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SCIENCE

Probing the Structure of the Deep Continental Crust

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There is a glaring deficiency in the theory of plate tectonics, the great scientific paradigm that burst upon the geological scene during the 1960's and that has provided earth scientists with an enhanced understanding of earth dynamics and a framework for the synthesis of observations on a global scale. In its simplest forms, plate tectonics, which is rooted in observations of the ocean basins, fails to account for much of the geology of the continents. Yet the continents are the places where most geological observations are made.

Summary. Old, buried, deformed, crystalline rocks apparently make up most of the 40-kilometer-thick continental crust. This part of the earth is poorly explored and constitutes a major frontier of modern earth science. Two techniques, seismic reflection profiling and drilling, which were developed by industry for other purposes, offer special potential for such exploration. Seismic profiling of the deep crust by COCORP (the Consortium for Continental Reflection Profiling) has already produced important information, including evidence for extensive thin-skinned thrusting of older rocks over a continental margin as the corresponding ocean basin closed. Deep drilling of crystalline rocks of the continents for scientific purposes is so far relatively unexploited in the United States but is already being carried on elsewhere. In general, big science is likely to become more important in basic geology as this frontier is explored.

As a consequence of this disquieting situation, throughout the past decade much effort has been expended by geologists, with partial success, to (i) develop the concept of plate tectonics in order to make it compatible with observations on land and (ii) make new observations of continental geology that seem relevant in this context. On the purely scientific side, this article is primarily about (ii), illustrating how new kinds of data on the deep continental crust, or continental basement, may help to modify the early models of plate tectonics and eventually provide a more comprehensive understanding of the earth.

Exploration of the continents is by no means the exclusive task of scientists attempting to develop a scientific theory, however. There are large and ever-increasing demands on industry, government, and academia for new geological information bearing on such urgent societal problems as mineral and energy resources, waste disposal, ground water, and earthquake and volcano hazards. This article is also, somewhat implicitly, about transfer of technology from industry, which develops it for applied purposes, to academia, which needs it for scientific study of the deep crust. Seismic reflection profiling and deep drilling are the cases in point. It is also about some trends that may affect geology in the future as earth scientists strive to capitalize and build on a new foundation and so advance the science and provide information society needs by incorporating more powerful means for exploring the earth.

For the external observer of modern earth science, it may be helpful to consider the exploration of the depths of the earth in perspective. Humans have long since explored the earth in all horizontal directions to their satisfaction, and in recent years it has become almost commonplace to send spacecraft upward for millions of kilometers to probe other planets or space. In the downward direction, however, the situation is strikingly different. There are almost totally unexplored regions within a kilometer or a few kilometers of any point on the surface of the solid earth—easy walking distance if the path were horizontal. Data on this vast buried frontier are generally sparse, of low resolution, and by no means uniform, for accessibility, cost, and potential for benefits have caused exploration efforts to focus on certain regions. The best known part of the solid earth is, of course, its land surface, but the sedimentary basins and the ocean floors have also received concentrated attention. Let us look briefly at the study of these regions as a background for discussion of exploration of the deep crust.

The Surface

Geologists began to explore the continents by measuring, mapping, and sampling for laboratory analysis the rocks of the earth's surface. Such work is by no means complete, and the task expands as new analytical techniques become available and new ideas require testing. However, on a reconnaissance scale, most of the land areas of the world have been seen by geologists and their observations have been recorded. The results are summarized in the beautiful, diverse, and strikingly complex maps that decorate the halls of every geology building and that hold huge quantities of information on the earth.

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But maps describe a world of two dimensions, and it has long been recognized that information on the third dimension, depth, is a prerequisite to understanding geologic features and their evolution. Geologists commonly seek information on the third dimension through study of features of high relief or penetration such as deep valleys, road cuts, tunnels, and shallow holes drilled for other purposes, but such information is essentially surficial in the context of study of the entire crust. A certain amount of generalized information on buried strata may be found in orogenic zones, areas of high deformation, where rocks once at depth may now be found at the surface. Natural samples from depth are also available in the form of xenoliths transported to the surface in igneous rocks, or the igneous rocks themselves. Such rocks are samples of the deeper strata as they were at an earlier time, and are not necessarily representative of the present. Nevertheless, a large amount of geochemical and petrological information on the deep crust is obtained in this manner and forms a subject of great potential and major importance to which justice cannot be done in this article, which focuses instead on the physical structure of the crust.

The Sedimentary Layer

When there is sufficient economic or other incentive, the depth dimension of geologic features is explored by drilling and by a variety of geophysical techniques. Such incentive arises in the search for petroleum, for example, and the exploration of the sedimentary basins by the petroleum industry is the classic example of intensive and successful application of the most modern technology to the study of a selected, buried portion of the earth.

With the exception of a limited number of areas in which old, hard, crystalline rocks are exposed at the surface—such as the Adirondack area of New York State or the Precambrian shield that makes up much of Canada—most of the surface of the continents is covered with a thin veneer of unmetamorphosed sedimentary rocks of Phanerozoic age, that is, less than 600 million years old. The rocks beneath the Phanerozoic sediments are typically, though not always, crystalline and of igneous or metamorphic origin. Such rocks are commonly referred to as basement, although that term is sometimes used by geologists in other ways, and they make up the bulk of the continents. The sediments are only a few hundred meters or less in thickness in many areas, but in others, the sedimentary basins, they are thicker and may be as much as about 15 km thick in some cases. Most petroleum is found in such basins. Study of sediments has provided much of what is known of earth history. The story is too lengthy to tell in detail here, but the point is that with application of modern technology, this buried portion of the earth has yielded its secrets and benefits in abundance.

Two Principal Techniques

Over the past century, techniques for exploring the sedimentary basins have been highly developed by the petroleum industry, particularly by U.S.-based companies. Although other methods are used and are important, the principal techniques for subsurface exploration by the petroleum industry are seismic reflection profiling and drilling. These techniques require some discussion here because of their relevance and potential for exploring the basement.

Seismic reflection profiling in its modern form is an elaborate and sophisticated version of echo sounding. In general, it provides far better resolution of subsurface geology than does any other geophysical technique. Explosives or truck-mounted vibrators are commonly used in spatial arrays as sources. Thousands of geophones (ground-motion detectors) form receiving arrays many kilometers in length. During a survey, sources and receiving arrays move along the surface of the earth, pausing every few meters to make another sounding and typically progressing at rates of a few kilometers per day. The data are recorded in digital form and reduced by using the most advanced signal processing techniques. The petroleum industry in the United States currently spends about $3 billion per year on such prospecting, and this large sum commands the best engineering practice. Although the technology is already highly developed, there is ample room for further progress, and one can anticipate additional important advances in the future.

Drilling is an important means for exploring the shallower parts of the earth's crust. Samples in the form of cuttings and cores are obtained, and a variety of additional information comes from drillers' records and from measurements made by lowering measuring devices into the holes, that is, logging. The level of drilling activity in the United States may be surprising. About 77,000 holes were drilled in the search for petroleum in the United States during 1981 alone. Most of these holes are relatively shallow, however. Comparatively few exceed depths of 5 km. The deepest hole drilled in the United States, and the world record for many years until recently, reached 31,441 feet, or 9.58 km. Most holes are terminated in the sediments; the few holes drilled by the petroleum industry that go through the sediments usually penetrate only a few feet of crystalline rocks and thus provide limited information on the basement. Some holes are drilled largely or entirely in crystalline rocks of the basement by the mineral industry, or for other specialized applications such as waste disposal or geothermal exploration, but these holes are few in number and are limited to sites with very special properties and so provide useful but not comprehensive information on the crystalline rocks of the crust.

Seismic reflection profiling and drilling, both developed for other purposes, are critical tools for study of the continental basement. Their potential is vast, and at present their application is limited primarily, though not entirely, by cost.

Some Related Points on Exploration of the Ocean Basins

Geological exploration of the ocean floors is in a more advanced stage than, and may serve as a model for, exploration of the deep continental crust. Ocean basin exploration proceeded at a modest pace until the end of World War II, but the next decades brought intensive exploration of this large part of the earth and the key observations that led to the concept of plate tectonics. The early work was done primarily by oceanographic institutions using a variety of geophysical techniques, including echo sounding of the sea floor, gravity, magnetics, seismic refraction, and, later, seismic reflection. Dredging of rocks of the ocean floor and coring that penetrated a few tens of feet into the sediments provided the geological samples.

The value of subbottom seismic reflection profiling for scientific studies of the deep-sea floor was not demonstrated until the early 1960's. Concurrently, the great increase in interest in offshore oil in many parts of the world brought full-scale entry of the petroleum industry into exploration of water-covered areas, and the seismic reflection technique was developed rapidly with arrays of air guns replacing explosive sources, long streamers with hundreds of detectors serving as receiving arrays, digital data processing, and specialized ships. Methods for drilling on the shelves in increasingly greater water depths were also developed during this period, a trend that continues today. In the late 1960's, industry's expertise in drilling was coupled with academic interest and federal (National Science Foundation) funding to make possible the program of the *Glomar Challenger*, an oceangoing drilling vessel that conducted the first—and highly successful—program of drilling deep-sea sediments and the bedrock beneath. This program provided what for some is the most convincing evidence for plate tectonics. In its later years it became an international effort with funding from a number of industrialized nations.

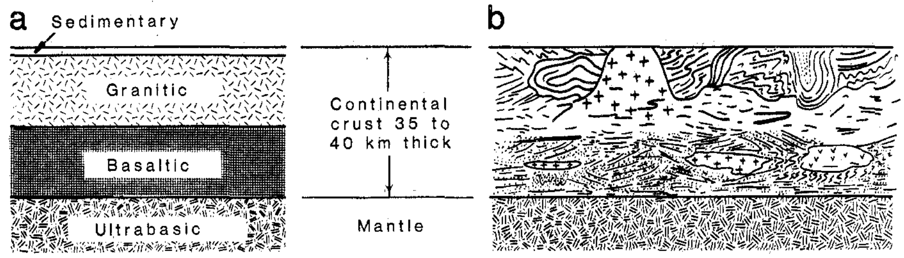

Fig. 1. (a) Traditional but outdated model of continental crust consisting of a thin layer of sediments overlying a granitic layer of about half crustal thickness, in turn overlying a basaltic layer of about half crustal thickness, with the mantle beneath. (b) Modified from Smithson's generalized crustal model (*1*) showing three zones including an upper zone of supracrustal and granitic rocks, a middle migmatitic zone and a lower andesitic zone with the mantle beneath. Lateral variations are a key point of this model.

In drawing a parallel with exploration of the deep continental basement, it is important to note in the case of the oceans not only that industrial techniques were brought into pure science with great success, but also that preliminary geophysical exploration defined the problems before the successful but expensive drilling program began. In effect, the pattern set by the industry in the search for petroleum was brought successfully into scientific study of the ocean basins. The same pattern may prevail in exploration of the basement.

The Continental Basement

Historically, the continental basement has been explored by a variety of geophysical techniques that measure such properties as seismic wave velocity, density, conductivity, and magnetism as a function of spatial coordinates. These methods have revealed much of what is known of the deep crust and have continuing potential. The seismic refraction method, which has been widely used and highly productive, relies on observation of waves which travel along deeper layers of generally high velocity and are refracted back to the surface. Seismic refraction studies show that rocks of the continental crust extend to depths of about 40 km, where they lie on the Moho, the upper surface of the ultrabasic rocks of the mantle.

From early measurements it was deduced that the continental crust typically consists of a thin layer of sediments, overlying a "granitic" layer of about half crustal thickness, in turn overlying a "basaltic" layer of about half crustal thickness, with the mantle beneath (Fig. 1a). This view of the crust was widely held and still appears in some textbooks, but it has long been abandoned as inadequate by researchers in the field, even though the true structure of the crust remains far from well known. To what extent the crust is made up of horizontal layers is an important question. When contrasted with the contorted character of most crystalline rocks exposed at the surface of the basement, simple layered models of the crust present a dilemma. Surely the complexity of the surface rocks must continue in some form to some depth in the earth. On the other hand, at some greater depth where the rocks have no strength, density stratification in spherically concentric layers may prevail. Many data, including those to be discussed shortly, indicate that significant lateral heterogeneity occurs throughout the continental crust at least on some scales, but other evidence such as the rather uniform thickness of the continental crust everywhere may indicate significant gravity-driven flow on a larger scale. Figure 1b shows a model of the crust proposed by Smithson (*1*) to replace the granite-basalt model of Fig. 1a. Probably this model is much more realistic than that of Fig. 1a and a step in the right direction, but it is generalized and is not intended to depict real spatial variations. The need now is to map deep crustal structure so that it can be related to mapped surface geology.

A New Phase of Exploration of the Continental Basement

During the 1970's it became apparent that, in spite of the continuing improvement of conventional methods of exploring the continental crust and their potential for further contribution, new methods for probing the basement with still greater resolution would be required. The obvious choices were the seismic reflection profiling method and deep drilling, both methods in use in highly developed form in the petroleum industry. To date, there has been little drilling of the basement in the United States for solely scientific purposes, partly because of the cost but partly also because a drilling program must have specific targets and the continental basement is so poorly known that it is difficult to select optimum targets. The preliminary stages of a scientific drilling program for the United States have begun, however, with some "piggybacking" (a term used in this context to describe the deepening for scientific reasons of holes drilled for other purposes) and preliminary plans for deep holes in geothermal and mineral deposit regions. It seems inevitable that, at some time in the future, mankind's curiosity and needs will dictate the drilling of many holes to probe the unexplored regions of the United States.

The Soviet Union, which trails the United States substantially in capability for drilling for petroleum, has operated a strong program of seismic exploration of the deep crust for decades and is currently engaged in a major drilling program to complement the seismic work and to further explore the deep crust. A record-setting hole is being drilled in the Kola Peninsula (in the Barents and White seas), apparently primarily for scientific purposes. Reports are limited, but indications are (*2*) that the hole was sited to probe, among other things, the Conrad discontinuity, the boundary between granite and basalt as seen in Fig. 1a, which is located at 7 km in this region by the Soviet method of deep seismic sounding. The hole, which was begun in the 1970's, has exceeded 11 km (~ 36,000 feet) in depth and has penetrated first Proterozoic rocks and then Archean rocks below about 7 km. The Archean rocks are gneisses and amphibolites, with an increasing percentage of amphibolite with depth. Thus the model of Fig. 1a is inappropriate. The strata maintain high dips at depth. Records of ancient life have been found at depth. These results are exciting, and more comprehensive reports are eagerly awaited. The hole is planned to go to 13 km according to one report, 15 km according to another.

A second deep hole is being drilled in the Kura depression at Saatly in Azerbaijan near the Caspian Sea and is said to have already exceeded a depth of 7.5 km (24,600 feet). The source of a gravity high is one target. The Soviet Union has a plan for ten deep drill holes, five in petroleum regions and five in ore regions. Holes will be located in the Urals, Ukraine, Central Asia, northern Siberia, the north slope of the Caucasus Mountains, and western Siberia. This drilling program is apparently being conducted for a combination of applied and basic purposes. For this reason it is difficult to compare the Soviet program with the U.S. effort, which probably overwhelms the Soviet effort in the case of petroleum exploration but is not yet comparable to it in drilling deep holes on land for scientific purposes. West Germany is also developing an extensive land-based deep drilling program. The U.S.-led program with the *Glomar Challenger* has, of course, had world leadership in deep-sea drilling, as has the U.S.-based petroleum industry in drilling of the continental shelves.

As a result of industry's desire to drill to great depths in the search for natural gas, some rotary rigs are now available or being constructed in the United States with the capacity to drill to 50,000 feet, or more than 15 km. Of course, many problems will arise in probing such depths, and rig capacity alone does not guarantee penetration to the rated depth. There are also substantial problems in constructing the logging tools to make deep measurements. There is clearly a technological frontier here that industry or others, perhaps government laboratories with experience in drilling holes for deep nuclear explosions, will someday conquer, and a spin-off may occur in the form of enhanced capability for scientific exploration to depths of as much as 15 km. There seems little hope, however, of drilling to depths much greater than 15 km within the next few decades.

In the United States the application of seismic reflection profiling to study of the basement is in a more advanced stage than is drilling. In 1974 an organization called COCORP (Consortium for Continental Reflection Profiling) was formed specifically to apply the seismic reflection profiling technique of the petroleum industry, with appropriate modification, to study of the basement. A nationwide effort, COCORP currently consists of one special field crew operated on a full-time basis by a subcontractor, Petty-Ray Geophysical Division of Geosource, Inc.; an overall project management, data analysis, and interpretation team and a Megaseis seismic data processing facility at Cornell University, the prime contractor and operating institution; and various advisory committees consisting of personnel drawn from government, industry, and universities throughout the United States. The Vibroseis technique developed by Continental Oil Company is used. Data are available to all interested parties, and many contribute to the overall results. Some universities conduct related field research on technique through a program called CERP (COCORP Extended Research Project); others conduct research on data process-

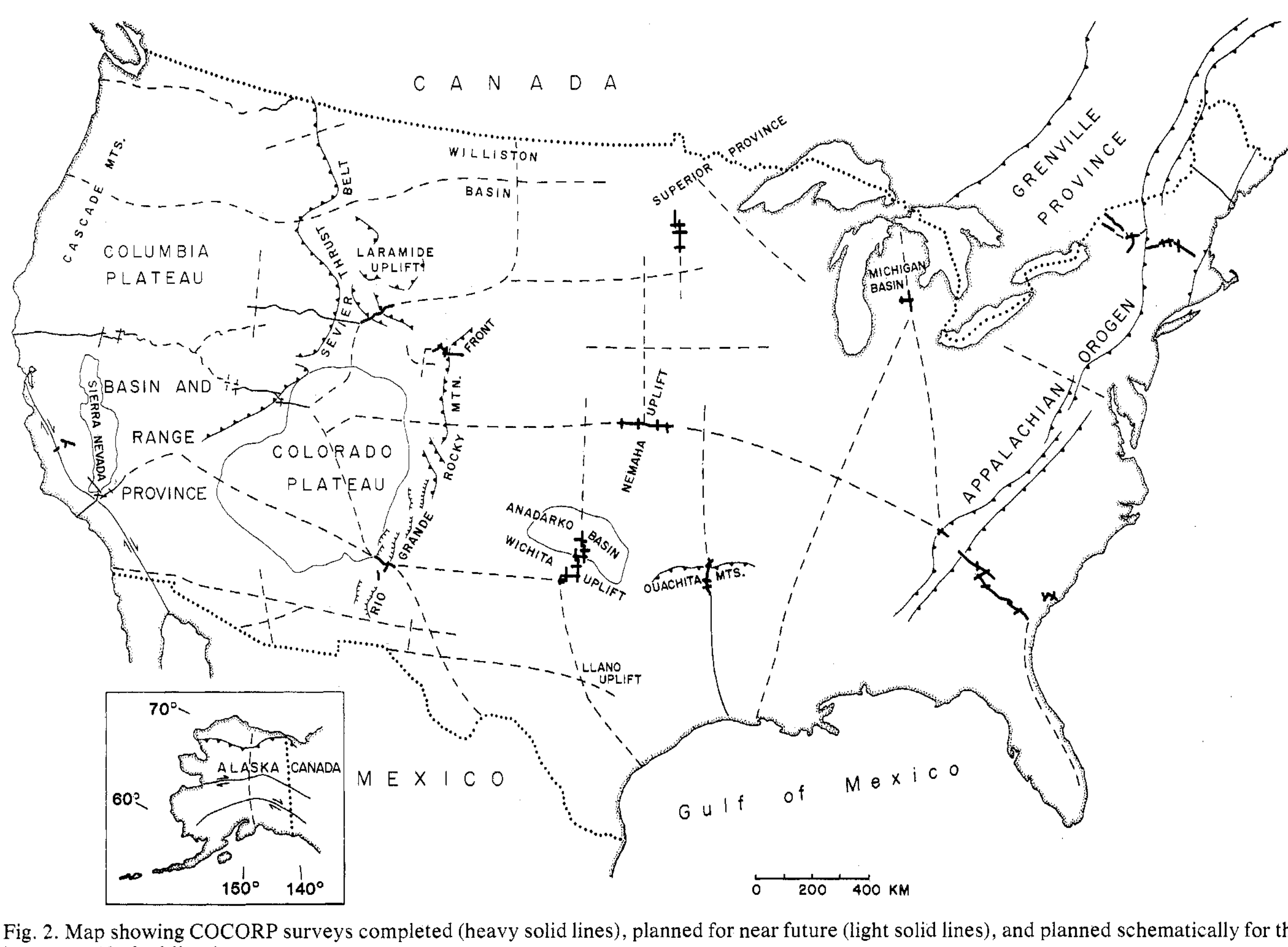

Fig. 2. Map showing COCORP surveys completed (heavy solid lines), planned for near future (light solid lines), and planned schematically for the long term (dashed lines).

ing and interpretation. The blending of industrial, academic, and governmental interests and expertise is a critical component of the program.

To date, seismic profiles totaling about 4000 km, a distance equivalent to one traverse across the United States, have been carried out at the sites indicated in Fig. 2.

From the time of the first field tests in 1975, when the issue was whether the seismic reflection technique could produce any information of value on the complex rocks of the continental basement, COCORP has moved to its present state, when novel and important information is obtained in almost every survey. Occasionally, as one might expect while probing a new frontier, surprising observations appear.

Many COCORP studies have already been reported in the literature, generally on a site-by-site basis (*3*). Too numerous to summarize in detail here, they include studies of a magma body buried in the crust at a depth of 20 km under the Rio Grande Rift of New Mexico; investigation of the midcontinent geophysical anomaly, a huge Precambrian rift, in Michigan and Kansas; discovery of a deep Proterozoic depositional basin in the crust southwest of the Wichita Mountains of Oklahoma and documentation of the thrusting of those mountains over the Anadarko Basin to the northeast; and tracing of major faults from the surface to depths of at least 25 km in several parts of the United States. In the Wind River Mountain area of Wyoming, data on one such fault suggest that the Wind River uplift, and by implication other similar Laramide uplifts, are the result of horizontal compression in the crust, a point of some importance for understanding these unusual features and for petroleum exploration in the area. The widespread success of COCORP is a simple consequence of the application of a technique for measuring a previously unmeasured, fundamental property of geologic structures, in this case, the third dimension. An important part of the process is the capability for tracing features such as faults or lithologic strata from the surface, where they are known, to great depths, and hence for identifying the features at depth.

Perhaps the most important general result of COCORP surveying to date has been demonstration of very large scale, thin-skinned thrusting of generally older rocks onto younger sediments of preexisting continental margins. COCORP sites in the southern Appalachians (*4*), the northern Appalachians (*5*), and the Ouachitas (*6*) provide such evidence,

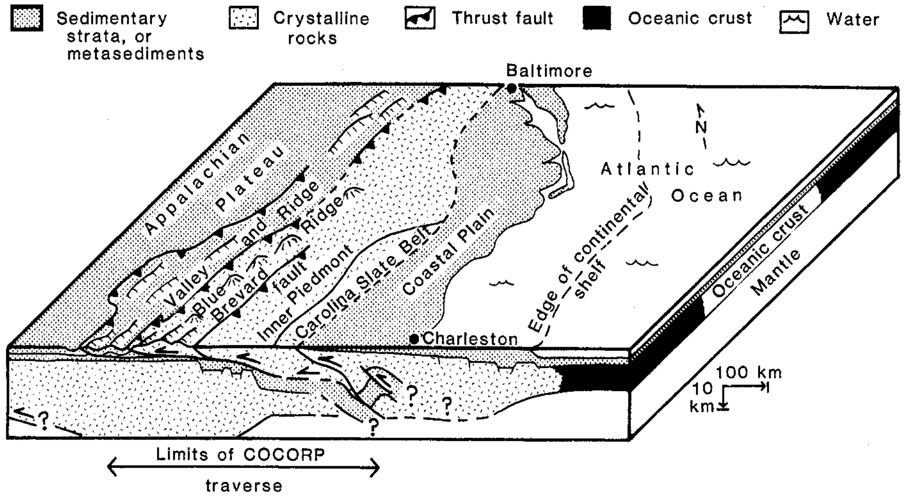

Fig. 3. Diagram illustrating the modern Atlantic margin of the southeastern United States. Cross section shows how rocks of the southern Appalachian thrust sheet now overlie a former continental margin, which before burial resembled the modern margin.

and various surveys by others now support these conclusions. In fact, such thin-skinned thrusting may be the key in relating many aspects of continental geology to plate tectonic theory.

Thin-Skinned Thrusting and Plate Tectonics

The idea that thin sheets of rocks have been thrust horizontally for distances of at least a few tens of kilometers has been in geology for many years, but has not always been widely accepted. Among other things, recognition of the large nappes of the Alps and the theory of Hubbert and Rubey (*7*), which showed that such thrusting was mechanically possible with sufficient pore pressure in the thrust zone, helped build the case in favor of thin-skinned thrusting.

When the concept of plate tectonics arose, thrusting on a scale previously undreamed of suddenly became acceptable to most geologists. Many thousands of kilometers of displacement must have occurred along thrust faults as ocean floors disappeared into subduction zones. In this context displacements of a few tens or even hundreds of kilometers, which once seemed formidable, were relegated to secondary status, but faulting of such scale may be the key to the geology of parts of the continents, and hence have great importance.

COCORP surveys in the southern Appalachians show that generally younger sedimentary rocks of the Valley and Ridge Province in the western part of the Appalachians can be traced to the east beneath the crystalline and generally older rocks of the Blue Ridge and Piedmont provinces and probably the Coastal Plain Province as well (Fig. 3). The COCORP data support and give greater credibility to the ideas of Hatcher (*8*) and others, who indicated that the Blue Ridge and part of the Piedmont Province had overthrust the sediments, but amplify that concept significantly to include perhaps the entire Piedmont and Coastal Plain provinces as part of the thrust sheet.

In addition to the COCORP data for the southern Appalachians, COCORP data for the northern Appalachians and for the Ouachitas, SOQUIP (Société Québéçoise d'Initiative Pétrolière) data for Quebec, and studies by the U.S. Geological Survey, Virginia Polytechnic Institute, and the petroleum industry in various parts of the Appalachians support this concept. Thus thin-skinned thrusting of basement rocks seems firmly established for the crystalline Appalachians as thin-skinned thrusting of sedimentary rocks of the Valley and Ridge Province had been accepted before. As the Appalachians are commonly thought of as a representative mountain belt, there is the implication that the thin-skinned thrusting phenomenon may have prevailed at one time or another in many other areas of the earth as well. For example, on the North American continent, the western Cordillera is similar in many respects to the Appalachians. Thin-skinned thrusting of basement may have occurred there. It is also possible that the Grenville orogenic belt of eastern North America and of Proterozoic age may have been the site of thin-skinned thrusting, but this point is speculative at present. These ideas call for testing through further observation.

Of interest is the way in which the Appalachian orogenies, and those of other similar belts, may be fit into the theory of plate tectonics. In the plate tectonic model of the earth the fundamental units, eight major plates of lithosphere some 100 km in thickness, cover the surface of the earth and move relative to one another. New lithosphere is created and added to the trailing edge of the plate where the plates spread apart, and older lithosphere is destroyed in the process of subduction where two plates converge. Continents are parts of the plates and move about as passengers on them. New lithosphere generally makes up the oceanic part of a plate. Thus, when the pattern of plates changes and a continent splits apart, an ocean is formed between the two diverging continental fragments. The ocean grows as the sea floor spreads. Characteristically, after opening and expanding for many millions of years, an ocean contracts and closes. Eventually the opposing continental masses collide. This cycle of ocean opening and closing, for which the prime example is provided by the modern Atlantic and its forerunners, is called the Wilson cycle. The Wilson cycle has grown in importance as continental geology, and particularly the geology of orogenic belts, has been fit into the concept of plate tectonics, because ocean opening and closing leaves a decipherable record in continental rocks.

In the case of the Appalachians, a simplified version of what may have happened is the following. During late Precambrian time a preexisting continent split apart to form North America and one or more other land masses. An earlier version of the Atlantic Ocean grew between these continents. Continental margins complete with platform, shelf, slope, and rise sediments, resembling the modern Atlantic margin, developed at their edges. As the ocean closed in Paleozoic time, debris of the sea floor, including some of the margin sediments, slices of basement rock, island arcs, and microcontinents, slid onto and over the continental margin of that time. Major collisions produced orogenies. The process culminated in a collision between North America and the opposing continent to produce the Appalachian orogeny. At a later date, the modern Atlantic began to open more or less along the seam of the previous collision. This story may be expanded in considerable detail to fit the geological observations of the Appalachians and their variations along and across the trend of the feature. For example, the great sedimentary trough that extends along the Appalachians and west of the thrust sheet must to a large extent be the result of subsidence of the crust due to loading by the overthrust material. Thus, the role of the Wilson cycle and consequent thin-skinned thrusting of materials onto the margin of the continent appears to be of key importance in understanding the geology of a major portion of the continent. How the concepts of the Wilson cycle and thin-skinned thrusting may apply in detail to other parts of the world is an important and timely topic. The story of the western United States provides a case in point.

Studies of the tectonics of the eastern and western parts of the United States have evolved in a somewhat different way but appear about ready to coalesce. Both areas have been studied by a variety of geological and geophysical techniques. Of the latter, seismic reflection profiling has played a prominent role in the East and is only now being applied to the West, whereas the emphasis has been the reverse in the case of paleomagnetism. Paleomagnetic studies of rocks show the direction of the earth's magnetic field relative to the rock when the rock was formed or modified. Consequently, such data give some information on how the rocks of a region have moved relative to the field and to rocks of other regions. In the West, paleomagnetic and geologic studies have demonstrated that much of the western Cordillera is made up of accreted terranes—pieces of anomalous material from the sea floor such as microcontinents, arcs, and plateaus that have been added to the continent during ocean closing, or at least during episodes of subduction. A process much like that suggested for the early stages of the Appalachian orogenic belt may be envisaged, although final continent-to-continent collision has not yet occurred in the West. As little is known of the deep structure of the western accreted terranes, the mechanism of accretion is not clear. The paleomagnetic evidence shows that the accreted terranes have

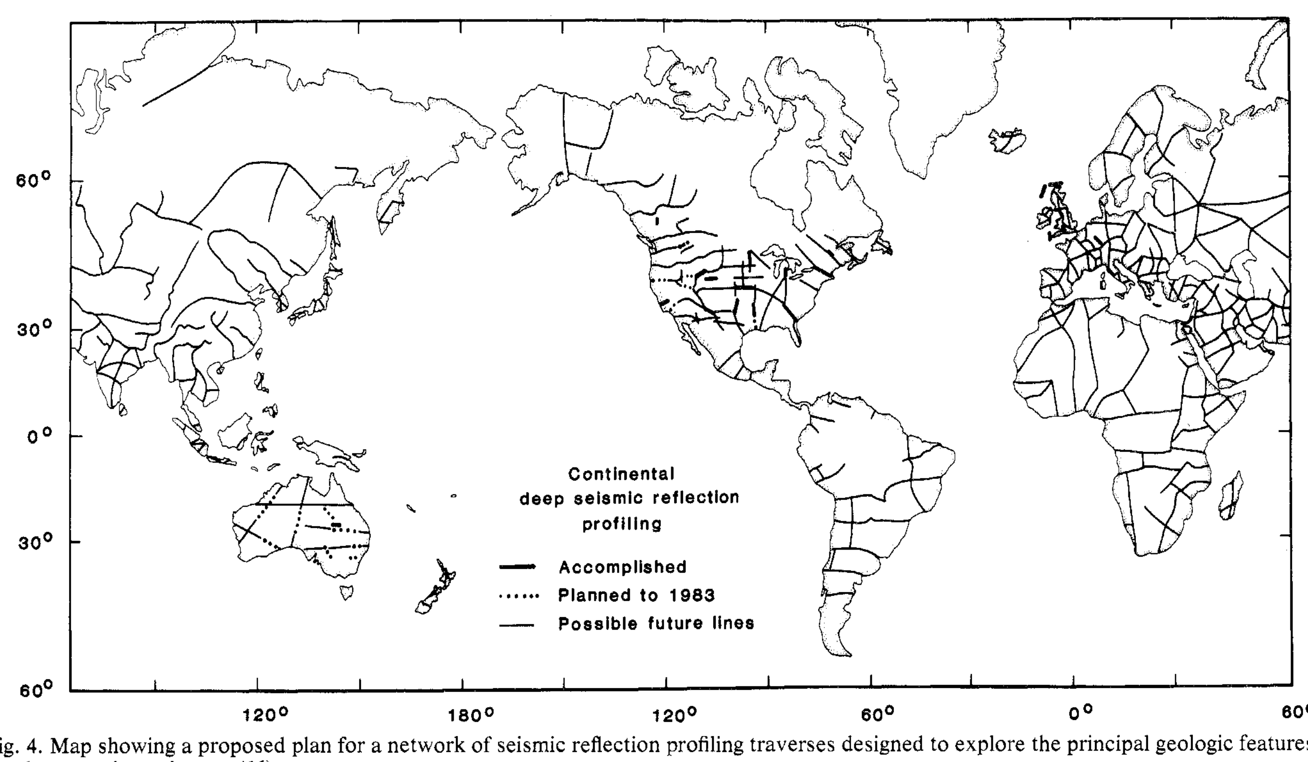

Fig. 4. Map showing a proposed plan for a network of seismic reflection profiling traverses designed to explore the principal geologic features of the deep continental crust (*11*).

moved through a range of latitudes and that they have rotated, generally in the same sense but not with the same total rotation. It has been suggested that each terrane is associated with a block of lithospheric thickness and that these blocks have moved to the north and rotated like giant roller bearings about a vertical axis as they rolled along the boundary of the continent (*9*). An alternative hypothesis is that the terranes are relatively thin and that they crossed the ocean obliquely to produce the required latitude change and consistent sense of rotation and then slid upon the continent, perhaps with additional rotation in the process. This subject is in a state of flux just now, and it is one of the most exciting topics of present-day geology (*10*). It is an important topic because large parts of the continents, such as much of the western Cordillera of the United States and Canada, and parts of Alaska and China are thought to be made up of accreted terranes. Reconciling the differences among existing hypotheses will probably require collection of additional information.

It seems certain that one major result of the effort to explore the continental crust will be the recognition of substantial and widespread mixing of components of the crust through tectonic deformation. Older crystalline rocks may have commonly been thrust over younger sediments. Water in these sediments may have been trapped in the crust in localized regions for long periods of time. Some newly discovered, shallowly buried sediments may be considered as targets for petroleum exploration. Deeply buried sediments may have been metamorphosed to crystalline rocks, and expelled magmas in the process. In other words, there is a sign that a new level of understanding of the tectonics of the crust may be in the offing, a new tectonic framework in which to relate a variety of geologic processes ranging from mineral and energy resource concentration to the more basic aspects of crustal geology.

A Systematic Survey of the Continents

To capitalize on this opportunity, a continuing program of worldwide exploration of the continental crust will be required. This point is recognized through such programs as the International Lithosphere Project for the decade of the 1980's, the North American Decade of Geology, and the Continental Scientific Drilling Program. Figure 2 shows schematically COCORP's plan for exploring the United States in a comprehensive fashion. This plan can be carried out at the current modest pace of 500 to 1500 km per year or accelerated by the addition of more crews. Seismic reflection profiling of the basement is also being carried out or is planned for the near future in a number of other countries, including Australia, Canada, West Germany, the United Kingdom, France, China, and the Soviet Union. Figure 4 shows one plan for a systematic survey of the continents by this technique. This map is intended to depict schematically a reasonable goal for the earth science community over the next decade or two. It would not, and could not, be carried out by one organization. Individual countries and regional organizations would have to contribute to the overall effort. At first glance, a survey of this scale may seem like a huge task, and of course the effort required is not trivial. However, neither is it unreasonable. Some 200,000 km of line are shown in Fig. 4, about 50 times the distance surveyed by COCORP to date. COCORP operates with only one crew, however. Within the next year five to seven seismic crews will be engaged in deep crustal exploration in various parts of the world on at least a part-time basis. If that effort could be expanded to ten crews working full time, perhaps half the lines proposed in Fig. 4 could be surveyed in 10 years at a cost of roughly $50 million per year. Many activities in science and elsewhere operate on such budgets and more. Ten crews represent 1 percent of the seismic crews currently active throughout the world in the search for petroleum.

Such a comprehensive program of crustal exploration should be complemented by deep drilling for scientific purposes, as done today in the Soviet program, and by a variety of other kinds of geological, geophysical, and geochemical investigations. Although such a massive effort to explore the continents may seem unrealistic in a shortsighted view, it seems inevitable in the context of the history of man's exploration of the earth and the rapid growth of numbers of human beings dependent on the earth for their livelihood.

How the science of geology and its relation to other components of society may change as geology moves into a new era is an interesting question. Probably the ratio of big science to little science will grow. Traditionally composed primarily, at least in academia, of little science, in which the working unit is an independent investigator with one or two assistants or students, geology has already experienced the encroachment of big science. The Deep Sea Drilling Project, oceanographic vessels, COCORP, and large expensive analytical or experimental facilities are some examples. Big science programs involve teams of workers, some of whom may never be in contact with the material that is the basis for the "great idea" or the "key paper," but who are absolutely essential to the conduct of the science. Such workers will require incentives, and they will have skills, motives, and other characteristics that are nontraditional in little science. Those who are rooted in tradition or who understand the beauty of revelation at a lonely outcrop may be uneasy with the growth of this component of earth science, but the demands of society are not likely to leave geologists with the luxury of little science alone.

It will be a challenge for academia to maintain the vitality of little science, with its essential contributions of imagination, innovation, contemplation, and synthesis, and to develop simultaneously organizations capable of the management, specialization, and team effort necessary for big science. A similar dilemma has been faced by other sciences and solved in a variety of ways, through institutes, centers, consortia, independent organizations for operation of special facilities, contractors, and government activities. How the earth sciences shall evolve remains to be seen. The one certainty, if history provides useful lessons, is that the continental basement will be explored and that, in the process, mankind will achieve a new level of understanding of geology with accompanying benefits.

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12. This is in part a review article on COCORP studies and, as such, is based on the efforts of the entire COCORP staff, the COCORP committees, Petty-Ray Geophysical Division of Geosource, Inc., Crew No. 6834, and many others who have given assistance in one form or another to the COCORP operation. Many kindly made comments while the article was in manuscript form. M. Barazangi and F. A. Cook kindly provided figures. The COCORP project is funded by the National Science Foundation under grants EAR80-18363 and EAR80-25361. Department of Geological Sciences of Cornell University Contribution 716.