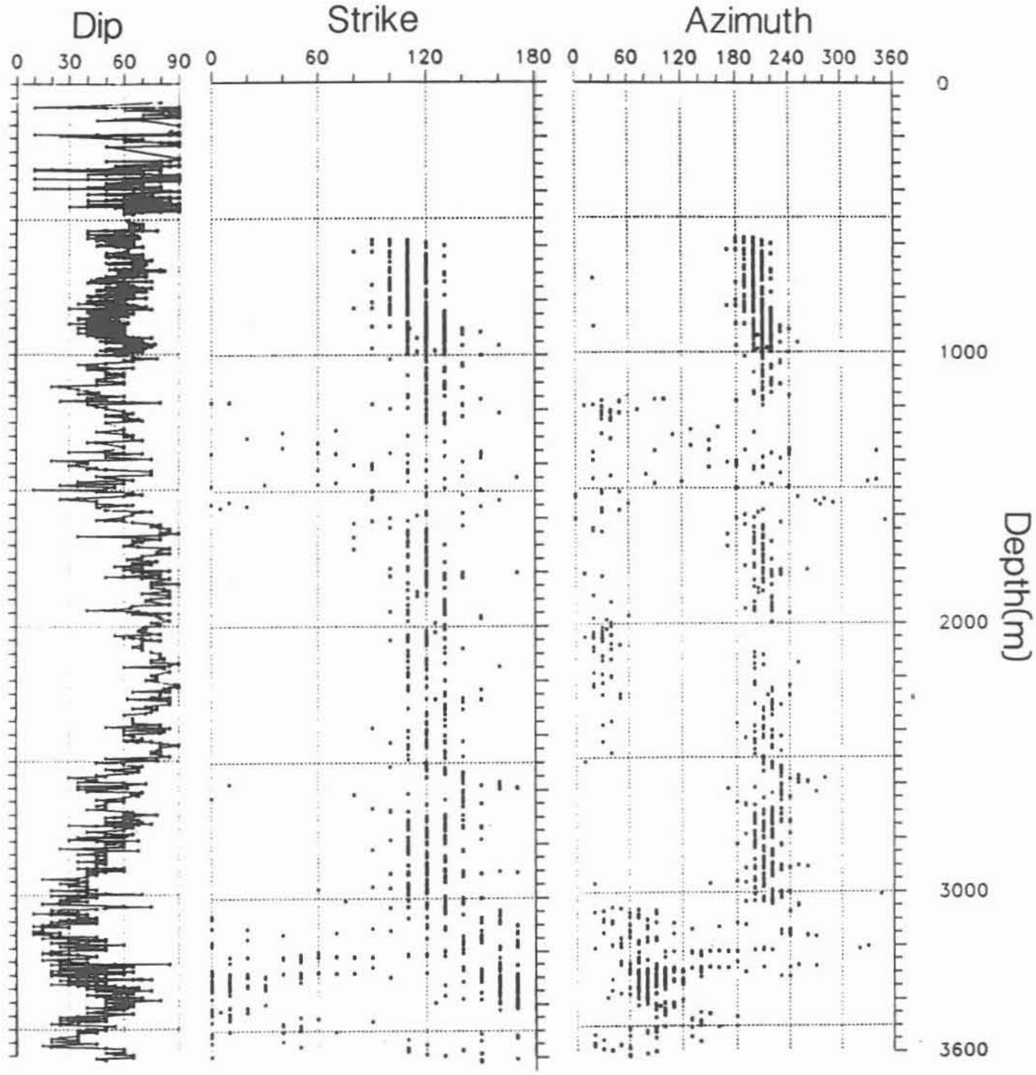


Fig. 11. Dip, strike and azimuth of foliation

Although it was known from surface geology that the ZEV rocks underwent a complex deformation history characterized by penetrative foliation and multi-stage post-metamorphic cataclasis both the steep inclination of the structures and the intensity of the cataclastic deformation of the basement penetrated by the pilot hole were a great surprise.

The foliation dips about 70-90° in the uppermost 500 m and between 1600 and 2300 m but is almost flat at a depth of around 3200 m. The average dip is 60° and there is no indication that there is a systematic decrease with depth as was suggested by the geological starting model. The foliation strikes WNW-ESE and preferentially dips to the SSW above 3200 m and NNE below that depth (Fig. 11). Evaluation of the structural data and reconstruction of the tectonic situation yielded a rather complicated picture and suggest that the pilot hole might have penetrated a huge fold structure (see Fig. 8).

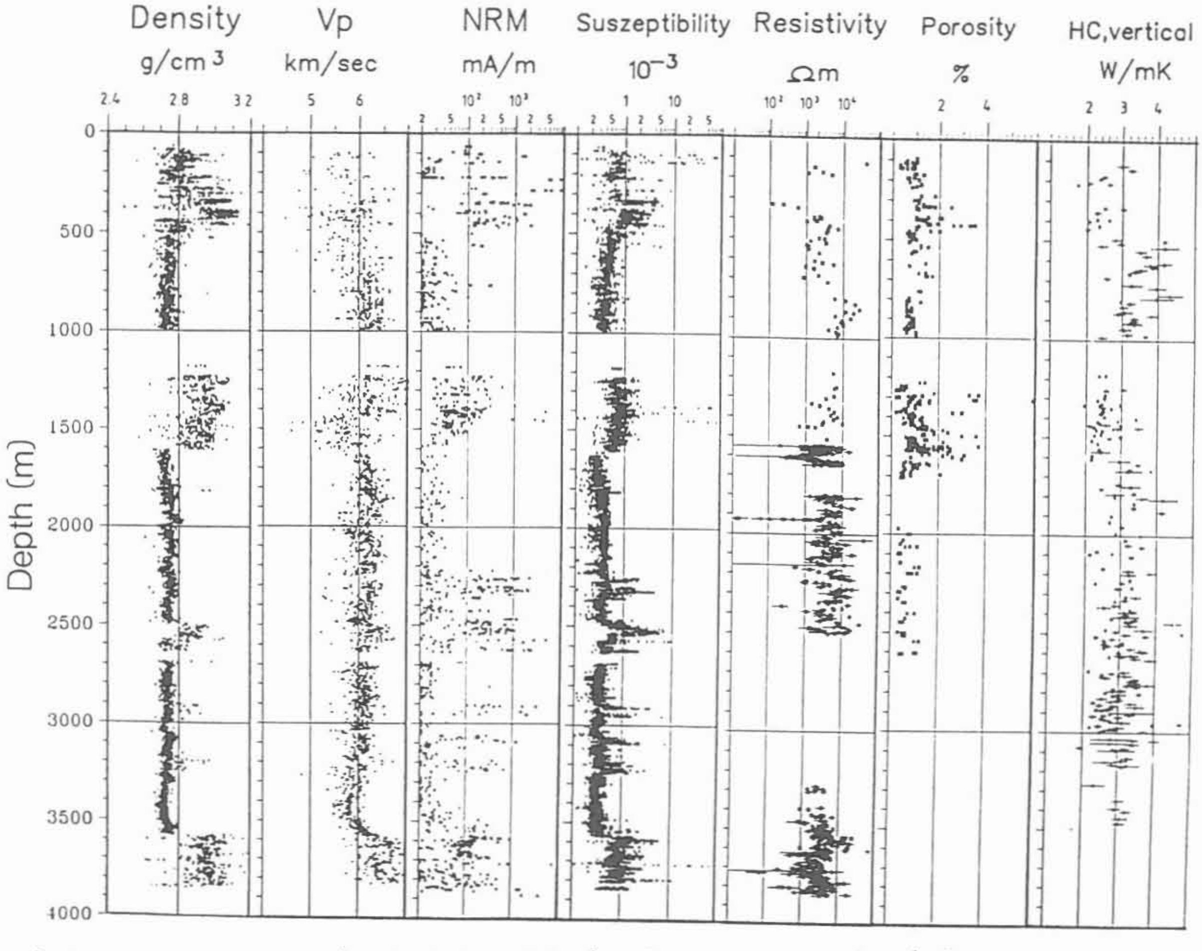


Fig. 12. Petrophysical data obtained on core material

The lithostratigraphy of the drilled basement section is reflected in the downhole variations of the petrophysical rock properties. Fig. 12 summarizes the data obtained on cores and cuttings by the geophysical working group of the field laboratory (Lippmann et al. 1989). As seen from these plots, there is an excellent correlation between lithology and density. The paragneisses are distinguished by very uniform density values of about 2.75 g/cm^3 whereas the metabasic rocks display average densities of 3.0 g/cm^3 with a relatively broad scatter of between 2.8 and 3.2 g/cm^3.

Except for the paragneiss/amphibolite transition at 3575 m, the p-wave velocities do not correlate as well with the lithology. On average, the values are slightly above 6 km/s and vary between 5 and 7 km/s. In many cases, there are only minor velocity differences between paragneisses and metabasic rocks. However, the p-wave velocities show a marked anisotropy which is especially pronounced in the strongly foliated paragneisses but is also detected in massive metagabbros. Preliminary investigations indicate that the in-situ velocity anisotropy of the paragneisses is around 10% (Lippmann et al. 1989).

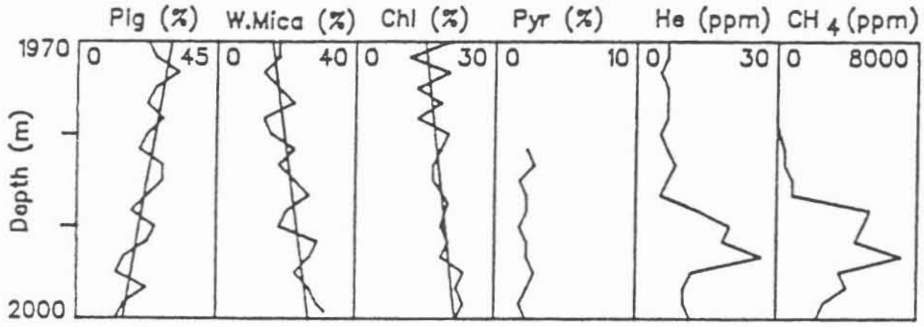


Fig. 13. Changes in mineralogical composition of drilling mud and composition of gases when approaching a shear zone

Major portions of the recovered basement rocks are affected by cataclastic deformation. The sequence is frequently cut by steeply dipping cataclastic shear zones up to 5 m in width, the formation of which was connected with an intense alteration of the host rocks under lower greenschist-facies conditions. Chloritization and serizitisation are widespread phenomena (see also Fig. 13). These shear zones often contain relatively high amounts of graphite, which locally is conspicuously enriched in veins up to several centimeters thick. On-line gas mass-spectrometry carried out in the field laboratory proved to be a very effective means of tracing graphite-containing shear zones. When approaching such a zone, the gas composition of the drilling fluid changed considerably and especially the contents of methane and helium become strongly enriched (Fig. 13).

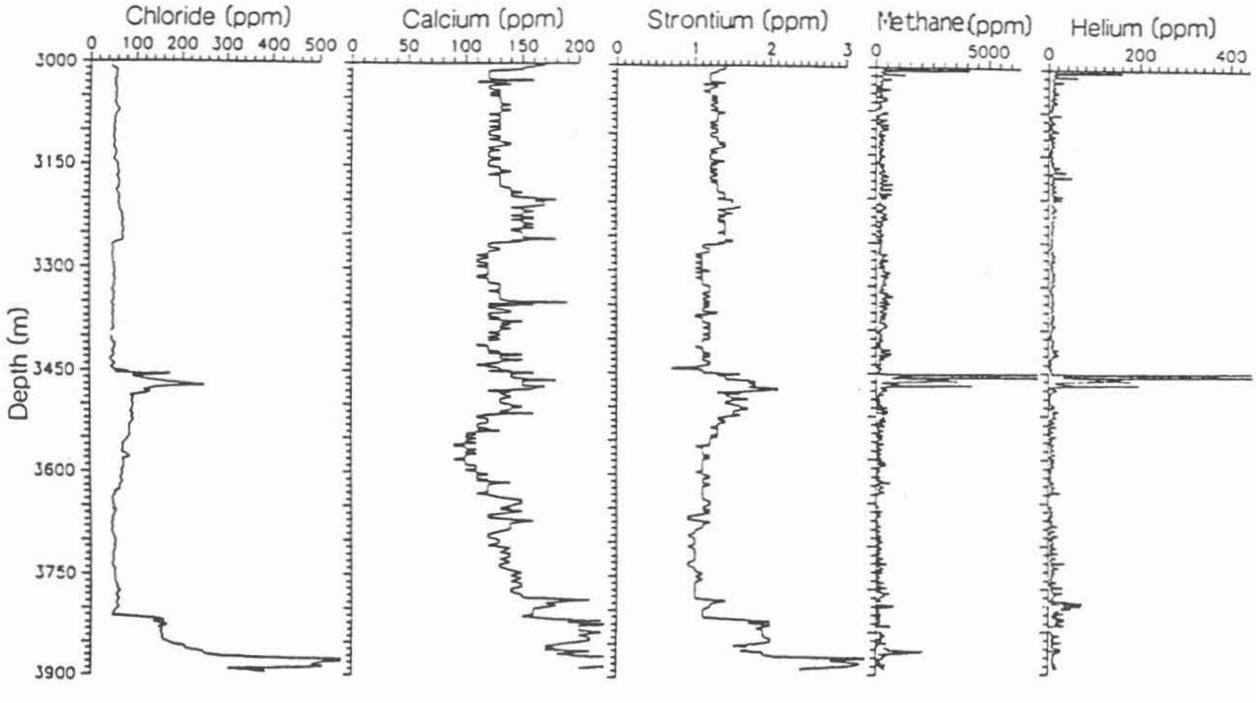


Fig. 14. Selected chemical data obtained on drilling fluid and gases

Despite the cataclastic deformation and a relatively intense veining of the basement rocks, practically no fluid inflow was observed in the borehole above 3400 m. It, therefore, was a surprise when just below this level the first open fractures were encountered which appear to become more abundant with depth. Online analysis of the drilling fluid revealed that these fractures contain gas and saline waters (Fig. 14).

Also unexpected was the early occurrence of core disking first observed at 3575 m which indicates strong horizontal stresses at these depths.

The greatest surprise encountered thus far, however, is the measured temperature profile. Figure 15 shows the actual temperatures obtained and the lower and upper limits predicted from pre-drilling geothermal investigations. The expected temperature gradient of about 22°/km was only found in the uppermost 500 m of the hole. Below that depth the temperature gradient increases to reach values of between 28° and 30° C/km (see also Fig.17).

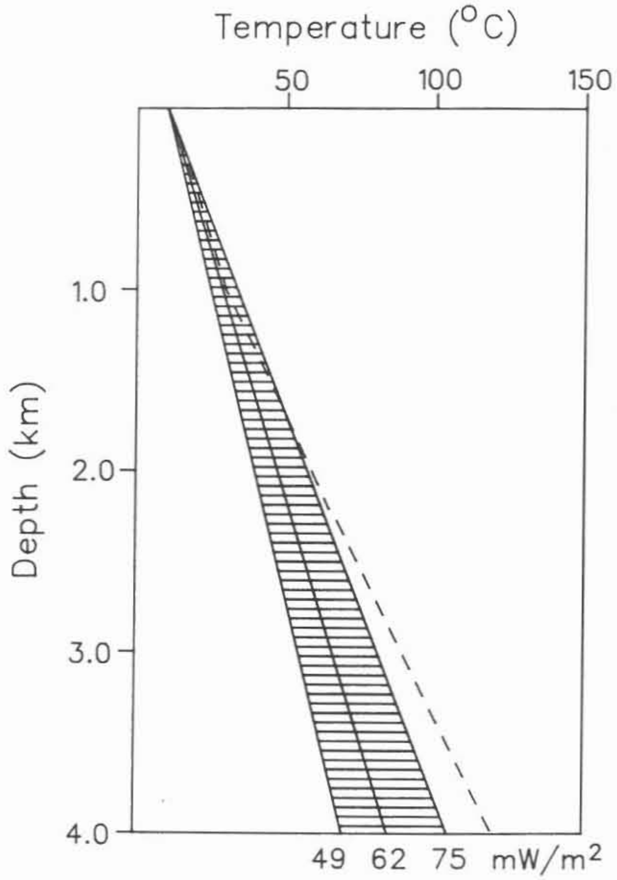


Fig. 15. The temperatures encountered in the KTB pilot hole

MAJOR UNSOLVED PROBLEMS

The results obtained thus far already require modification of preexisting models and pose a number of new scientific questions. Among these are:

(1) What is the reason for the unexpectedly steep inclination of structures in the entire drilled section and how deep do the shear zones reach? Are we dealing with a local phenomenon associated with the Fichtelnaab fault system or does the western margin of the Bohemian Massif represent an old and repeatedly reactivated deformation zone between two large crustal blocks? In the latter case, the Variscan thrust and nappe structures could have been overprinted by late- and post-Variscan transpressional and wrench-tectonics which might have caused steep monoclinal folding and intense shear deformation of the ZEV rocks and even their substratum. At present, there is no indication that the bottom of the postulated ZEV nappe has been reached and it appears that the starting tectonic model has to be modified or even replaced by an alternative model.

(2) Have seismic reflectors been penetrated in the pilot hole and, if so, what is their nature? Pre-stack migration of the DEKORP 4 data in the vicinity of the drill site and evaluation of the first VSP experiments (Kästner at al. 1989) confirms that the main borehole will encounter quite a number of prominent reflectors which are especially abundant in the depth range of between 8 and 12 km. The data also suggest that the pilot hole already penetrated a reflective horizon at a depth of around 3400 m which roughly coincides with the first occurrence of fluid-filled fractures.

(3) What is the depth distribution of the principal in-situ stresses? Relaxation experiments on recovered core material yielded first data on the stress regimes at greater depth and allow a rough estimate of the principal in-situ stresses. To obtain information on the time-dependent strain retardation and to estimate magnitude and orientation of the principal in-situ stresses, core samples of different lithology (length of sample 100 mm, diameter 94 mm) were measured with a multi-component dilatometer. Depending on rock type and texture, the values of maximal and minimal radial principal retarded strains and the vertical strain are quite different.

(4) What is the source of the gases and saline waters? Among the gases analyzed so far methane and helium are of special interest since they are reliable indicators of inflow horizons and even graphite-containing shear zones. As is seen from Fig.16 the shear zone at 2000 m is distinguished from the inflow zones at 3400 and 3800 m by significantly different CH_4/He-ratios of the gases dissolved from the drilling fluid. The markedly higher methane contents of the shear zones are due to graphite enrichment. The open fractures at 3400 m are developed in paragneisses which have higher methane and helium contents than the metabasic rocks. Therefore, the different concentrations and ratios found for the fractures at 3800 m, which occur in metagabbros, are probably due to primary differences. The results obtained suggest that there is no hydraulic connection between the two fracture systems at 3400 and 3800 m (Erzinger et al. 1989). Preliminary determinations of the $^3He/^4He$-ratio of the helium sampled at about 3455m point to a significant mantle component of about 20 % (Heusser et al. 1989).

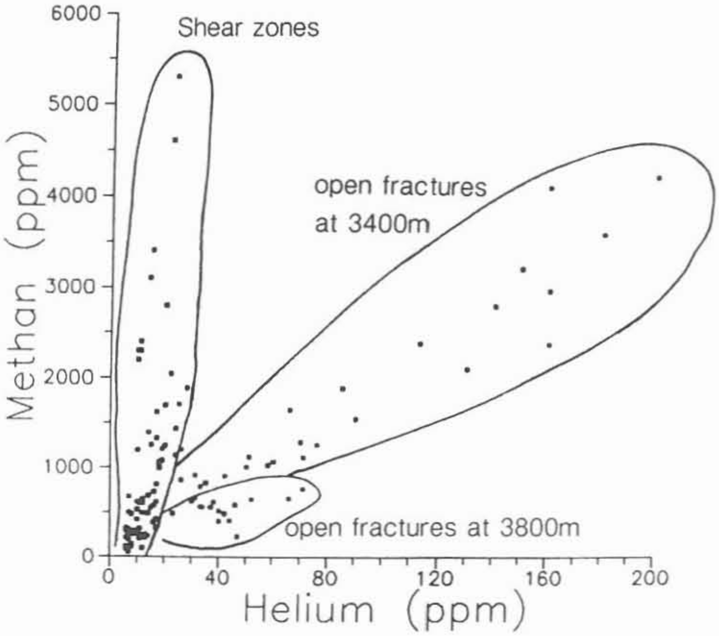


Fig. 16. Methane and helium contents in shear zones and fractures

(5) What is the source of graphite found in shear zones and how was it formed? The intense hydration of the paragneisses in connection with graphite enrichment and the occasional intimate intergrowth of graphite with chlorite and calcite indicate the presence of an H_2O- and CO_2- rich fluid and suggest a graphite deposition according to the equation: $CH_4 + CO_2 = 2C + 2H_2O$.
The carbon isotope data obtained so far are still ambiguous. The values measured (^{13}C -19 to -22 %) are intermediate between those typical for carbon derived from mantle CO_2 and carbon derived from organic matter (Hoefs pers. comm.). Therefore, the ultimate origin of the carbon and its mechanism of transportation and precipitation are still unclear.

(6) What is the reason for the low electrical resistivity and the high self-potential anomaly observed around the borehole? Geoelectrical measurements carried out in the immediate vicinity of the drill site revealed the existence of a prominent shallow electrical conductor between 300 m and at least 1500 m depth and yielded the highly surprising result that the drill site is located on a very large and unusually high electrical selfpotential anomaly about -600 mV (Haak et al. 1989). Graphite might decrease the electrical resistivity of metamorphic rocks by several orders of magnitude if it forms coherent films along grain-boundaries. Among the questions to be investigated, therefore, is the importance of graphite in producing these phenomena.

(7) What are the reasons for the unexpected temperature profile? A first interpretation of the temperature gradient downhole, the thermal conductivity of the rocks and the resulting heatflow (Fig.17) suggests that the temperatures within the upper 500 m of the basement might have been systematically lowered by cooling of

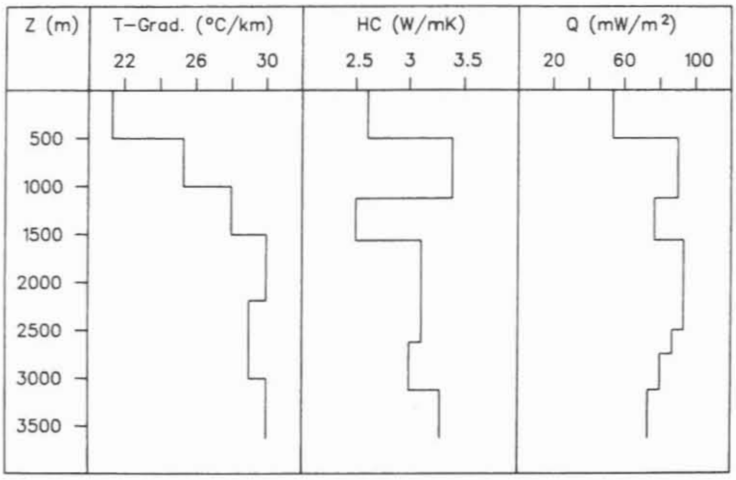


Fig.17 . Downhole distribution of temperature gradient, thermal conductivity and heatflow

the crust through ground water convection (Burkhardt et al. 1989). The higher heatflow values observed at greater depths are presently interpreted to be the result of a higher than expected basal heatflow component. Among the questions to be investigated, therefore, is the role of the Tertiary Eger graben (see Fig. 1) and its associated alkalibasaltic magmatism as a source of the higher than predicted heatflow values.

REFERENCES

Behr HJ (1987) KTB und kontinentale Krustenforschung - warum ein wissenschaftliches Tiefbohrprogramm? KTB-REPORT 87-1, Projektleitung KTB im NLfB, Hannover, pp 1-15

Behr HJ, Emmermann R (1987) Scientific objectives and site- selection studies of the Continental Deep Drilling Program of the Federal Republic of Germany (KTB). In: Behr et al. (eds) Observation of the Continental Crust through Drilling II. Springer, Berlin Heidelberg New York London Paris Tokyo, pp 85-120

Burkhardt M, Erbas K, Giese P, Haack U, Hornamand H, Huenges E, Stiefel A, Wilhelm H, Zoth G, Buntebarth G, Schulz R (1989) Das vorhergesagte und das gemessene Temperaturprofil. In: Emmermann and Giese (eds) KTB REPORT 89-3, Projektleitung KTB im NLfB, Hannover, pp 216-242

Chur C, Sperber A (1988) The drilling concept of the Continental Deep Drilling Program of the Federal Republic of Germany (KTB). In: Boden and Eriksson (eds= Deep drilling in crystalline bedrock, (vol 2) Springer, Berlin Heidelberg New York London Paris Tokyo, pp 224-234

Emmermann R (1986) Das Deutsche Kontinentale Tiefbohrprogramm. Geowissenschaften in unserer Zeit 4: 19-33

Emmermann R, Behr HJ (1987) Location for super-deep borehole confirmed. Tectonophysics 139: 339-340

Emmermann R, Dietrich HG, Heinisch M, Wöhrl T (1988) Tiefbohrung KTB Oberpfalz VB. Ergebnisse der geowissenschaftlichen Bohrungsbearbeitung im KTB-Feldlabor (Teufenbereich von 0 - 480m). KTB REPORT 88-1, Projektleitung KTB im NLfB, Hannover

Emmermann R, Dietrich HG, Heinisch M, Wöhrl T (1988) Tiefbohrung KTB Oberpfalz VB. Ergebnisse der geowissenschaftlichen Bohrungsbearbeitung im KTB-Feldlabor (Teufenbereich von 480 - 992 m). KTB REPORT 88-2, Projektleitung KTB im NLfB, Hannover

Emmermann R, Dietrich HG, Heinisch M, Wöhrl T (1988) Tiefbohrung KTB Oberpfalz VB. Ergebnisse der geowissenschaftlichen Bohrungsbearbeitung im KTB-Feldlabor (Teufenbereich von 992 - 1530 m). KTB REPORT 88-6, Projektleitung KTB im NLfB, Hannover

Emmermann R, Dietrich HG, Heinisch M, Wöhrl T (1988) Tiefbohrung KTB Oberpfalz VB. Ergebnisse der geowissenschaftlichen Bohrungsbearbeitung im KTB-Feldlabor (Teufenbereich von 1530 - 1998 m). KTB REPORT 88-9, Projektleitung KTB im NLfB, Hannover

Emmermann R, Dietrich HG, Heinisch M, Wöhrl T (1989) Tiefbohrung KTB Oberpfalz. Ergebnisse der geowissenschaftlichen Bohrungsbearbeitung im KTB-Feldlabor (Teufenbereich von 1709 - 2500 m). KTB REPORT 89-2, Projektleitung KTB im NLfB, Hannover

Emmermann R, Lauterjung J, Stroh A (1989) Das lithostratigraphische Profil der KTB-Vorbohrung bestimmt durch röntgenographische Phasenanalyse von Bohrklein. In: Emmermann und Giese (eds) KTB REPORT 89-3, Projektleitung KTB im NLfB, Hannover, pp 152-164

Erzinger J, Heinschild HJ, Figgemeier C, Samel M (1989) Ergebnisse der Gasanalytik in der KTB-Vorbohrung. In: Emmermann und Giese (eds) KTB-REPORT 89-3, Projektleitung KTB im NLfB, Hannover, pp 42-45

Franke W (1989) Tectonostratigraphic units in the Variscan belt. Geol. Soc. Amer. Spec. Paper 230: 67-90

Haak V, Stoll J, Winter H (1989) Why is the electrical resistivity around the KTB-hole so low? In: Emmermann and Giese (eds) KTB REPORT 89-3, Projektleitung KTB im NLfB,Hannover, pp 54-60

Herold CP, Müller H, v Tapavicza S (1988) A new high temperature stable drilling mud additive for geological and deep drilling operations. In: Boden and Eriksson (eds) Deep drilling in crystalline bedrock (vol 2). Springer, Berlin Heidelberg New York London Paris Tokyo, pp 306-314

Heusser E, Kirsten T, Richter H, Oehm J (1989) Edelgasisotopensystematik im Bohrkernabschnitt 500 m - 1500 m. Poster. In: Emmermann and Giese (eds) KTB REPORT 89-3, Projektleitung KTB im NLfB, Hannover

Kästner U, Bram K, Hubral P, Macdonald C, Rühl T, Sandmeier KJ (1989) Seismic investigations at the KTB drilling site. In: Emmermann and Giese (eds) KTB-REPORT 89-3, Projektleitung KTB im NLfB, Hannover

Lippmann E, Bücker C, Huenges E, Rauen A, Wienand J, Wolter KE (1989) Gesteinsphysik im KTB-Feldlabor: Messungen und Ergebnisse. In: Emmermann and Giese (eds) KTB REPORT 89-3, Projektleitung KTB im NLfB, Hannover, pp 120-129

Müller H, Tapfer M, Emmermann R, Wimmenauer W (1989) Die Paragneise im Profil der KTB-Vorbohrung. In: Emmermann and Giese (eds) KTB REPORT 89-3, Projektleitung KTB im NLfB, Hannover, pp 61-66

Reinhardt J, Kleemann U, Blümel O, Schreyer W (1989) Geothermobarometry of metapelites as a key to the pressure and temperature history of the ZEV (Zone von Erbendorf-Vohenstrauss), NE Bavaria. In: Emmermann and Giese (eds) KTB REPORT 89-3, Projektleitung KTB im NLfB, Hannover, pp 24-32

Rischmüller H, Chur C (1987) Technical concept and status of planning for the wells of the Continental Deep Drilling Program (KTB). In: Behr et al. (eds) Observation of the Continental Crust through Drilling. Springer, Berlin Heidelberg New York London Paris Tokyo, pp 136-147

Schüssler U, Richter P, Okrusch M (1989) Metabasites from the Oberpfalz target area, Bavaria - Geochemical characteristics and examples of mobile behaviour of "immobile" elements. Tectonophysics 157: 135-148

Weber K, Vollbrecht A (1986) Ergebnisse der Vorerkundungsarbeiten Lokation Oberpfalz. 2. KTB-Kolloquium Seeheim /Odenwald

CONTINENTAL DRILLING – A KEY PROJECT OF THE INTERNATIONAL LITHOSPHERE PROGRAM (ILP)

K. Fuchs

Paper presented at the International Seminar on
"Superdeep Drilling and Deep Geophysical Sounding"
Yaroslawl (USSR)
August, 1988

CONTINENTAL DRILLING - A KEY PROJECT OF THE INTERNATIONAL LITHOSPHERE PROGRAM (ILP)

The exploration of the lithosphere is expanding rapidly from the investigation of structure to that of physical properties and state, composition, and processes related to transport of matter and energy on macro- and micro-scales. Among the key projects defined by the International Lithosphere Program some are especially related to this subject of mobility.

- **Real time tectonics**: todays rates of plate motion, as determined from modern geodetic satellite and space methods (Smith et al. 1985) are compatible with those determined from magnetic lineations and directions of transform faults on the ocean floor for the last 80 million years (Minster and Jordan, 1978).
- **Seismic tomography**: convection pattern of hot and cold material become visible (Anderson and Dziewonski, 1984).
- The **World Stress Map** project is aimed at delineating sources of stress in the lithosphere and asthenosphere responsible for plate motions and tectonic activity (Zoback and Zoback, 1978).
- **Reflection survey of the continental crust** has revealed patterns in the upper and lower crust which image tectonic deformation and physical properties (Oliver,1986).

Global Geoscience Transects Project (GGT). - In 1985 a new project was launched in the ILP. It is the GGT project with a specially formed Coordinating Committee under the chairmanship of J. Monger/ Canada and H.-J. Goetze/West-Germany. Its goal is to construct geoscience cross-sections from all available geophysical, geological and geochemical information. The sections will be on equal scale, with the same projection, legend and colour code to facilitate a world-wide comparison. The predictive part of the transect will form the basis for future model testing by controlled experiments. ICL established on a working level the first international network of Global Geoscience Transects with dedicated teams around the world (Monger, 1986).

Deep Continental Drilling. The direct access to rocks at depth under in-situ conditions is the most advance possibility to verify geological-geophysical models of the earth interior established from surface observations only. The International Lithosphere Program is the only platform for international cooperation in the field of deep continental drilling. It has cosponsored a series of international conferences dedicated to deep drilling in Tarrytown 1984 (Raleigh, 1985), in Seeheim 1985 (Behr et al., 1987), and in Mora/Orsa 1987 (Boden and Erikson, 1988; as well as the international seminar at Yaroslawl in 1988.

Deep Drilling and Transects

The seminar at Yaroslawl had a special feature: for the first time reports on deep drilling are combined with reports on transects and on deep geophysical research. The idea to link deep boreholes by seismic lines with deep penetration even into the mantle arose in the USSR and was announced by Kozlovsky (1983).

Although deep boreholes are not reaching the depth of the deep geophysical probing of the lithosphere and asthenosphere, the combination of super-deep drilling and geophysical transects is important for a number of reasons:

- A borehole is a one-dimensional information which requires extrapolation into its three-dimensional neighbourhood and interpolation between neighbouring holes.
- Transects should pass through boreholes because the holes are located at geologically crucial positions and here in their vicinity the most accurate seismic information is normally available.
- The geophysical elucidation of the depth range beneath the bottom of the hole is important for a better understanding of the deep seated roots of the processes at drillable depth.

International Cooperation

From the seminar at Yaroslawl an improvement of international cooperation in deep drilling and deep geophysical research is expected because the seminar is held in the country leading in the field of super-deep drilling, because progress is reported from a number of other countries and because the results from deep drillholes and deep geophysical transects are reviewed together.

International cooperation should now grow beyond meetings of scientists at international conferences. The next steps are experts meetings on dedicated topics both in science and technology, agreements on exchange of data and cores, and of experts to participate in experiments on the drill sites, in the laboratory and in field surveys in foreign countries. The large expenses of super-deep drilling and deep geophysical research cannot be justified if the expertise of the international community is not involved in every one of these ventures.

The outcome of this conference could have an important influence on decisions on deep continental drilling in many countries around the globe.

Future of Deep Continental Drilling

Deep continental drilling is a challenge both to science and technology. We cannot reach the large depths at high temperatures, and other hostile conditions without stretching our technological abilities to and beyond its present limits and without enormous technological advances. We also have to realize that this takes the major part of the financial costs of this big science experiment. Our colleagues in drilling technology deserve high respect for their ingenuity, their endurance and their willingness to cope with unusual ideas of earth scientists.

But even more so, we must come to accept that the success of deep drilling depends ultimately on the success of science. In the end we will not be asked how deep or to what temperature we have drilled, but rather what scientific breakthroughs occurred which would not have happened without drilling.

There are three major dangers for the scientific success of deep continental drilling:

- we are blinded by technological success
- we are too easily satisfied and
- we are not willing to go to scientific limits.

This conference is so important to deep continental drilling in all parts of the world because it deals with frontier research in the Solid Earth Sciences, but also because this new earth science tool is expensive. This research tool is comparable in size to the tools of other big sciences like: nuclear accelerators, radio telescopes, satellites, and big research vessels.

It is interesting to observe that in the related science disciplines there was and is a wide **consensus** that such big tools are necessary for the progress of science and require special funding, i.e. with special protection and not in competition with normal research in the same field. It would simply be unfair that, e.g., an astronomer applying for a personal computer should be in competition with a project for a new radio telescope, or vice versa.

A similar consensus should be reached in the solid earth sciences. Although the funding structure is different from country to country, this discipline cannot avoid to reach an international decision on such a consensus. Those who have already embarked on the road of deep drilling have a high responsibility to the rest of the world to demonstrate that deep drilling is in fact the tool which is opening new doors in the solid earth sciences which could not be achieved by surface bound methods.

These are the questions which have to be answered to the earth science community and to the scientific community at large:

- which new doors are expected to be opened by deep drilling which lead to a better understanding of our planet and to testing of existing hypothesis?
- which gaps of our knowledge can be closed by deep drilling which cannot be closed by any other way?
- last not least, what intellectual awards, what science is coming out of deep drilling?

Bertolt Brecht is saying in his 'Life of Galilei':

> 'Astronomy did not move for thousand years,
> since they had no telescope'.

Earth Sciences have a telescope - deep drilling and deep geophysical probing ! - Are we dedicated enough to use this telescope to go beyond our present limitations, to reach for new frontiers of the earth sciences ?

References:

Anderson, D.L., and A.M. Dziewonski, Seismic tomography. Scientific America, **251**, 4, 60-68, October, 1984

Behr, H.-J., F.G. Stehli, and H.Vidal, Observation of the continental crust through drilling II, Springer, Heidelberg, 229 p., 1987

Boden, A., and K.G. Erikson, Deep drilling in crystalline bedrock, Springer, Heidelberg, Vol. 1, 364 p., Vol.2, 538 p., 1988

Brecht, B., Leben des Galilei, edition suhrkamp, 131 p., 1963

Kozlovsky, Y.A., Complex program for the study of the Earth's interior. Soviet Geology, **1**, 3 - 12, (in Russian), 1983

Minster J.B., and T.H. Jordan, Present-day plate motions. J.Geophys.Res., **83**, 5331-5354, 1978

Monger, J., The Global Geoscience Transects Project, Episodes, **9**, 4, 217-222, 1986

Oliver J., A global perspective of seismic reflection profiling of the continental crust. In: Reflection Seismology: A Global Perspective, AGU Geodynamic Series Vol. 13, 1-3, 1986

Raleigh, C.B. (editor), Observation of the continental crust through drilling I. Springer, Heidelberg, 364 p., 1985

Smith, D.E., D.C. Christodoulis, R.Kolenkieewicz, P.J. Dunn, S.M. Klosko, M.H. Torrence, S. Fricke, and S. Blackwell, A global geodetic reference frame from LAGEOS ranging. J.Geophys.Res., **90** (B11), 9221-9233, 1985

Zoback, M.L., and M.D. Zoback, Global patterns of intraplate stress: a status report on the World Stress Map project, submitted to Nature, 1988

SCIENTIFIC DEEP DRILLING AND GEOPHYSICAL SOUNDING – A MUTUAL SCIENTIFIC CHALLENGE TO UNDERSTAND THE PROCESSES SHAPING THE EARTH'S CRUST

K. Fuchs
P. Hubral

Paper presented at the International Seminar on
"Superdeep Drilling and Deep Geophysical Sounding"
Yaroslawl (USSR)
August, 1988

1. The new Frontier in the Exploration of the Lithosphere - Introduction

The new frontier in the exploration of the lithosphere is the combination of remote sensing and imaging with deep drilling, whereby the latter provides direct access to the deeper part of the crystalline Earth's crust. Super-deep drilling into depth ranges with conditions of high pressure-temperature and high chemical reaction rates challenges the imagination and abilities of the best of the engineers. Super deep drilling is also a tremendous challenge to all geoscientists since it provides **'ground truth'** for a wide spectrum of remote sensing and imaging methods that can be applied to the crystalline crust.

2. Geophysical Sounding and Imaging of the Earth's Crust - The Earth Becomes Transparent

From the beginning of seismic exploration for oil and gas, the now widely used method of reflection seismics acquired its credibility only by drilling. In the light of modern high-tech seismic instrumentation it still remains somewhat a miracle that these early seismic surveys produced results, which could be tested by drilling. This fact is reflected in the following text from an old advertising brochure of SEISMOS, Hannover, 1934:

> 'A number of drillholes were lowered to depths between 150m and 750 m without any indication of the existence of a saltdome. In 1933 the region was surveyed by the seismic method. Already during the first few days the presence of a saltdome was clearly established. Because of the unsuccessful drillholes doubt was shed upon the result of the seismic survey. Therefore, it was decided to test the seismic result by drilling at a place, where the saltdome was seismically predicted at a depth of 160m. Exactly at a depth of 160m salt was encountered.'

Drilling sites were from then on located by seismic surveys. Testing of seismic predictions by drilling led to improved seismic modelling, which in turn increased seismic prediction capabilities. It is well known that the technology of both the seismic and the drilling method was improved over the years dramatically. Especially the seismic method experienced a tremendous advance in the 1960's when digital recording was introduced.

Modern reflection surveys are unraveling the **three-dimensional structure** of sedimentary basins (Figure 1). The cube provides a 3D image of the reflectivity of a specified block in the basin. This image is obtained as the final step in a chain of rather comprehensive seismic processing packages that often comprise many more than familiar seismic processing routines such as static and residual correction, deconvolution, normal moveout correction, CDP stacking, post stack migration etc.. This chain of processes is constantly improved and perfected due to intensive research that makes use of the latest advancements in tomography, inverse scattering and communication theory. Images as those of Figure 1 have become the basis for a strong interaction between the drilling engineer and the exploration geologist and geophysicist. The testing of the seismic images of sedimentary basins by direct access through drilling was the basis of a continuous improvement of acquisition, processing and interpretation methods. Drilling established the success of modern geophysical sounding methods. However, it must be kept in mind that this "successful marriage" between the seismic reflection method and drilling is so far only established in oil exploration and for sedimentary basins. What are the chances of a similar happy marriage in the new environment of the crystalline crust? We are eagerly awaiting the answer.

A. Sedimentary vs. Crystalline Reflections

The exploration of the crystalline crust is a new challenge both to the drilling engineer and to the seismologist. When Junger (1952) reported the first deep crustal reflections down to Moho, only a few trusted him. There were numerous attempts to verify the hypothesis of the deep origin by statistical analysis of a multitude of records and by special experiments. The ultimate test by deep drilling had to wait for another two or three decades.

B. Open Problems in the Interpretation of Crystalline Reflections

Today it is known that the crystalline crust is returning seismic energy to the surface. Figure 2 is an example of a modern reflection section from the Black Forest (Lueschen et al, 1987). In many cases the lower part of the young continental crust is highly reflective in a laminated pattern, which is contrasting with the transparent appearance of the upper crust with its few discrete reflectors. Differences in wave propagation in the sedimentary and crystalline part of the crust are to be expected, some are listed in the following Table:

Sedimentary Basins	Crystalline Rock
Layers with strong velocity change justify CDP technique and post-stack migration. Extended reflectors, nearly horizontal.	Nearly constant velocity background with an abundance widely spread scatterers justifies inverse theory and pre-stack migration.

At our disposal today are already **thousands of kilometers of research reflection profiles** on the deep continental crust. These have revealed clear patterns within the crystalline parts. But there is only poor circumstantial evidence on what is causing the reflections.

A number of **possible models** have been proposed to explain the nature of the reflective patterns, such as:

Physical models:

Scatterers, diffractors, Fresnel zones, laminated media, focussing/defocussing, object dimension/wave length, wavefront healing

Geological models:

Mylonite zones, magmatic intrusions, cracked media (wet/dry), metamorphic contrasts

Todays seismic **processing methods** are highly sophisticated, but it is often forgotten that they have been developed for sedimentary structures. More and more observations point to the fact that the processing methods may not be the best for the processing of crystalline data, where complex structural patterns prevail over nearly horizontal elements.

In essence this means that we do as yet not know the nature of the reflectors within the crystalline crust. Neither do we know whether our presently available processing methods are ever likely to provide us with a complete picture of the crystalline crust, e.g., whether steeply dipping patterns remain unresolved in the present data processing.

3. The New Frontier in the Exploration of the Lithosphere

Four cases will be presented to illustrate the challenge of the new frontier in the exploration of the lithosphere:

- Presite survey at the KTB-drilling site in the Oberpfalz
- VSP observations at the KTB site
- S-wave observation - a new tool in crustal exploration
- 3D-seismic and VSP.

A. Presite Survey at the KTB-Drilling Site in the Oberpfalz

Reflection and refraction seismic investigations in the Oberpfalz have formed the basis for the decision on the final location of the KTB-drilling site. A grid of reflection lines (Figure 3) together with a network of wide angle observations covered the region chosen for the presite investigation (DEKORP Research Group, 1988).

Figure 4 is a typical seismic migrated section from the vicinity of the KTB-drilling site in the Oberpfalz. An abundance of laminated reflectors in the upper crust and a shallow high velocity body detected by the refraction survey are prominent characteristics of the overthrusting regime at the mega-suture zone of the Variscan mountain system (Weber and Vollbrecht, 1988).

A comparison of CMP stack sections with records in crystalline rock often shows that classical CMP-processing may wipe out clear indications of reflected/diffracted energy possibly arising from strongly dipping and scattering elements (Louie et al., 1988). Figure 5 shows the fundamental difference that CMP reflections have in layered (left) and diffracting (right) media. While CMP primary reflections in layered media possess clearly separated hyperbola at different zero-offset times, those of diffractions may have the same zero-offset time (and different moveout) for different scatterers.

B. VSP Observations at the KTB-Site

The same insufficiency as indicated above is also true for a comparison of VSP records and CDP sections at boreholes in sedimentary and crystalline rocks. While in sedimentary basins surface and borehole seismic measurements in general match very well, this appears to be far less the case in crystalline rock. In contrast to the VSP in sediments where upward traveling P- and S-wave energy generally correlates well on all traces in the records, the first VSP sections in the KTB-hole (Figure 6) shows upgoing energy which appears like reverberations and is only correlated over a small range of traces.

C. S-Wave Observations and Stress - New Dimensions in Crystalline Exploration

Recent shear wave experiments in the crystalline crust of the Black Forest have shown (Figure 7) that propagation of S-waves in the upper crust is quite different from that of compressional waves. The P-wave pattern of reflected energy reveals the contrast between an almost transparent upper crust and the strongly laminated lower crust. Surprisingly this contrast disappears in the light of S-waves: both upper and lower crust return a considerable amount of S-wave energy. It appears that the early returning S-wave energy arises from P- to S-conversions in the upper crust.

One possible candidate for the explanation of the observed difference in P- and S-wave propagation in the upper crust is the presence of fluid filled cracks. Such fluid filled cracks would be almost transparent for P-wave but would affect S-wave propagation.

The elucidation of the physical and geological reason for the different behaviour of P- and S-waves in the upper crust is a **prime target for testing by deep drilling.** Open, fluid-filled cracks at depth can only be discovered **in-situ** and not in outcrops where the cracks would have disappeared. Especially the combination of the two modern logging tools - **Acoustic Borehole Televiewer** (BHTV) and **Formation Micro Scanner Tool** (FMST) - offers the possibility to determine the presence and orientation of fluid filled cracks on the borehole wall.

A comparison with the orientation of the stress tensor determined from breakouts analysis in the borehole is a unique possibility to test the hypothesis that the cracks might have been opened in the present tectonic stress field. The depth distribution of such cracks and their relation to the present stress field is of utmost importance to a better understanding of transport processes through the crust.

D. Integrated 3D-Seismic - A Necessity in Crystalline Exploration

The network of seismic lines for the presite survey was not dense enough to provide a seismic model in which the positions and the nature of the individual reflectors and patterns can be verified by drilling through coring and downhole logging. The reflection section, migrated in two dimensions, e.g., is very likely contaminated with energy returning to the surface from off the vertical plane. Therefore, it is expected that a three-dimensional migration would produce vertical slices cleaned from off-plane energy.

Crystalline rocks form a genuinely three-dimensional earth structure, in which the main objects returning energy to the surface are scatterers of irregular distribution, shape and size within a medium with little variations in average velocity and with small velocity contrasts. In this situation 3D acquisition and processing techniques become an absolute necessity to:

- correctly migrate the scatterers to their proper locations within the 3D-space
- substantially enhance their horizontal (lateral) resolution and
- ultimately provide estimates of physical parameters.

A 3D-seismic survey (<u>Figure 8</u>) will be performed at the KTB-site in the period between the completion of the pilot hole and the beginning of the main hole. The following acquisition scheme will be implemented.

On an approximately 18km x 18km grid the survey lines will be laid out such as to achieve with respect to each subsurface point a nominal omni-directional subsurface coverage of 1500%. In order to achieve a bin size of 50m x 50m, 10 parallel geophone lines with 48 geophone groups - corresponding to 480 traces - will be placed on parallel lines 400m apart. The geophone groups themselves will have a separation of 100m. The vibrator lines are perpendicular to the geophone lines. The vibrator position interval will alternatively assume 100m, 200m and 300m. Attempting a 10-fold vertical stack 40 vibrator positions can be used per day. With the above arrangement moving in altogether 4 parallel strips the survey area will be covered in approximately 70 days.

The above 3D-seismic experiment is likely to be combined with a number of other seismic experiments: VSP, MSP (moving source profile), S-wave, reflection, observation, refraction seismics, anisotropy experiments. These form a comprehensive package of integrated seismics.

It is important that the 3D-seismic image of the rock around the KTB drill site is established before the drill bit reaches the main structures (e.g. high velocity body) to be tested by drilling.

4. Conclusions

We are at the beginning of a new era in the exploration of the lithosphere. The cooperation between drilling engineer and remote sounding geoscientists is analogous to the interaction between surgery and x-ray tomography. Only the knife of the surgeon provides the ultimate test to what x-ray imaging has predicted of the human body in a non-invasive way. In the scenario of the Earth the geophysicist tells the engineer where to drill, and predicts the most important depth-ranges crucial for the testing of specific models of the Earth's interior. Drilling also provides the surprise of facing the unexpected. This in turn leads to new and better understanding of the physical, chemical state and evolution of the Earth's crust. Geophysical methods extend this information to larger depth and into the immediate neighbourhood of the borehole.

International cooperation in this new exploration of the lithosphere is a must. It has been the privilege of earth scientists from the beginning to share their observations and their ideas. Earth scientists know that new ideas develop best in a climate of international cooperation, stimulation, and peaceful competition.

5. References

DEKORP Research Group, Results of the DEKORP 4/KTB Oberpfalz deep seismic reflection investigations. J.Geophys., **62**, 69-101, 1988

Junger, A., Deep basement reflections in Big Horn County, Montana. Geophysics, 16, 499-505, 1951

Louie, N.J., R.W. Clayton, and R.J. LeBras. Three-dimensional imaging of steeply dipping structure near the San Andreas Fault, Parkfield, California. Geophysics, **52**, 2, 176-185, 1988

Lueschen, E., F. Wenzel, K.-J. Sandmeier, D. Menges, Th. Rühl, M. Stiller, W. Janoth, F. Keller, W. Söllner, R. Thomas, A. Krohe, R. Stenger, K. Fuchs, H. Wilhelm, and G. Eisbacher. Near-vertical and wide-angle seismic surveys in the Black Forest, SW Germany. J.Geophys. **62**, 1-30, 1987

Weber, K. and A. Vollbrecht, The crustal structure at the continental deep drilling site, Oberpfalz. in: Exploration of the Deep Continental Crust, editors, German Deep Drilling, Springer Verlag, Heidelberg, in press, 1988

6. Figure Captions

Figure 1: Seismic tomography. 3D-cube of finally processed seismic reflection data (courtesy of PRAKLA-SEISMOS)

Figure 2: Black Forest reflection section from the central part of profile 8402. a) Stacked section, b) migrated section. Note the difference between the highly reflective lower crust and the almost transparent upper crust, which shows a bright spot at 3.5 s TWT (from Lueschen et al., 1987)

Figure 3: Location map of KTB and DEKORP lines in the Oberpfalz

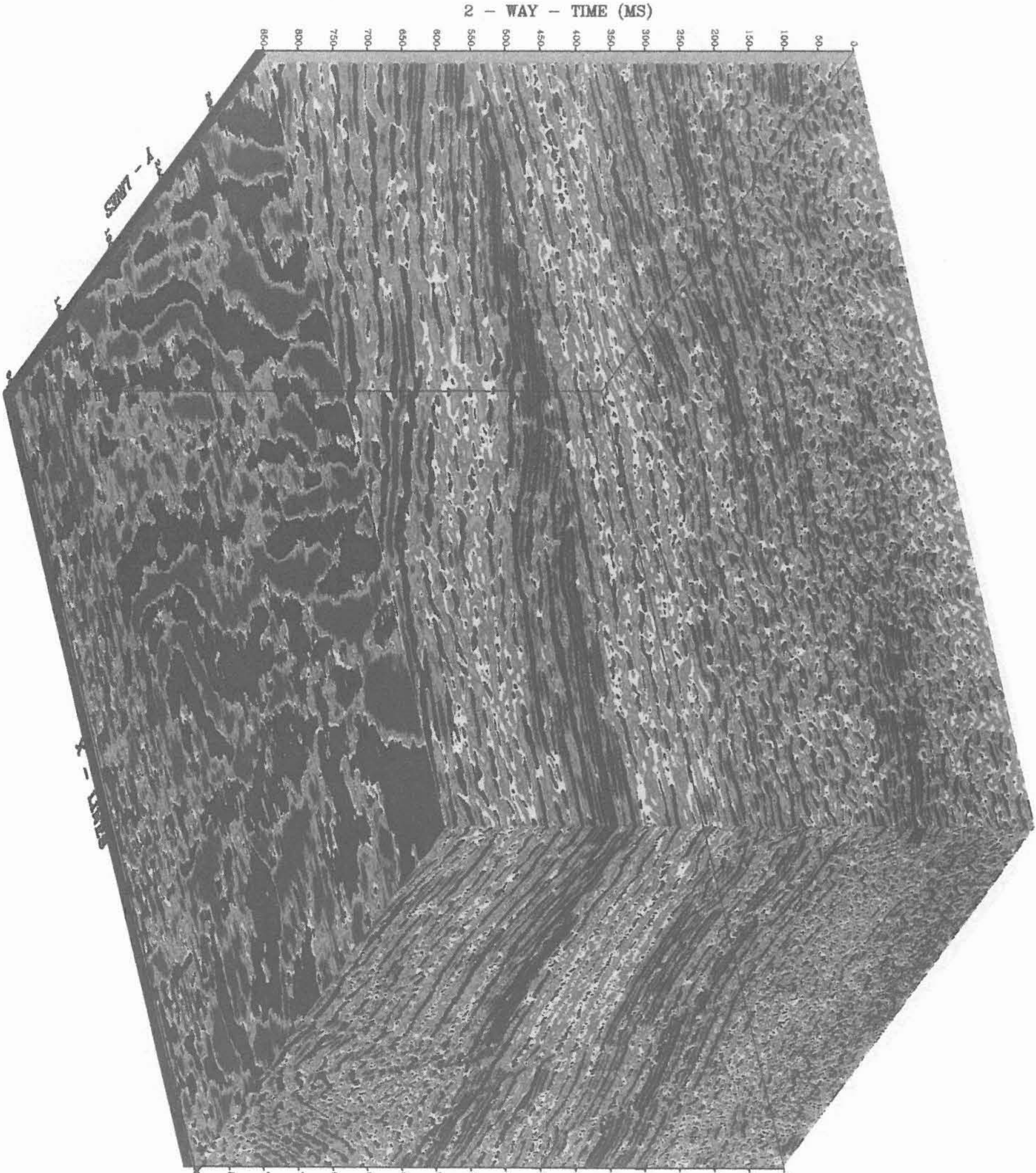
Figure 4: Seismic migrated section of KTB profile 8502 (from DEKORP Research Group, 1988)

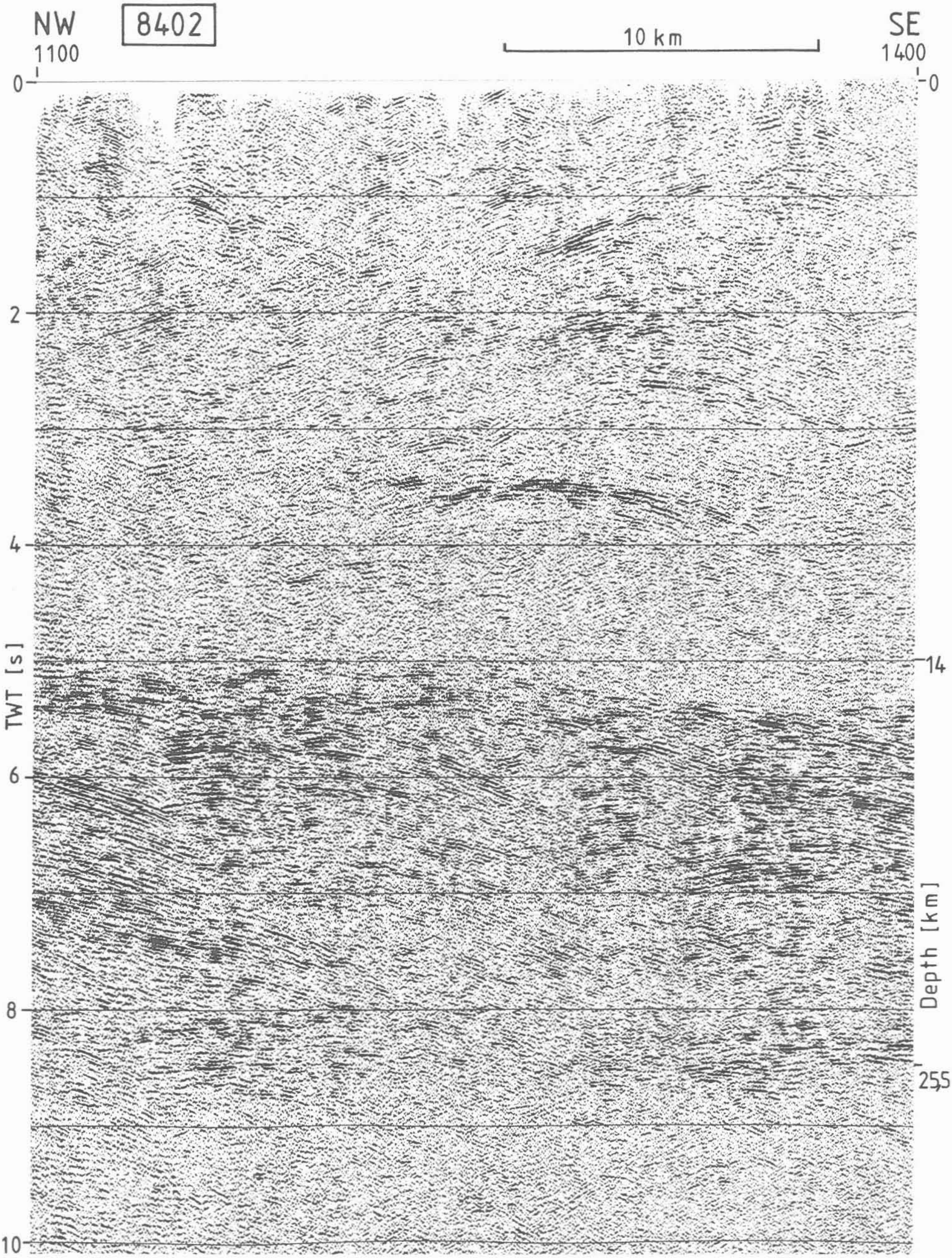
Figure 5: Sketch that demonstrates the principal difference between moveout curves resulting from reflecting and scattering objects in a CMP survey.

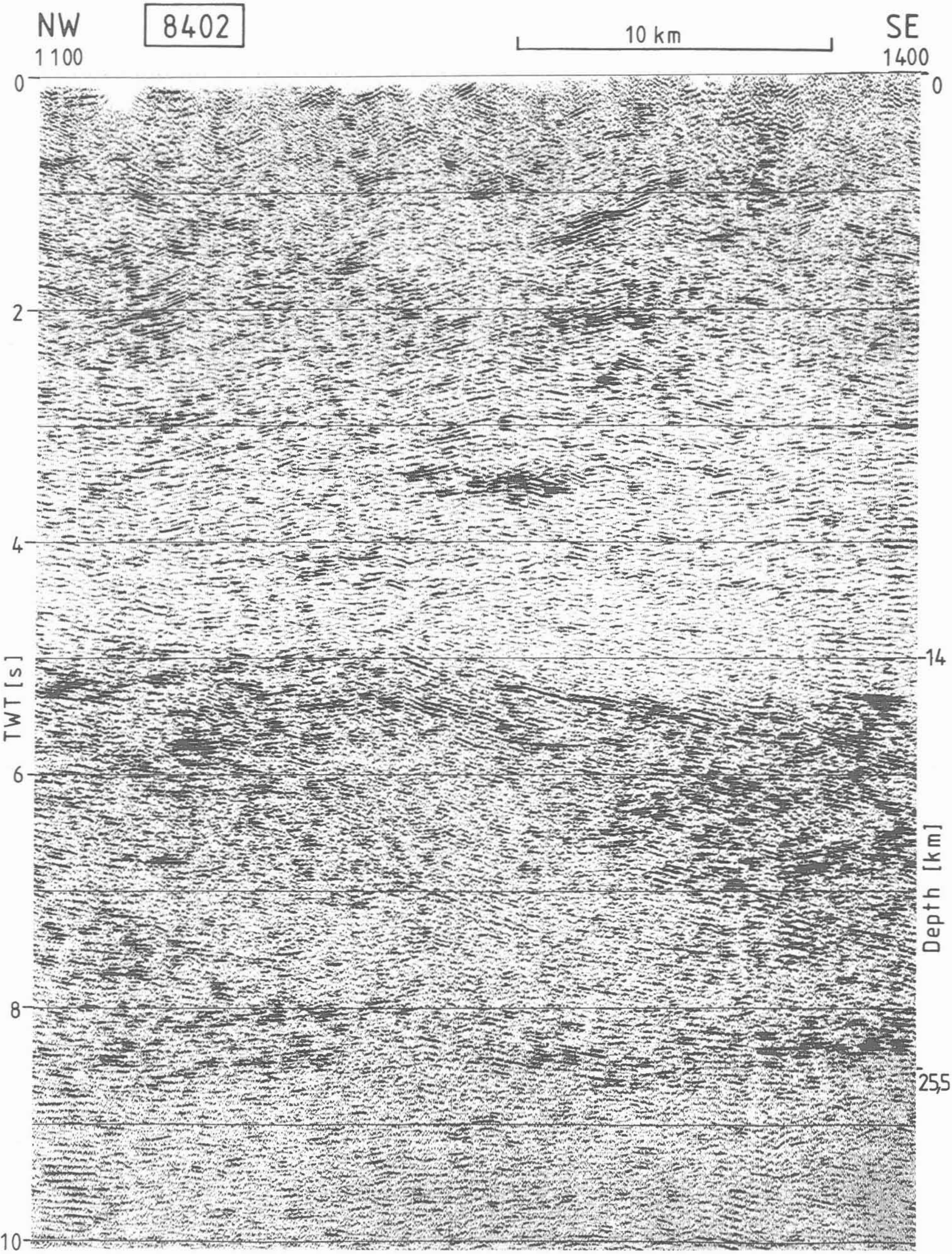
Figure 6: Unprocessed field VSP record from the KTB hole down to 2200m.

Figure 7: Three-component reflection shot records from the Black Forest(compare Figure 2). The record at the right is the vertical section Z stretched in time by the factor square root of 3, allowing a direct comparison of P and S phases. Note that the correspondence of reflected S-wave energy down to the crust mantle boundary (Mss) at 16 s TWT.

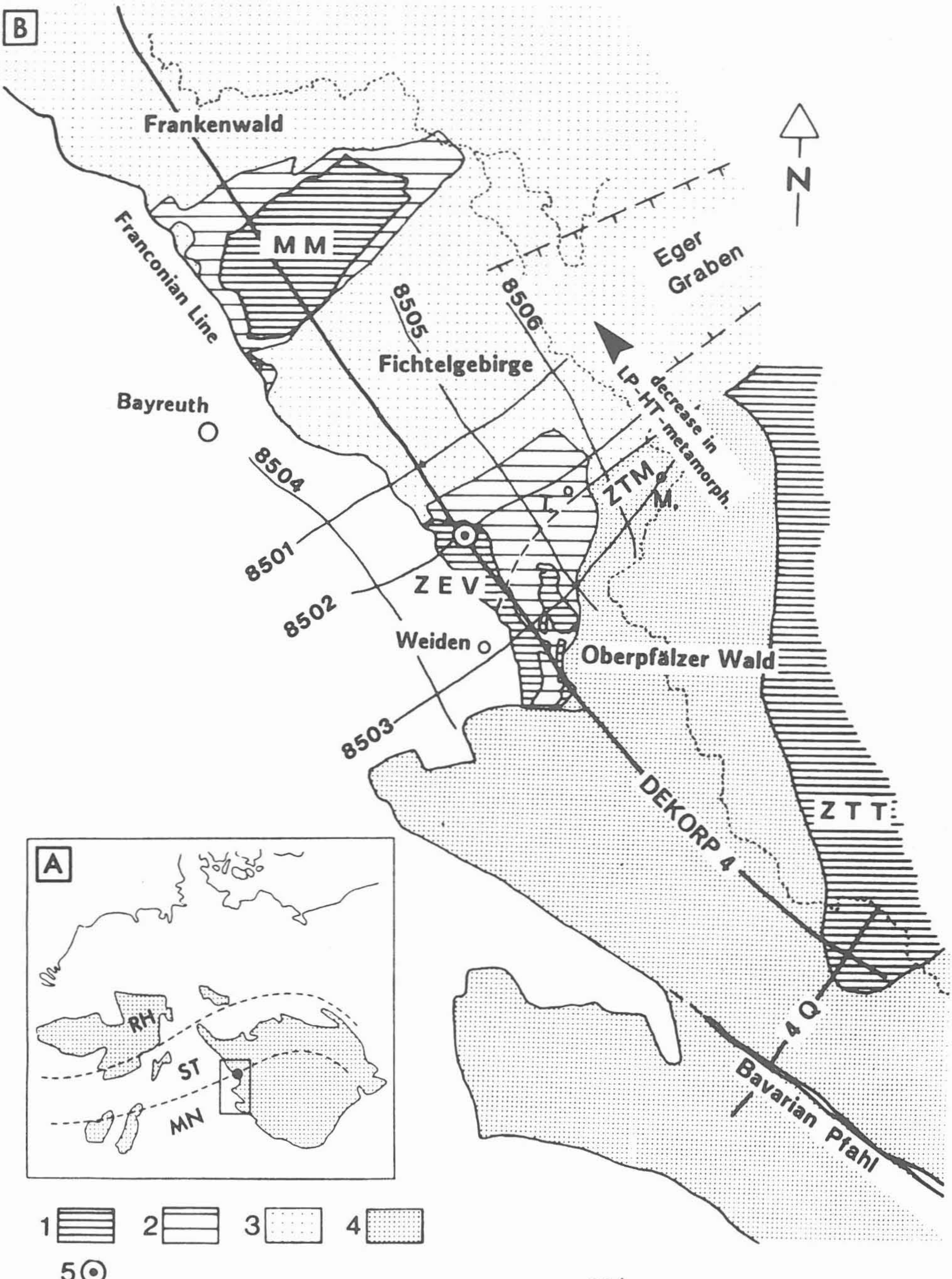
Figure 8: Proposed survey lines for 3D-seismic acquisition scheme at the KTB location.

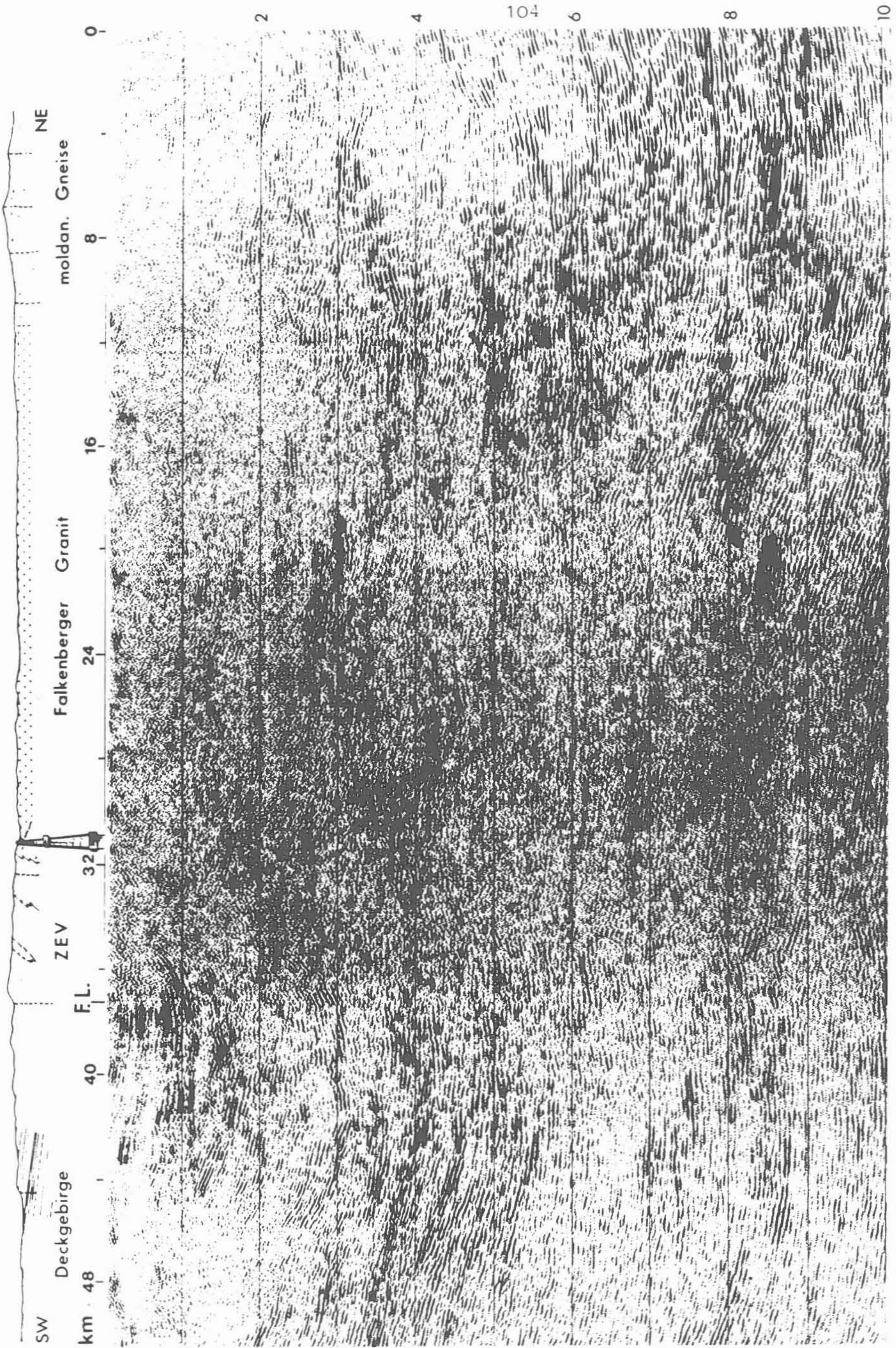

2 - WAY - TIME (MS)
850
800
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
Y - LINES
X - LINES
850
800
750
700
650
600
550
500
450
400
350
300
250
200
150
100
50
0
2 - WAY - TIME (MS)

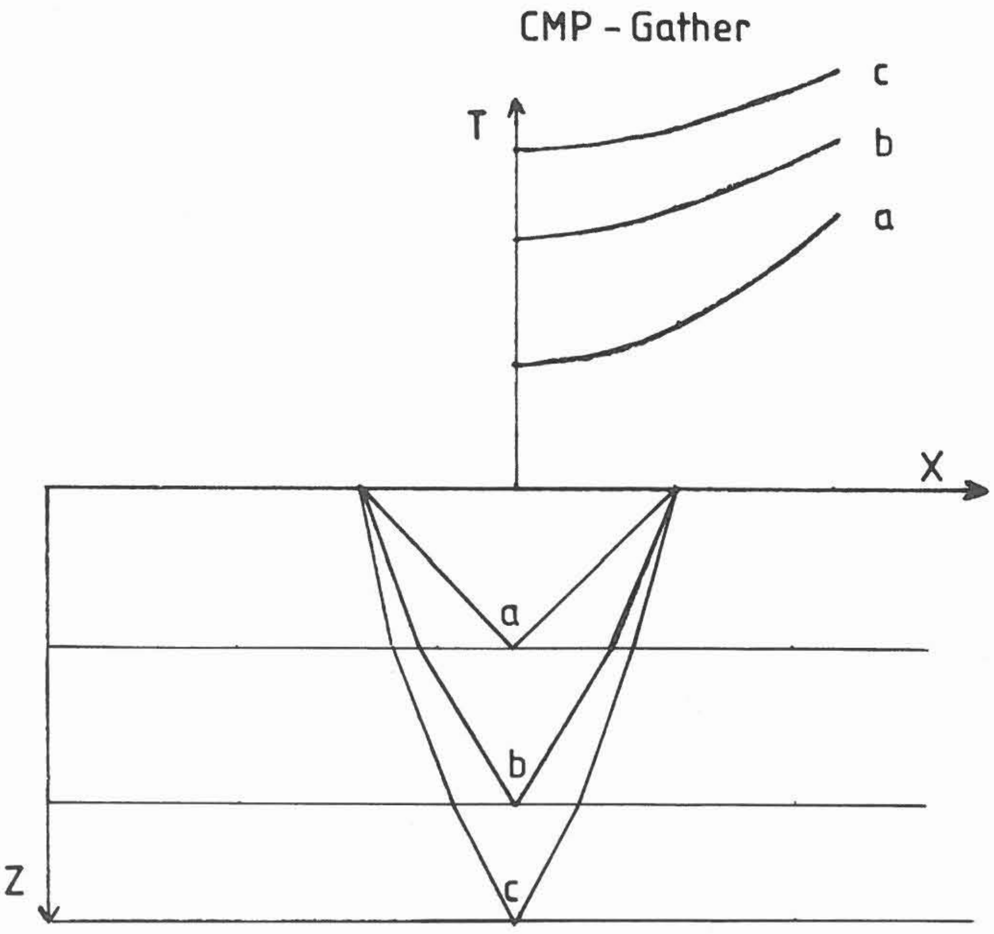

NW
8402
10 km
SE
1100
1400
0
2
4
6
8
10
TWT [s]
0
14
25,5
Depth [km]



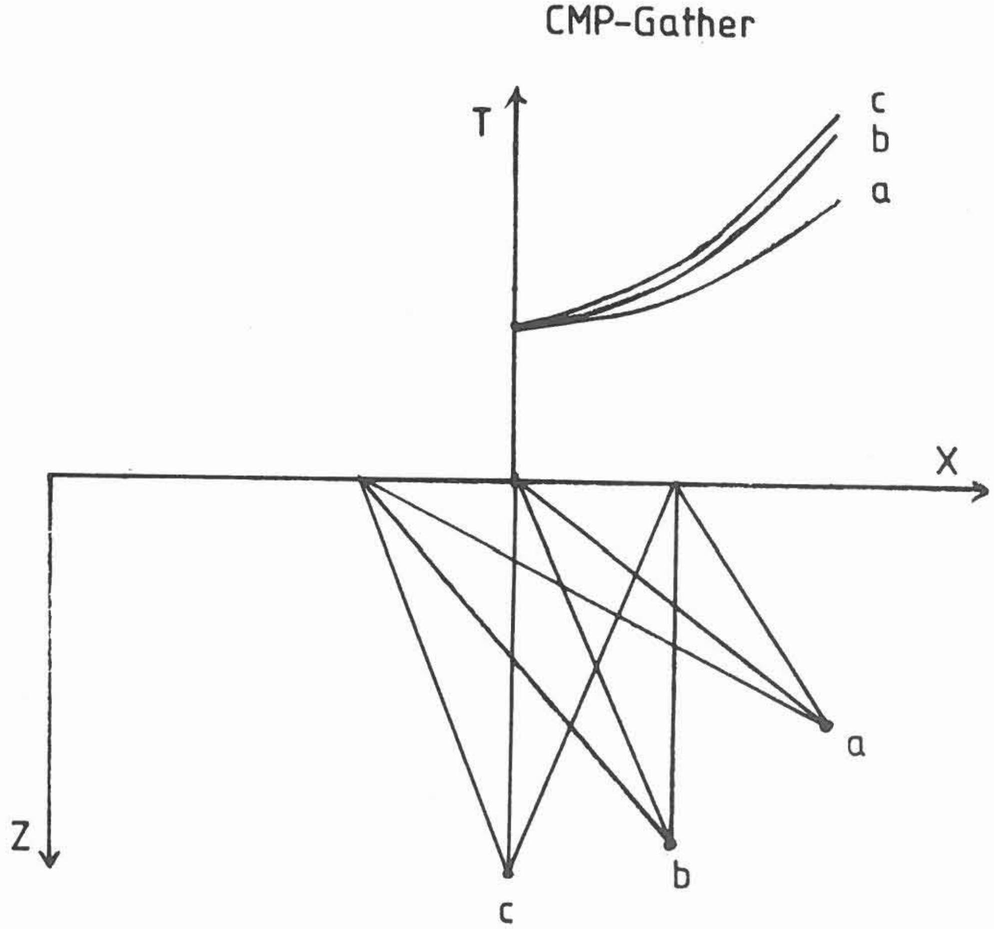
NW
8402
10 km
SE
1100
1400
0
2
4
6
8
10
TWT [s]
0
14
Depth [km]
25,5


B
Frankenwald
N
MM
Franconian Line
Eger Graben
8505
8506
Fichtelgebirge
decrease in LP-HT-metamorph.
Bayreuth
8504
ZTM
T.
M.
8501
ZEV
8502
Weiden
Oberpfälzer Wald
8503
DEKORP 4
ZTT
4 Q
Bavarian Pfahl
A
RH
ST
MN
1
2
3
4
5
50 km


SW
NE
km
0
8
16
24
32
40
48
moldan. Gneise
Falkenberger Granit
ZEV
F.L.
Deckgebirge
2
4
6
8
10
TWT
s
104

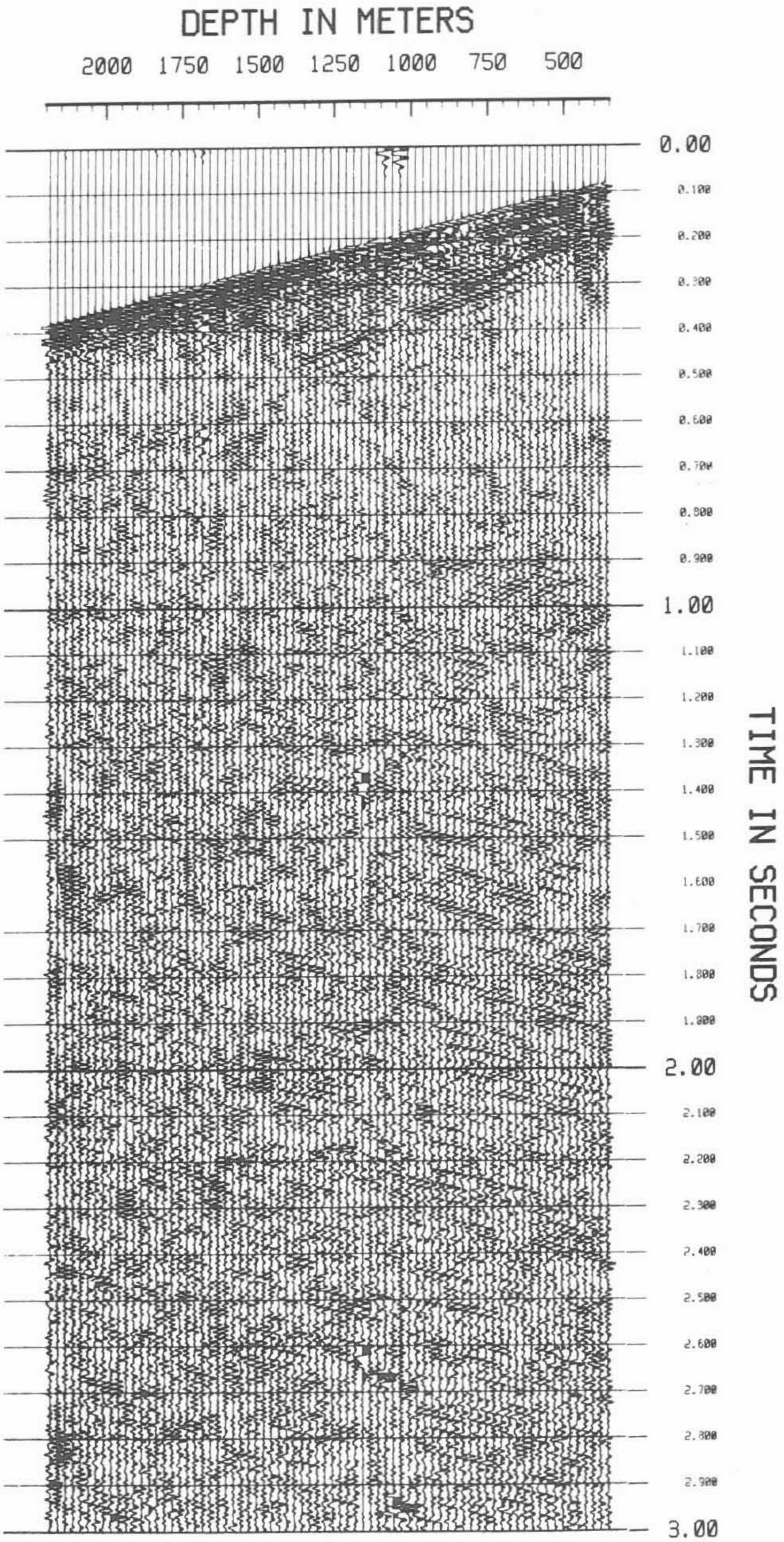


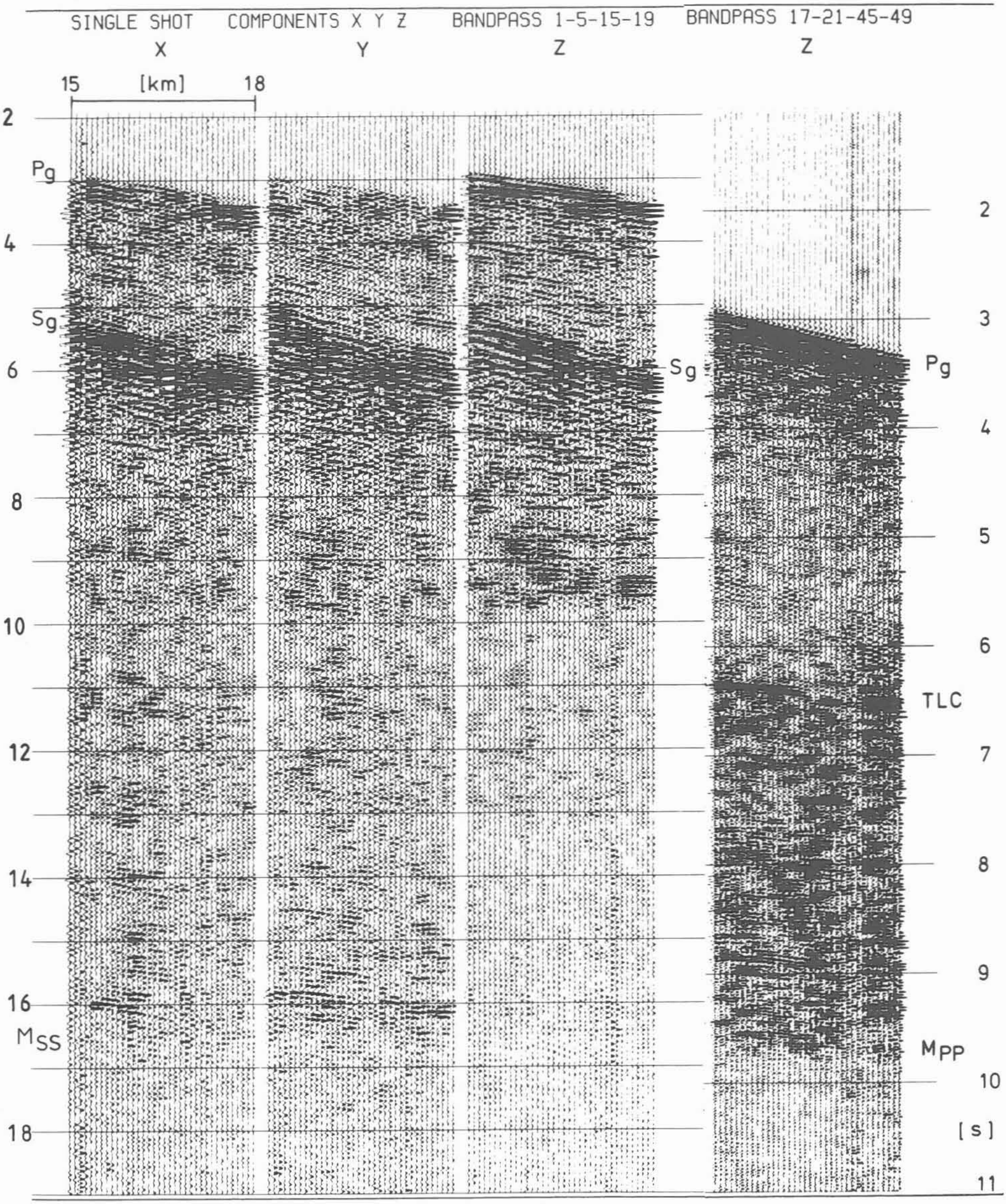
layered medium

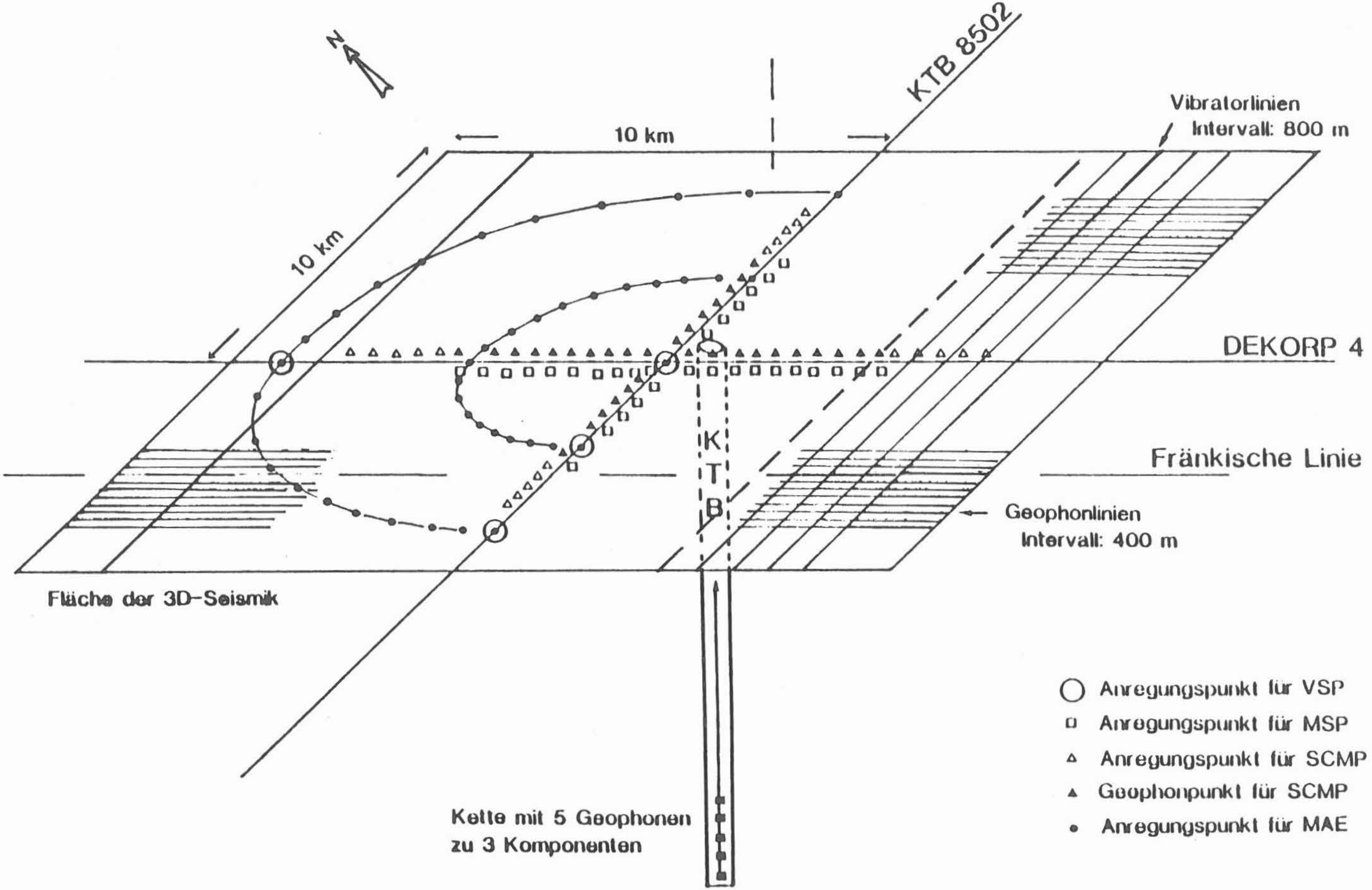


scattering medium

VERTICAL


DEPTH IN METERS
2000
1750
1500
1250
1000
750
500
0.00
0.100
0.200
0.300
0.400
0.500
0.600
0.700
0.800
0.900
1.00
1.100
1.200
1.300
1.400
1.500
1.600
1.700
1.800
1.900
2.00
2.100
2.200
2.300
2.400
2.500
2.600
2.700
2.800
2.900
3.00
TIME IN SECONDS


SINGLE SHOT
COMPONENTS X Y Z
BANDPASS 1-5-15-19
BANDPASS 17-21-45-49
X
Y
Z
Z
15
[km]
18
2
4
6
8
10
12
14
16
18
Pg
Sg
Sg
MSS
2
3
Pg
4
5
6
TLC
7
8
9
MPP
10
[s]
11


N
KTB 8502
10 km
10 km
Vibratorlinien
Intervall: 800 m
DEKORP 4
Fränkische Linie
K
T
B
Geophonlinien
Intervall: 400 m
Fläche der 3D-Seismik
Kette mit 5 Geophonen
zu 3 Komponenten
○ Anregungspunkt für VSP
□ Anregungspunkt für MSP
△ Anregungspunkt für SCMP
▲ Geophonpunkt für SCMP
• Anregungspunkt für MAE

FLUID-DEPENDENT PROCESSES AND THEIR DOCUMENTATION IN FLUID INCLUSIONS IN ROCKS FROM THE KTB

E. Althaus

Paper presented at the International Seminar on
"Superdeep Drilling and Deep Geophysical Sounding"
Yaroslawl (USSR)
August, 1988

FLUID-DEPENDENT PROCESSES AND THEIR DOCUMENTATION IN FLUID INCLUSIONS IN ROCKS FROM THE KTB

Fluid research has been one of the major objectives in the German Continental Deep Drilling Project right from the beginning. Manyfold fluid-dependent processes occur within the lithosphere. It is not only transport of fluid or the energy combined with it but also the interaction of lithospheric rocks with percolating or co-existing fluids that requires primary interest.

The influence of fluid-dependent processes on rocks may be subdivided in chemical and physical processes. Chemical processes influence in the first line the rock composition both by re-crystallization or mineral and rock alteration, by mineral dissolution or by mineral deposition. Fluid-dependent physical processes are connected with rock properties like electrical conductivity, wave velocities, mechanical stability or rigidness of the rocks in question. Of course these catalogues are by no means complete. It must also be envisaged that both co-genetic or primary fluid events as well as secondary ones may occur. The question is, however, how to discriminate between them, and which influence do the different processes exert.

Out of the manifold kinds of interaction between fluids and rocks, a few problems have been selected which illustrate the role and importance of fluids for crustal processes (Fig. 1). The first group of questions is correlated with mineral and rock stability. It is quite obvious that mineral stability is governed by fluid- rock interaction which might change the mineral contents of a rock to a considerable extent (metasomatism). This, however, is not the subject of the present discussion. Equally important as phase composition of a rock is its mechanical stability. It of course, strongly influenced by the mineral composition as well as the mineral texture. It is also dependent on the fluids present in the rock.

Among the different kinds of rock fluids, one is particularly important in this respect, namely the contents of fluid inclusions in minerals. There have been many discussions about the primary or secondary nature of fluid inclusions. It is no doubt that in many cases primary co-genetic fluid inclusions might survive in minerals even after a long geological history. This persistance of fluid inclusions, however, is strongly influenced by processes of rock deformation. The important points in this respect are listed in Fig. 2. One important topic is that in aqueous inclusions the P.T. development of the trapped fluid follows different characteristics than those of the rock itself.

As has been shown (WALTHER and ALTHAUS, 1986), negative differential pressures will develop between fluid inclusions and the surrounding mineral. The development of differential pressure is shown in Fig. 3. If there is no shear movement within the rock, this fact is of no importance for the preservation of fluid inclusions. If, however, the rock is deformed, the fluid inclusions with underpressures of an order of 1 to 2 kbars will act as centres of mechanical instability. That means that deformation of minerals will start at the zones of fluid inclusions. This process will destroy the original population of fluid inclusions, and both the volume and the contents of the cavities will be redistributed within the minerals.

It is obvious that during the deformation process free fluids might be present within the rock. It has been shown by deformation experiments in the course of work in the Sonderforschungsbereich 108, "Stress and Stress Release in the Lithosphere", that in the presence of free fluids the rock strength is reduced considerably (Fig. 4). From these data it is obvious that as soon as fluids are set free within the rock, the deformation process will be enhanced considerably and might well lead to cataclastic deformation. The brittle-ductile transition, therefore, is a process dependent of fluid contents and on the presence of fluid inclusions.

As can be seen from the second topic dealt with in Fig. 1, there is a distinct interrelation between rock composition and fluid contents. Compositions of fluids are not independent of the bulk rock composition. There has been no definite proof so far that genuine mantle fluids are trapped in crustal minerals without interaction with crustal chemistry. A very instructive example for fluid contents in minerals of deep-seated origin has been found recently in granulites from Calabria, Southern Italy, by ISTRATE and ALTHAUS (1988). In the massive of the Sila Mountains a series of lower crustal rocks has been preserved, more or less granulitic in composition. In these rocks early, probably cogenetic, fluid inclusions have been found (Fig. 5). They contain primary fluids that have survived all subsequent geological processes, presumably because no pervasive deformation has occured. These fluid inclusions are poor in water, as might be expected of granulitic rocks, but they are rich in methane and nitrogen and, in a few cases only, also in carbon dioxide. Those fluid inclusions which exhibit high concentrations of methane occur in rocks which are rich in graphite. It is assumed that they have been formed by interaction of an aqueous fluid with these graphite bearing rocks which has generated both CH_4 and CO_2; the methane, therefore, is not of mantle origin but has probably formed by fluid-rock interaction.

Besides these primary inclusions, another generation is present which has been formed by secondary retrograde processes. These fluids are aqueous and typically highly saline. Therefore, two distinctly different generations of fluids can be observed, that means, the influence of two independent fluid events.

This leads us to the question how fluid events might be distinguished and characterized, and how they might be registered in a rock of deep seated origin. Of course, there are several criteria which can be applied to analyse fluid inclusion populations for different fluid events. (Fig. 6).

Mechanical and geometrical criteria can be derived from microscopical examination, for instance, if fluids are arranged on lines or planes or fractures, or show effects of necking-down, they must be classified as secondary. It can also be tried to distinguish fluid events from each other by statistical methods. Frequently, this is done by plotting a certain fluid parameter like homogenization temperature or salinity versus the number of observations, sometimes statistics in density distribution is applied.

Figs. 7 and 8 show examples of that kind. From these figures it is evident that there is a maximum of densities and salinities which suggest a certain fluid event to have occured with fluid composition according to that maximum. This maximum, however, is entirely meaningless, as will be shown below. A way must be found by which genetical conclusions can be drawn from the distribution of fluid inclusions. One such method is to use a different approach in analyzing fluid data. It has turned out to be more effective to plot the data for fluid composition and density in a different way. Fig. 9 shows a plot of salinity versus density for the same gneissic rocks as in Figs. 7 and 8 (Urach borehole). Its most conspicious feature is the occurence of a boundary line to the right of which no data points plot. The same applies for metadiorites from the same borehole (Fig. 10). The boundary lines in both figures can be correlated with P.T. data of the rocks. It can be deduced that they correspond with the P.T. data of trapping of the last fluid generation. From the position of the boundary line, it is inferred that this occured at a temperature of 150 °C and a pressure of 700 bars (after BAUER, 1987). Lines that can be traced at lower densities correspond to fluid events at higher P.T. conditions. From this discussion, it can be concluded that indeed fluid events of different generations can be reconstructed if the data are treated adequately: that means analysing the whole population of fluid inclusions in appropriate phase diagrams.

The results of the preceding discussion have been applied to rocks from the KTB pilot borehole. The samples investigated so far are listed in Figs. 11 and 12. The fluids are characterized by a typical hydrosaline composition. In most of them CO_2 and/or CO are present. They are probably not cogenetic with the bulk rock paragenesis. They have evidently been influenced by fluid rock interaction and have been trapped not during the general main rock formation process but during a later secondary deformation event. The original fluids may have been formed at considerably greater depths at pressures and temperature considerably exceeding those prevailing now.

It can be concluded that the rocks may have contained a higher concentration of original fluid inclusions before deformation. The deformation process has probably occurred while the rocks were at lower temperature and pressure than during their primary crystallization. That means that the fluid inclusions have passed throug an intervall of high differential underpressures by a process like the one depicted in Fig. 3. Under these conditions, they had been subjected to a deformation process which has destroyed the old inclusions liberating their contents, at least partly. These liberated fluids were then able to react with the bulk rock material and to adjust their chemical composition to the P.T. conditions prevailing during the deformation process. The CO found in several inclusions can be taken to verify this fact. This new fluid has been trapped in fluid inclusions of a new generation now preserved in the rock. The process of liberation of fluids by disruption of fluid inclusions, however, has intensified the deformation process itself as soon as it had started. This might well have been the reason for the formation of strongly deformed parts which can be observed in the rocks now.

The topics discussed above have been reconstructed from the observation of rocks that are at low P.T. conditions at the moment. As can be seen from Fig. 3, the most interesting area for rocks of the type observed in the pilot borehole is around 300 °C at 2 kbars, that means under conditions which can be expected in a depth of about 10 km. If this area is hit by the deep borehole, fluid inclusion research will become a highly interesting topic in the deep drilling project.

BAUER, F. (1987): Die Kristallin-Gesteine aus der Bohrlochvertiefung Urach 3 und ihre fluiden Einschlüsse: Eine Interpretation der hydrothermalen Überprägung anhand der Fluid Daten aus Einschlußmessungen - Ph-D Thesis, Karlsruhe

ISTRATE, G. and ALTHAUS, E. (1988): $CH_4 \pm N_2$ Fluide Einschlüsse hoher Dichte in den Granuliten Calabriens, Italien - Fortschr. Miner. 66, Beih.

WALTHER, J. and ALTHAUS, E. (1988): 2. KTB-Kolloquium Seeheim 19.9. - 21.9. Poster Programm S. 46

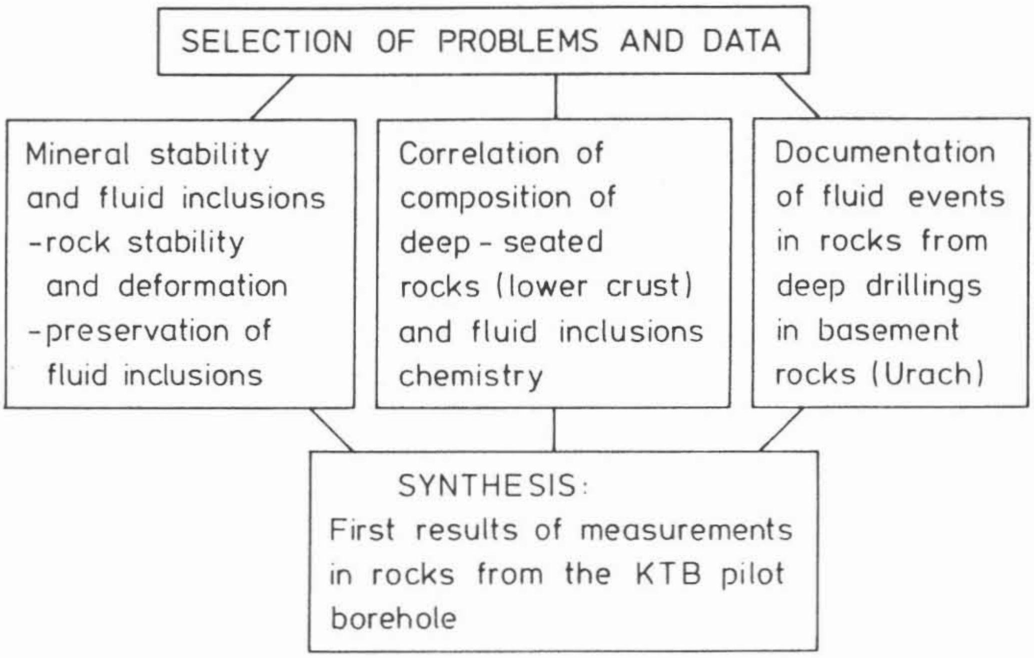


Fig. 1: Some problems of fluid rock interaction in deep seated crustal rocks

MINERAL AND ROCK STABILITY AND FLUID INCLUSIONS

- Development of differential pressures
- Deletion and reorganization of fluids by tectonic movements
- Rock deformation in presence of fluids

Fig. 2: Interrelation between rock stability and fluid contents

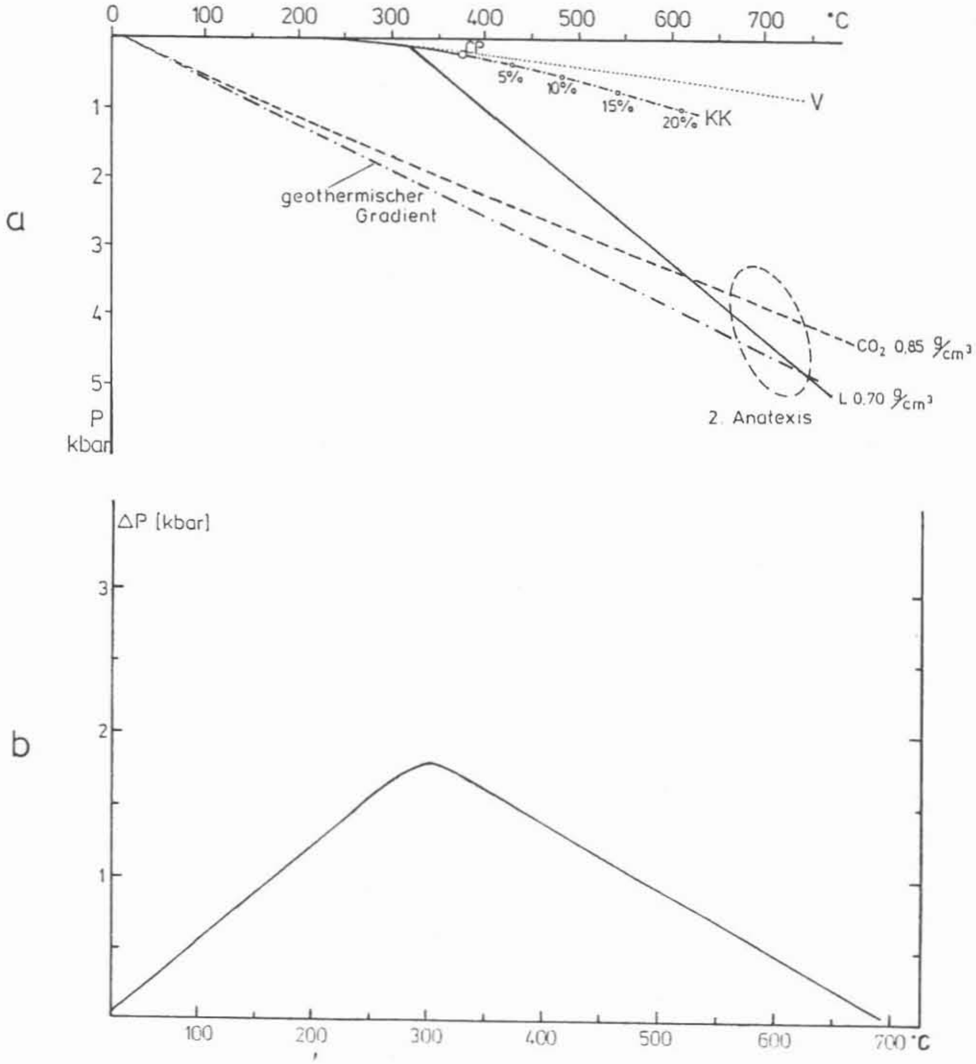


Fig. 3: Development of differential pressures in fluid inclusion during cooling and uplift.

Deformation Experiments

1. Dry

T = 250 °C
stress - to - rupture 150 MPa

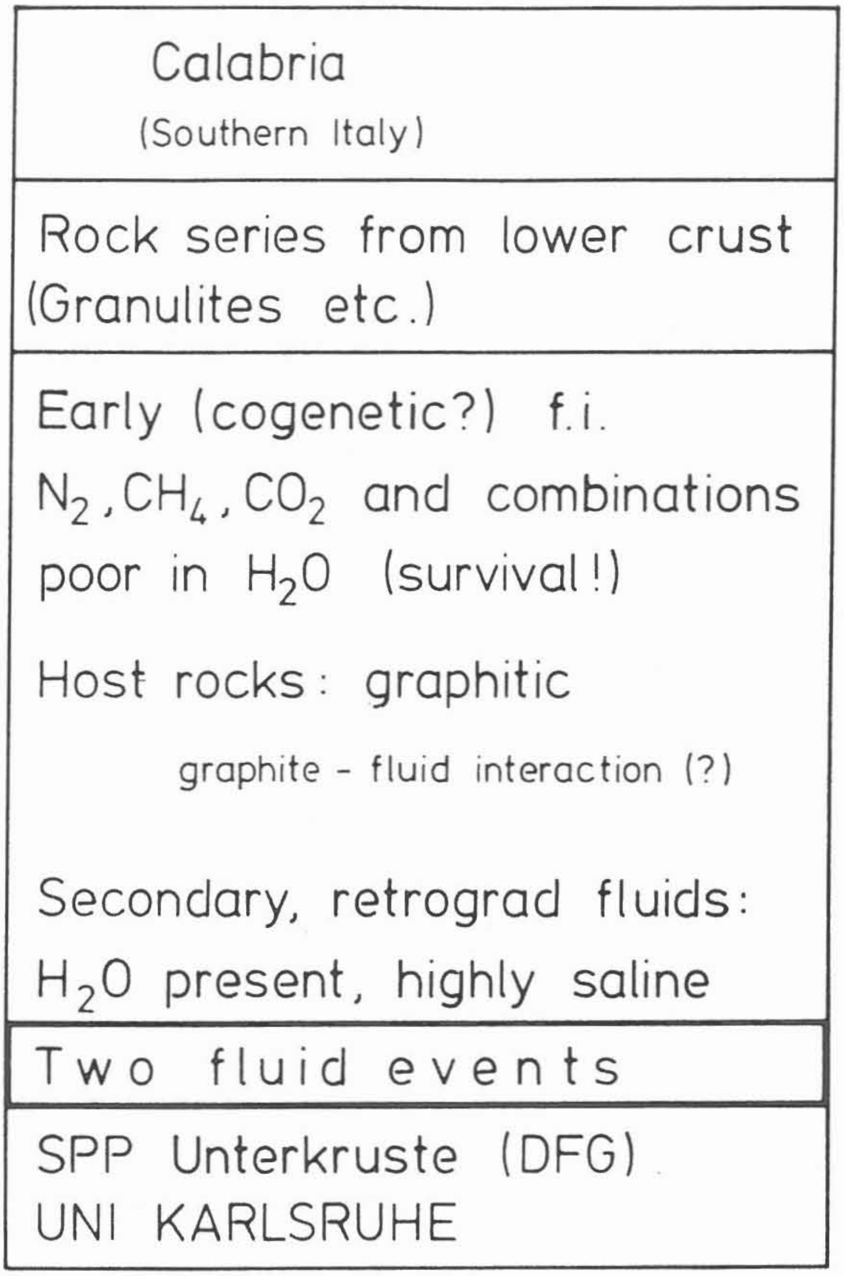
2. Water „saturated"

T = 250 °C
$P_{ext.}$ (P_f) = const. 65 100 MPa
deformation 5300 7000 µm/m
str.-to-rupt. (ΔP) 64 66 MPa

T = 250 °C
$P_{ext.}$ (P_f) variable 65 to 10 MPa
deformation = const. 3750 µm/m
str.-to-rupt. 127 MPa (P_f = 10)

SFB 108 UNI KARLSRUHE

Fig. 4: Correlation between rock strength and presence of fluids



Calabria

(Southern Italy)

Rock series from lower crust (Granulites etc.)

Early (cogenetic?) f.i.

N_2, CH_4, CO_2 and combinations

poor in H_2O (survival!)

Host rocks: graphitic

graphite - fluid interaction (?)

Secondary, retrograd fluids:

H_2O present, highly saline

Two fluid events

SPP Unterkruste (DFG)
UNI KARLSRUHE

Fig. 5: Fluid inclusions in rocks from the lower crust of calabria

REGISTRATION OF FLUID EVENTS

MECHANICAL CRITERIA?
GEOMETRICAL CRITERIA?
STATISTICS?

Statistics based on Phase Diagrams
Example: System H_2O - NaCl
Rocks: Urach borehole; depth 3300 m
temperature ≈ 140 °C

Evaluation: Salinity vs. density
One generation of f.i. does not necessarily mean constant salinity or density

P,T data for formation of f.i. from SD - diagrams

Urach, last generation (boundary line)
≈ 150 °C / 700 bars

SFB 108 UNI KARLSRUHE

Fig. 6: Analysis of fluid events of different generation

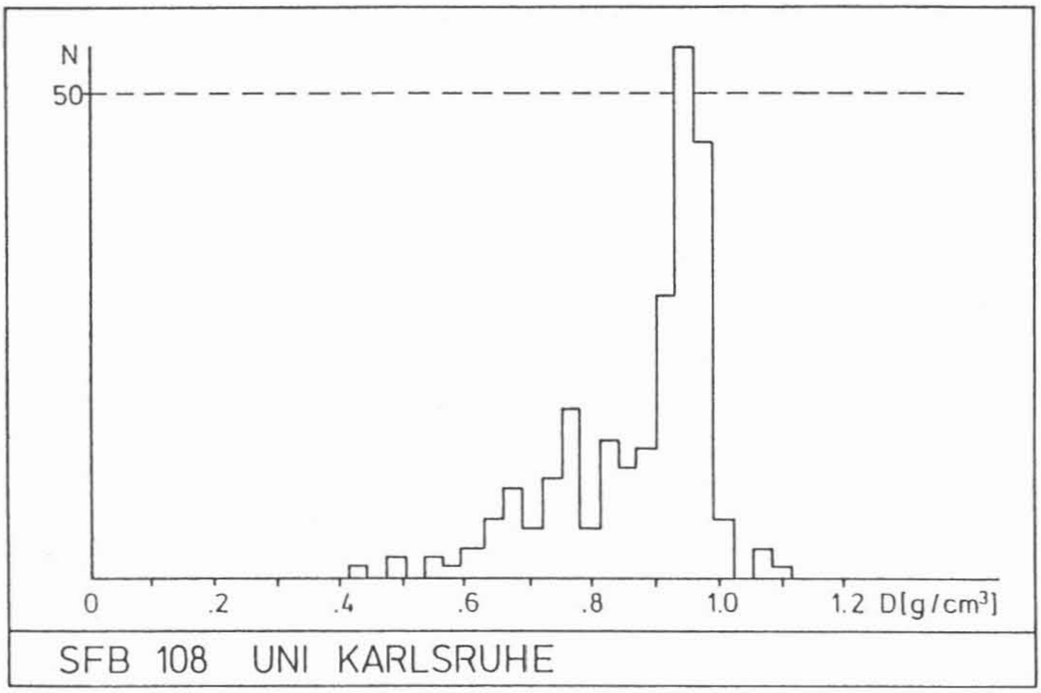


Fig. 7: Distribution of densities in fluid inclusions from the gneiss of the Urach borehole

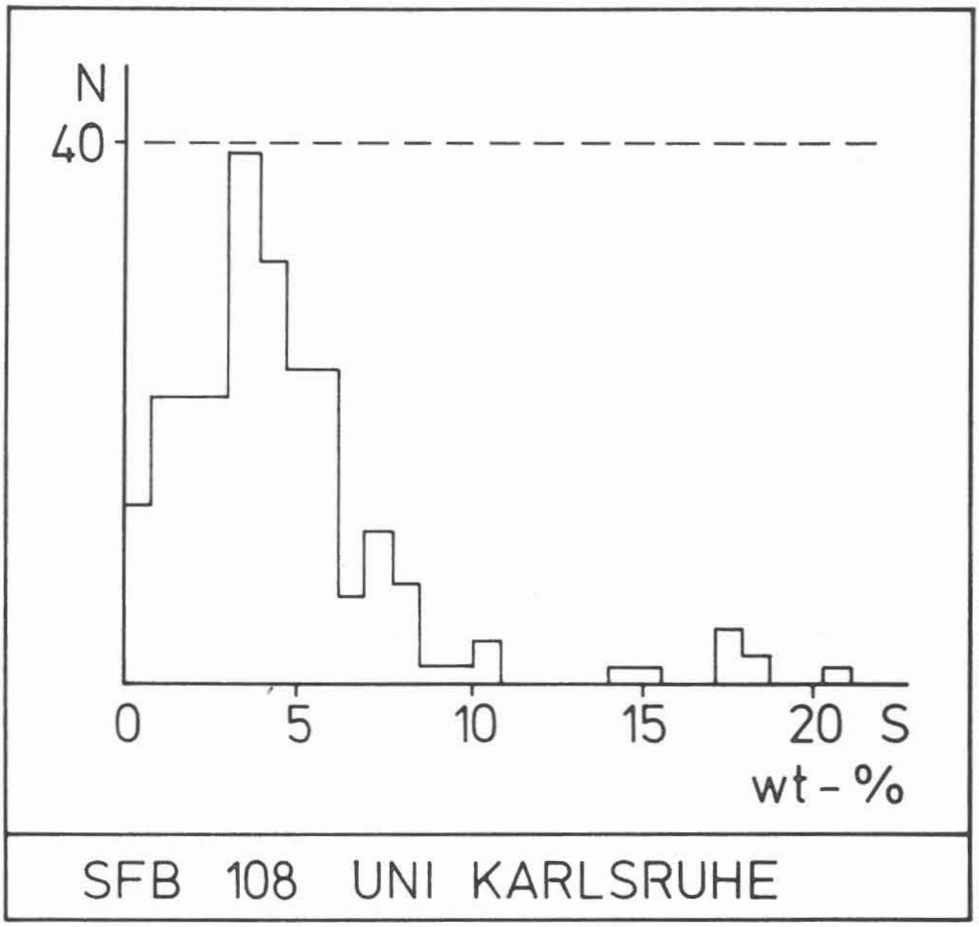


Fig. 8: Statistical distribution of salinities for the same rocks as in Fig. 7

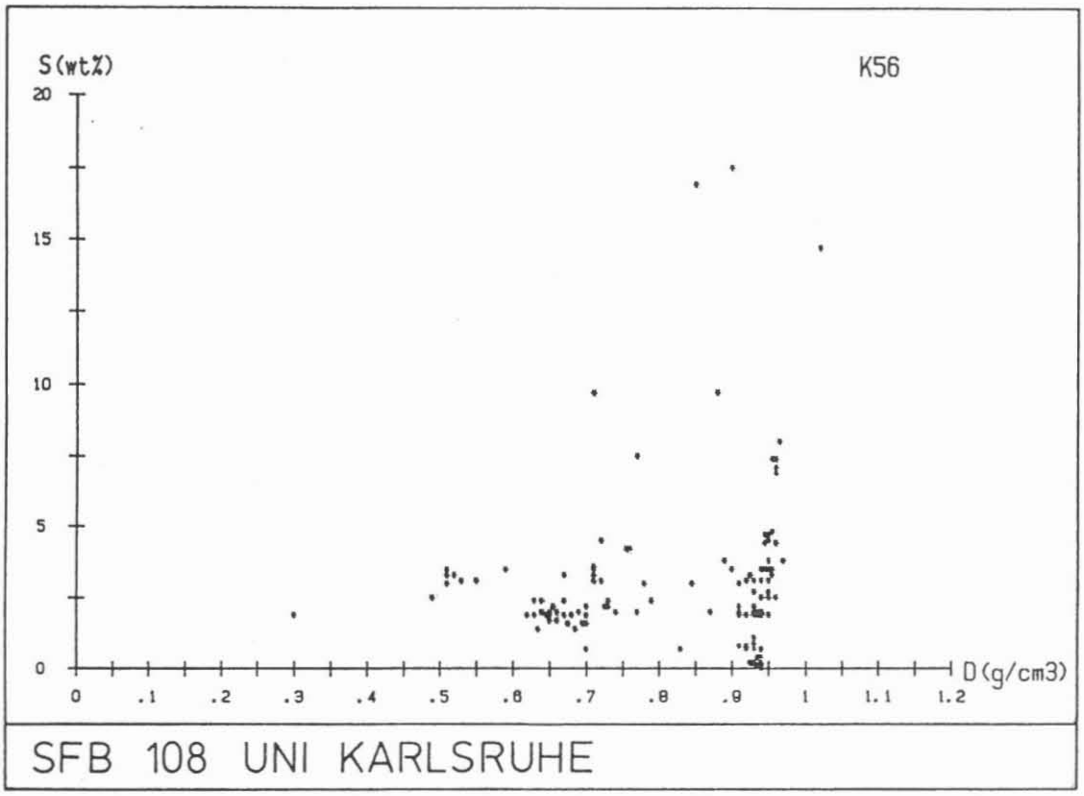


Fig. 9: Densitiy versus salinity plot of gneisses from the Urach borehole.

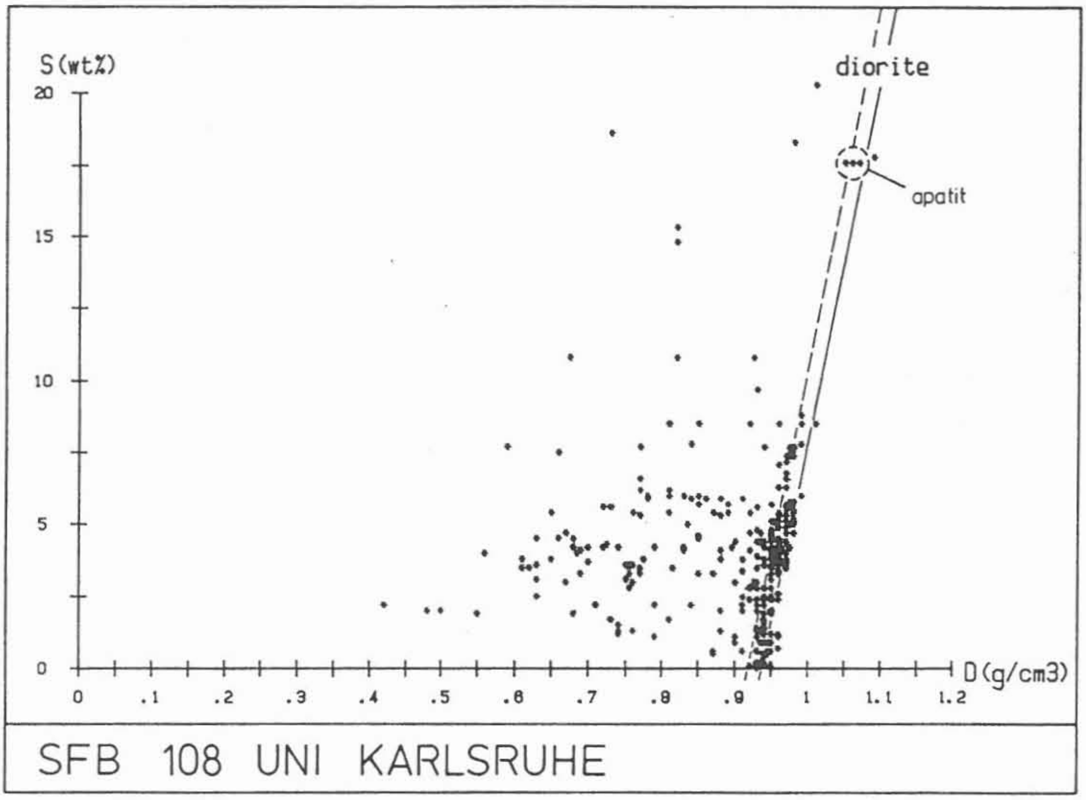


Fig. 10: Salinity versus density diagram for metadiorites from the Urach borehole

KTB Samples

Depth: 0 to 500 meters

amphibolite
garnet - hornblende - gneiss
kyanite - sillimanite - gneiss
cataclastically deformed

FLUIDS:

hydrosaline + CO_2 ± CO
not cogenetic with bulk
paragenesis

- fluid - rock interaction
- trapped during deformation

KTB UNI KARLSRUHE

Fig. 11: KTB rocks analysed for fluid inclusions

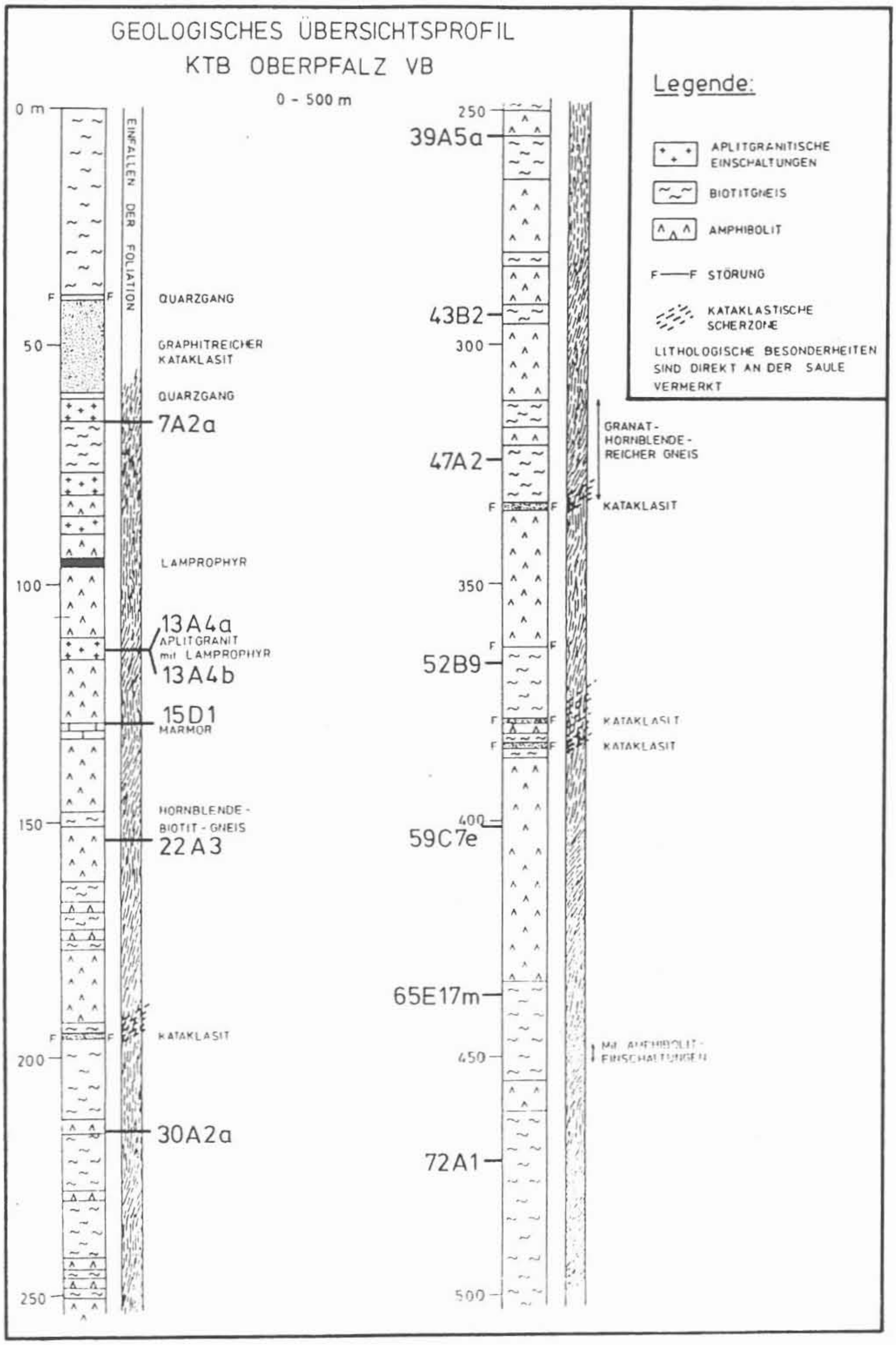


Fig. 12: Position of KTB rock samples analysed for fluid inclusions

BOREHOLE GEOPHYSICAL OF KTB

R. Hänel
J. Draxler

Paper presented at the International Seminar on
"Superdeep Drilling and Deep Geophysical Sounding"
Yaroslawl (USSR)
August, 1988

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.

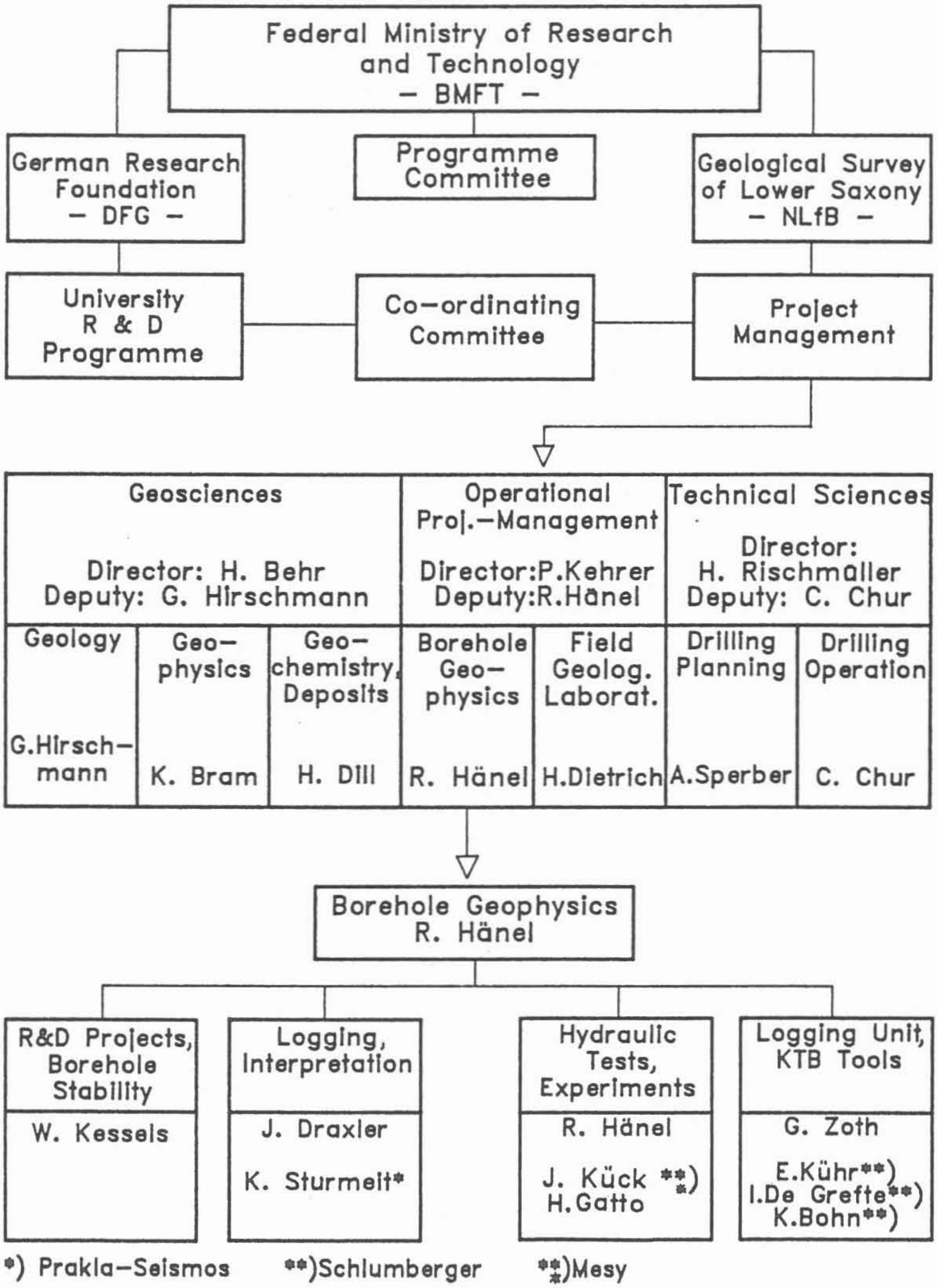
The drilling of the pilot borehole started September 1987. The envisaged depth will be 5000 m, and the present depth is about 3000 m (August 1988).

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.



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.

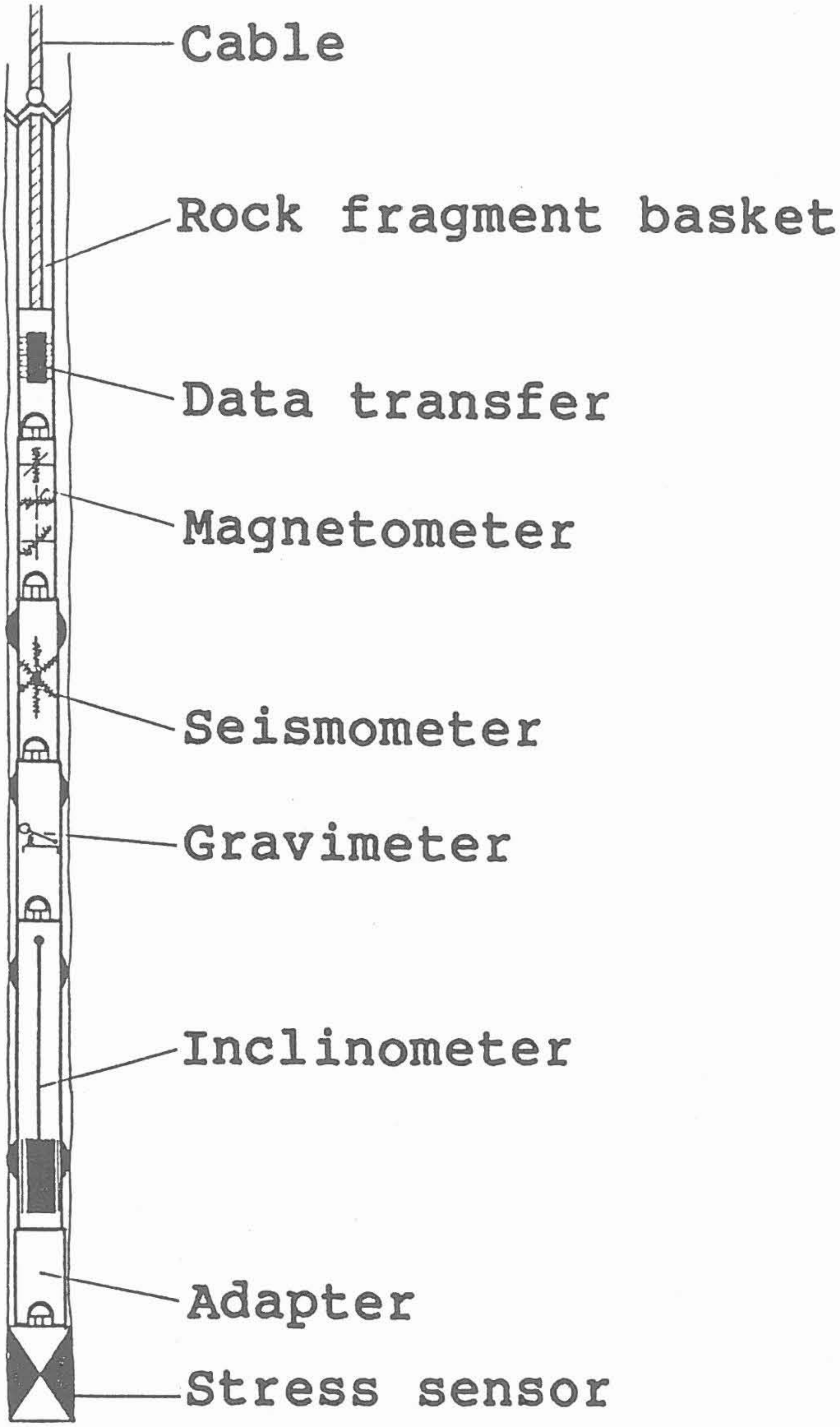


Figure 1: A possible concept for the Deep Earth Observatory.

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).

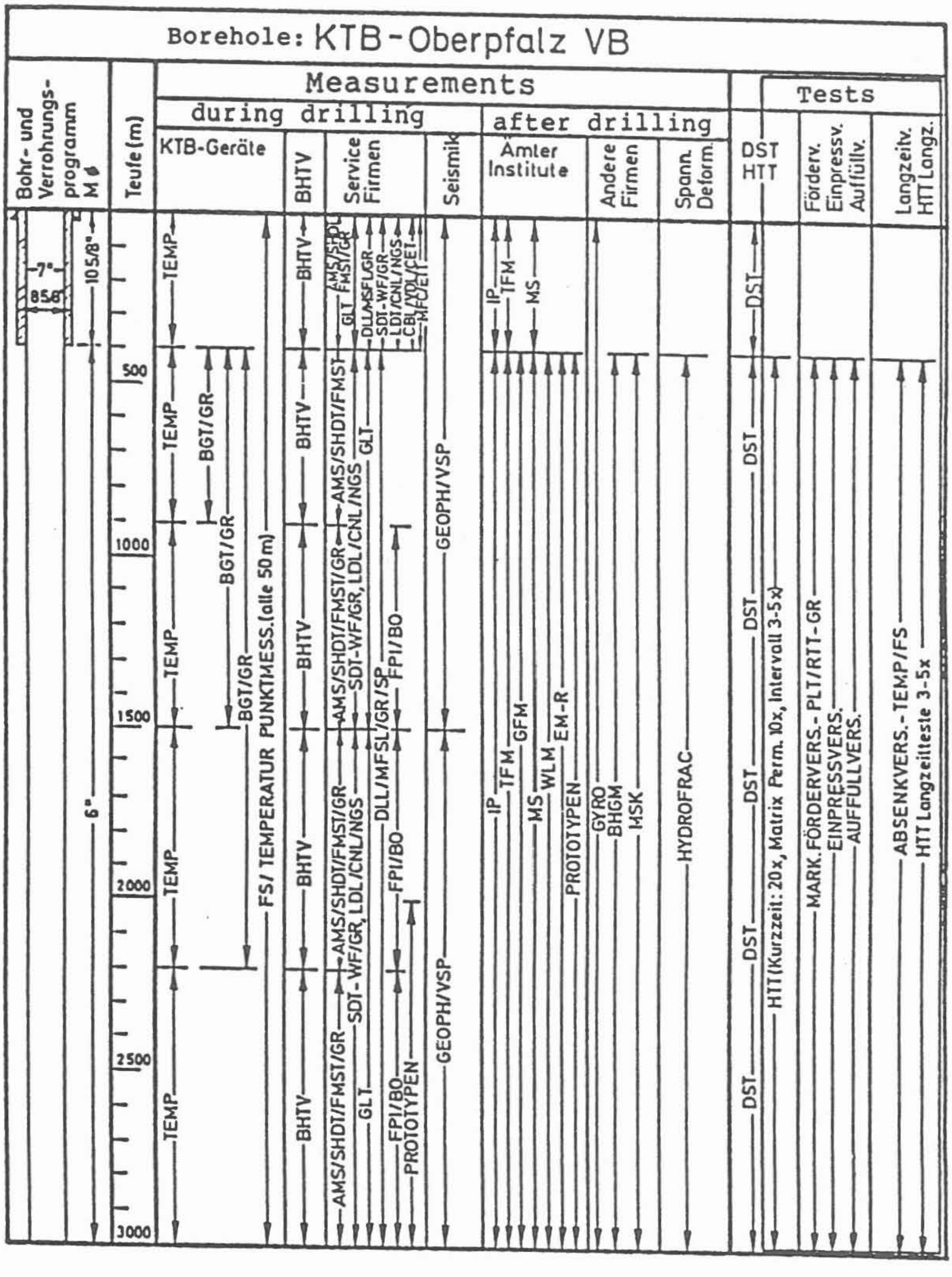


Figure 2: The plan of borehole measurements for the pilot borehole from August 21, 1987.

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.

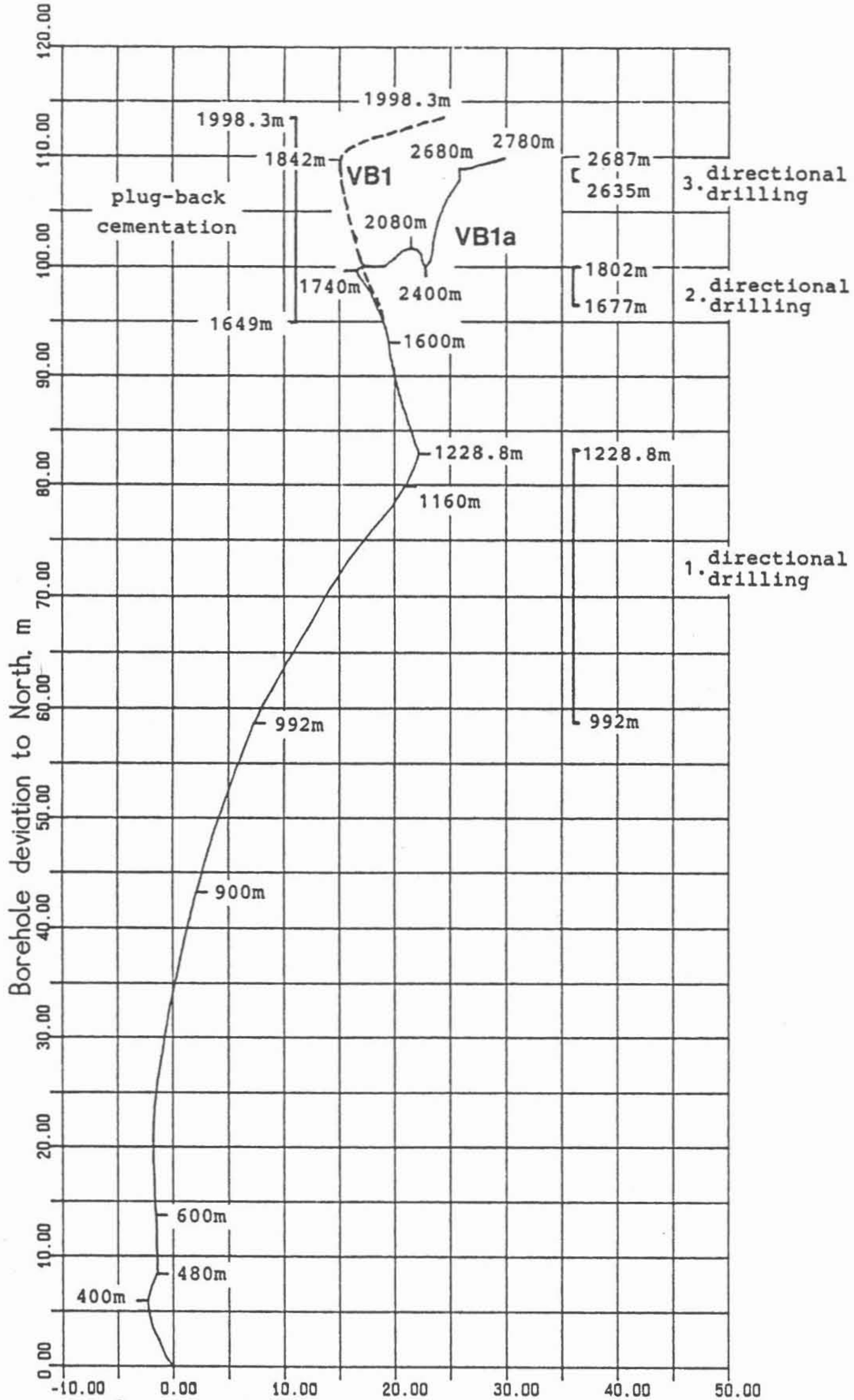


Figure 3: Horizontal projection of the pilot borehole including information about directional drilling and plug-back cementation work.

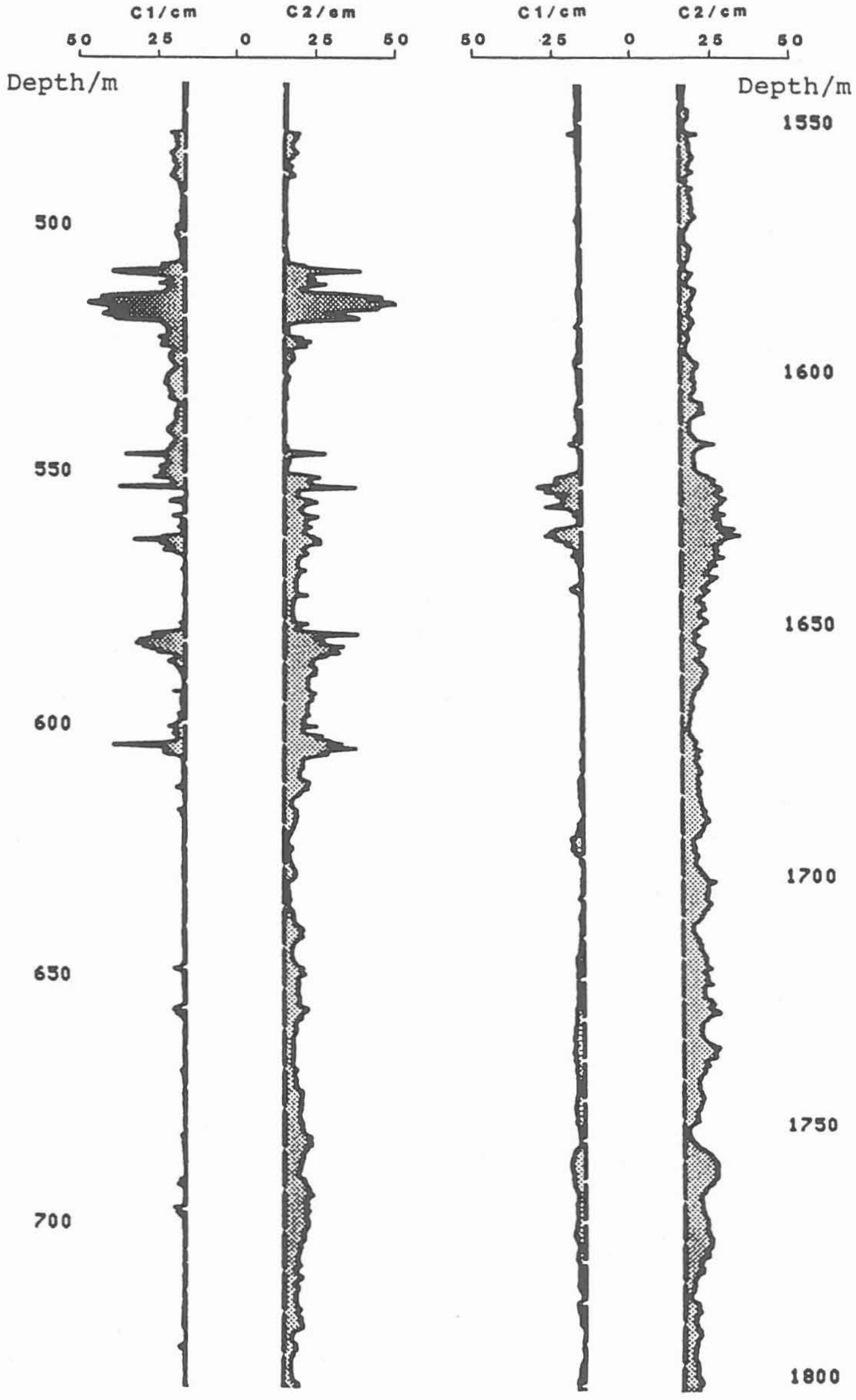


Figure 4: Two caliper sections showing extreme enlargements.

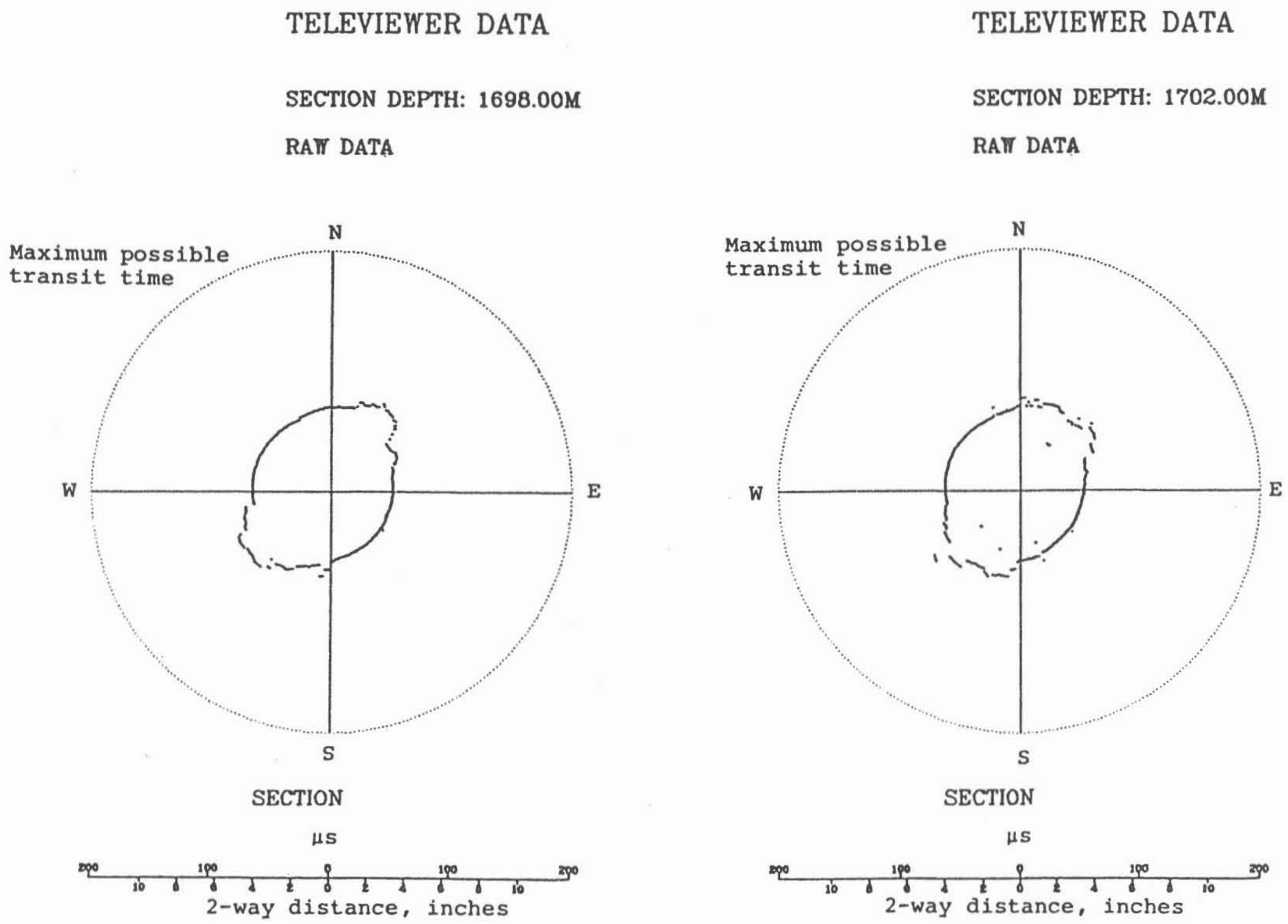


Figure 5: Two borehole cross sections from transit time of Borehole Televiewer demonstrating enlargements.

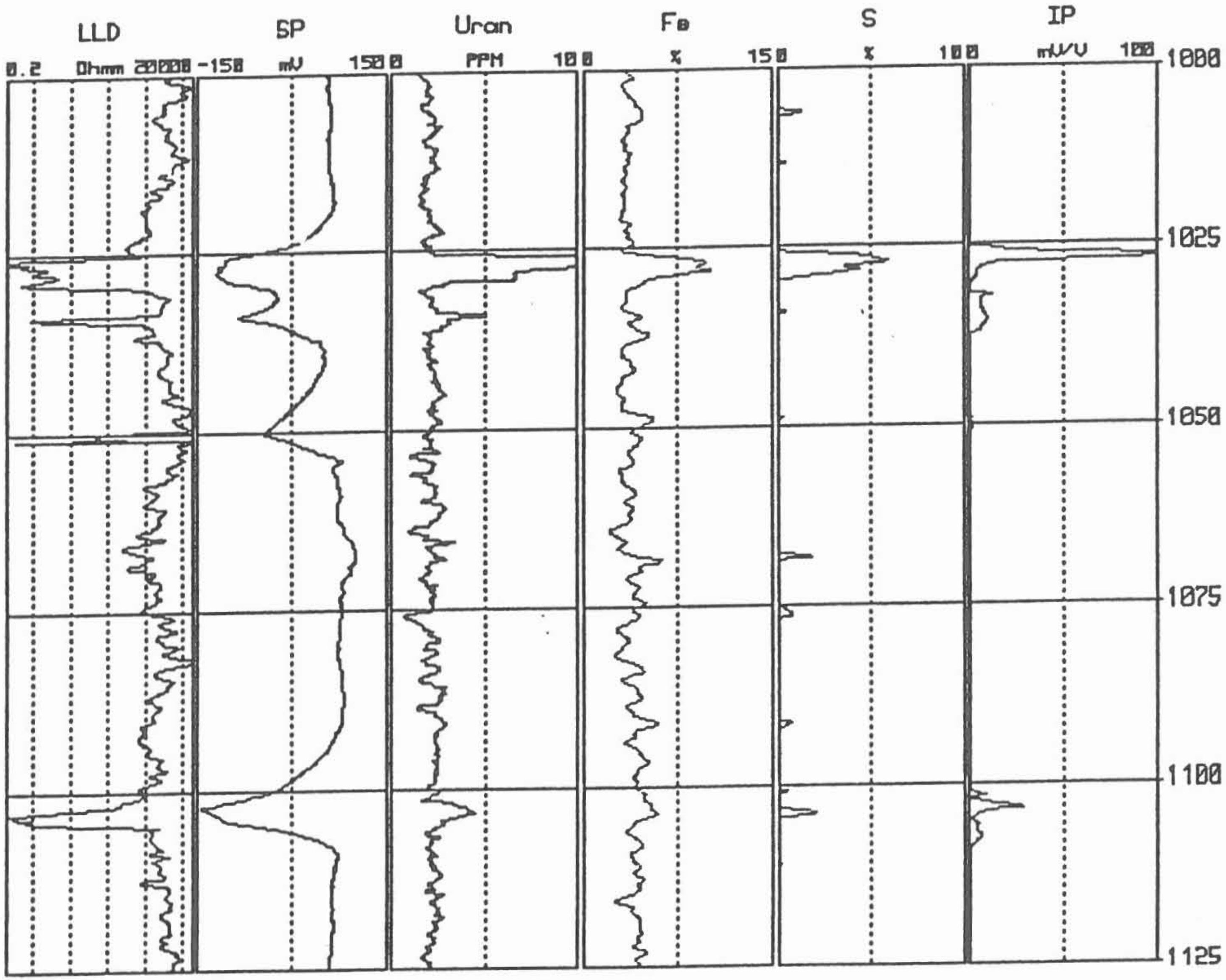


Figure 6: Graphite and Pyrite bearing zones detected by means of Dual Laterolog Deep (LLD), Spontaneous Potential (SP), GLT Geochemical Log and Induced Polarisation (IP).

(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.

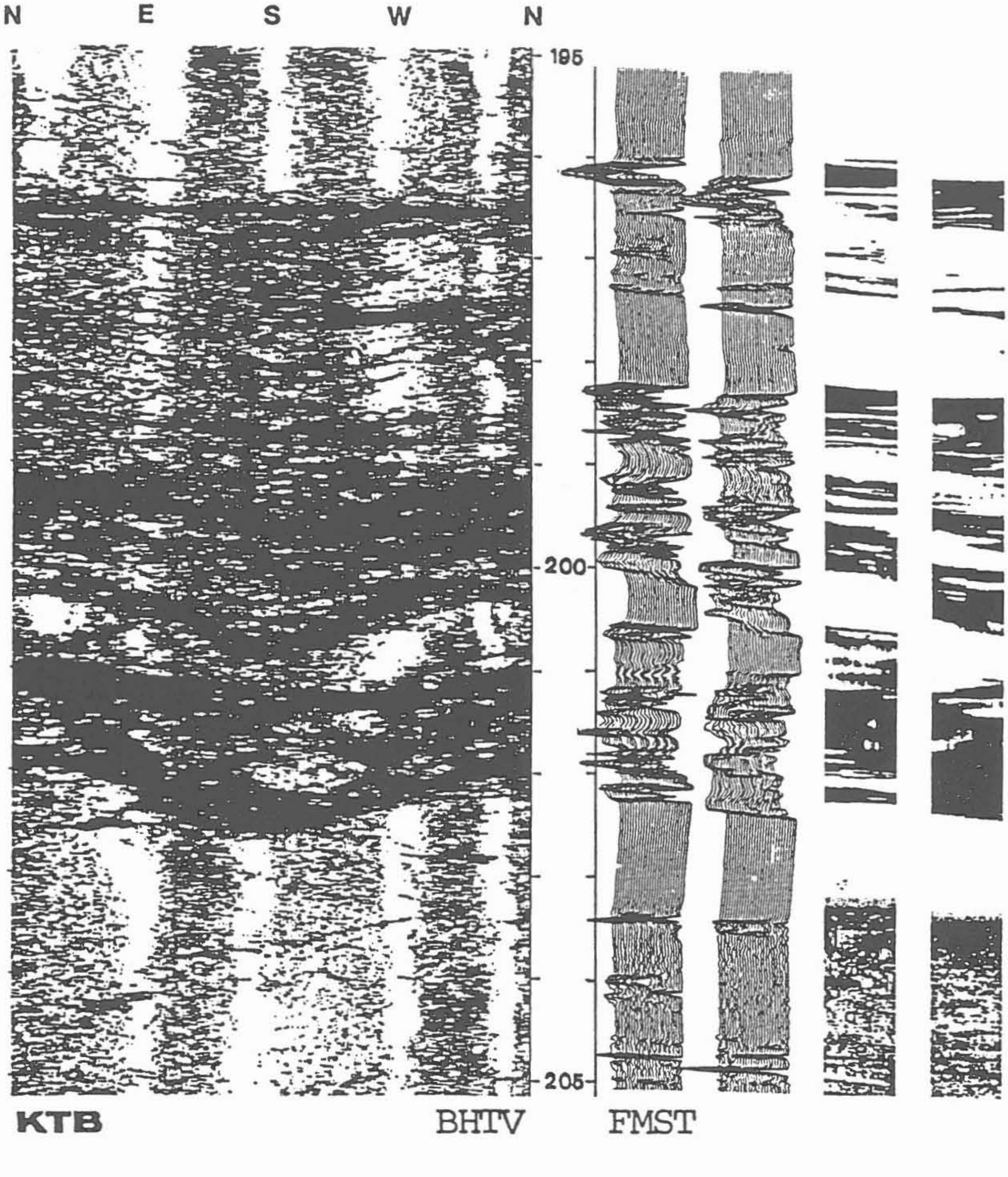


Figure 7: Borehole Televiewer (BHTV) and Formation MicroScanner Tool (FMST) records showing open fractures due to the low resistivity of FMST.

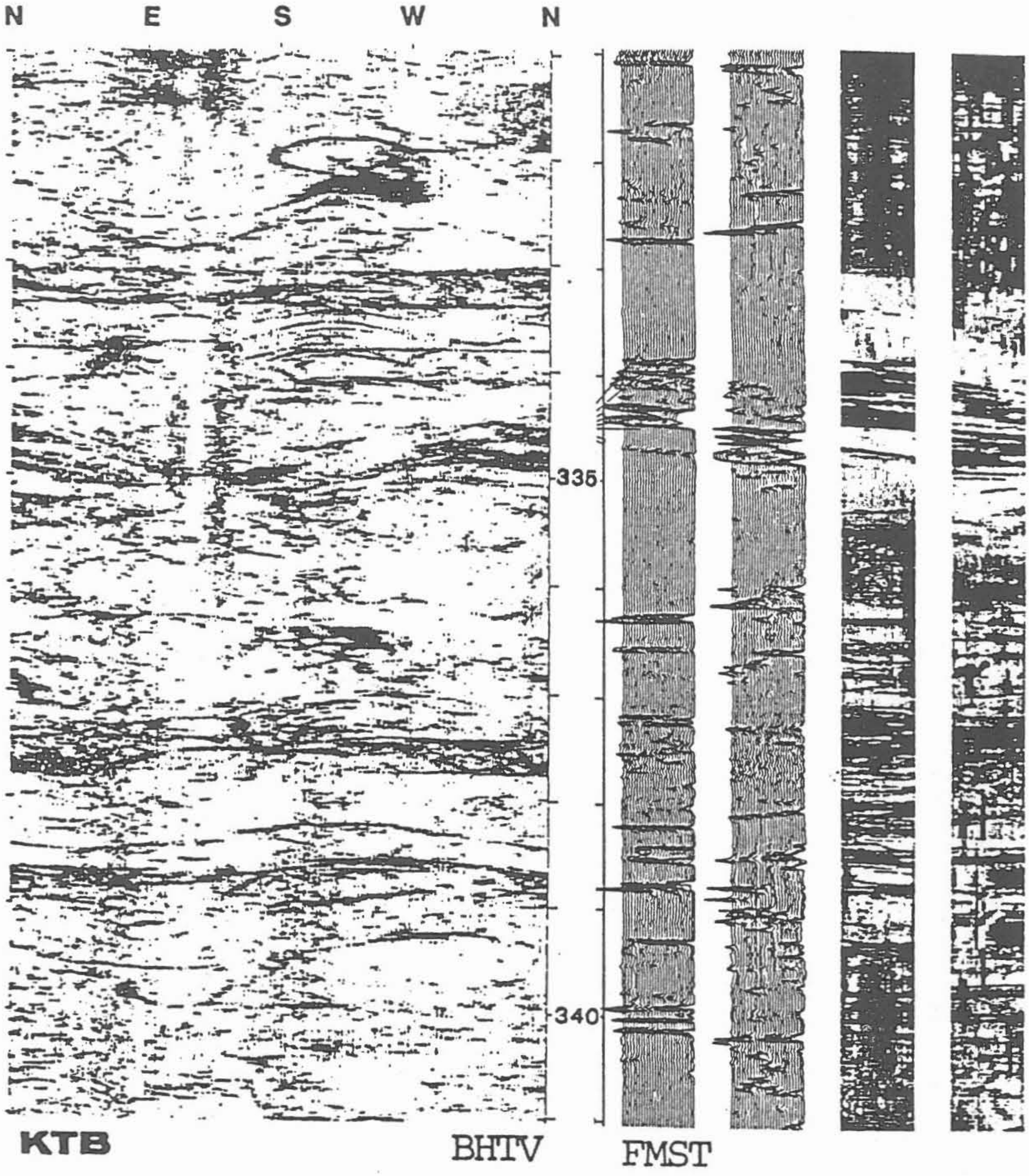


Figure 8: Borehole Televiewer (BHTV) and Formation MicroScanner Tool (FMST) records showing no significant fractures.

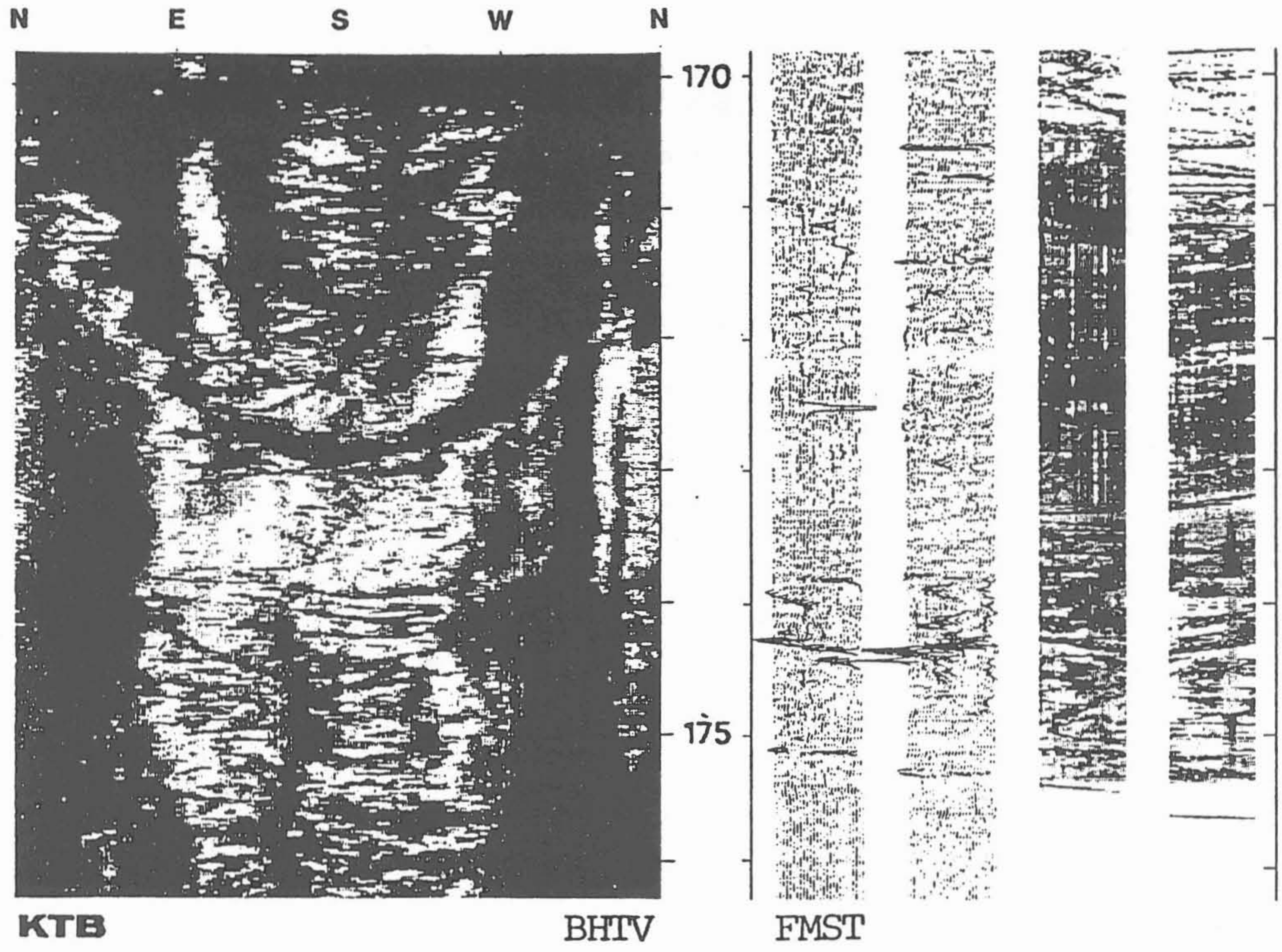


Figure 9: Borehole Televiewer (BHTV) showing a fracture at about 172.5 m depth. The Formation MicroScanner (FMST) gives no information at that depth. Therefore, a 'closed fracture' must be assumed.

(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.

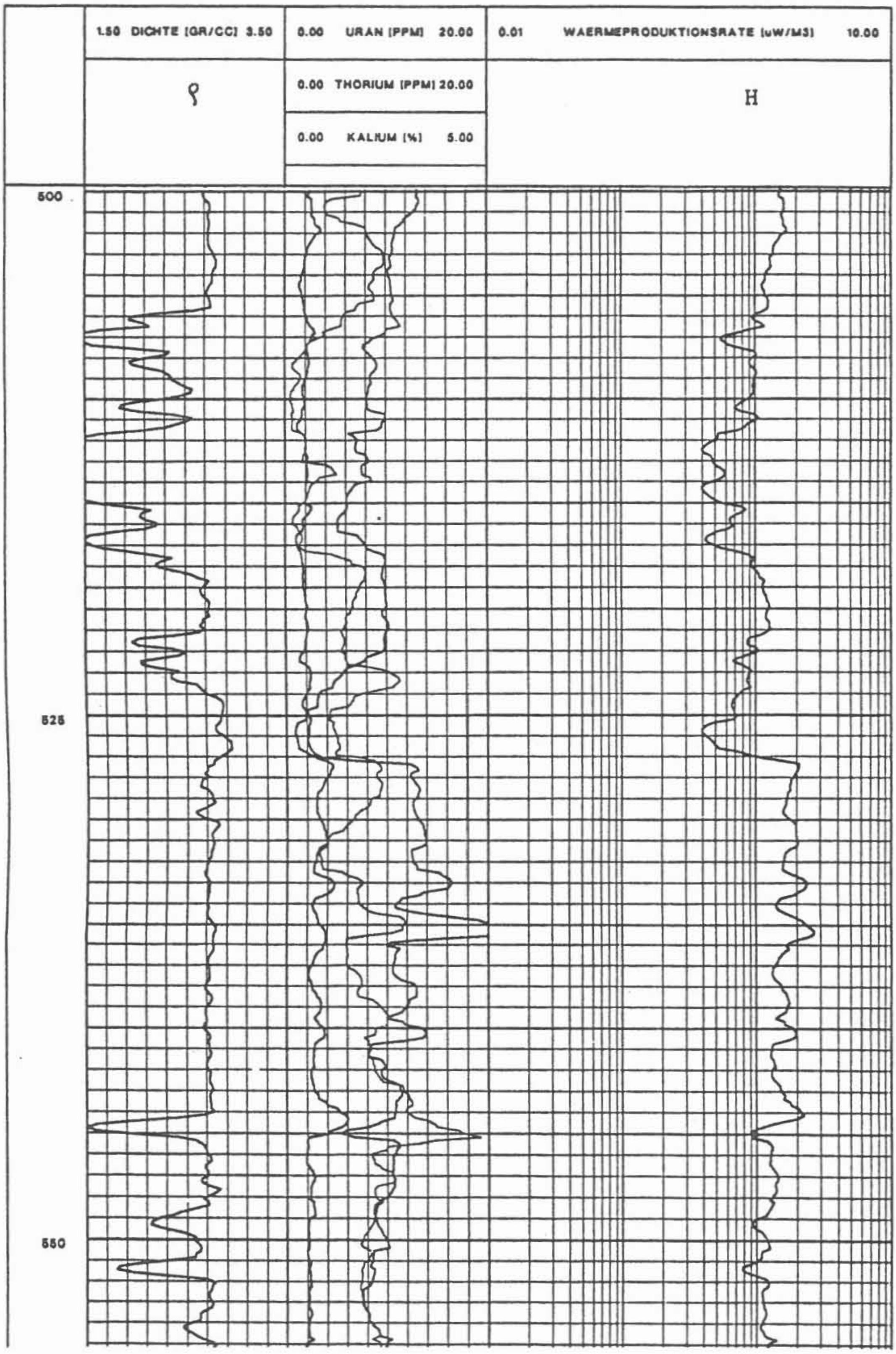


Figure 10: Logging data of density (ϱ), uranium, thorium, and potassium as well as the calculated heat generation H.

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.

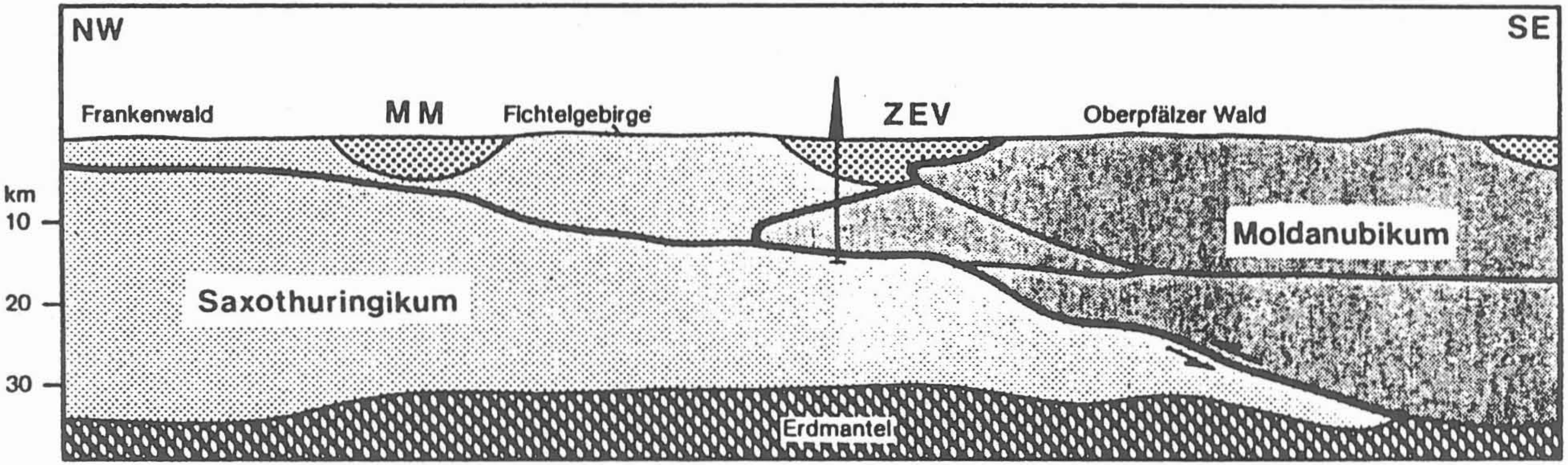


Figure 11: Simplified schematic geological profile for the KTB location Oberpfalz; MM = Münchberger Gneiss, ZEV = Zone of Erbendorf-Vohenstrauß.

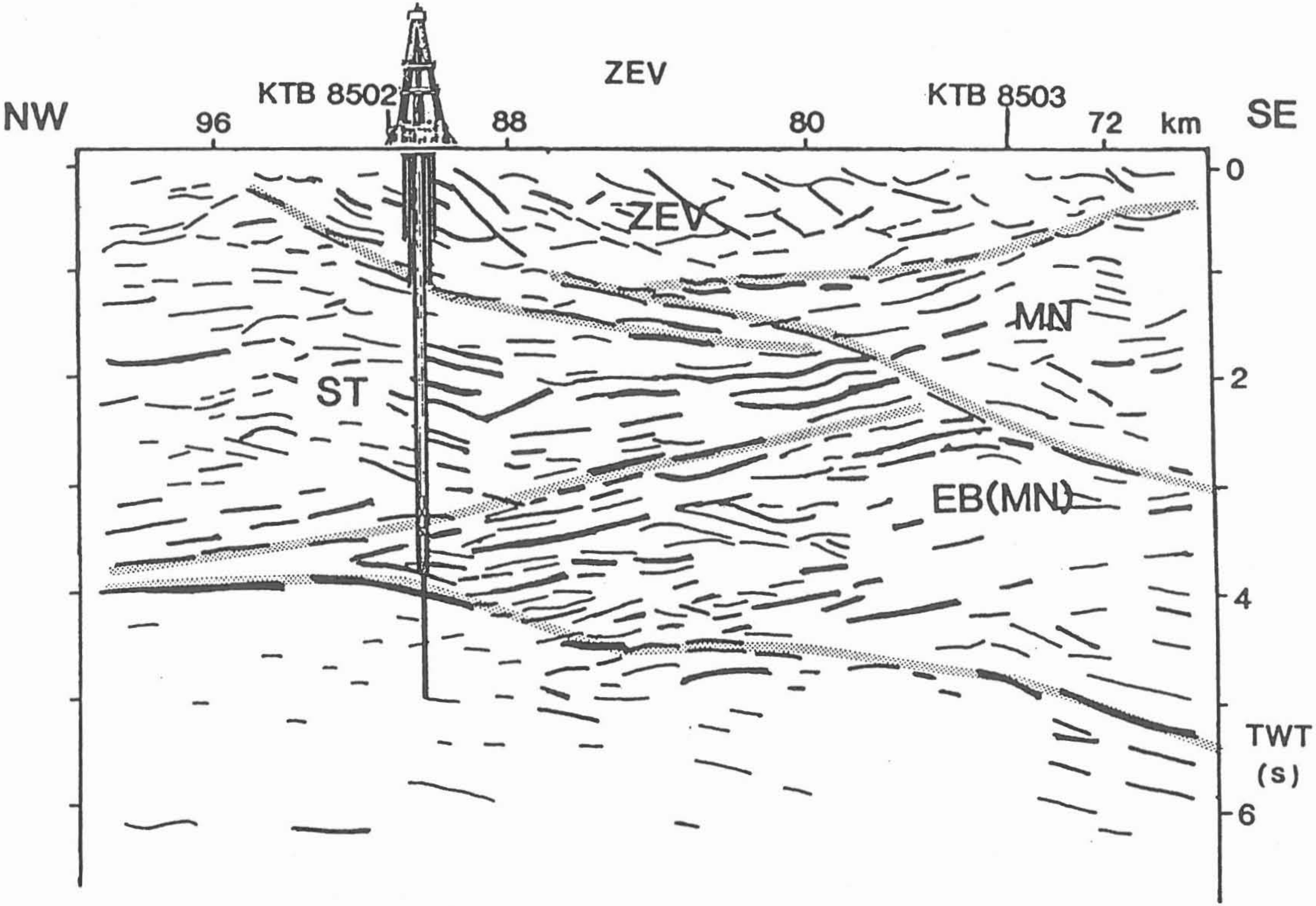


Figure 12: Central part of the line-drawing DEKORP 4 with structural interpretation;
ST = Saxothuringicum, MN = Moldanubicum, ZEV = Zone of Erbendorf-Vohenstrauß,
EB = Erbendorf Body.

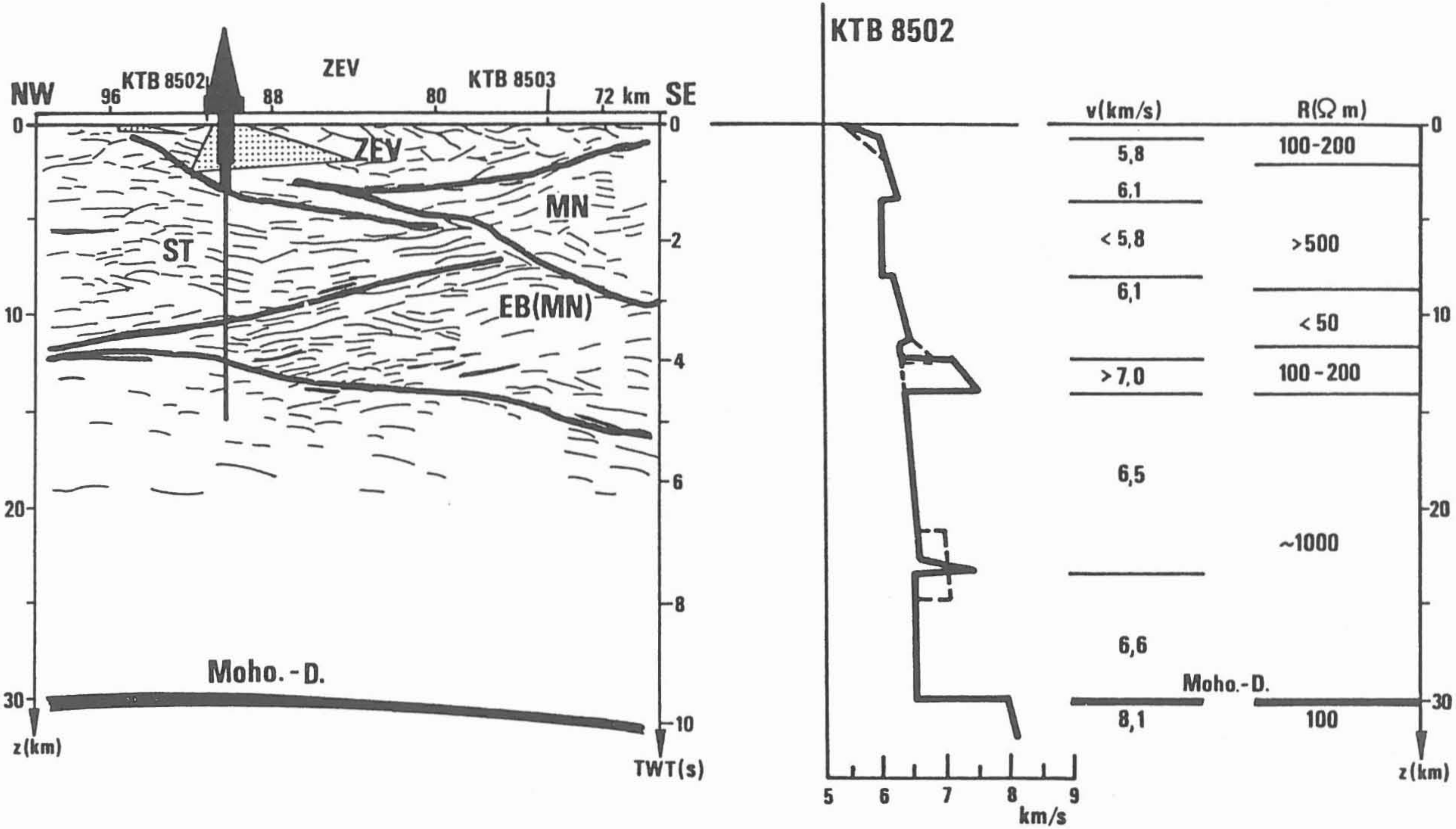


Figure 13: On the left repetition of Fig. 12, and on the right the V_p velocity and the electrical resistivity R below the borehole.

(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 with Δz >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.

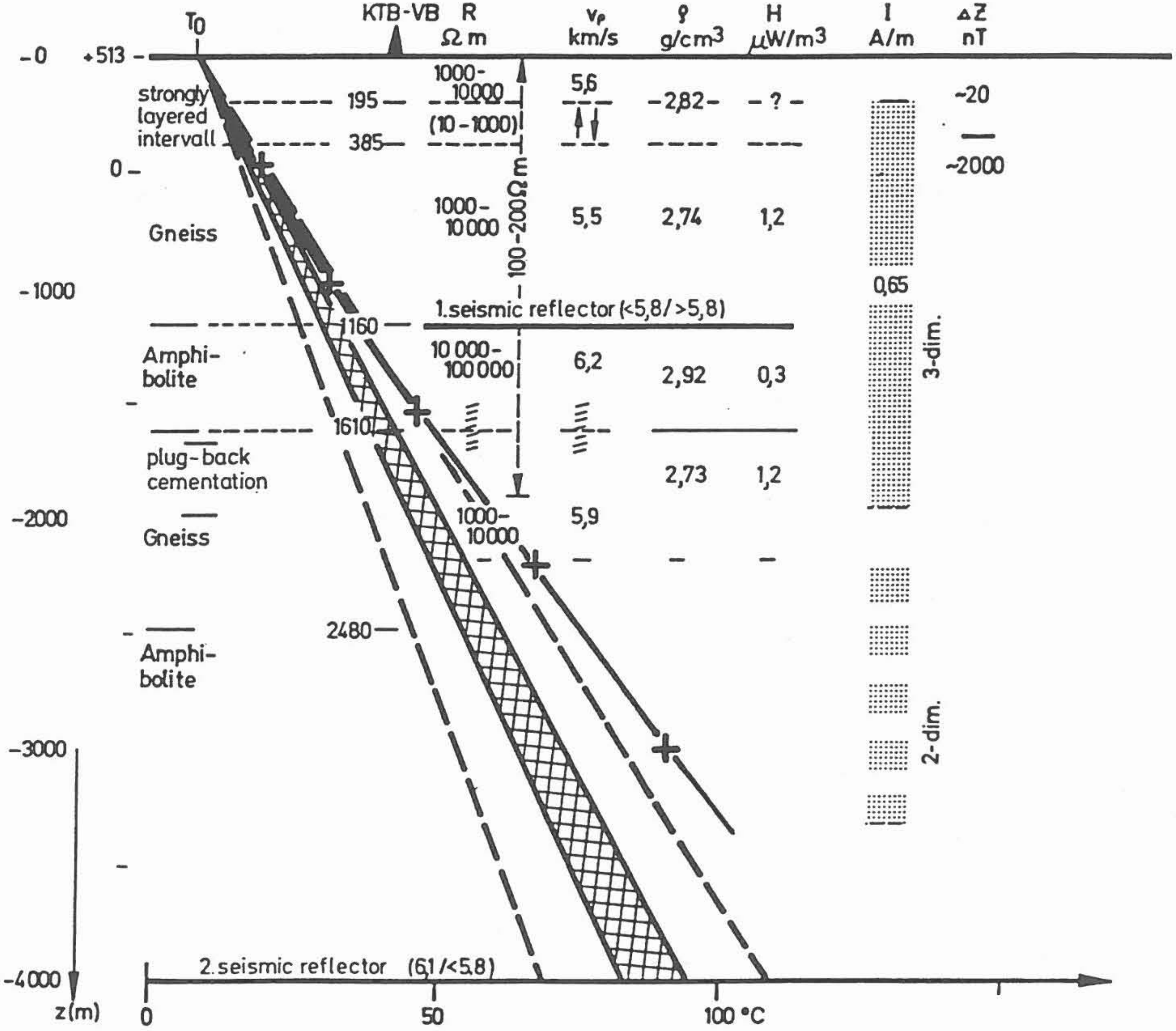


Figure 14: Logging results compared with other information.

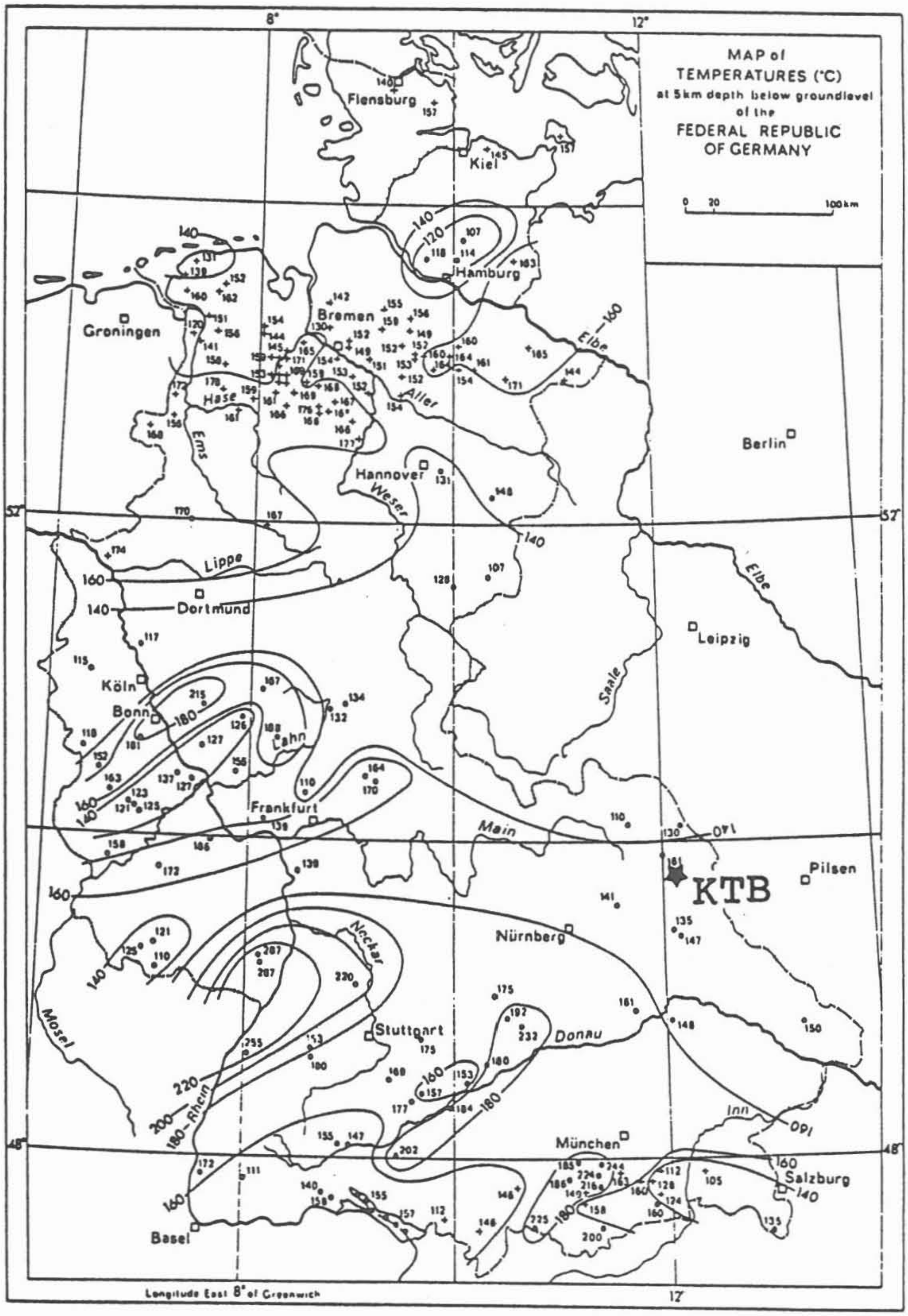


Figure 15: Temperature distribution at 5 km depth.

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 $R < 500$ Ω 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

$$R_p \quad 160\,\Omega\,\mathrm{m},$$

and which is in good agreement with the measured value $R_p = 100 - 200$ Ω 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.

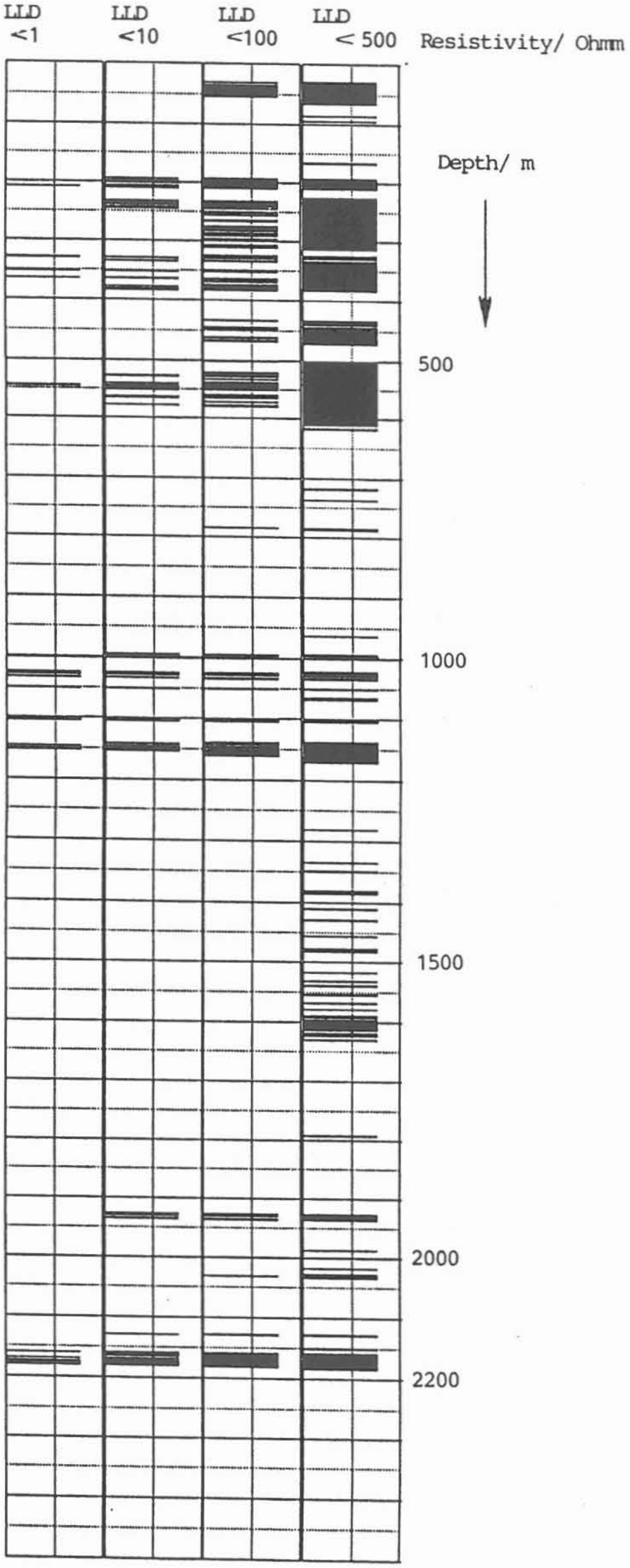


Figure 16: Resistivity distribution for $R < 1, 10, 100$ and $500 \Omega m$ from the Dual Laterolog; LDD=Laterolog Deep.

REFERENCES

Bosum, W., Hahn, A., Geipel, H. & Rolf C. (1988): Bericht über magnetische Messungen in der Bohrung KTB-VB Oberpfalz mit Hilfe eines 3-Komponenten Bohrlochmagnetometers und gesteinsmagnetische Untersuchungen. - NLfB, Hannover, Archiv-Nr. 103 533, 37 S.

Burkhardt, H., Honarmand, H. & Wägerle, P. (1986): Geothermie. - 2. KTB-Kolloquium, Seeheim (Odenwald) 19.9. - 21. 9.1986, 150 - 160.

DFG (1981): Kontinentales Tiefbohrprogramm der Bundesrepublik Deutschland. - Kommission für Geowissenschaftliche Gemeinschaftsforschung, Mitteilung XI, Bonn, 70 p.

DEKORP Research Group (1988): Contributors: Bortfeld, R. K., Keller, F., Sieron, B., Söllner, W., Stiller, M., Thomas, R., Franke, W., Weber, K., Vollbrecht, A., Heinrichs, T., Dürbaum, H.-J., Reichert, C., Schmoll, J., Dohr, G., Gebrande, H., Bopp, M., Neurieder, P. & Schmidt, T.: Results of the DEKORP 4/KTB Oberpfalz deep seismic reflection investigations. - J. Geophys., 62, 69 - 101.

Devay, L. & Hänel, R. (1983 a): Tätigkeitsbericht der Arbeitsgemeinschaft Bohrlochmessungen (ARGE 2). - BGR/NLfB, Hannover, Archiv-Nr. 94 671, 59 S.

Devay, L., Fries, A. P. & Hänel, R. (1983 b): Tätigkeitsbericht der Arbeitsgemeinschaft Bohrlochmessungen (ARGE 2), Bericht 2. - BGR/NLfB, Hannover,Archiv-Nr. 95 173, 174 S.

Emmermann, R. (1986): Das deutsche Kontinentale Tiefbohrprogramm. - In: Geowissenschaften in unserer Zeit, 4. Jahrg., Nr. 1, VCH Verlagsgesellschaft mbH., D-6940 Weinheim p. 19 - 33.

FKPE (1986): Geophysikalische Schlüsselexperimente in der KTB. - Forschungskolloquium Physik des Erdkörpers, Universität Bochum, Geophysics, 98 p.

GEOMETRA (1988): Ergebnisse geowissenschaftlicher Umfelduntersuchungen. Elektromagnetischen Tiefensondierungen 1987. - KTB-Report 88-3, Hannover, 195 S.

Grubbe, K., Hänel, R., Jobst, St., Reichert, Ch. & Zoth, G. (1983). Forschungsvorhaben: Vertikalbewegungen und ihre Ursachen am Beispiel des Rheinischen Schildes, Teilprojekt Geothermik. Schlußbericht. - BGR/NLfB, Hannover, Archiv-Nr. 93 273, 50 S.

Hänel, R. (1986): Logging Strategy for the KTB (Seeheim, Sept. 19 - 21, 1986). - BGR/NLfB Archives No 100 042, 22 p.

Hänel, R. (1987): Grundlagenforschung und Bohrlochgeophysik (Bericht 2) Arbeitsprogramm KTB-Bohrlochgeophysik sowie Bohrlochmeßprogramm KTB-Oberpfalz VB (1.9.1987). - KTB-Report 87-3, Hannover, 203 S.

Hänel, R. & Draxler, J. K. (1988): The logging strategy for the Continental Deep Drilling Programme of the Federal Republic of Germany. - Deep Drilling in Crystalline Bedrock (Eds. A. Bodén & K. G. Eriksson), Springer Verlag, Vol. 2, p. 428 - 443.

Herron, M. M. (1983): In: The emergence of geochemical well logging. - The Technical Review, A Schlumberger Publication, April 1987, p. 27 - 35.

Kessels, W. (1987): Installation eines Deep Earth Observatoriums Vorbohrung (DEO-V) in der KTB-Vorbohrung, Projektvorschlag. - BGR/NLfB, Hannover, Archiv-Nr. 101 873, 9 S.

Krynine, P. D. (1948): The megascopic study and field classification of sedimentary rocks. - J. of Geology, 56, p. 130 - 165.

Plaumann, S. & Pucher R. (1986): Gravimetrie - 2. KTB-Kolloquium, Seeheim (Odenwald) 19.9. - 21.9.1986, 65 - 70.

Pucher, R. (1986): Interpretation der magnetischen Anomalie von Erbendorf (Oberpfalz) und dazugehörige gesteinsmagnetische Untersuchungen. - Geol. Jb. E 33, Hannover, 31 - 52.

Rybach, L. (1988): Determination of heat production rate. - In: Handbook of Terrestrial Heat-Flow Density Determination (Eds. R. Haenel, L. Rybach and L. Stegena), D. Reidel Publ. Comp., Dordrecht, p. 125 - 142.

Schmoll, J., Bittner, R., Dürbaum, H.-J., Heinrichs, T., Meißner, R., Reichert, C., Rühl, Th. & Wiederhold, H.: Oberpfalz Deep Seismic Reflection Survey and Velocity Studies. - Submitted for publication, 1988.

APPENDIX

Poster 1: Objectives, Realisation of borehole measurments

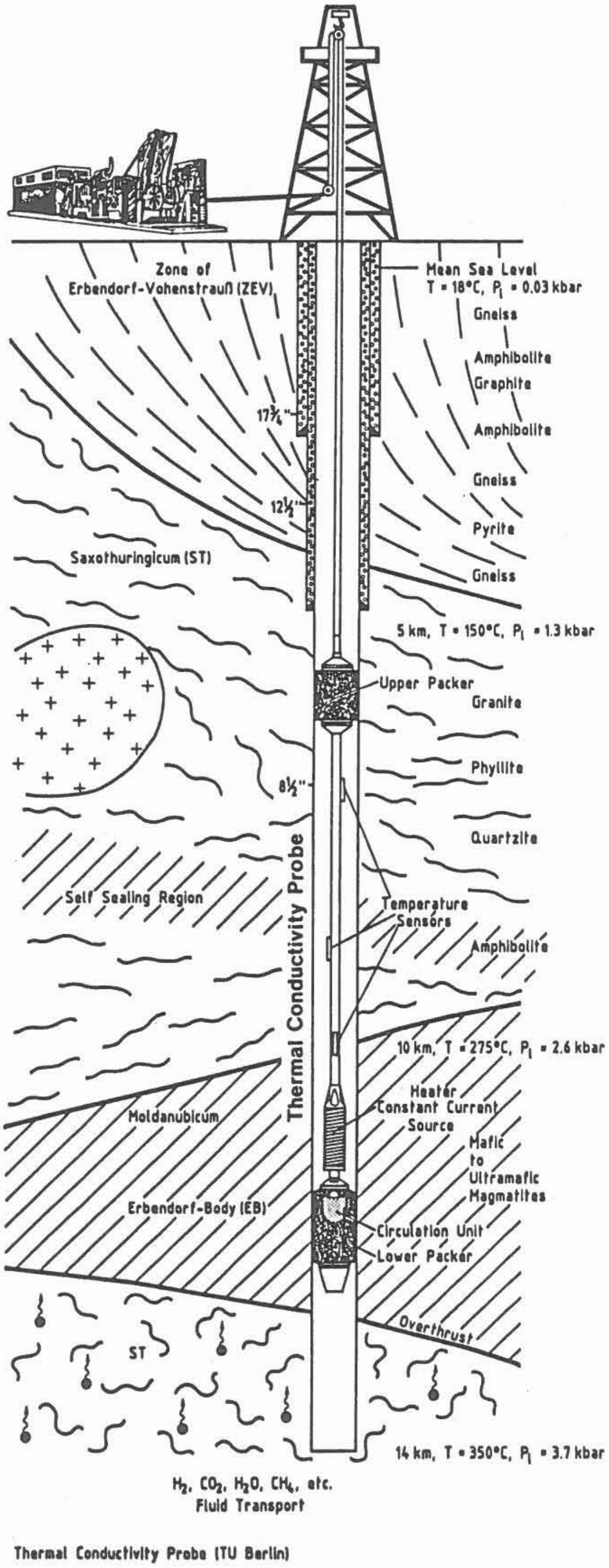
Poster 2: Research and development projects for borehole geophysics

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:

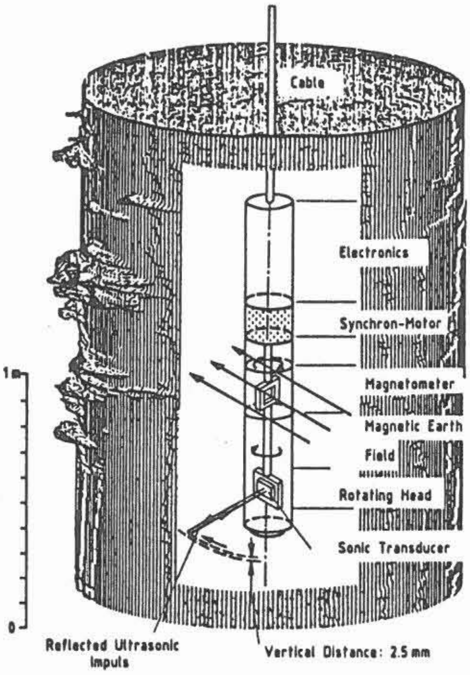
- Time-consuming measurements, which otherwise could require costly stand by time of the drilling rig, e.g. magnetotelluric measurements, fluid influx, etc.
- Long-term observations of transient phenomena e.g. earthquakes, microseismicity, rock stress and deformation

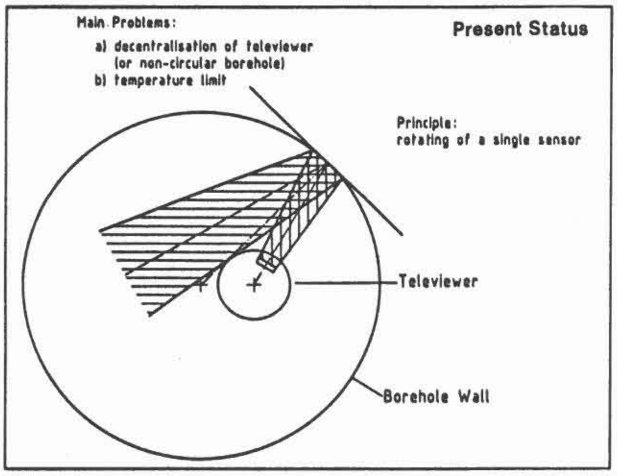
* Trademark Schlumberger

KTB BOREHOLE MEASUREMENTS

RESEARCH AND DEVELOPMENT

Acoustic Borehole Televiewer
Principle of standard version:

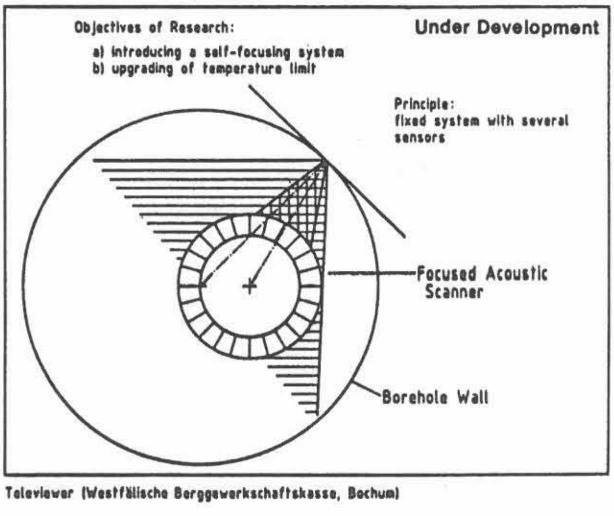




Present Status

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

Principle:
rotating of a single sensor



Under Development

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:

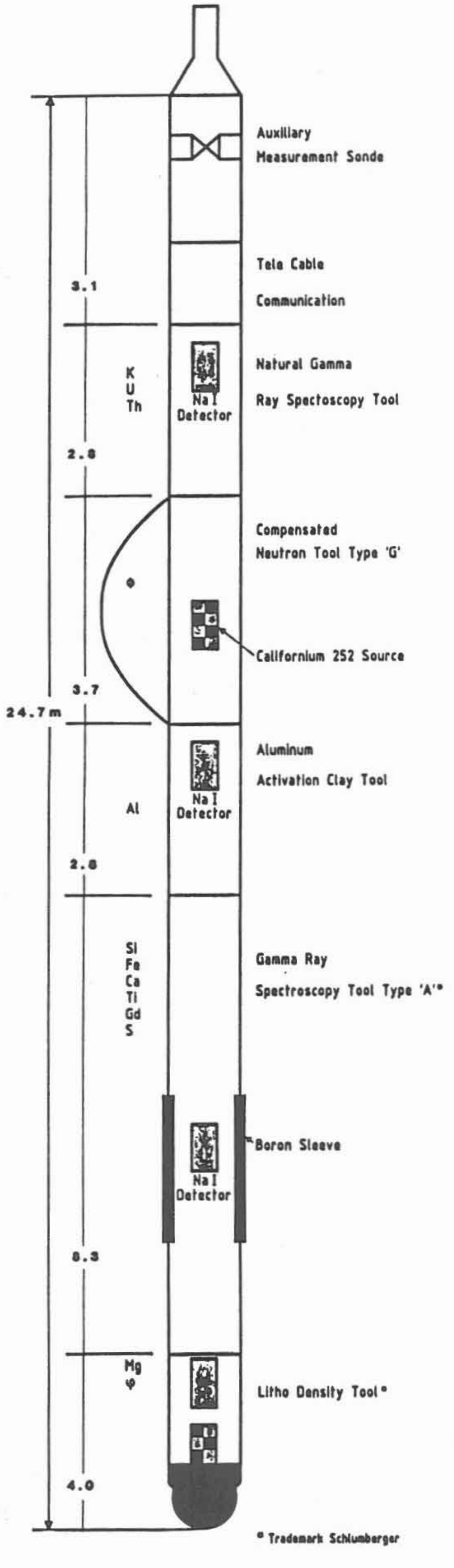
Development and improvement of tools up to about 300°C with regard to the scientific objectives, such as e.g.:

- 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.

® Trademark Schlumberger

KTB BOREHOLE MEASUREMENTS

RESULTS, EXAMPLE 1



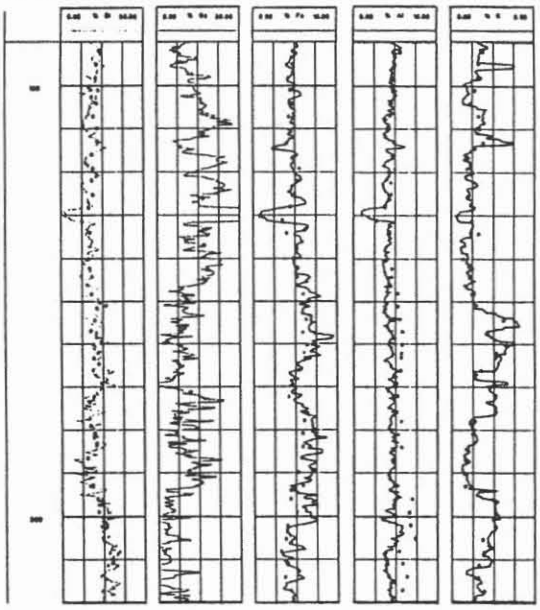
* Trademark Schlumberger

Geochemical Mineral Logging - the future has started

Advantages: Fast and continuous information with high accuracy

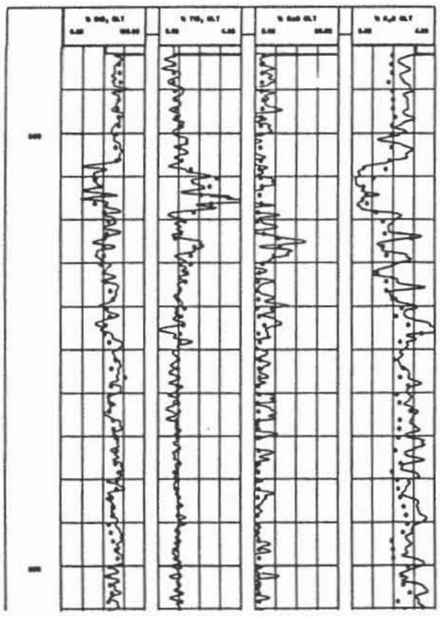
Elements (points represent core data from Field Laboratory)

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



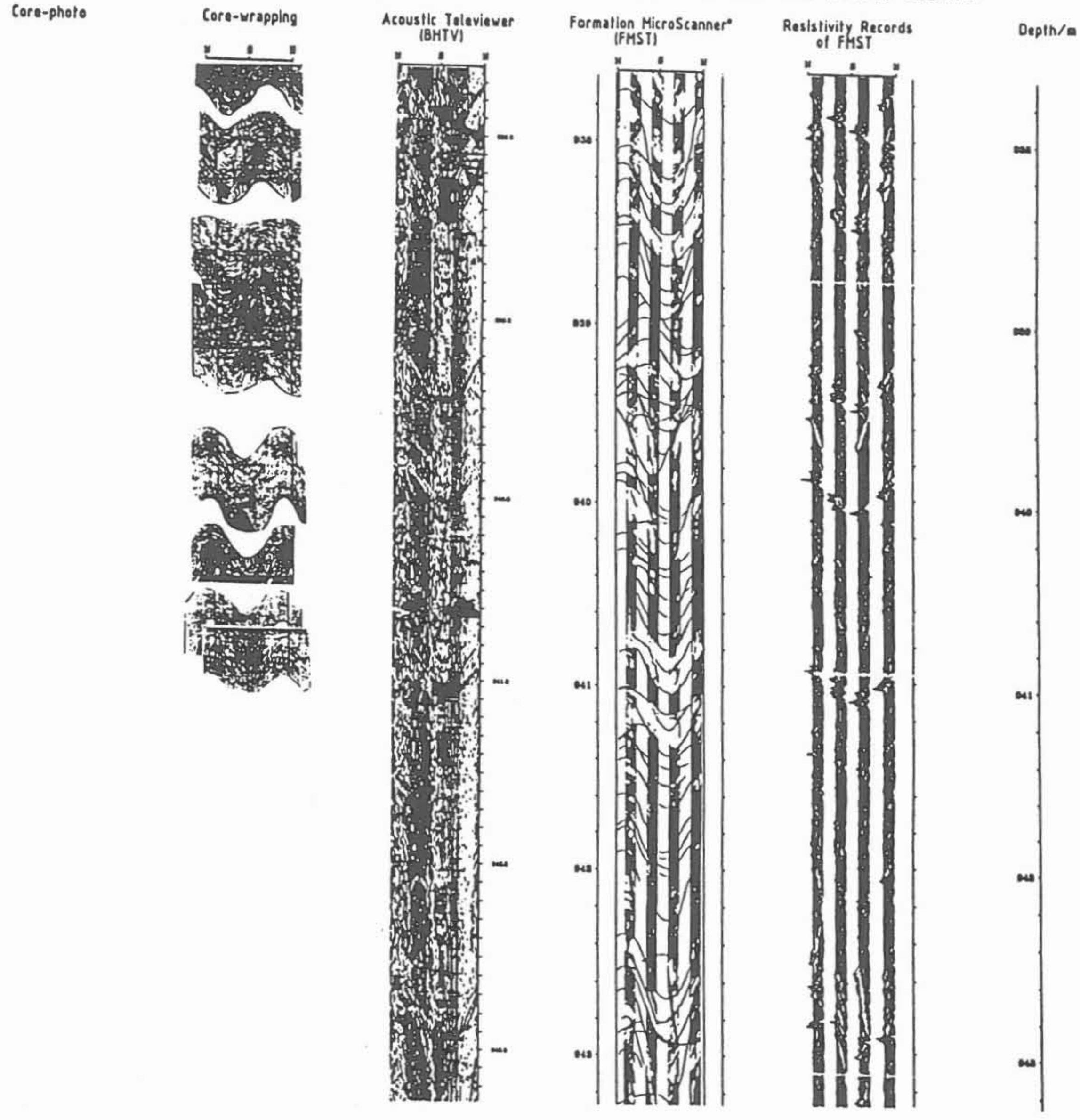
Other information:

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.

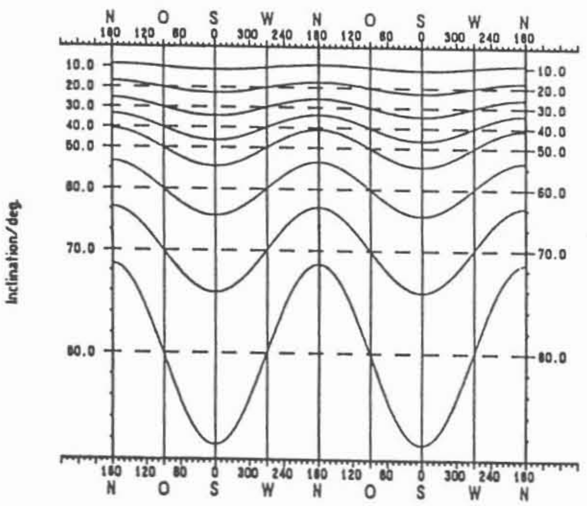
KTB BOREHOLE MEASUREMENTS

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.

* Trademark Schlumberger

THE GERMAN CONTINENTAL DEEP DRILLING PROJECT (KTB)

– AN OVERVIEW –

H. Rischmüller

Paper presented at the
"28th International Geological Congress"
Washington (USA)
July, 1989

Introduction

The German Continental Deep Drilling Program is a non-commercial project of basic geoscientific research (Fig. 1). The deep and the superdeep borehole are an integral part of the project as well as the accompanying comprehensive geoscientific work. Only the borehole can deliver the data dealing with the composition and the physical state of rocks and fluids at great depths which allow a reliable interpretation of surface and well logging data and provide a higher level of accuracy of geophysical evaluation - making the borehole a telescope into the earth's crust.

In Germany, the first ideas concerning a continental deep drilling program were discussed as early as in 1977. From 1980 to 1983 forty proposed drill sites were screened in order to be able to focus the scientific work for the following three years, and to concentrate the funding to a thorough and extensive investigation of the two sites Oberpfalz and Schwarzwald. In October 1986, the results concerning both sites were presented to the geoscientific community, and the drilling site Oberpfalz turned out to be the geologically most promising one. Exactly one year later, the drilling of the pilot hole started. In 1984, all institutions involved in the project, the Federal Ministry of Research and Technology, the universities represented by the German Research Foundation, and the Federal and local Geological Surveys, agreed to form an interdisciplinary management group allocated to the Lower Saxony Geological Survey in Hanover. This management group achieved a fast project progress since 1985. All interested scientists were tied into the project by an organization structure which forms a firm link between the scientists at the universities and the project group.

The project concept

The geoscientific targets, the results of the geophysical, the geological and the geochemical site exploration and the available experience were the basis for the technical concept, the drilling strategy, and the main topics of research and development of the KTB.

The drilling concept may be viewed as a synergism of the pilot hole, the ultra deep hole and the research and development program. With its important objectives the pilot hole is an essential part of the KTB. It serves the following purposes

> Acquisition of a maximum of geoscientific information at lower costs and risk as compared to the expensive heavy rig of the ultra deep hole.
>
> Minimization of core runs and logging in the large diameter straight vertical upper section of the ultra deep hole.
>
> Analysis of the temperature profile for planning the ultra deep hole.
>
> Obtaining data about problem sections with inflow or lost circulation, well bore instabilities and/or breakouts.
>
> Test of drilling and logging tools with regard to the ultra deep hole.

To accomplish these objectives, the pilot hole had to meet the following requirements:

- maximum depth of 5,000 m,
- 6" bit size and 4" core diameter and
- continuous coring with maximum core recovery.

A new drilling concept was developed, combining the rotary drilling and the wireline coring techniques. A high speed top drive (Fig. 2), a 6" external flush mining drillstring (Fig.3), a double tube wireline core barrel system (Fig. 4), combined with MWD, and high performance diamond core bits were developed, improved and successfully tested in the pilot hole. The availability of a solids free highly lubricant drilling fluid system is another reason for the successful drilling operation in the pilot hole.

Drilling the pilot hole started on September 22, 1987 and was finished on April 4, 1989 after 560 days of drilling and logging. Fig. 5 shows a view of the well site. Total depth is 4,000.10 m of which 3,594 m = 90 % have been cored (Fig. 6). 451 m were cored with 10 5/8" rollercone core bits and 3,143 m with 6" thin kerf diamond core bits. A total of 9 surface set and 60 impregnated diamond core bits (Fig. 7) were used, the average bit life of the diamond bits being 48 m and the rate of penetration (ROP) being 1,66 m/h. The bits purchased from 3 major manufacturers have been improved continually, 5 diamond bits had a bit life of more than 118 m, and a ROP of 2,3 m/h. The average core length was 3.5 m. Due to lost bottom hole assemblies after fishing jobs, 2 side tracks had to be performed, the first in 1,998 m depth, and the second in 3,767 m depth. The mining drillstring had to be taken out of operation in February 1989 due to oxygen-pitting-corrosion on the internal pipe wall between the couplings. Because of this, a Dynadrill-Downhole-Motor (DHM) with hard rock roller cone bits and a 3 1/2" rotary string were used after the successful second side track. The performance was much poorer compared to the diamond coring system, ROP being only 0.84 m/h and bit life 12.31 m, respectively.

The evaluation of the rig time break down and the overall performance (Fig. 8) shows that despite the good results of bit life, ROP, and the excellent core recovery of 98 %, there is potential and need for further improvement of this type of drilling technology, firstly to avoid directional drilling and fishing by using a straight hole drilling technology and secondly to bring down the time for tripping the drill string and the core barrel.

The pilot hole penetrated into a succession of highly metamorphic paragneisses and metabasites, most probably precambrian in age. The rocks are folded, and prevailingly, rather steeply inclined. They are disrupted by a great number of faults and by - often graphite-bearing - cataclastic zones. These zones caused reduced borehole stability and led to breakouts.

The trajectory of the pilot hole (Fig. 9) is mainly determined by the steep (south) dipping of the formations. Total deviation is 190 m. Coring had to be interrupted three times for directional drilling to bring the hole back to nearly vertical direction. Two sidetracks were necessary. The upper one, caused by stuck pipe and a massive influx of graphite into the borehole, was performed by conventional technique with benthousing and downhole motor. For the sidetrack in the deep section, an open hole packer was placed above the fish and then connected with an oriented wedging device.

Temperature in 4,000 m depth is 118 °C and 1/3 higher than predicted (Fig. 10). Assuming a linear temperature increase, a temperature of 290 °C in about 10,000 m depth is likeley to be expected, with a drawdown to 195 °C due to mud circulation.

A comprehensive logging program was run in the pilot well, last not least to examine and to calibrate the tools for use in crystalline rock. A most modern logging unit and logging tools were purchased, and specialists operating the unit and tools were leased.

From four drillstemtests only one detected a small fluid inflow. A major fluid inflow occured after having finished drilling in about 3,997 m depth. Corresponding to an initial differential pressure of about 40 bars a fluid inflow into the borehole of 9.2 cubic meters of medium saline water was measured.

A speciality and an essential part of the geoscientific research is the field laboratory on the well site, staffed with scientists of all relevant disciplines of 8 universities. Continuous petrological, geological, geophysical and geochemical measurements and an intensive mud logging are the basis of scientific evaluation and a great help for the drilling operation.

The ultra deep well

Based on the results of the pilot well, the planning for the ultra deep well, which is located at 200 m distance from the pilot well, had to be revised. The critical temperature range with respect to drilling and logging technology of 250 to 300 °C, whose investigation is a major geoscientific objective on the other hand, will be reached at 10,000 m depth or less (taking into account linear extrapolation of the temperature gradient).

This is the reason to base the technical planning (Fig. 11) and the funding on 10,000 m total depth, including an option to continue drilling down to 12,000 m if the temperature is lower than expected. More than 4/5 of the major geoscientific objectives can be met down to 10,000 m depth. The final decision on the total depth will be made when the well has reached a depth about 8,000 m. Due to the wellbore instabilities encountered in the pilot hole, the revised drilling and casing program implies now 5 instead of 3 separate cased sections in the former planning. To make use of the application of bits and downhole equipment of international standard and proven dimensions the final diameter at total depth is planned to be 8 1/2".

Due to the extensive coring and logging program in the pilot well, coring in the upper section of the ultra deep well (corresponding to the pilot wells total depth) can be avoided, and logging can be minimized. Below the total depth of the pilot well, about 1,000 m coring and comprehensive logging programs before installing the casing sections are planned.

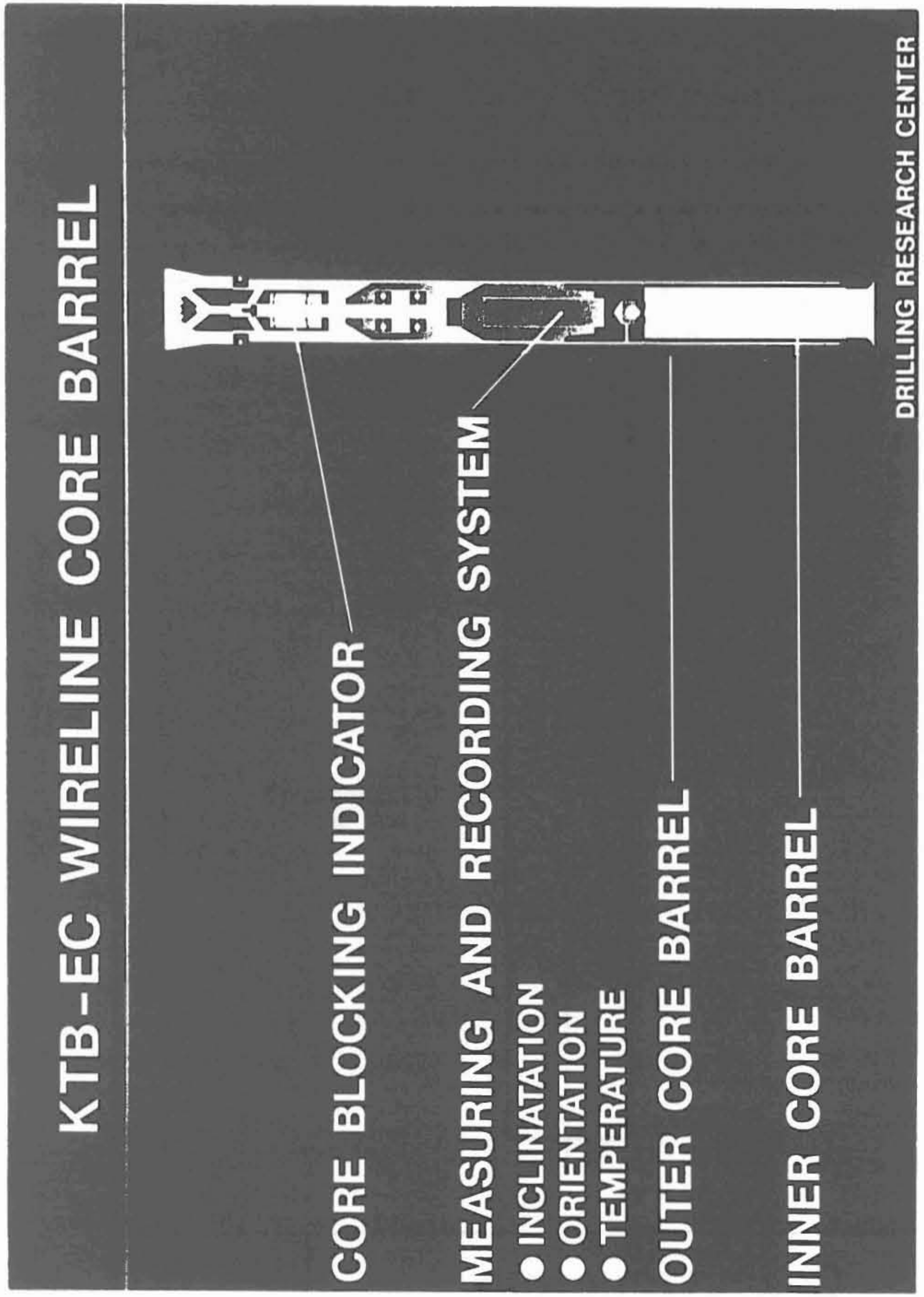
To avoid too extensive side forces and wear of down hole equipment, a straight vertical hole in the upper section of the ultra deep hole is mandatory. Therefore the success depends to a high extent on a reliable and efficient straight hole drilling technology (Fig. 12). Intensive R & D efforts and sufficient funding are allocated to solve this problem. Self adjusting steerable systems seem to be a promising approach. The basic principle is a kind of selfsteering stabilizer with an integrated MWD-system for operational control. Other main R & D efforts are focused on the development of advanced coring systems, high temperature mud, high strength drill string and high temperature logging strategies. To meet the requirements of depth and scientific crystalline rock drilling, several studies for rig layout and construction were performed. The result is the decision to build a new rig with an automated pipehandling system and a load capacity for at least 12,000 m depth. A view on the rig is given in Figure 14 and a short technical description in Figure 15.

Drilling the ultra deep well will start in August/September 1990. The time needed to reach 10,000 m depth is estimated with 4 1/2 years, which means drilling will last until the end of 1994.

International cooperation

International interdisciplinary cooperation has proven to be highly beneficial for all national and international projects of lithosphere research. All concerned disciplines should be tied in, including the geosciences, drilling and measuring technology. The KTB, the German contribution to the International Lithosphere Program, has encouraged and developed cooperation with a number of nations and institutions, namely ODP and DOSECC (USA), BRGM (France) the Svedish Gas Project, Canada, the BGS (UK), Czechoslovakia, Japan, the Peoples Republic of China, the German Democratic Republic, and last not least, the leading country of ultra deep drilling, the USSR, where the cooperation will be intensified in the near future.

List of Figures:



KTB-EC WIRELINE CORE BARREL

CORE BLOCKING INDICATOR

MEASURING AND RECORDING SYSTEM

- ● INCLINATATION
- ● ORIENTATION
- ● TEMPERATURE

OUTER CORE BARREL

INNER CORE BARREL

DRILLING RESEARCH CENTER

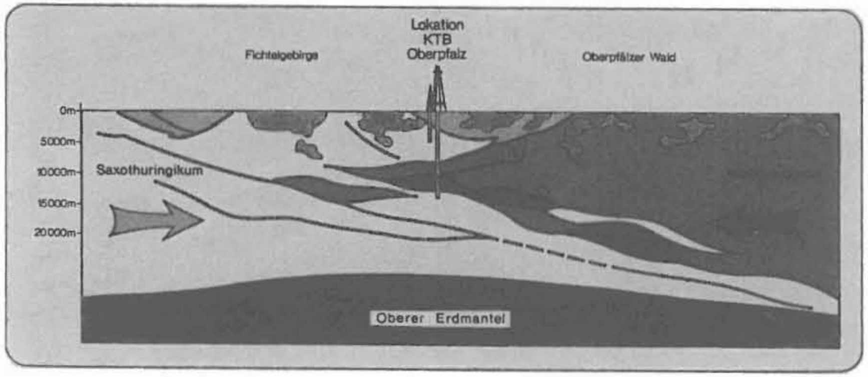
4

1

KTB

KONTINENTALES TIEFBOHRPROGRAMM DER BUNDESREPUBLIK DEUTSCHLAND

Projekt der Grundlagenforschung
über die physikalischen und chemischen Bedingungen und Prozesse
in der tieferen Kruste
mit dem Ziel,
den strukturellen Aufbau, die Dynamik und die Evolution
intrakontinentaler Krustenbereiche
zu verstehen



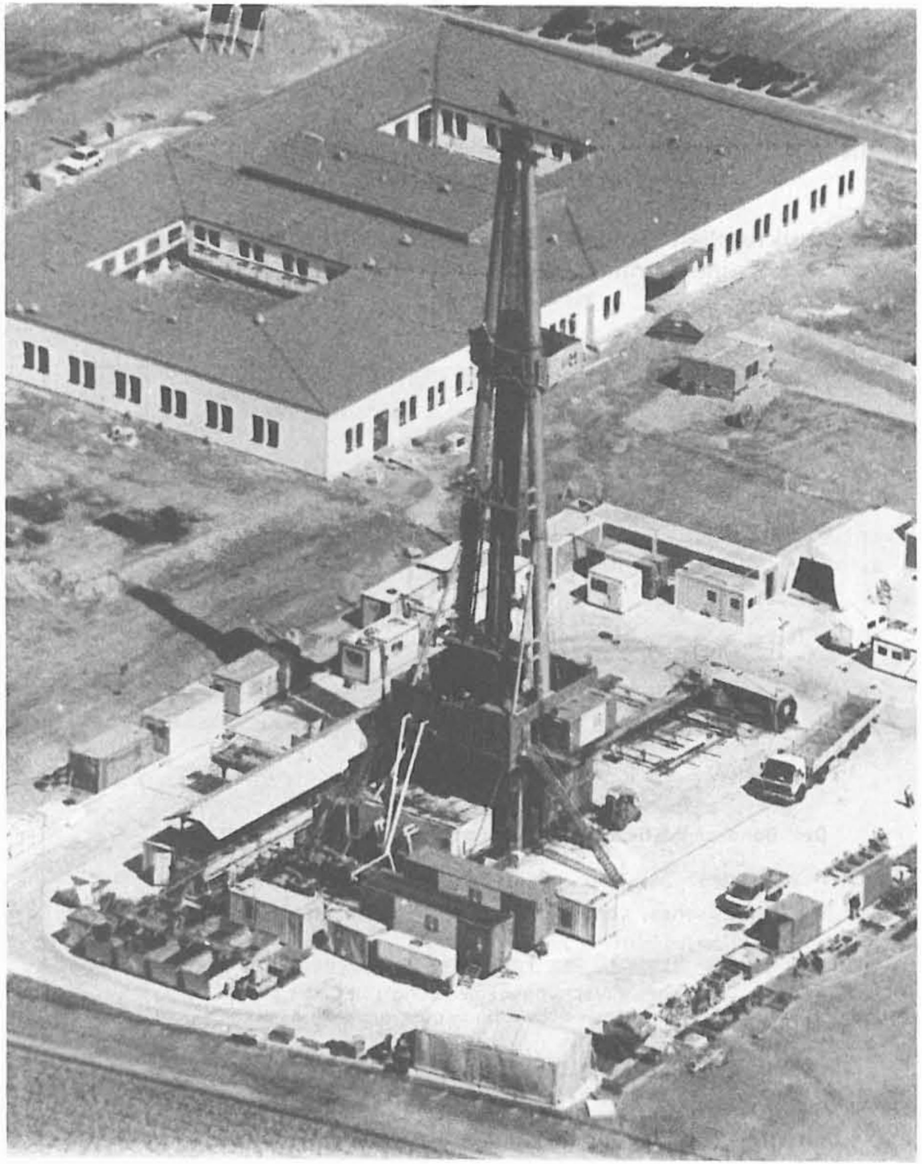
Projektfinanzierung :
Der Bundesminister für Forschung und Technologie (BMFT)

Projektleitung :
Niedersächisches Landesamt für Bodenforschung (NLfB)

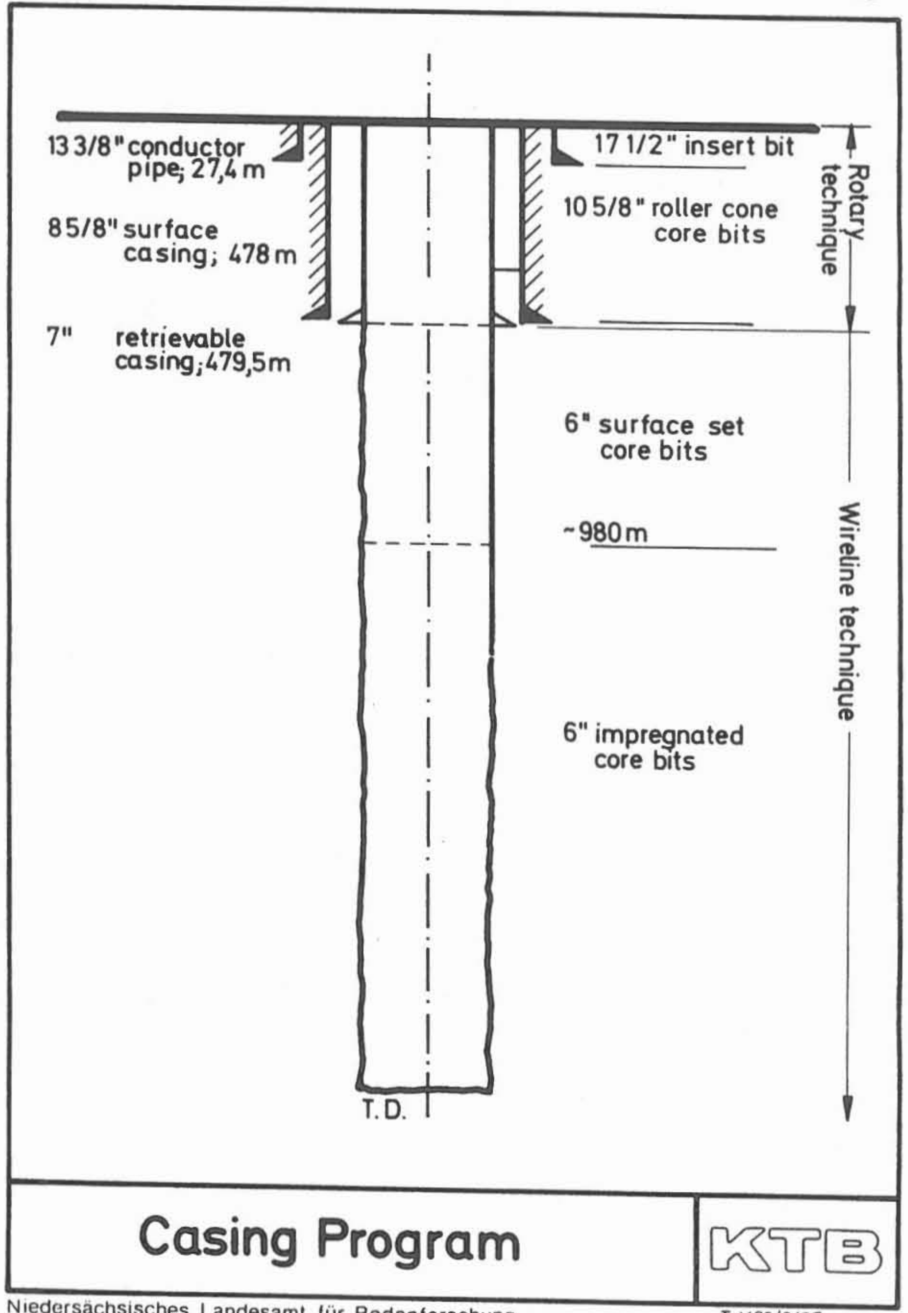
Koordination des Forschungsvorhabens :
Deutsche Forschungsgemeinschaft (DFG)
im Rahmen des Schwerpunktprogrammes KTB

Beteiligte Universitäten :
Aachen (TH), Bamberg, Bayreuth, Berlin (FU, TU)
Bochum, Bonn, Braunschweig (TU), Clausthal (TU),
Darmstadt (TH), Erlangen - Nürnberg, Frankfurt, Freiburg,
Gießen, Göttingen, Hannover (TU), Heidelberg, Karlsruhe,
Kiel, Köln, Mainz, Marburg, München, Münster,
Regensburg, Saarbrücken, Trier, Würzburg

5



6

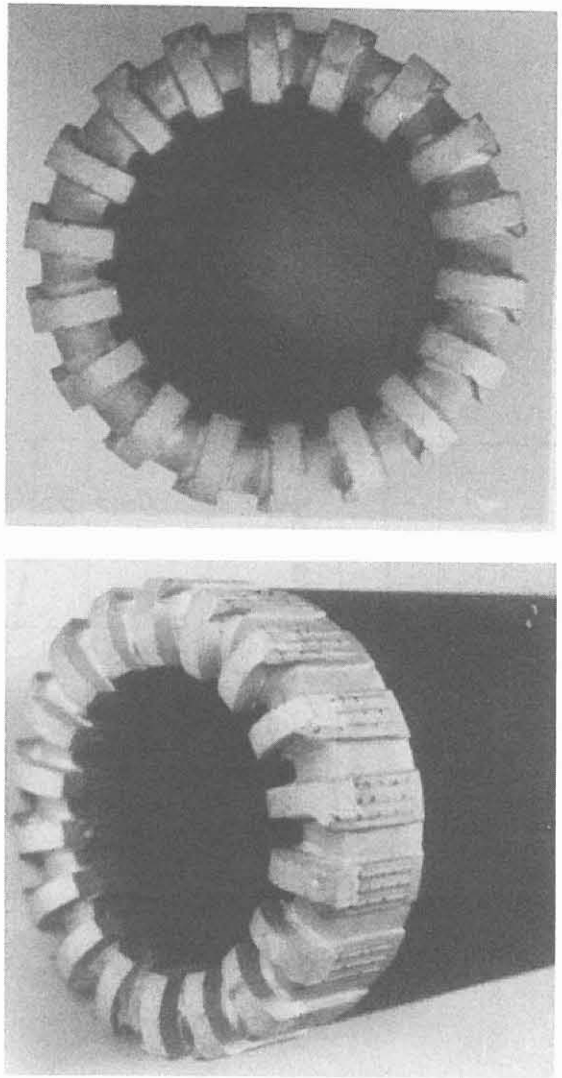


Casing Program

Niedersächsisches Landesamt für Bodenforschung

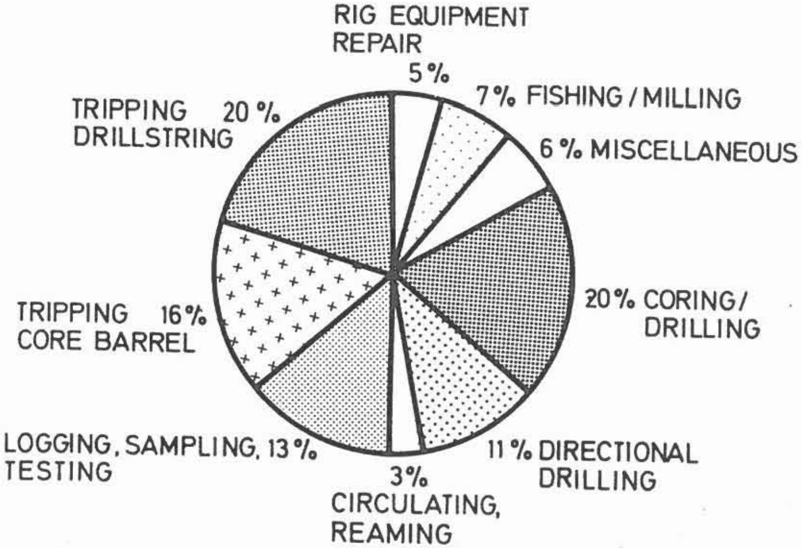
T 1189/8/88

7



8

	PLANNED	REACHED
BIT LIFE (DCS) (m)	20	48
AVERAGE CORE LENGTH (m)	4	3,5
AVERAGE ROP (m/h)	1,5	1,68
TRIPPING DRILLSTRING (h/1000 m)	3	4,5
TRIPPING WL-CORE-BARREL (h/1000 m)	1,15	0,95
CORE RECOVERY (%)	85	98



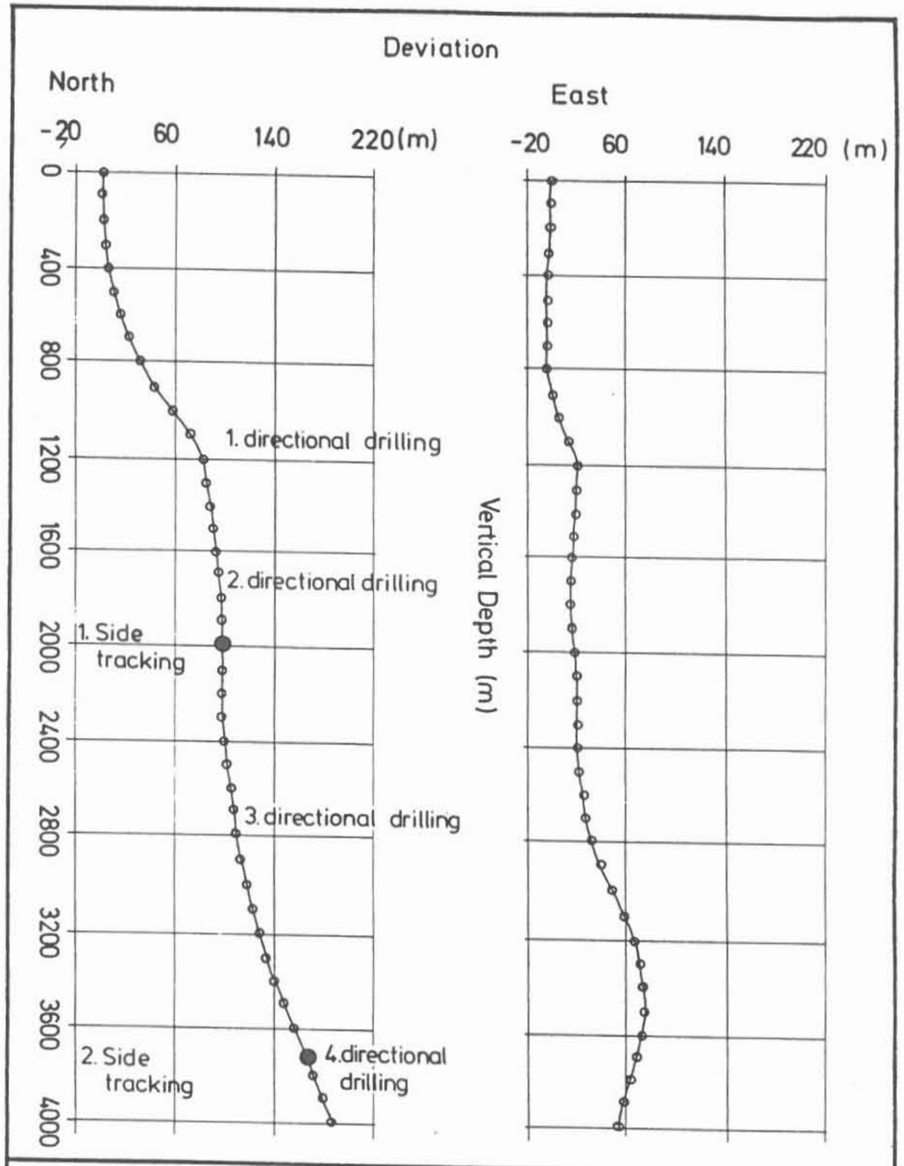
KTB-PILOT WELL, TOTAL RIG TIME BREAKDOWN
TD = 4000,10 m, 560 days

KTB

T 2101 / 7.89 / Ri

Niedersächsisches Landesamt für Bodenforschung

9



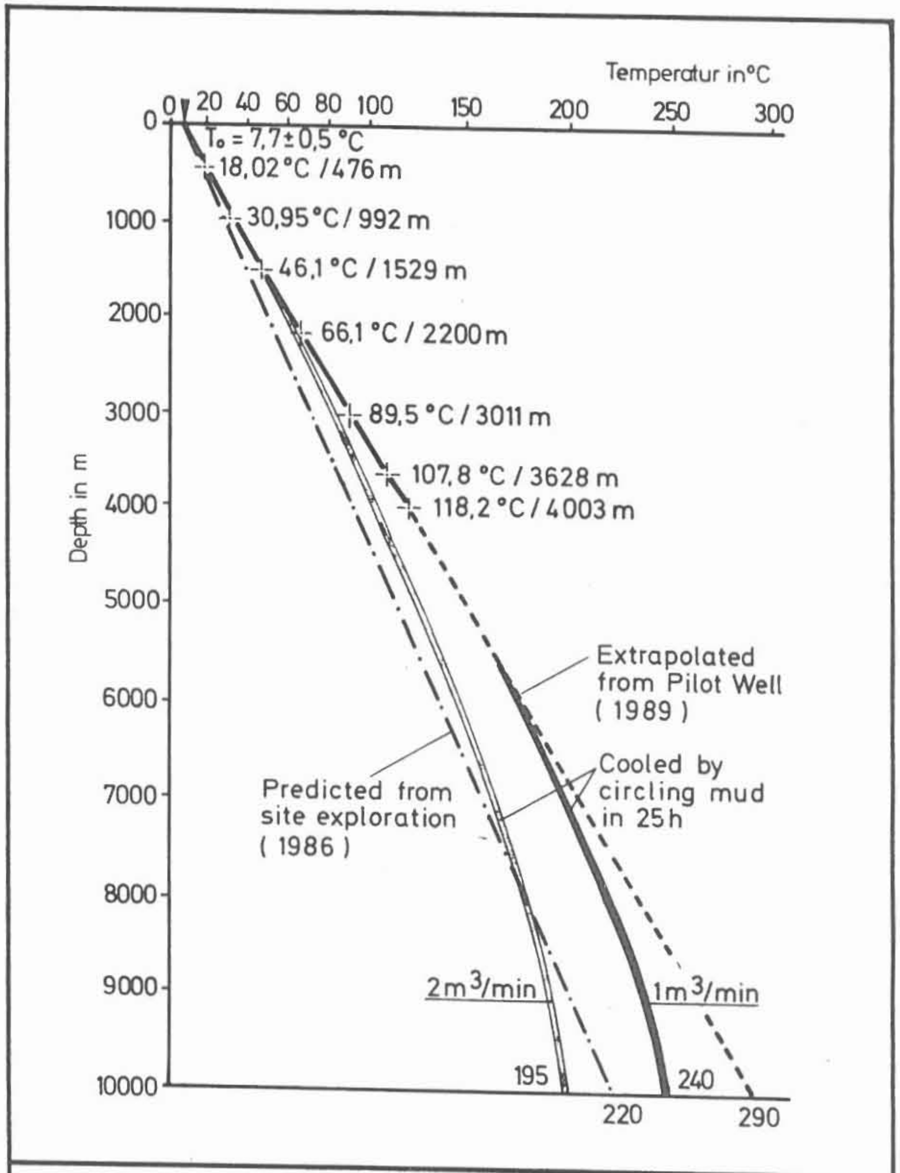
KTB - Pilot hole, well bore trajectory

KTB

T 2100/6.89/Ri

Niedersächsisches Landesamt für Bodenforschung

10

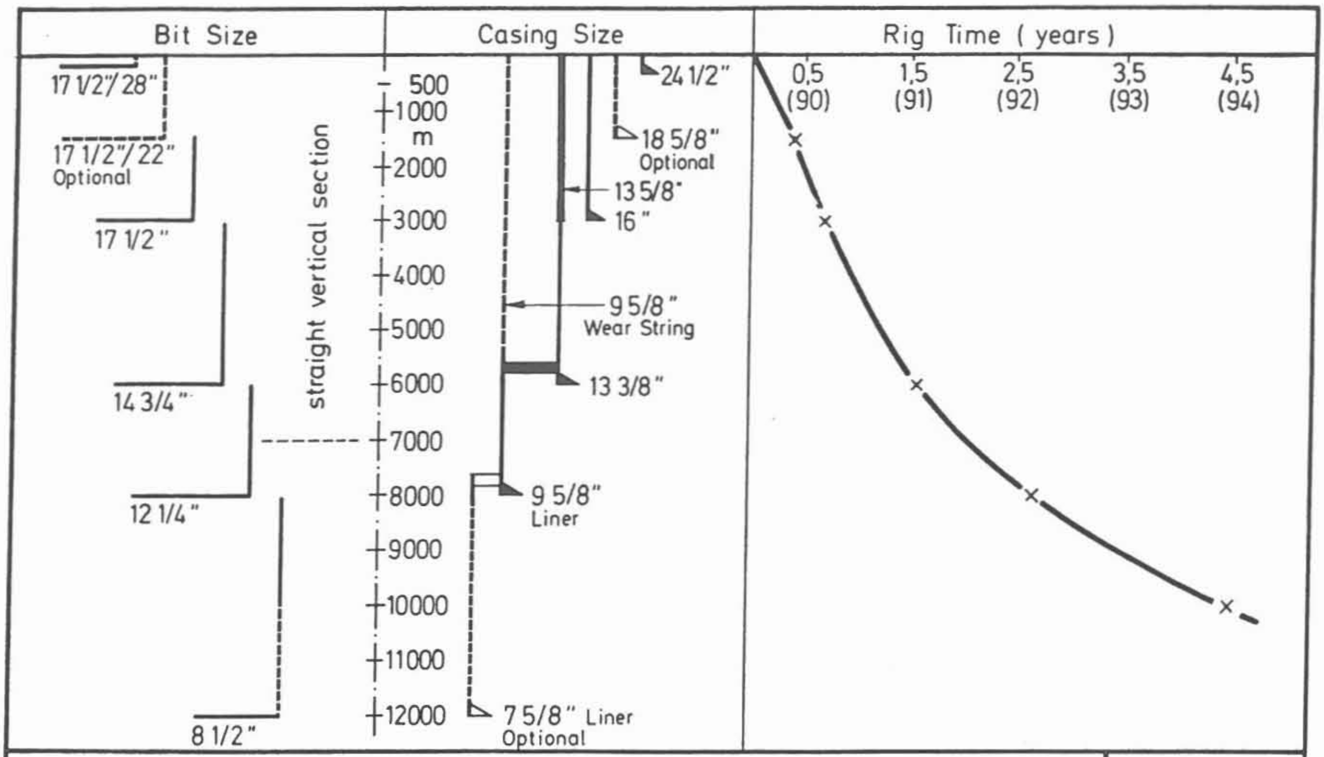


Expected temperature for planning the KTB-Deep hole

KTB

T 2102 / 7.89 / Ri

Niedersächsisches Landesamt für Bodenforschung

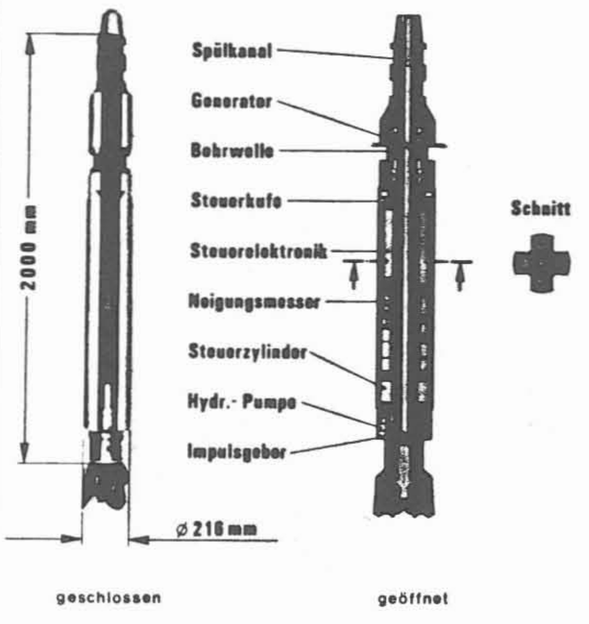


KTB - Ultradeep Hole : Bit- and Casing Program, calculated Rig Time

T 2099/6.89/Ri

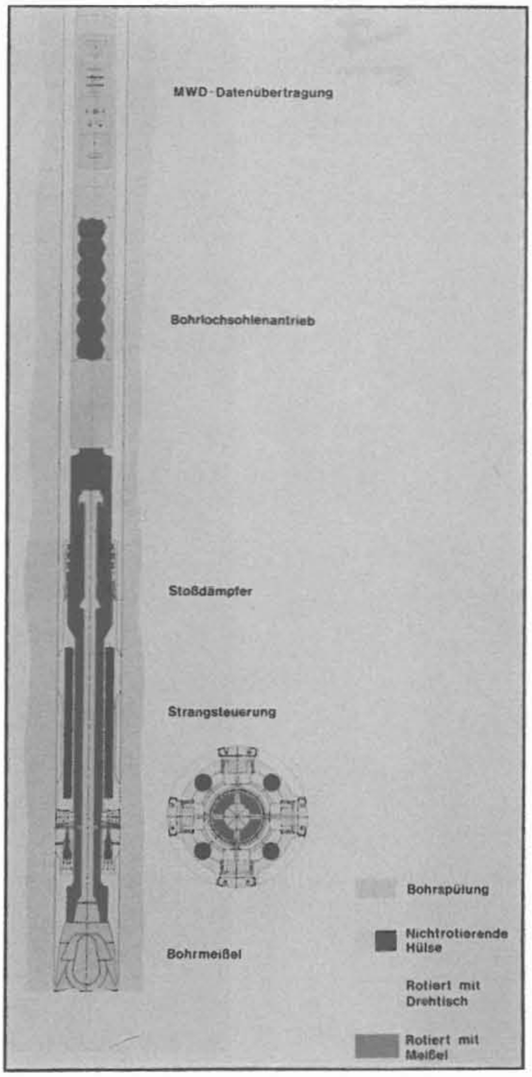
Niedersächsisches Landesamt für Bodenforschung

11

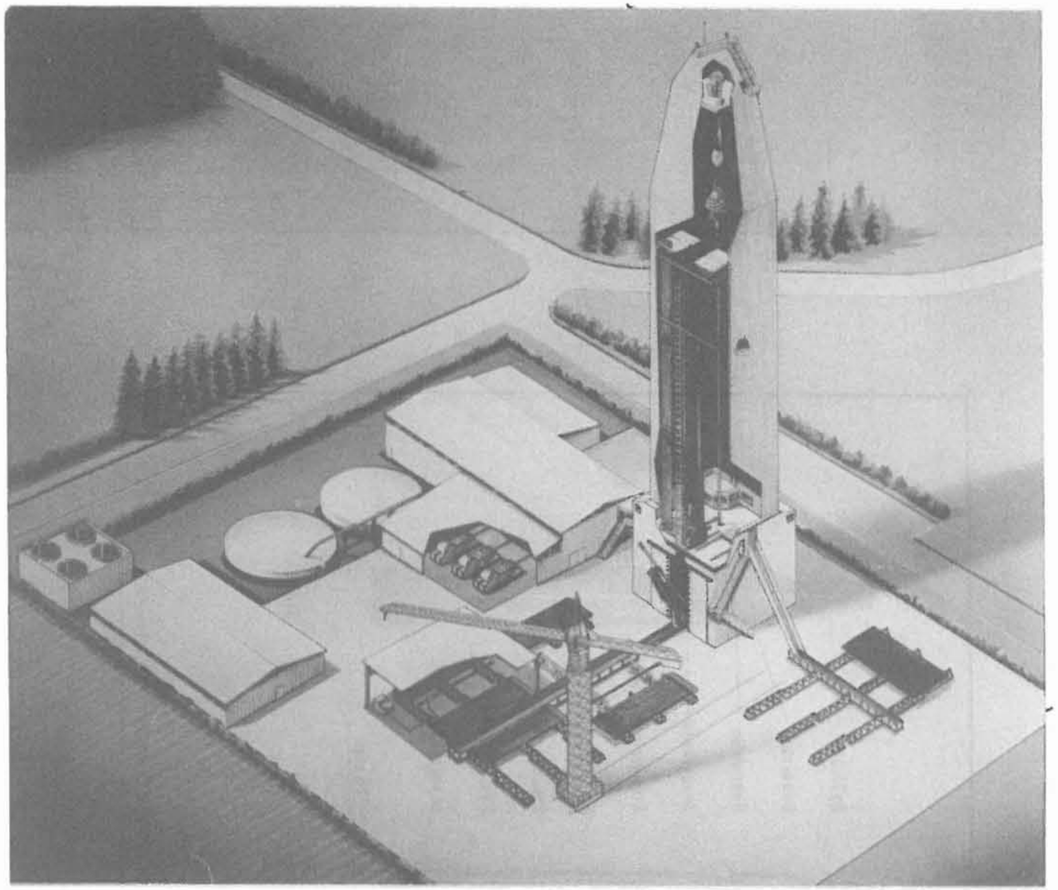


SELBSTTÄTIG STEUERNDE ZIELBOHRSTANGE ZBE

12



13



KEY DATA OF THE KTB - ULTRA DEEP DRILLING RIG FOR 12000 m TD.

- **STATIONARY DRILLING TOWER:**
  - **Total height** **83 m**
  - Derrick height 63 m
  - (to handle 40 m DP-sections)
  - **Regular hook load** **5500 kN**
  - Extraordinary hook load 8000 kN
- **SUBSTRUCTURE:** to stack **12000 m 5 1/2"/5" DP**
  - Standback load 5500 kN
  - Rotary table load 8000 kN
- **DRAW WORK:** ConEmsco C 3 or Wirth GH 3000
  - Cable-Ø 1 3/4"
  - Input **2220 kW**
- **MUD PUMPS:** Number 3
  - Input **3100 kW**
  - max. pressure 350 bar
- **ENERGY SUPPLY:** Electricity from public network
  - **9 Motors with 6060 kW** total input
  - (AC or DC not yet decided)
- **MUD SYSTEM:**
  - Volume of active tanks 150 m^3
  - Volume of reserve tanks 300 m^3
  - Volume of trip, pill and measuring tanks 50 m^3
  - **Total tank volume** **500 m^3**
- **ADVANCED SOLIDS CONTROL SYSTEM:**
  - 3 Shale shakers
  - 2 x 12 Desilters (cyclones)
  - 4 Centrifuges (Z 73)
  - Vacuum degassers
- **AUTOMATED PIPEHANDLING**/hook retractor **system**, pick up and lay down system with continuous pipe inspection
- **ADVANCED DRILLING INSTRUMENTATION SYSTEM**

STEUERSTABILISATOR ZUM VERTIKALBOHREN

PROJEKTDURCHFÜHRUNG

Dr.-Ing. Rainer Jürgens
Eastman Christensen GmbH, Celle

Dipl.-Ing. Manfred Lohmann
Schwing Hydraulik Elektronik GmbH+Co, Herne

Dipl.-Berging. Volkmar Mertens
Bergbau-Forschung GmbH, Essen

Ziel der gemeinsamen Entwicklungsarbeiten ist die Bereitstellung von Vertikalbohrsystemen für den Einsatz in der KTB-Hauptbohrung. Es werden die Systeme STEUERSTABILISATOR, ZIELBOHRSTANGE und NAVIGATIONSBOHRSYSTEM in enger Zusammenarbeit entwickelt.

Dazu bringen Bergbau-Forschung und Schwing die Erfahrungen einer erfolgreichen Zielbohrstangen-Entwicklung für Bergbauzwecke ein, während Eastman Christensen sein Know-How aus der langjährigen Entwicklung von mechanischen, hydraulischen und elektronischen Systemen für Tiefbohrungen zur Verfügung stellt.

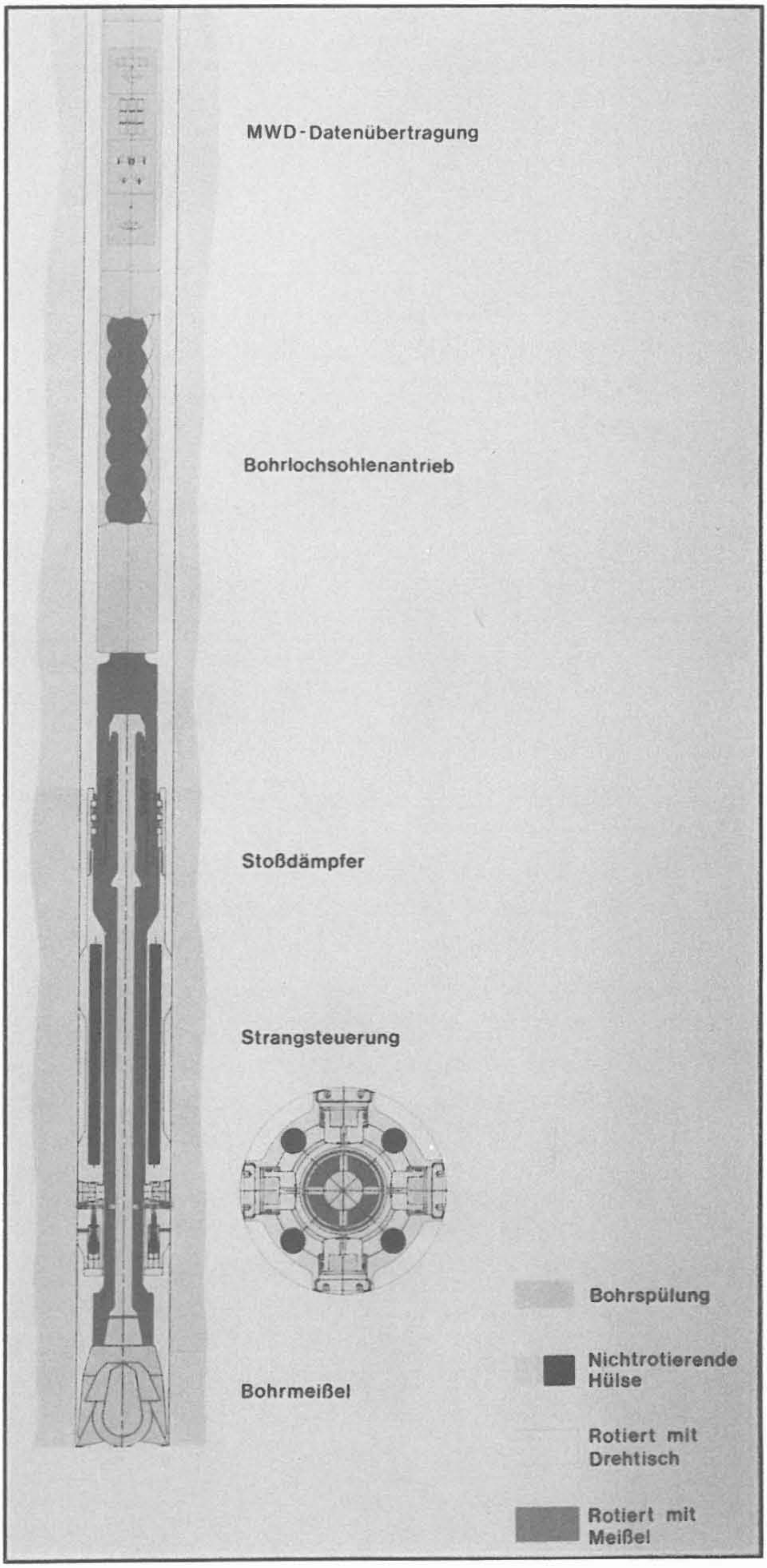
ANFORDERUNGEN

Die Kontinentale Tiefbohrung der Bundesrepublik Deutschland soll sich bis zu einer Endteufe von ca. 14000 m erstrecken. Erfahrungen aus vergleichbaren wissenschaftlichen Bohrprojekten haben gezeigt, daß die bohrtechnischen Probleme mit der Teufe überproportional zunehmen. Die mechanische Belastung des Stranges beim Ausbau aus dem Bohrloch sowie beim Rotieren von der Erdoberfläche bestimmen die erreichbare Endteufe. Es müssen technische Systeme bereit gestellt werden, die ein präzises Vertikalbohren ermöglichen, weil dann optimale mechanische Bedingungen vorliegen. Aufgrund des bisher nicht vorhandenen Anforderungsprofils gibt es solche Bohrwerkzeuge für die Bedingungen der übertiefen KTB-Bohrung noch nicht.

LÖSUNGEN

Aus Gründen einer optimalen Vorbereitung auf die für das Schicksal der Bohrung unverzichtbare Vertikalität, insbesondere in den oberen Sektionen, werden drei unterschiedliche Werkzeugtypen geplant und gebaut.

Der STEUERSTABILISATOR besitzt Sensoren zur Messung einer möglichen Abweichung von der Vertikalen. Die Meßwerte werden direkt in Steuersignale für hydraulisch betätigte Verstelleinrichtungen zur Kompensation der Abweichung umgesetzt. Als Betriebsmedium für die Hydraulik dient die Bohrspülung. Die Versorgung mit elektrischer Energie erfolgt durch Batterien. Sensorik und Elektronik sind durch spezielle Stoßdämpfer von den Erschütterungen des Bohrprozesses abgeschirmt. Meßdaten werden durch Druckimpulse in der Spülung an die Oberfläche übertragen. Der Antrieb des Bohrmeißels erfolgt vorzugsweise mit einem Bohrlochsohlenmotor, der seine Energie ebenfalls aus der Bohrspülung bezieht. Die wesentlichen Komponenten des Prototyps haben ihre Standfestigkeit unter Tiefbohrbedingungen bereits in Serienwerkzeugen von Eastman Christensen unter Beweis gestellt.



CURRENT STATE OF THE KTB
– TECHNICAL CONCEPT –

Summary of results and experiences of KTB pilot hole drilling operation with outlook on the ultradeep hole

B. Engeser
C. Chur
W. Kessels

Paper presented at the
"28th International Geological Congress"
Washington (USA)
July, 1989

OBJECTIVES

The drilling concept of KTB may be viewed as a synergism of a pilot hole, the ultradeep hole and a broad research and development program. Therefore, the pilot hole is an essential part of the KTB with important functions for the realization of the entire program.

The pilot hole serves the following purposes (Fig. 1):

- Gathering geoscientific data by means of continuous coring, logging, tests and analysis of cuttings and mud.
- Analysis of the temperature profile to determine the temperature distribution with depth for the ultradeep hole.
- Minimization of core runs and borehole measurements in the ultradeep hole over the section of the pilot hole.
- Obtaining data about problem sections like inflow or lost circulation zones and their pressure gradients in the depth intervals of the anchor casing of the ultradeep hole.
- Testing of drilling and logging tools which will be necessary for the ultradeep hole.

PILOT HOLE DRILLING CONCEPT

To accomplish these objectives, the pilot hole had to meet the following requirements (Fig. 2):

- Minimum depth of 3,000 m with capability of a maximum depth of 5,000 m.
- 6" hole diameter for full logging and testing program.
- Continuous coring from surface to total depth.

To realize these requirements within the given financial and time constraints, a combination of rotary drilling and wireline coring technique has been employed.

Years of experience in the mining industry demonstrate the excellent efficiency of the wireline coring technique with diamond core bits and special external flush drill strings in crystalline rock exploration.

DRILLING RIG

To realize a depth capacity of 5,000 m with a borehole diameter of 6", a rotary rig with the following specifications was modified for wireline coring (Fig. 3).

The rig is equipped with a hydraulic top drive with 464 kW and a rotational speed of 300 RPM at a torque capacity of 11,000 Nm. Maximum rotational speed is 600 RPM at 5,800 Nm.

The hydraulic top drive is mounted on a travelling guide carriage welded on a cross beam in the mast.

To guarantee regular weight on bit, an automatic feed control is installed.

DRILL STRING AND WIRELINE CORING SYSTEM

For applications of the wireline coring technique to a maximum depth of 5,000 m in a 6" borehole, an entirely new drill string and coring system had to be developed and manufactured. The technical specifications are shown in Fig. 4.

The complete string including the core barrel is external flush.

The coring system consists of an inner and outer core barrel with a positive pressure indication at surface in case of a core jamming.

On top of the inner barrel a memory tool is integrated, recording bottom hole temperature and wellbore inclination for each core run. Read out of the data at surface is possible whenever a core barrel is retrieved.

In the meantime the memory tool could be successfully adapted for measuring of relative bearing angle. In combination with the regularly run azimuth-measurement it is now possible to get oriented cores whenever wanted.

RESULTS AND EXPERIENCES OF DRILLING OPERATION

On September 22, 1987, drilling started with a 17 1/2" roller cone insert bit down to 27.5 m. Out of the 13 3/8" conductor pipe the hole was deepened with rotary technique and 10 5/8" roller cone core bits down to 478.5 m.

Then the 8 5/8" anchor casing was run and cemented (Fig. 5).

After deepening the hole to 480 m a 7" retrievable casing was freely hung off down to 479.5 m. This casing serves as a guide string for the 6"-coring phase because of hydraulic reasons, and guarantees wear protection for the anchor casing.

From 479.5 m down to the present depth of 3,800 m, wireline coring with 6"-hole diameter was used, interrupted by three directional drilling correction jobs due to severe inclination build up.

During a directional drilling work the rotary drill pipe got stuck in a depth of 1,998.8 m due to a sudden borehole-instability on a weak graphite-bearing zone in this depth. The problem was overcome by a successful sidetrack at a depth of 1,680 m.

For directional control, Moineau-motors with different directional control systems which means bent subs, bent housings and steerable systems with a theoretical build down rate of 0.2° to 0.75° were applied.

The general problem due to the complex geological situation with layers of gneisses and amphibolites as well as heavily disturbed cataclastic zones is to maintain the predicted drop down rate and keeping the azimuth in the desired direction. This is the main reason for the uneven borehole-trajectory (Fig. 6).

Extensive logging and testing programs were carried out in 500 m-intervals, which is documented in a 15 % amount of total time in the cumulative time breakdown analysis (Fig. 7).

At the beginning of January 1989 a depth of 3,800 m has been reached with 5,000 m expected in June 1989.

DRILLSTRING

During the pilot hole drilling operation, the new drillstring has been proven as a very reliable and successful tool. The experiences show clearly that there is a much higher risk for getting stuck with the rotary string than with the wireline-string. This was the reason to apply the wireline string for a Drillstem-Test in October 1988.

The string has been proven as absolutely gas-tight at a nitrogen pressure of 200 bars.

CORE BITS

In the 10 5/8" phase, a 8 1/4" x 4" core barrel with 4 roller-type and 6 roller-type roller cone core bits was used.

Average core recovery was 43 % with a maximum of 79 % in the depth interval between 400 and 478.5 m.

Generally, the commonly known experience was confirmed, that an acceptable core recovery with roller cone core bits is achievable only in competent rocks.

Below 480 m down to a depth of 3,800 m, totally 3,052.8 m, have been cored with mainly impregnated core bits. Surface set bits were used in the upper part down to approximately 800 m.

A permanent improvement of core bit design led to the results shown in Fig. 8.

Average drilling parameters for coring with impregnated bits have been (Fig. 9):

- weight on bit: ~ 30 - 40 kN
- rotary speed: 280 - 300 RPM
- pump rate: 220 - 250 l/min

DRILLING FLUID SYSTEM

A newly developed drilling fluid is used for the first time in the KTB pilot hole. Due to the scientific aims of KTB it was imperative to look for a drilling fluid minimizing any impairment of the geoscientific investigations.

The new product was developed in cooperation with KTB, Henkel KGaA, and NL Baroid International.

The main features of the mud system are the inorganic composition and the promising high temperature stability, which makes an application in the ultradeep hole feasible.

The completely inorganic one component system of high constancy provides excellent conditions for geochemical investigations especially for detection of small influx quantities of hydrocarbons or saline waters.

Furthermore, the good carrying capacity in combination with a strong shear thinning behaviour has to be mentioned. The environmental behaviour due to the simple inorganic composition is of advantage for mud disposal.

Fig. 10 shows the strong reciprocal correspondence of pump pressure and torque. At a constant pump rate this demonstrates the impact of drilling fluid viscosity.

This can be explained by a kind of hydrodynamic lubrication effect commonly known in the theory of journal bearings.

There is evidence that the hydrodynamic bearing effect is also responsible for the very low amount of drill string wear while drilling the pilot hole.

Typical properties of the drilling fluid during wireline coring operation are shown in Fig. 11.

The relative high viscosity is necessary because of the torque correlation mentioned before.

BOREHOLE STABILITY

The change in borehole diameter, computed from four-arm caliper and borehole-televiewer data has been investigated regularly while drilling the KTB pilot hole.

The recording of technical parameters and frequent caliper-logs covering the total open hole interval are a good basis for thorough observations of thermo-mechanical effects. Alteration load tests made with a tri-axial pressure cell are part of the research and development program as well.

Caliper logs over the first 500 m of the pilot hole show breakouts in different forms.

The time dependent increase of the borehole diameter is mainly caused by borehole erosion as demonstrated in Fig. 12.

Particularly variations in the mud conditions are responsible for instabilities in the KTB pilot hole. Caliper logs run before and after a strong reduction of mud viscosity required for a Drillstem Test, show a rapid increase of the borehole diameter after the test.

Capillary suction time measurements proved to be a good indication for free water content of the drilling mud which is of major importance for borehole stability, particularly in weak cataclastic zones.

By reducing the free water content of drilling mud indicated by an increase in the CST-value, it was possible to stabilize borehole breakout development as already shown in Fig. 12.

SOLIDS CONTROL

In wireline coring technique, settling pits are conventionally used for separation of the drilled cuttings.

Impregnated diamond core bits however produce a very fine cutting material, which makes settling a very ineffective method. A typical grain size distribution of the drilled cuttings is shown in Fig. 13.

Therefore, KTB runs a decanting centrifuge as the main solids control equipment.

The successful performance of the centrifuge is documented by a solids concentration in the underflow of more than 60 % and a separation efficiency with 90 % solids smaller than 5 microns.

One of the scientific objectives is the quick detection of lithology changes by cutting analysis. The cuttings separated at the centrifuge underflow have been proven as an ideal material for analyzing and correlating mineral content by means of X-ray diffractometry and fluorescence analysis.

The slip velocity of the very fine material can be neglected therefore allowing an accurate lag correction. A comparison between the X-ray analysis of cuttings and logging results shows good correlation (Fig. 14).

MUD LOGGING SYSTEM

An extensive mud logging system is used in the KTB pilot hole to achieve the scientific objectives.

Drilling parameters as well as the physico-chemical parameters of the drilling fluid are measured and recorded continuously. The measured data is stored together with the important parameters of lithology and mud chemistry in a data base system.

Various sensors are installed for the first time on a drilling rig.

More than 50 parameters are continuously measured and can be displayed on online color screens.

The accurate measurement of the in- and outflowing mud stream by mag-inductive sensors enables the scientists to carry out a mass balance for all of the components of the active mud system.

Fig. 15 shows the parameters measured at the outflowing mud.

One of the objectives is to detect and analyze even small amounts of gas in the outflowing mud stream. For this reason two special gastraps are installed supplying the online process mass-spectrometer in the field laboratory as well as a gas chromatography with an FID and TC detector. Furthermore, a newly designed gas separation system for continuous non-air contaminated gas sampling has been installed and was tested successfully.

An unexpected result was the high amount of artificial hydrogen in the drilling fluid, which is strongly correlated to diamond core bits and not detected drilling with roller cone bits, as shown in Fig. 16.

There is evidence that this hydrogen is generated by thermal reactions during the cutting action of diamonds.

Fig. 17 shows a typical plot of drilling data together with scientific data from X-ray diffractometer and mass spectrometer by use of the data base system.

All these parameters are, of course, available for advanced statistical analysis.

DRILLING CONCEPT OF THE ULTRADEEP HOLE

The technical concept of the ultradeep hole was developed using the following criteria: (Fig. 18):

1. Application of bits and downhole equipment of internationally standardized and proven dimensions.
2. Diameter of borehole as large as necessary, but as small as possible.
3. Diameter of 8 1/2" at total depth, provided no excessive difficulties are encountered while drilling.

Including the experiences of the pilot hole this led to the bit and casing programs shown in Fig. 19.

Down to 7,000 m the ultradeep hole will be drilled as vertical as possible by means of the automatic vertical drilling system.

If necessary a 11 3/4"" wear protection casing can be run with a subsequent reduction in hole diameter to 10 5/8".

There is no open hole interval longer than 4,000 m in this concept which is of particular importance for long term borehole stability problems.

DRILLING RESEARCH AND DEVELOPMENT PROJECTS

The objective of the KTB ultradeep hole is to reach a target depth of 14 km with a maximum gain of geoscientific information and within the given budget and time constraints.

Soon it became evident that application of conventional rotary drilling technology is not sufficient to fulfil these requirements.

Therefore, a program of accompanying research and development projects in the field of drilling technology was worked out together with the specifications for a new "tailormade" drilling rig.

Among the variety of technical and scientific projects the following projects are of particular importance (Fig. 20):

- Development of an automatic vertical drilling system.
- Advanced coring systems.
- Development of a high strength steel drill string.
- Development of new logging tools.

A nearly vertical borehole especially in the upper part of the hole is mandatory for reaching the target depth of 14 km.

Therefore, an automatic vertical drilling system, for application in the 17 1/2" and 14 3/4" phase of the ultradeep hole is currently developed in cooperation with KTB, Bergbauforschung GmbH, Schwing and Eastman Christensen.

The working principle is a kind of selfsteering stabilizer with an integrated MWD-system for operational control. The system has been proven successfully for vertical upward drilling in the mining and tunneling industry and shaft sinking applications as well (Fig. 21).

DRILLING RIG

As a part of the R & D projects, the German Drilling Industry developed in close cooperation with KTB an optimal concept for a newly designed drilling rig.

The main technical data are given in Fig. 22.

Currently the engineering is carried out by DEUTAG, DST and ITAG.

CONCLUSIONS

The KTB pilot hole has proven that the combination of the rotary drilling technique and the wireline coring technique is an efficient system for continuous coring in hard crystalline rock applicable down to more than 3,000 m.

Furthermore, it is the only technique today to recover continuous core in high quality with a borehole diameter allowing the total variety of logging and testing tools.

For the planning strategy of ultradeep boreholes, drilling a pilot hole can be assumed as a valuable tool to minimize the risks and, finally, to save money.

Last but not least, drilling a pilot hole makes scientists and technicians better capable of understanding each other enabling the project management to focus research and development efforts on projects mandatory for the technical and scientific success.

- Nominal hook load capacity	5 500 kN
- Maximum hook load capacity	8 000 kN
- Set-back capacity	2 x 14,000 m of 5 in. DP
- Drawworks	2 200 or 2 900 kW
- Mud pumps	3 x 1 200 kW
- Electric power supply by local utility companies	
- Derrick height	80 m

Special features:

- Automated pipehandling / hook retractor System with pickup and lay down facilities (40 m Stands handling capacity)
- Advanced Drilling instrumentation system with central process computer
- Advanced solids control system

Technical Data for
KTB - Ultra Deep Drilling Rig

KTB

	Drillpipe	Drillcollar
Pipe-length (m)	9	9
Nominal weight in air (kg/m)	25.0	43.9
Outside diameter (mm)	139.7 (5.5")	139.7 (5.5")
Inside diameter (mm)	125.5	111.3

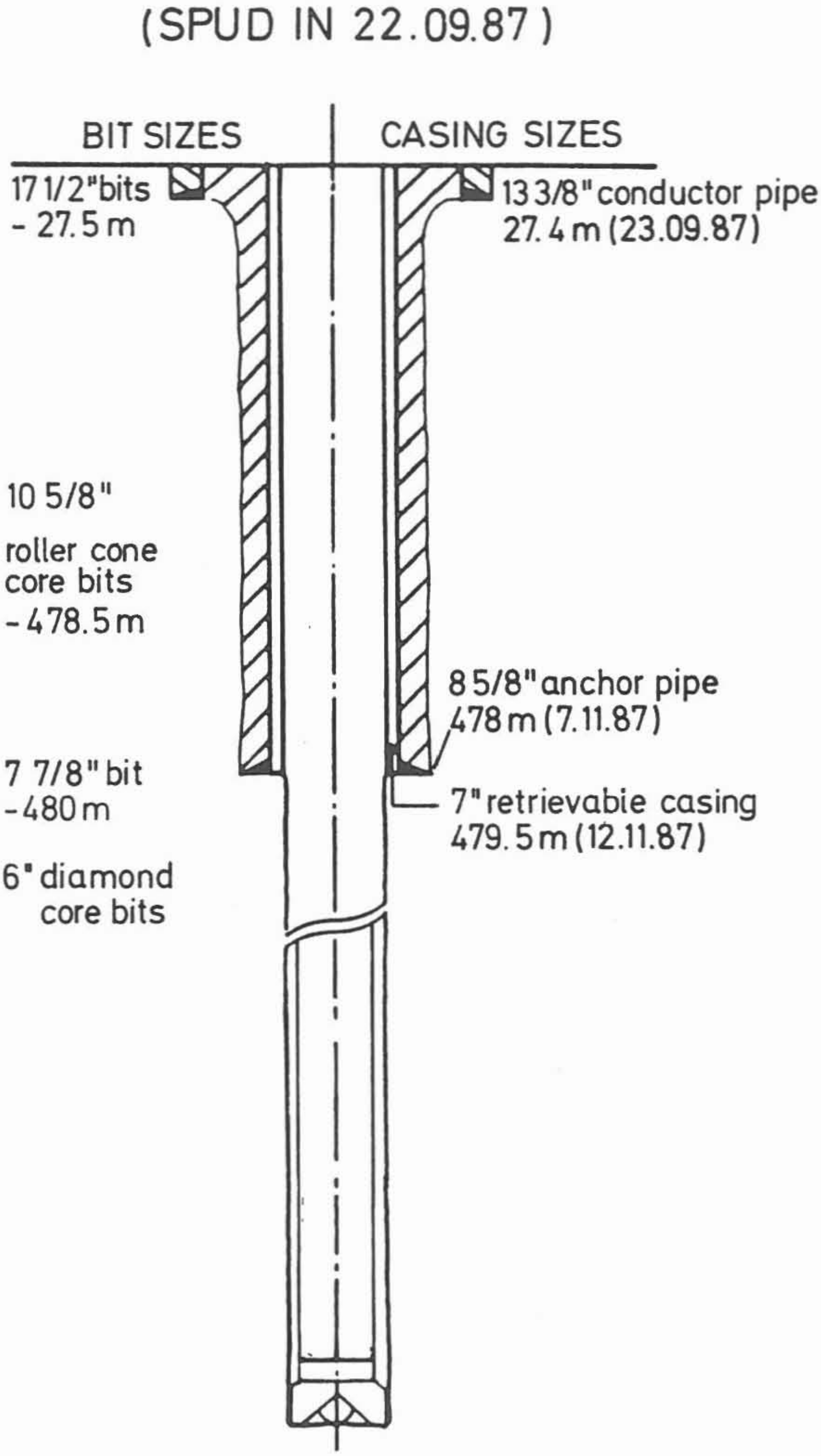
Tool joint OD:	139.7 mm
Tool joint ID:	110.0 mm
Nominal annular clearance:	6.3 mm
Type of thread:	modified Buttress
Maximum Torque:	22 kNm
Maximum Tensile Load:	2, 300 kN
Safety factor at 3000 m:	2
Maximum internal Pressure (Drillpipe):	737 bar
Maximum Collapse Pressure (Drillpipe):	402 bar

Core bit OD (mm):	152.4 (6")
Core diameter (mm):	94
Outer core barrel OD (mm):	139.7 (5.5")
Inner core barrel OD (mm): wireline retrievable	106
Core barrel length (m):	6

Special features:

- integrated memory tool for recording of Bottomhole temperature, inclination and relative Bearing angle
- Surface core jamming indication by pump pressure increase

Technical spezifications of KTB wireline Drillstring and WL-Coringsystem

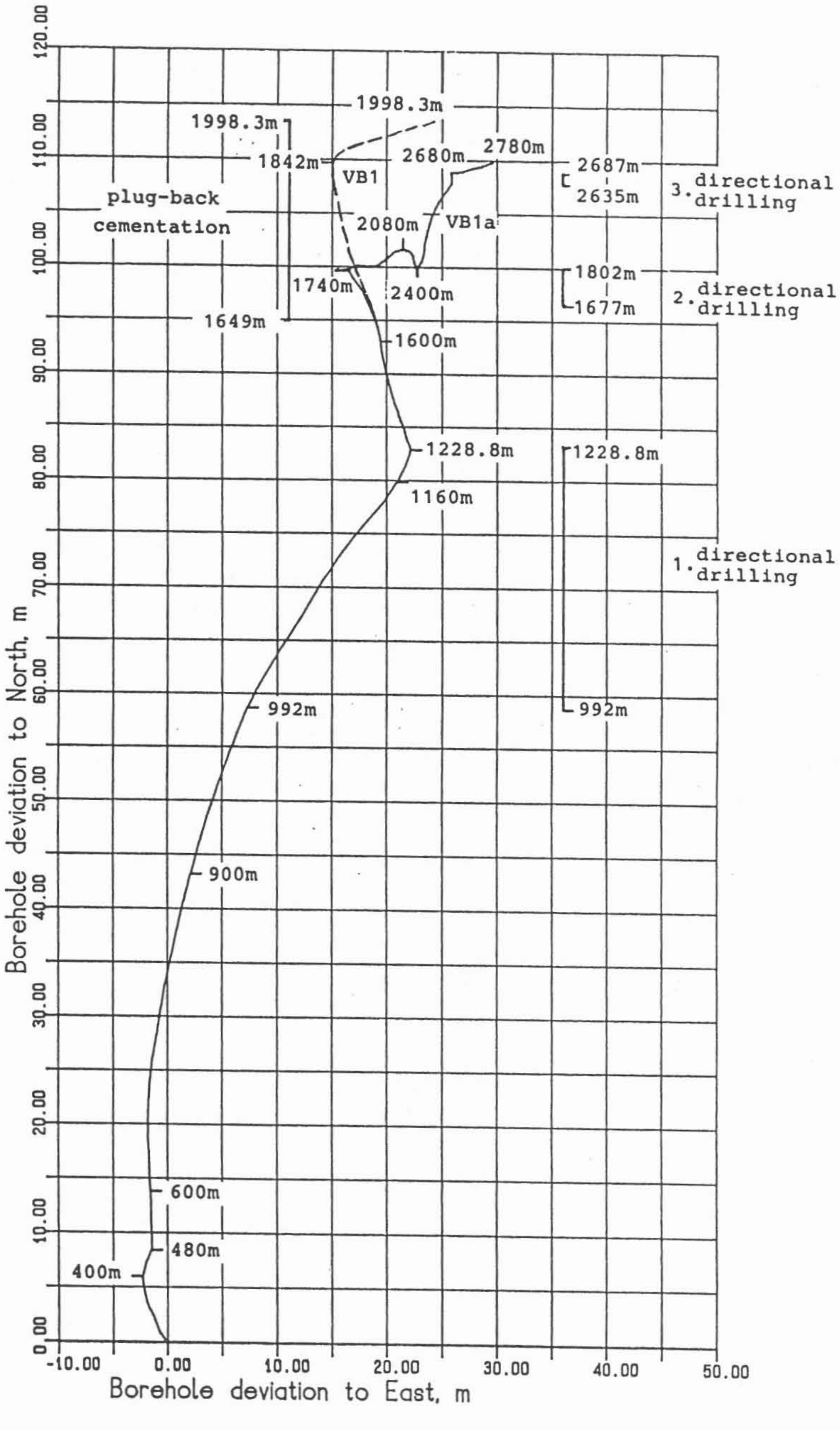


KTB-Oberpfalz VB

KTB

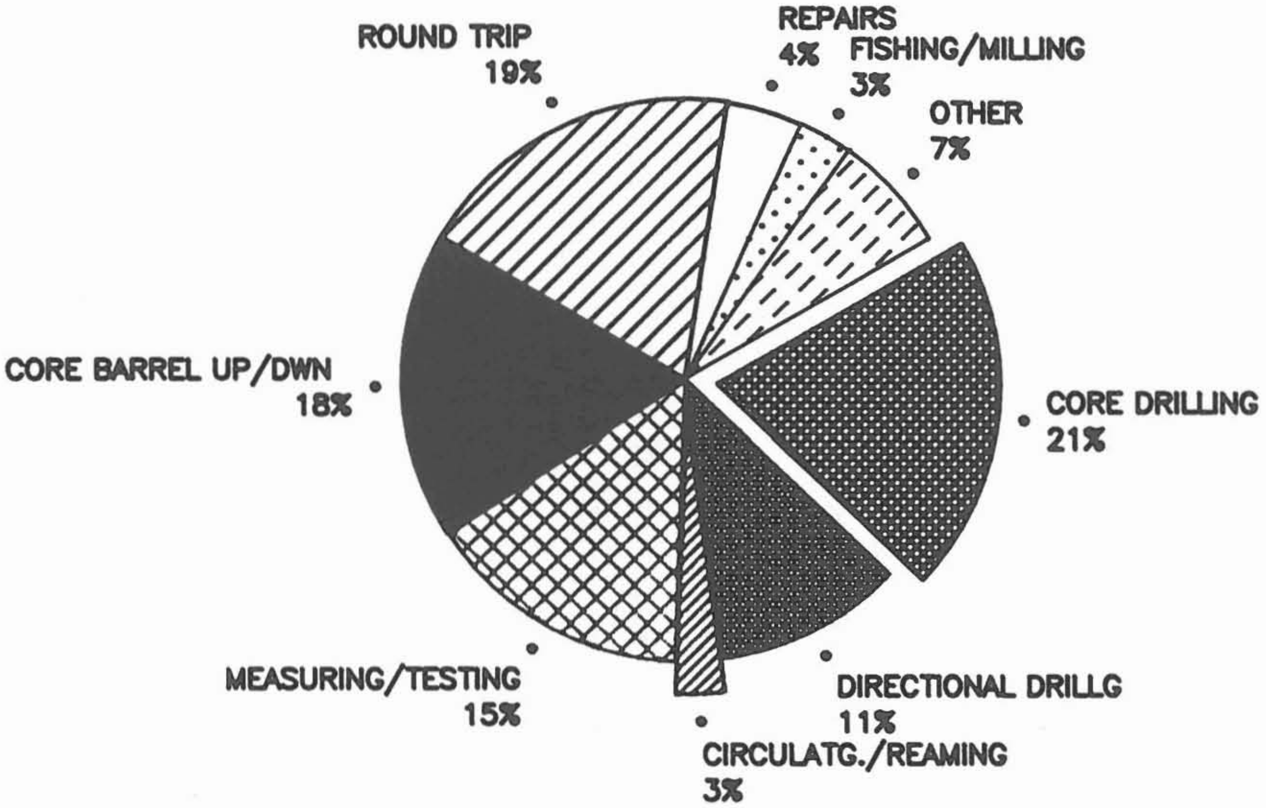
Niedersächsisches Landesamt für Bodenforschung

T 2001/9/88


1998.3m
1998.3m
1842m
2680m
2780m
2687m
2635m
3. directional drilling
VB1
plug-back cementation
2080m
VB1a
1802m
1740m
2400m
2. directional drilling
1677m
1649m
1600m
1228.8m
1228.8m
1160m
1. directional drilling
992m
992m
900m
600m
480m
400m
Borehole deviation to North, m
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
90.00
100.00
110.00
120.00
-10.00
0.00
10.00
20.00
30.00
40.00
50.00
Borehole deviation to East, m

KTB PILOT WELL

Rig–Activity Sep. '87 – Dec. '88 (cumulative)



ARGE KTB–MUD–LOGGING

BLS, GEO–data, PREUSSAG Dr. Ujma, Jan.09.1989

10 5/8" Roller cone core bits

Depth interval:	27.5 – 478.5 m
Cored interval:	450.4 m
Average bit life:	50.0 m
Max. bit life:	112.5 m
Average corerecovery:	43 %
Average penetrationrate:	1.2 m/h

6" Diamond core bits

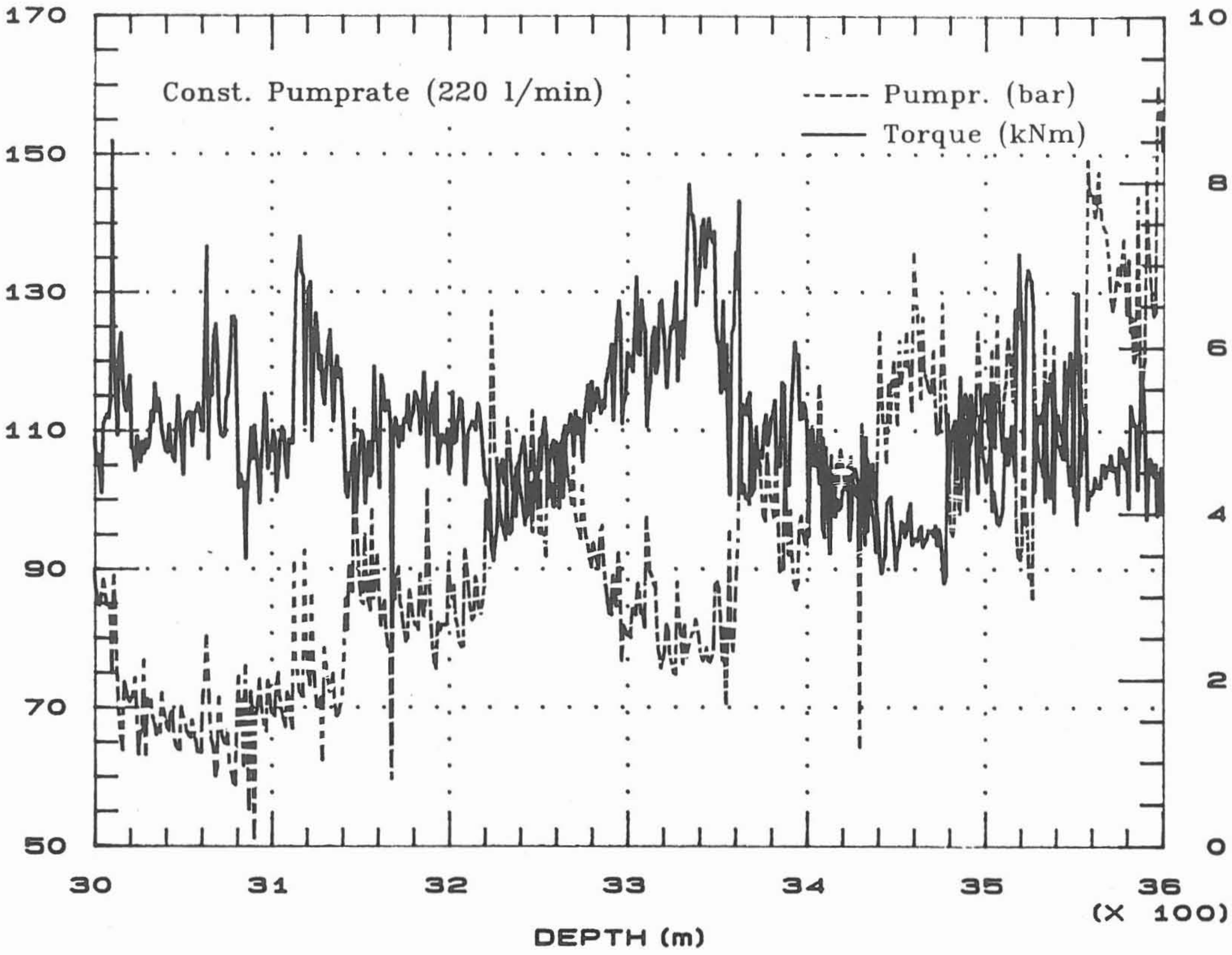
Depth interval:	480 – 3803.2 m
Cored interval:	3052.8 m
Core recovery:	2982.7 m ≙ 97.7 %
Total number of core runs:	852
Average length of a core run:	3.5 m

	Surface set bits	Impregnated bits
Total number of core bits	9	55
Average bit life	35.8 m	49.4 m
Max. bit life	89.5 m	135.5 m
Average penetrationrate	1.8 m/h	1.7 m/h

Results of coring operation

KTB – Pilot hole (Date January 2, 1989) Depth: 3803.2 m

KTB



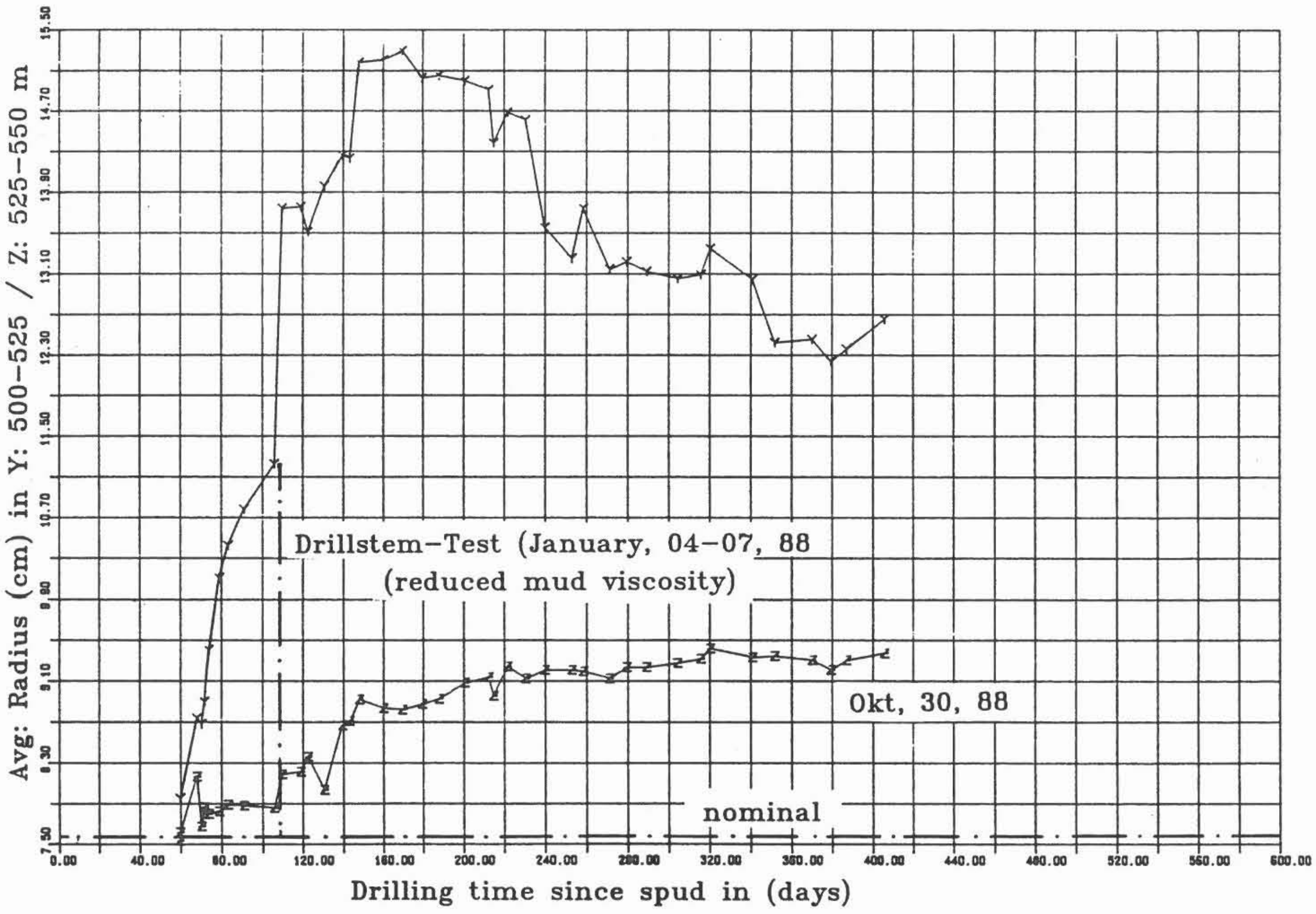
TORQUE and PUMPPRESSURE vs DEPTH
(Depth Interval 3000m-3600m)

- specific gravity: 1.03 kg/dm
- Bingham: plastic viscosity: 13 cp
  yield point: 12 lb/100 sqft
- powerlaw: n: 0.54
  K: 0.41
- Gelstrength: 10 sec, 2 lb/100 sqft
  10 min, 3 lb/100 sqft
- API – Filtrate: 26.5 ml/30 min
- CST (capillary suction time): 2258 sec
- sand content: 0.1% (by Vol.)
- pH: 10.5
- chloride: 62 ppm
- conductivity: 3 ms/cm

Mud Properties for KTB – Drilling Fluid System

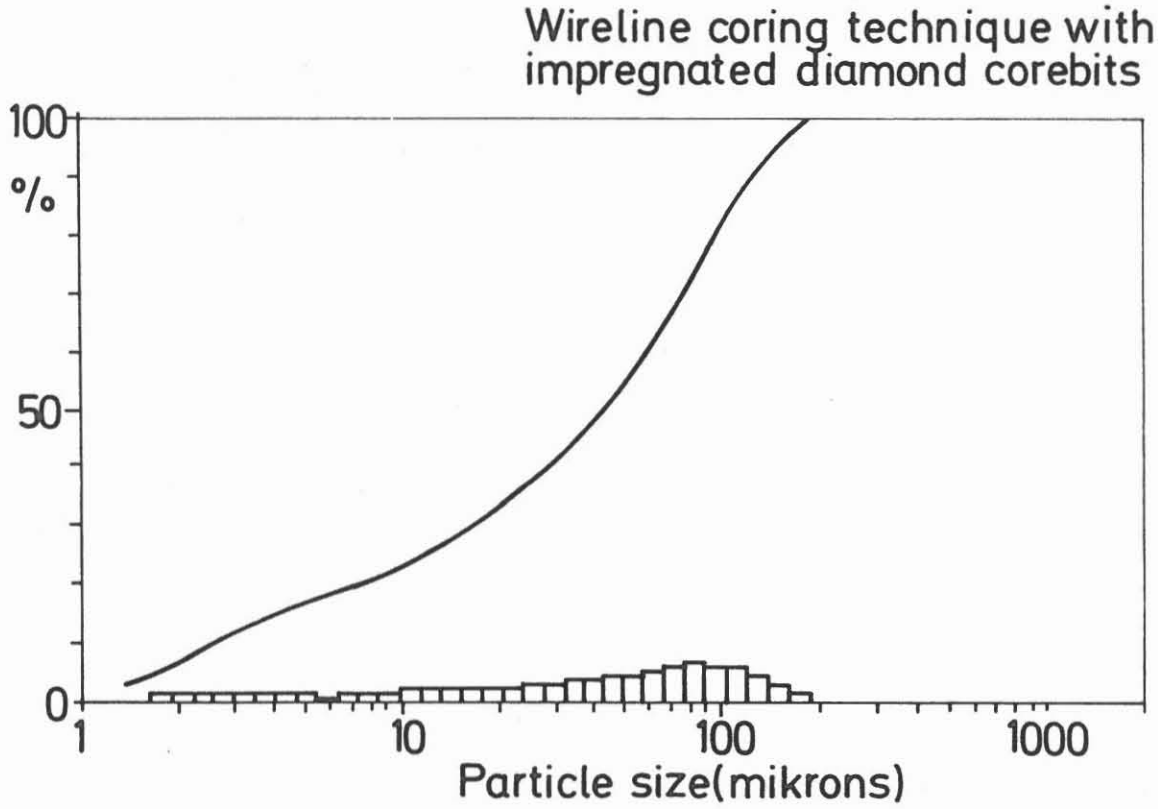
KTB

T1186/8/88 Niedersächsisches Landesamt für Bodenforschung



Development of the average borehole radius for two depth intervals (500–525m and 525–550m) while drilling the KTB pilot well

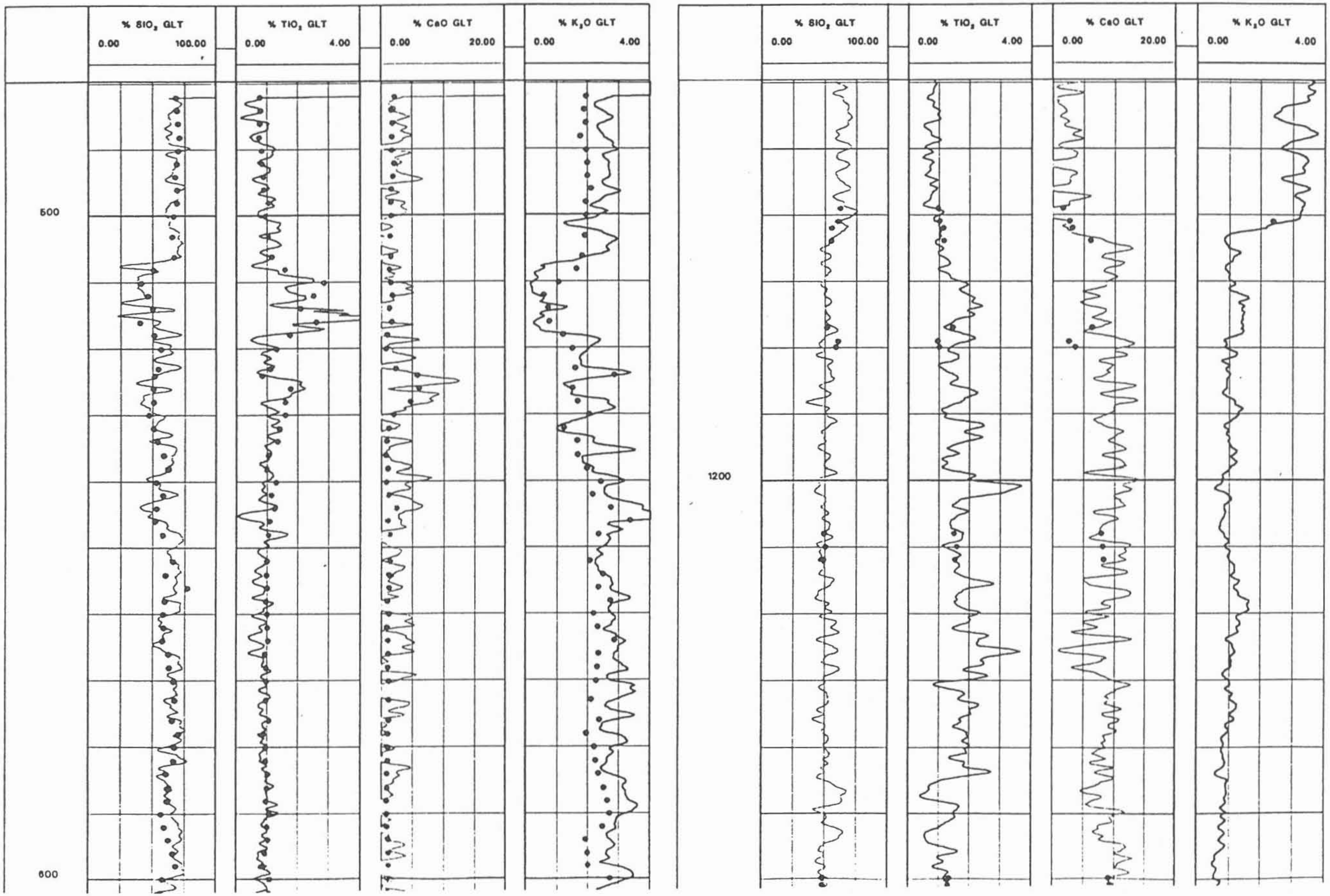
KTB

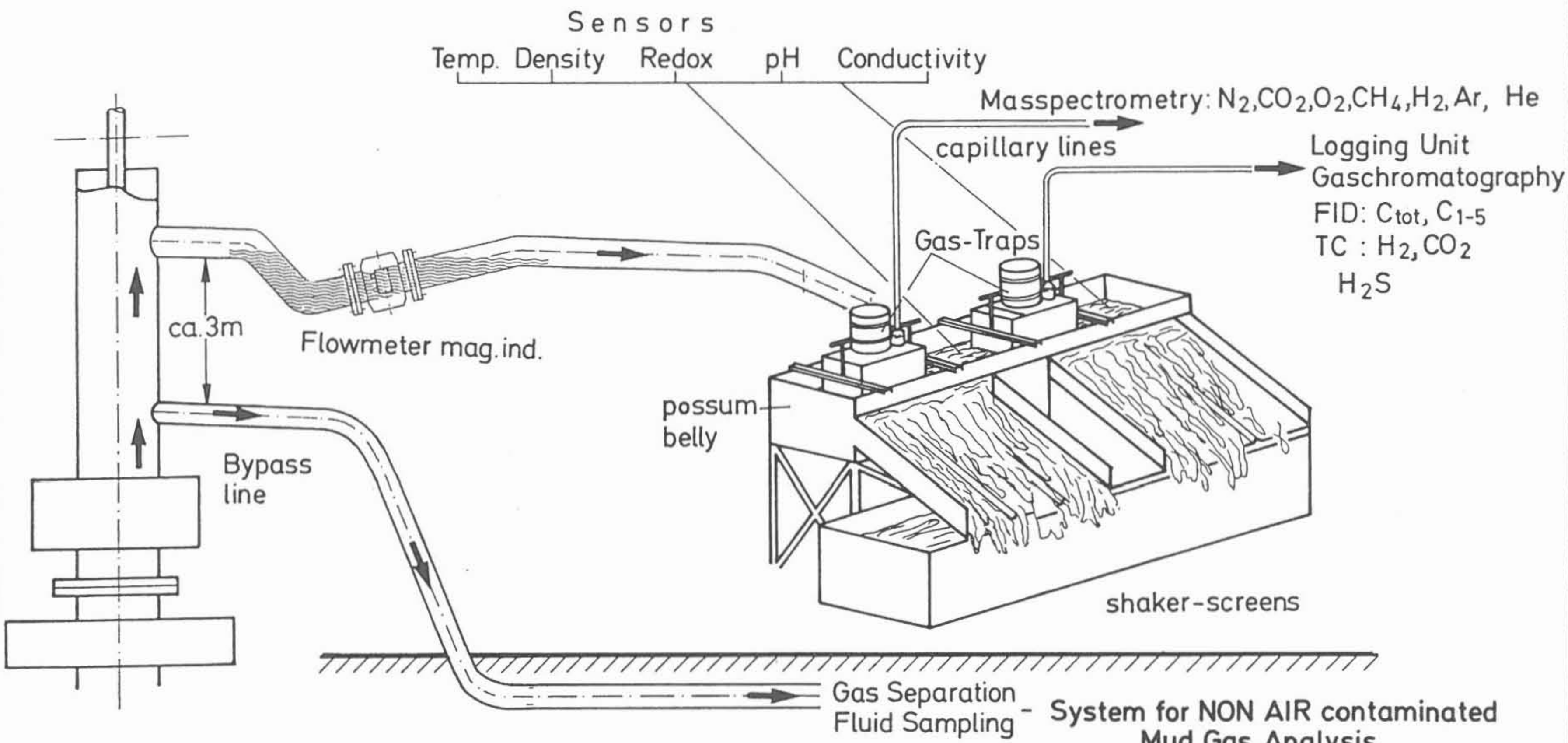


Grain Size Distribution of KTB-Drilling mud (Decanter input)

KTB

COMPARISON GLT : CENTRIFUGE SAMPLE X - RAY FLUORESCENCE

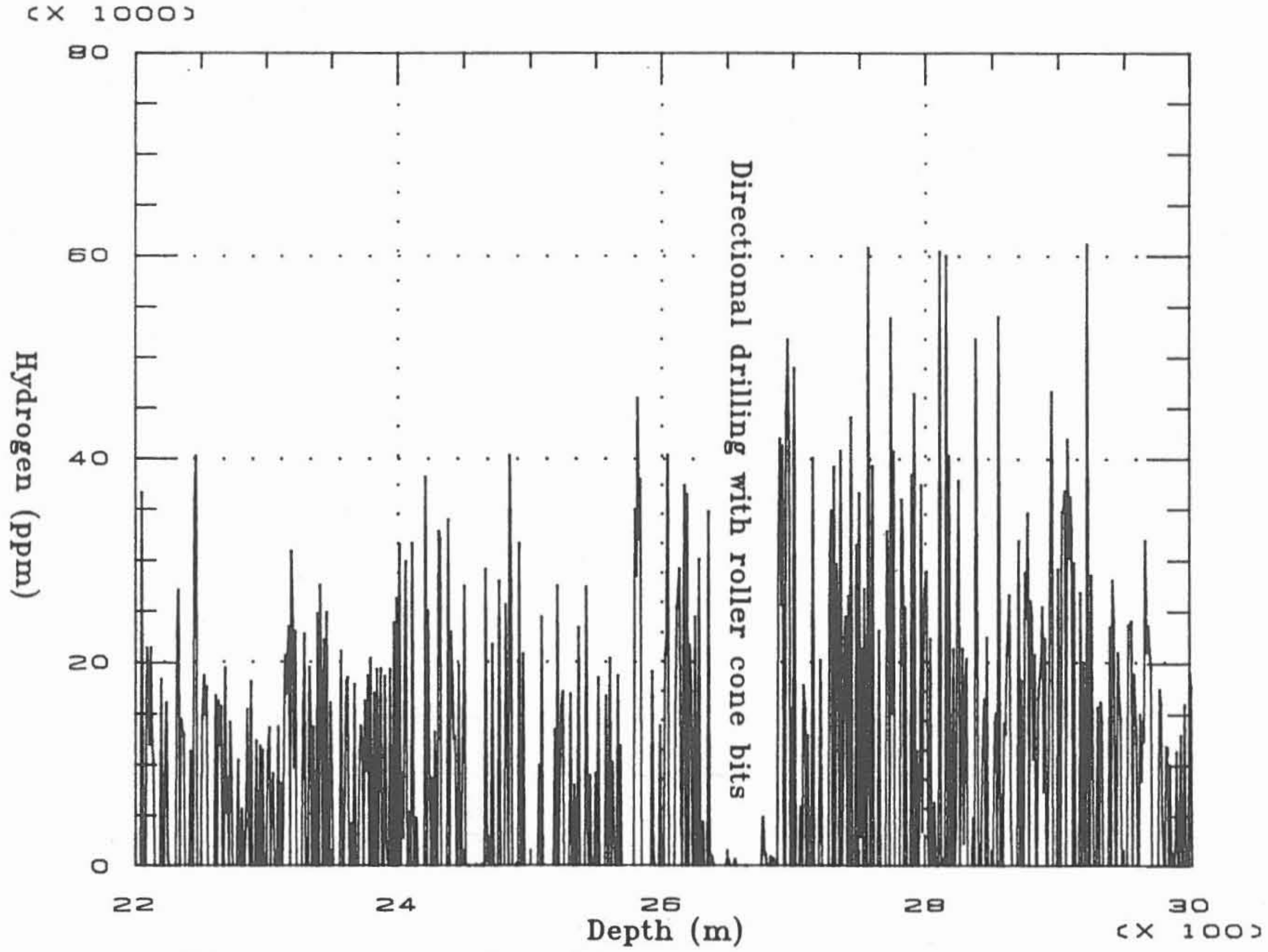




System for NON AIR contaminated Mud Gas Analysis
[currently tested]

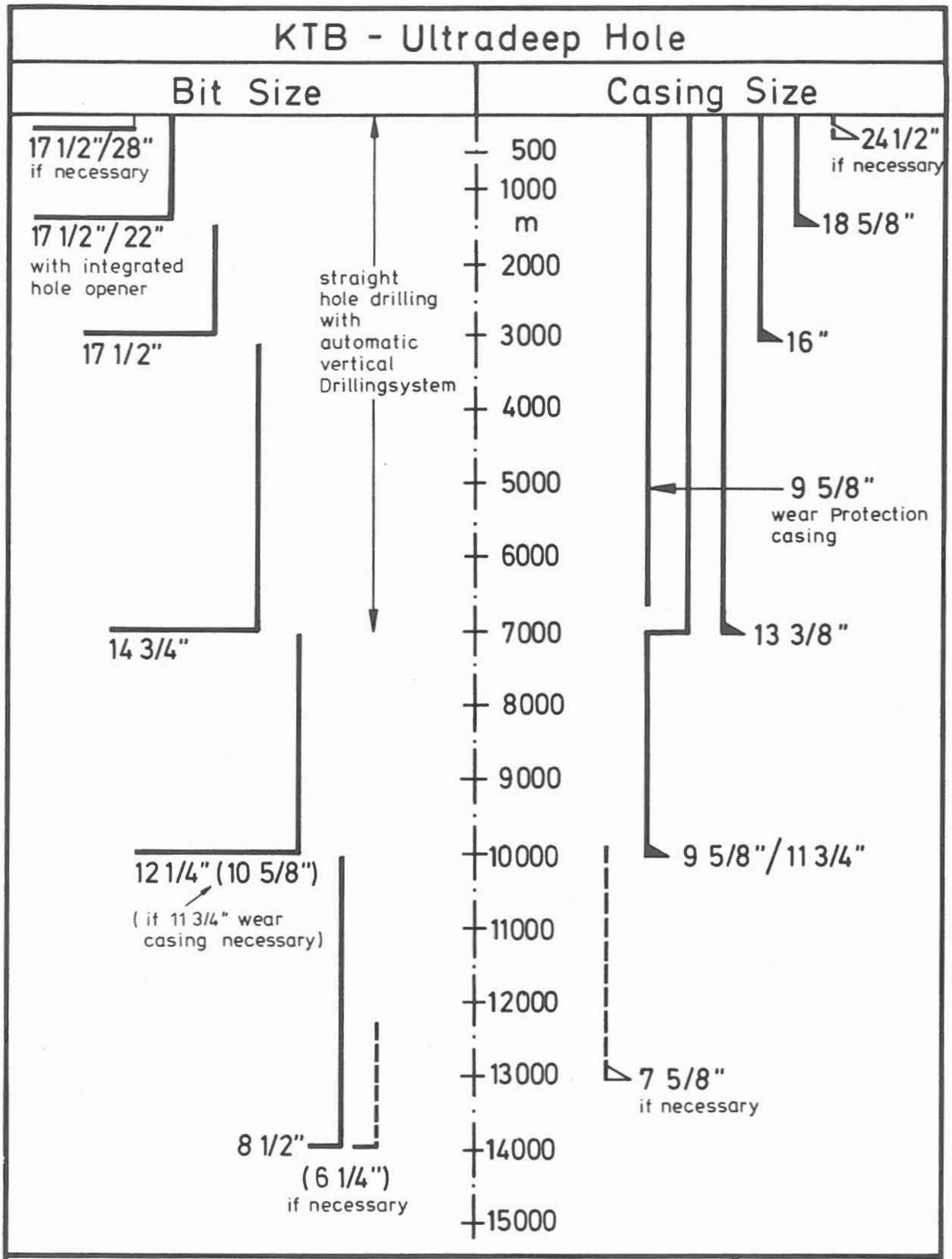
Mud Flowout Measuring Technology for KTB – Pilothole

[Engeser]



Hydrogen content of drilling mud vs. Depth

KTB



KTB - Ultradeep Hole
Bit - and Casing Program

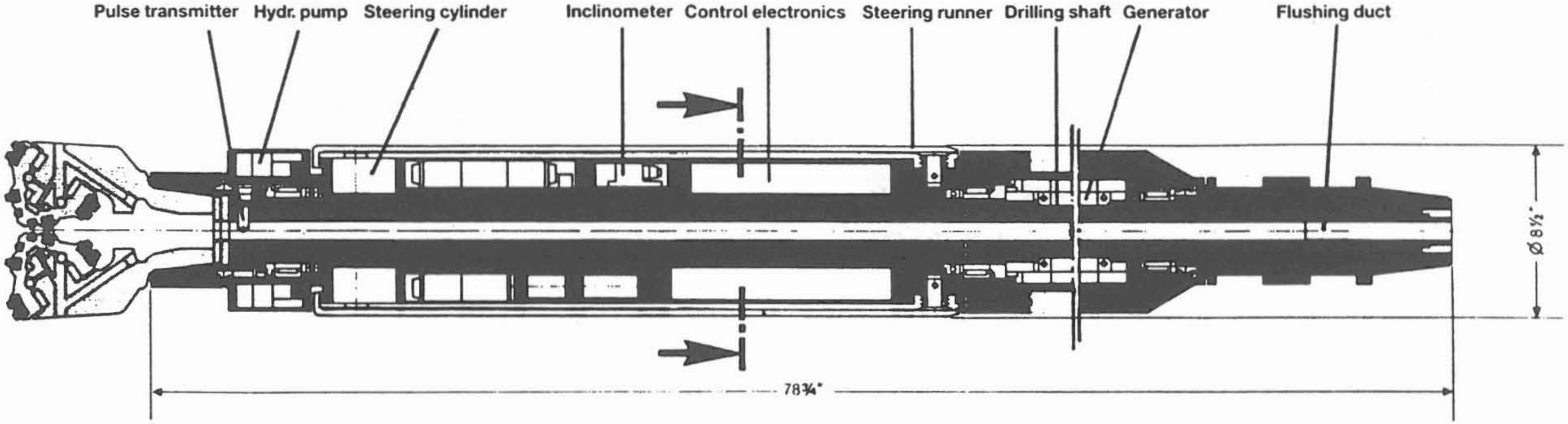
T 1037 / 12.88

Niedersächsisches Landesamt für Bodenforschung

- Derrick height: 49.3 m
- Nominal hook load capacity: 2040 kN
- Racking capacity: 5000 m of 5 1/2" DP
- Travelling guide carriage for hydraulic top drive
- Drawworks (GH1400E): 1240 kW
- Mudpumps: 2 x 590 kW
  1 x 130 kW (hydraulic drive)
- Hydraulic top drive: 464 kW
  Torque capacity: 11000 Nm at 300 RPM
  Maximum Rotary speed: 600 RPM at 5800 Nm
- Automatic drillingcontrol (WOB or ROP)
- Major components electrically driven

Technical specifications of the pilot hole drilling rig

Automatic directional drilling device ZBE 3000



All dimensions indicated in inch

A NEW HIGH TEMPERATURE STABLE MUD ADDITIVE FOR DEEP DRILLING OPERATIONS

– Presentation of Laboratory Results and First Field Data from the Continental Deep Drilling Program of the FRG (KTB) –

C.-P. Herold
S. v. Tapavicza
H. Müller
W. R. Clements
J. M. Braun
S. Smith
B. Engeser

Paper presented at the International Seminar on
"Superdeep Drilling and Deep Geophysical Sounding"
Yaroslawl (USSR)
August, 1988

1. INTRODUCTION

Within the "International Lithospheric Program", superdeep wells are planned in various countries. The purpose of this international program is to thoroughly investigate the geological and geochemical composition of the continental crust.

One such superdeep well with a depth of presently about 12 km has been drilled on the Kola Peninsula in the USSR (Kozlovsky 1987).

Within the "Continental Deep Drilling Program of the Federal Republic of Germany" (KTB), a pilot well with an intended depth of 3 - 5 km is presently being drilled. The actual depth of this hole is about 3000 m. After finishing this pilot hole, the main borehole with a planned depth of 12 - 14 km (Rischmüller & Chur 1987) will be spudded in 1990, close to the pilot hole.

Contrary to commercial drilling programs for oil and gas exploration, these two wells are drilled mainly through crystalline rock. The prime intention here is an extensive geochemical and geophysical investigation of the drilled formations. Thus, contamination of cores and cuttings must be minimized during the drilling process, permitting intensive analytical investigations. Also, any influx of gases and liquids from the rock will be recorded by continuous control of the drilling fluid (Engeser & Ujma, 1986) and should therefore not be disturbed by the mud system.

In the main borehole, at a depth of 12 - 14 km, high pressures and temperatures of about 300 °C to 350 °C are to be expected. From the geological point of view, it would be ideal to drill with distilled water. For technical reasons, however, this is not feasible. Therefore, a compromise had to be found where the drilling fluid would have to provide sufficient carrying capacity, lubricity and hole stability, yet, minimizing any influence and disturbance of the analytical investigations.

The requirements were a demanding challenge for the development of a new type of drilling fluid system. The result of this development, as elaborated in the laboratories of Henkel KGaA, was a special synthetic silicate based product.

This new product, Dehydril HT/THERMA-VISR has been used since September 1987 in the mud system at the KTB pilot hole. For servicing this KTB drilling project, a joint working group of Henkel KGaA and Baroid Petroleum Services was formed. In the following, we will report on a unique drilling fluids test apparatus and interpret the behavior of this novel drilling fluid system.

2. DRILLING FLUIDS TEST APPARATUS

A few years ago, Baroid Petroleum Services designed and built a test system to measure drilling fluid properties under conditions that simulate actual downhole temperatures and pressures. The system was partially funded by the United States Department of Energy. It measures density, rheology, corrosion and both static and dynamic filtration. It operates at pressures up to 1,480 bar and temperatures up to 370 °C. Differential pressure across the filter is variable up to 70 bar. Shear rates in both the filter and rheometer are variable up to 2,000 sec^{-1}. It is the only instrument of its kind in the world.

Filtration is another important consideration and the test system is capable of making both dynamic and static measurements. The filtration cell uses radial flow through synthetic cylindrical cores. In general, natural cores have not been strong enough to withstand the differential pressures in the system. Differential pressures up to 70 bar are possible, superimposed onto system pressures of up to 1,000 bar. Shear rates across the face of the filter can be varied up to 2,000 sec^{-1}. There are three of these filtration cells within the large dynamic high pressure high temperature test system.

In general, the filtration of drilling fluids is dependent upon a number of factors, including: ratio of pore size to fluid particle size, compressibility coefficient, pressure, temperature, and shear rate. Filtration data has been modeled to standard equations (Fisk and Jamison 1988) to determine compressiblity coefficients. The results not only describe the behaviour of the fluid against a permeable formation, but give some insight into the chemistry and physics of the fluid itself.

Most of the real world drilling fluids that have been investigated have had compressibility coefficients in the range of 0.4 to 0.8. The effect is that fluids with low compressibility coefficients give higher filtration rates with increasing pressures. Whereas, fluids with highly compressible filter cakes do not change much with pressure.

The test system described has been, in part, to study the new high temperature stable mud additive Dehydril HT for deep drilling operations.

3. HIGH TEMPERATURE STABLE MUD ADDITIVE

Dehydril HT/THERMA-VIS is a purely inorganic material, composed of sodium, lithium, magnesium, silicon and oxygen.

As an inorganic product, it does not require protection from microbial degradation. Therefore, no biocides need to be added. In the KTB drilling mud, the synthetic inorganic polymer is the only mud additive. Aside from minor amounts of alkalis, e.g., soda (Na_2CO_3) or caustic (NaOH), no additional chemicals are used. The entirely inorganic character of the system also permits immediate detection of very low traces of hydrocarbons and the organic material in the drilled formation, if present. This is of major importance for the evaluation of the scientific drilling program.

The new drilling mud additive has very interesting rheological properties. In aqueous solution, its shear thinning properties, as shown in Figure 1, are of major importance for designing the mud sytems. On the KTB drill site the following procedure was used to prepare the aqueous drilling fluid.

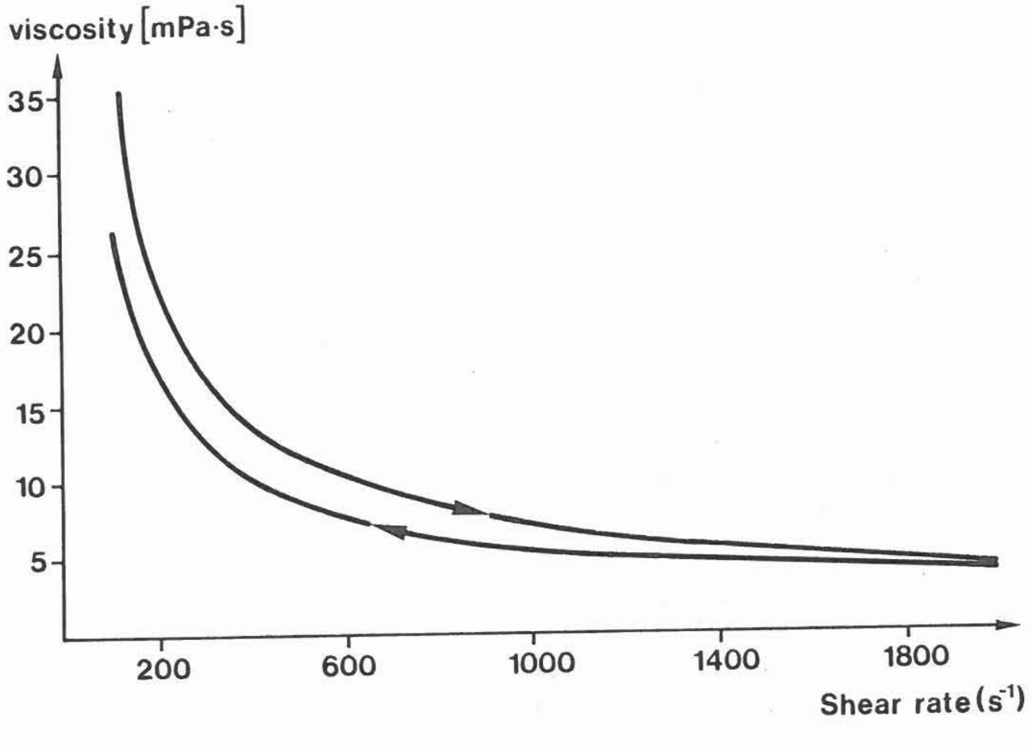


Figure 1: Rheological Behaviour of Dehydril HT (1,5 % solution; 25 °C)

A container is filled with 1 - 2 m^3 of fresh water. Dehydril HT/THERMA-VIS powder is added through the hopper to obtain at least a 2.5 % solution. To achieve optimal rheological properties, this concentration solution has to age for a certain period. Normally, 16 hours are recommended when the solution is stored in tanks. When using mud guns or other high shear equipment, this aging process can be drastically reduced.

In a second step, this 2.5 % concentrate is diluted to the desired concentration. Alkalies, electrolytes or other additives may be added in a third step.

At the KTB pilot hole, a wire line coring-technique is used to pull out the drill cores through the drill pipe. This technique together with diamond bits results in a high core recovery and reduces the time necessary to drill the core.

However, this technique also results in a very narrow annulus between drill stem and borehole wall of about 5 - 10 mm. Good lubricating properties of the drilling mud are required. Furthermore, since the pressure drop in the narrow annulus at high viscosities is high, the mud viscosity must be maintained at relative low values of about 5 - 10 mPa.s to avoid fracturing or damaging the formation. This can be achieved with an additive concentration of about 1.25 %.

Solids control in the mud on the KTB-site is maintained by a centrifuge. Hereby, it is possible to separate most of the cuttings down to a median size of < 10 microns.

Therefore, the KTB mud always contains a certain amount of very fine cuttings which cannot be removed by the centrifuge, but which do not disturb the analytical investigations or logging and do not negatively influence the rheological properties of the mud. Nevertheless, mud properties have to be controlled regularly to avoid the accumulation of fines.

4. KTB-MUD PROPERTIES

This paper describes the main properties of the new temperature stable drilling mud, as used in the KTB pilot hole. This mud contains 1.25 % synthetic inorganic polymer, fines (cuttings), and alkalies - soda or sodium hydroxide to achieve a pH of 9 - 11 - whereby the oxygen-corrosion is substantially reduced.

Typical rheological data of the KTB mud in various depths and geological formations are shown in Figure 2.

Depth [m]	Density [g/cm^3]	pH	Plastic Viscosity [mPa·s]	Yield [lb / 100 ft^2]	Gel Strength 10' / 10" [lb / 100 ft^2]
0	1,010	10,10	5	10	4 / 32
252,6	1,045	10,11	7,5	16	17 / 68
1006,2	1,015	9,33	8	18	19 / 39
1507,6	1,020	9,47	7	11	9 / 36
2001,3	1,030	10,46	17	18	7 / 22

Figure 2: Typical Rheological Dehydril HT-Mud Data for KTB Pilot Hole (determined with Fann 35 at 20 °C)

One of the most important properties of the KTB mud is its excellent thermal stability at high temperatures. In Figure 3, the rheological behavior of a 1.25 %-Dehydril HT solution, registered with a FANN 50 Viscosimeter is shown. This solution has been heated up to 230 °C and then cooled down into two cycles.

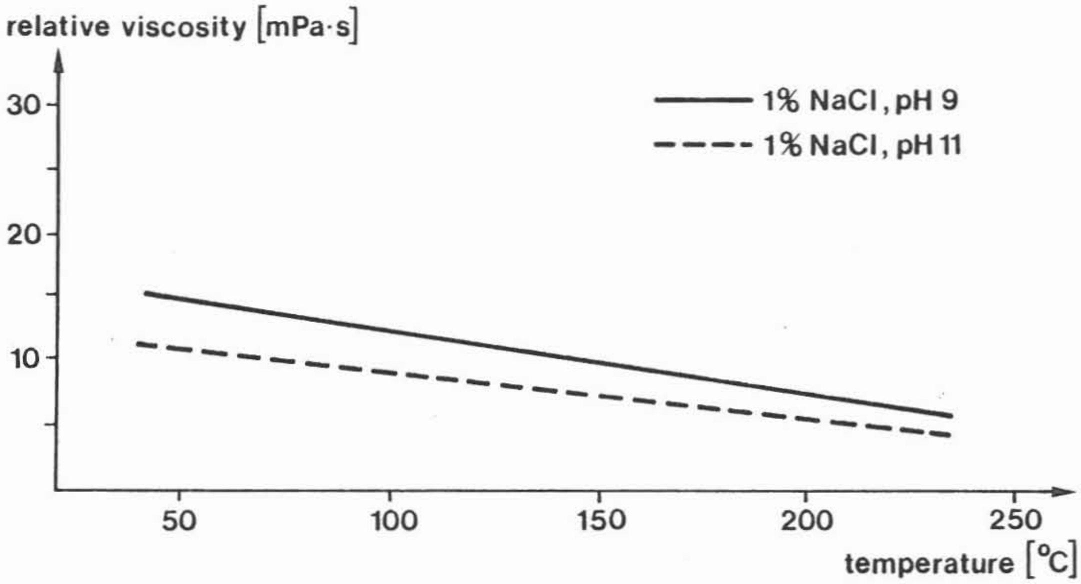


Figure 3: Rheological Behaviour of Dehydril HT: Influence of Temperature in 1 % NaCl Solution) (1,25 % Dehydril HT solution; 2 heating and colling cycles)

In the main KTB borehole, with an intended depth of 12 - 14 km, temperatures of about 300 °C to 350 °C are expected. The experiments show that even at these extreme borehole conditions, the Dehydril HT/THERMA-VIS mud will maintain the required rheological properties. Furthermore, because of the non-existence of thermal degradation products, evaluation of the deep formations will not be disturbed.

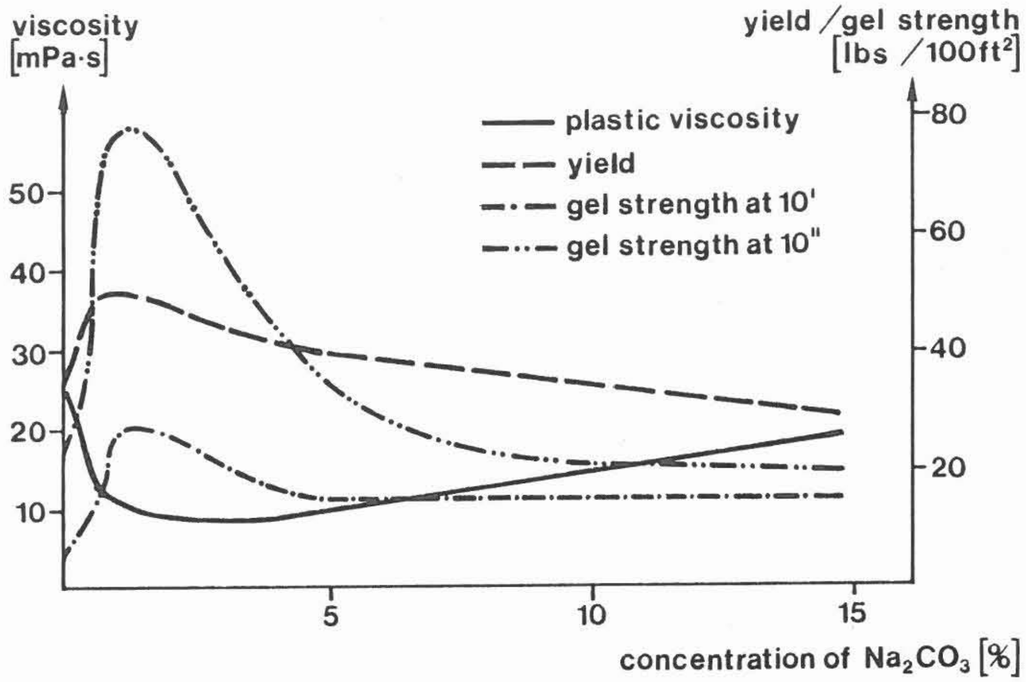


Figure 4: Rheological Data for Dehydril HT Drilling Muds in Presence of Na_2CO_3 (determined with Fann 35 at 20 °C)

Another essential question is the influence of liquid inclusions in the formation that contain electrolytes, or the influence of rock material on the properties of the drilling mud system. Experiments with several electrolyte types have been performed. Figure 4 shows, as a typical example, the influence of Na_2CO_3 in the KTB mud. When the salt concentration is increased, plastic viscosity, yield and gel strength all go through a maximum, which can slightly differ with various salts. At higher concentrations, typically above 1 %, all the values level off. Higher salt concentration will then influence the rheological properties only to a minor degree.

Electrolyte	Concentration [%]	Plastic Viscosity [mPa·s]	Yield [lb / 100 ft²]	Gel Strength 10' / 10" [lb / 100 ft²]
KCL	0,1	18	51	12 / 86
	1	13	36	19 / 23
	10	10	45	17 / 20
$MgCl_2 \cdot 6\,H_2O$	0,1	23	35	39 / 130
	1	11	49	17 / 30
	10	6	44	16 / 20
$CaCl_2 \cdot 2\,H_2O$	0,1	15	20	6 / 15
	1	16	40	25 /26
	10	13	36	23 / 27

Figure 5: Influence of Different Electrolytes on Rheology of Dehydril HT-Muds (determined with Fann 35 at 20 °C)

Figure 5 shows some rheological data for the mud in the presence of various other salts. The KTB borehole will be drilled as long as possible with an unweighted mud. Yet, if the condition of the formation renders it necessary, a weighted mud has to be used. So far, several concepts have been investigated. In all cases, both the requirements of the drilling engineers as well as the demands of the geologists have to coincide. Consequently, new, untypical ideas have been evaluated in the meantime.

Weighing Material	max. Density [g/cm³]	Remarks
Na_2CO_3	1,15	max. density is too low
MgO	1,5	all grades so far tested are not suitable
TiO_2	1,5	abrasive, too small grain size gives too high viscosity
$BaSO_4$	2,0	Suitable; Thailand quality does not interfere with analytical investigations
$CaCO_3$	1,5	Suitable; clean types do not interfere with analytical investigations

Figure 6: Alternative Concepts for weighing KTB-Drilling-Mud based on Dehydril HT

Figure 6 shows the main weighting concepts taken into consideration. The results of all these investigations were that $BaSO_4$ or $CaCO_3$ are the most suitable alternatives.

Mud	Density [g/cm^3]	Plastic Viscosity [mPa·s]	Yield [lbs / 100 ft^2]	Gel Strength 10' / 10” [lbs / 100 ft^2]
unweighted	1,02	7	14	3 / 18
weighted with $BaSO_4$*	1,2	8,5	18	15 / 40
”	1,5	10	22	7 / 60
weighted with $CaCO_3$**	1,2	8	22	22 / 84

Suplied by
*Baroid ** Baracarb® 5

**Figure 7: Rheological Data with Weighted KTB-Muds
(determined with Fann 35 at room temperature)**

Figure 7 shows some rheological data with $BaSO_4$ and $CaCO_3$ weighted muds.

Aside from the high temperature stability, which is one of the main requirements for ultra-deep drilling, the new higher temperature stable mud additive exhibits good lubricating and clay protecting properties.

Dehydril HT/THERMA-VIS solutions inhibit the swelling of shales, which is an important additional advantage of this mud system. This is demonstrated in experiments with red clay, that, due to its strong hydration properties, is causing tremendous problems for inhibiting drilling fluids.

As purely inorganic material it is not biodegradable in the sense of degradation of organic matter to CO_2 and H_2O. This also implies that in the case of influx to rivers or other surface waters no oxygen consumption will occur and, therefore, organisms will not be harmed because of oxygen deficiency, as could result from biodegradation of organic matter.

Furthermore, the product does not contain any essential nutrients such als nitrogen or phosphorous, so eutrophication cannot occur.

Toxicity against different organisms is extremely low. In fact, the rheological properties at high concentrations of Dehydril HT/THERMA-VIS solutions limit the toxicity tests because of mechanical reasons: the tested fish specimens could not swim nor move their gillplates once the concentration was increased above approximately 1.5 %. Figure 8 shows a summary of the main ecological and toxicological properties.

Biodegradability	not relevant
Biological Oxygen Demand	0
Contents of Nutrients	0
Fish toxicity (golden orfe)	LCO>5.000 mg/l
Bacterial toxicity (Oxygen consumption test with Pseudomonas putida)	NOEC>10.000 mg/l
Acute toxicity (oral, rat)	LD_{50} = 8.000 mg/kg

Figure 8: Ecological Behaviour of Dehydril HT

5. CONCLUSIONS

Dehydril HT/THERMA-VIS is a new inorganic viscosifier, which, because of its excellent temperature stability, is well suited for ultra-deep and geothermal drilling.

Dehydril HT/THERMA-VIS shows good lubricating properties, inhibits shale swelling and does not require any protection by biocides.

Dehydril HT/THERMA-VIS is ecologically safe. As an inorganic silicate compound, it does not consume oxygen. The product is non toxic to fish, bacteria or warmblooded animals. It does not contain any nutrient elements such as phosphorous or nitrogen.

Due to its high temperature stability and its excellent carrying capacity for drilled cuttings as well as its lubricity, it is possible to formulate a drilling fluid for scientific ultra-deep horeholes solely on the basis of Dehydril HT/THERMA-VIS and additions of alkalies. Such a drilling fluid will not impair the geochemical analysis and will easily be removed from the drilled cuttings, thus allowing optimal evaluation of the drilled formation.

6. ACKNOWLDEDGEMENTS

The authors acknowledge and express their thanks to all the colleagues at Baroid Petroleum Services, at the KTb project group, with the Institute für Tiefbohrtechnik, Erdöl- und Erdgasgewinnung at the University of Clausthal, and at the Henkel KGaA laboratories for suggestions, advice and support.

Dehydril HT is a trademark of Henkel KGaA.

THERMA-VIS and DYNAMIC HTHP are trademarks of Baroid Petroleum Services.

7. REFERENCES

Engeser, B. and Ujma, K.-H. (1986): Konzeptive Überlegungen für Spülungssysteme in heißen und übertiefen Forschungsbohrungen im kristallinen Gebirge. 3. Vortrags- und Diskussionstagung "Chemische Produkte in der Erdölgewinnung", Clausthal-Zellerfeld.

Fisk, J. and Jamison, D. (1988): "Physical Properties of Drilling Fluid at High Temperatures and Pressures", IADC/SPE Drilling Conference.

Koszlowski, Ye. A. (1987) : The Superdeep Well of Kola Peninsula, Springer-Verlag.

Rischmüller, H. and Chur, C. (1987): The Continental Deep Drilling Program of the Federal Republic of Germany - Technical Concept and State of Planning. Erdöl, Erdgas, Kohle 103: 11 - 16.

REPORT ON TECHNICAL EXHIBITION AND EXCURSION

C. Marx
C. Chur

August, 1988

The seminar was organized in

- 2 plenary sessions,
- 3 section meetings:
  - Section A: Regional Deep Geophysical Research
  - Section B: Techniques and Technology of Superdeep Borehole Drilling
  - Section C: Methods and Technical Facilities of Geologo-geophysical Research in Boreholes and Surroundings
- Poster presentation
- Round-table discussion
- Technical exhibition
- Excursion to Krivoy Rog well site

TECHNICAL EXHIBITION

The Russian equipment exhibited deserves special attention.

1. Gear reduction tool 7-3/4" (195 mm), pictures 1, 2
   Reduction ratio: 3.69 one stage, 3.65 m, 660 kg
   13.62 two stages, 4.20 m, 720 kg

The reduction tool can be employed with various turbines of Russian design (tables 1 and 2), thus resulting in a rotational speed from 30 to 300 min-1 for the bit. Moineau motors of a type such as Dynadrill 1000 can also be used with the gear reduction tool.

The model exhibited is evidently a new version, because it can be employed in either the one- or two-stage version without special modifications or length additions. The second stage can be obtained by replacing one stage by a cross-over spindle.

2. Apparatus for determining rotational speed of turbines, picture 3

A mechanical-hydraulic tool driven be the rotor of the turbine operates with an extreme reduction ratio and drilling fluid pulse system for indicating the actual speed of a turbine.

3. Aluminum drill pipe (RDP) with steel connections, picture 4

The drill pipe on display had a wall thickness of 1" (25.4 mm) and a conical thread connection to the steel tool joint. (A special report on the discussion on aluminum drill pipe follows.)

4. Moineau motors

The following sections of Moineau motors were shown:

- 9/10 MM version with hollow rotor, chrome-plated, picture 5
- 5/6 MM version with rotor constructed of metal sheets with a thickness of about 3 mm, chrome-plated, picture 6

5. Model of 7-3/4" turbine with about 20 stages, reduction gear, and roller core bit, picture 7

6. 217-mm roller core bits, new and used, pictures 8, 9

Four roller cones with five cutting rows and a gauge row were exhibited. The TC inserts were chisel-shaped. The number of inserts per row was as follows:

- for gauge protection:	26 inserts;
- OD-row:	20 inserts;
- second row:	18 inserts;
- third row:	14 inserts;
- fourth row:	9 inserts;
- fifth row:	3 inserts.

The diameter of the inserts was reduced toward the center of the cone to about one-half the size of the OD inserts.

7. Scale models of drill pipe inspection unit for tool joints and drill pipe, picture 10

8. Scale model of hole opener which employs two or more turbines in a bundle, picture 11

The bundle body was designed in the form of drill collar for large-hole drilling with the use of deadweights for high mass concentration.

In addition to the drilling equipment mentioned above, the exhibition featured models of shelters, living quarters, storage bins (silos) for cement and drilling fluid materials, personal computers for drilling supervision, as well as heat- and pressure-resistant components of electronic devices for the investigation of superdeep boreholes. The latter have the following specifications:

$T_{max} = 250\ ^{o}C$
$p_{max} = 200$ MPa

9. Discussion with Russian experts on aluminum drill pipe (ADP)

The paper of K. Sträter and E. Quadflieg, Mannesmannröhren-Werke Düsseldorf on "Material Selection and Concept for the Drill Strill to be Used for the Continental Deep Drilling Project KTB" was the cause of a controversial open discussion with Russian experts. Dr. Fain, responsible for ADP development in the Soviet Union, and other tubular goods for the Kola borehole, summarized the Russian standpoints favoring ADP during the section meeting as follows:

- The reduction in strength of ADP at elevated temperature is well known. We strictly disagree with the conclusions drawn by Dr. Quadflieg with respect to its application to superdeep drilling. Kola is the proof that ADP provides a reliable drill string which can be employed at a temperature up to 220 oC.

- The weight reduction with ADP, as compared with steel drill pipe, is about 50 percent, in spite of the use of steel tool joints.

- ADP can better protect the casing against wear than does steel drill pipe.

- Corrosion can be controlled with the drilling fluid used.

The Russian experts invited the German participants interested in more information on the subject of ADP to attend a separate meeting. The Russian group was headed by Dr. B. N. Khakhaev, Nedra.

ADP is employed in combination with downhole motors (DHM). In addition, the drill string is rotary-rotated at 4 to 6 min-1 in Kola SG 3, and the torque is limited to 2400 to 2700 N.m.

It can also be used for rotary drilling. Explanations were given by Dr. Fain, chief metallurgist for Kola SG 3 and promotor of ADP:

Because of reduction in strength of ADP with temperature, the drill string is normally a combination of three different grades of ADP. The strength is plotted against the temperature for the three available grades in figure 1. The data given by the Russian experts are presented in the table included in figure 1.

For specific applications, the optimal capacity of the ADP drill string can be obtained by selecting the appropriate wall thickness.

A configuration of various geometries used with aluminum drill pipe is shown in figure 2. The connection between ADP and steel tool joints is specially designed for thread profile, and a shrink fit system is employed for improving make-up.

Corrosion

Inhibitors are available for controlling corrosion. Documented instructions indicate which of the ADP is to be used in a given borehole situation when load and temperature profiles are known.

Design

The design cannot be directly compared with that of steel drill pipe. As mentioned above, some designs employed in superdeep borehole drilling are shown in figure 2. For wear protection in the middle of the ADP, an upset can be provided with or without hard material.

For reverse circulation, the OD may be reduced, while the ID of the pipe has the same dimension as the tool joints.

For Kola SG 3, the steel pipe was preferably designed to be flush at the OD (with the tool joint?) and had a pronounced internal upset of the pipe at both ends to the steel connector. At least 27 m above the bit, the core receiver (inner barrel) was designed for allowing hydraulic lifting of the cores into the core barrel.

For cement jobs and in risky operations involving a hazard of getting stuck, ADP without steel connectors may be used for allowing easy milling.

Spiral ribs in combination with upsets in the middle of the pipe were provided for reducing vibration and improving bit performance.

For general turbine core drilling, ADP is employed, but its use is not limited to drilling with downhole motors.

The side force on the casing and borehole is greatly reduced with the use of ADP. Since Young's modulus, E, is about three times the value for steel,

$$(E_{el,ADP} = 3\ E_{el,steel}),$$

not only side forces are decreased; fatigue failure also does not occur.

Some peculiarities associated with the use of ADP deserve mention and are summarized as follows:

- In rotary drilling, the number of revolutions executed by the rotary table before the bit starts turning is three times higher than for steel pipe.

- The string can be designed by utilizing the properties of the three grades introduced by the USSR, and a wide choice of wall thickness is available for adjusting to the depth and temperature.

- In Kola, practically no failure was experienced with ADP.

- Easy milling helps in cases of stuck pipe.

At the end of the presentation, Dr. Khakhaev and Dr. Fain indicated their willingness to design a drill string for use at KTB, if boundary conditions are specified on our part.

After the presentation, the following questions were raised and answered by the Russian experts:

Q: What is your experience with the use of ADP with respect to corrosion and connections between aluminum pipe and steel connectors?

A: We had problems at the beginning, but were able to solve them. Excessive torque did not occur, and we kept the drilling fluid in the pH-range from 7 to 9.5, since we know that the corrosion rate increases at a pH-value above 9.5. As already mentioned, special corrosion inhibitors for ADP are available. Corrosion was always very slight in the borehole, but more pronounced in air. Steel corrosion problems between ADP and tool joints did not occur

Q: Did you experience axial vibration during rotary drilling or turbine coring with your four-roller-cone core bit design?

A: Axial vibration did not cause major problems. I wish to point out further advantages of ADP with respect to casing wear. We experienced less casing wear because of:

- lower string weight;
- higher elasticity of the drill string;
- casing somewhat protected against wear by powdered aluminum covering the inside of the casing.

Q: How often did you change your wear casing in Kola?

A: After ten kilometres of pipe movement, we turned the casing through 90 degrees. We replaced the casing after four turns.

Q: What is your experience with drill pipe fatigue?

A: We rely on good pipe inspection (flaw detection) by means of ultrasonic (US) testing. 250 m is under inside inspection (?)

Q: Do you have a process for inspecting drill pipe during round trips?

A: Yes, but only for the pipe, not for the tool joint.

Q: What is the joint stability between ADP and steel joints?

A: The aluminum thread may be damaged by the steel thread because of excessive load, torque, and axial load.

Q: Do you apply grease between steel and aluminum during make-up?

A: No; the joints are made up by heat shrinking and controlled torque.

Professor Rischmüller expressed his thanks for this discussion and stated that there are no contradictory opinions. He promised to send KTB specifications for enabling the Russian side to perform calculations and provide recommendations for an ADP string design.

It was agreed to address the specifications for this cooperation to:

Cand. Tech. Sc. Vladimir S. Basowitch,
Deputy Head of Geological Prospecting Expedition
Kolskaya GRESD

10. Krivoy Rog - excursion, 29 August 1988

10:30 to 12:30 h House of Technique in Krivoy Rog

1. General survey of area and town
2. Geological situation in the area of Krivoy Rog superdeep borehole - 8, by N. S. Kuslov

12:30 to 17:00 h Drill site, laboratories, and downhole tools

The rig is a standard derrick with a capacity of 300 t (10 lines):

depth capacity with ADP (downhole motor and wireline): 7000 m;
depth capacity with steel pipe and rotary drilling: 6000 m;
electrically powered drawworks: two 600 kW units, with DC motors;
pumps: four 600 kW duplex and 1 mixing pump of same size.

For the depth range from 7000 to 12 000 m, a new derrick structure of type Uralmesh 15 000 will be employed.

Program and status

The total depth planned is 12 km. During phase 1, with the derrick on the drill site, a depth of 3550 m was reached with a borehole inclination of 35 degrees. The deviation was allowed for reasons of investigation. The vertical borehole with a diameter of 480 mm to a depth of 3550 m was drilled by a method using turbobundle (two turbines).

- Casing: 420 mm to depth of 3550 m

General lay-out and equipment

Square kelly and swivel: 250 bar, 250 t

Hydraulically operated slips and air tongs for spinning

Reverse circulation installation for pump-out of downhole coring system in 12 min from a depth of 1600 m at a pumping rate of 30 l/s

One drill string ADP, one drill string steel drill pipe

During the visit, the rig crew demonstrated the pump-out of the downhole coring tool, replacement of the core barrel, and pumping-in of the same equipment. The traveling speed of the equipment was about 0.6 m/s. The actual depth was about 1600 m; coring was performed only for correlation and demonstration.

The pump-out time for the 132 mm downhole tool was 12 min. The arrival of the equipment at the surface is indicated by a sensor in combination with a light signal. After reaching the fishing spear, a central collar is lifted by the upward movement. A hydraulic damping system with a locking device for the tools similar to the fishing spear for wireline tools is employed.

The downhole tool (picture 12, figures 3 and 4) which was pumped out consisted of:

- a core bit, 132 x 69 mm; average tool life: S = 8 to 40 m (picture 13); (AUF DER VORLAGE STEHT ,,bis **14** m" BITTE PRÜFEN!)

- core barrel with one three-blade spiral stabilizer above the core bit; core barrel length: 6 m;

- reamer section, 132 x 217 mm: with four blades, picture 13

  The blades are about 8 cm in width, and the inserts are diamond-impregnated (Slavotitsch). They are hydraulically extended by normal drilling fluid circulation after the tool has reached bottom position, and retracted by reverse circulation applied for pump-out operation.

- speed reducer: 7-3/4" (195 mm)

The data are compiled in tables 1 and 2. The speed reducer is sealed and hydraulically balanced, and features roller bearings. The planetary gears have a reduction ratio of 3.69; a second stage with the same ratio can be added in series, thus providing a total reduction ratio of 13.62. The speed reducer is connected by a square pin at the top and a square box at the lower end.

The circulating fluid passes through the speed reducer by way of a separate annulus between the gear housing and outer barrel. In the case of the pump-out version, the cross-over section to the core barrel has a reduced diameter of 132 mm. The bevelled shoulder from the 132 mm section to the 195 mm section is the lower shoulder which matches the corresponding shoulder at the mantle tube of the drill string.

- Turbine

One of the several turbine designs with bearing sections is specified in table 1.

- Upper section of the downhole tool (picture 15, 15a) with:

  - torque splines which are hydraulically extended during drilling by fluid circulation;

  - a radial connection to the mantle tube by means of two rubber cups subjected to the circulation pressure;

  - central fluid passage for by-passing the annulus;

  - fishing neck for wireline retrievers

For application of the hole-opener system (pictures 16, 17) with two turbines combined to form a bundle, steel drill pipe is preferred.

The steel drill pipe used on this location had threaded connections to the tool joint and, in addition, a circumferential welded seam between the tool joint and pipe. The operations manager for Krivoy Rog, P. Stanko, explained that three versions of steel drill pipe are in use with respect to the connection between the tool joint and pipe:

1. threaded connection with shrink fit;

2. threaded shrink-fit connection with additional welding;

3. friction welding between the tool joint and pipe.

For interbedded harder streaks, the reamer does not cut effectively, and the system for coring and hole opening is withdrawn from operation. The lower part of the internal drilling system is now replaced by a wireline-retrievable three-cone roller bit (picture 18). This bit section is fully exchangeable with the core barrel plus reamer section. After the hard streaks have been penetrated, operation of the system with the coring equipment and four-blade hole opener (132 to 217 mm) is resumed.

In the case of continuous sections of rock which is too hard for the reamer section, the pump-out system must be replaced by the turbine coring tool with retrievable inner barrel and hydraulic lifting of the core into the inner barrel during the coring operation. This hydraulic lift is achieved by reversing a portion of the drilling fluid stream through the inner barrel in a manner similar to that for a reverse circulation tool.

The formation at a depth of 1600 m had a drillability index of 8 on the scale from 0 to 12, where 12 corresponds to quartzite.

For the maximal flow rate applied - in this case, 50 l/s (3m³/min) - the solids control equipment consists of

three shale shakers (picture 20);

desander, desilter, degasser (picture 21);

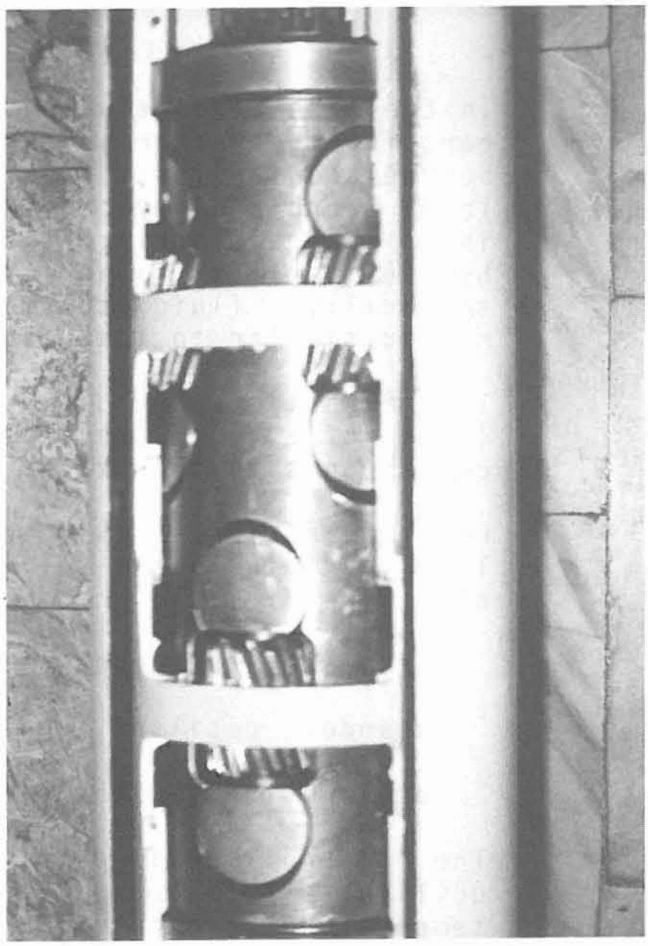
settling tanks with level indicators (picture 22).

The return line is open, the pressure line from the drilling fluid pumps is insulated for a wintertime temperature of about -10 oC. The pumps are located in a separate building with ample space (picture 23).

The front of the V-door is served by a beam crane with an electric hoist (picture 24).

At the end of the catwalk, a powerful wireline hoist (picture 25) was being installed in front of the crane for retrieving the coring and hard rock drilling bit assembly by means of wirelining instead of a pump-out operation, which is associated with the risk of fracturing formations. Evidently, the wireline was not previously available in the quality required for heavy-duty operations in superdeep boreholes. The equipment to be lifted has a weight of 1.5 t.

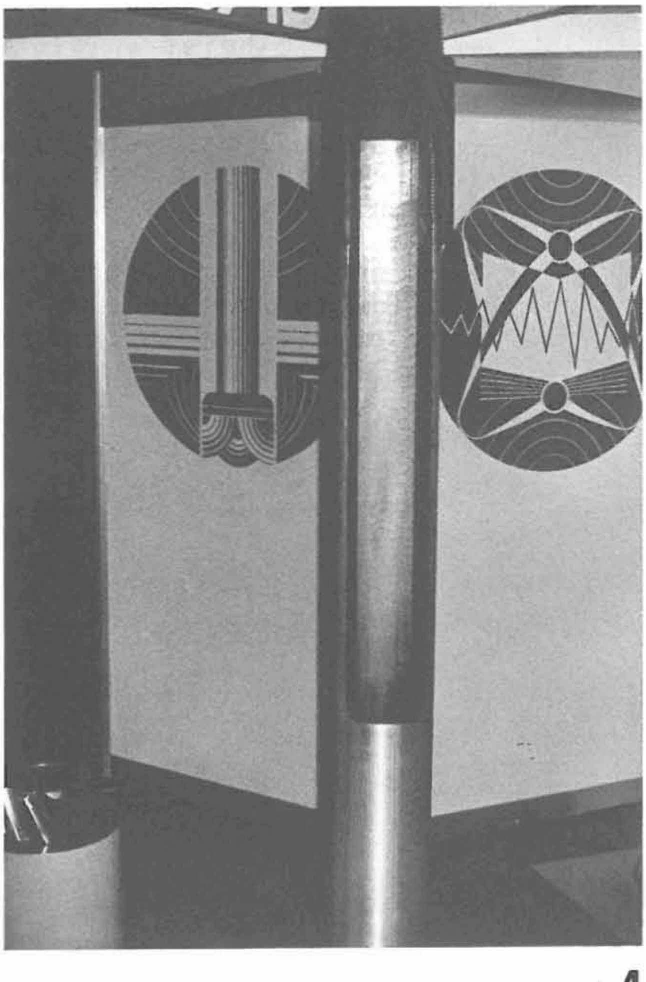
1



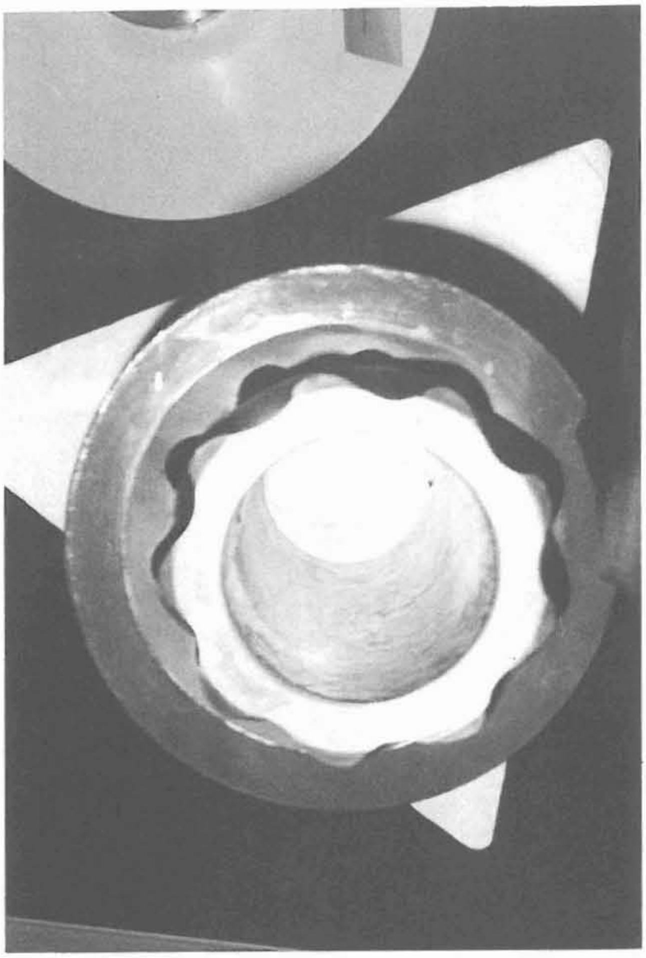
2


АВТОНОМНЫЙ
АДАПТИВНАЯ
УСТАНОВКА
ДАТЧИК
ОБОРОТОВ ЗАБОЙНОГО ДВИГАТЕЛЯ
ТЕЛЕМЕТРИЧЕСКОЙ СИСТЕМЫ

3



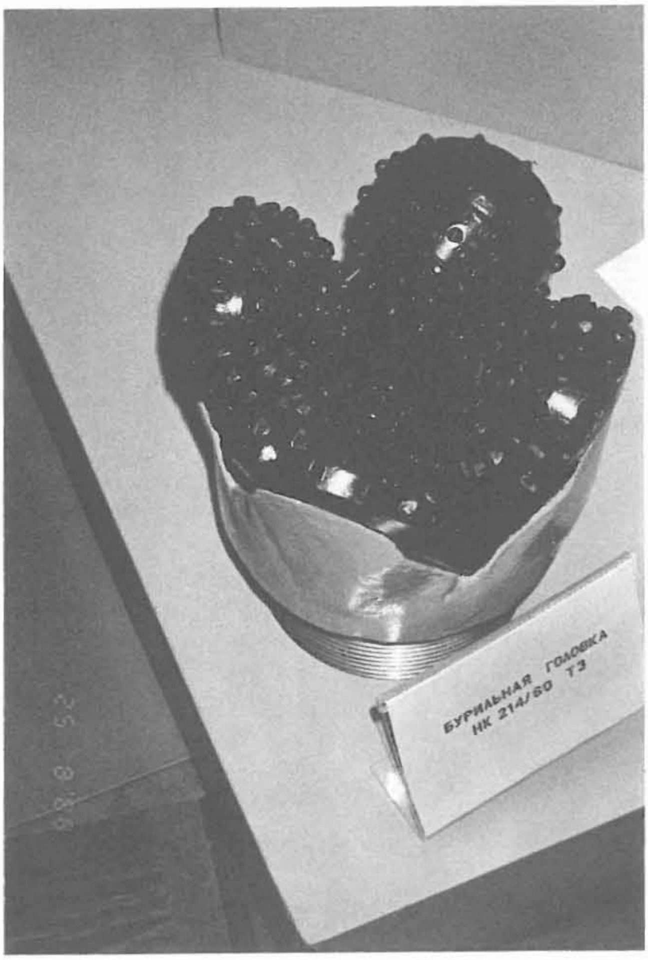
4



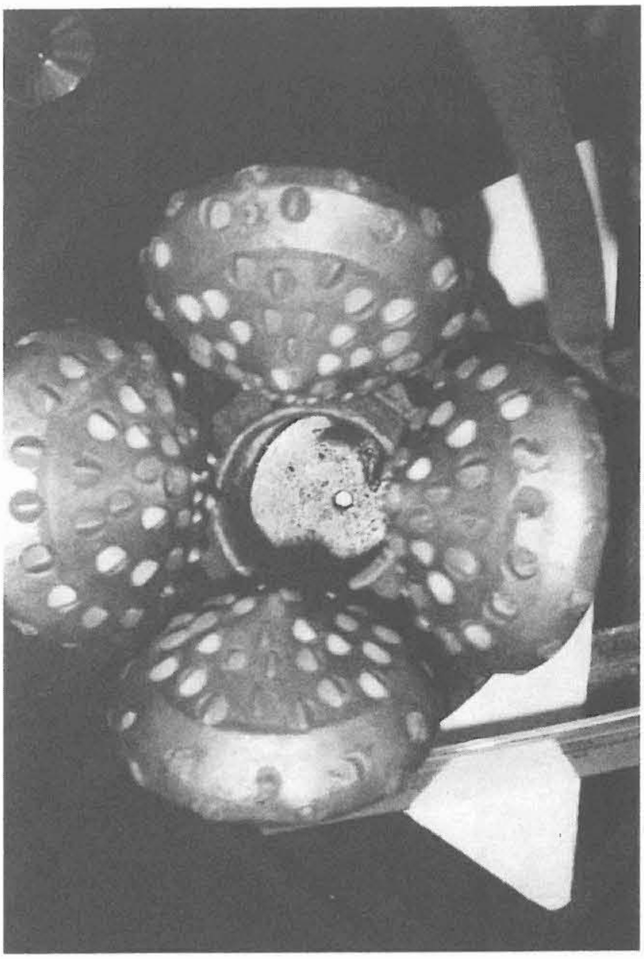
5

6

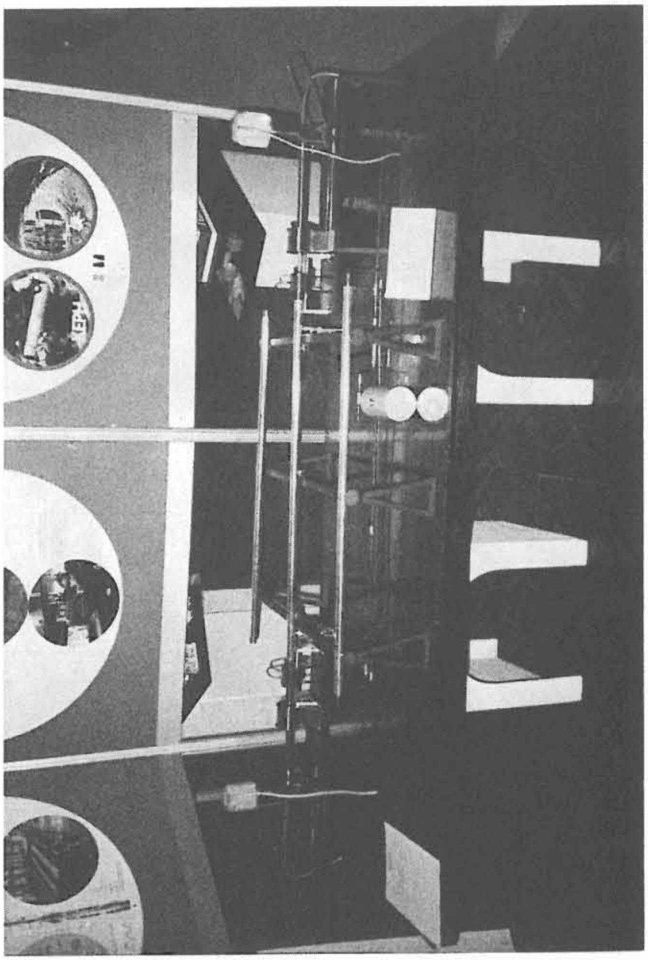
7



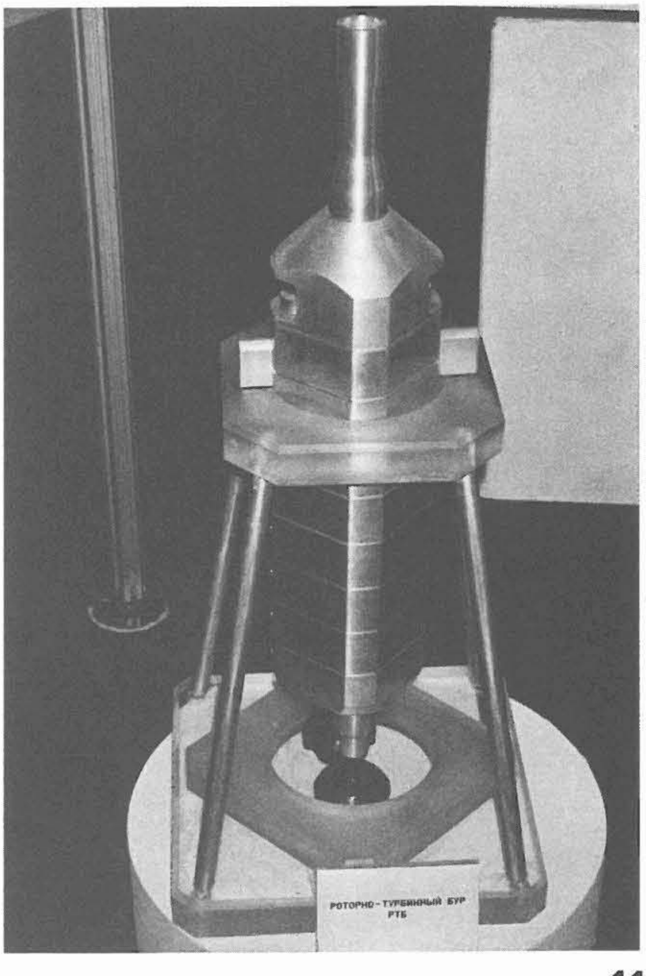
8



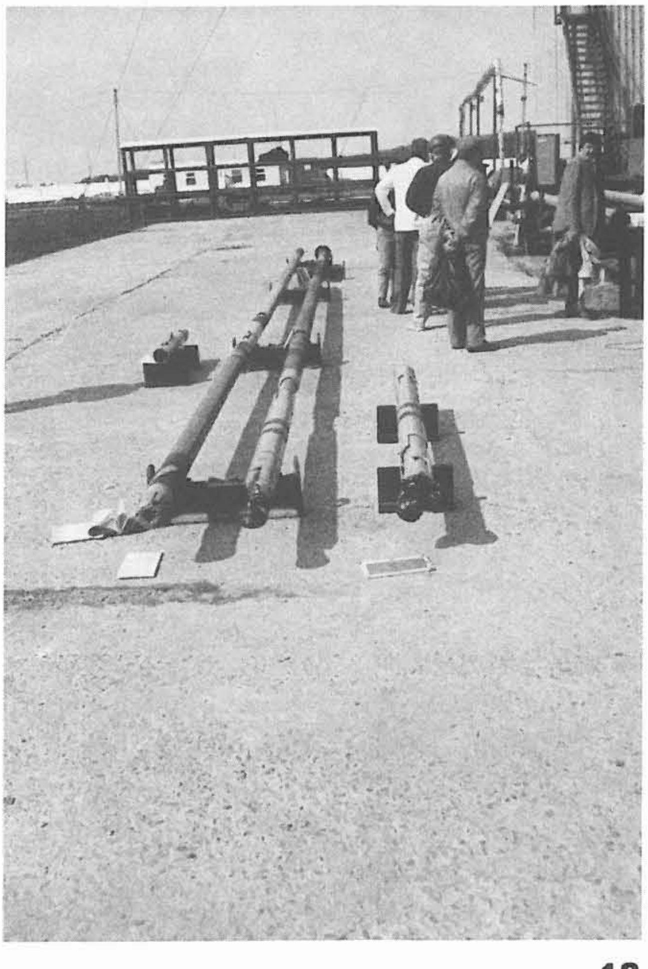
9



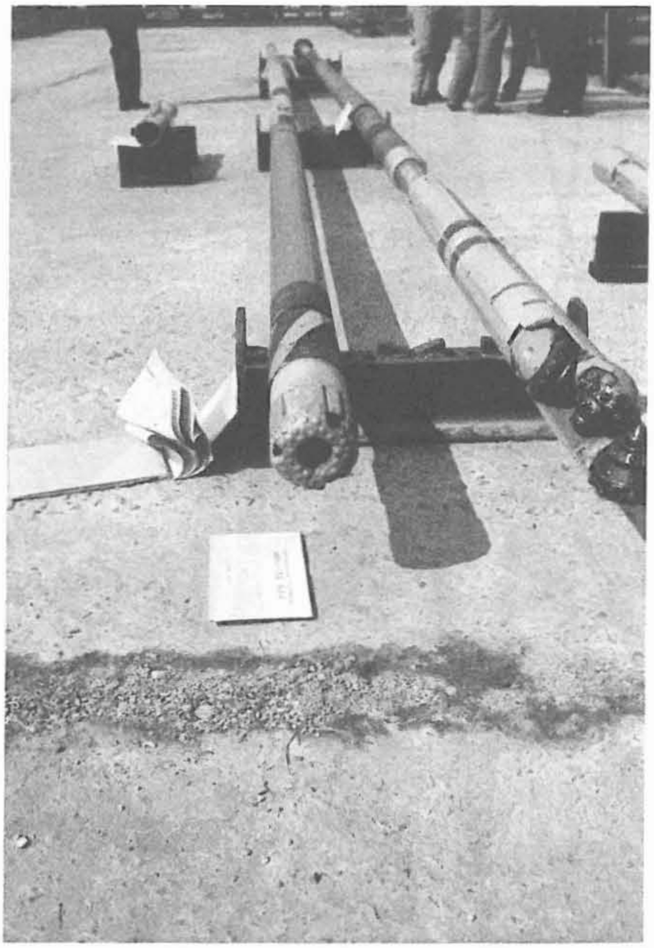
10



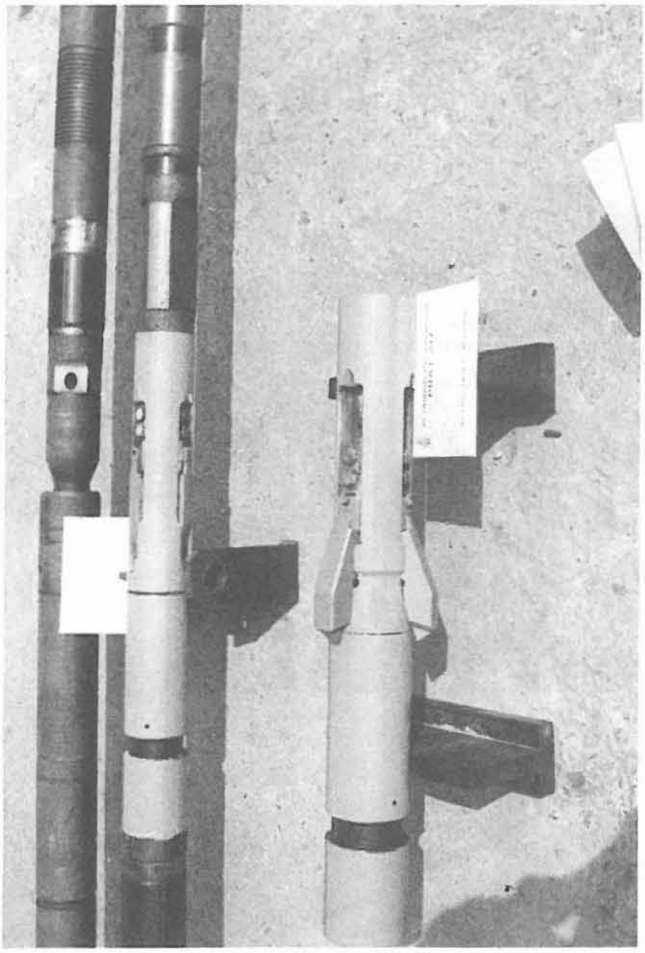
11



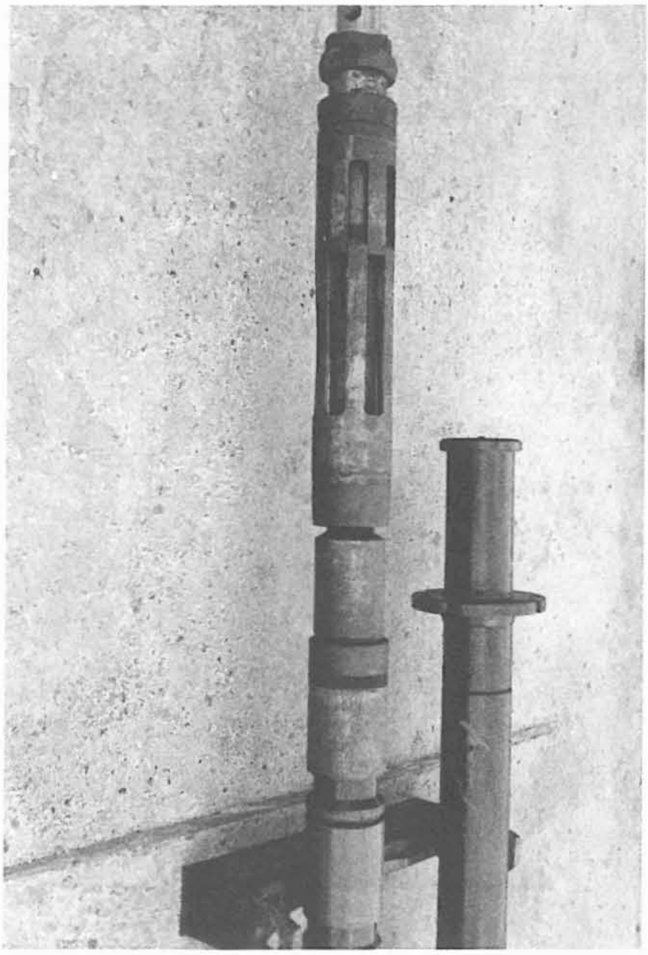
12



13

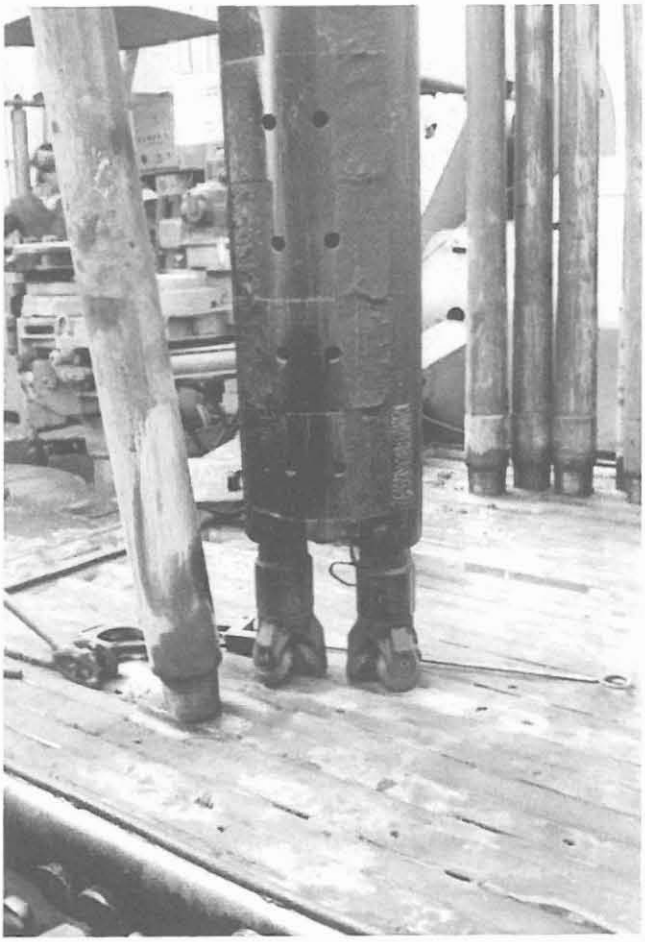


14



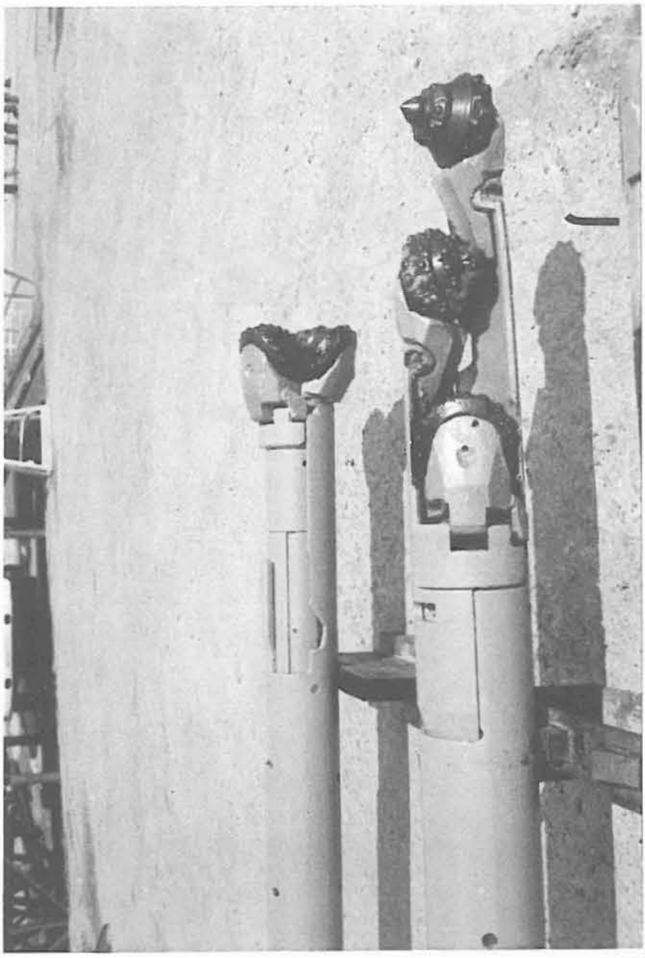
15

15 a



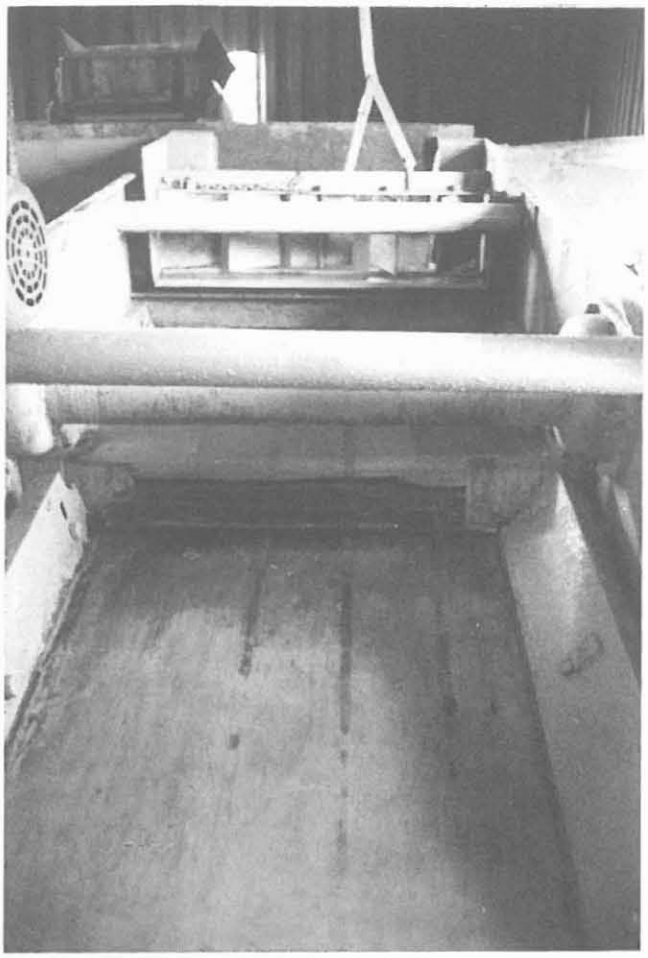
16

17



18

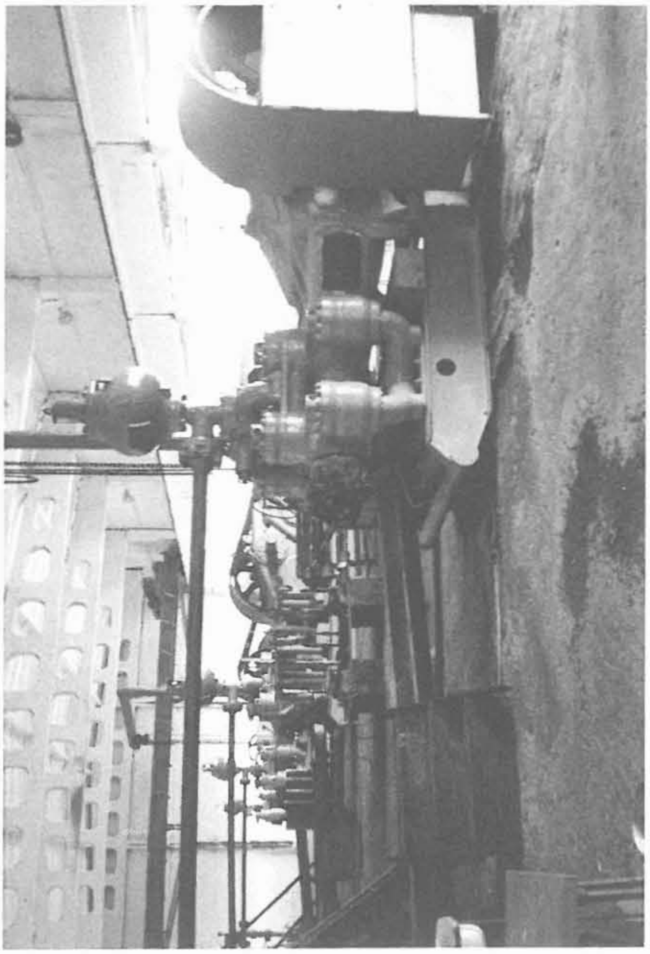
19



20

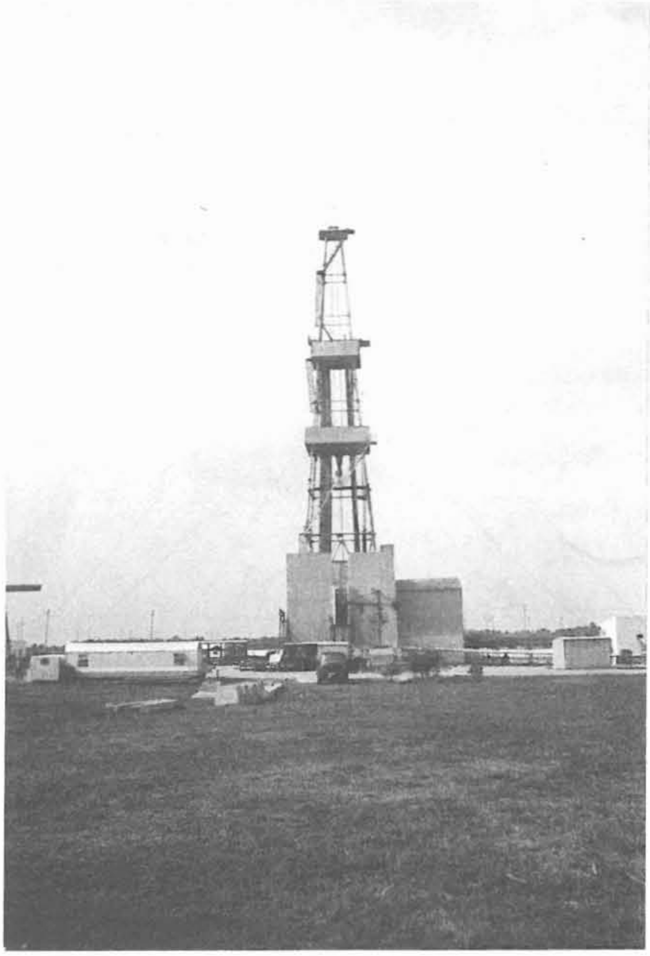
21

22



23

24



25

Kurlov N.S

INFORMATION

to the participants of the International Seminar at the Krivoy Rog Superdeep Borehole-8

Esteemed guests!

To realize geological tasks a program of complex research is worked out by the Ministry of Geology and Academy of Science organizations. This program envisages examination both the borehole and the area of its location (in the surroundings of Krivbass). Such an approach is necessary to interpret the results obtained from the borehole in drilling and also to specify the project technico-geological conditions.

Let me briefly report some features of the region geological structure as it's difficult to understand results obtained without such preliminary acquaintance.

The borehole is located in the northern part of the Krivbass Saksagan region, which is a part of Krivoy Rog-and-Kremenchug structure. We believed the structure was made up by Krivoy Rog series, occurring upon the Archean plagiogranitoids of the PreDnieper and Kirovograd blocks.

The series is d vided into five formations (upwards): Novokrivoy Rog - essentially metabasites, Skelevatskaya formation - arkose metasandstones, metaconglomerates, fillites; Saksaganskaya productive formation - ferrous quartzites, gespillites, various schists; Gdantsevskaya - biotite-graphite schists, marbles with the layers of poor ferrous quartzites; Gleevatskaya - polymictic metaconglomerates, metasandstones, apoaleurolite and apopelitic schists.

Degree of the regional metamorphism of the Krivoy Rog series increases from the south to the north from greenschist till epidote-amphibolite facies. We believed the rocks had been dislocated with formation of sinclinal structure. The eastern flank of this structure has been preserved completely while the western one (in the south) remained in fragments and on the north it is cut by deep fault.

A number of problems doesn't fall uniformly in this stratigraphic-tectonic scheme. These are as follows:

1. In the northern part of Krivbass amphibole-magnetite quartzites occur together with metabasites and various schists associating with schists and marbles of Gdantzevskaya formation. These rocks form enlongated layers, which are known in literature as West-Annovsk and Far West bands. Some geologists (Belevtzev Ya.N. et al.) reckon these layers to be of the Saksagan formation and that they are elevated from depth in the form of scaled-skinned structure along faults. A group of other geologists (Reshetnyak V.V. et al.) refer these bands to younger than Saksagan independent ferrous-siliceuous formations. The latter concept served as a basis in development of Krivoy Rog superdeep borehole project.

2. The West-Inguletz synclinorium occurs to the west and north-west of the Krivoy Rog - Kremenchug structure. It is situated also on the Archean plagiogranitoids of Krivoy Rog - Kirovograd block. The synclinorium is made up by rocks of Ingulo-Inguletz series. This series has the same age as Krivoy Rog's one, but differs from the latter by the smaller thickness and higher degree of regional metamorphism.

The Ingulo-Inguletz series includes the following formations: Zelenoretchenskaya formation which consists of sillimanite quartzite, hornblende amphibolites, gneisses which are similar to Novokrivoy Rog series. The Artemovskaya formation is made up by pyroxene and amphibole - magnetite quartzites, biotite and amphibole gneiss, it is analogous to the Sagsagan formation; Rodionov formation consists of quartz sandstones, ophicalcites, calcifiers, biotite and graphite-biotite gneisses, it also contains sparse thin interlayers of magnetite quartzite; and at last - Spasovskaya formation is represented by diopcide and hypersstene gneisses and schists.

The degree of metamorphism of Ingulo-Inguletz series increases from south to north from epidote-amphibolite to amphibolite facies. Metamorphics of the Early-Proterozoic and Archean plagiogranitoids have been intensively subjected to the processes of granitization and reomorphism. These processes result in the formation of anathectic and reomorphic plagiomicroclinic granites, akerites and polymigmatites of Kirovograd-Zhitomir complex. A granitization in the rocks of Krivoy Rog series are considerably poor and has a local character.

It is very important to stress the following: the bodies of the silicate-magnetite quartzites of the Artemov formation are located in the northern part of the West-Inguletz structure and form here a group of magnetic geophysical anomalies. The group of these anomalies called on the Ukranian shield "The Region of Right Bank magnetic anomalies" - as it is located on the right bank of the Dnieper River.

In this region there is a junction of Inguletz and Krivoy Rog - Krementchug structures. Many scientists consider the so-called deep western fault to be a boundary between these structures. But in this case it is not clear why the rocks of Ingulo-Inguletz series grade into the rocks of Krivoy Rog series at one and the same level of metamorphism. Moreover, during the investigations of this area in 1987-88 within the traditional Krivoy Rog - Kremenchug structure, rocks very characteristic to Western Inguletz structure were reported. These are biotite-graphite gneisses, calciphiers, ophicalcites, meta-sandstones with quartz-diopside matrix, etc.

It is strange and unreal to find in the area of the so-called deep western fault a stratigraphic contact through ancient metamorphic eroded crust between Lower Proterozoic metamorphics and Archean plagiogranitoids.

The above mentioned problems remained under discussion for a long time. And as a result of the superdeep borehole drilling in Krivoy Rog and regional geologo-geophysical survey more or less certain answers to these problems have been obtained. Now let me discuss the main results of drilling and survey of the borehole area.

Statistic data

The borehole was spudded on September 7, 1984. Down to the depth of 950 m a drilling was done without coring. The interval 0-950 m was drilled with continuous coring by "Sputnik-I" borehole. The depth of the borehole is 3351 m, from the depth of 950 m the core was recovered. Core recovery amounted 94%, the total core recovery-1550 m, linear core recovery was 64%.

The borehole diameter is 215,9 mm, the core diameter depending on the technology used was 52 mm, 60 mm and 80 mm; zenith angle at the bottom-hole is 34°, azimuth is 270°, downhole temperature is 57°C, temperature gradient is 1,5°/100 m. The complex study of the Earth's crust at drilling of the Krivoy Rog super-deep borehole included the following kinds of work and methods:

1. Drilling
2. Core and cutting sampling and their documentation
3. Determination of rock physical properties
4. Core sampling for chemical, mineralogical and spectral analyses
5. Downhole geophysical studies including downhole complex: technical, electric, magnetic, acoustic, radioactive, thermal, density, seismic analyses, mud logging, etc.
6. Sampling of drilling mud, formation fluids and their analyses.
7. Carrying out regional and local field geological and geophysical studies on the site simultaneously with drilling. Regional studies are carried out by the Krivoy Rog geological expedition in the region of 52 th. km^2. They include magnetic, gravity and seismic surveys, shallow borehole drilling in order to determine physical and geophysical rock properties, deep borebole drilling in the most interesting geological and structural intersections. The information obtained is used for the reconstruction of the geological history of the region from the geodynamical point of view, metallogenic evaluation of different structural complexes, deep structure of the Krivbass surroundings.

Local detailed geological studies are done by geological survey of the Krivoy Rog superdeep borehole in the region of 400 km^2. A geological survey is done here, study of the previously drilled boreholes with sampling for chemical and analitical investigation with a purpose of correlation of geological section in super-deep borehole and specification of its structural position.

8. Sampling monomineral fractions of accessary ore and rock-forming minerals for their precisive studies, which include determination of radiogenic age, isotope composition of oxygen, sulphur, lead, hydrogen, inner mineral structure and other properties.

9. Complex information systematisation and processing for geological and geophysical borehole section construction and different models of the borehole site.

The borehole research on "Super-deep drilling and complex research of the Earth's interior" is done by the USSR Ministry of Geology, the USSR and Ukraine Academy of Sciences and is coordinated by Interbranch scientific council on "Super-deep drilling and complex research of the Earth's interior".

The core along the axis is cut into two parts: one of them is being stored, the other one - is the object of research.

The research is held according to the plan in the following scheme:

1. Stratigraphy and structural and formational analysis.
2. Petrography and mineralogy
3. Radio and geological chronology, geochemistry of stable and radioactive isotopes
4. General geochemistry
5. Geophysics and petrophysics
6. Hydrogeology
7. Ore formation
8. Laboratory analyses
9. Drilling and coring technology.

Most of the organizations have chosen the necessary core specimens to be analysed. Some of the results have already been obtained by the expedition. A set of downhole logging has been performed.

To determine strike and dip of metamorphics a method of electrical correlation in "Borehole-surface" version has been performed additionally.

Dear collegues!

According to the project at the first stage of drilling the borehole should penetrate rocks of the Krivoy Rog series down to 7 km depth. The series consists of the following formations: Gleevat, Gdantsevskaya and Upper Saksagan.

But in the interval of 63-2351 m the borehole intersected the sequence of metamorphics which, with an ancient zone of weathering, occursupon plagiogranitoid close by their composition to the Archean rocks.

In the penetrated section the composition of the primary rocks is close to the Krivoy Rog series composition but differs from it by higher degree of metamorphism and thickness. The thickness tends out to be 8-10 time less than that of the Krivoy Rog series.

From the other hand by degree of metamorphism and lithological composition the section proved to be very similar to that of the Ingulo-Inguletz series of the northern part of the West-Inguletz structure.

The section was very close to the sections of those intricate Far Western and West-Annovskaya bands which do not have exact stratigraphic position in stratigraphy and structure of the Krivbass.

A special attention was given to study these bands and the area of the Right Bank anomalies.

Works to correlate the section penetrated have been performed. They include the set of the following indications: lithologo-formational, structural, geophysical, geochemical, isotopic, radiologic, etc.

Complex investigations revealed the following:

1. The isotopic age of zircons from plagiogranitoids proves to be of 2960 mln years - the Archean time.

2. Comparison of plagiogranitoids with those from the area of borehole site by petrophysical, geochemical properties pointed to the fact that they belonged to the plagiogranitoids of the Kirovograd block.

3. Staurolite-andalusite quartzites and quartz-sandstones occuring at the bottom of metamorphics happened to be ancient redeposited metamorphized zone of weathering of Archean plagiogranitoids. Relic minerals pirofillite and diaspore were found in the quartzites.

4. Quartz-staurolite-mica schists, quartzites down the section represent the ancient crust of weathering preserved in situ.

5. The results of lithological, geochemical petrochemical, isotopic, geophysical and other investigations of metamorphics penetrated by the borehole confirmed they are close to the rocks composing Far-West, West-Annovskaya bands and Right Bank magnetic anomalies, i.e. to the formations of Ingulo-Inguletz series rather than Krivoy Rog series of the eastern flank of Krivoy Rog structure.

This conclusion is confirmed by difference between the formation temperature of the Krivoy Rog and Ingulo-Inguletz series. The temperatures were established by X-ray spectral measurements of granites, isotopic investigations of oxygen and quartz, thermobaric measurements of fluid inclusions in carbonates and quartz.

The isotope composition of oxygen in magnetite from the ferrous quartzites shows different conditions of sedimentation and evolution of metamorphism in both series.

Ferrous quartzites in this borehole, as far as their geochemistry is concerned, radically differ from those of the Krivoy Rog series and are close to Ingulo-Inguletz series.

The rocks of the Far Western and West-Annovskaya bands were subjected by granitization more intensively than those of the Krivoy Rog structures. On the first two bands different gneisses, calcifiers, metamorphic pyroxenites, bodies of anathectic plagioglase microclinic granites and ackerites, similar to those of the West-Inguletz sinclunorium.

Thus, lithological and structural position, which was revealed by the Krivoy Rog superdeep borehole, proved to be different from that one, characteristic to the eastern flank of the Krivoy Rog structure.

6. Naturally the question arises - where and how are these structures made up by Ingulo-Inguletz and Krivoy Rog series conjugated? and how deep does the productive Saksagan series under the plagiogranitoids occur?

As a result of geodynamic research of the Krivoy Rog super-deep borehole site by Kalyaev and Reshetnyak, the principles of paleographic reconstruction of Early Precambrian are worked out. According to these ideas Krivbass is a fragment of intercratone paleorift, that is assymetric monocline remained due to uncomplete subduction in the zone of Vadati-Zavaritsky-Banioff. On this way metamorphic rocks, intersected by the borehole, correlate with sections of the Far West, West-Annovskaya bands and the Right Bank Magnetic anomalies. They make up complex sinclinal fold, which together with Archean granites overthrusted upon the Krivoy Rog series. The latter uniformly subsides to the west under the nappe zone in the junction of Pridneprovsky and Kirovogradsky blocks. These blocks, made up by Archean plagiogranites, have their own Proterozoic "nature" and conjugate to the nappe zone. The nappe is well distinguished by seismic measurements and is fixed by tristed and decompacted rocks, by development of metasamatic microline, albite, anathectic bodies of ackerites and Early Proterozoic granites, by intensive reomorphism of Archean plagiogranites, localization of characteristic geochemical anomalies and by other processes. That 's why the Krivoy Rog series are to be penetrated at 4500-5000m depth. To the north of the borehole on the extention of the Krivoy Rog -Kremenchug structure in the crystalline basement down to the depth of 1000-1500m a geologo-structural position similar to that expected in the superdeep borehole is revealed. Rocks of the Krivoy Rog series section, including Saksagan one uniformly dip to the west and along fault overcovered by the plates of reomorphised Archean plagiogranites. The Ingulo-Ingulетz series occur on the granite. The idea of the Krivbass deep structure is difficult to be understood as new results on deep structure open new prospects in searching for ferrous and other metals in the underthrusted block.

Dear guests! Thanks for your attention! You may have a look at the specimens of rocks and ores sampled from the Krivoy Rog borehole and in adjacent area. My collegues-geologists will help you to be aquainted with the collection.

NEW STRATEGIES FOR ULTRADEEP CORING IN CRYSTALLINE BEDROCK

H. Rischmüller
R. Jürgens
C. Marx
J. Oppelt
A. Sperber
U. Deutsch

Paper presented at the International Seminar on
"Superdeep Drilling and Deep Geophysical Sounding"
Yaroslawl (USSR)
August, 1988

1 INTRODUCTION

The concept of the German Continental Deep Drilling Program ("Kontinentale Tiefbohrung der Bundesrepublik Deutschland" or "KTB") emphasizes the scientific investigation of the continental crust in order to improve the understanding of the dynamics of intracotinental structural evolution. A drilling location was chosen on the western flanks of the Bohemian Massif in the northeast of Bavaria near the Oberpfalz town of Windischeschenbach.

A total depth of about 12000 to 14000 m for this superdeep borehole to be drilled into the crystalline rock formations has to be reached to meet the scientific goal. This extreme depth poses a very unusual challenge with respect to drilling technology in general. Up to now, only one borehole in the world has approached a comparable depth which is the KOLA SG-3 well. From the publications on this drilling project which is also under way for purely scientific purposes, many technical problems have become apparent to drilling specialists all over the world. Although the geological structures differ from those found in Germany, similar problems will have to be expected for the KTB superdeep hole.

Apart from preparing the planning of the geoscientific experiments and investigations, major emphasis therefore has to be placed on providing the most adequate drilling methods and systems which are capable of meeting the anticipated environment and resulting requirements. It is generally agreed that oilfield drilling technology will only partly be able to meet this task. Tools and drilling systems have to be modified from other already existing technologies such as the mining drilling business or have to be designed totally new.

In order to provide a long enough period of time for conducting such developmental work, and, nevertheless, at the same time to be able to start the scientific investigation of the crystalline rock at the Windischeschenbach location, a new well planning approach was used. This concept consists of drilling a small diameter pilot hole to start with and afterwards spud a second borehole on the same site which has the large diameter required to reach a maximum depth of 14000 m.

The pilot hole has meanwhile been spudded in September 1987. After drilling and coring, mainly by using roller cone bits of 10 5/8" diameter down to 480 m, a 6" anchor casing has been cemented down to this depth. Below 480 m, a specially designed wireline drill string is used which allows to obtain continuous cores of 94 mm diameter from the 6" (152.4 mm) borehole. A total depth of 3000 m has been determined as the minimum target. Any extension below this depth would be appreciated, because the drilling/coring process works quite effectively. Moreover, as the geological scientists have been provided with the core material down to that particular depth, no coring over extended sections is required in this section of the main borehole. The superdeep well which is to be drilled at a distance of no more than 200 m from the pilot hole, can concentrate on other criteria, e.g. verticality of upper sections or optimized penetration rates, because the formation samples have already been obtained earlier.

A major requirement for taking cores from the superdeep KTB well (KTB-HB) will first appear when the hole has arrived at a depth below the TD of the pilot hole. This is the section of the borehole ranging from about 3000 or 4000 m to 12000 or

14000 m, where new coring tools and coring systems have to be provided which are capable of meeting the requirements of effectively taking core samples from the very hostile environment created by the ultradeep target in crystalline bedrock. Existing experience from other drilling activities in crystalline rock has show that, apart from all other technical difficulties, coring under these conditions presents an extremely demanding challenge to both tools and equipment. As the available technology does not provide a comprehensive system for coring in ultradeep crystalline rock, a major development effort has to be made in order to achieve the key scientific objective of the German Continental Deep Drilling Program, the KTB.

2 CORING REQUIREMENTS FOR KTB SUPERDEEP HOLE

Drilling a superdeep hole down to a maximum depth of 14000 m is in the center of interest during the course of the geoscientific KTB project. Below the casing depth of approx. 3000 to 5000 m, depending on the TD reached by the nearby pilot hole, an average of 1/3 of the remaining proposed hole section will be drilling by coring tools in order to provide rock samples for scientific evaluation.

Requirements of adequate coring systems on the one hand are determined by the influence of physical and geological parameters. This is especially true for more extended depths of the well. On the other hand, additional aspects will become apparent with respect to handling capabilities of coring systems.

In general, all coring tools have to show a sufficiently high mechanical stability and reliability in order to be able to withstand the expected downhole conditions. A summary of the most important borehole parameters influencing the coring process is given in Table 1.

- Temperature
- Rock Stresses
- Rock Strength
- Rock Abrasiveness
- Rock Inhomogeneity
- Borehole Depth

Table 1: Effective borehole parameters in deep crystalline rock environment

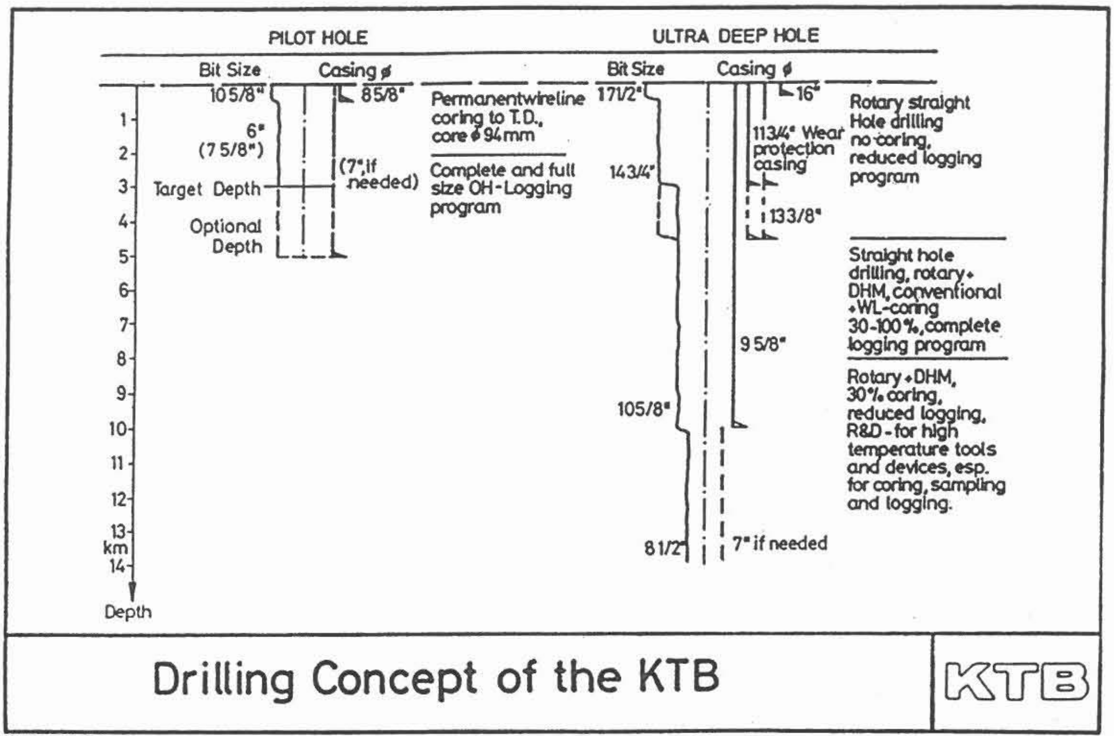
Selection and design of coring systems have to take into consideration critical parameters as listed in Table 2.

- Core Bit Wear
- Inclination Build-up
- Poor Control of Coring Process
- Low Rate of Penetration
- Low Footage of Core Bits
- Hole Fill by Abrasive Rock
- Core Jamming within Barrel
- Vibrations on Drill String
- Wear on Drill String
- Exceeding the Temperature Limitation of Tools
- Exceeding the Load Capability through extended Length of String
- Mud Losses
- Poor Core Recovery

Table 2: Critical effects during coring of deep crystalline rock

Well Planning

The basic drilling concept of the German Continental Deep Drilling Program includes the drilling of a pilot hole (KTB-VB) at a distance of 200 m from the site of the main well before spudding this main well (KTB-HB). Coring in the superdeep borehole will be performed only in sections below the TD of the pilot hole, e.g. from 3000 m to 5000 m (Fig. 1).



T 1117/9.87

Niedersächsisches Landesamt für Bodenforschung

Fig. 1: Well planning for KTB well (Ref. 5)

In addition to the expected overall reduction of drilling time this concept offers a good chance for improving the verticality of the upper hole section.

Geological environment

The well target is located in the Oberpfalz area at the edge of the Bohemian Massif. A preliminary geological prognosis has been published for this location (Ref. 5) by the KTB Technical Project Group. However, the given data are rather vague, except for those layers which have already been drilled in the pilot well.

In any case, uninterrupted crystalline rock will be encountered with the possible exception of a shallow layer of cap rock. Due to the expected abrasiveness, critical tool parts have to be protected against severe wear through special measures such as coatings with hard metal or stabilizers. Due to the extreme formation hardness, the systems under development have to be designed for enhanced sturdiness. There is a risk that diamond cutters may already be damaged during tripping of the string.

Temperature, pressure, and stresses in the borehole

The downhole formation temperature is a critical parameter for the reliable operation of roller cone core bits, downhole motors, coring systems, other moving downhole tools, and even the drill string itself. Development expenditures for the required tools will considerably increase with increasing temperature. A simplified view of the temperature environment for the Windischeschenbach/Oberpfalz location is shown in Fig. 2.

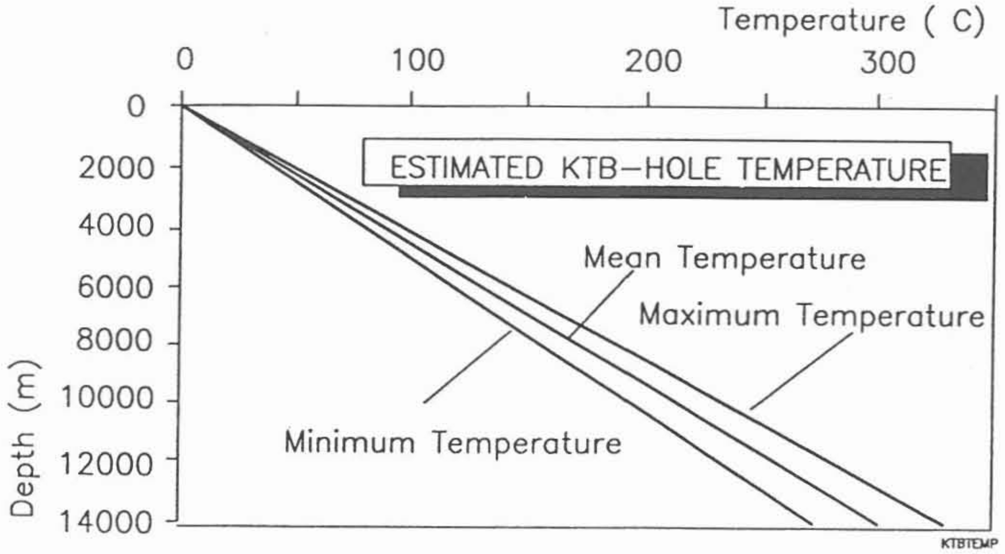


Fig. 2: Estimated depth/temperature diagram for the drilling site

If compared with a temperature gradient of 3 grd/100 m, which is a common order of magnitude, a medium value of 2 grd/100 m leads to moderate temperatures of about 300 °C at 14000 m. Naturally, the mud circulation temperature will always stay below the undisturbed formation temperature. The interim report on the KOLA SG-3 well confirms this very clearly (Ref. 6). In this case, a maximum difference of 30 degrees occurred between circulating mud and undisturbed rock temperature. For safety reasons, the latter has to be considered for design purposes.

Borehole stresses are primarily determined by the geostatic pressure, i.e. the weight of the rock formation. The drill site formation will exhibit an average density of 2.9 kg/dm^3. According to the geological prognosis, a downhole pressure of 4000 bars may be estimated at a depth of 14000 m. Taking a specific mud weight of 1.05 kg/dm^3, a mud pressure of only 1000 bars would be opposed by a rock pressure four times that amount.

A general distribution of stresses at the borehole wall is shown in Fig. 3 (Ref. 7).

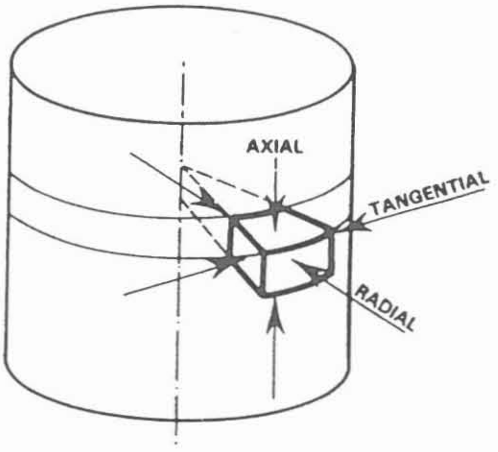


Fig. 3: Stress distribution at the borehole wall (Ref. 7)

Elevated temperatures are critical to many of the presently used coring tools or corresponding components. Some of the materials under use completely lose their function. In other cases, the performance will change considerably.

The stress environment as roughly outlined above will cause drilling problems with respect to the borehole shape and the quality as well as quantity of cores recovered. Both have become known from the KOLA SG-3 well and, with limited experience, from the Gravberg 1 (Siljan Ring, Sweden).

If boreholes are out of gauge over distinct lengths due to rock spalling, the stabilization of the core barrel is affected. Existing vibration might then be intensified which will result in severe problems with respect to maintaining the required trajectory. Breakout and collapse of the borehole wall as well as other instabilities will lead to a fill up with abrasive particles. Especially when tripping the string into the hole, there is a danger of relatively large sized particles entering the inside of the drill string, thus causing major functional troubles when resuming the coring process.

During coring, stress relief will result in volume changes of formation. This may give rise to core jamming and to the tendency that the rock sample will split along pre-existing planes of weakness. In order to overcome or, at least, to minimize these difficulties, the inner surface of the core barrel should be as smooth as possible with a slightly increased inner diameter. Special problems might occur if cores break into thin slices (core disking), as happened during the course of drilling the KOLA well.

Fundamental scope of development of coring tools

Every KTB coring development has to use the existing tools and systems from deep hole drilling as well as mining drilling as a basis. With respect to section of moderate depth, major resources have to be allocated for improving the economy of the coring process. When getting into deeper sections, the reliability of coring systems has to be raised by technological improvement in such a way that coring with a good recovery rate will not disturb deepening the hole. When reaching the superdeep sections of the hole, coring systems have to be designed primarily towards a direction which allows to recover some core at all.

With respect to development planning, characteristic sections of depth are determined as shown in Table 3.

Depth Limitation (m)	Section	Coring Intervals (m)	Major Goals
3000 (5000)	TD KTB-VB	50	Full size coring, sidewall coring, spot coring
6000	Moderate depth	350 - 1000	Core recovery, economy, core quality
10000 (12000)	TD 10 5/8" hole	1300 - 2000	Core recovery, core quality
14000	TD KTB-HB	700 - 1300	Core recovery

Table 3: Coring systems for different sections of the KTB main well

Down to the TD of the pilot well (KTB-VB), no continuous coring is required to be performed in the main well. For the purpose of confirming results from the pilot hole, a limited number of samples might be taken by discontinuous spot coring or by sidewall coring out of the already deepened open hole. In addition, this section of the hole might also be used for the testing of tools which will be under development at this time for more extended depths.

Major research efforts will have to be made to develop coring means and methods which do not require tripping the complete drill string out of the hole after one core barrel has been filled. These systems are to be identified as continuous coring systems. One advantage of such systems is that much time will be saved if the string can remain in a superdeep hole while recovering the core. Another advantage which may be even more beneficial to the whole drilling operation, is the possibility to recover a jammed core sample by wireline or other means.

Reflections on coring and verticality of hole

Verticality of hole is of superior importance for meeting the ambitious goal of a 14000 m TD. Down to TD of the pilot well, no extensive coring is required in the main well. The most adequate systems for vertical full size drilling will be employed here where a truly vertical hole course is really essential. However, the deeper sections which will be cored rather extensively, also require to maintain a straight and vertical course of the hole. Otherwise, there is the danger that the deepest parts of the hole will have to be plugged back if torque and drag exceed the strength of the drill string due to unfavorable direction changes.

There are different principal methods for recovering cores and maintaining verticality as listed in Table 4.

- Take cores and make correctional runs some time afterwards in deeper section if deviation gets untolerable
- Use "hybrid" pilot coring system, trying to pilot core as vertical as possible and later on ream the hole following the course of the pilot
- Use pilot coring system with internal whipstock for borehole corrections
- Pilot core for optimum recovery over a certain length without considering hole verticality, then change BHA completely and employ special full size vertical drilling system to drill optimized vertical hole without considerations on coring

Table 4: Proposed methods for coring and vertical drilling

The decision which method to apply will depend on the drilling parameter environment, lengths to be cored, etc.

3 EXPERIENCE AVAILABLE WITH CORING CRYSTALLINE ROCK

An effective and systematic approach to coring systems development has to make use of the internationally gained experience with drilling of crystalline rock. In addition, the overall state of the art of progressive coring systems from other applications has to be taken into consideration.

Crystalline rock coring performance

Drilling or coring for oil and gas is usually conducted in sedimentary rock formations. However, no continuously operating systems are used here, because they are not needed. As regards drilling and coring in crystalline rock, only limited experience is available in this case. These types of wells are usually either drilled for purely scientific reasons or for the exploration of waste storage facilities. In addition, the few data available are difficult to compare due to unknown drilling and borehole parameters.

From the existing experience with diamond core bits the following conclusions may nonetheless be reached:

- Rate of penetration and footage will both be improved by a reduction of the ratio of borehole to core area (CR = characteristic ratio). Some recent results with respect to footage are shown in Fig. 4 for comparison.
- For equivalent characteristic ratios, a better overall performance is achieved with smaller borehole diameters.

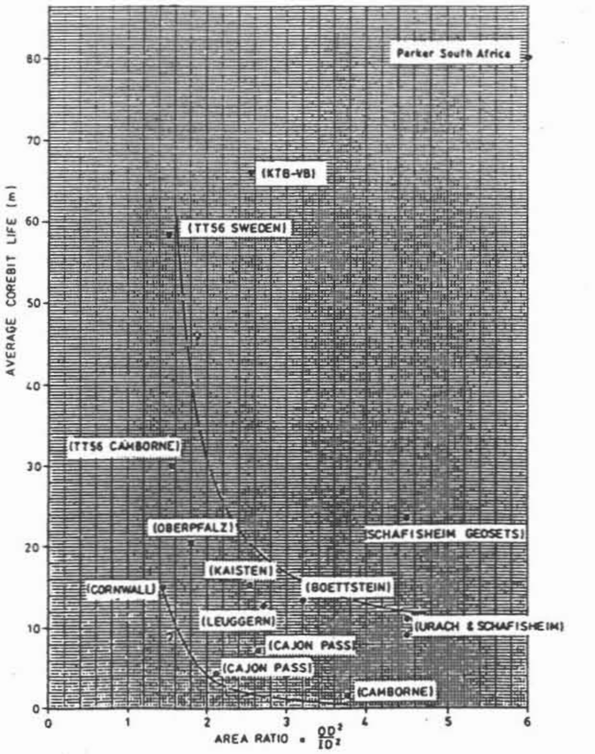


Fig. 4: Average footage of diamond core bits in crystalline rock

- The rate of penetration may be increased through elevated rotary speed corresponding to 2 to 3 m/sec cutting speed at the diamonds, e.g. by employing high-speed top drives or downhole motors. However, this requires effective cooling of the cutting elements at the bottom of the hole.

- Diamond coring performance in deep holes is generally inferior to that in shallow holes. This is due to the fact that with increasing depth the more problem of cutting is overlaid by several additional difficulties.

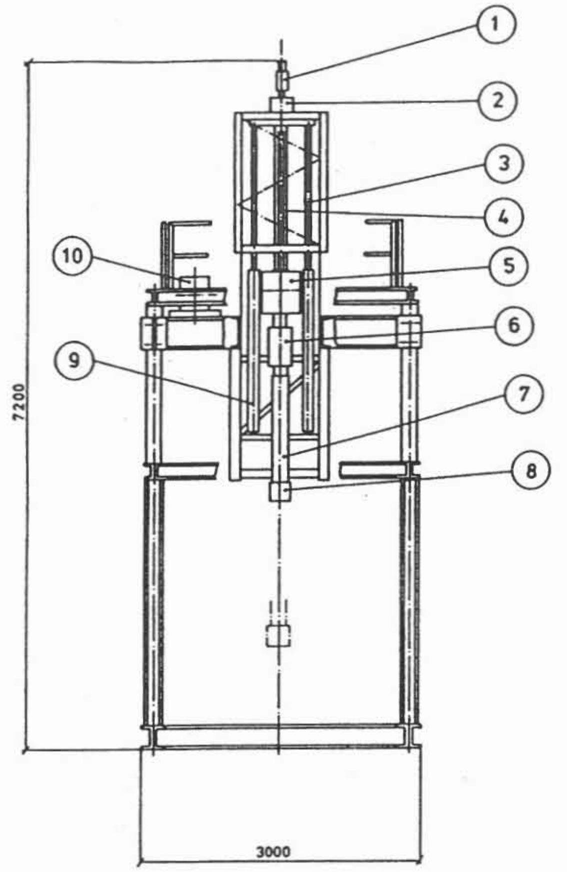
However, these indications may only be trusted to a limited extent. Even for identical geological environments, significant differences in performance may occur which are mostly due to drilling operation parameters being adjusted only more or less for optimum results.

Another major point of interest is to deal with the existing development potential for diamond core bits. Through adequate design modifications, especially diamond impregnated tools may be improved considerably with respect to performance. In order to evaluate different design and material options in the laboratory, this first stage of evaluation is preferably done on a drill test rig. Some recent test results on different core bit design alternatives are shown in Table 5 in terms of related WOB, ROP, and footage. Obviously, considerably different results were obtained, especially with respect to the footage s^*. A sketch of the Eastman Christensen Celle drill test rig is shown in Fig. 5.

This test rig offers a maximum WOB of 2000 kN and maximum RPM of 1300 1/min. Core bits up to the 6 3/4" size may be tested. The measuring data automatically are retrieved and stored. A computer control system allows to drill with constant ROP or with constant WOB.

Test No.	Design-Type	WOB/AD (N/mm^2)	ROP•AK/AD (m/h)	s^* (m/mm)
1	A	14.2	16.3	6.3
2	B	15.7	31.0	16.6
3	C	13.2	28.5	28.4
4	C	11.6	15.4	18.6
5	C	12.4	15.6	49.4
6	D	8.2	40.0	51.7
7	D	8.2	32.5	9.9
8	D	8.2	15.0	39.5
9	E	11.7	27.1	6.8
10	F	9.2	19.3	18.6

Table 5: Performance of diamond impregnated core bits size 96 x 63 mm (Formation: Amphibolit; Mud: water)



1	SWIVEL
2	FORCE TRANSDUCER
3	PULL ROD
4	SPLINED SHAFT
5	BEVEL GEAR
6	TORQUE INDICATOR
7	CORE BARREL
8	CORE BIT
9	HYDRAULIC CYLINDER
10	ELECTRIC MOTOR

Fig. 5: Drill test rig of Eastman Christensen GmbH, Celle

The test results have shown that the performance of the core bit may be improved considerably by optimizing the fluid flow around the cutting surfaces, especially with impregnated cutting elements. However, the transformation of a laboratory development to real borehole application needs careful planning, because this drilling environment differs from the laboratory operating conditions in some aspects.

Thick kerfs and large area ratios (R-factor) will influence distinctly negatively the diamond coring performance. With respect to an optimized coring effectiveness, thin kerfs and small area ratios would be the ideal solution, as sometimes realized in mining drilling.

For roller cone core bits, little experience with coring of crystalline rock is available. Leaving aside the KOLA SG-3 well, some information has been published from the Los Alamos Hot Dry Rock Project, the NAGRA radioactive waste storage exploration project, the Camborne School of Mines HDT project, and the Gravberg-1 well in central Sweden. In addition, two different types of roller cone core bits have recently been employed in the upper section of the KTB pilot hole.

Since 1974, experience has been gained with six different roller cone core bit designs. Basic design alternatives are the four-cone core bit, the hybrid four-cone core bit with additional diamond PCD cutting elements for improving the core quality, and the six-cone core bit which has three cones for cutting the hole and the other three for cutting the core.

- Due to the reduced dimensions in comparison with full size roller tools, certain general problems occur with bearing performance. According to information available, however, some progress has been made in this area during the last few years.

- The cutting and wear behavior of hard metal inserts has also undergone some improvement. Further performance increase is believed realistic by coating these cutting elements with superhard materials, e.g. diamond.

- Core recovery with roller core bits seems to be generally inferior to the quality and quantity achievable with diamond core bits.

- Core recovery obviously becomes more critical with increased depth. Therefore, adequate means have to be developed with high priority which support the entering of the cores into the roller cone bit/core barrel system under the stress environment of superdeep boreholes.

- Due to their basic functional principle, roller cone bits will exhibit a penetration rate performance which is comparable to that of well designed diamond coring systems of the same characteristic area ratio.

Today, the general conclusion may be drawn that roller cone core bits will operate in crystalline rock only to depths which do not yet exhibit stress relief phenomena. This is also true for the so-called "Hybrid Core Bits". Roller cone bits offer the general advantage of increased sturdiness. They are thus suitable for performing reaming operations when being tripped into the hole, and the debris at the bottom of the hole may well be crushed into small particles. These cutting and coring tools are capable of withstanding rough treatment without damage. Major improvement is required regarding an effective integration of the roller cone core bit into the core barrel design, in particular with respect to the core catching mechanism.

Existing Coring Systems

In the Western world, at least, systems for continuous coring in crystalline rock have been developed systematically only for the purpose of mining drilling exploration.

However, the diamond coring systems for mining applications, partly operated in connection with wireline core barrel retrieving mechanisms, are not suitable for use in the depths and diameters encountered in the superdeep KTB hole. There is, nevertheless, much sense in adopting some parts or components from the mining technique and modifying them for integration into the proposed new systems. The widely used principle of continuous coring systems is a characteristic feature of the mining technology. The wireline drill string recently developed for the specific purpose of coring the KTB pilot hole seems to prove that reasonable combinations of features from both the mining and the oilfield drilling techniques offer a new performance potential for crystalline rock drilling.

As regards the oilfield rotary drilling, a basic distinction may be made between rotating the complete string by the rotary table or top drive or driving the bore bit by use of a downhole motor. Performance losses through friction in the hole usually increase with depth. In addition, significant wear of the rotating drill string is likely to occur with crystalline rock. Therefore, the general recommendation can be made from the experience available that downhole direct drives should be preferred, at least for intermediate depths of about 6000 to 7000 m. Regarding possible motor types, only mud driven positive displacement motors (Moineau geometry) or turbines are of importance. Using Moineau motors is, however, limited with regard to depth, because standard elastomer fills of stator tubes will operate only up to about 150 °C. As a medium term development goal, a temperature limit of 200 °C seems to be realistic.

Drilling turbines will require relatively few modifications before being applicable for high temperature environments. However, manufacturing costs of turbines are generally quite high. Also, the existing turbines are not suitable for use with roller cone bits due to their high level RPM performance. Considerable development efforts are thus required to reduce the speed (Ref. 8).

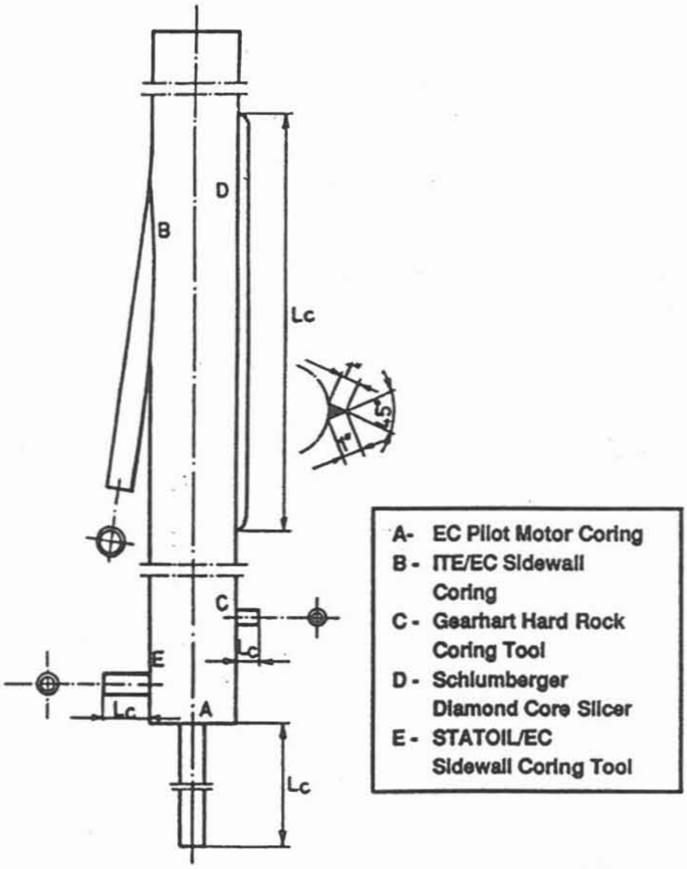
The means for taking the core sample itself certainly is the most critical part of the whole coring system. In the upper section of the hole down to about 6000 m, the existing systems will allow to take some cores. In order to improve coring effectivity and quality, however, this range also requires distinct development efforts. With respect to diamond core bits, the major goal is to increase the penetration rate. Roller cone systems strongly need an optimum tuning of the bit/barrel system. Initial steps for improvement have to include design and coating of inner barrel, optimization of core catching mechanism, and measures to stimulate the penetration of rock into the barrel. No continuously operating system exists for this range.

As regards depths below 6000 m, there seems to be no realistic chance at all to recover noteworthy amounts of rock samples with the existing technology. All components, such as actuation drive, core taking facility, and core bit, have to be reworked considerably to allow proper functioning in the hostile environment of extreme temperature, formation stresses, and depth. These parameters become even more critical for depths below the 10000 m mark. As a general conclusion, no system is available that would allow to take continuous cores in crystalline rock with diameters and depths as required in the KTB main well.

As to sidewall coring systems, after thorough investigations, only four basic principles seem to be worthwhile to be pursued further (Table 6). Of these, only the Gearhart and the Schlumberger tool have been used commercially in the field. Both are driven by electric motors which require an electricity supply from the surface through a multi conductor wireline cable. Torque is created hydraulically in the Gearhart tool. The ITE-EC-system as well as the Statoil-EC-system are both run into the hole on the drill pipe. As regards the ITE-EC-tool, a core barrel and a motor are afterwards run into the hole on a wireline while with the Statoil-EC-system a spear with core magazine is run on the wireline. Both tools are driven by the mud flow. The maximum operating depth is limited by the temperature resistance of different critical parts. The principles of operation resp. functions of the various tools is compressed in Fig. 6.

Type	Cutting Tool	Downhole Motor Type	Rotation power via	Control via	Core diameter/ length (mm)	Core magazine	Depth limit parameters
ITE-EC Moineau-System	Impregnated diamond core bit	Moineau motor	Mud/ string	Wireline	41	1	150 °C
Gearhart Hard Rock Coring Tool	Impregnated diamond core bit	Hydraulic motor	Electric conductor	Multi-Conductor	24/44	12	150 °C 1380 bar
Schlumberger Diamond Core Slicer	Diamond saw blades	Electric motor	Electric conductor	Multi-Conductor	25.4 x 914	4	150 °C 1380 bar 6700 m
Statoil-EC SWC	Impregnated diamond core bit	Hydraulic motor	Mud/ string	Multi-Conductor	37/89	15	70 °C (120 ° C) 3000 m (6000 m)

Table 6: Characteristic information on four different sidewall coring systems



ITE, 1988

Fig. 6: Dimensions of wireline retrieved cores

4 DEVELOPMENT POTENTIAL FOR KTB CORING SYSTEMS

Many alternative means may be used for the realization of systems for continuous coring downhole and into the sidewall for the KTB-HB. The scope of development goals will be outlined in this chapter. In view of the limited time and total expenditure for development in this matter, some key alternative systems will have to be selected for further development. Finally, a proposal will be made concluding the development of hardware which is deemed essential for the scientific goal of the KTB program.

4.1 Systems for continuous downward coring

As a key feature, continuous coring systems offer saving a considerable amount of trip time by allowing to retrieve the formation samples without tripping out the entire drill string. The life of a core bit should then attain a multiple of the length of one core. In addition, such a system is also highly justified if frequent retrieval of the core barrel is required due to core jamming. The optimum continuous coring system should allow to pull the worn bit in addition to the inner barrel on the wireline. In this case, the drill string could remain in the hole over the complete coring interval.

An overview of alternative continuous coring systems is given in Fig. 7. A basic distinction can be made between systems where the core bit is driven on the rig floor and those which employ downhole motors. As a very promising alternative design proposal, both types of actuation may be employed in combination systems. Hammer drilling has already proven to offer excellent performance in hard rock destruction in shallow holes. Such systems may be used in combination with rotary tables as well as downhole motors.

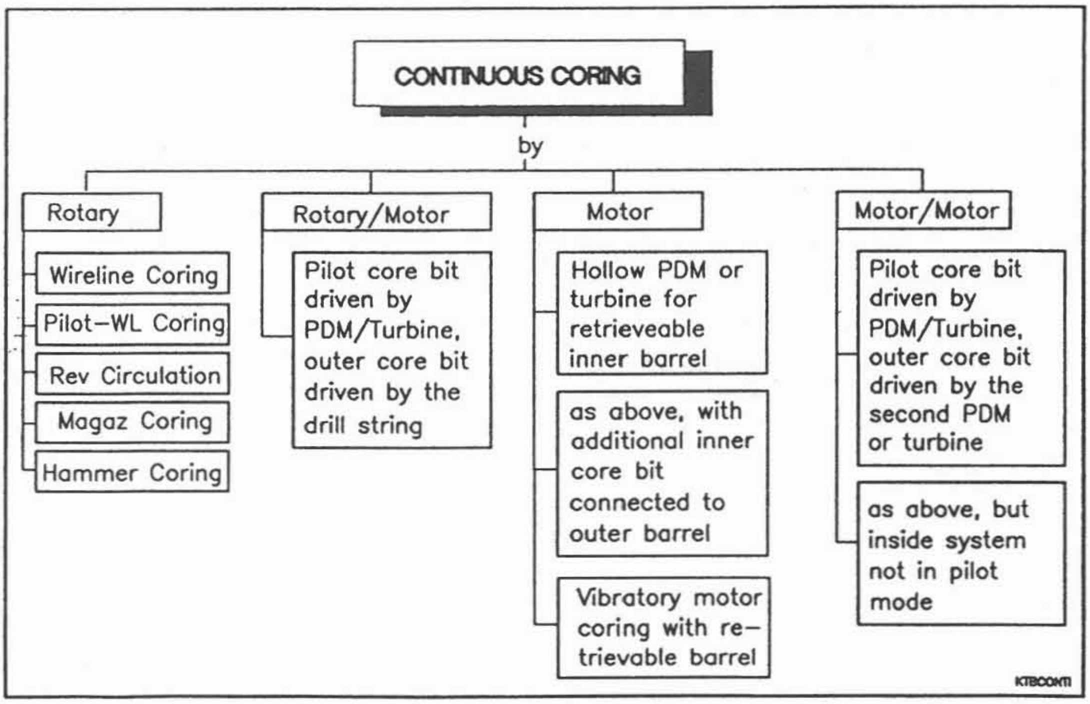


Fig. 7: System options for continuous downward coring

4.1.1 Rotary table driven systems

When using the rotary table or top drive, the wireline coring system as has been used in mining for quite a long time has to be mentioned first. As a basic function principle, the inner barrel together with the core sample is pulled to the surface using a wireline. In mining techniques usually special drill strings are used for this purpose which have only slight restrictions of inner diameter within the tool joint section. If a standard API rotary string were to be applied, the outer diameter of the core barrel has to be accommodated to the reduced tool joint passage. The system as described above is generally operated with one string of constant diameter.

As a modification to this standard design, a principle according to Fig. 8 may be realized. In this case, the hole is drilled with the standard rotary technique to the depth where the coring operation is to be started. After tripping out of the hole, a mining wireline drill string is connected to the API string which should have a length equal to the expected footage of the diamond core bit connected to it. This tapered drill string is now run into the hole. A pilot hole is then drilled with the lower part of the combination string. Continuous core recovery is realized by tripping in and out the inner barrel of the mining system. The inner core barrel has to feature dimensions which will allow to pass through the tool joints of the API string.

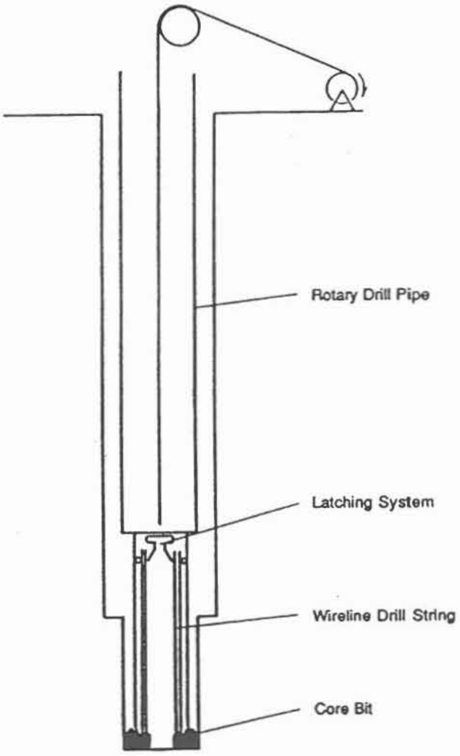


Fig. 8: Mining wireline string on bottom of rotary string

A roundtrip is required only if either the core bit is worn or the length of the mining string has been drilled. The hole diameter will afterwards be enlarged to the size of the upper borehole section by means of a full size bit being connected directly to the API string.

Modified mining diamond coring systems will generally perform better when operated with RPM higher than usually possible with rotary tables. Thus, a primary solution would be to drive the mining string according to Fig. 8 by a downhole motor. This will virtually mean that the "rotary table is shifted to the bottom of the hole", which has several advantages over the standard method. As a first step, the nonrotating part of the motor is connected to the rotary string while the motor drive shaft forms the crossing to the mining string. In order to allow the wireline retrieval of the inner barrel, a sufficiently wide passage diameter has to be provided inside the rotating shaft. In this case, the motor would preferably consist of a large diameter drilling turbine. As a second alternative a mining core barrel and connected downhole motor could be mounted sliding within a bottom drill collar of the rotary string. This latter principle has already been realized as a prototype tool within the course of the international scientific "Ocean Drilling Project". The combination of diamond core bit, core barrel, positive displacement motor, and latching means, is lowered into the drill string. After radial engagement to the drill collar, the mining barrel and core bit are moved by the PDM while the WOB is built up by hydraulic thrust.

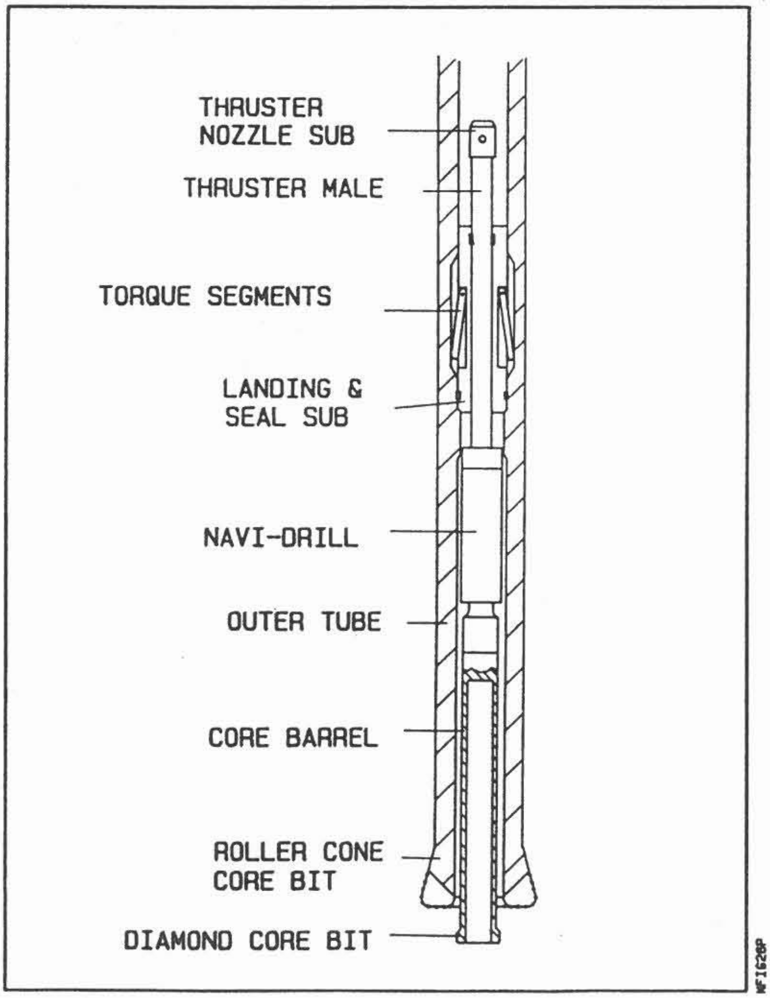


Fig. 9: Pilot motor coring system

For both systems employing the "rotary table on bottom" principle patents have been granted or are pending in favor of Eastman Christensen Company. This is also true for the additional feature which allows to install extension pipes in the inner parts of the embodiment as shown in Fig. 9 in order to increase the depth of the pilot hole.

Up to now, it has generally been assumed that the retrieval of the core sample, eg. inner barrel, is done by connecting an overshot and wireline to the inner barrel for pulling it out of the hole. As an alternative method, however, it needs to be considered whether pumping the core out of the string through a reversal of the mud circulating direction would be possible. The feasibility of such a process which is quite often used for special mining purposes depends on several parameters such as the pressure build up in the annulus between string and formation, the fluid losses to the formation, and the design of the drill string. Another option would be to provide the core barrel with a self-propelling mechanism for transportation to the surface. This principle will need thorough investigation.

Magazine coring offers the opportunity to store downhole a certain number of small core samples.

Due to the effectivity of this special rock destruction process, the feasibility of applying hammer drilling techniques for the coring operation in crystalline rock should be investigated further. Early development of mud driven hammers for oil well application be AMOCO in the '60s had been abandoned due to technical (mud solids content) and economic reasons. In the People's Republic of China, development was restricted to the application in the mining exploration drilling for extremely hard rock. For more than 10 years now, the mud operated downhole hammers have been widely used in the field with excellent results. Lifetime of a hammer tool is reported to reach more than 500 hrs, up to 950 hrs so far. three different hammer designs for coring drilling are documented:

- Double acting nonspring type hammer
- Positive and negative acting spring loaded hammer
- Fluid hammer with no moving parts in the valve.

In accordance with the Chinese mining standard, the hammers are available in the sizes 54, 76, 89, and 150 mm OD. The drilling fluid operated downhole hammers are used in combination with impregnated diamond bits. Because of their availability, the impregnated bits are manufactured with small size grit (50 - 70 US-mesh) and hard matrix for improved bit life. This application led to hammer systems with high frequencies, i.e. 20 - 40 Hz, and low impact energy, i.e. 20 J for hammer type SC-54 and 140 J for hammer type SC-150. The basic design of the fluidic valve hammer is shown in Fig. 10.

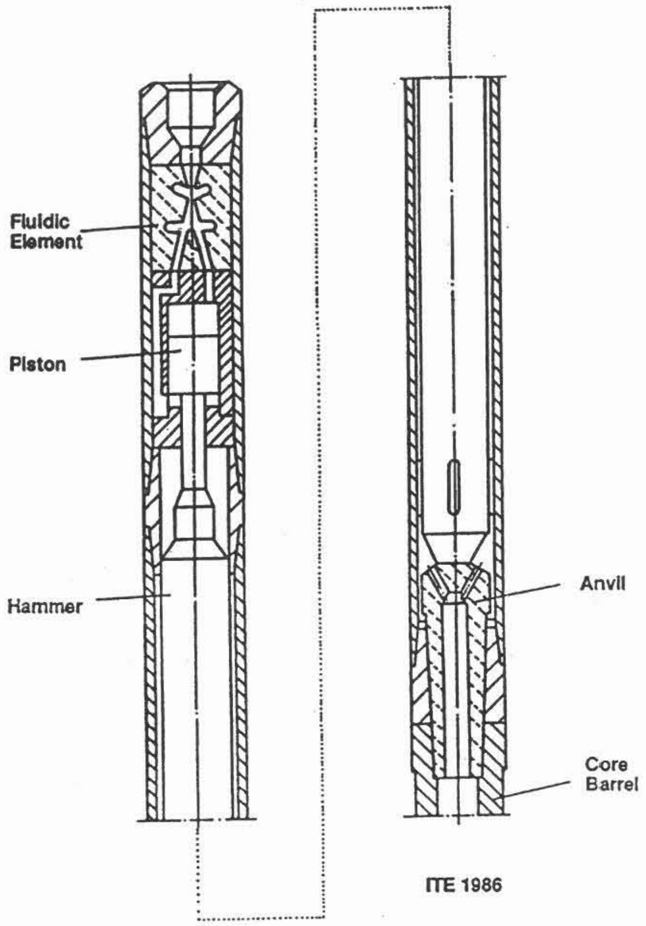


Fig. 10: Basic design of fluidic valve coring hammer

For the KTB drilling program, solid-free drilling fluid was developed. This improves the chance of employing hammer drilling in noncoring operations for the large hole size as well as for the coring operation.

One scenario to apply hammer coring in hard rock and large size boreholes can be envisaged in case the roller core bit leads to poor core recovery because of core breakage. A core bit designed with large sized diamond cutting TC-inserts may be operated successfully by using a hydraulic downhole hammer. In order to apply wireline technique to recover the inner barrel, this would necessitate building a downhole hammer with a hollow shaft. Another approach would be to use the hydraulic hammer in combination with the pilot motor coring system as shown in Fig. 9. In this case, the hammer would be positioned between the downhole motor and the core barrel.

At present, first tests are being performed to optimize the diamond bit for hammer coring in hard crystalline rock. Instead of diamond grit normally used as cutting elements in hard rock coring, new synthetic diamond material known as TSD, such as Geoset or Syndax-3, may serve the purpose.

4.1.2 Application of rotary table and downhole motor

Continuous coring by using a combination of rotary table and downhole motor actuation has already been mentioned in connection with Fig. 9. Within the ODP project, a roller cone core bit of 10 1/2" (267 mm) had been used with this tool. The inner system had been rotated by a Navi-Drill Mach 3 size 3 3/4".

Instead of using the PDM which has the disadvantage of limited temperature capability, a turbine might be employed for the same purpose. As a modification of the described system the outer part of the turbine might be fixed to the rotary drill string while an inner drill string is pushed forward through the hollow rotor of the turbine (Fig. 11). In this case, the downhole motor remains on the bottom of the large diameter hole to actuate the wireline retrievable inner drill string. The turbine also remains on bottom when the thin inner string is pulled out of the hole for core recovery or extension. After having cored a certain distance of about 100 m, the borehole diameter has to be increased to full size by rotating the outer string from the surface. During this phase, a special pilot will guide the outer core bit to follow the section cored.

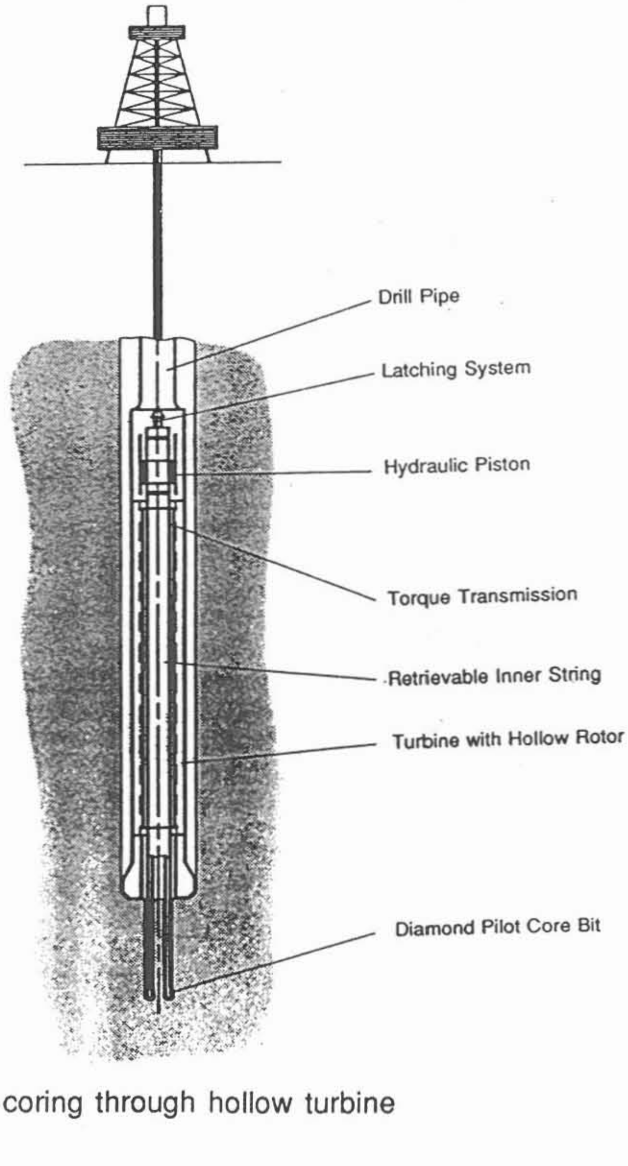


Fig. 11: Pilot coring through hollow turbine

4.1.3 Using a downhole motor

Due to increased borehole friction when rotating the core bit from the surface will cause major problems in extended depths. Then the exclusive employment of direct bit drives is highly recommended. In order to provide the possibility of retrieving the core without tripping the string, the core barrel has to be pulled through the inner part of the motor.

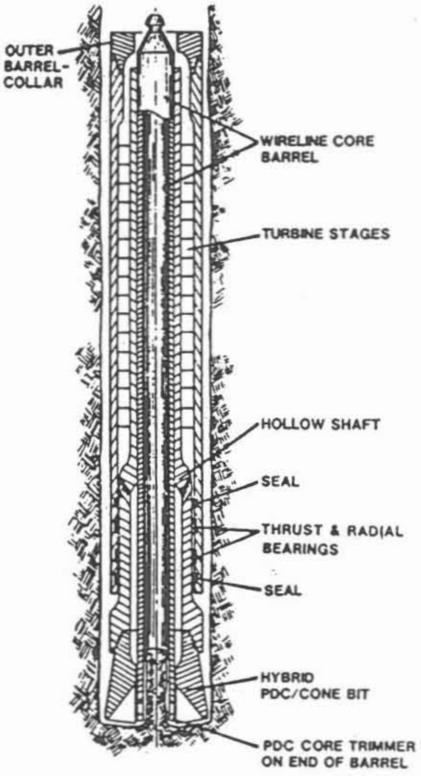


Fig. 12: Drilling turbine with hollow rotor and wireline retrievable inner barrel (Ref. 3)

Such a principle is shown in Fig. 12, where a turbine is used for driving the core bit. In order to support a free penetration of core into the inner barrel inside the rotor part, the inner barrel should be prevented from rotating. Modern double tube core barrels use ball bearings for this purpose. For systems with discontinuous core recovery, Eastman Christensen has already realized an improved embodiment. In that case, the nonrotating drill string is connected to the inner part of the motor which is also fixed to the core barrel. Thus a relative movement between core and barrel is not at all possible.

In order to facilitate core recovery without tripping the string, the inner barrel must be designed retrievable by wireline or reverse circulation. Fig. 13 shows an optimized system featuring at the same time the characteristics of

- direct bit drive
- inner barrel connected to string
- inner barrel retrievable through string for core recovery.

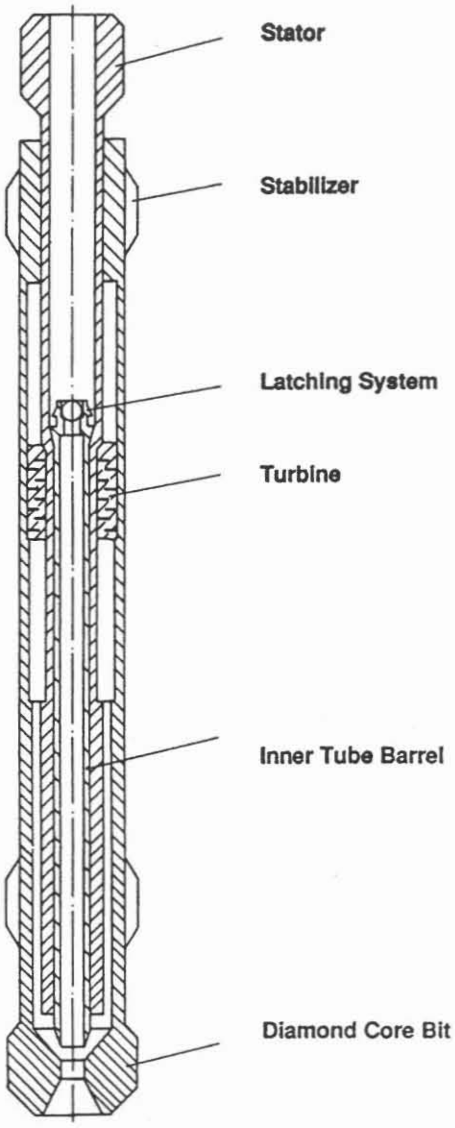


Fig. 13: Turbine corer with stationary inner part, rotating outer barrel, and retrievable inner barrel

Due to the required design dimensions, the core diameter has to be reduced as compared with the nonretrievable version. The kerf of the diamond core bit has to be increased correspondingly which, in turn, leads to a principally inferior performance.

According to the systematic overview in Fig. 7, another modification of the described embodiment might at least be considered in theory, where a second core bit is running inside the outer one. The inner core bit is driven via a planetary drive from the outer barrel at elevated speed, thus optimizing the cutting behavior with respect to both the borehole and the core. A clear disadvantage of such a system would be the required complex mechanical parts.

4.1.4 Using two downhole motors

Major advantages of a pilot coring system with downhole motor can be identified as improved core recovery and core quality. In order to enlarge this pilot hole to the original diameter, the drill string has to be rotated from the surface in a second phase of operation. This is likely to cause problems when reaching deeper or superdeep sections.

In order to overcome such trouble, the use of a downhole motor for this purpose too has to be considered. As long as the protruding inner system is under operation, the outer system would not move. Having pulled out the inner system, the outer one would be activated enlarging the hole diameter. As another modification, both systems could be put into action at the same time. Thus core recovery with the nonprotruding inner system core-drills the large diameter outer hole.

4.2 Sidewall coring systems

As mentioned already earlier when describing the state of the art, the three systems

- EC-ITE with Moineau motor and built-in whipstock
- Gearhart hard rock coring tool
- Schlumberger Diamond Core Slicer

seem to offer some potential for application in the hostile environment of the KTB crystalline rock borehole. The sidewall coring tool which was developed as far as the first prototype stage in cooperation between Eastman Christensen and Statoil of Norway offers some promising advantages over the other systems. However, it seems to be questionable whether the high development expenditure required would be justified under economic aspects with respect to the limited application with the KTB project.

The Gearhart and Schlumberger systems both are electrically driven and connected with the surface by electric cables. Therefore, the resistance in the cable will increase considerably with depth, thus requiring very high voltages to be provided. The cores retrieved with the Gearhart tool are of 24 mm diameter and 44 mm length which corresponds with a rather small rock volume of 20 cm^3. Evaluation of cores gained with the Schlumberger diamond sawing tool is rather inconvenient due to the unusual noncylindrical shape.

Therefore, one recommendation is to try the commercially available Gearhart tool on the one hand. In addition, however, a system should be further developed which fits as far as possible into the complete range of tools that is to be used for the KTB. This means in particular that the actuation of the operation should be done by the drilling mud very close to the place of coring.

From this point of view, the tool shown in Fig. 14 has to be looked at as only one of several possible embodiments featuring a

- whipstock as integral part of the drill string
- retrievable combination of diamond core bit, core barrel, and motor
- packer for settling the string in the hole.

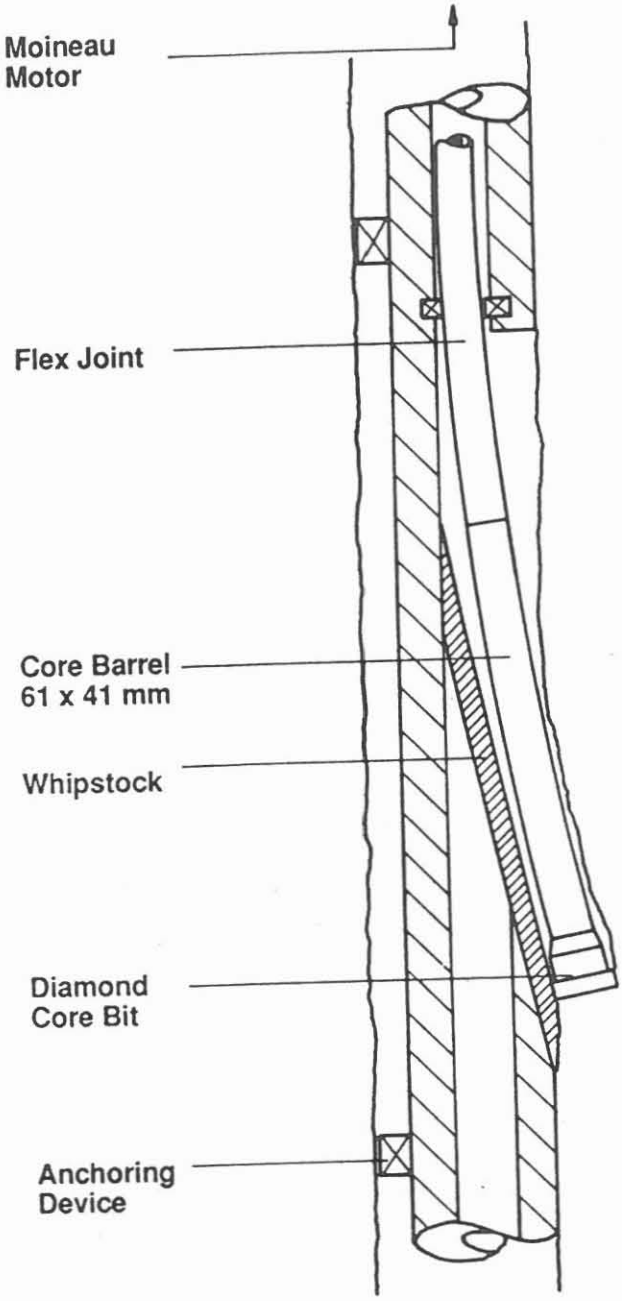


Fig. 14: Laboratory tested sidewall coring prototype tool developed by EC-ITE

The system according to Fig. 14 has been developed jointly by ITE and EC within the course of the German government subsidized development project 03E-3001-A. Weak points of the present development stage include the strength of whipstock, flexible shaft, and the operating temperature of the packer elastomer. The temperature limitation of the motor elastomer becomes critical at more extended depths, because the stator is operated under the influence of the fresh drilling mud. As an alternative, the motor itself may be integrated into the drill string. The motor would then preferably be built as a turbine.

5 REALISTIC CORING SYSTEMS DEVELOPMENT CONCEPT

By analyzing the state of the art in coring systems, the anticipated drilling environment for the KTB superdeep borehole, as well as the requirements regarding core recovery, a variety of approaches may be taken for the development of optimized systems.

A classification of different goals may be proposed with respect to corresponding sections of depth. Some of the technical problems to be expected in the upper section down to 6000 m depth are listed in Table 6.

- Mud Losses in vuggy or permeable formations
- Core jamming
- Abrupt directional changes of borehole trajectory
- Borehole temperatures up to 150°C
- Getting stuck through debris from brittle zones
- Severe rock bit wear and low footage
- Difficulties to break the core in dense and compact formations
- Core losses on bottom of the hole

Table 6: Anticipated coring problems for depths between 3000 and 6000 m

The following additional difficulties have to be taken into consideration for the 6000 to 10000 m range.

- Increased borehole temperature of up to 235°C
- Core disking due to stress relief effects
- Sedimentation of cuttings on the borehole bottom due to low mud weight
- Considerable friction between borehole wall and rotating string, especially at places of increased dogleg severity
- Damage to the borehole wall by tripping operations
- Exceeding the depth capabilities of conventional steel wirelines
- Control of coring operation badly disturbed due to extended distance from surface to bottom

Table 7: Additional coring problems for depths between 6000 and 10000 m

As regards the ultimate section of the proposed superdeep borehole down to 14000 m, additional difficulties will occur. A reduction of borehole size from 10 5/8" to 8 1/2" is likely to be required for this section of hole. Thus the number of system options will be reduced considerably. These critical parameters have to be faced in addition.

- Increased borehole temperature of up to 330 °C
- Core jamming, ROP, WOB, and borehole course have to be checked by some kind of telemetry system
- Operation with rotary table no longer possible
- Problems regarding cuttings removal in upper sections with standard flow rates and small annulus at the core barrel
- Due to extremely high stress differences, cores will be destroyed before entering the bore barrel

Table 8: Additional coring problems for depths between 10000 and 14000 m

Coring systems to be employed in these sections have to work with these problems occurring. Drilling experience from other critical environments have shown that more than one alternative coring system should be made available in case that one concept fails due to problems not foreseen.

It is then recommended that both completely new systems as well as others which are based on proven components should be included in this plan. In view of limited time and financial resources, a clear selection of key development areas has to be made.

5.1 Systems for continuous downward coring

Downward coring systems are proposed for the major part of the development work for several reasons.

- The borehole is deepened at the same time while coring
- Options to recover extended cores of 6 to 9 m length or more at a single run
- Relatively large core diameter
- Possibility of adopting comprehensive experience from spot coring of sedimentary rock in oilfield drilling and from continuous coring operations in mining drilling
- Options to gain oriented cores.

Continuous coring systems should be preferred over discontinuous systems for several reasons.

- Improved overall economy through core recovery without roundtrip of string
- Saving of additional roundtrips in case of jammed core

- Integration of wireline or cable measuring system
- Adaptation of special retrievable inner core barrels to optimize core quality

In view of the hostile environment encountered in deep crystalline boreholes, major emphasis must be placed on designing sturdy and reliable coring systems.

5.1.1 Basic assumptions for development

On the basis of the above mentioned know-how, some basic assumptions will be defined which will later on lead to the proposal of a development project.

- Roller cone bits with TC inserts provide a fair penetration rate.
- The footage of roller cone core bits has been improved considerably in the past. Potential for further improvement remains.
- Diamond core bits are a promising tool with respect to core recovery and core quality.
- Roller bits have to be run at low RPM ($n < 120\ \mathrm{min}^{-1}$) while diamond tools should be operated at elevated cutting speeds ($v = 2 - 4$ m/s).
- A wireline is employed for transportation of core or core barrel to the surface.
- The importance of downhole motors increases with depth due to several reasons.
- Positive displacement motors based on the Moineau principle have limited depth capabilities due to temperature limitations of the elastomer stator. The critical depth may be raised to higher values if the motor is used only inside the drill string under the influence of fresh mud.
- The drill string run in the 10 5/8" borehole offers a minimum passage diameter of 4" (1016 mm).

In addition, a close contact of all parties involved in the development or planning of other equipment such as drill rig, drill string, mud pumps, etc. is essential for the optimum design of continuous coring systems.

5.1.2 Proposed development subjects

The proposed development project does not include improvement of discontinuous systems which might turn out to be desirable within the course of drilling the hole. Also, the aspired increase of ROP and footage with diamond and roller cone bits will not be considered here.

One basic condition for designing continuous coring systems effectively is an inner diameter as large as possible. The development concept will first have to concentrate on the 10 5/8" diameter section according to the well planning in Fig. 1. This diameter is planned for the depth between 5000 and 10000 m. The hole would be deepened further with this diameter if technically feasible. A minimum inner diameter of 4" (101.6 mm) serves as an important design parameter for many of the proposed systems.

A wireline is planned to be used to retrieve the core to the surface. Systems operating on the reverse circulation principle may be built as an additional design option. Conventional steel wirelines do not offer the strength required for extreme depths. A new concept therefore has to be developed. Possible options include the employment of alternative materials, e.g. high strength plastics, or nonconventional geometries, e.g. tapered steel wirelines with reduced diameter and weight in the lower sections. As regards synthetic materials, such as KEVLAR (Du Pont), certain temperature limitations have to be considered. When designing a new wireline, an electrical conductor line might be included for data transmission purposes.

Coring tools for the 10 5/8" borehole diameter

Due to the effective rock destruction mechanism in crystalline rock, the roller cone core bit has to be included in every development plan. Some experience, although from shallower depths, was gained in the upper section of the KTB pilot hole. Results from the Gravberg-1 well in Sweden confirm that the core recovery has to be considered as very critical, especially with greater depths.

It is therefore recommended to follow up on a development by steps which is based on the employment of a roller cone core bit according to Table 9. This comprehensive system reflects the accepted superior quality of the diamond coring process.

- Core barrel with roller cone core bit 10 5/8" x 3 1/4", inner barrel with outer diameter below 100 mm is wireline retrievable througho, the string
- Core barrel with 10 5/8" roller core bit is wireline retrievable. Pilot coring system consists of diamond core bit size 100 mm x 61 mm, mining core barrel HWD4, and modified 3 3/4" Moineau motor
- System as described above, however, inner core barrel protrudes at a certain angle for directional correction operations
- Core barrel with roller bit 10 5/8" x 3 1/4" is driven by 8 1/2" Moineau motor, inner barrel, and non-rotating inner motor part are wireline retrievable

Table 9: Continuous coring system for roller core bit and 10 5/8"

The basic design will feature a double tube core barrel for roller bits with wireline retrievable inner barrel as known from the mining wireline diamond coring technique. A diamond core bit may be used instead of the roller tool. If the core quality proves to be lower than expected, a hybrid system combining both the advantages of diamond and roller coring should be employed. A modified version of this type of tool would also probably be applicable for directional drilling while coring at the same time.

Having reached certain depths, it might be worthwhile to rotate the string only at reduced speed for the purpose of minimizing friction and wear. It is now proposed to use a downhole motor with low RPM characteristics which drives an outer barrel with retrievable inner core barrel (Fig. 15) connected with the motor shaft.

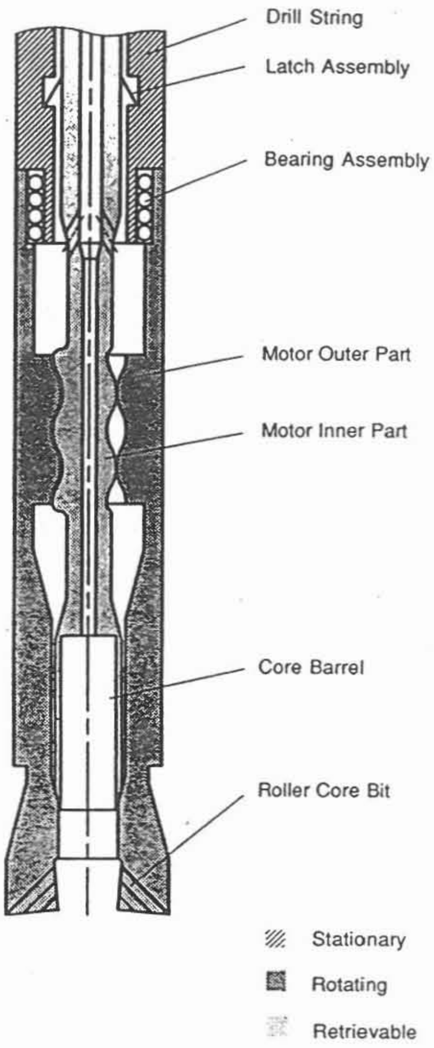


Fig. 15: Motor coring system with retrievable inner barrel and motor shaft

The combination of motor shaft and inner barrel is pulled out of the hole on the wireline for core recovery. Inner barrel and motor shaft are nonrotating.

Diamond coring would be an alternative to operation with roller tools. The core barrel might be rotated by a turbine at elevated speed which will lead to the well known advantages of diamond coring. A summary of the most important key data of such a device is given in Table 10.

Coring principle	Rotating turbine outer tube with diamond core bit and wireline retrievable inner barrel inside a non-rotating turbine shaft
Hole diameter of turbine shaft	101.6 mm (4")
Core bit	Diamond core bit 10 5/8" x 3 3/8" (270 x 86 mm)
Kerf of core bit	92 mm thickness, 515 cm^2 kerf area
Turbine	8 1/2" turbine having RPM of 887 1/min and T = 2964 Nm at a flow rate of 2400 l/min

Table 10: Continuous diamond coring system with turbine for 10 5/8" borehole

The basic design would also allow to run a pilot coring system inside the hollow turbine shaft. This measure might prove to be justified if the core recovery with the full size coring tool becomes critical due to formation problems. If the coring turbine should have to be used with roller core bits, a considerable reduction of RPM would be required.

Coring systems for 8 1/2" borehole sizes

The proposed concept for continuously coring the 8 1/2" section is strongly affected by the reduced dimensions, thus leading to solutions different to those for the 10 5/8" range. Realizing a wireline retrievable pilot coring system, for example, would mean a too high expenditure. The availability of reliable roller core bits of the size is rather doubtful. Also, driving the core bit from the surface has to be looked upon as a critical method. On the other hand, the small diameter is favorable for running diamond tools under technical as well as economic aspects.

Taking into consideration the working conditions as known today, the development of a turbine coring system is proposed. Due to economic reasons as many components as possible from already existing equipment should be utilized for this purpose. A retrievable inner barrel shall be run inside the hollow rotor of a 7 1/4" turbine. The most important system parameters of such a tool are given in Table 11.

Coring principle	Rotating turbine outer tube with diamond core bit and wireline retrievable inner barrel inside a non-rotating turbine shaft
Hole diameter of turbine shaft	101.6 mm (4")
Core bit	Diamond core bit 8 1/2" x 1.875" (215.9 x 47.62 mm)
Kerf of core bit	77 mm thickness, 307 cm^2 kerf area
Turbine	7 1/4" turbine having RPM of 790 1/min and nominal T = 3000 Nm

Table 11: Continuous diamond coring system with turbine for 8 1/2" borehole size

The inner barrel having a maximum outer diameter of 71.4 mm has to pass through the tapered string in th 8 1/2" section of the hole. Therefore, a minimum inner diameter of 3" (76 mm) should be provided here. Diamond core bits have to be optimized with respect to ROP and, more importantly, footage. The combination of these features

- high RPM
- diamond core bit
- integral connection of motor and core barrel

provides the optimum conditions for core recovery at extreme depths.

5.2 Sidewall coring systems

Presently available commercial systems have already been discussed earlier. This overview has shown that virtually only one of these, the Gearhart tool, offers the possibility of sidewall coring with crystalline rock without additional development expenditures. However, clear limitations exist with respect to the dimensions of the core as well as the depth capability. Further improvement of this system does not seem recommendable, because of fundamental disadvantages of the drive system.

With respect to the foreseeable development potential, the mud driven downhole motor with connected core barrel should be given preference. The combination of diamond core bit, core barrel, and motor is forced to penetrate the formation via an inclined plane (whipstock). Apart from the PDM, also a turbine shall be used for actuation which would offer an extended depth capacity. Several embodiments of this basic principle should be taken into consideration. If a decision has been made in favor of following up this kind of sidewall coring system, it has to be decided whether the already existing laboratory prototype by EC-ITE shall be improved or development of a modified concept is preferred.

6 KTB CORING PROJECT PLANNING

One major goal of the evaluation of development options performed above has been to preliminarily determine major guidelines to be followed in the process of developing adequate coring systems in hardware. A final decision on this subject has to be made by the KTB project group after consulting technical and drilling specialists from the industry and scientific organizations.

The overall goal is to provide coring systems which are capable of retrieving cores from the KTB superdeep well over about 1/3 of the section which has not been cored before in the pilot well. One major requirement has been that downward as well as sidewall coring systems should operate on a continuous basis. No tripping of the string is required for retrieving the core samples to the surface.

The hardware development planning for such systems is in the center of interest of this report. However, there are other challenges in connection with the coring and drilling operations that will also have to be considered before and during the development of the continuous systems. These are, amongst others, the need for drilling or coring a trajectory as vertical as possible, the employment of hammer drilling systems including combinations with coring systems, and the development of new downhole measuring and control technologies.

The plan for the development of continuous coring tools reflects the minimum required. The different components have ben planned in such a way that a high degree of compatibility is achieved. Additional items would require also an extension of the proposed budget. If borehole sizes drop below the 8 1/2" diameter, no continuous systems should be developed.

Basic systems as shown in Fig. 16 are now proposed for development.

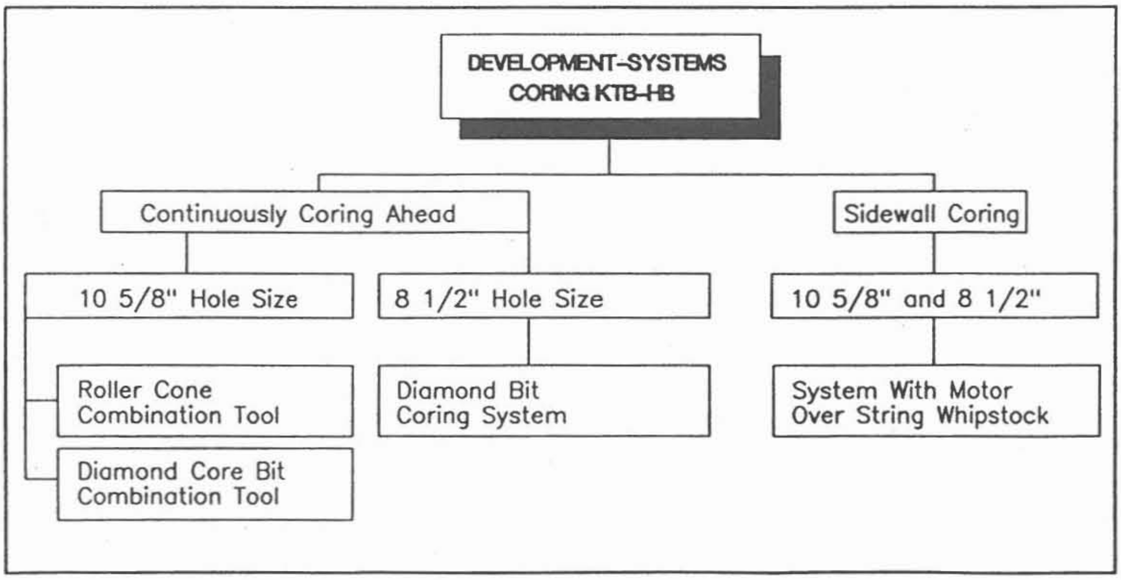


Fig. 16: Continuous coring systems for KTB superdeep well

The separate components considered important for this development are shown in Table 12. Items marked with priority "a" shall form the central development program for downward and sidewall coring systems while options for possible additions are marked by characters "b" or "c".

Item	Component	Priority
1	High strength wireline with 14000 m ultimate depth capacity	a
2	CB with retrievable inner barrel for RC 10 5/8" x 3 1/4"	a
3	same as item 2, but RC 10 5/8" x 4" and pilot coring motor 3 3/4" PDM with DC 100 x 61 mm	a
4	as item 3, but 3 3/4" turbine instead of PDM	c
5	as item 3, but inner system protruding over inclined plane for correction work	b
6	as item 2, but PDM for driving the CB	a
7	8 1/2" TURB with 10 578" x 3 3/8" DC and retrievable inner barrel	b
8	as item 7, but pilot coring system 3 3/8" instead of retrievable inner barrel	b
9	as item 7, but TURB and reduction gear and RC	c
10	7 1/4" TURB with hollow rotor and retrievable inner barrel, DC 8 1/2" x 1.875"	a
11	Sidewall coring tool, protruding on inclined plane, with PDM	a
12	as item 11, but stationary TURB instead of PDM	b

CB	Core Barrel
RC	Roller cone core bit
PDM	Positive displacement motor
DC	Diamond core bit
TURB	Drilling Turbine

Table 12: Development components

A preliminary time schedule for conducting the minimum expenditure development work characterized is shown in Fig. 17.

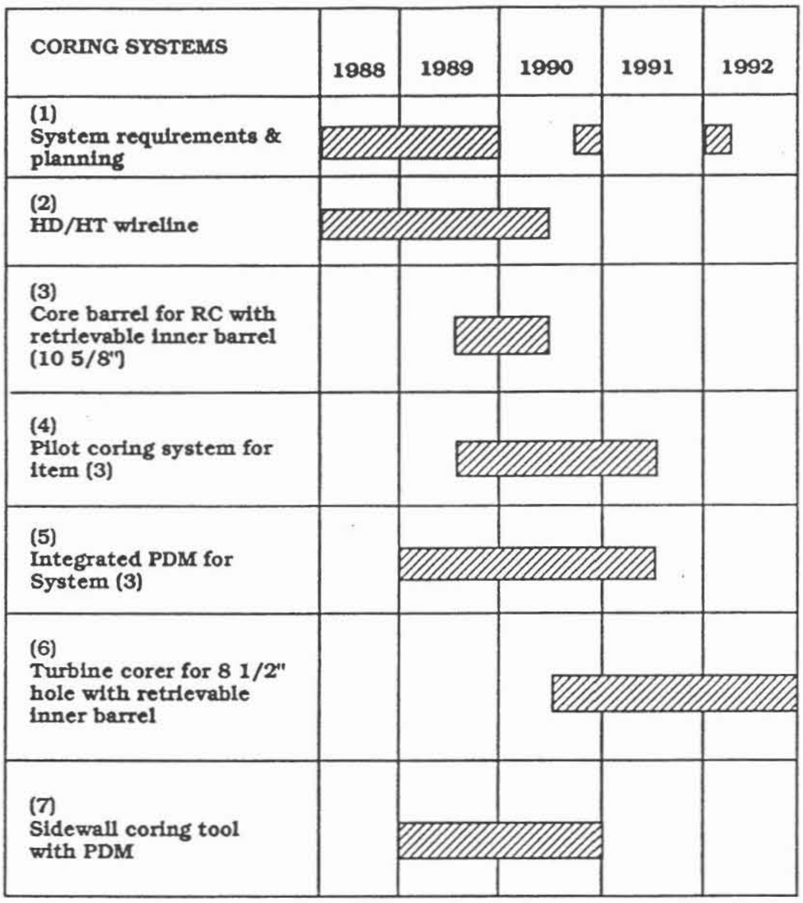


Fig. 17: Schedule for coring systems development

Item (1) mainly calls for the detailed determination of system requirements and consideration of related challenges such as vertical hole drilling and coring. The availability of an adequate wireline is essential for any great depth continuous coring system. In order to be able to start continuous coring after having drilled the upper section of the hole, a core barrel for roller cone core bits with retrievable inner barrel will be developed. Major effort has to be put into the improvement of the penetration process of core into the inner tube. Already during this stage the planned development of retrievable pilot motor coring systems has to be considered. Some preliminary experience with such systems already exists at Eastman Christensen Company. Patent protection is provided for certain embodiments of this principle (Ref. 9).

The systems mentioned up until now are all actuated from the surface. However, the application of downhole motors is often preferred for medium and large depths. Development item (5) therefore features a 8 1/2" Moineau motor with retrievable inner barrel and rotor.

For the 8 1/2" section, a turbine corer with a wireline retrievable inner barrel should be developed due to the high temperature environment.

A major area of application for sidewall coring tools is anticipated to occur in the upper section of the hole where no downward coring runs are planned. A definite decision should be made after further discussion whether to develop a system based on the PDM or the turbine. The latter would also offer the possibility for use in deeper sections of the hole at elevated temperatures. If the turbine stages are mounted within the downhole drill collar, only the inner barrel would have to be retrieved after each operation cycle on wireline. In view of a broad application this tool should be designed for use both in the 10 5/8" (or larger) and the 8 1/2" sections.

7 CONCLUSION

Coring of extensive borehole sections is a major challenge for the drilling of the KTB superdeep hole which is going to be spudded late 1990. However, the coring requirements have to be considered also in view of the absolute necessity for drilling the hole as vertical as possible.

Presently no coring systems exist for the required borehole diameter which provide the opportunity to retrieve the core sample without tripping the whole string. Experience is available only from mining drilling where smaller diameters are applied in shallow holes and, more recently, from the KTB pilot hole. The anticipated total depth of the scientific KTB project and the behavior of the rock formations present additional challenges.

For the recovery of small cores from the wall of the open hole, only one tool is presently commercially available. Relatively small core dimensions, system reliability which is not altogether satisfying, and limited depth capability have to be mentioned as disadvantages with respect to this tool.

After evaluation of the anticipated borehole conditions as well a summarizing the existing experience with coring hard or crystalline rock, possible development directions have been presented.

Major subjects of a realistic development concept for the 10 5/8" hole diameter include roller cone coring systems with or without downhole motor and hybrid systems with a small diameter pilot core barrel and a diamond core bit located in the bottom drill collar.

Regarding the proposed 8 1/2" diameter lower hole section, development emphasis should be concentrated mainly on a turbine coring system (turbo-corer) with diamond core bit and hollow rotor for storing the rock sample.

For taking samples from the borehole wall, the development work should follow the principle of incorporating a motor driven tool which penetrates the formation by drilling along a drill string integrated whipstock. Such a system offers some advantages with respect to simplicity of parts and components over tools which cut into the wall at an angle of 90 degrees.

All systems generally are based upon the application of a steel or plastic wireline to recover the rock sample to the surface. This basic component also needs development. All proposed systems utilize the drilling mud for torque generation, if the string is not rotated from the surface.

This program is strictly limited to the development of continuous systems for coring ahead or into the borehole wall. The presented schedule does not include downhole measuring systems for fluid downhole hammers which are looked upon a supporting the crystalline rock destruction process effectively.

When establishing this development program, existing core barrel and downhole motor equipment have been taken into account in order to enhance compatibility and to reduce additional expenditure.

8 LITERATURE

NOEVIG; T. (1977): Status report on coring procedures in deep-drilling technology. Project report, Energy research and development program - Technische Universität Clausthal

MARX, C. AND YOUNG, F. (1983): Darstellung von Kerngewinnungsverfahren und Bewertung ihrer Einsatzmöglichkeiten in übertiefen Bohrungen, Clausthal

ROWLEY, J.C. (1985): Coring technologies for scientific drilling projects - an overview, Los Alamos National Laboratory, Report No. LA 10485-OBES

OPPELT, J. (1987): Studie Vorbohrung KTB-Bergbautechnik, Eastman Christensen GmbH, at the request of KTB-Projektleitung

WOHLGEMUTH, L. (1987): Personal communication, KTB-Projektleitung

KOZLOVSKY, Y.A. (1987): The superdeep well of the Kola peninsula, Springer Verlag (Original Edition Moscow, 1984)

MAURY, Y.M. and SANZAY, J.-M. (1987): Borehole Instability: Case Histories Rock Mechanics Approach and Results - SPE/IADC Paper No. 16051 - Drilling Conference, New Orleans, Louisiana

KRÜGER, V. AND DAENICKE, H. (1988): Studie Untertageantriebe, Eastman Christensen GmbH, NLfB, Project AZK/15-RG 86040

OSTERTAG, A. and BIEHL, J. (1987): DE 3,701,914 "Direktangetriebenes Kernbohrwerkzeug" - Eastman Christensen patent

MATERIAL SELECTION AND CONCEPT FOR THE DRILL STRING OF THE GERMAN CONTINENTAL DEEP DRILLING PROJECT (KTB)

E. Quadflieg
A. Sperber

Paper presented at the International Seminar on
"Superdeep Drilling and Deep Geophysical Sounding"
Yaroslawl (USSR)
August, 1988

1 INTRODUCTION

The investigation which is the subject of this report is the part of a study on the suitability of high-strength steel and light metal materials for drill pipe. This study describes the current state of research regarding the behaviour of materials to be considered for the drill string in a 14,000 m deep well.

The requirements on the materials are determined by the borehole parameters, particularly the high well temperature, and the extreme string length. A further aspect concerns the question, whether corrosion resistant materials are available to enable the drill cuttings to be extracted without contamination from corrosion products.

2 INVESTIGATION METHOD

From the large number of steels and light metals available, those high-strength materials were selected and combined in classes, whose properties appeared suitable regarding the requirements placed on the drill string (Fig. 1).

These requirements were classified in categories which cover the mechanical and technological properties including corrosion and wear behaviour as well as the features governing the suitability of materials for drill pipe manufacture. As a further assessment criterion, the behaviour in the case of multiple make-up was considered (Fig. 2).

For each class of materials, an individual qualitative comparison was made between material properties and the requirement categories. The results obtained were then summarized in a general assessment.

3 RESULTS

In the following, those material properties will be discussed which are of special importance and finally caused the elimination of the respective class of materials.

The assessment of the tensile properties was based on the worst-case condition resulting from the simultaneous loading by:

- the string weight including drill collars (in water),
- the margin of overpull, and
- the axial loads due to internal pressure according to closed vessel conditions.

Taking into account the expected high borehole temperature of up to 300 °C, the materials must possess adequate tensile properties not only at ambient temperature, but also at elevated temperatures. The high temperature yield strength of metallic materials decreases at higher temperatures (Fig. 3).

High-strength aluminium alloys exhibit a marked drop in the tensile yield strength (R_p 0.2) already in the temperature range between 100 and 200 °C. Therefore, the combined load from the relatively low string weight including the required margin of overpull and the mud pressure will overstrain the material at temperatures above 100 °C. Accordingly, aluminium alloys cannot be considered as suitable materials for the described application.

Similarly, the tensile strength of the high - alloy 20 % Cr. steels (class IV) is also not high enough to withstand the axial load. This class of materials was excluded from further considerations, especially since other corrosion resistant materials with adequate tensile properties are available.

All other classes of materials exhibit sufficiently high tensile properties. This result is represented in the so-called rupture length, which is understood to be the string length, at which the load due to the string weight equals the yield strength of the materials (Fig. 4).

In the course of drilling operations as the total sum of the individual drilling periods, the pipes are subjected to high temperatures plus high tensile loads for extended periods, with the tensile/temperature load combination varying for different string depths.

At temperatures below 350 °C, creep processes may take place in metallic materials and lead to strains of 0.2 % and higher within a relatively short period of time. For ferretic steels, the effect of these processes is negligible, so that the high temperature strength can be used in the design of components.

Titanium and titanium alloys are particularly susceptible to creep. At about 300 °C, the tensile properties of titanium alloys are governed by its creep behaviour. At a temperature of 315 °C and at a load of only 60 % of the high temperature strength, ß-titanium alloy, for instance, will fail after 1,100 hrs. Titanium alloys are therefore not suitable for applications at temperatures above approximately 200 °C. Nevertheless, this type of material can still be used in the upper part of the drill string, where the temperatures are lower, in order to reduce the total string weight.

Borehole deviations generate rotating bending loads in the drill string during rotary drilling. This load becomes the more critical, the higher the initial axial tension resulting from the string weight.

Although it is well known that the bending fatigue strength of material increases with increasing tensile properties, this relationship is true only under laboratory conditions (Fig. 5). Due to the surface condition related to production and application of components such as drill pipe, their bending fatigue strength is lower and almost entirely independent of the tensile properties.

The additional effects of a corrosive environment cause the bending fatigue strength to drop to an even lower level. During tests, the effect of drilling mud was simulated using tap water or a 20 % sodium chloride solution.

According to estimates, deviations in the borehole of 1.5°/100 ft may lead to rotating bending stresses of about ± 100 N/mm^2. Under these conditions, none of the materials examined proved resistant to fatigue. Theoretically, under the combined load of the total string weight and corrosive conditions, the drill pipes in the upper section of the drill string may reach their fatigue limit and have to be replaced after a few days of drilling operations.

This means that the deviations in the upper section of the borehole must be kept extremely small, i.e. less than 1°/100 ft. In addition, the drill pipes must be inspected regularly at short intervals.

The material assessment with regard to corrosion resistance concerned two aspects. Firstly, the type of corrosive environment to be expected under actual drilling conditions must be considered. Secondly, as already mentioned, it was to be considered whether the drill cuttings could be extracted in their original condition - i.e. free from corrosion products - for geoscientific investigation purposes.

In the wall, sweet water can be extracted, with minor contents of salt and CO_2, from the rock. For the drilling mud, Ca-chloride solution may be used. Under these conditions, low-alloy steels according to classes I and III will suffer weightloss corrosion. Provided suitable measures are taken - this concerns especially the removal of dissolved oxygen in the drilling mud - corrosion processes can be kept within acceptable limits.

When aluminium materials are used, exact limits must be observed with regard to the pH-value and the salt content in the drilling mud, in order to avoid detrimental corrosion damage. Under drilling conditions, it is unlikely that the required stringent control of these limit values can be maintained.

For the case that the drilling string must be kept free from corrosion, high-alloy steels and nickel base alloy (classes IV/V) can be used.

In addition to the technological properties, another important aspect when assessing the suitability of a material concerns its processing behaviour for the manufacture of high-quality drill pipe. Furthermore, in view of the expected large number of round trips, the unproblematic multiple make-up/break-out behaviour is a factor of vital importance.

According to our knowledge, drill pipe in high-alloy corrosion resistant steels has not yet been produced. However, these materials have been successfully run as production tubing in highly corrosive gas wells.

High-strength titanium alloys have also been used for the manufacture of pipe. However, with these materials - similar to high-alloy steels - there are still some aspects to be solved regarding the shaping of drill pipe and the welding behaviour of weld-on connectors.

On the rig multiple break-out and make-up behaviour of the connections, when the drilling bit needs to be changed, or measurements must be taken, is an important factor. Low-alloy steel drill pipe has been sufficiently tested. With corrosion resistant steels and titanium alloys, no such experience is available. However, it is known from other application areas that special protective measures have to be developed, to decrease the galling tendency of these materials during make-up.

4 DESIGN CONCEPT FOR THE DRILL STRING

Based on the qualitative assessment of the individual material characteristics, the general assessment is differentiated between "suitable", "suitable with minor/major restrictions", and "not suitable" (Fig. 6).

Aluminium materials are ruled out, because of their low high temperature yield strength above 100 °C, and due to the additional problems of controlling the corrosion by salt solutions used as drilling mud.

The martensite precipitation hardening steel (class II), which exhibits the highest tensile properties, is also ruled out, because of its insufficient toughness.

The high-strength low-alloy steel (class I) largely complies with the requirements, but corrosion products must generally be accepted.

The high-alloy corrosion resistant materials (classes III/IV) meet the requirements to a great extent.

Because of their susceptibility to creep, titanium alloys (VI) are only suitable for depths in which, according to the temperature profile of the well, temperature stays safely below 200 °C.

Based on these results, the following alternatives are available for the design of a 14,000 m drill string:

- high-strength low-alloy steel as pipe materials with steel tooljoints, or
- Hastelloy C 276 nickel base alloy as pipe and tooljoint material, or
- a combination string with titanium alloy in the upper string section and high-strength low-alloy steel or a corrosion resistant material in the lower string section.

Given 14,000 m string length, this combination results in a total weight reduction of about 9 %.

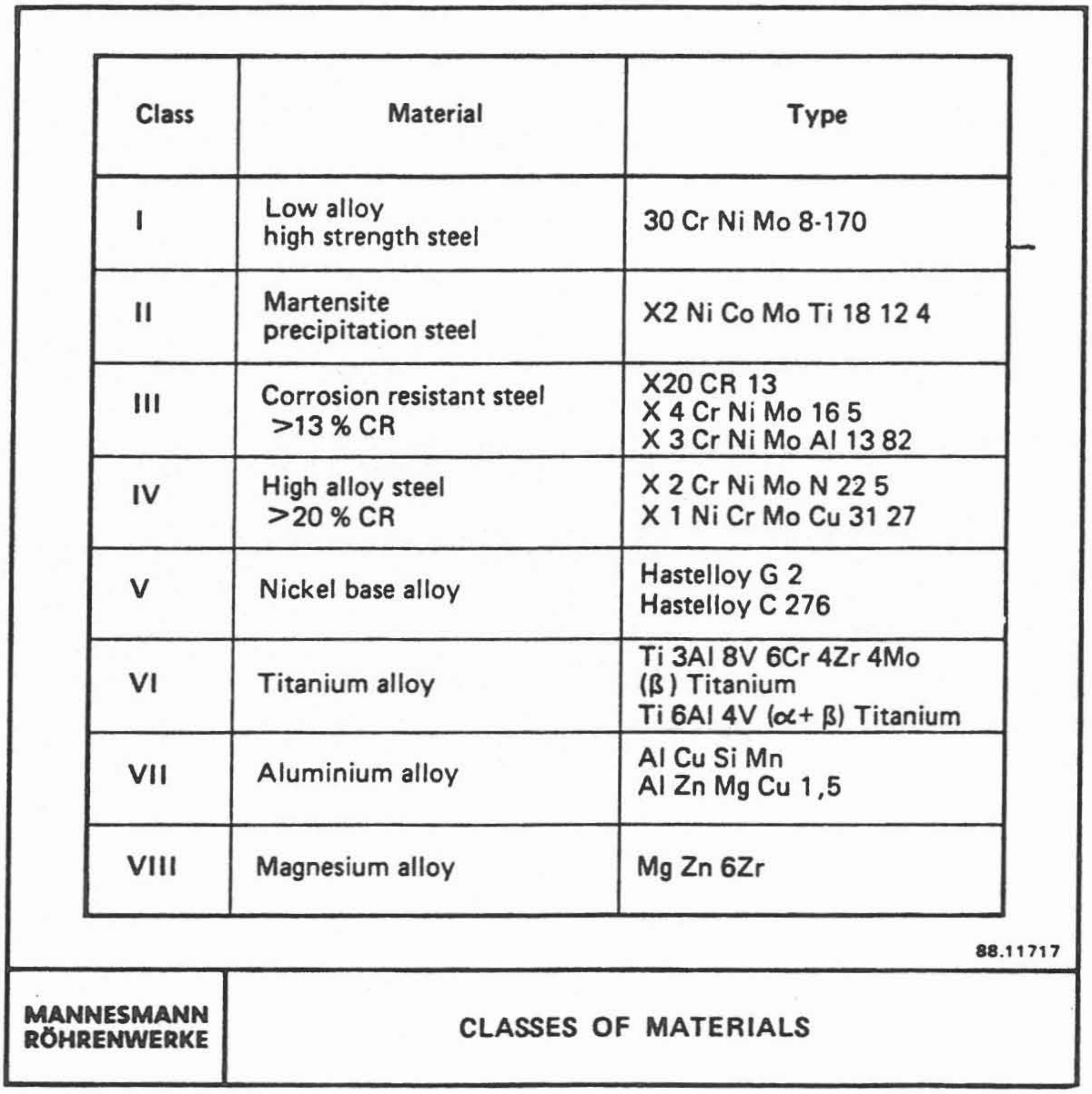
Apart from the technical aspects, the material costs must also be taken into account.

According to the literature and market information, the following cost relations were established for plain-end pipe of comparable sizes:

High-strength low-alloy steel	Basis	Factor 1
High-alloy steel $\geq$ 20 % Cr		Factor 13
Hastelloy C 276		Factor 30
Titanium alloy Ti 6AL 4V		Factor 30

The materials discussed offer a number of alternative solutions which permit flexible decisions, which can be adapted to the actual requirements of the main well.

Finally, it should be pointed out that the study, on which this paper is based, has been prepared for the KTB project as the result of cooperative contributions from numerous authors of Mannesmannroehren-Werke and of the Mannesmann Research Center.



Class	Material	Type
I	Low alloy high strength steel	30 Cr Ni Mo 8-170
II	Martensite precipitation steel	X2 Ni Co Mo Ti 18 12 4
III	Corrosion resistant steel >13 % CR	X20 CR 13 X 4 Cr Ni Mo 16 5 X 3 Cr Ni Mo Al 13 82
IV	High alloy steel >20 % CR	X 2 Cr Ni Mo N 22 5 X 1 Ni Cr Mo Cu 31 27
V	Nickel base alloy	Hastelloy G 2 Hastelloy C 276
VI	Titanium alloy	Ti 3Al 8V 6Cr 4Zr 4Mo (ß) Titanium Ti 6Al 4V (α+ ß) Titanium
VII	Aluminium alloy	Al Cu Si Mn Al Zn Mg Cu 1,5
VIII	Magnesium alloy	Mg Zn 6Zr

88.11717

MANNESMANN RÖHRENWERKE

CLASSES OF MATERIALS

Bild 1

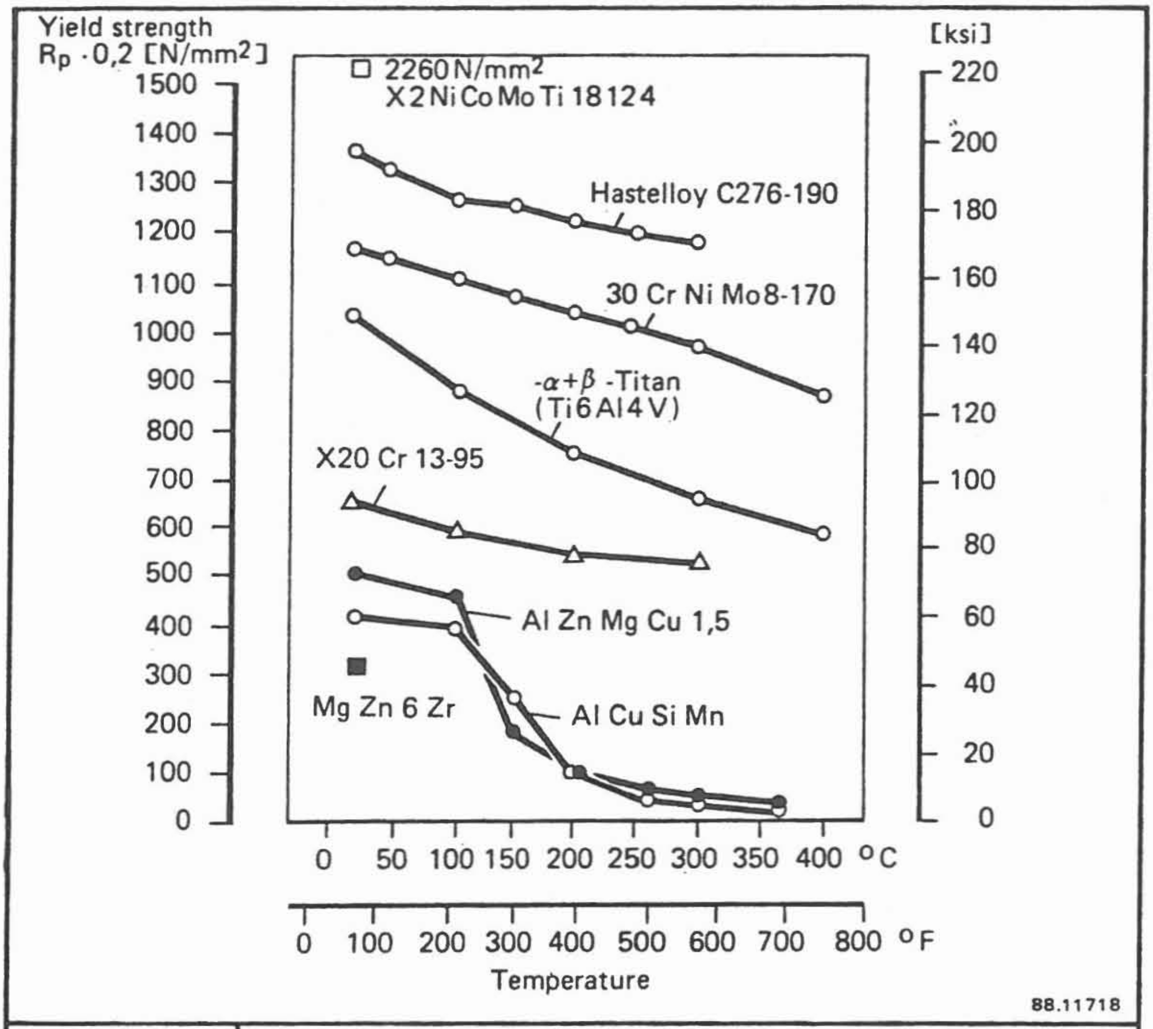
Material requirements	Drillstring requirement categories
Tensile properties	Σ String weight + Margin of overpull (MOP) $\leq$ Tensile yield Total weight $\leq$ Permanent operating hook load
Impact strength	Absorbed impact energy $\geq$ 50 Joule at ambient temperature
Creep resistance	Rp 0,2 at 100 000 h and 300°C
Fatigue resistance	– Combined fatigue and tensile strength – Combined fatigue and corrosion resistance
Corrosion resistance	– Ca-Chloride based mud – Borehole media
Wear resistance	– Abrasion – Mud wear – Interaction of erosion and abrasion
Producibility	– Pipe – Tooljoint
Make and break behaviour	Comparable to API-drillpipe

88.11716

MANNESMANN RÖHRENWERKE

REQUIREMENT CATEGORIES FOR PIPE AND TOOLJOINT

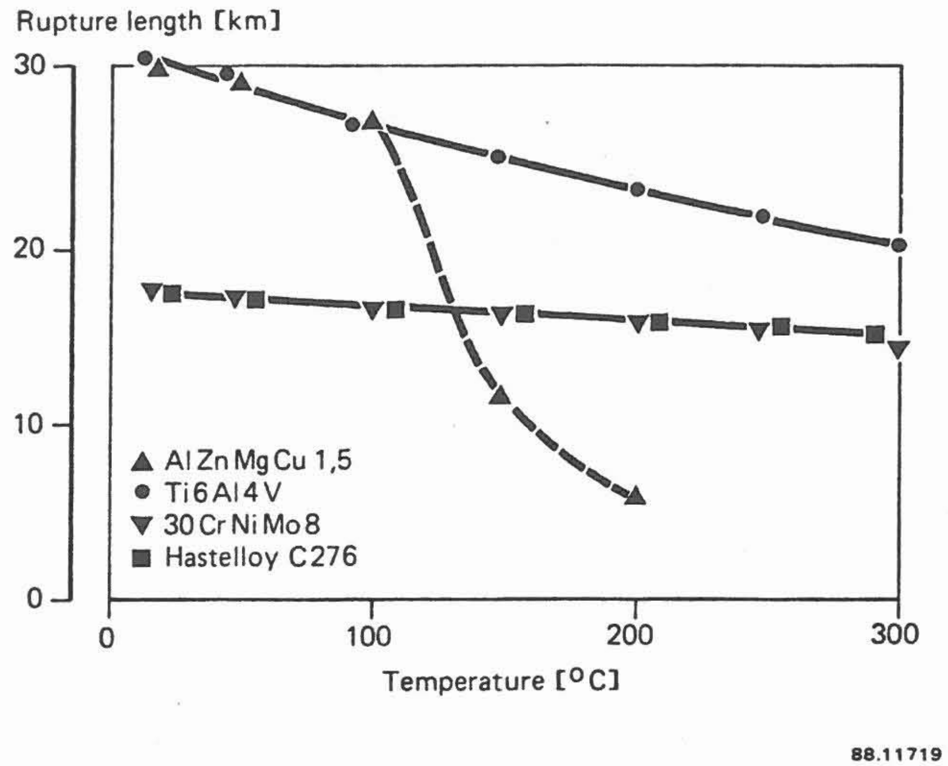
Bild 2



MANNESMANN RÖHRENWERKE

YIELD STRENGTH $R_p \cdot 0,2$ OF VARIOUS MATERIALS
vs. TEMPERATURE

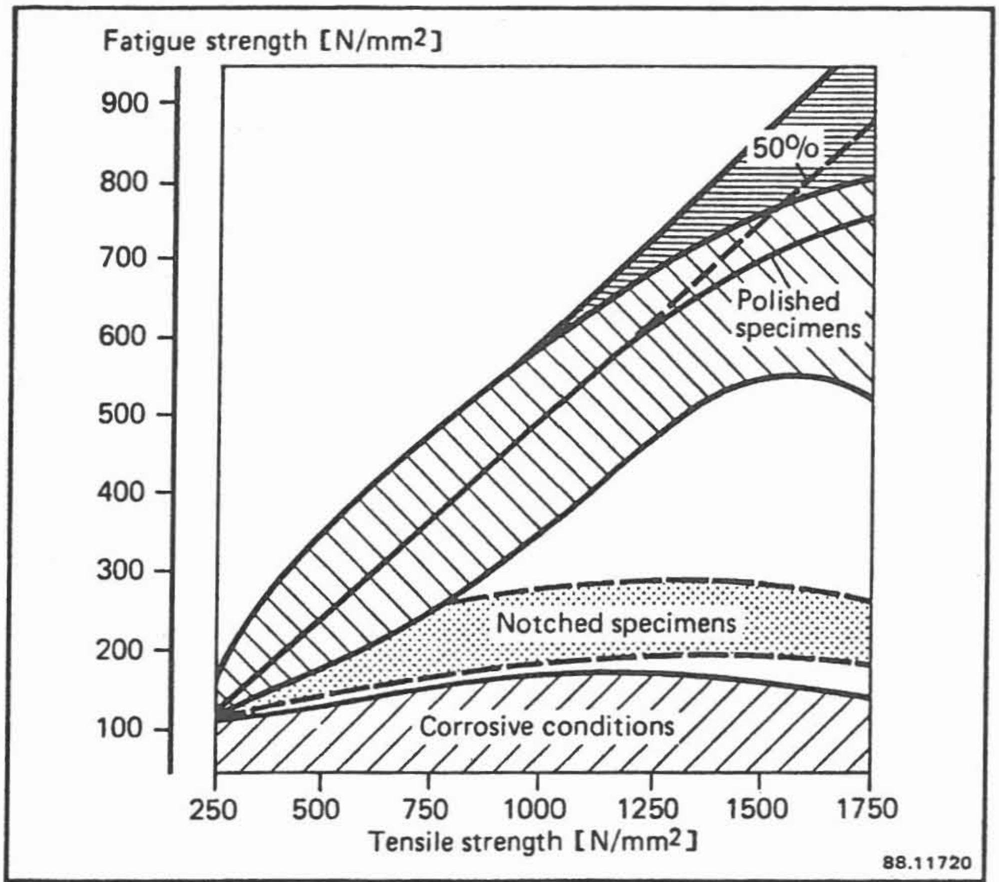
Bild 3



MANNESMANN RÖHRENWERKE

RUPTURE LENGTH vs. TEMPERATURE
(Related to yield strength and under consideration of boyancy)

Bild 4



MANNESMANN RÖHRENWERKE

FATIGUE STRENGTH vs. TENSILE STRENGTH ACC. TO BULLENS FOR POLISHED AND NOTCHED SPECIMENS IN LABORATORY AIR AND UNDER CORROSIVE CONDITIONS

Bild 5

Material properties Material groups		Tensile strength	Impact strength	Creep resistance	Fatigue resistance	Corrosion resistance	Wear resistance	Producibility	Make and break behaviour	Total valuation
I	Low alloy steel	●	●	●	■	■	■	●	●	●
II	Martensite steel	●	□	●	■	■	■	■	?	□
III	Corrosion resistant steel (>13 % CR)	●	■	●	■	■	■	■	?	■
IV	High alloy steel (>20 % CR)	▲	●	●	■	●	■	■	?	▲
V	Nickel base alloy	●	●	●	■	●	■	■	?	■
VI	Titanium alloy	●	▲	▲	■	■	■	■	?	▲
VII	Aluminium alloy	□	▲	□	▲	▲	□	●	?	□
VIII	Magnesium alloy	□	?	□	□	□	□	?	?	□

● suitable for use

▲ with major restrictions

? unknown

■ with minor restrictions

□ not suitable for use

88.11721

MANNESMANN RÖHRENWERKE

VALUATION MATRIX FOR PIPE AND TOOLJOINT

Bild 6

AUTHORS

- Prof. Dr. E. **Althaus**
  Mineralogisches Institut der Universität Karlsruhe
  Kaiserstr. 12

  D-7500 Karlsruhe 1

- J. M. **Braun**
  NL International, Inc.
  Wernerusstr. 22

  D-3100 Celle

- Dipl.-Ing. C. **Chur**
  Niedersächsisches Landesamt für Bodenforschung
  \- Projektgruppe KTB -
  Außenstelle Windischeschenbach
  Postfach 67

  D-8486 Windischeschenbach

- Ph.D. W. R. **Clements**
  NL Baroid
  P.O. Box 1675

  Houston, Texas 77251 (USA)

- Dr. U. **Deutsch**
  Technische Universität Clausthal
  Institut für Tiefbohrtechnik, Erdöl- und
  Erdgasgewinnung (ITE)
  Agricolastr. 10

  D-3392 Clausthal-Zellerfeld

- Dipl.-Ing. J. **Draxler**
  Niedersächsisches Landesamt für Bodenforschung
  - Projektgruppe KTB -
  Postfach 51 01 53

  D-3000 Hannover 51

- Prof. Dr. R. **Emmermann**
  Niedersächsisches Landesamt für Bodenforschung
  - Projektgruppe KTB -
  Postfach 51 01 53

  D-3000 Hannover 51

- Dipl.-Ing. B. **Engeser**
  Niedersächsisches Landesamt für Bodenforschung
  - Projektgruppe KTB -
  Postfach 51 01 53

  D-3000 Hannover 51

- Prof. Dr. K. **Fuchs**
  Geophysikalisches Institut der Universität Karlsruhe
  Hertzstr. 16

  D-7500 Karlsruhe

- Prof. Dr. R. **Hänel**
  Niedersächsisches Landesamt für Bodenforschung
  - N 1.1 -
  Postfach 51 01 53

  D-3000 Hannover 51

- Dr. C.-P. **Herold**
  Henkel KGaA
  Postfach 11 00

  D-4000 Düsseldorf 1

- Prof. Dr. P. **Hubral**
  Geophysikalisches Institut der Universität Karlsruhe
  Hertzstr. 16

  D-7500 Karlsruhe

- Dr. R. **Jürgens**
  Eastman Christensen GmbH
  Christensenstr. 1

  D-3100 Celle 1

- Dr. W. **Kessels**
  Niedersächsisches Landesamt für Bodenforschung
  \- Projektgruppe KTB -
  Postfach 51 01 53

  D-3000 Hannover 51

- Prof. Dr. C. **Marx**
  Technische Universität Clausthal
  Institut für Tiefbohrtechnik, Erdöl- und
  Erdgasgewinnung (ITE)
  Agricolastr. 10

  D-3392 Clausthal-Zellerfeld

- H. **Müller**
  Henkel KGaA
  Postfach 11 00

  D-4000 Düsseldorf 1

- Dr. J. **Oppelt**
  Eastman Christensen GmbH
  Christensenstr. 1

  D-3100 Celle 1

- Dr. E. **Quadflieg**
  Mannesmannröhren-Werke AG
  Postfach 1 12 04

  D-4000 Düsseldorf 1

- Prof. Dr. H. **Rischmüller**
  Niedersächsisches Landesamt für Bodenforschung
  - Projektgruppe KTB -
  Postfach 51 01 53

  D-3000 Hannover 51

- S. **Smith**
  NL Petroleum Services
  Greenwell Road, East Tullos

  Aberdeen AB1 4AX (UK)

- Dipl.-Ing. A. **Sperber**
  Niedersächsisches Landesamt für Bodenforschung
  - Projektgruppe KTB -
  Postfach 51 01 53

  D-3000 Hannover 51

- Dr. S. v. **Tapavicza**
  Henkel KGaA
  Postfach 11 00

  D-4000 Düsseldorf 1