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DRILLING TECHNIQUES PRESENTLY IN USE BY THE GEOTHERMAL STUDIES PROJECT, U.S. GEOLOGICAL SURVEY

by

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ABSTRACT

During the past two decades, the heat-flow studies program within the Geologic Division of the U.S. Geological Survey has evolved from one in which holes drilled for other purposes (mining and oil exploration, nuclear tests, hydrologic studies, etc.) provided the bulk of the data to a program in which the "free" holes, while still providing cost-effective and useful data, are being supplemented increasingly by holes drilled specifically for heat-flow determinations at locations where thermal data of high quality are needed, and where nobody else is interested in drilling. Ideally, heat-flow holes should be located in areas with moderate local relief and should be completed so that vertical water movement is inhibited. The most satisfactory test media for heat-flow determinations are crystalline rocks (particularly granites) and unconsolidated sediments; carbonate rocks and volcanic terranes can provide useful heat-flow data, but they present greater challenges both in drilling and interpretation. Drilling techniques have evolved from that of the continuously cored diamond-drilled hole (adapted from mining exploration) to adaptations of the shot-hole and blast-hole techniques used in petroleum exploration, water-well construction, and quarry operations. Spot cores are obtained where necessary to provide specific petrologic, geochemical, and physical data, but primary reliance is placed on ditch samples from rotary or percussion drilling for routine measurements of thermal conductivity and heat production. In shallow (50-100 m) holes in low temperature environments, plastic casing is used to maintain access for later temperature measurements. For deeper holes, steel casing is preferred. The annulus between casing and borehole wall in the lowermost 50 to 80 meters of heat-flow holes is routinely grouted off with a specially designed mixture of cement, bentonite, salt, and water to prevent vertical water movement.

INTRODUCTION

The Geothermal Studies Project of the Geologic Division, U.S. Geological Survey, has been involved in measuring heat flow on continents for about 20 years. In the early period, the emphasis was on taking advantage of "free holes", that is, holes drilled by the mining and oil industry and by other government agencies such as the then Atomic Energy Commission. From visits to perhaps a thousand sites, we were able to cull about 100 reasonably reliable values of heat flow (Sass and others, 1971). The low success ratio was due primarily to the fact that most holes were not cased and were found to be blocked at depths too shallow to allow confident estimates of temperature gradient. In some cases, hydrologic effects were of sufficient magnitude to render the data unsuitable for estimates of regional heat flux. To supplement the data obtained from "free holes" we (and other heat-flow groups) contracted for a limited number of holes to be drilled specifically for heat-flow determinations (see Lachenbruch, 1968). Recently, with the funding of regional and site-specific heat-flow studies related to geothermal energy and the energetics of earthquakes (see Lachenbruch and Sass, 1973; Blackwell and Baag, 1973), it has been found both possible and necessary to drill patterns of holes specifically for heat-flow determinations.

Because of the numerous inquiries we have received from both academic and industrial sources and the widespread interest in the technology of heat-flow drilling, we present here a summary of the techniques now in use by this project. This summary is by no means intended to be a state-of-the-art "cookbook" on how to drill heat-flow holes. As those who have experience in exploration drilling realize, each new prospect presents unique problems that require ingenuity and a flexibility of approach. Our primary purpose is to pass on a few "rules of thumb" we have formulated in order best to adapt the skills of our drilling contractors to the specific problems of geothermal research.

Acknowledgments. We are indebted to Jim Robison and Art Lachenbruch for their critical comments. Many of the lessons embodied in this report have been learned at the feet of a succession of experienced and conscientious drillers, all of whom we thank for their valuable advice (both solicited and otherwise).

REQUIREMENTS FOR AN OPTIMUM HEAT-FLOW HOLE

When in the "scrounge" or free-hole mode, it is reasonable to attempt a determination of heat flow on any hole that is easily accessible; however, when drilling a hole specifically for heat flow, it is necessary to impose a number of constraints on site location, depth, mode of completion, etc., to maximize the probability of obtaining meaningful data.

The most important of these constraints are:

1) Topography. When the local relief exceeds the depth of the hole, large and often uncertain corrections must be applied; thus, we try to avoid these situations if at all possible. In any event, we attempt to locate all drill sites at least one relief-height away from the brink or toe of local topographic features. When this is done, the maximum steady-state topographic correction to the temperature gradient usually is less than 15%; also, if the local relief is at least two hole depths away from the hole, the correction will be constant with depth (see Lachenbruch, 1969).

2) Rock type. Some rocks provide inherently better heat-flux plates than others. We have found that crystalline basement rocks, particularly granites, consistently yield reliable heat-flow data and present few drilling problems. The low porosity of these rocks also allows reliable determinations of thermal conductivity on chips.

Sedimentary terranes, particularly carbonate rocks result in more drilling problems and more hydrologic problems in the interpretation of data. Among consolidated rocks, extrusive volcanic rocks have resulted in the worst drilling problems and the lowest quality heat-flow data. Unconsolidated sediments, particularly impermeable lake sediments, often provide an excellent heat flux "window" through which to view the thermal state of the underlying consolidated rocks. Where an exploration program calls for a hole to be drilled in exactly a given spot, all considerations of rock type become moot; however, in regional studies, it is often possible to move a site a few kilometers to take advantage of a favorable medium.

3) Hole depth. Apart from topographic considerations already mentioned, there are optimum depths for various types of heat-flow holes. Perhaps the most universal constraint is the depth of penetration of the annual temperature wave which varies from a few meters in dry unconsolidated material to as high as 40 to 50 meters in rocks of high conductivity. For an isolated regional heat-flow datum, experience has shown that the minimum acceptable depth is about 100 meters. At the other extreme, holes as shallow as 10 meters may be useful in defining the conductive anomalies associated with geothermal systems.

4) Completion techniques. The factor that distinguishes heat-flow holes from most other types of exploration holes is the necessity for repeated logging over periods of weeks to months after the hole is drilled. This imposes a requirement for some kind of access pipe. Because the drill commonly connects previously isolated aquifers, it is also desirable, for both environmental and scientific reasons, to seal off the annulus between pipe and borehole wall.

BACKGROUND

During the past 15 years, a number of techniques (based on standard exploration procedures) for drilling heat-flow holes has evolved. Our original approach was geared to obtaining a limited number of heat-flow data of the highest quality at critical points to supplement data from "free" holes. The holes generally were diamond drilled and continuously cored to depths of 300 to 600 m in crystalline rock. The need for more heat-flow data and the consequent necessity to obtain a large number of high quality heat-flow values within a reasonable time frame and budget resulted in a fundamental change in approach.

Continuously cored diamond-drill holes are expensive and time consuming. Diamond-drilling technology has shown little change over the past 30 to 40 years while material costs have escalated; consequently, the cost per meter has risen out of proportion to increases in productivity.

A joint project in 1975-1976 with Lawrence Berkeley Laboratories and the USGS in Grass Valley, Nevada, afforded our first opportunity to experiment with alternate drilling techniques in sedimentary basins. Conventional drilling techniques using seismic shot-hole types of rigs and bentonite muds for the drilling fluid allowed a dramatic increase in production relative to continuous coring and an order of magnitude reduction in the cost per meter of hole (Sass and others, 1977).

Having realized real cost savings using conventional drilling technology in sedimentary basins, additional effort then centered around improving penetration rates in harder materials. Using the same drilling techniques and air as the fluid medium a 50% increase in production was realized in harder sedimentary rock units and in some types of volcanic rocks. However, water entry, air volume and air pressure limited the depth capability of the equipment. If "rotary air" is the sole means of drilling, site selection becomes a problem and can inadvertently bias the sample towards areas of abnormally deep water tables.

The next step was an improvement in production rates in crystalline rock types. A similar need also occurred in the mining and water well industries and led to the development of the downhole percussion hammer. Application of downhole hammer technology to the shot-hole drilling rig brought about a tremendous increase in production and dramatically reduced the cost per meter.

CURRENT DRILLING PROGRAMS

Listed below are typical instructions provided to our drilling contractors for holes presently being drilled.

Crystalline rocks. Rig up, set surface casing if required, drill a 146 mm hole with a downhole hammer and high pressure air, (use foam if necessary), to 165 m, set 32 mm casing and cement. Catch samples every 3 m and bag at 6 m intervals. Depths of holes to adjust according to terrain and drilling difficulties.

Unconsolidated sediments. Rig up and drill a 120 mm hole with a drag bit using mud or air and mud to 60 m, run in situ heat-flow probe (see Sass and others, 1979), drill to 90 m, run in situ heat-flow probe, fill hole with cuttings and cap with cement plug. Adjust depth and probe intervals for best results.

Sedimentary and other non-crystalline rocks. Rig up, set surface casing if required, drill a 120 mm hole with drag or roller bits using air or mud to 150 m, core 0.75 to 1.5 m, drill to 200 m, core 0.75 to 1.5 m, drill to 225 m, set 32 mm casing and cement. Catch ditch samples every 3 m, and bag every 6 m. Preserve core in a double thickness of 0.2 mm plastic tubing, seal ends, insert into 76 mm PVC tubing, add water and cap tubing. Depth and core intervals are adjusted to accommodate terrain, drilling difficulties and program objectives.

DRILLING TECHNIQUES

Introduction. Three types of drilling and two types of coring techniques in current use are discussed in the following paragraphs. In each case every effort is made to limit the amount of equipment on location to that necessary to accomplish the job. For our drilling contracts, we try to limit the equipment to a drill truck, water truck and service pick-up. If it is necessary to add a compressor truck, then the service pick-up should be equipped with a tow bar. Good planning and efficient operations require that moves between sites be accomplished safely, quickly, and in one trip. This is particularly true where driller's services are contracted by the hour, as they are in most of our contracts.

Rotary-mud drilling. Rotary mud drilling requires a rig similar to a Gardner-Denver Mayhew 1000 with a depth capability of 325 m (1000+ feet) using 73 mm O.D. (2 7/8") drill pipe. Mud pumps should be 127 x 152 mm (5" x 6") or larger duplex slush pumps with pressure capabilities to 5000 kPa (750 psi). Maximum productivity can be achieved with this type of drilling rig if it is equipped with pipe slides, breakout tongs, sand line and quick release hoisting plugs. The water truck should also be equipped with pipe slides, mud storage racks and a self-loading water tank of at least 6 m^3 (1800 gallon) capacity.

The drilling fluid is native mud or water and high-yield Wyoming type bentonite. Other proprietary products may be added to the mud system depending on such drilling problems as lost circulation, sloughing shale or artesian flow. A portable mud pit of 1 to 2 m^3 capacity (300 to 600 gallons) normally is used. Unfortunately, this leads to the use of a high solids mud which in turn slows the drilling rate, increases wear on pump parts and decreases bit life. Some solids can be removed by shoveling cuttings from the pit or thinning the mud system with additional water.

Management of the mud system depends to a great extent on tradeoffs among environmental factors, location of the water supply and cost. In most cases, less-than-optimum drilling rates must be tolerated to accommodate the limitations of the mud system. Drilling rates using the rotary-mud technique can vary from a low of 3 m per hour up to 35 m per hour or more.

Rotary-air drilling. Rotary-air drilling requires a rig of the same capability as rotary-mud with the addition of a low pressure air compressor; many rotary-mud types of rigs may be equipped with low pressure air at slight additional cost. The air compressor should have a minimum capacity of 0.235 m^3/s (500 cfm) at 350 kPa (50 psi). Compressor capacity must be capable of maintaining an annulus velocity of at least 20 m/s (4000 fpm) for adequate removal of cuttings. Low pressure air drilling with conventional roller bits or drag bits will increase drilling productivity substantially over that of mud drilling. Water injection should be available to control dust and to slug the hole in order to control accumulations of cuttings and to prevent "booting-off." Foaming agents can also be used if water influx increases to the point of creating drilling problems with straight air.

Air drilling can often be used in areas of severe lost circulation with considerable success. However, the limiting factor is the driller's capability to control the influx of water to rates less than roughly 2 L/s (30 to 40 gpm). Ideally, air-drilling should be limited to competent formations above the water table or to impervious, unfractured formations. Drilling rates using rotary-air vary from a low of 4 m per hour up to 40 m per hour or more.

Downhole hammer drilling. Downhole hammer drilling as developed by the quarry and water well industries, has been adapted for heat-flow drilling with a dramatic increase in productivity in crystalline rocks. Basically the same type of rotary drilling equipment can be used as for mud and air drilling with the addition of a high pressure air compressor. Currently manufactured downhole hammers are available with pressure ratings to 2400 kPa (350 psi) although air at 1720 kpa (250 psi) is more commonly used and is readily available. Ideally, the air supply should have capacity in excess of the hammer's rated maximum input. The annulus velocity should be in excess of 20 m/s (4000 fpm). Excess air can be bypassed at the top of the hammer to assist in the removal of cuttings and water.

Water and foaming agents can be injected into the air stream to control dust. Foam can also be used to lower the hydrostatic pressure in the annulus and allow drilling to continue below the water table in fractured crystalline rocks. Holes with water flows up to 9 L/s (150 gpm) have been successfully drilled by the proper application of foam.

Downhole hammer drilling increases the shock and vibration loads on the drilling equipment and experience indicates that only heavy-duty rigs designed for depths of 325 m with 89 mm (3.5 inches) O.D. drill pipe should be used. Change-over subs, tool joints, water swivels and the kelly will all experience shock loads that may lead to metal fatigue and subsequent failure unless they are properly designed to withstand the increased loads. If lighter weight drill pipe is used, it is important to have 30 or 60 m of 89 mm O.D. drill collars available. If at all possible, hydraulic control of bit weight and feed rate should be available since downhole hammers generally drill with less weight on bottom than conventional rotary bits. Drilling rates with downhole hammers vary from 7.5 m per hour up to 60 m per hour.

CORING TECHNIQUES

For crystalline rocks of low porosity (∿1%), satisfactory determinations of both thermal conductivity and heat production usually can be obtained from measurements on cuttings. Thus, our coring operations usually are restricted to obtaining "spot" cores at two or three depths in sedimentary or volcanic rocks.

Two distinctly different types of coring techniques are available depending on the hardness of the formation:

1) In unconsolidated materials, soft sands and shales the use of a Pitcher or Dennison type of sampler yields the most consistent results. Core samples are limited to a maximum of 1 m but are commonly only 0.5 to 0.75 m long. Both of these core barrels are modified Shelby tube devices with the core being retrieved inside a thin wall metal tube. Relatively undisturbed core samples can be obtained provided the driller doesn't overdrill the cored interval thereby compressing the core. The unused portion of the Shelby tube is cut off, discarded and the remainder is tightly sealed inside a 76 mm (3") I.D. plastic tube with capped and sealed ends. Thermal conductivities are measured using standard needle probe techniques, both longitudinally and axially (see e.g., Sass and others, 1977).

2) Consolidated and crystalline rocks are cored using conventional double tube core barrels similar to a Christensen 89 x 64 mm core barrel. Diamond or tungsten carbide core bits are used as required. Core runs are limited to 1.5 m for maximum recovery especially in broken or highly fractured rock units. Cores retrieved are double bagged in 0.2 mm plastic tubing, sealed and inserted into 76 mm I.D. plastic tube with sealed ends. A small

quantity of water is added to the tube to maintain the bagged core in a 100% humidity environment. Thermal conductivities are measured with a standard divided-bar apparatus from "cookies" cut from the core or by needle-probe techniques where the core is too soft to machine (see e.g., Sass and others, 1971).

Both types of core barrel are sufficiently strong to withstand the rough handling and excessive loads typically imposed by shot-hole drilling rigs. Caution should be exercised when using barrels similar to those used by the diamond drilling industry due to their lighter construction and more restrictive fluid passages.

Plugged core barrels, short core runs and poor recovery are both expensive and time-consuming. Most of these problems can be attributed to either poor mud or poor coring techniques. Holes should be carefully conditioned prior to coring to prevent the build up of drilled solids on the bottom of the hole. Fresh mud should be mixed for use prior to coring and in some cases it will be necessary to change over the complete mud system. It is very important to reduce the solids content of the mud to levels approaching that of fresh mud.

Drilling techniques vary depending on the type of barrel in use; however, manufacturer's recommendations modified by actual field experience will usually suffice to achieve satisfactory core recovery.

WELL-COMPLETION TECHNIQUES

Introduction. Holes originally drilled for other than heat-flow purposes were often left uncased which resulted in loss of the hole as a heat-flow datum. Uncased holes often bridged over or provided a communication channel between aquifers with different heads. In either case, the value of the hole for interpretive purposes was substantially reduced.

The bridging problem was solved by committing the necessary funds to provide for a casing string to prevent collapse of the hole. Standard 32 mm nominal diameter steel pipe ("inch-and-a-quarter black iron, threaded and coupled") was used as the minimum size suitable for our continuous temperature logging equipment. Smaller casing is, of course, possible; however, the availability of radiation logging tools for casing under 32 mm nominal diameter is extremely restricted.

The hydrologic communication problem was solved by filling the annulus between the casing and the hole with a neat cement grout. Other substances such as a bentonite slurry or a proprietary resin mix can also be used; however, cost, availability and effectiveness should be considered prior to selecting these mixes.

In the next few paragraphs, we will discuss the various choices in casing, grout mixes and cementing techniques.

Casing programs. Basically there are three types of casing programs currently being used. The most common casing program is that of a single 32 mm steel pipe to the total depth of the hole, grouted over the lower 50 to 80 m of hole, backfilled with cuttings to within ∿6 m of the surface, and plugged with 6 m of cement-filled annulus at the top.

Another type of casing program is used when it is desirable to gather hydrologic data in addition to heat-flow data. Typically the deep dual-purpose hole will be completed as discussed below except for an increase in the volume of the cement mix. After the cement has set for several days or weeks, the casing is perforated at selected intervals with shaped charges to provide communication between the casing and aquifer.

In shallower holes (50-150 m), it is possible to run two parallel strings of casing; one for heat flow and one for piezometric measurements. The lower casing string has a well screen and is set below the upper casing string by approximately 3 to 6 m. Pea gravel is placed in the hole around the well screen prior to running the upper casing string. The second casing can be cemented in place similar to the standard completion; however, precautions must be taken with the lower casing to prevent cementing the well screen. Any number of variations in casing programs can be used in completing heat-flow holes as long as the primary objective of sealing the annulus is achieved.

Our original heat-flow holes were core-drilled 60 to 76 mm in diameter and were cased with 32 mm steel pipe. Subsequent holes were rotary- or hammer-drilled 120 to 152 mm in diameter and were cased with either 32 mm steel pipe, 50 mm steel pipe or 50 mm ("two-inch") plastic pipe.

Plastic pipe is less expensive, is easier to handle and costs less to ship than steel. However, it is very difficult to remove from a hole, has a low burst pressure, and it is subject to coupling failure due to large manufacturing tolerances. Plastic pipe is suitable for shallow exploration programs (50-100 m) such as discussed by Sass and others (1977). It is, however, quite unsuitable for 150-meter or deeper holes, and for any holes in which temperatures exceed 40°C.

Steel pipe has several distinct advantages such as, strength, adequate pressure ratings and availability. It also has an advantage in situations where it is necessary to spud or wash the casing to the bottom of the hole. Its disadvantages, of course, are weight and cost. We have experienced only minor casing failures with steel pipe, provided we exercised reasonable care during the threading and coupling operations.

Grouting operations. The original grouting operations used either the drilling contractor's pump or oil field cement-pumping equipment hired by the job. Mixes consisted of neat cement slurries sometimes with additives such as pozzolan, gilsonite and calcium chloride. Problems that developed while trying to grout long strings of 32 mm steel pipe in small diameter holes using small triplex pumps led to the use of larger pumping equipment. However, the larger oil field equipment was too big and consequently it was difficult to obtain good grout mixes at low pumping rates.

Attempts to grout holes using a 127 x 152 mm duplex slush pump, as commonly found on most shot-hole drilling rigs, were partially successful; however, while batch mixing the cement slurry it was difficult to prevent settling of cement solids to the bottom of the mixing tub. Accordingly, a cement slurry was designed taking into account problems related to mixing conditions and our completion requirements.

At the present time, our grout mix consists of cement, salt, bentonite and water. The salt acts to either retard or accelerate the setting time depending on the percentage of salt added to the mixing water, but more importantly, it keeps the cement in suspension. The bentonite increases the yield, lowers the water loss and helps to reduce friction losses while pumping.

A typical mix consists of 0.28 m^3 (10 sacks) cement, 18 kg (40 pounds) of salt, 23 kg (50 pounds) of bentonite, and 0.5 m^3 (150 gallons) of water. The approximate yield of this mix is 0.65 m^3 (23 ft^3 or 200 gallons); just enough to fill a galvanized sheet metal watering trough and sufficient to fill the lowermost 65 m of a 120 mm hole cased with 32 mm pipe. The salt, water and bentonite are mixed prior to adding the cement. It is important to note that high yield peptized bentonites are not suitable for this cement mix; only high grade Wyoming bentonite is recommended. The cement is added to the mix while vigorously stirring the slurry using the rig mud pump; every effort should be made to prevent settling of the cement mix. A 10-sack mix can usually be batched in 20 to 30 minutes without difficulty.

A typical cementing job might proceed as follows:

1) Install a cement plug latching collar (Figure 1) on the bottom joint of the casing string.

2) Run 32 mm steel pipe to total depth and install a 38 mm full opening ball valve on the top joint of casing.

3) On top of the ball valve, attach a water swivel and grout hose, then hoist pipe 0.5 to 1 m off bottom.

4) Circulate clear water to establish communication through the casing. Shut the ball valve and prepare cement mix, open the ball valve and pump grout mix; if possible, move the pipe up and down repeatedly 1 to 5 m while pumping to insure maximum displacement of the mud column by the grout mix.

5) Close the ball valve after pumping the cement mix, and thoroughly flush the mud pump and all suction and discharge hoses of grout mix.

6) Disconnect the water swivel and insert a wiping plug, reconnect the water swivel, open the ball valve and pump the plug down the casing with

clear water. When the plug latches into the latching collar, the pressure will rise very rapidly. Shut off the pump, slowly release the pressure, repressure to insure a positive latch, slowly release the pressure to 170 kPa to 340 kPa (25 to 50 psi) and close the ball valve. The pipe should be reciprocated while pumping the plug and then landed on bottom just prior to the plug hitting the latch. (Excess cement can be placed in the annulus at the top of the hole.)

7) The ball valve is left closed for 24 hours prior to releasing the pressure on the casing. An illustration is included (Figure 1) showing a typical cement latching plug and collar assembly.

Grouting does, of course, have its advantages and disadvantages. Among the disadvantages are:

1) More heavy equipment must be carried around.

2) The driller's pump eventually gets clogged with cement.

3) Longer times are required between drilling and obtaining near-equilibrium temperature measurements because heat is liberated by the cement as it cures. For the logs illustrated in Figure 2, there is a suggestion that equilibrium temperatures have not been reached after 100 days, even though the gradients are well established. A counter-example in Figure 3 shows that the equilibrium temperatures in an "ungrouted" hole are established within three weeks of drilling.

The second log (solid line, Figure 3) illustrates one of the advantages of grouting. After two months, a bulge has appeared between depths of 20 and 40 meters. This is probably the result of the drilling mud settling out, allowing water at 40 meters to enter the annulus, travel upward and exit at about 20 meters. If we had only the second log, we would be uncertain as to whether the bulge represented water movement in the annulus or in the formation. Only in a grouted hole can this ambiguity be resolved. Examples of grouted versus ungrouted holes at Long Valley, California, (e.g., Figure 4) were discussed by Lachenbruch and others (1976).

We believe that our "10 sack" grouting procedure strikes a happy medium between doing nothing at all and undertaking a complete top-to-bottom grouting job involving expensive oil-field type equipment. The mixing tub and all of the ingredients for a single grouting job (except for the water which the driller carries anyhow) can be carried in a pickup truck. The lowermost 50 to 80 meters (usually the interval of most intense interest) can be sealed off at moderate cost with minimal logistic problems.

POSSIBLE FUTURE IMPROVEMENTS

Continued cost savings in future drilling programs might be possible by using the changing technology available to the drilling industry. In particular, the evolution of top-drive rotary drilling rigs using flush joint drill pipe and higher pressure downhole hammers should increase productivity. Trailer-mounted mud pits with shaker screens and desilters are now available and offer cost savings by lowering wear on bit bearings, and pump components. These portable mud pits also allow mud to be recycled, eliminate some environmental damage and produce cleaner ditch samples. Cost savings for the cementing and casing operations are unlikely unless an inexpensive light casing retaining most of the strength characteristics of steel pipe becomes available. In any event, the increased cost of technically improved equipment will have to be measured against increased productivity to prove or disprove real cost savings.

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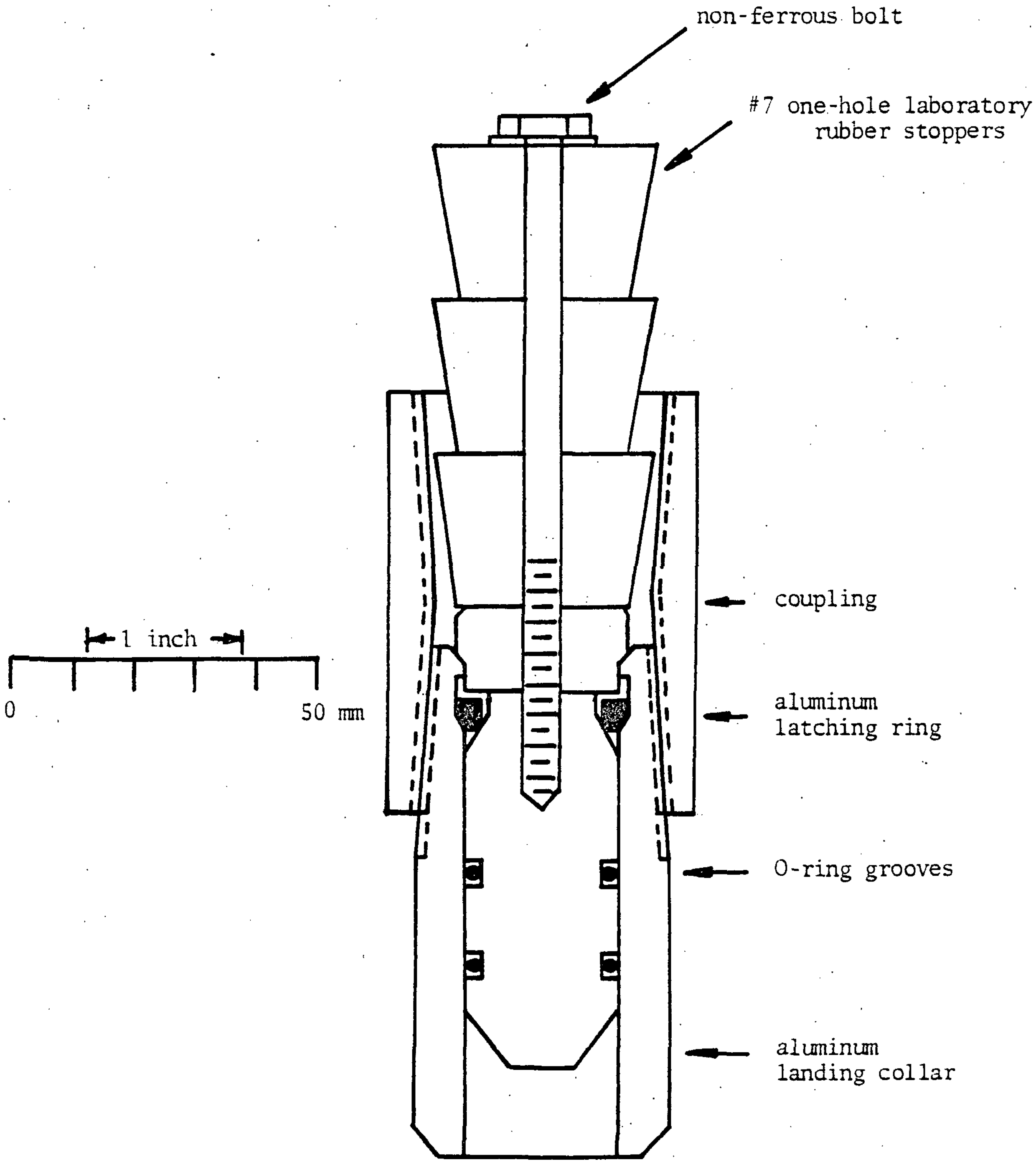

Figure 1. Drawing of a drillable latch-down tubing plug and landing collar for use in 32 mm I.D. ("inch-and-a-quarter") casing shown in latched position.

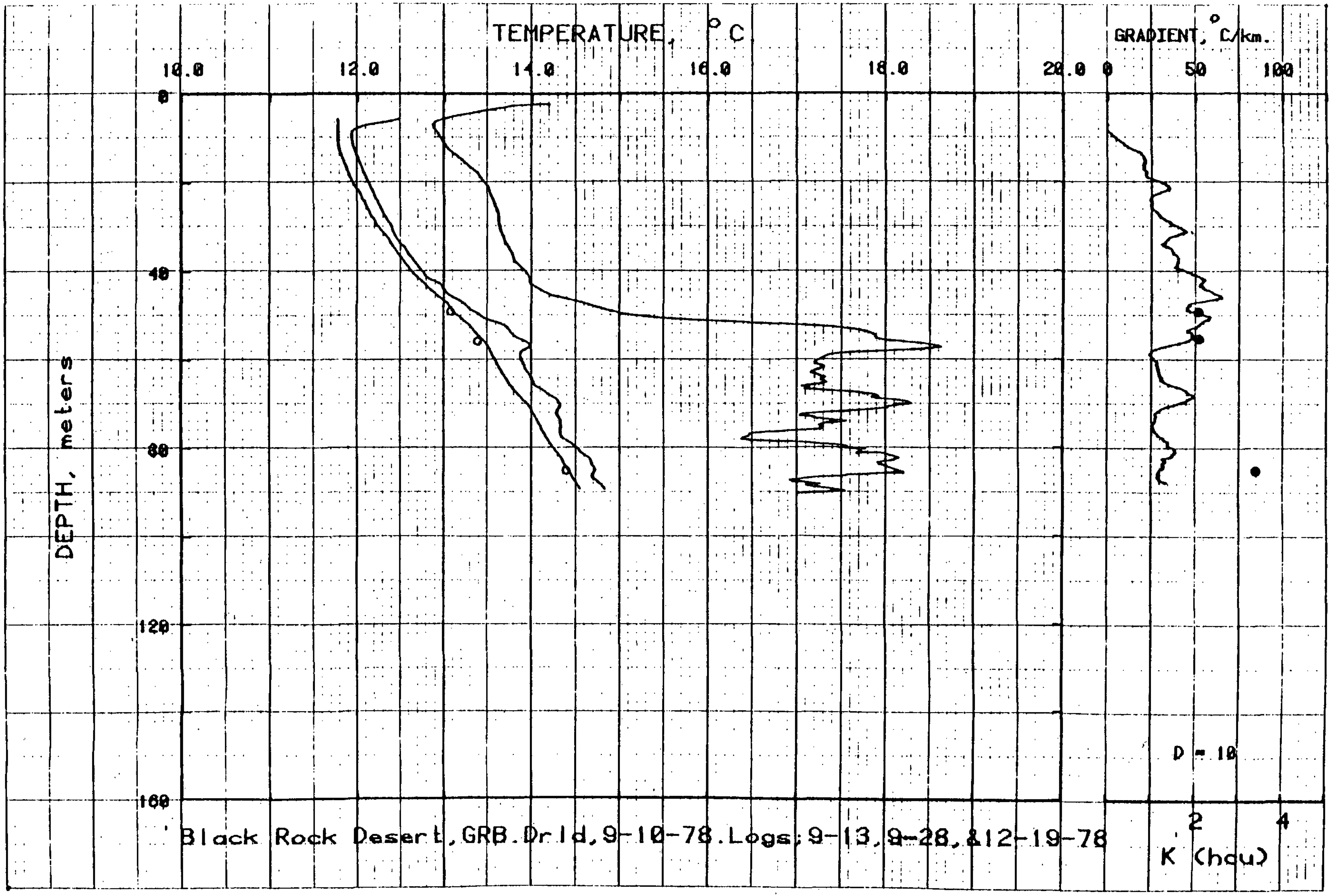

Figure 2. Temperature logs obtained 3, 18, and 100 days after drilling of a hole in the Black Rock Desert, Nevada. Open circles are formation temperatures obtained during drilling using the downhole heat-flow probe (Sass and others, 1979).

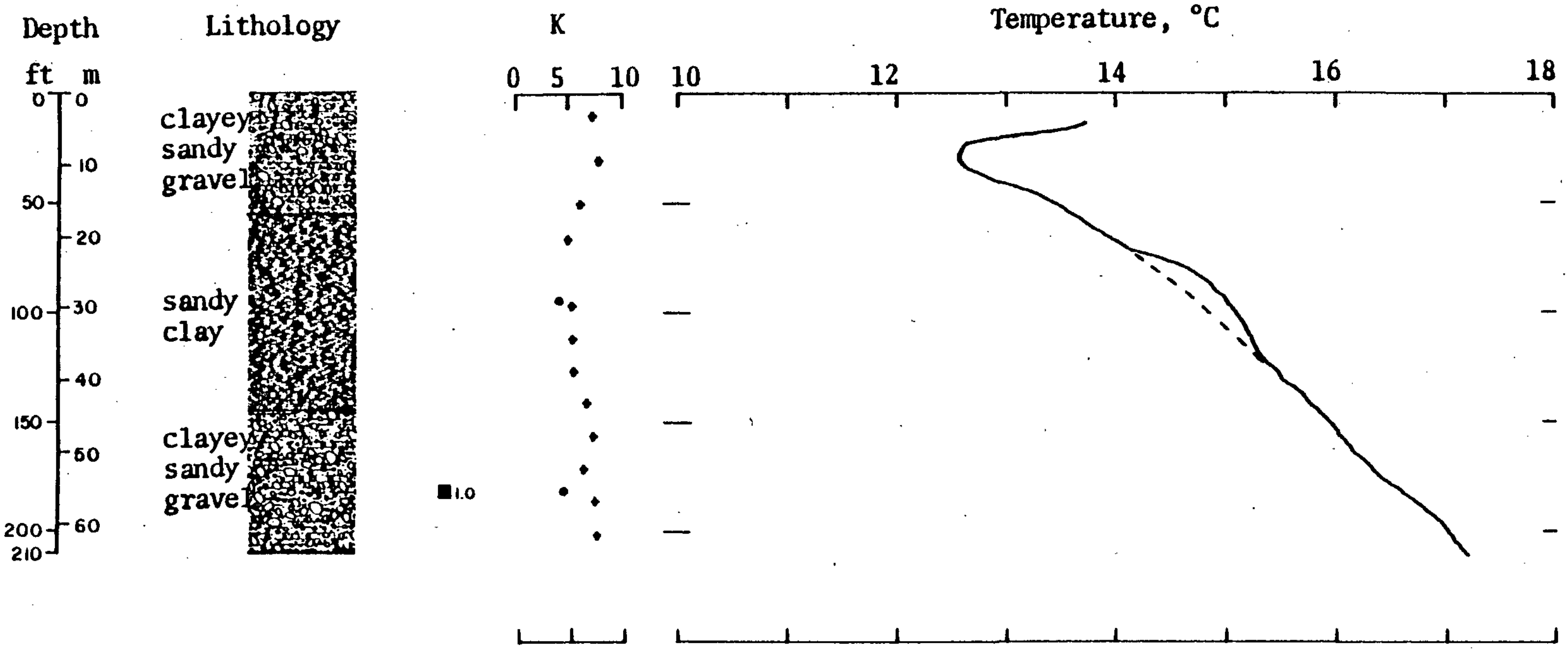

Figure 3. Lithology, thermal conductivity, and temperature profile for Hole Q-18, Grass Valley, Nevada from Sass and others, 1977. Annulus was originally filled with drilling mud. Dashed line is profile obtained three weeks after drilling. Solid line, a profile obtained about six weeks later.

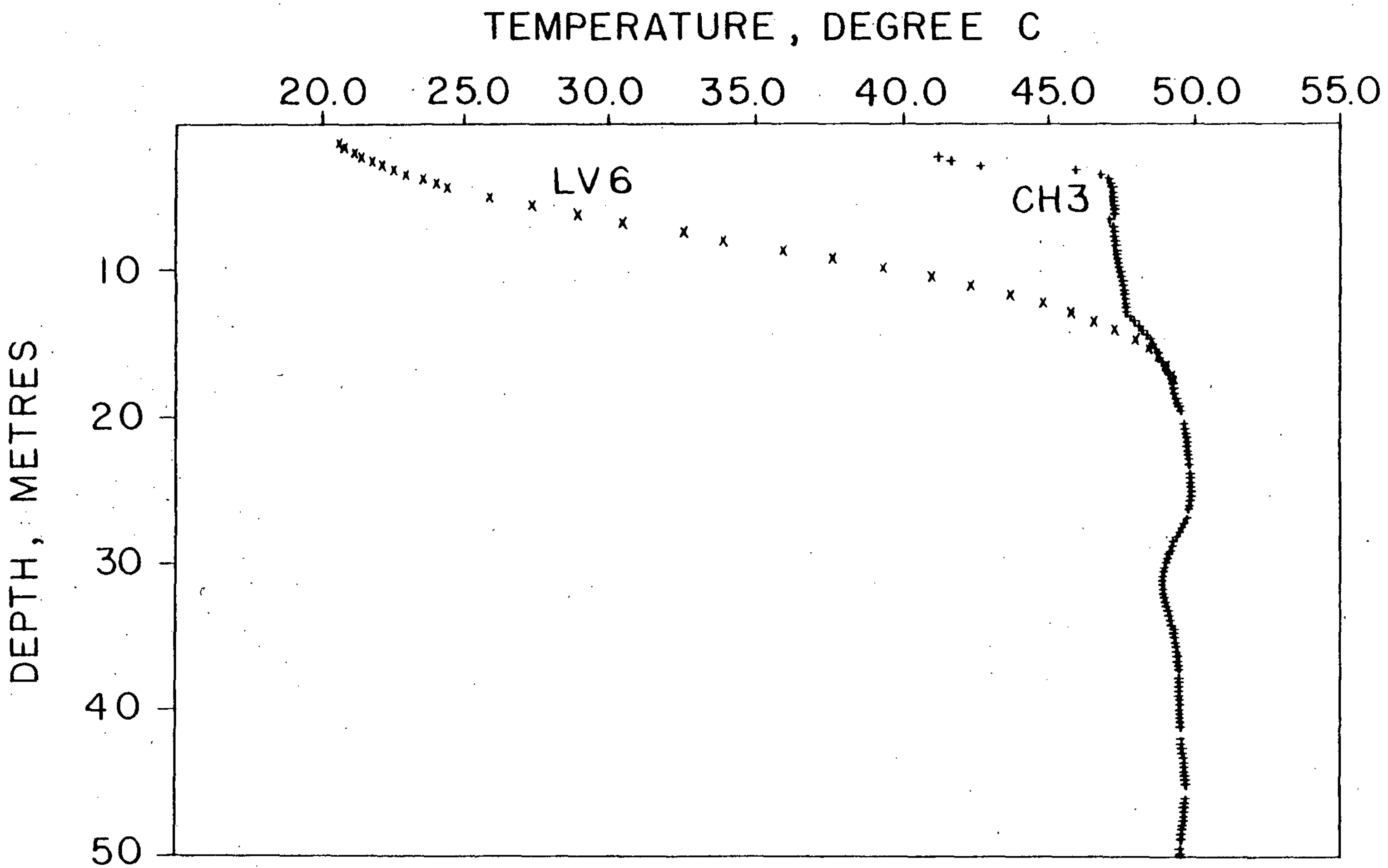

Figure 4. Comparisons of ungrouted (LV-6) and grouted (CH-3) sections of neighboring holes at Long Valley, California (from Lachenbruch and others, 1976).