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# The Scientific Value of Coring the Proposed Southern Appalachian Research Drill Hole

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Committee on Continental Scientific Drilling
Board on Earth Sciences
Commission on Physical Sciences, Mathematics, and Resources
National Research Council



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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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# Preface

At an early stage of its activities, the Continental Scientific Drilling Committee considered suggestions and preliminary proposals outlining the scientific problems that could be attacked by drilling and the site best suited for the effort. High on the priority list—indeed, the Committee rated it as having the highest scientific priority of all the first proposals—was a deep hole in the Southern Appalachians that would test the model of thin-skinned overthrusting. This model, first suggested by scientific reflection profiling by COCORP, had implications for mountain building in general and would be an integral component of the plate tectonic hypothesis.

Because the proposed hole would be as deep as 10 km, the Committee wanted to ascertain what other data could be obtained and what other important problems could be attacked with this hole. An integral question is the comparative utility of cutting versus core in obtaining these data. Accordingly, an ad hoc task force was assembled to study the question and list those problems that can best be answered by coring.

In preparing the report, the Task Force kept in view the value of coring in general, while considering the Appalachian hole as a specific instance. The Continental Scientific Drilling Committee endorses this report of the Task Force and its recommendations.

# Contents

# Summary and Recommendation

The revolution in earth sciences brought about by the theory of plate tectonics was possible largely because major concepts could be tested by drilling in the ocean floor. The more complex structures and longer histories of the continents are difficult to interpret in the framework of plate tectonics. Geophysical methods that explore the continental lithosphere from its surface indicate large structures that appear to have formed as a result of plate interactions, but whose existence and nature can only be demonstrated by direct sampling. The drill, so successful in recovering rock samples used to prove the fundamental hypotheses of plate tectonics for the oceanic lithosphere, is now considered a critical research tool for unraveling the history of the continents and understanding the processes that formed them.

Recent improvement in prospects for funding for a national program of dedicated research drilling prompted the Continental Scientific Drilling Committee to suggest that highest priority be given to research drilling to test the thin-skinned tectonic thrusting model for the southern Appalachians (Continental Scientific Drilling Committee, 1984). Results of surface geologic mapping (Hatcher, 1972), seismic reflection profiling (Cook *et al.*, 1979), and potential field studies (Hatcher and Zietz, 1980) are all consistent with the hypothesis that extensive sheets of Precambrian and

Paleozoic crystalline rock, generally 6 to 15 km thick, have been thrust at least 260 km to the west over lower Paleozoic sedimentary rocks of the proto-Atlantic continental margin. A dedicated research drill hole would be designed to study and ultimately pass through the crystalline overthrust to penetrate these sedimentary rocks, perhaps even reaching the underlying basement. The hole would be sited so that these goals could be achieved with a target depth of 10 km.

The southern Appalachian research drill hole is being proposed to solve a major geologic problem, the thin-skinned thrusting hypothesis, the solution of which will have application to many of the important orogenic belts of the world. The hypothesis cannot be tested without adequate samples of rocks from all depths in the hole, especially the greatest depths. Success of the project depends upon our ability to identify rock units and structures encountered in the hole. Samples for chemical and physical studies must be significantly larger than the grain size of the rock, free of contamination, and accurately fitted into the general geologic setting. Preferably the samples should also display a continuity and coherence sufficient for an observer to spot important small features such as veins, fractures, alteration zones, and critical contacts. Continuous drill core is ideal for this purpose, and it can be obtained in adequate diameter (preferably greater than 4 cm) and length for scientific study. In contrast, cuttings from drill holes in crystalline rocks tend to be fine grained, and logging techniques in such terranes are not yet calibrated with the sophistication typical of petroleum exploration in sedimentary basins.

*The Continental Scientific Drilling Committee therefore recommends extensive coring as essential to achieving the scientific goals of the Southern Appalachian research project. Moreover, if nearly continuous core is recovered, a vast amount of new information can be obtained on the deformational and thermal history of the southern Appalachians and on the chemical and physical properties of the rocks.*

The equipment to core the entire 10-km hole can be assembled from existing technology. Only after rigorous evaluation of the cost of continuous core should a decision be made to core less than the entire hole. If that be the case, at least 30 percent should be cored, with emphasis on the bottom 2 km. Results of core studies will be used to improve interpretations of geophysical and well-logging data for similar terranes and will be applicable to understanding physical and chemical processes within many other orogenic belts.

This report concerns scientific problems that can be addressed through studies of core samples from the southern Appalachian scientific research drill hole, requirements for obtaining the core samples in suitable size and condition, and some approaches to the coring process. Although aimed at this specific target, the types of scientific problems and methods of study are common to many projects likely to be approached with the drill as a research tool. Properly curated and preserved in a repository, lengths of drillcore from a variety of depths and localities in the continental crust of North America will represent an enormously important scientific resource. Such a resource would have lasting value and would, in fact, perhaps gain in value as more and more sophisticated analytical instruments are manufactured and as new geological insights are developed. Obtaining sufficient amounts of core to achieve the goals of each drilling project should be one of the highest priorities of the Continental Scientific Drilling Program.

# 1
# Introduction

## TESTING THE THIN-SKINNED THRUSTING HYPOTHESIS

The southern Appalachians are made up of several subparallel belts or terranes (Figure 1). From northwest to southeast these are the foreland composed of the Cumberland Plateau and Valley and Ridge province, the Blue Ridge, Inner Piedmont including the Chauga Belt, Avalon Terrane composed of the Charlotte and Carolina Slate belts, and the Brunswick Terrane (Hatcher *et al.*, 1982). These belts are separated in most cases by faults that dip to the southeast. The proposed drill site would be located in the Inner Piedmont such that underlying Blue Ridge rocks and the intervening Brevard fault zone would be encountered before parautochthonous sedimentary rocks and Grenville basement are penetrated (Figure 2). A wide variety of rock types can be expected, from weakly metamorphosed sedimentary rocks to granitic gneisses. All are likely to be anisotropic, and rocks in the vicinity of fault zones may be mylonitic. Because the surface geology is well known, the succession of rock types to be expected in drilling can be anticipated. Existing geophysical surveys and those now being carried out in the site selection process allow these projections to be made with a comparatively high degree of

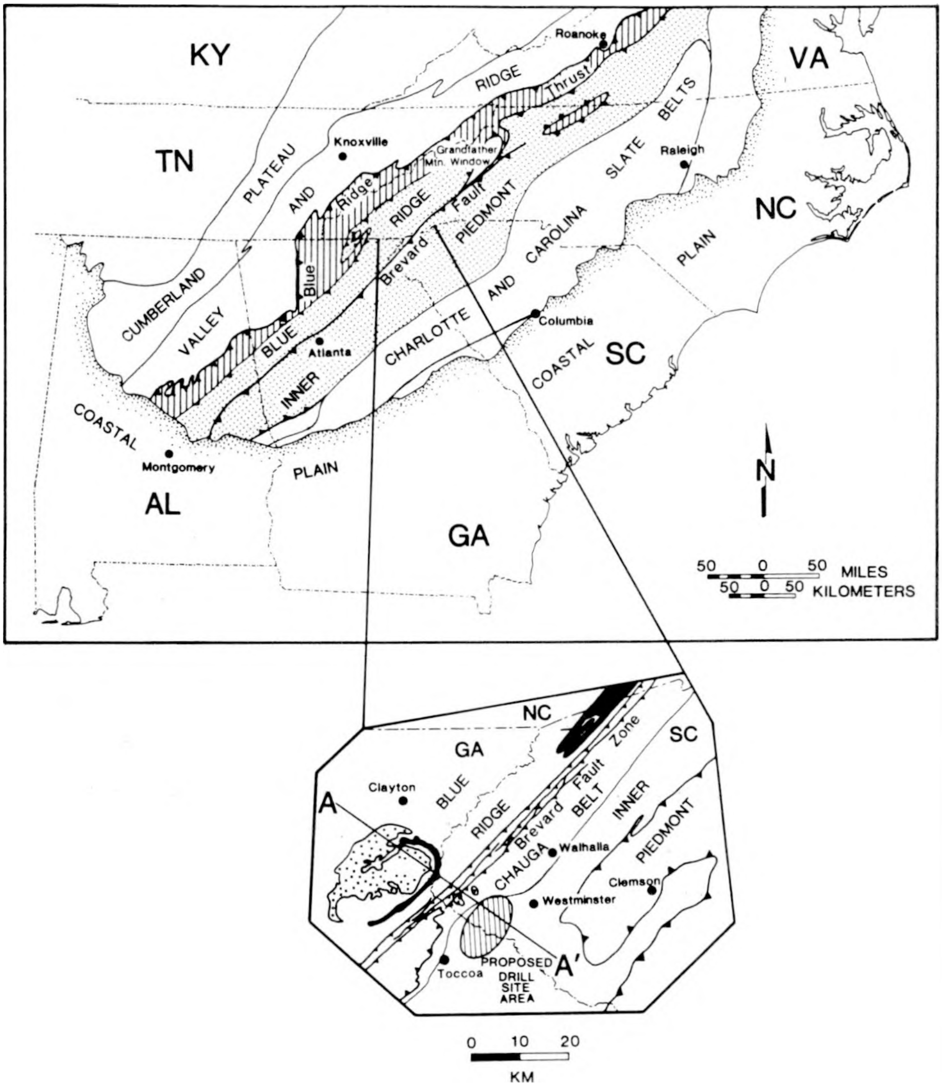


FIGURE 1 Major subdivisions of the southern Appalachians and detail of the proposed site study area. AA'—abbreviated section shown in Figure 2.

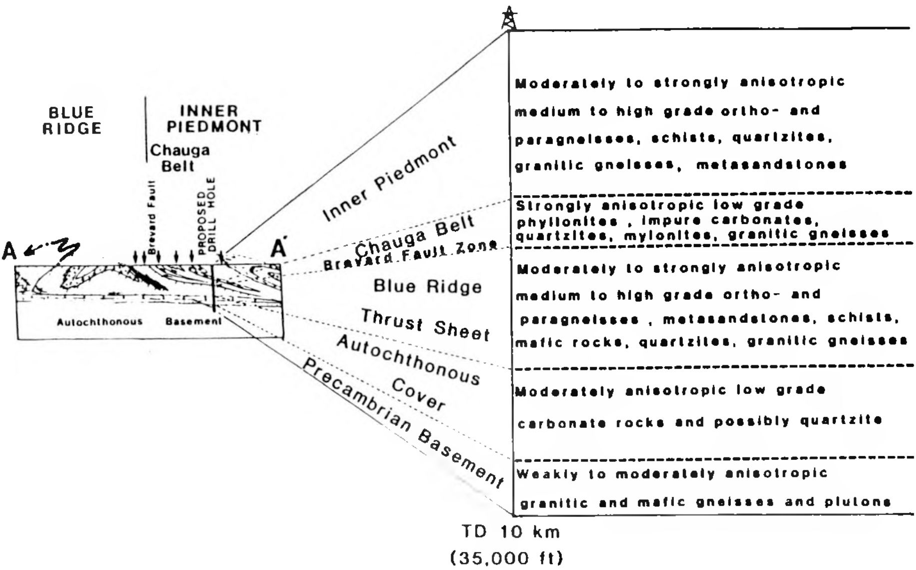


FIGURE 2 Enlarged portion of Transect Section E-5 (Figure 1) showing the possible tectonic units and generalized lithologies likely to be encountered if the deep hole were drilled directly on the line. The striped area is the Blue Ridge thrust sheet containing a highly deformed and transported mass of basement (black). Arrows above surface indicate the approximate locations of six proposed shallow boreholes projected into the line of section. The entire section is 55 km in length. There is no vertical exaggeration. Location of this section is shown as A-A' in Figure 1.

confidence. Confirmation of the thin-skinned thrusting hypothesis will depend on identification of key groups of rocks in the hole. Since all of the rocks in the thrust sheet have been metamorphosed, fossils will not be present. Rocks beneath the master detachment thrust should be of lower metamorphic grade and thus may contain fossils. Correlations of high grade metamorphic rocks with surface exposures to the west will have to be made on the basis of stratigraphic succession of rock types, chemical and isotopic compositions, radiometric ages, and similarity of thermal and deformational histories.

Preliminary identification of rock units can be made at the drill site by geologists familiar with the area. Cuttings a few millimeters in size probably would be sufficient for this purpose, but the prospect of obtaining such coarse material from hard crystalline rocks is slim. Core samples are superior, but they may

TABLE 1 Major geologic targets to be cored in a southern Appalachian research drill hole.

| Target | | Estimated Depth (km) |
|---|---|---|
| Inner Piedmont | | |
| Amphibolite | | |
| Granitic Gneiss | | 0-4 |
| Biotite Gneiss | | |
| Chauga Belt | | |
| NW | SE | |
| | Henderson Gneiss | |
| Chauga River Fm. | Poor Mountain Fm. | 4-5 |
| Brevard Fault Zone | | |
| Blue Ridge | | |
| Talullah Falls Fm. | | |
| Grenville Basement (allochthonous) | | 5-8 |
| Sole Thrust | | 8 |
| Platform Sedimentary Rocks | | |
| Knox Group and pre-Knox rocks | | 8-9 |
| Grenville Basement (autochthonous) | | 9 |

not be representative of lithologically heterogeneous units unless sufficiently long intervals are cored continuously. Table 1 gives suggested *minimum* lengths of core needed from each major geologic unit and fault zone thought to be present. Most units probably could be identified with 3 meters of core. Recovery of contact zones between units will require much longer cored intervals unless groups of units have been tectonically thinned on one limb of a fold. In the Chauga Belt, for instance, 30 meters of core might transect as many as three stratigraphic units. Although microstructures and geometric relationships between lithologies cannot be elucidated from cuttings, they may be critical to identification of stratigraphic units. Once the response of specific rock units is known, logs may simplify correlation. Advance calibration of logging tools could be done in other suitable drill holes in the appropriate terranes. In a limited coring program, anticipating where cores should be taken on the basis of on-site examination of cuttings is risky and could result in failure to core critical intervals. Other methods of downhole sampling would have to be employed,

TABLE 2 Minimum lengths of core needed for various types of studies or laboratory measurements. Core diameter assumed to be at least 2.5 cm unless otherwise noted. Tabulated minimum lengths for physical property measurements assume fine- to medium-grained rocks with internal structures on a scale significantly less than core size.

| Investigation | Minimum length (m) |
|---|---|
| Identification of geologic units | 10 |
| Study of contact and fault zones+ | 10 |
| Geochemistry | 0.4-8 (2.5 cm dia.)* |
| 0.04-0.8 (7.6 cm dia.)* | |
| Deformation | 10 |
| Metamorphic petrology | less than 10 |
| Geochronology | 1.5-7 (2.5 cm dia.)* |
| 0.2-0.7 (7.6 cm dia.)* | |
| Thermal conductivity | 0.01* |
| Seismic velocity | 0.1* |
| Magnetic properties | 0.02* |
| Electrical properties | 0.02 |
| Hydraulic properties | 0.02 |
| Elastic and deformational properties | 0.02 |

+excluding Brevard fault zone and sole thrust
*per sample

necessitating interruption of drilling or postponement of sampling until completion of the hole but without setting casing.

Continuous core doubtless would be ideal for answering the fundamental scientific questions posed by the southern Appalachian hole. Less extensive coring, such as 30 percent of the hole, may be a viable option if cuttings are sufficiently coarse for unambiguous field identification and if later downhole sampling is possible (Table 2). If the entire hole is not cored, coring should emphasize the base of the overthrust sheet and the platform sediments below. Perhaps as much as 1000 meters of core are needed from this interval in order to extract the maximum amount of information on the timing, mechanics, and conditions of overthrusting. Coring at shallower levels should emphasize ductile fault zones that separate terranes. Such zones may be only a few meters thick, so that approximately 10 meter cores would be adequate to sample their entire thicknesses, provided that the depths of these zones can be predicted accurately.

# 2
# Chemical and Isotopic Composition of Rocks

Many important geochemical problems can probably be solved only with samples obtained from deep drill holes in the continental crust. Much more can still be done, of course, with surface materials. However, major advances in knowledge are likely to come about only through geochemical studies of new samples from heretofore inaccessible portions of the earth's crust. Enormous advances have taken place in our ability to obtain important geochemical information from very tiny samples, mainly as a result of the study of lunar rocks. Any information obtained from lunar samples was extremely valuable, even for samples that could not be placed into accurate geologic context. The lunar sampling program and the continental drilling program are very dissimilar, and have vastly different geochemical sampling requirements. To make major new advances in our understanding of the geochemical evolution of the earth, it is essential that studies be made of samples whose relationships to each other and to other known geologic features and structures are accurately known.

Although it is certainly true that important geochemical information could be obtained from cuttings from very deep holes, simply because such samples are not obtainable in any other way, the information would be of limited value. The data thus acquired would pale into insignificance compared to the increase in our understanding of the evolution of the earth that would come about through studies of sections of continuous core from a series of deep holes in the continental crust.

## GENERAL SAMPLING REQUIREMENTS FOR GEOCHEMISTRY

More often than not, the most valuable geochemical samples taken from surface outcrops are not those from the relatively abundant rock types, but those rare samples at important geologic contacts, or those present as veins, mineralized fractures, alteration envelopes, or fault zones. Such anomalous materials generally are more readily observed in core samples than in surface outcrops. Given the choice in sampling near-surface rocks, even where outcrops are excellent, geochemists and petrologists typically choose drill-core material over outcrop samples because of the freshness and continuity of drillcore. Thus, a good case can be made that continuous core is better for most geochemical sampling than the best surface outcrops.

For many petrological purposes, it is important to make accurate major and trace element analyses of whole-rock samples. This is particularly useful in igneous petrology, but it has increasing significance in metamorphic and hydrothermal studies as well. A key problem is collection and preparation of the sample to ensure that it is: (1) large enough to be representative of the rock mass being sampled; (2) collected and handled in such a way that it is free of contamination, at least for the elements being analyzed; and (3) fresh and unweathered. In recovered drilling samples, item (3) will not be a problem, and with high quality core, requirements (1) and (2) also can be met. Special care will have to be taken to ensure that samples are free of contamination from drilling mud or tools. Because of the low permeability anticipated for core samples, surface contamination and contamination from fluid penetration can be eliminated by sawing or grinding off the outer part of the core. However, if only cuttings are available, then most whole-rock studies cannot be done, because items (1) and (2) simply cannot be satisfied. For example, in trace-element studies, a few grains of galena (PbS) from a vein that was inadvertently mixed in the cuttings would invalidate the lead isotopic composition of a whole-rock sample.

The problem of obtaining a representative rock sample that is homogeneous on the scale of interest for any type of whole-rock chemical analysis is related to the size of crystals that make up the rock. A standard procedure is to crush a large sample and take a small split of crushed rock for final preparation of powder suitable for analysis. For fine- and medium-grained rocks, about 0.5 kg of crushed rock is sufficient. This is equivalent to about 40 cm of (uncontaminated) 2.5 cm (1 inch) diameter core or 4 cm of 7.6 cm (3 inch) diameter core (Table 2). Coarse grained rocks, such as porphyritic granites or augen gneisses that might be encountered, could require crushing on the order of 10 kg of material (800 cm or 80 cm, respectively, of the above cores) in order to obtain a representative split of perhaps 0.1 kg for powdering. Concern for contamination by crushing equipment becomes significant when working with such large samples. Splits of less than 1 kg could be taken from rock crushed for mineral separations for geochronology so that very large segments of core would not be destroyed solely for chemical analysis. Clearly, larger core diameter is desirable to minimize the proportion of contaminated material that will need to be removed before crushing.

## MAJOR ELEMENT GEOCHEMISTRY

Characterization of igneous rocks recovered from continental drilling requires accurate knowledge of major element compositions. Such information is vital to correlations of metamorphic rocks beneath the drill site with those exposed elsewhere at the surface. Moreover, knowledge of rock composition is necessary for many aspects of petrologic studies of metamorphic rocks, especially those involving mass transfer. Problems of contamination are less severe than for complementary trace element studies, but samples must be large enough to be representative of the rock volume of interest. Core samples are essential for meaningful whole-rock analyses. Representative samples of all igneous rocks returned from the hole, and sufficient metamorphic rocks to adequately characterize geologic units, should be analyzed. Rock powders prepared for major element analysis will be suitable for many other geochemical determinations.

## TRACE ELEMENT GEOCHEMISTRY

Although most of the elements occurring in rocks are present in only low concentrations, accurate knowledge of their abundances is important in interpreting the origin of all types of rocks. It is likely that virtually every trace element will be analyzed in certain important samples obtained from the deep continental drilling program. For many samples, only the more geochemically useful trace elements will be analyzed, but these include a wide variety: several of the rare earths, as well as Ba, Sr, Rb, Zr, Hf, Nb, Ta, U, Th, and most of the valuable ore metals (Ni, Cu, Zn, Pb, Hg, Mn, Cr, Sn, Ag, Au, etc.). Mineral separates also may be analyzed.

Trace element studies will be critical in establishing correlations between geologic units in the southern Appalachian hole and surface outcrops. Carbonate rocks beneath the sole of the thrust brought up as lenses in the Brevard fault zone, for example, may be correlative with rocks exposed to the west in the Valley and Ridge province. Continental or oceanic crustal signatures of igneous rocks and some indication of the tectonic environment of their formation will be apparent from trace element data. Vertical variations in trace element abundances will help to establish the extent of elemental mobility during metamorphism and deformation.

## RADIOGENIC ISOTOPE GEOCHEMISTRY

Radiogenic isotope geochemical techniques are among the most definitive of all geochemical studies, and for that reason their sampling requirements constrain those of the entire geochemical program. The most important radiogenic-isotope systems are the U-Pb, Th-Pb, Sm-Nd, Rb-Sr, and K-Ar parent-daughter pairs. From each we obtain: (1) the time of crystallization of the rock and(or) age information about the geologic events that affected the rock since its formation; and (2) the geologic processes that created the rock or later affected it, including the type of parent material and the nature of any later metamorphism or hydrothermal alteration. In addition, the distribution of these elements in the crust will provide important information for a large number of geochemical and geophysical studies, including heat-flow, fluid-flow, and elemental migration, because the radioactive parents listed above are the major heat-producing materials in the earth's interior. Except for K, all the radiogenic isotope systems listed above occur as trace elements in most minerals and rocks of the earth's crust. They are thus extremely susceptible to contamination. The most useful type of drilling sample would be a pristine section of core large enough (preferably at least 4 cm in diameter) to obtain interior samples.

In addition to its utility as a geochronological tool, radiogenic isotope geochemistry has the power to characterize deep crustal rocks on the basis of the isotopic compositions of Sr, Nd, and Pb in igneous rocks emplaced at shallower levels or erupted at the surface (e.g., Farmer and DePaolo, 1984). Because metamorphism affects the mobility of these elements and their parents in different ways, components of magmas that were derived in part from metamorphic rocks can be detected and the general age and degree of metamorphism determined (e.g., amphibolite vs. granulite). Radiogenic isotopes also yield information on mantle or oceanic crustal contributions to igneous rocks. For example, isotopic studies of igneous rocks within a tectonostratigraphic terrane, now present as a thin thrust sheet, and very likely to indicate whether that terrane originally formed on oceanic or continental crust; if continental, the age of the crust might also be obtained. Isotopic studies should be carried out on igneous rocks from all terranes encountered in the southern Appalachian drill hole in order to test hypotheses of terrane origins and indicate the nature of underlying crustal types. The mobility of radiogenic daughter products makes them ideal tracers for studying elemental migration during metamorphism and deformation. Vertical profiles through terranes and their contacts would contribute greatly to multidisciplinary investigations of elemental mobility.

## STABLE ISOTOPE GEOCHEMISTRY

Stable isotope studies have become extremely important in understanding the origin and history of sedimentary, igneous, and metamorphic rocks. Major categories of investigation are: (1) isotopic geothermometry (O'Neil and Clayton, 1964), which requires the separation and analysis of individual minerals from cogenetic mineral assemblages; (2) fluid-rock interaction (Taylor, 1974), which also requires analysis of mineral separates, vein and fracture material, and fluid inclusions in minerals; and (3) isotopic tracers of geologic processes, utilized in a somewhat similar way and often in conjunction with radiogenic isotope systematics (James, 1982).

The geochemically most important stable isotopes are the elements of low atomic number or those that have a complex chemistry. Particularly important are those with a variety of oxidation states, namely, hydrogen (D/H), carbon ($^{13}C/^{12}C$), nitrogen ($^{15}N/^{14}N$), oxygen ($^{18}O/^{16}O$), and sulfur ($^{34}S/^{32}S$). All these elements except oxygen are present in small amounts in most rocks. However, some of them may be present as major constituents of certain minerals (sulfides, carbonates), and in such cases it is essential to obtain mineral separates. Others are present in most minerals in trace amounts or as fluid inclusions (hydrogen, nitrogen, carbon). Contamination problems are least severe for oxygen, but even for $^{18}O/^{16}O$, at least 0.1 kg samples are needed because mineral separates (typically about 100 mg) are usually essential for geochemical studies. Thus the same considerations of contamination, accurate representation of geologic units, and knowledge of interrelationships between samples that have been stated for other geochemical studies apply to the sample requirements for almost all stable isotope analyses. Identification and recovery of small veins enriched in sulfides, carbonates, or hydroxyl-bearing minerals will generally be necessary to make useful S, C, and H isotope interpretations of continental drilling samples. This can only be done with drill-core material.

Results of stable isotope studies will define the extent of fluid mobility within terranes and across their contacts. Fluids can be characterized as to their origin, and this information can be added to interpretations based on metamorphic petrology. The character of protoliths of metasedimentary rocks, such as those below the master sole thrust, may be elucidated. Stable isotope data will also contribute to identifying crustal or mantle components of igneous rocks encountered in the hole. If any mineralized areas (e.g., sulfide bodies) are penetrated, stable isotope investigations will be essential in determining the origin of ore-forming fluids and the extent of rock-fluid interaction.

# 3
# Fluid Inclusions

Minerals in metamorphic rocks contain fluid inclusions in an impressive variety (Hollister and Crawford, 1981). The inclusions are thought to trap fluids that existed when the minerals in the rocks crystallized. They are mixtures of water, carbon dioxide, methane, and nitrogen in almost all possible proportions. In addition, salts (principally sodium and calcium chlorides) may be dissolved in the aqueous fraction of the inclusions. The nature of fluids at depth has profound implications for heat and mass transfer and for metamorphic reactions in rocks. Fluids in fluid inclusions have been studied from numerous widely separated rock samples from metamorphic terranes, but no study has been possible of samples recovered in sequence from a deep drill hole in an orogenic terrane. Although fluid inclusions are likely to be present in cuttings, only in core samples could fluid inclusions be studied in the context of the petrogenesis of their host rocks as determined by metamorphic petrology.

# 4
# Organic Geochemistry

An important implication of the thin-skinned thrusting hypothesis is that Paleozoic platform sedimentary rocks beneath the sole of the overthrust may have hydrocarbon potential (Cook *et al.*, 1979). The approximately 8-km depth and likely degree of deformation and metamorphism (chlorite zone of the greenschist facies) of these rocks beneath the drill site suggest that if hydrocarbons are present in significant quantities, they will be in the form of natural gas. More likely, hydrocarbons would be unstable this far southeast of the Valley and Ridge province (Hatcher, 1982), although some methane might be present. Nevertheless, documentation of organic materials would have far-reaching implications for the hydrocarbon potential of correlative rocks to the west at shallower depths and for other overthrust terranes. Organic constituents of fluids trapped in overlying crystalline rocks may be related to metamorphism of the platform rocks during and following thrusting. Coring would provide an opportunity to study organic constituents as a function of depth and metamorphism in pristine samples. Analysis of organic components and light stable isotopes of the elements that form them should be undertaken wherever possible in samples from the southern Appalachian drill hole.

Sampling for organic geochemical studies requires knowing the depth, temperature, and geologic history of the material. Core would allow these criteria to be satisfied. Migration of hydrocarbons across interfaces between rock types can only be studied if samples are obtained at the very close intervals that cores provide. If light hydrocarbon gases are present, it will be necessary to use a high pressure coring device to ensure that none of the gases escapes during collection. After collection it would be highly desirable to freeze the cores to eliminate loss of volatile components prior to analysis. Contamination will be a major problem in samples from a southern Appalachian hole because organic content is likely to be low. Oil based drilling muds should be avoided, and care will be required to protect the core from contamination from pipe grease or other sources of organic material in the vicinity of the drilling rig.

# 5
# Deformational History

Rock samples recovered from a deep drill hole can yield a wealth of information on geologic structures and rock mechanics within terranes and at their tectonic contacts. Models of deformation mechanisms and related physical and chemical processes that operate in orogenic belts such as the Appalachians are derived from observation and interpretation of rock textures at many scales. Optical, scanning-electron, and transmission-electron microscopy provide information beyond that obtained from study of macroscopic structures. Some discussions of deformation textures in rocks are given by Spry (1969), Vernon (1975), Nicolas and Poirier (1975), and Hobbs *et al.* (1976).

Interpretation of deformation textures is based on knowledge of discrete grain-scale deformation mechanisms, each of which is dominant at a particular set of physical conditions (pressure, temperature, fluid properties), has a particular rheology (flow law), and produces characteristic textures or microstructures (e.g., Tullis *et al.*, 1982). Experimental deformation studies under controlled conditions have succeeded in reproducing many of the microstructures observed in naturally deformed rocks, and they show how textures vary as a function of lithology, finite strain, presence of water, and other parameters. Although recent work has contributed to increased ability to interpret natural deformation textures, some caution is necessary because rocks can have complex deformation histories, and their textures may reflect only the last increment of deformation. Relict textures that measure evidence of earlier deformations, however, are commonly present. Some examples of the sorts of information that can be obtained from a study of deformation textures of rocks likely to be recovered from a southern Appalachian research drill hole are given below.

## GRAIN-SCALE DEFORMATION MECHANISMS

The chief mechanisms are fracture, cataclastic flow, pressure solution (the dissolution of material from highly stressed interfaces and redeposition on low stress interfaces), dislocation creep, and grain boundary sliding. Identification of the dominant mechanism allows an inference to be drawn about the mechanical behavior (rheology) as well as the physical conditions of deformation. Complex textures may give evidence for more than one episode of deformation, occurring under different conditions and at different times. For instance, grains flattened by dislocation creep may be offset by later grain-scale faults, indicating a cooling accompanying uplift or perhaps an increase in fluid pressure. Such information complements that obtained from geochronology and metamorphic petrology.

Knowledge of the operative grain-scale deformation mechanisms is important for understanding deformation on larger scales, such as the mechanism of emplacement of thrust sheets and the degree of basement involvement in orogenic belts. For example, Schmid (1975) has convincingly shown that the Glarus thrust in the Alps was emplaced on a 1-meter thick layer of calcite mylonite that underwent grain boundary sliding and behaved in a macroscopically superplastic fashion. This mechanism allowed for extremely sharp strain localization. At present there is much debate about the apparent tendency for a number of major thrust sheets to be located within dolomite layers (Burchfiel *et al.*, 1982), because this rock type is traditionally thought to be very strong. However, it appears that dolomite may have an anomalously low friction coefficient, especially in the presence of water (Weeks and Tullis, 1984), and some evidence of this is given by the textures of its gouge products. These results have important implications for the situation in the southern Appalachians, particularly with regard to the master sole thrust which is thought to occur in dolomitic rocks.

## CONDITIONS OF DEFORMATION

Deformation textures can be used as rough indicators of deformation temperature, based on a number of calibrations between experimental studies and natural occurrences. For example, quartz shows the beginnings of syntectonic recrystallization at about 300°C, and it is completely recrystallized at only moderate strains from 350°C to higher temperatures; the recrystallized grain size increases with temperature. Feldspar, on the other hand, does not show syntectonic recrystallization until a temperature of about 450°C is achieved. Some textures, such as filled veins and fibrous overgrowths, can be used to infer high fluid pressures. These fluid properties should be consistent with results of petrologic studies.

## TYPE AND AMOUNT OF FINITE STRAIN

Studies of deformation textures determine the amount of strain that different rocks have undergone. Similarly, if the strain occurred by simple shear, the orientation and sense of shear can be defined (Simpson and Schmid, 1983). There are a number of ways in which the type and amount of finite strain can be determined. These involve strain markers, such as grain, pebble, and fossil shapes, or foliations and lineations. Deformation under some conditions, such as dislocation creep accompanied by syntectonic recrystallization, produces equigranular textures that do not indicate any strain; in such cases, measurement of the preferred crystallographic orientation of quartz can be useful in determining the type of strain and its approximate magnitude. Deformation by pressure solution results in textural relations that can supply information about the strain history of rocks. Curved quartz fibers precipitated on rigid grains, such as magnetite or pyrite, provide evidence of changes in orientation of the rock with respect to the stress axes over time. Evidence for strain history is also gleaned from foliations and lineations, which may show deformation after formation; e.g., an early foliation may be subsequently crenulated. Such textures may be preserved by mineral inclusions in porphyroblasts (Bell and Rubenach, 1983). Because of their small size, lack of preservation of fractures and veins, and lack of information on circulation, cuttings would be inappropriate for strain analysis. Core samples are required to carry out useful studies of rock deformation.

## TYPE AND MAGNITUDE OF DIFFERENTIAL STRESS

This information can be obtained from orientations of extension and shear fractures, both macroscopic and grain-scale, and from the orientation of crystallographic twins in grains of calcite, dolomite, or pyroxene. In addition, twins can give an indication of the magnitude of the stress (Tullis, 1980). Recent paleopiezometric techniques can be applied to rocks that have been deformed by steady state dislocation creep in the absence of subsequent annealing. Experiments and theory show that in such cases there is a relation between stress magnitude and recrystallized grain size, subgrain size, and dislocation density (Christie and Ord, 1984). Finally, if direct measurements of in-situ stress in the bore hole are to be made as accurately as possible, oriented core is essential to provide rock samples on which to make the relevant elastic tests.

## DEFORMATION OF THE SOUTHERN APPALACHIAN OROGEN

Given that information on deformation mechanisms, amounts of strain, and stress parameters can be provided by study of deformation textures in core samples, what are some of the important geologic problems to be solved or processes to be studied in an ultra-deep drill hole in the southern Appalachians? One of the most important functions of a cored hole will be to provide calibrations of surface geophysical and down-hole logging techniques that are at present poorly known for crystalline rocks. A major question concerns the seismic expression of mylonite zones: do they produce a definite and unique signal? In addition, is there evidence for transport of the Inner Piedmont as a thrust sheet over relatively undeformed basement, and if so, how sharp is the detachment surface and what mechanisms of deformation were dominant? Did the deformation involve lithologic control of strain? To what extent was basement involved in the deformation? Other fault zones besides the sole thrust will be encountered and should be sampled in a drilling program. Is the Brevard zone a sharply defined mylonite zone of finite width at depth, similar in character to what is seen in surface outcrops?

One cannot accurately predict in advance where the structurally significant sections will be, yet thorough sampling of ductile fault zones is necessary if the maximum amount of information on deformation is to be obtained. Continuous core through these zones and representative core samples from less strained sections will be needed. Furthermore, only through coring will there be exact positional control on samples, not only to place rocks in proper sequence in the hole but, equally important, to allow determination of the spatial orientations of structural features. Core of any diameter that might be obtained will be adequate for microstructural studies as long as a high percentage of recovery is achieved through important intervals (Table 2). Orientation of structures with respect to vertical can be easily determined in normal core, but the azimuths of these features cannot. The problem of obtaining samples of known orientation in three dimensions can be solved by sidewall sampling of critical intervals after macroscopic examination of core. Such oriented samples would also be of great value for paleomagnetic studies and physical property measurements.

# 6
# Metamorphism

Modern metamorphic petrology has evolved largely from research in the New England Appalachians and in the Alps. The metamorphic histories of terranes in some cases can now be related to large scale tectonic processes, such as the thin-skinned thrusting thought to have occurred in the southern Appalachians. The proposed deep research drill hole offers an exciting opportunity to apply new techniques in metamorphic petrology, and to integrate the results of it with those of geochronologic and deformational investigations. In addition, sampling at depth with the drill will circumvent the problem of deep weathering of many rock units, particularly in the terranes southeast of the Brevard fault zone. Above all, research core drilling will provide a truly vertical section through a major metamorphic terrane that cannot be obtained from surface outcrops.

## METAMORPHIC ISOGRADS

Metamorphic petrologists have traditionally deciphered the thermal structure of continental crust in orogenic belts by mapping isograds based on the appearance and disappearance of certain minerals produced by chemical reactions in rocks during metamorphism. The shape of isogradic surfaces at depth is almost completely unknown. Attempts to project these surfaces downward are largely conjectural because the positions of isograds at depth are controlled by processes of heat and fluid flow that do not necessarily follow simple geometric rules. Only in a few cases have isogradic surfaces been mapped over vertical distances of more than 1 km and never over more than approximately 2 km. Yet the geometry of isogradic surfaces is a powerful probe into the thermal structure of the crust during orogeny and offers a key to the nature of the heat source for metamorphism. Correlation of isograds mapped at the surface with those established in core samples from the southern Appalachian site would provide points on isogradic surfaces over vertical distances approaching 6 to 8 km. This unprecedented increase in scale of observation could make possible pioneering investigations of the thermal structure of the crust before the main overthrust event, and investigations of heat sources and the controls of heat flow that ultimately determine the types of metamorphic rocks that are developed deep in the continental crust.

## PRESSURE-TEMPERATURE PATHS

Petrologic study of metamorphic rocks provides unique ways of characterizing the emplacement of large thrust sheets. New developments in metamorphic petrology permit determination of pressure-temperature (P-T) paths that individual samples followed during their crystallization. The P-T paths are based on studies of mineral assemblages, compositional zoning in minerals, and mineral and fluid inclusions in crystals (Hollister, 1979; Spear *et al.*, 1984). The estimated P-T paths provide fundamental insights into a rock's tectonic history because rates of thermal equilibration of large rock masses generally are much slower than tectonic motions. For example, rocks from a relatively hot sheet, thrust over cooler rocks, would record a P-T path of cooling and decompression. Rocks from the lower plate would record increasing temperatures and pressures with final values that converge with the final conditions preserved in the samples from the upper plate. Furthermore, P-T paths determined for rocks can be quantitatively modeled to estimate thrust sheet thickness, initial pre-thrusting temperatures, and details of post-thrusting uplift, erosion, and heat flow (England and Thompson, 1984).

An exciting prospect for the southern Appalachian site would be determination of P-T paths followed by rocks in the Blue Ridge terrane above the main thrust surface as they cooled and were uplifted, and by the platform sedimentary rocks below as they were deformed, metamorphosed, and finally equilibrated in a steady-state geothermal gradient. Such a study would provide independent confirmation of the thin-skinned thrusting hypothesis. Besides offering verification of the large thrust sheet model, the P-T paths could characterize the initial conditions of the thrusting event and help to determine the timing of earlier thrusts in the upper plate. Temperature-time paths deduced from mathematical models of the P-T paths would complement thermal histories obtained by geochronological techniques.

## POLYMETAMORPHISM

Many rocks of the southern Appalachians are polymetamorphic, having been subjected to as many as three major episodes of regional metamorphism corresponding to the Taconic, Acadian, and Alleghenian orogenies. Local polymetamorphism may have occurred near faults associated with emplacement of thrust sheets, as described above. The effects of polymetamorphism are manifest in a number of ways, such as textural relations among minerals (e.g., psuedomorphs, reaction rims), solid inclusions in refractory minerals (such as garnet) that are not in chemical equilibrium with the rock's matrix, and anomalous chemical zoning in minerals. Systematics of mineral textural relations, microstructures, and geochronologic data allow polymetamorphism to be distinguished from sequential metamorphic reactions that take place when rocks are buried and heated, and then uplifted and cooled. Specific metamorphic episodes probably can be correlated with major tectonic events that define the various orogenies, even in the complex polymetamorphic terranes of the southern Appalachians, through coordinated petrologic, microstructural, and geochronologic analysis of drill-core samples.

## HEAT AND MASS TRANSFER DURING METAMOSPHISM

Petrologic studies of metamorphic rocks can provide information on the mechanism and patterns of heat and mass transfer during metamorphism. Analysis of reaction progress in metamorphic rocks, particularly when reactions involve volatile gain or loss, can record the time-integrated flux of fluid through rocks associated with a particular interval of their history as well as the amount of heat added to or extracted from them (Ferry, 1983). Water/rock ratios, for example, can be estimated and compared with stable isotope data from the rocks. Compositions of fluids that coexisted with observed mineral assemblages can be calculated from thermochemical data and compared with fluid inclusions. Knowledge of these parameters can help to constrain models of deformational processes and thermal history that are based on other types of observations.

Because of the fine grain size of cuttings from drilling of crystalline rocks and the variable response anticipated from different rock compositions, core is essential for research in metamorphic petrology at the southern Appalachian site. As anyone who has seen outcrops in metamorphic terranes can appreciate, rock type commonly changes on a centimeter scale. To ensure success in deciphering P-T paths and understanding reactions, continuous coring over intervals of at least 10 m (Tables 1 and 2), and perhaps as much as 50 m, is required because of the heterogeneity of metamorphic rock that will be encountered at depth in the hole. In addition, useful rock types such as pelitic schists often constitute less than 1 to 5 percent of an outcrop. Continuous coring will be needed both to assure representative sampling of all rock types present and of less common rocks that are of unusually great petrologic significance.

# 7
# Geochronology

The proposed drill hole would provide a continuous unweathered section through many of the major tectonostratigraphic terranes of the southern Appalachians and their contact zones. This would allow systematic determination of a variety of radiometric ages and would provide rigorous chronologic control for regional tectonothermal events. Samples from the hole also could be used for investigating diffusion-controlled radiometric systems in conjunction with companion isotopic and petrologic investigations (although if this were the primary objective, a site with a higher geothermal gradient would be chosen).

## REGIONAL GEOCHRONOLOGY

The tectonothermal evolution of the southern Appalachians is complex, with effects of at least three major events locally recorded: Lower-Middle Ordovician (broadly termed "Taconic"), Lower-Middle Devonian (broadly termed "Acadian"), and Late Carboniferous-Permian (Alleghenian). The regional significance of these distinct events has not been clearly determined. Resolution of the tectonothermal chronology of the crystalline terranes of the southern Appalachians is largely dependent on radiometric dating, but interpretation of results in such high-grade, potentially polymetamorphic terranes is commonly equivocal. This, in part, is a result of the nature of many isotopic systems where mobile radiogenic daughter products (Ar, Sr, Pb) are lost by intracrystalline diffusion until post-metamorphic or post-magmatic cooling through specific "closure" temperatures is achieved. Subsequent reheating may partially or completely reopen intracrystalline isotopic systems. Because closure temperatures within various mineral and whole-rock isotopic systems are different (Dodson, 1979), a spectrum of isotopic ages may be recorded within a single geologic unit. It is generally impossible to evaluate the geologic significance of individual age determinations, and a multidisciplinary approach is required.

Available geochronological data from the southern Appalachians show the expected divergence of ages recorded by different isotopic systems. Zircon U-Pb and whole-rock Rb-Sr data suggest widespread Ordovician and (or) Devonian tectonothermal activity (Tull, 1980; Glover *et al.*, 1983), whereas many K-Ar and Rb-Sr mineral ages are generally Late Carboniferous to Permian (Dallmeyer, 1978). $^{40}Ar/^{39}Ar$ incremental-release dating (Dallmeyer, 1979) has the potential of distinguishing gas-retention (cooling) K-Ar ages from disturbed K-Ar dates, which are likely in terranes affected by multiple thermal events.

The drill hole would provide a complete profile through many of the southern Appalachian tectonostratigraphic terranes. Fresh continuous sections across tectonic contacts, usually deeply weathered in typically poor surface exposures, would be a major focus of geochronologic and petrologic research. U-Pb dating of zircon and monazite, together with Rb-Sr whole-rock analyses, would be employed to most closely date high-temperature events. The U-Pb system is particularly useful because two radioactive isotopes of U produce different Pb daughter product isotopes. For example, analysis of multiple fractions of zircon from the same sample has the power to date major thermal disturbances and to determine the original crystallization age of a rock. A companion study of relic detrital zircons may define their provenance and thus constrain the origin of exotic terranes such as the inner Piedmont. About 2 kg of rock (150 cm of 2.5 cm diameter core or 16 cm of 7.7 cm diameter core) may yield sufficient zircon for analysis of several fractions; 10 kg samples are preferred, and up to 50 kg samples are commonly used in detailed studies of zircon-poor rocks (Table 2).

Because recent work has shown that even Rb-Sr whole-rock ages may, in part, relate to diffusive loss of radiogenic Sr during prolonged post-metamorphic cooling or subsequent alteration, a variety of scales of whole-rock sample suites should be analyzed including contiguous, thin-slab suites. These requirements, together with the large sample sizes needed for adequate zircon extraction, necessitate continuous core across all major tectonic contacts penetrated. With drill-core samples and the sophisticated mineral separation and analytical techniques that are now available, it is possible to separate and analyze the rare minerals that are essential to our obtaining the complete range of age information available in the mineral assemblage of a rock. Mineral separates for Rb-Sr, K-Ar, and $^{40}Ar/^{39}Ar$ analyses and fission track dating may be prepared from the material processed for zircon and other accessory mineral concentration. It is anticipated that similar multifaceted geochronological investigations would be carried out on each major geologic unit. About 10 m of continuous core would be required from each unit selected (Tables 1 and 2). The total number of units chosen would be dictated by the overall geologic complexity of each terrane encountered.

If core is not obtained for a substantial part of the hole, $^{40}Ar/^{39}Ar$, K-Ar, and Rb-Sr mineral dates should be determined on mineral concentrates prepared from cuttings collected over very restricted depth intervals. These would give a more complete view of the time-temperature record within each terrane and thus help to define contrasts across tectonic contacts. However, isolated age information on a series of rock samples has limited usefulness, unless those samples can be placed into geologic context as can be done for drill-core samples. Without such ancillary geologic information, geochronological data will have only a fraction of their potential impact.

## DOWN-HOLE THERMAL STUDIES

As noted earlier, radiogenic daughter products such as $^{87}Sr$ and $^{40}Ar$ produced within a mineral are not retained until temperature drops below a specific "closure" temperature. Assuming that the geochronological closure of a mineral isotopic system is in large part controlled by intracrystalline volume diffusion of radiogenic daughter products, Dodson (1979) derived an expression that related closure temperature to average cooling rate between open and closed system behavior, and various solid-state parameters that govern the diffusive mobility of daughter atoms during cooling. These solid-state diffusion parameters are known with varying degrees of certainty for the common rock forming minerals. Combined with empirical field controls, the diffusion parameters suggest the following "closure" temperatures at cooling rates between 10 and 100°C/Ma: hornblende = 525 ± 25°C (K-Ar), muscovite = 400 ± 25°C (K-Ar), biotite 300 ± 25°C (K-Ar and Rb-Sr).

Retention of fission tracks within minerals is also thermally dependent. These tracks are paths of damage produced within a crystal lattice by movement of heavy, charged particles which are liberated during spontaneous, intracrystalline fission of naturally occurring isotopes with high atomic numbers (mainly $^{238}U$). Although these tracks remain within most minerals for geologic times at low temperatures, the damage is annealed at higher temperatures and the tracks fade (Naeser and Faul, 1969). The rate of thermal annealing varies for different minerals, and therefore variations in fission track mineral ages can be used to help resolve the thermal evolution of geologic units. The observed track density represents approximately the time elapsed since the temperature dropped below a value at which 50 percent of the tracks were retained. Experimental studies suggest the following 50 percent track retention temperatures at cooling rates of between 10 and 100°C/Ma: epidote = 550 ± 25°C, zircon = 425 ± 25°C, sphene = 375 ± 25°C, phlogopite = 175 ± 25°C, and apatite = 125 ± 25°C. Clearly, core from any deep drill hole will be useful for evaluation of temperature controls for both fission track annealing and mineral closure temperatures.

# 8
# Heat Flow

Historically, heat flow on continents has been used as a constraint on models for chemical and physical processes occurring within the earth. Systematic differences in heat flow between physiographic or tectonic units are now apparent. These differences are an important factor in formulating models of the tectonic and thermal history of continents.

The definition of equilibrium (steady-state) heat flow is:

$$q = K(\mathrm{d}T/\mathrm{d}z)$$

where $q$ is heat flow, $K$ is rock thermal conductivity, and $\mathrm{d}T/\mathrm{d}z$ is the geothermal gradient. In the absence of heat sources, determinations of heat flow at various depths in the southern Appalachian hole should be the same, irrespective of the thermal conductivity of the interval over which the product $K(\mathrm{d}T/\mathrm{d}z)$ is determined. A corollary to this is that several determinations of heat flow should be made in the hole at depths where the average rock thermal conductivity is different to confirm the equality, and therefore the reliability, of a heat flow determination.

## THERMAL CONDUCTIVITY

Methods of measurement of thermal conductivity have been summarized by Roy *et al.* (1981). Reliable determinations of thermal conductivity of rocks from depths of several km or greater must be made on representative core samples. Conductivities measured on contiguous samples over a volume of approximately 10 $cm^3$ can differ by 50 percent even though the precision of each determination is 1 percent. An average value for many samples must therefore be taken over the interval for which the average thermal conductivity is desired. Conductivity measurements should be made on at least one sample per meter of core for a typical 30 m interval used for a heat flow determination. Several methods are used to estimate thermal conductivity for a vertical interval given many determinations on small samples (Roy *et al.*, 1981). All emphasize the heterogeneity of rocks, and the desirability for continuous core over the interval where heat flow is to be determined. The most accurate determinations are made on approximately 1 cm thick disks cut from cores between 2 and 4 cm in diameter (Table 2). Conductivity of isotropic rocks can be calculated from measurements on cuttings. Conductivity anisotropy can be significant in the deformed metamorphic rocks that will be penetrated in the southern Appalachian drill hole. Meaningful determination of vertical conductivity will require core samples. Oriented core is unnecessary because only the inclination of planar structures or fabrics, not their azimuth, is needed.

## GEOTHERMAL GRADIENTS

Temperature logs are readily obtained to a precision of ±0.01°C. For a reliable heat flow determination, the geothermal gradient ($dT/dz$) must be measured over the same interval as that for which a representative thermal conductivity has been determined. This interval must be one over which the geothermal gradient is not disturbed by ground-water circulation. Intervals of about 30 m should suffice for accurate gradient determinations, although shorter intervals probably could be tolerated. Measurements must be repeated after drilling has ceased, commonly several times, until drilling-related thermal disturbances have relaxed.

Although it may not be possible to determine a steady-state gradient over a small interval while drilling is in progress, it *is* possible during drilling to identify the presence of cracks that transmit water and therefore might preclude a reliable heat flow determination after steady-state thermal conditions have been reached.

Cracks that transmit water have characteristic thermal signatures (Drury and Jessup, 1982). Precision temperature logs should therefore be obtained at every opportunity during the drilling program to characterize, where possible, the hydraulic transmissivity of rock units penetrated by the deep hole. These data may be used to help decide on the amount of core to be taken over a deeper part of the same lithostratigraphic interval for thermal conductivity measurements.

## HEAT GENERATION

Variations in heat flow in the eastern United States are caused primarily by differences in crustal concentrations of the radioactive, heat-producing isotopes of U (contributes 40 to 45 percent), Th (40 to 45 percent), and K (10 to 20 percent). A U atom gives off about 4 times the heat of a Th atom, but because Th/U ratios in rocks are commonly around 4, Th is about as important as U for heat production. Minimum sizes of representative samples are determined by the same criteria as for other geochemical analyses. Sampling intervals depend on the degree of heterogeneity of the geologic unit of interest. Meaningful data for radioactive element distribution in layered metamorphic rocks, like those we expect to encounter in the southern Appalachian hole, will require careful examination and extensive sampling of essentially continuous core. Because the bulk of the U and Th in rocks commonly resides in rare grains of accessory minerals, along grain boundaries, or in veins or segregations, the distribution or redistribution of these elements in rocks cannot be understood without thin sections made from core.

## SIGNIFICANCE OF HEAT FLOW DATA

The highest heat flow values in the eastern United States are associated with syn- and post-metamorphic granites, and most heat flow determinations have been made in granitic rocks (Sass *et al.*, 1981). Birch *et al.* (1968) determined heat flow in New England and the Adirondacks and found that heat flow ($q$) was related to surface heat generation ($A$) by

$$q = q* + DA$$

where $q^*$ is a constant ("reduced heat flow") and $D$ is a constant with units of depth. Continental heat flow provinces are defined on the basis of $q^*$, assumed to be the flux from the lower crust and upper mantle. The simplest models that result in a linear relation between $q$ and $A$ are: (1) the concentration of heat-producing elements is constant from the surface to a depth $D$; and (2) the distribution of heat-producing elements decreases exponentially downward from the surface to a depth of approximately $3D$, where $D$ is a logarithmic decrement describing the rate of change of the concentration of heat-producing elements. These models place severe constraints on crustal structure wherever a linear relationship is observed. Lachenbruch (1968) pointed out that Model 2 will account for effects of differential erosion above heat flow sites, whereas Model 1 will not.

The Piedmont heat flow and heat generation values, determined in post- and late synmetamorphic (254-330 Ma) granite plutons and metagranites, lie in a belt approximately parallel to major structural trends in the Appalachians. These data can be modeled with $q^* = 30\,\mathrm{mW/M^2}$ and $A = 8$ km. Costain and Glover (1980) have proposed that the occurrence of a master sole thrust that truncates granites in the allochthonous plate may be responsible for the linear relation between heat flow and heat generation from many of the plutons of the eastern Piedmont. In this interpretation, $D$ is a measure of the depth to the master thrust. The interpretation of $D$ as a logarithmic decrement, however, would require an uninterrupted exponential decrease of U and Th to a depth of approximately $3D$ or about 20 km. Redistribution of mobile heat-producing elements during metamorphism might account for an exponential distribution. The proposed deep hole would make possible a unique test of these competing models for radioelement distribution.

An understanding of the linear relation between heat flow and heat production has important tectonic implications not only for the eastern United States, but for any tectonic province where it is observed. The proposed deep hole, together with supplementary shallow heat flow sites, offers a unique opportunity to resolve the significance of the linear relation between heat flow and heat production in this region and perhaps provide constraints that are applicable globally. Because of the known low heat production of carbonates, quartzites, and Grenville basement below the master decollement, it should be possible to determine q* directly from measurements in the 10-km hole.

# 9
# Seismic Velocity Determination

Laboratory measurements of rock velocities at ultrasonic frequencies and high pressures are commonplace. Bonner and Schock (1981) provide a recent update and summarize dimension requirements for reliable velocity determinations. For determination of compressional velocity, the length of a cylindrical specimen must be less than 6 times the diameter, or interactions with the sides of the core sample will cause the simple plane wave to become dispersive. Because the distance traveled by the wave should be at least 50 times the mean grain diameter to obtain a velocity representative of the whole rock, velocity determinations should be made on large samples (10 cm long; Table 2) of rocks with a grain size greater than 2 mm (many granites, for example).

The need for core samples becomes all the more obvious when a representative average compressional velocity for a rock unit is desired. The proposed 10 km deep drill hole that will intersect observed reflectors and known structures offers an excellent opportunity for calibration of seismic reflection and refraction experiments in the southern Appalachians through determination of average compressional velocities of tectonostratigraphic units on the basis of laboratory measurements on cores. Removal of samples from confining pressure and differential stress conditions at depth may induce changes, such as opening of microcracks and loss of pore fluids, that result in decreases in seismic velocities. Laboratory measurements can be made under appropriate confining pressures, and core samples can be handled in such a way as to prevent dehydration. The effect of elevated temperature on velocity may be significant, but it is generally less than effects of microcracks. Because of the low geothermal gradient in this region, measurements at high temperatures will not be necessary.

Anisotropy of the metamorphic rocks of the Appalachian orogen will affect seismic velocity determinations. In order to measure velocities in directions other than the vertical, oriented sidewall samples may be needed. These measurements could be made on the same samples used for microstructural and other studies. Conventional core samples may be adequate for relatively fine-grained rocks if orientation can be established from planar structures and dip logging records.

# 10
# Interpretation of Logs

Downhole logging devices provide virtually continuous information on rock properties from top to bottom of a well that can be used to infer rock types, fracture densities, and fluid parameters. Calibration of logs has become quite sophisticated in the oil field environment, but experience is limited (Daniels *et al.*, 1983), to say the least, in crystalline terranes such as the southern Appalachians. Core samples can provide information with which to calibrate logs. Borehole logging and core analysis acquire complementary pieces of information, and each produces information not available from the other. This is the fundamental reason that the Ocean Drilling Program requires both continuous core and logging in all holes more than 400 m deep.

Because one never returns 100 percent of the cored section to the surface, logs are useful for locating where the core came from and for providing geophysical and geochemical measurements of the missing interval. But in order to know which sections are missing, core measurements must be used to match log results. This circular reasoning can be circumvented by spotting sidewall core at exact depths in the well. These then serve to locate not only the logs, but the cores as well. Sidewall diamond-drill coring technology has developed to the point at present where both continuous and discrete interval coring from a wireline can be done economically. Both will be required by a scientifically rigorous investigation of deep continental drill holes.

Logging tools measure over larger volumes around the hole than are represented in the recovered core. Laboratory measurements may be made on the core to observe small scale features such as crack morphologies or fluid inclusion chemistry that are not observable by logging tools. Drill hole measurements determine the in situ physical and chemical environmental conditions, but laboratory pressure vessels can measure core properties in a wide variety of physical and chemical environments. Such laboratory measurements are especially important when information must be extrapolated deeper than the hole was drilled. Borehole measurements may be obtained in areas where core recovery is poor, but only core provides continuous data. Even though drill hole logs look continuous, there are usually only a few measurements per meter of hole—thin beds and fault planes are sometimes missed.

The same information cannot be acquired from cuttings as from core. Cuttings frequently exhibit changes in clay mineralogy due to the high temperature of the drilling process. They are contaminated by pieces of the drill bit and drilling fluids. They are mixed over long depth intervals, making location of lithologic contacts uncertain. Finally, much textural information concerning bulk density, porosity, pore morphology, hydraulic conductivity, and so forth is lost.

## MAGNETIC PROPERTIES

If oriented samples are obtained (Table 2), the tools of paleomagnetics may be applied (Van der Voo and Channell, 1980). They may yield information about rock history through the alteration of magnetic minerals, magnetostratigraphy, and magnetic anistotropy; ages may possibly be obtained from paleopole positions and reversals. At a minimum, without oriented core, the results may be useful in determining paleotemperatures or for mapping stratigraphic horizons from changes in magnetic properties (Strangway, 1981) such as alteration of magnetic minerals, magnetic susceptibility, and field intensity. Both kinds of information will be useful in interpreting surface magnetic anomaly signatures. Magnetic field intensity and magnetic susceptibility drill hole logs are available, but the remaining measurements are only available through core studies. In addition to all the usual problems and uncertainties in working with cuttings, pieces of the drill or core bit appear in the cuttings, destroying their utility for magnetic measurements. At intervals throughout the hole (determined from the continuous core and logs), gyro-oriented sidewall samples should be acquired for paleomagnetics, strain, and other measurements requiring oriented core.

## ELECTRICAL PROPERTIES

In order to measure the electrical properties of rock samples, the core must be sealed to isolate it from the atmosphere to prevent changes in water content and chemistry. Electrical measurements will yield information related to texture, porosity, permeability, chemical reactivity, alteration, clay mineralogy, and so forth. Some of these may be affected by rock anisotropy so that oriented samples will be needed. Of particular interest are the electrochemical measurements that make possible investigation of active processes, such as oxidation-reduction and ion exchange reactions, as well as the diffusion and kinetic coefficients of the reactions (Olhoeft, 1981).

By putting core samples in laboratory environmental chambers, electrical properties can be used as monitors of changing mineralogy and chemistry as the sample is subjected to different conditions of pressure, temperature, and environmental chemistry. This is a powerful technique for extrapolating conditions in the crust away from the original hole in depth, lateral extent, and time.

Electrical properties are sensitive to small amounts of clay minerals and their distribution within the rock. Different electrical responses and hydraulic conductivities are obtained from pore-bridging, pore-lining, and pore-blocking clay morphologies. Electron microscopy of core samples is required to distinguish these morphologies and calibrate the interpretation of the electrical (and other) bore hole logging measurements. In addition to calibration of logging results, knowledge of electrical properties of rocks encountered in drilling will aid in interpretation of geophysical studies, such as magnetotelluric soundings that might be carried out far from the drill hole but in geologically similar terrane (Stanley *et al.*, 1977).

## HYDRAULIC PROPERTIES

Both these measurements are best done in situ, because the area of investigation for core is too small to be representative of the general geological environment. Core measurements, however, are crucial to calibration and proper interpretation of in situ measurements. Porosities from a variety of logging techniques give values representative of microcrack, grain-boundary, fracture, and closed-structure geometries. Core measurements are necessary to calibrate the small-scale porosity measures so that larger-scale porosities determined from logs are themselves accurate. Permeability measurements made in borehole are effective bulk values applicable only over the interval tested. That is, packers can be spaced so that either horizontal bulk permeability or effective vertical permeability can be measured. Permeability measurements on core give a grain-size lower-limit to these in situ measurements. The difference between permeability measured in the laboratory on core and that at various scales measured in situ provides essential information about structural control of hydrological parameters not available by any other means. Core sample size requirements are similar to those for other physical property measurements (Table 2).

## ELASTIC AND DEFORMATIONAL PROPERTIES

Elastic constants are used in modeling rock deformation. Dynamic elastic constants can be obtained from measurements of density and of compressional and shear wave velocities as functions of pressure on core samples of most rocks. Static conditions, in which a sample is loaded by an externally applied stress, are more appropriate for measurement of elastic constants for materials that deform by creep. Fracture and frictional strengths also must be known in order to accurately model rock deformation, especially faulting. Such data are useful in interpretation of in situ stress measurements. Preservation of core material in a condition that is representative of rock properties at depth is essential. Sample requirements are similar for all these types of determinations. Core samples about 2.5 cm in diameter and 7.5 cm long are sufficient (Table 2). The small improvement in quality of data yielded by oriented cores probably does not outweigh the additional effort and expense that may be necessary to achieve it.

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