D. Foley

**SAMPLING AND INTERPRETATION
OF
DRILL CUTTINGS
FROM
GEOTHERMAL WELLS**

**JEFFREY B. HULEN
BRUCE S. SIBBETT**

Earth Science Laboratory

**University of Utah Research Institute
420 Chipeta Way, Suite 120
Salt Lake City, Utah 84108
(801) 581-5283**

1981

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

**SAMPLING AND INTERPRETATION OF DRILL CUTTINGS FROM
GEOTHERMAL WELLS**

Jeffrey B. Hulen and Bruce S. Sibbett

from: Society of Professional Well Log Analysts, Geothermal Log
Interpretation Handbook, 2nd edition (in press)

Also presented at: Introduction to Geothermal Log Interpretation, Geothermal
Resources Council Tech. Training Course No. 7, April 22-23, Reno, Nev. (1981).

ABSTRACT

Drill cuttings from geothermal and mineral exploration boreholes, by contrast with those from most petroleum wells, commonly are derived highly fractured and faulted, hydrothermally altered igneous and metamorphic rock sequences, and are likely to be severely contaminated. Characterization of a subsurface resource from cuttings thus requires not only especially careful sample collection, preparation, storage and examination, but also a thorough knowledge of drilling technology, local geology and the full range of potential borehole contaminants.

Accurate identification of lithology from cuttings is critical for recognition and correlation of rock types likely to selectively host the desired commodity. However, many of the rocks encountered in geothermal and mineral exploration boreholes (such as gneisses and granitic rocks) can resemble one another closely as cuttings even though dissimilar in outcrop or core. In such cases, the actual rock type(s) in a cuttings sample generally can be determined by comparison with simulated cuttings from representative surface rocks, and with various geophysical and other well logs. Many other clues in cuttings, such as diagnostic metamorphic mineralogy, or sedimentary rounding and sorting, may help identify subsurface lithologies.

Faults and fractures commonly are the dominant physical controls on geothermal and mineral resources. Faults occasionally can be recognized directly in cuttings by the presence of slickensiding, gouge, or other crushed material. More commonly, however, the "gouge" observed in cuttings actually is pseudo-gouge created beneath a bit during drilling. Since most faults and all fractures produce no direct evidence apparent in cuttings, they are best recognized indirectly, either by commonly associated hydrothermal alteration,

or by responses on appropriate geophysical well logs.

Hydrothermal alteration, useful for locating and defining a geothermal or mineral resource, is far more difficult to recognize and interpret in cuttings than in core or outcrop. Alteration textures and paragenetic relationships can be obscured or obliterated as cuttings are produced. Less resistant alteration (and rock-forming) minerals can be disaggregated during drilling and lost from cuttings during sampling or washing. Relict and contemporary alteration can be indistinguishable, and a wide variety of borehole contaminants can closely resemble natural alteration products encountered during drilling. These contaminants also can produce confusing geochemical signatures.

INTRODUCTION

Drill cuttings, because of their low cost and ease of recovery relative to core, are the standard borehole rock samples. They are commonly the only source of the direct downhole geologic information essential for a successful subsurface investigation. Cuttings, however, are fragmentary, mixed and frequently contaminated samples of formerly more or less coherent rock, and therefore are more difficult than core to interpret reliably. Imaginary reconstruction from cuttings of the rock penetrated by a borehole requires, in addition to thorough knowledge of local geology, a full understanding of the means by which these samples are produced and transported in drilling fluid, collected, prepared, stored and examined. These processes are each discussed in this paper, then applied to interpretation of lithology, contact relationships, fracturing and faulting, geochemistry and hydrothermal alteration.

Logging of relatively undisturbed sediments and sedimentary rocks is thoroughly covered by previous publications (e.g. Swanson, 1981; Low, 1977; Maher, 1964; Hills, 1949). Therefore, this paper will emphasize characterization of cuttings from fractured, altered, dominantly igneous and metamorphic terrain such as commonly penetrated in geothermal and mineral exploration boreholes. Many of the concepts and techniques discussed also should be useful for interpreting cuttings from petroleum wells in structurally complex sedimentary sequences like those of the Rocky Mountain Overthrust Belt.

PRODUCTION OF CUTTINGS

Thorough knowledge of how cuttings are produced and transported to a sampling point will ease their interpretation by allowing a clear distinction

between original rock features and those induced by drilling. Only those aspects of the drilling process which directly affect cuttings will be discussed in this paper. A more comprehensive survey of drilling techniques and equipment is provided by Moore (1974).

Cuttings are produced beneath a bit by a combination of impact, which crushes and fractures a rock, and drag, a gouging and fracturing action. The relative importance of drag and impact in generating cuttings depends largely on bit type.

Drag and claw bits, designed for softer rocks, penetrate by gouging and fracturing without impact (Fig. 1). Rotation combined with drawdown (weight-on-bit) produces crushed zones in front of the teeth of these bits (Nishimatsu, 1972). Chips are formed between fractures propagated from these crushed zones to the rock surface or to pre-existing fractures (Appl and Rowley, 1963; Varnado, 1980).

FIG. 1 -- Conceptual illustration of cuttings production by a drag bit.

Tricone bits produce cuttings by impact with subordinate drag. Those designed for moderately hard rocks have offset cones, the axes of which do not cross the bits' center of rotation (Moore, 1974). Because of this offset, the milled teeth or tungsten carbide inserts on the cones cannot track properly, and a slight gouging action results. Hard rock tricone bits have little or no cone offset and correspondingly reduced gouging action. A conceptualized penetration sequence for a tricone bit, based in part on rock penetration experiments by Sikarskie and Cheatham (1973) and Somerton (1959), is illustrated in Figure 2. The bit tooth (or button) strikes the rock essentially vertically, forming a compacted crushed zone directly beneath the

Figure 1. Conceptual illustration of cuttings production by a drag bit. A, rotation combined with drawdown causes the bit tooth to gouge the rock, forming a crushed zone from which fractures are propagated forward to the rock surface or to pre-existing fractures. B, further movement of the tooth dislodges the crushed zone and a drill chip while forming a new crushed zone and fractures. The dislodged crushed zone may survive transport up the borehole to appear in cuttings as pseudo-gouge. Modified from Nishimatsu (1972), Appl and Rowley (1963) and Varnado (1980).

Figure 2. Conceptual illustration of cuttings production by a tricone bit. A, bit tooth (or insert) (1) strikes the rock under heavy drawdown, forming a crushed zone from which fractures are propagated to the surface or to pre-existing fractures. B, as the bit cone rolls forward, tooth (2) strikes the rock. This second impact, together with slight lateral tooth movement and drilling fluid circulation, dislodges the chips and crushed material (pseudo-gouge) formed by the previous impact. Based on experimental work by Sikarskie and Cheatham (1973).

tooth point. Fractures are propagated downward and outward from this crushed zone to intersect pre-existing natural fractures or those induced by previous impacts. Chips formed between these fractures are dislodged by subsequent impacts together with slight lateral tooth movement and the jetting action of drilling fluid. The crushed zone may survive transport up the borehole as friable pseudo-gouge (to be subsequently discussed in detail), which in cuttings commonly resembles naturally occurring fault gouge.

FIG. 2 -- Conceptual illustration of cuttings production by a tricone bit.

Diamond drill bits, of unit construction and studded with small diamonds, penetrate exclusively by rotary grinding and produce extremely fine cuttings. Cable tools, by contrast, drill by repeated impact of a heavy chisel-shaped bit with a single tooth. Although such a bit could produce very large chips, cable tool cuttings are generally rather small, since they are not continuously removed from the hole and therefore are extensively recut.

Cuttings production is affected not only by bit type, but also by such other variables of the drilling process as rotary drilling speed, drawdown or weight-on-bit, and density and circulation rate of drilling fluid. Mud- or water-drilled cuttings travel up a borehole annulus at a moderate rate (average about 100 ft/min -- Low, 1977) with little or no milling and mixing. Those drilled and transported in air or an air-water-foaming agent mixture, however, may be significantly mixed and abraded. To remove cuttings effectively, air or air-based drilling fluids must be circulated at 3000 to 7000 ft/min (Hobbs, 1979; Wolke, 1980), rates which temporarily may be boosted even higher by penetration into a high-pressure gas or steam zone. Such high fluid velocities cause considerable turbulence and resultant abrasion of cuttings by impact with the hole wall, the drill string and other chips.

Cuttings from deeper air-drilled holes, which require the highest fluid circulation rates, commonly are rounded and pitted through selective erosion of softer minerals such as micas and clays. In shallower air-drilled holes or in those where a foaming agent is added to help transport cuttings, sample abrasion and selective mineral attrition may be minor.

Chip size, shape and texture are strongly influenced by the physical characteristics of the rocks penetrated. Large cuttings are favored by rocks which are soft, heterogeneous, coarse grained and poorly consolidated, and highly fractured. By contrast, hard and unfractured rocks, or those which are fine grained and readily disaggregated, tend to yield small cuttings. In monomineralic isotropic rocks, bit type and drilling method will be the dominant factors in chip formation, but rock characteristics remain important controls. Cuttings from a brittle isotropic rock such as quartzite, for example, tend to be thin conchoidal fragments (Somerton, 1959) whereas in a soft rock such as claystone shavings may be produced.

SAMPLE COLLECTION

Effective logging and subsurface interpretation require careful collection and handling of cuttings samples. Poor samples can cause a variety of interpretive errors. Fine grained ore minerals, as one example, can be lost from mud-drilled cuttings if openings in shaker screens (used to separate cuttings from mud) are too large. These errors can be minimized or eliminated if sampling procedures are designed and supervised by geoscientists familiar with drilling methods and with the geology of the site to be drilled.

Cuttings samples should be as representative as possible of an entire drilled interval. Since the geology of geothermal systems and mineralized

terrain can be very complex and can change abruptly, cuttings should be collected at relatively short intervals to minimize or avoid homogenization of multiple lithologies or alteration types in a single sample. Ten feet probably should be the maximum interval for routine sampling. Samples taken continuously, when practical, are more representative than "grab" or spot samples, which can miss entirely a geologic unit smaller than the sample interval.

Mud- or water-drilled cuttings, especially those from deep, large-bore wells, commonly are separated from drilling fluid on sloped, vibrating and/or rotating shaker screens ("shale shakers"), the many designs of which are beyond the range of this discussion. Cuttings, which through screen vibration may be partially classified according to chip size and density, are collected either directly from the shaker or from its discharge. Screen openings should be as small as practical to retain finer grained material, the loss of which can bias sample interpretation and analysis. Openings of 0.77 mm to 1.54 mm are typical, but finer screens commonly are used for fine grained sediments such as penetrated in Imperial Valley, California, geothermal wells (Westin, 1980). Material which passes through shaker screens can be removed from the drilling fluid by desanders, desilters and decanting centrifuges, and considered along with corresponding coarser cuttings if necessary.

Shallow mud- or water-drilled boreholes are generally completed by small rigs without shaker screens. Cuttings from these wells are collected with drilling fluid either from a mud ditch between the open hole and a mud pit, or, if surface casing is installed, in a bucket at the end of a short discharge pipe. The bucket can be emptied and cleaned at the end of each interval to ensure representative sampling. Alternatively, samples from the

pipe can be caught in a strainer, although this method will result in loss of finer grained material with drilling fluid through openings in the strainer screen. Yet another method, successfully used on several geothermal boreholes in Nevada, involves channeling fluid and cuttings over a stacked set of sample splitters (H. D. Pilkington, AMAX Exploration, Inc., pers. comm., 1980).

Air-drilled boreholes do not require shaker screens. On shallower holes of this type, samples are collected from the mound of cuttings which forms around the orifice. On deeper holes, such as typically drilled in The Geysers geothermal area, California, returns (air and cuttings) are conducted away from the well head through a baffle line, where water may be added. The moistened mixture then enters a muffler, or cyclone separator. The gaseous fraction of the returns, along with some rock powder, is exhausted from the top of the muffler; remaining coarser cuttings and water flow out the bottom. At The Geysers, this coarser fraction generally is trapped in a half-culvert lined ditch, from which samples are collected at regular intervals. The ditch is cleaned after each sample to minimize contamination (M. Twitchell, Aminoil, Inc., pers. comm., 1980).

Sample Lag

As cuttings are collected, a sample generally is labelled with current drilling depth. However, because drilling continues while cuttings are in transit to the collection point, this recorded depth is greater than the actual depth of the sample. The difference between the two depths is the sample lag, discussed in detail in Low (1977) and Hobbs (1979), who also provide methods for its calculation. Lag is negligible for air-drilled boreholes, in which cuttings transported in a high-velocity air stream reach the surface almost immediately after they are produced. Lag also is minimal

in mud- or water-drilled boreholes penetrating the hard igneous and metamorphic rocks typical of geothermal systems and mineralized terrain, since drilling rates in these rocks rarely exceed 3-10 ft (1-3 m) per hour.

Field Preparation, Packaging and Storage

Borehole cuttings generally will be studied not only on site while drilling is in progress, but later, when detailed examination and analysis may be necessary for further characterization or location of a resource. Thus, cuttings samples should be field-prepared and packaged so that physical and chemical changes during storage are minimized or eliminated.

Field preparation generally involves only washing the samples to remove foreign material, although this process commonly is deferred until cuttings are actually needed for study. Among the advantages of field washing are reduction of subsequent laboratory preparation time and acceleration of sample drying through removal of drilling fluid and other contaminants. Drilling fluid may contain active chemicals such as caustic soda which can react with cuttings if they are stored wet before washing. Disadvantages of field washing include lack of time and proper equipment and unavailability of de-ionized water if required. Hasty washing, generally through insufficiently fine screens, may result in loss of the finer grained component of cuttings with drilling fluid. Washing with de-ionized water may be required if chemical analysis of cuttings is anticipated.

Sample containers should be large enough to contain 500 g or more of cuttings, sufficiently durable to withstand transportation and storage, and completely identified (borehole, depth interval, etc.) with permanent waterproof ink on securely attached labels. Type of package required will depend on the nature of studies planned for the cuttings. Those to be

analyzed for volatile elements such as arsenic and mercury, for example, should be packaged in air-tight glass or heavy plastic. Although containers made of these materials are bulky and may cause handling problems (such as glass breakage), they eliminate element loss and cross-contamination of samples. Generally, however, cuttings will be placed in cloth or paper bags, which are relatively inexpensive and easy to handle. Since they are porous, these bags also facilitate sample drying.

Most samples should be stored dry, since moisture may alter the appearance and composition of cuttings. Drill steel, for example, readily rusts when moist and may stain and obscure cuttings or may resemble indigenous limonite (Hulen, 1978). Wet storage also promotes hydration and resultant softening of formation clays, which then are lost from samples when subsequently washed. Dried drilling mud may weakly bind cuttings, but it is easily redissolved and removed by washing.

SAMPLE PREPARATION

Careful preparation of drill cuttings for examination or analysis helps ensure they will yield maximum information about a subsurface resource. The wide range of analytical techniques available, and the special sample preparation each requires, exceed the breadth of this discussion. This section will be confined to sample cleaning, a preliminary process required for nearly all methods of cuttings study, and to preparation of samples for binocular microscopic and petrographic examination.

Mud-drilled cuttings should be washed to remove drilling mud and other foreign debris, such as lost circulation material, in such a way that loss of natural constituents of the drilled rock is minimized. An effective washing

method involves pouring water over a sample in a shallow pan, gently stirring, and carefully decanting. The process is repeated until most lost circulation material has floated from the cuttings and the decanted water is clear of drilling mud. This method is preferable to washing cuttings in a screen, through which much of the fine fraction of a sample can be lost along with drilling fluid. Even the decanting method, however, can remove some natural clay and silt from such materials as alluvium or soft argillized rock if samples are over-washed.

De-ionized water may be useful for washing cuttings in preparation for chemical studies. In many cases, however, this special technique may be superfluous. Mud-drilled cuttings, for example, already may be contaminated with a wide variety of ions derived from drilling fluids and additives and adsorbed on natural rock clays and micas.

After washed cuttings have been dried, either naturally or in an oven at low heat, remaining larger or heavier foreign debris such as cottonseed hulls and various metals can be removed by hand-picking. Drill steel can be magnetically removed, but this method will also remove some natural magnetite as well as any mineral with which it is intergrown.

Air-drilled cuttings are devoid of the introduced clays, lost circulation materials and other additives used for mud drilling and therefore require washing only to remove fine rock dust, which may obscure larger cuttings during binocular microscopic examination. Metals, however, are very common contaminants in these cuttings (Wolke, 1980). Steel and iron, the most prevalent, can be removed magnetically (inevitably along with some natural magnetite) if not thoroughly rusted. Other metals can be hand-picked, but in spite of meticulous effort, the cuttings may remain slightly contaminated.

Such residual contamination should be taken into account if the cuttings are further analyzed by chemical or other methods.

Binocular microscopic study requires little preparation of drill cuttings after washing. The samples can be examined loose in small dishes, but pouring cuttings out of and back into bags is time consuming and messy. This problem can be avoided by examining samples in shallow paper cups, which then can be capped for storage.

Cuttings can be examined most efficiently when glued on chipboards (Fig. 3) or canvas strips. These devices, at an appropriate scale and with depth intervals clearly marked, allow rapid examination and comparison of large numbers of samples while eliminating unnecessary sample handling. Chips are firmly secured for easy scratch testing. Subtle variations in color and texture, which could be overlooked without multiple sample comparison, are detected easily on chipboards. Canvas strips, as an added advantage, can be rolled up for easy storage. The small amount of each sample (typically about 1.5 g) used to prepare these boards or strips, however, may not always be adequately representative.

FIG. 3 -- Drill cuttings mounted on chipboards.

For petrographic study, cuttings are embedded in epoxy which then is sliced to make a grain-mount thin-section. These sections must be prepared with care, since differential settling rates of chips with different sizes and/or specific gravities in the viscous epoxy can result in a non-representative slice. Even with careful preparation, thin-sections can be less representative than chipboard intervals, since they incorporate a far smaller portion of an entire cuttings sample.

SAMPLE BIAS CAUSED BY DRILLING AND SAMPLE PREPARATION

The different mineral constituents of a rock may offer variable resistance to crushing during drilling. Softer, more brittle or otherwise weaker minerals, for example, are likely to be selectively pulverized or disaggregated (Somerton, 1959). Thus reduced in grain size, they may be lost from a cuttings sample, either with drilling fluid at the collection point or later when the sample is washed. Harder, more resistant constituents thereby may become enriched in cuttings relative to the rock from which they were drilled. For example, graywacke cuttings from the deeper portions of many air-drilled wells in The Geysers geothermal area are richer in quartz than the corresponding rock in the borehole (M. Twitchell, Aminoil, Inc., pers. comm., 1980).

Cuttings samples enriched in certain minerals and depleted in others compared to their source rocks can cause a variety of interpretive errors. Soft, argillized and sericitized intervals in a borehole, for example, can be overlooked or underemphasized if clays and sericite are eliminated from cuttings. Removal of clays and limonites from a sample may significantly diminish potential geochemical anomalies, since many diagnostic trace elements are known to be concentrated in these minerals (Levinson, 1974, 1980). Samples enriched in quartz, one of the best natural heat conductors (Kappelmeyer and Haenel, 1974) will yield erroneously high thermal conductivity values and correspondingly low thermal gradients.

Selective mineral depletion in cuttings also affects poorly consolidated clastic sedimentary rocks. These rocks tend to break around, rather than through grains, liberating finer grained matrix constituents and cement to be removed from samples along with drilling fluid. In this way, fine grained,

uranium-bearing organic carbon is commonly washed out of cuttings from roll-front sandstone uranium deposits such as those of the Crooks Gap and Gas Hills districts of Wyoming. Similarly, intergranular limonite or hematite, which are commonly coprecipitated with (or adsorb) valuable ore metals, can be flushed from cuttings and can stain drilling fluids bright orange- or reddish brown.

CONTAMINATION OF CUTTINGS

Drill cuttings, particularly those from boreholes in highly fractured terrain, frequently are contaminated with a variety of indigenous and introduced debris. Recognition and description of these contaminants is crucial for an accurate subsurface investigation. Fragments from intervals higher in the borehole, for example, if incorporated into subsequent samples, will misrepresent the actual rock penetrated. Analyses of contaminated cuttings will be in error relative to the parent rock. This section briefly discusses common contaminants, methods by which they can be identified, and their influence on physical and chemical measurements of cuttings samples.

Indigenous contaminants in cuttings samples are those derived from previously drilled intervals in the borehole. Generally, they are referred to as caved or sloughed fragments, although rather than always caving into the borehole (as is common during "trips" for bit changes -- Low, 1977) they are probably often eroded or plucked from its walls by upward-flowing drilling fluid. They also may be recycled cuttings -- either those not removed from drilling fluid at the collection point and then recirculated, or those carried into and subsequently flushed from cavities in the borehole wall.

Caved or sloughed fragments in cuttings samples traditionally are

identified by their large size relative to coexisting actual drill chips (e.g. Low, 1977). Thus, samples commonly are passed through coarse screens and the larger fragments discarded prior to examination and interpretation. We believe this technique generally should not be applied to geothermal wells or other boreholes in fractured terrain. Cuttings from fracture zones in these wells can be anomalously large as well as representative of the interval drilled. In samples from well Utah State 14-2 at Roosevelt Hot Springs KGRA, for example, within a fractured, hot water entry zone between 487.7 and 548.6 m (1630 and 1800 ft) (Glenn and Hulen, 1979), average chip size is three to five times as large as in surrounding unfractured rock (Fig. 4). These larger cuttings probably reflect the ease with which fractured rock is dislodged by the drill bit.

FIG. 4 -- Anomalously large cuttings from a fractured probable hot water entry zone in Thermal Power Company geothermal well Utah State 14-2, Roosevelt Hot Springs KGRA, Utah.

Caved fragments may be recognized more reliably, though not unfailingly, by their incongruity in cuttings samples. As a clear hypothetical example, a discrete, rounded and frosted quartz pebble in a sample consisting mostly of angular gabbro chips has certainly caved into or otherwise contaminated the sample, probably from an overlying alluvial horizon. Angular granitic chips in the gabbro sample, however, may be contaminants or may represent in situ dikes or xenoliths. Thorough knowledge of surface geology is essential in determining which of these possibilities is most likely.

Introduced or foreign contaminants in drill cuttings include: cement; drilling muds and mud additives; lost-circulation materials; metal from drillstrings, bits, casing and drillable components of cementing assemblies; thread compounds and other greases; paint and rubber; and material sloughed

Figure 3. Drill cuttings mounted on chipboards.

Figure 4. Anomalous large cuttings from a fractured probable hot water entry zone (above 1800 ft) in Thermal Power Company geothermal well Utah State 14-2, Roosevelt Hot Springs KGRA, Utah.

from the sides of ditches and settling or sampling pits. Most of these substances are readily recognized as contaminants, but several may strongly resemble naturally-occurring materials likely to be encountered in the borehole. A list of the more common contaminants (many of which are further discussed in subsequent sections on lithology and hydrothermal alteration) is provided in Table 1.

Table 1. Common introduced contaminants in drill cuttings.

Borehole cement is an especially troublesome contaminant in cuttings, since it can resemble a variety of rock types and alteration products. It is typically a soft, light gray to buff, finely speckled substance (Fig. 5) which may appear spongy or vesicular, and which effervesces vigorously in dilute hydrochloric acid. Depending on the additives it contains (Table 1), cement easily can be confused in cuttings with chalk, marl, calcareous claystone or siltstone, calcareous tuff, travertine, or any bleached, calcitic, hydrothermally altered rock, particularly an aphanitic volcanic. If cement incorporates cuttings or rock debris from the borehole wall it can also resemble breccia with a matrix of rock flour and calcite. Cement is most likely to contaminate cuttings at and immediately below the bottoms of casing strings, but may slough into any sample collected from lower in the borehole.

FIG. 5 -- Perlite-bearing borehole cement cuttings from Getty Oil Company geothermal well Utah State 52-21, Roosevelt Hot Springs KGRA, Utah.

Physical and chemical analyses of cuttings, frequently helpful in locating and characterizing a subsurface resource, can be seriously compromised by sample contamination. For instance, thermal conductivity measurements, used to determine heat flow in geothermal exploration (Sass et al., 1971), will be erroneously high in samples contaminated with steel or

Table 1. Common introduced contaminants in drill cuttings.

MINERALS	ORGANIC AND SYNTHETIC MATERIALS	METALS (SEE TABLE 2)
<u>Drilling mud clays:</u> -Bentonite (montmorillonite ± illite, mixed-layer clay and kaolinite) -Attapulgite or sepiolite <u>Drilling mud weighting Agents</u> -Barite -Hematite -Calcite -Galena -Ilmenite <u>Cement</u> <u>Cement additives</u> -Silica flour -Perlite -Pozzolan -Diatomaceous earth -Bentonite -Hematite -Barite -Mica -Quartz sand -Gypsum	<u>Drilling mud thinners and dispersants</u> -Lignite and lignosulfonate <u>Drilling mud lubricants</u> -Silica or glass spheres <u>Lost-circulation materials</u> -Nut Shells -Wood fiber -Cane fiber -Seed hulls -Paper -Lignite (coarse) -Cellophane -Processed formica and other plastics -Miscellaneous locally available material such as alfalfa cubes <u>Cement Additives</u> -gilsonite and coal <u>Rubber and Plastic</u> -Jackets on cement plugs	<u>Metal shavings from the drilling system</u> -Steel, brass, etc. <u>Drillable metal from downhole cementing assemblies</u> -Lead, iron and aluminum <u>Coloring agents</u> <u>Metals in thread compounds and other greases</u>

Figure 5. Perlite-bearing borehole cement cuttings from Getty Oil Company geothermal well Utah State 52-21, Roosevelt Hot Springs KGRA, Utah. A, cement cuttings (medium gray with white speckles) with grains of granitic alluvium. B, thin section (transmitted light) of cement chips shown in (A) mounted in epoxy; matrix is cement; white, angular fragments are quartz; larger subrounded light gray inclusions are partially devitrified perlite; dark inclusions are an unidentified opaque mineral.

other conductive metal. Density measurements on these metal-contaminated samples will also be high relative to the corresponding undrilled rock. Perhaps most frequently misleading, though, are geochemical analyses of contaminated cuttings.

Influence of Contamination on the Geochemistry of Drill Cuttings

Multi-element solids geochemistry has long been successfully applied by the mining industry to the search for and characterization of mineral deposits. These deposits commonly are surrounded by geochemical haloes, the nature and intensity of which, as detected in soil, rock, core and cuttings, can be used to predict directions to and distances from ore-grade mineralization (Levinson; 1974, 1980). Geothermal systems also are geochemically zoned. Ewers and Keays (1977), Bamford et al. (1980) and Christensen (1980a, 1980b) have demonstrated that solids geochemistry can be useful in estimating the size and configuration of a geothermal system and in locating or predicting approach to thermal fluid entries within these systems. At Roosevelt Hot Springs KGRA in Utah, for example, thermal fluid flow paths are commonly signalled by anomalous concentrations of mercury, arsenic and lithium in drill cuttings and in specific gravity concentrates prepared from these cuttings (Bamford et al., 1980).

The geochemistry of a cuttings sample, however, may not accurately reflect the geochemistry of the rock from which it is obtained. Clays, iron oxides, sulfides and other minerals in which diagnostic trace elements commonly are concentrated (Levinson, 1974, 1980), for example, may be enriched or depleted in cuttings relative to their source rocks by drilling, sampling and sample preparation. A potentially useful geochemical indicator may be diluted beneath its detection limit by contamination of a cuttings sample.

Most importantly, though, metallic contaminants in cuttings can produce confusing or false geochemical signatures. The more common of these contaminants, their sources and chemistry are presented in Table 2.

Table 2. Chemistry of common metallic and metal-bearing contaminants in drill cuttings.

Figure 6 exemplifies spurious cuttings geochemistry due to metallic contamination. Lead values in cuttings are plotted on the figure opposite cementing locations in the upper part of a well in the Roosevelt Hot springs KGRA, Utah. Strong lead anomalies in the well clearly coincide with cementing sites and are, in fact, due to incorporation in cuttings of drillable lead components of downhole cementing assemblies (Bamford et al., 1980).

FIG. 6 -- Lead geochemistry of cuttings compared with cementing depths in the upper portion of Thermal Power Company geothermal well Utah State 14-2, Roosevelt Hot Springs KGRA, Utah.

EXAMINATION AND DESCRIPTION OF CUTTINGS

The methods used to examine cuttings and the detail with which they are logged will depend largely on the unique requirements of each drilling project. Even cursory cuttings logs, however, should record a minimum number of fundamental features, some or all of which are certain to help characterize or locate the resource under investigation. These features include, but may not be limited to: color(s), rock type(s), grain size(s), rock fabric(s), original mineralogy, alteration mineralogy and intensity, presence of gouge or other evidence of faulting, presence of drill-produced pseudo-gouge, size and shape of drill chips, and types and amounts of contaminants.

Binocular microscopic examination, at 5X to 50X, is adequate for routine

Table 2. Chemistry of common metallic and metal-bearing contaminants in cuttings.

Contaminant	Source	Elements Present
Steel (and rust)	Drill pipe, drill collars, bits, subs, reamers, stabilizers, casing, miscellaneous surface components	(1) Fe, Mo, Cr, Ni, V, S
Tungsten carbide	Bits, stabilizers, reamers, hole openers	W
Thread compounds and other greases	Tool joints, etc.	(2) Pb, Zn, Mo, Cu, Li, Al
Monel metal	Non-magnetic drill collars	(3) Cu, Ni
Cast aluminum, lead and iron; iron filings	Drillable metal components of downhole cementing assemblies	(4) Al, Pb; Fe (Al and Fe may be alloyed with or contaminated by minor amounts of other metals)
Paint	Painted components of the drilling system	(3) (Examples) Blue: Cu, Co, Sn Red: Cd, Fe White: Pb, Zn, Ti
a. Galena b. Barite c. Hematite	Mud weighting agents	(5) a. Pb, S b. Ba, Cu, Pb, Zn, Ag, Mn, Ni, Sr S c. Fe
Chrome- and ferrochrome lignosulfonates	Mud thinners	Cr, Fe

(1) U. S. Steel, 1964 (2) Bestolife, 1980-81; Jet-Lube, 1980-81; Oil Center Research, 1980-81; (3) Chemical Rubber Company, 1976-77 (4) Smith, 1974; Bamford et al., 1980; Halliburton Services, 1980-81; R. W. Bamford, pers. comm., 1981. (5) Dypvik, 1981.

data from Bamford et al., 1980

Figure 6. Lead geochemistry of cuttings compared with cementing depths in the upper portion of Thermal Power Company geothermal well Utah State 52-21, Roosevelt Hot Springs KGRA, Utah.

cuttings logging. Wetting the cuttings may enhance the visibility of otherwise obscure features such as finely disseminated sulfides. As previously discussed, most cuttings can be logged routinely using chipboards. For intervals of special interest or complexity, however, a fairly large sample portion (at least 10g) should be examined. Smaller portions, such as those used to prepare chipboards or grain-mount thin sections, may not be adequately representative of the rocks penetrated, particularly if the rocks are heterogeneous, coarse-grained, or hydrothermally altered.

Simulated drill cuttings of representative surface rocks, both altered and unaltered, greatly facilitate identification and description of downhole rock types and alteration. These simulated cuttings, prepared by crushing and screening selected hand samples, should be consulted with caution, however, since not all rocks encountered in a borehole will have surface equivalents.

Petrographic examination may be necessary to confirm or expand preliminary descriptions of cuttings. However, it should complement, rather than supplant, careful binocular microscopic study. For example, a fine grained, light-colored but otherwise nondescript chip which could be either cement or a calcareous tuff or mudstone, generally can be positively identified only in grain-mount thin section. Certain other rocks, though, such as those which are strongly argillized and iron-stained, remain obscure even petrographically. Thin sections are most useful for identifying unaltered, homogeneous rocks with grain size less than drill chip size. If grain size exceeds chip size, the characteristic intergrain relationships of a rock are obliterated.

Cuttings log formats and styles should be tailored to the particular

needs of each subsurface investigation. Useful examples of log formats for sedimentary sequences are provided by Hills (1949), Low (1977), Maher (1964) and Hobbs (1979). Log formats for geothermal and mineral exploration boreholes will be similar to these examples but also should provide columns for graphically recording alteration and mineralization, which are very useful in resource exploration and characterization. Regardless of format and detail, logs should include both descriptions of cuttings as well as some interpretation of those descriptions, since an examiner can best interpret how the rocks penetrated in a borehole relate to the overall geology of a project area.

INTERPRETATION OF LITHOLOGY FROM DRILL CUTTINGS

Correct identification of subsurface lithology is important not only for stratigraphic and structural correlation, but also because certain rocks may selectively host the resource under investigation. Careful rock type determination also allows more accurate geophysical well log interpretation. The use of geophysical logs in petroleum wells to characterize sedimentary sequences is well-documented (for example, Maher, 1964). Such logs are also useful, moreover, for deciphering the complex igneous and metamorphic geology commonly encountered in geothermal and mineral exploration boreholes (Keys, 1979; Sanyal et al., 1980). Potassic igneous rocks such as granite and rhyolite, for example, produce conspicuous positive gamma-ray anomalies (Keys, 1979). Rocks rich in hydrous minerals such as biotite and chlorite are characterized by their spuriously high responses on neutron porosity logs (Nelson and Glenn, 1975). Graphitic rocks which cause resistivity lows can be confused with conductive thermal water entry zones in geothermal wells (Sibbett and Glenn, 1981).

Rocks which are recognized readily in outcrop or core frequently can be difficult to identify and differentiate as drill cuttings. Larger-scale diagnostic features, including boulders, bedding and segregation banding, phenocrysts, flow-breccia, xenoliths, and grain boundaries in coarser grained rocks, can be obliterated by the drilling process. Dissimilar rock types thus can closely resemble one another in a cuttings sample. At the Roosevelt Hot Springs KGRA, for example, massive Tertiary granitic rocks are believed to be far superior as reservoir hosts to the foliated Precambrian gneisses they intrude (Sibbett and Nielson, 1980), yet the two rock types can be mistaken for one another in drill cuttings (Fig. 7). As previously discussed, rock identification can be complicated further by contamination and by compositional discrepancies between cuttings and their source rocks.

FIG. 7 -- Hand samples and simulated drill cuttings of Precambrian gneiss and Tertiary quartz monzonite from Roosevelt Hot Springs KGRA, Utah.

Local lithologies typically vary widely in character and composition from general descriptions provided by regional reports and maps, textbooks or manuals. Thus, direct knowledge of local geology, as well as field experience in the type of geologic environment being drilled, are essential for determination of rock types from cuttings, especially in complex igneous and metamorphic terrain.

The remainder of this section will discuss in detail recognition and interpretation of the major lithologic groups as drill cuttings -- alluvium and other unconsolidated deposits, sedimentary rocks (clastic and chemical), volcanic and hypabyssal rocks, and plutonic and metamorphic rocks. The discussions on sediments and sedimentary rocks will emphasize those occurring in the structurally complex and commonly altered sequences likely to be

Figure 7. Hand samples and simulated drill cuttings of Precambrian gneiss and Tertiary quartz monzonite from Roosevelt Hot Springs KGRA, Utah. A, hand samples (gneiss at left). B, simulated cuttings of gneiss. C, simulated cuttings of quartz monzonite.

encountered in geothermal and mineral exploration boreholes. Interpretation from drill cuttings of the unaltered, relatively undisturbed sediments and sedimentary rocks which host petroleum reservoirs is thoroughly discussed in Hills (1949), Maher (1964) and Low (1977). Wells (1969) and Hobbs (1979) provide guidelines for logging, respectively, cuttings from placer deposits and coal sequences.

Alluvium and Other Unconsolidated Deposits

Many geothermal and mineral exploration boreholes are collared in unconsolidated surficial deposits. A good lithologic log may be the only source of data for these deposits, since the upper parts of boreholes commonly are cased to depths of several hundred feet before any geophysical logs are run.

Because unconsolidated materials are disaggregated almost totally when drilled, many of their depositional features are obliterated. Much of the matrix material, for example, including clay, silt and fine sand, may be lost with drilling fluid at the sampling point or during washing. Matrix grain size and degree of sorting largely determine alluvial permeability, so the loss of matrix from a sample precludes accurate assessment of the efficiency of an alluvial horizon as an aquifer. Since the matrix material generally contains most alteration and other secondary minerals, its loss also can eliminate valuable clues to the nature of and distance from a resource.

In spite of these difficulties, considerable information can be gained from careful logging of alluvial cuttings. Such features as degree of rounding and sorting, lithologies and minerals present, grain size distribution, cementation and alteration will assist with stratigraphic correlation between holes and may provide control on structures and alluvial

aquifers.

Post-depositional alteration in alluvium can be good evidence for contemporary or recent geothermal activity. It can be distinguished from pre-depositional alteration by the relationship of alteration to grain surfaces. Whereas pre-depositional alteration is confined to individual grains, post-depositional alteration may affect grain surfaces and the matrix between grains. Euhedral crystals and stains or crusts on grain surfaces are especially indicative of late-stage alteration. Thorough knowledge of surface bedrock alteration also is useful in deciding age relationships of alteration minerals in alluvium.

The depth and nature of the contact (faulted or depositional) between alluvium and bedrock in a borehole are extremely important for the interpretation of various geophysical surveys as well as subsurface structure. Generally this contact is easily determined unless the bedrock is immediately overlain by compositionally identical gravel, conglomerate or, in the case of weathered crystalline rock, by a thick grus. Alluvium generally contains variably-colored, multiple lithologies, whereas bedrock tends to be homogeneous and uniformly colored. Angular chips are typical of bedrock, but also may be produced from larger pebbles, cobbles or boulders in gravel or conglomerate. Chips from these sediments, however, may retain a few rounded surfaces which belie their origins. Gravels generally are yellowish to brownish colored from surface weathering during erosion, transport and deposition. Chips from paleo-weathered zones on bedrock may be colored similarly, but will be invariably angular.

Drilling rate and other borehole logs may help identify a bedrock-alluvium contact. For example, drilling rate typically decreases dramatically

in bedrock, with a corresponding increase in the density response. Drilling rate, however, is affected by other factors than formation hardness, and hardness contrast, in fact, may be greater at the base of a weathered zone than at the base of alluvium. A gradational contact between grus and its parent crystalline rock sometimes can be interpreted from the drilling rate and the degree of weathering observed in cuttings.

A number of features may help distinguish a bedrock-alluvium contact as faulted or depositional. A depositional contact, for example, may exhibit a paleosol, regolith, or weathered zone at the top of bedrock. A fault contact, by contrast, generally lacks a weathered zone, although it may be characterized by brecciation and alteration of one or both formations. A faulted contact may cause a sharp deflection of a drill hole which will be apparent on a directional survey. Surface traces of known faults can be projected downward to the borehole, and the angles of the projections compared with actual measured dips on the faults to determine the probability that these structures intersect the borehole to form the bedrock-alluvium contact. Similar downward projections of bedrock erosional slopes should make clear if the borehole bedrock-alluvium contact is more likely to be depositional.

Sedimentary Rocks

Common sedimentary rocks -- sandstones, siltstones, shales and carbonates -- are very well documented (see, for example, the references in the introduction to this section), since they host or are associated with petroleum reservoirs. Terrestrial volcaniclastic rocks, however, particularly as drill cuttings, are less thoroughly understood. Since these rocks are commonly encountered in geothermal and mineral exploration boreholes, they

will be emphasized in the discussion which follows.

Tuffaceous or volcanoclastic sediments possibly are the most difficult clastics to log, since they tend to occur in complex sequences which may include waterlain, air-fall and non-welded ash-flow tuffs, lahars, lava flows and dikes. Tuffaceous sediments typically are very heterogeneous, poorly sorted and altered. Bedding in these immature sediments generally is too ill-defined to be evident, although bedding may be indicated by rapid changes in color and texture from sample to sample.

Volcanoclastic or tuffaceous sediments commonly are so argillized that most original textures are destroyed. The argillized sediments thus may resemble similarly altered glassy volcanic or subvolcanic intrusive rocks or tuffs. The sediments, however, commonly contain relict rounded detrital grains. Free euhedral crystals in the argillized matrix are more typical of altered volcanic or subvolcanic intrusive rocks, whereas broken crystals generally indicate a pyroclastic origin.

Descriptions of tuffaceous or volcanoclastic sedimentary rocks should include, in addition to grain size, sorting, rounding, lithology, mineralogy and alteration, the type of cementing material and potential porosity. Although formation color in the subsurface is often different from that of the outcrop, it should be noted for help in correlation between boreholes. The degree of lithification or metamorphism also is important. For example, a shale has poor reservoir potential but a slate -- its metamorphic equivalent -- may develop fracture permeability.

Siliceous and calcareous sinter, distinctive hot spring deposits in outcrop, can as cuttings resemble a wide variety of other rock types and

alteration products. Siliceous sinter is of particular interest in geothermal exploration, since it indicates past or present reservoir temperatures of at least 180°C (White et al., 1971). In cuttings, however, it can be mistaken for a bedded siliceous sediment or hydrothermal silicification. Some siliceous sinter can be identified by a tendency to be porous and to incorporate frothy-appearing petrified plant debris or casts, as at Baltazor Hot Springs KGRA, Nevada (Hulen, 1979). Spring-deposited calcareous sinter (travertine) can be nearly impossible to distinguish in cuttings from cave travertine, fresh water limestone, algal deposits, borehole cement, hydrothermal vein calcite, or practically any fine grained calcareous sedimentary rock. Petrographic study may be necessary to help clarify the origin of a suspected travertine sample.

Volcanic, Subvolcanic and Hypabyssal Rocks

Volcanic, subvolcanic and hypabyssal rocks include a wide variety of rock types, fabrics and modes of formation. Pyroclastic rocks are particularly difficult to work with in cuttings because most large-scale textures such as sorting and bedding will be destroyed by drilling. Familiarity with the unique textures and mineral compositions of these rocks will aid the logger. Uncompacted pumice, for example generally will be destroyed during drilling but fiamme (compacted pumice), shards and eutaxitic texture may be visible with a binocular microscope. The fragmental texture of a pyroclastic rock (which may require petrographic confirmation) may give chips a mottled appearance even when altered. Phenocrysts generally are present both in tuffs and flows, but if broken are much more typical of a pyroclastic origin. Cinders will contain unbroken phenocrysts, but also rounded vesicles. As previously discussed, non-welded tuffs may be hard to distinguish from tuffaceous sediments, but clast rounding and sorting as well as a high content

of rounded multi-lithologic clasts suggests water deposition. Rounding alone, however, is not definitive evidence of sedimentary origin, since soft tuff chips can be highly rounded during transport up the drill hole.

Lava flows and subvolcanic or hypabyssal intrusives may be impossible to differentiate as cuttings, but several features, if present, may be helpful for their identification. Flows, particularly near their tops and bottoms, are more likely to contain rounded vesicles or amygdules and chilled and oxidized flow breccia. Subvolcanic or hypabyssal rocks, on the other hand, may have chilled borders but generally lack margin breccia and, unlike flows, may have fault contacts. Baking of the country rock on both contacts of the body in question would be evidence for an intrusive origin. Mineralization and alteration in the country rock adjacent to the contact also would suggest the body to be an intrusive.

Metamorphic and Plutonic Rocks

The metamorphic rocks, as a group, are perhaps the most difficult to recognize in drill cuttings. Lower-grade metamorphic rocks as cuttings may be indistinguishable from their igneous and sedimentary parent lithologies. Chips of high-grade gneiss and migmatite, on the other hand, may closely resemble plutonic rocks in texture and mineralogy. Distinguishing downhole plutonic rocks from coexisting gneisses can be crucial to a geothermal evaluation. Gneisses, if foliated, are less competent than massive plutonic rocks and are less likely to develop and sustain fracture permeability for thermal fluid flow.

Characteristic mineral assemblages in drill chips are the best indicators of metamorphism, especially the higher grades. For example, cuttings of a rock consisting mostly or entirely of quartz and biotite, or containing

diagnostic minerals such as cordierite, sillimanite and kyanite, are almost certainly of high-grade metamorphic origin. Lower-grade metamorphic minerals, such as chlorite, albite and epidote, are much less useful as genetic indicators, since they are also common in hydrothermally altered terrain (Rose and Burt, 1979).

Certain rock textures apparent in drill cuttings strongly suggest a metamorphic origin, whereas others are ambiguous, particularly in thin-section. Crystalloblastic textures, resulting from crystal growth in a solid medium, provide good evidence for metamorphism. Such textures are characterized by "triple point" grain boundaries and/or by a mosaic of more or less polygonal grains with boundaries bearing no definite relationship to crystallographic axes or cleavage directions. Foliation is diagnostic of a metamorphic rock only if particularly well developed (as in phyllites and mica schists), since it may also form in response to flowage in volcanics and at the margins of intrusives. Cataclasis, elongation of grains and grain aggregates, mortar texture, kink-banding and strain-shadowing, can be produced not only by dynamic metamorphism, but also by renewed movement of partially crystallized magma. Cataclasis and strain shadowing of minerals also may be produced by the drilling process.

The crystalloblastic series, which ranks minerals by tendency to form euhedral crystals in a solid growth medium, may help identify a rock chip as igneous or metamorphic. Quartz and feldspar rarely develop euhedral crystal faces in metamorphic rocks, for example, but are quite common in many plutonic rocks.

Alternating mafic and felsic segregations in gneisses and schists may be homogenized in a cuttings sample. In the absence of diagnostic minerals,

these layered metamorphic rocks can be distinguished from mineralogically similar but massive intrusive rocks by their geophysical well log responses. Whereas massive rocks produce fairly uniform geophysical signatures, layered rocks are characterized by fluctuating and highly variable responses.

RECOGNITION OF FAULTS AND FRACTURES FROM DRILL CUTTINGS

Recognition of faults and fractures is one of the most important aspects of subsurface exploration and development. Faults and fractures commonly are the dominant physical controls on the commodities under investigation. Faults, for example, host, truncate and displace ore bodies, provide traps for petroleum accumulation and, in geothermal systems, serve as major channels for thermal fluid flow. Permeability in most geothermal systems, in fact, is provided by faults and fractures developed in otherwise tight and impermeable host rocks (Sanyal et al., 1980).

Faults and fractures penetrated in drill holes traditionally are identified indirectly. They are commonly "lost circulation" zones which remove fluids from a drilling system. They also may contribute fluid to the system, causing a well "kick". In most cases, however, these structures are recognized by their responses on appropriate well logs, including caliper (borehole enlargement), acoustic velocity (which decreases in disrupted rock) and resistivity (which decreases in faults or fractures if saturated with conductive fluid).

Faults, particularly those developed in competent rocks, occasionally can be recognized directly from drill cuttings by the presence of slickensiding and chips of gouge, breccia, cataclasite and mylonite. Not all faults, however, provide such physical evidence of their existence. Gouge and

microbreccia generally are soft and friable, easily disaggregated by the drilling process and subsequently removed from cuttings during sample collection or washing. Faults disrupting incompetent rocks such as mica schists may even lack a crushed zone, and therefore may completely escape detection in cuttings samples.

Drilling produces artificial gouge, cataclasite and slickensides which can be confused with their natural counterparts. Cuttings produced from a block of massive, unfractured quartz diorite during laboratory air drilling experiments conducted in 1980 by Terra Tek, Salt Lake City, Utah, contain 1.5-2 volume percent pseudo-gouge¹ (Fig. 8; see also Figs. 1 and 2). This material, identical to that observed in cuttings from many boreholes, forms conspicuously light-colored, crudely discoid or tabular chips which, although friable, are commonly slickensided.

FIG. 8 -- Drill-produced pseudo-gouge chips hand-picked from laboratory air-drilled quartz diorite cuttings.

Several prominent characteristics of pseudo-gouge distinguish it, though not invariably, from fault-produced gouge and breccia. Pseudo-gouge is always friable, whereas natural material may be well-indurated and very resistant to crumbling. Only natural gouge and cataclasite can be hydrothermally altered (or cemented), although such alteration can be simulated by crushing and streaking of rock-forming or alteration minerals in the rock penetrated. Slickensides on pseudo-gouge chips, probably produced mainly beneath tungsten carbide "button" inserts in tricone bits, commonly are concave (Fig. 8), very smooth though not polished, and thinly smeared with mafic minerals or streaked

¹/ Actually pseudo-cataclasite, but herein referred to as pseudo-gouge for convenience.

Figure 8. Drill-produced pseudo-gouge chips handpicked from laboratory air-drilled quartz diorite cuttings. Note characteristic concave surfaces. Dark material is crushed and smeared biotite. Largest chip at upper left is 5 mm in length.

with dark bit metal. Natural slickensides, although rare in cuttings, are more likely to be flat or convex, polished, and furrowed or striated.

Fractures, along which no movement has occurred, generally cannot be directly detected in cuttings by visual examination. Where fractures have provided pathways for thermal fluid flow, however, as in geothermal systems and mineral deposits, their wallrocks may be hydrothermally altered. Thus alteration of cuttings may indirectly signal subsurface fracturing. Such alteration, however, commonly is accompanied by reduction or elimination of original permeability through formation of hydrothermal veinlets by open-space filling of former fractures.

Anomalous large cuttings also may indicate fracturing. In well Utah State 14-2 at Roosevelt Hot Springs KGRA, for example, within a geophysically confirmed (Glenn and Hulen, 1979), fractured hot water entry zone between 487.7 and 548.6 m (1600 and 1800 ft), average chip size (3-5 mm) is three to five times as large as in surrounding unfractured rock (Fig. 4). These larger cuttings may reflect the relative ease with which fractured rock is dislodged by the drill bit. In some cases however, larger cuttings may indicate only a change of bits; all other variables equal, a new bit will produce larger cuttings than a dull one.

INTERPRETATION OF HYDROTHERMAL ALTERATION IN CUTTINGS

Most mineral deposits and geothermal systems are accompanied by hydrothermal alteration of their host rocks. Alteration around mineral deposits commonly is strong, pervasive and arranged in well-developed zones or halos which in exploration boreholes can be used to determine vectors and approximate distances to mineralization (Levinson, 1974, 1980; Rose and Burt,

1979). In many geothermal systems, by contrast, alteration is generally weaker and more erratically distributed. Nonetheless, it can be used to help define the three-dimensional geometry of these systems and to locate and predict approach to thermal fluid entry zones (Elders et al., 1979; Browne, 1978; Sumi and Takashima, 1976; Browne and Ellis, 1970; Steiner, 1968).

Recognition and interpretation of alteration in cuttings is somewhat more difficult than in core or outcrop. The drilling process commonly destroys larger scale diagnostic features of the alteration and may result in elimination of certain alteration minerals from the cuttings with drilling fluid during sample collection or washing.

Alteration textures and paragenetic relationships may be obscured or obliterated in cuttings. All but the smallest veinlets and their cross-cutting relationships are destroyed during cuttings production. Interpretation becomes more difficult as drill chip size decreases. Simulated cuttings prepared from representative hydrothermally altered surface rocks as well as knowledge of surface alteration paragenesis are very useful for subsurface paragenetic interpretation from actual cuttings.

Softer, more brittle, more readily cleaved and finer-grained alteration (and rock-forming) minerals are readily disaggregated by the drilling process and therefore may be depleted in cuttings relative to corresponding undrilled rock. Hydrothermal clays encountered in mud-drilled wells commonly will be completely eliminated from cuttings (along with bentonitic clays present in the mud) during sample collection or washing.

Relict or paleohydrothermal alteration, particularly in cuttings, can be indistinguishable from alteration produced by a presently active geothermal

system. Even relict alteration zones are of interest, however, as they typically occupy zones of structural weakness which are readily refractured, providing channels for renewed thermal fluid flow. At Roosevelt Hot Springs KGRA, Utah, for example, refracturing of dense, silicified, chloritized and sericitized cataclasite zones is believed to be responsible for much of the geothermal reservoir's present permeability (Nielson et al., 1978; Sibbett and Nielson, 1980).

Alteration mineralogy relative to depth of occurrence in a geothermal system can provide clues to the age of alteration relative to present geothermal activity. Minerals which typically form at elevated temperatures and/or pressures and occur at shallow levels in active systems, such as epidote (Zen and Thompson, 1974) at Roosevelt Hot Springs KGRA are probably paleohydrothermal.

Various contaminants in cuttings may strongly resemble natural alteration minerals encountered during drilling. Drilling muds and mud additives are the contaminants most commonly mistaken for indigenous alteration products, but cements and metallic shavings can also cause interpretive errors.

The basic ingredients of drilling muds are clays which may also occur as hydrothermal alteration minerals in and around ore deposits and geothermal systems. Bentonite, from which standard drilling muds are prepared, is a highly variable clay consisting dominantly of sodium- and/or calcium montmorillonite, but which may also contain, depending on its source, kaolinite, illite, saponite and hectorite (Patterson and Haydn, 1975). Montmorillonite, kaolinite and illite are common alteration products in active geothermal systems (Browne, 1978) and in alteration haloes (particularly argillic) around many mineral deposits (Rose and Burt, 1979). Attapulgite

(palygorskite) and sepiolite, used to prepare salt-water-based and/or high temperature muds (Westin, 1980; Carney and Meyer, 1976) are much more restricted in natural occurrence (Patterson and Haydn, 1975) and therefore less likely to be mistaken for constituents of the drilled rock.

Drilling mud weighting agents, which are added primarily to control formation pressure and decrease caving, are prepared from a variety of heavy minerals which also occur as hydrothermal alteration products. The most frequently used weighting agent is barite which, although rarely reported from major active geothermal systems (Browne, 1978), is a common ore and gangue mineral in hydrothermal vein deposits. Other mud weighting materials likely to be confused with alteration minerals in drilled rock are used much less commonly than barite. They include ilmenite/magnetite, hematite, galena, (which may contain sphalerite as an impurity), and calcite or limestone.

Lost-circulation materials, added to drilling fluid to restrict or prevent fluid loss to pores, fractures, faults and solution cavities encountered during drilling, are generally low-density organic materials unlikely to be visually mistaken for hydrothermal alteration products. These organic materials include nut and seed hulls, hardwood and cane fibers, ground paper, wool, and alfalfa. Two other lost-circulation additives, however, processed mica and cellophane flakes, may mimic indigenous mica if cursorily examined. Impure processed mica (particularly vermiculite) additionally may contain substantial amounts of such impurities as chlorite, plagioclase, quartz and rutile.

Drilling muds and mud additives, readily confused with natural rock constituents during binocular or petrographic microscopic examination, are even more troublesome in analyses of cuttings by X-ray diffraction and atomic

absorption spectrophotometry. Dypvik (1981) has analyzed most of the common muds and additives by one or both of these methods. He has shown that not only drilling mud clays, but also many dominantly organic additives (such as, for example, walnut hulls) produce strong X-ray peaks which easily could be confused with patterns generated by natural constituents of the drilled rock. He has also shown that many additives contain significant amounts of metallic trace elements. Barite, for example, may be enriched not only in strontium (as expected), but also in silver, lead, zinc and manganese. As previously discussed, such spurious geochemistry in cuttings could lead to erroneous conclusions about the nature of and distance from a geothermal resource or mineral deposit.

Most metals abraded from drillstrings, casing, and downhole cementing assemblies, including steel, brass, bronze, monel, lead and aluminum can be recognized in cuttings as foreign debris by their characteristic ductility and tendency to form discrete, curled shavings and peels. Steel, however, readily rusts, particularly in samples stored under moist conditions. The rust strongly resembles naturally occurring earthy to waxy goethitic to hematitic "limonite" (Hulen, 1978) which, by contrast with steel, cannot be removed from cuttings magnetically.

Rust in cuttings commonly can be distinguished from naturally-occurring limonite by considering the depth of the sample relative to the base of oxidation as intersected in the borehole. Earthy iron oxide in a sample below this zone is likely to be rust, although isolated pockets of limonite may be locally present in deeply oxidized faults or fracture zones. Rust derived from steel and iron will also tend to occur only on chip surfaces whereas indigenous iron oxides may also occur in fractures, along crystal boundaries

and in the interiors of mineral grains.

SUMMARY AND CONCLUSIONS

Drill cuttings, in spite of their disadvantages as borehole rock samples relative to core, can provide valuable information about a subsurface resource if carefully sampled and interpreted. Interpretation of cuttings from geothermal and mineral exploration boreholes can be complicated by intricate igneous and metamorphic lithology, structure and hydrothermal alteration as well as severe contamination. These complications can be minimized by combining critical scrutiny of cuttings with a full understanding of both local (and regional) geology and the entire range of likely borehole contaminants. To be most effective in characterizing a resource, cuttings interpretation should be used in conjunction with all other methods of subsurface investigation, particularly geophysical well logging.

ACKNOWLEDGEMENTS

We gratefully acknowledge the generous financial support of the U. S. Department of Energy, Division of Geothermal Energy and the valuable suggestions and careful critical reviews of Dennis Nielson, Jon Zeisloft, Mike Wright, Jim Stringfellow and Mike Bullett. Drafted illustrations were prepared by Doris Cullen and Connie Pixton. Photographs were produced by the University of Utah Medical Illustrations Department. The manuscript was organized and prepared by Holly Baker.

REFERENCES

- Appl, F. C. and Rowley, D. S., 1963, Drilling stresses on drag bit cutting edges, in C. Fairhurst (ed.), Rock mechanics: New York, MacMillan Co., p. 119-136.
- Bamford, R. W., Christensen, O. D., and Capuano, R. M., 1980, Multi-element geochemistry of solid materials in geothermal systems and its applications, part I -- the hot-water system at the Roosevelt Hot Springs KGRA, Utah: Univ. of Utah Research Inst., Earth Sci. Lab., Rept. 30., 168 p.
- Bestolife, 1980-1981, Portion of products catalog in Composite catalog of oilfield equipment and services: Houston, World Oil, Gulf Publishing Co., p. 953-957.
- Browne, P. R. L., 1978, Hydrothermal alteration in active geothermal fields: Ann. Rev. Earth Planetary Sci., vol. 6, p. 229-250.
- Browne, P. R. L., and Ellis, A. J., 1970, The Ohaki-Broadlands hydrothermal area, New Zealand -- mineralogy and related geochemistry: Am. Jour. Sci., v. 269, p. 97-131.
- Carney, L. L., and Meyer, R. L., 1976, A new approach to high-temperature drilling fields: Soc. Petrol. Eng., 51st Ann. Fall Tech. Conf., New Orleans, La., Oct. 3-6, 1976, Paper SPE-6025.
- Chemical Rubber Company, 1976-1977, Handbook of Chemistry and Physics (58th edition): Cleveland, Ohio, C. R. C. Press.
- Christensen, O. D., 1980a, Geochemistry of the Colado geothermal area, Pershing County, Nevada: Univ. of Utah Research Inst., Earth Sci. Lab., Rept. 39, 31 p.
- _____, 1980b, Trace element geochemistry of gradient hole cuttings, Beowawe geothermal area, Nevada: Univ. of Utah Research Inst., Earth Sci. Lab., Rept. 48, 28 p.
- Dypvik, H., 1981, Drilling mud contamination of samples in x-ray diffraction and atomic absorption analyses: AAPG Bull., vol. 65, p. 744-748.
- Elders, W. A., Hoagland, J. R., and McDowell, S. D., 1979, Hydrothermal mineral zones in the geothermal reservoir of Cerro Prieto, Baja California, Mexico: Univ. of California at Riverside, Inst. of Geophysics and Planetary Physics, Rept. UCR-IGPP 79/2.
- Ewers, G. R., and Keays, R. R., 1977, Volatile and precious metal zoning in the Broadlands geothermal field, New Zealand: Econ. Geol., vol. 72, p. 1337-1354.
- Glenn, W. E., and Hulen, J. B., 1979, Interpretation of well log data from four drill holes at Roosevelt Hot Springs KGRA, Utah: Univ. of Utah Res. Inst., Earth Sci. Lab., Rept. 28, 74 p.

- Halliburton Services, 1980-1981, Sales and service catalog no. 40 in Composite catalog of oilfield equipment and services: Houston, World Oil, Gulf Publishing Co., p. 3285-3524.
- Hendrikson, R. R., Jones, A. H., Winzenreid, R. W., and Maish, A. B., 1980, Field drilling tests of improved geothermal unsealed roller-cone bits: Sandia Natl. Lab., Rept. SAND80-7079.
- Hills, J. M., 1949, Sampling and examination of well cuttings: AAPG Bull., vol. 33, p. 73-91.
- Hobbs, R. G., 1979, Guidelines for logging, describing and sampling cores and cuttings of coal and associated rocks at the drill site: U. S. Geol. Survey, Open-File Rept. 79-1522, 23 p.
- Hulen, J. B., 1978, Stratigraphy and alteration, 15 shallow thermal gradient holes, Roosevelt Hot springs KGRA and vicinity, Millard and Beaver Counties, Utah: Univ. of Utah Research Inst., Earth Sci. Lab., Rept. 9, 58 p.
- Hulen, J. B., 1979, Geology and alteration of the Baltazor Hot Springs and Painted Hills thermal areas, Humboldt County, Nevada: Univ. of Utah Research Inst., Earth Sci. Lab., Rept. 27, 20 p.
- Jet-Lube, 1980-1981, Oilfield products catalog in Composite catalog of oilfield equipment and services: Houston, World Oil, Gulf Publishing Co., p. 4157-4164.
- Kappelmeyer, O., and Haenel, R., 1974, Geothermics: Berlin, Gebruder Borntraeger, Geoexploration Monographs, Series 1, No. 4.
- Keys, S., 1979, Borehole geophysics in igneous and metamorphic rocks: Paper presented at 50c. Prof. Well Log Analysts 20th Ann. Symp., Tulsa, Oklahoma, June 3-5.
- Levinson, A. A., 1974 (with 1980 Supplement), Introduction to exploration geochemistry: Wilmette, Ill., Applied Publ. Co., 924 p.
- Low, J. W., 1977, Examination of well cuttings and the lithologic log in Leroy, L. W., Leroy, D. O., and Raese, J. W., eds., Subsurface geology (4th edition): Golden, Colorado, Colorado School of Mines, p. 286-303.
- Maher, J. D., 1964, The composite interpretive method of logging drill cuttings (2nd edition): Oklahoma Geol. Survey Guidebook XIV, 48 p.
- Maurer, W. C., 1976, Geothermal drilling technology: Proc., 2nd U. N. Symp. on Dev. and Use of Geoth. Resources, San Francisco, California, May 20-29, 1975, p. 1509-1521.
- Moore, P. L., 1974, Drilling practices manual: Tulsa, The Petroleum Publishing Co., 448 p.

- Nelson, P. H., and Glenn, W. E., 1975, Influence of bound water on the neutron log in mineralized igneous rocks: Soc. Prof. Well Log Analysts Annual Logging Symposium, New Orleans, Louisiana, June, Paper M, 9 p.
- Nielson, D. L., Sibbett, B. S., McKinney, D. B., Hulen, J. B., Moore, J. N., and Samberg, S. M., 1978, Geology of Roosevelt Hot Springs KGRA, Utah: Univ. of Utah Research Inst., Earth Sci. Lab., Rept. 12, 120 p.
- Nishimatsu, Y., 1972, The mechanics of rock cutting: International Jour. Rock Mech. Min. Sci., vol. 9, p. 261-270.
- Oil Center Research, Inc., 1980-1981, Product information catalog, 24p.
- Parks, R. D., 1957, Examination and valuation of mineral property: Reading, Mass., Addison-Wesley Publ. Co, Inc., 507 p.
- Patterson, S. H., and Haydn, H. M., 1975, Clays in Lefond, S. J., ed., Industrial minerals and rocks (4th edition): New York, AIME, p. 519-585.
- Rose, A. W., and Burt, D. M., 1979, Hydrothermal alteration in Barnes, H. L., ed., Geochemistry of hydrothermal ore deposits (2nd edition): New York, John Wiley and Sons, p. 173-235.
- Sanyal, S. K., Wells, L. E., and Bickham, R. E., 1980, Geothermal well log interpretation -- state of the art (final report): Los Alamos Sci. Lab. Rept. LA-8211-MS.
- Sass, J. H., Lachenbruch, A. H., and Monroe, R. J., 1971, Thermal conductivity of rocks from measurements on fragments and its application to heat-flow determination: Jour. Geophys. Res., vol. 76, no. 14, p. 3391-3401.
- Sibbett, B. S., and Glenn, W. E., 1981, Lithology and well log study of Campbell E-2, Geothermal test well, Humboldt House geothermal prospect, Pershing county, Nevada: Univ. of Utah Res. Inst., Earth Science Lab. Rept. (in press).
- Sibbett, B. S., and Nielson, D. L., 1980, Geology of the central Mineral Mountains, Beaver County, Utah: Univ. of Utah Research Inst., Earth Sci. Lab., Rept. 33, 42 p.
- Sikarskie, D. L. and Cheatham, J. B., Jr., 1973, Penetration problems in rock mechanics, in D. L. Sikarskie, (ed.) Rock mechanics symposium: Amer. Soc. Mech. Eng., AMD vol. 3, p. 41-71.
- Smith, D. K., 1974, Cements and Cementing in Moore, P. L., ed., Drilling practices manual: Tulsa, The Petroleum Publishing Company, p. 400-448.
- Somerton, W. H., 1959, Laboratory study of rock breakage by rotary drilling; pt. 2, discussion by R. Simon: AIME, Jour. of Petroleum Tech., vol. 11, Pt. 1, May, p. 92-97: Pt. 2, Dec., p. 78-80.
- Steiner, A., 1968, Clay minerals in hydrothermally altered rocks at Wairakei, New Zealand: Clays and Clay Minerals, vol. 16, p. 193-213.

- Sumi, K. and Takashima, I., 1976, Absolute ages of the hydrothermal alteration halos and associated volcanic rocks in some Japanese geothermal fields: Proc., 2nd U. N. Symp. on Dev. and Use of Geoth. Resources, San Francisco, California, May 20-29, 1975, p. 625-634.
- Swanson, R. G., 1981, Sample examination manual: AAPG Methods in Exp. Ser., 35 p.
- U. S. Steel (McGannon, H.E., ed.), 1964, The making and shaping of steel (8th edition), 1300 p.
- Varnado, S. G., 1980, Geothermal drilling and completion technology development program semi-annual progress report, April-September 1979: Sandia Natl. Lab., Rept. SAND79-2397, 232 p.
- Wells, J. H., 1969, Placer examination principles and practice: Washington, D.C., U. S. Government Printing Office, 209 p.
- Westin, S., 1980, Imperial Valley drilling procedure in Basic geothermal drilling and completion technology: Geoth. Resources Council Tech. Training course No. 3, March 24-26, Albuquerque, NM.
- White, D. E., Muffler, L. J. P., and Truesdell, A. H., 1971, Vapor-dominated hydrothermal systems compared with hot-water systems: Econ. Geol., vol. 66, p. 75-97.
- Wolke, R., 1980, Air drilling in Basic geothermal drilling and completion technology: Geoth. Resources Council Tech. Training Course No. 3, March 24-26, Albuquerque, NM.
- Zen, E., and Thompson, A. B., 1974, Low-grade regional metamorphism -- mineral equilibria relations: Ann. Rev. Earth and Planetary Sciences, vol. 2, p. 179-212.