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DEEP OBSERVATION and SAMPLING of the EARTH'S CONTINENTAL CRUST

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Reservoir Characterization Technical Conference in Houston, TX, USA, April 1985.

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WORKSHOP ON
CONTINENTAL SCIENTIFIC DRILLING
AIRPORT HILTON, HOUSTON, TEXAS
APRIL 29 THROUGH MAY 1, 1985

Sunday, April 28

Registration after 3:00 P.M.
Cocktails 7:00 to 9:00 P. M.

All sessions will be held in the Bengal-Calcutta Room

Monday, April 29

Morning Session Chairman: Dr. William Muehlberger

Welcome and Introduction
Dr. Barry Raleigh, DOSSEC
Dr. James F. Hays, NSF
Dr. Frank Stehli, SAC

Miss Carla Gerrard
U. S. Naval Weapons Center
Navy Geothermal/Geotect Energy R&D Program Drilling Plans

Dr. Matt Walton
Minnesota Geological Survey
Core Drilling Technology for Ultradeep Scientific Holes

Dr. George Plafker
U. S. Geological Survey
Middleton Island, Gulf of Alaska: A Possible Site for Deep Drilling into an Active Subduction Zone

COFFEE BREAK

Dr. Art McGarr
U. S. Geological Survey
Deep Drilling near Parkfield, CA to Investigate Thermomechanical Processes Leading to a Magnitude 6 Earthquake

Dr. Mark D. Zoback
Stanford University
Scientific Drilling and Experimentation at Cajon Pass, a Site Near the San Andreas Fault in Southern California

Dr. Ronald L. Bruhn
University of Utah
Proposed Deep Drilling of the Wasatch Normal Fault Zone, Utah

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Dr. Mary Lou Zoback
U. S. Geological Survey
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Dr. John Eichelberger
Sandia National Laboratories
Direct Observation of Very Young Igneous Intrusions

Dr. John Rundle
Sandia National Laboratories
Investigation of Active Tectonic and Magmatic Processes in Long Valley, via Surface and Borehole Techniques

COFFEE BREAK

Dr. Fraser Goff
Los Alamos National Laboratory
Investigation of Magma-Hydrothermal Systems: CSDP Proposal for the Valles Caldera, New Mexico

Dr. George R. Priest
Oregon Department of Geology & Mineral Industries
Scientific Drilling in the Cascades Volcanic Arc

Dr. Wilfred A. Elders
University of California
Salton Sea Scientific Drilling Project (SSSDP) Status Report, April 1985

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Dr. James D. Hoover
University of Texas at El Paso
A Deep Drill Hole on the Central Basin Platform of West Texas

Dr. Marco T. Einaudi
Stanford University
Deep Observation of Continental Crust and Fossil Hydrothermal Systems at Yerington, Nevada and Red Mountain, Arizona

Dr. Robert O. Fournier
U. S. Geological Survey
Deep Continental Scientific Drilling in Yellowstone National Park

COFFEE BREAK
Dr. Phillip Bethke
U. S. Geological Survey
Hydrothermal Systems: Research Drilling Opportunities in the Creede Mining District, Colorado

Dr. Richard R. Donofrio
Astro Geological Resources, Inc.
Significance of Ultra-Deep Basement Astroblemes

Dr. Jack B. Hartung
Howard University
Scientific Drilling of the Manson, Iowa, Structure

Afternoon Session Chairman: Dr. Gary Oelheoft

Dr. William M. Roggenthen
South Dakota School of Mines and Technology
Drilling Target: Harney Peak Granite: Exploration of the Root Zone of an S-Type Granite System

Dr. W. R. Van Schmus
University of Kansas
Project Upper Crust: A Program for Shallow to Intermediate Depth Scientific Drilling and Associated Studies in the Continental Interior

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Dr. Matt Walton
Minnesota Geological Survey
A Proposal for a Technological and Geological Drilling Experiment in the Minnesota River Valley

Dr. M. E. Bickford
University of Kansas
Proposal for a Six Kilometer Drill Hole in the Eastern Arbuckle Mountains, Oklahoma, the Spavinaw Creek Area, Oklahoma or the St. Francois Mountains, Missouri

Dr. John H. Sass
U. S. Geological Survey
A Crustal Drilling Experiment Near the Southern Margin of the Colorado Plateau and the San Francisco Volcanic Field

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Morning Session Chairman: Dr. James Kelsey

Dr. Robert D. Hatcher, Jr.
University of South Carolina
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Dr. Arthur E. Nelson  
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Recent Geological and Geophysical Investigation in Southern Appalachians and  
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University of Missouri—Columbia  
The Ouachita Folded Belt, a Site for Deep Continental Drilling

Afternoon Session Chairman: Dr. Robert Schock

Dr. Lynton S. Land  
University of Texas at Austin  
A Proposal for Deep Scientific Drilling & Associated Exploration and  
Research, Texas Gulf Coast

Dr. Gerard Bond  
Lamont–Doherty Geological Observatory  
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Experiment in determining crustal structural & evolution of an active island  
arc–trench system

Dr. Carl M. Wentworth  
U. S. Geological Survey  
Structural and Tectonic History of California Coast Ranges: Testing  
an Obduction Model—Franciscan Emplacement Inferred from Seismic  
Reflection Profiles and Other Geophysical Data

Dr. John F. Casey  
University of Houston  
Proposal to Drill in the Bay of Islands Ophiolite Complex, Western  
Newfoundland
HYDROTHERMAL SYSTEMS: RESEARCH DRILLING OPPORTUNITIES IN THE CREEDE MINING DISTRICT, COLORADO

P.M. Bethke, U.S. Geological Survey, MS 959, Reston, VA, 22092
A program of scientific drilling in the Ag-Pb-Zn-Cu Creede district presents an exceptional opportunity to establish, for the first time, the physical connection between the epithermal ores deposited along the top of a deeply circulating hydrothermal system and the roots of that system. Although many epithermal ore deposits and the roots of many hydrothermal systems have been studied comprehensively in both surface and underground exposure, each environment is diverse in its characteristics, and the high degree of speculation concerning the connections between specific types of root zones and specific types of epithermal ores perpetuates a century-old controversy. The establishment of such a connection in at least one system is required in order to use our advanced knowledge of each environment, together with comparisons to modern geothermal systems, to develop a comprehensive, quantitative model of a complete and representative ore-forming hydrothermal system. The development of such a total-system model critically important to our understanding of hydrothermal ore-forming systems, and is equally applicable to our understanding of active geothermal systems. This paper reviews this research.

The Creede system was selected by the U.S. Continental Scientific Drilling Committee as the highest priority drilling target for mineral-resource objectives because of (1) the extensive base of knowledge of the geological, geochemical, and hydrologic evolution of the district, (2) the relatively simple structure of the district, (3) the growing economic importance of epithermal precious-metal deposits, and (4) the similarity of the Creede system to active geothermal systems in silicic volcanic terranes.

More than 25 years of extensive and intensive geologic and geochemical studies have resulted in an exceptionally well documented, comprehensive model of the Creede mineralizing system and its relation to the volcanic evolution of the central San Juan Mountains. Ore deposition followed the last known volcanism in the area by about 1 Ma. The ores are hosted by rhyolitic ashflows erupted from a series of nested calderas forming the Central San Juan Caldera Complex. They were deposited along the interface between surface waters and an underlying, hot, deeply circulating, near-neutral, chloride-rich brine. The deep brine was charged primarily by meteoric waters whose salinity and isotopic composition resulted from evaporation in a closed-basin lake. Pb-isotope studies indicate that much of the lead, and therefore presumably other metals, was leached from the Precambrian rocks deep in the system. Sulfur-isotope studies suggest that most of the sulfur underwent substantial isotopic evolution in the closed-basin lake prior to incorporation into the ore-forming hydrothermal fluids. Circulation of the deep brine was fracture controlled. Intermittent boiling took place along the top of the system, and mixing of the deep brine with overlying groundwaters has been documented by detailed fluid inclusion studies. Physical and chemical conditions in the ore zone and their fluctuations in both time and space have been deduced from detailed ore-petrology studies. Such essential documentation has been for Creede far better than for any other hydrothermal ore deposit. Nevertheless, many critical elements of the model remain unproven and must be sought by drilling in the roots and margins of the system.
A drilling program to consist of 1 or 2 holes, from 3 to 5 km deep, has been designed to test the roots of the hydrothermal system; the program will be augmented by 2 or more shallow (<1 km) holes to test the hypothesis that the ore fluids were dominated by evaporatively evolved pore waters in the lacustrine sediments of the Creede Formation which fills the moat of the Creede caldera. All holes will be diamond drilled and continuously cored by use of wireline coring techniques.

The primary objectives of the program are to test those elements determinable only through drilling including (1) The physical and chemical conditions in the root zone, (2) the nature of the heat source and of the heat-transfer mechanism, (3) other possible sources of the salinity, metals, sulfur, and fluids, (4) the nature of, and relations between, deep lithologies, (5) the nature of deep alteration and, possibly, mineralization, and (6) variations in type, magnitude and distribution of the paleo-permeabilities. Knowledge of these elements will allow the development of a quantitatively verifiable, predictive model of the dynamics, evolution, and transport properties of a hydrothermal system representative of both active geothermal systems in silicic volcanic terranes and a large and very important class of precious-metal deposits.

Secondary objectives include (1) the testing of deep-hole logging techniques in Creede's relatively benign environment for eventual use in probing more hostile active geothermal systems and (2) providing a factual basis for the geophysical extension of geologic data.

In spite of the advanced state of knowledge of the geology and geochemistry of the Creede district, a few site characterization studies are required prior to drilling. These include (1) geophysical studies to refine the location of the pluton postulated to have driven the ore-forming system, to define the depth and attitude of lithologic breaks at depth, and to outline the bottom of the Creede formation, and (2) Development of diagnostics such as a detailed and precise geochronology of volcanic and subvolcanic rocks and hydrothermal alteration and detailed petrographic studies of lithologies likely to be encountered at depth.
PROPOSAL FOR A SIX KILOMETER DRILL HOLE IN THE EASTERN ARBUCKLE MOUNTAINS, OKLAHOMA, THE SPAVINAW CREEK AREA, OKLAHOMA, OR THE ST. FRANCOIS MOUNTAINS, MISSOURI

M. E. Bickford, University of Kansas, Dept. of Geology, Lawrence, KS 66045
(Representing CISCO, Continental Interior Crustal Studies Consortium)*

PROPOSAL FOR A SIX KILOMETER DRILL HOLE IN THE EASTERN ARBUCKLE MOUNTAINS, OKLAHOMA, THE SPAVINAW CREEK AREA, OKLAHOMA, OR THE ST. FRANCOIS MOUNTAINS, MISSOURI

M. E. BICKFORD, Dept. of Geology, Univ. of Kansas, Lawrence, Kansas 66045 (Representing CICSCO, Continental Interior Crustal Studies Consortium)*

The southern and eastern midcontinent is extensively underlain by rhyolite, dacite, and related epizonal granitic plutons. Rocks of this type that underlie western Ohio, Indiana, Illinois, and southeastern Missouri are 1.45 to 1.48 Ga old, whereas those underlying southwestern Missouri, southern Kansas, Oklahoma, and the Panhandle region of Texas are 1.34 to 1.40 Ga old. Both terranes consist almost entirely of metaluminous to marginally peraluminous high-silica rocks. Sedimentary rocks, metamorphic rocks, and igneous rocks of either mafic or intermediate character are notably rare.

Related plutons, typically rapakivi granite with abundant magnetite and sphene, occur within older rocks to the north of these terranes. Plutons 1.45 to 1.48 old are known from Labrador to southern California, and plutons 1.34 to 1.40 Ga old are known in the subsurface of Missouri and eastern Kansas, where they presumably intrude rocks formed at least 1.65 Ga ago. The mesozonal San Isabel Batholith in the Wet Mountains of south-central Colorado was emplaced 1.36 Ga ago in a crust at least 1.7 Ga old.

The distribution of the granite and rhyolite suggests that these terranes are veneers. Sm-Nd studies by Nelson and DePaolo (1985) yield mantle separation ages for these rocks of about 1.80 Ga, suggesting that they were derived from and lie upon eastern extensions of orogenic terranes exposed in Colorado, New Mexico, and Arizona. The occurrence of the San Isabel Batholith within 1.70 Ga old rocks is consistent with this model and also implies that rhyolitic to dacitic volcanic rocks may have covered much of southern Colorado prior to uplift.
Despite the absence of significant volumes of basalt, it is likely that the granite-rhyolite terranes were formed during a period of extensional tectonics and crustal melting that followed accretion of arc terranes. Extensional faulting must have been broadly distributed, but not of sufficient duration and extent to allow basaltic magma to reach the surface in significant volume.

Because these rocks constitute a major part of the continent, and because their origin is of major importance in deducing the tectonic history of the continent, the model presented above should be tested. The ultimate test is to drill through the inferred veneer of rhyolite and shallow granite. In this way the nature of the transition could be observed, the thickness of the granite-rhyolite veneer could be determined, and samples of the older crust could be obtained for age determination, isotopic analysis (Sm-Nd, common Pb, Rb-Sr), and chemical analysis.

The best site for the proposed drill hole would be where there is the greatest likelihood of penetrating the silicic rocks and sampling older crust beneath. In most of the region the basement is overlain by one to three kilometers of Phanerozoic sedimentary rocks. Therefore, the best sites for the proposed drilling should be in one of three areas of exposure: (1) The St. Francois Mountains of SE Missouri; (2) The eastern Arbuckle Mountains of Oklahoma; and (3) The Spavinaw Creek area in northeastern Oklahoma. Each of these areas has something to recommend it. The St. Francois Mountains is the best studied area and the area of largest exposure. About 900 sq. km of Proterozoic rocks are exposed, all of which are volcanics or epizonal plutons. The total thickness of volcanic section is at least 3 km, but the structure and stratigraphy are well enough known that a stratigraphically low site could be chosen. The Spavinaw Creek locality has
only about 2 or 3 square km of exposure. The rock exposed is granophyre, but rhyolite is widely distributed in the subsurface of NE Oklahoma. Its proximity to the northern limit of the volcanic terrane in southeastern Kansas could indicate that the silicic veneer is not very thick in NE Oklahoma. The Eastern Arbuckle Mountains is an anticlinal uplift that exposes Proterozoic basement. The rocks exposed are fine to coarse-grained plutons. The structural uplift, absence of volcanic rocks, and somewhat deeper emplacement aspect of the plutons suggest that drilling could begin here as deep within the proposed veneer as possible. The only disadvantage for this site is that there may be structural complexity that is not completely understood.

All of these sites should be carefully studied prior to a drilling commitment. Seismic studies would appear to be most important to determine any structural complexities present and to locate, if possible, the base of the proposed volcanic veneer. Where ever it is drilled in this area, the hole will provide a valuable site for heat flow and heat generation studies, studies of uplift rates by examination of fission-track ages, measurement of in situ stress, studies of chemical variations in the rocks and their petrogenesis, and age determinations.

INSTRUMENTING CONTINENTAL DRILL HOLES IN THE ALASKA PENINSULA—A UNIQUE EXPERIMENT IN DETERMINING THE CRUSTAL STRUCTURE AND EVOLUTION OF AN ACTIVE ISLAND ARC–TRENCH SYSTEM

Gerard Bond, Lamont-Doherty Geological Observatory, Palisades, NY 10964

Steven Lewis, Nicholas Christie-Blick, John Diebold, Klaus Zacob, Michelle Kominz, Mike Steckler, Lamont-Doherty Geological Observatory; David Scholl, Roland Von Huene, Alan Cooper, Terry Bruns, U.S. Geological Survey; Steve Altaner, Steve Marshak, University of Illinois
801 150201, 580201, 150303

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INSTRUMENTING CONTINENTAL DRILL HOLES IN THE ALASKA PENINSULA
A UNIQUE EXPERIMENT IN DETERMINING THE CRUSTAL STRUCTURE AND EVOLUTION OF AN ACTIVE ISLAND ARC-TRENCH SYSTEM
by
GERARD BOND and STEVE LEWIS (coordinators), NICHOLAS CHRISTIE-BLICK, JOHN DIEBOLD, KLAUS JACOB, MICHELLE KOMINZ, and MIKE STECKLER, Lamont-Doherty Geological Observatory; DAVID SCHOLL, ROLAND VON HUENE, ALAN COOPER and TERRY BRUNS, U. S. Geological Survey; STEVE ALTANER and STEVE MARSHAK, University of Illinois

The Alaska Peninsula belongs to a category of island arc-trench systems that have a fundamental role in the accretionary growth of continents and formation of continental crust. In spite of the importance of these systems, little is known of their uplift and subsidence history, thermal evolution, distribution of stress and crustal structure. The Peninsula offers unusual opportunities to incorporate continental drilling in a program of research to address these problems in one of the largest areas of accretionary tectonics in the world.

Statement of the Problem.- The Alaska Peninsula is located within the present Aleutian arc-trench system where the Pacific plate is subducting at rates of 7 cm/yr beneath the North American continental margin. The arc-trench system is underlain by a crust composed largely of accreted terranes that are separated by profound structural boundaries. Crust of this type represents an early stage in the evolution of true continental crust; yet, little is known of its seismic velocity and structure at depth. Much of the Peninsula is under N-S oriented horizontal compression. The origin of the compressive stress, its propagation through the arc-trench system and its role in growth and deformation the crust are poorly understood. One of the most remarkable structures of the Peninsula is a deep backarc basin, the Bristol Bay basin, that contains over 5 km of Cenozoic sediments. Preliminary modeling of the basin indicates that it formed by flexural bending of relatively thin lithosphere in response to growth of crustal and subcrustal loads, as yet unidentified, that were emplaced near the volcanic chain. Little is known of the nature and structure of the crust beneath such a basin. Moreover, a fundamental question in the evolution of a compressive arc-backarc complex is how the growth of crustal and subcrustal loads causing backarc subsidence are related to the magmatic and deformation history in the arc complex and, ultimately, to the plate tectonic history of subduction and accretion. Finally, the loads that caused the subsidence of the Bristol Bay backarc basin may have been produced, in part, by backarc thrusting. If this hypothesis is substantiated by the proposed research, the Alaska Peninsula will exemplify the early stages in processes that lead to a mature continental orogenic belt such as in the western United States and Canada.

Proposed work.- We propose to use existing deep, exploratory wells in the Alaska Peninsula to conduct a number of novel experiments that would bear on the evolution of the crust and large-scale structures in this island arc-trench system. Five onshore wells in the Peninsula are cased to depths of 2 to 3.4 km and are suitable for reentry. It will require relatively modest costs and only one or two summer seasons to open all five wells and to emplace instruments, including geophones, thermistors and stress gauges, at selected depths outside of casing. The resulting vertically arrayed network would cover more than 13,500 square kilometers of the arc. Such a down-hole network will have substantial advantages over one on the surface by eliminating surface noise and high attenuation of seismic waves in poorly consolidated near-surface layers. Moreover, it is the only means of obtaining temperatures and stress/strain observations as a function of depth.

The network in the wells will be used to gather a wide range of geophysical data that have not been obtained previously from an island arc-trench system. The down-hole geophones will serve as receivers for seismic experiments conducted by ships shooting from both sides of the Peninsula. The experiments will include vertical seismic profiling (VSP), near vertical reflection, wide angle reflection, and refraction. The few kilometers of land-locked profiles could be occupied by arrays of digital recorders in cooperation with the IRIS-PASSCAL program. The down-hole thermistors will produce much needed information on the thermal structure of an arc complex. The instruments could be monitored for several years thereby providing long-term, continuous acquisition of various geophysical data.
In addition to the seismic experiments, the offshore program will involve collection of multichannel data, preferably with two-ship profiling, for additional information on stratigraphy and structure in the offshore areas. We also anticipate that one or two ocean drilling projects (sponsored by NSF Oceanography) could be undertaken in the forearc and backarc region to further constrain details of structure and stratigraphy.

The project also will include the acquisition of geological data that are required to establish the chronology of deformation events in the Peninsula and to refine the evolution of the backarc basin. The kinematic history of the arc complex is poorly understood, and detailed geological mapping and analysis of microscopic and mesoscopic structures is required within and adjacent to the network of instrumented wells. In addition, quantitative subsidence analyses and two-dimensional modeling will be done to identify the processes and their timing that formed the backarc flexural basin. Stratigraphic data suitable for analysis are available from the wells, including a COST well over 5 km deep offshore, and we anticipate industry cooperation in refining ages, thicknesses and lithologies.

**Site survey.** Prior to undertaking the seismic experiments, existing commercial seismic and well-log data will be compiled to obtain constraints on subsurface velocities and the subsurface structure and stratigraphy. A limited amount of geologic mapping may be necessary around wells spudded in deformed rocks. In addition, the well sites will be examined to determine the logistical preparations required for reentry.

**Expected results.** The data gathered from the network and related studies will produce an exceptional geological and geophysical database in an island arc-trench system where compression, subduction and arc volcanism are strongly active. The seismic experiments will probe the shallow, intermediate and possibly deep structures of the region. The velocity data will also allow tracing of the stratigraphy in the wells into the offshore portion of the backarc basin to obtain accurate regional control for reconstructing its evolution. As this is a region of ongoing strong seismic and volcanotectonic activity, the instrumented network would provide continuous VSP and tomography from deep-seated (50-200 km) seismic sources directly beneath the wells.

The geological studies will establish the temporal framework that relates the results of the seismic experiments to the tectonic evolution of the arc and backarc complex. Surface studies of deformation history will be especially important if the seismic data indicate thrusting along the volcanic arc, since thrust sheets could constitute, in part, the crustal loads that formed the backarc basin. Preliminary subsidence analyses and two-dimensional modeling of the backarc basin suggest that unconformities separating distinct subsidence events are broadly coeval with episodes of plutonism in the arc and that the rigidity of the sub-basin lithosphere is weak, indicating a young apparent thermal age of perhaps 40 to 60 m.y. These results, which clearly have important implications for the evolution of the arc-trench system, will be refined by the geological and geophysical data gathered from the proposed research. Finally, once the nature of surface and subsurface structures is known and the chronology of vertical motions and deformation are established, they can be compared with the known history of the incoming plates and terranes as a means of testing models for the origin and propagation of stresses across a compressive arc-trench system and their role in the evolution of mature continental orogens.

**Timetable and costs.** Because the project is not dependent on extensive site surveys and long and unpredictable drilling times, the timetable of research has considerable flexibility. The reentry and instrumentation of the wells could begin immediately along with the site surveys. The seismic experiments could begin after well instrumentation, as soon as ships are available. It is important to stress that the project is cost efficient in that drilling experiments are least expensive onshore and seismic experiments are least expensive offshore. We estimate that the total cost of the project would be ~$10,000,000 of which probably less than $7,000,000 would be requested from the Continental Drilling Program. The rest would be requested for work under the NSF-funded Oceanography-Ocean Drilling and the IRIS-PASSCAL programs. The region is under active exploration for hydrocarbons and we anticipate financial, as well as technical and scientific support from industry.
PROPOSED DEEP DRILLING OF THE WASATCH NORMAL FAULT ZONE, UTAH

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A deep drill hole into the Wasatch normal fault zone in northern Utah will provide fundamental data on crustal rheology, regional tectonics and earthquake generation along an active, extensional, intraplate boundary. The drill hole will provide the opportunity to measure the thermal, mechanical and chemical properties of 1) a Holocene normal fault zone capable of generating magnitude 7 to 7.5 earthquakes within a major urban corridor, and 2) the intraplate boundary between the Basin-Range and Rocky Mountain Province, which is marked by changes in crustal thickness, heat flow, seismicity, stress field and structure. The drill site should be located in either the Ogden, Salt Lake or Provo segments of the Wasatch fault zone based on considerations of regional structure, available seismic reflection data and earthquake risk. The hole should penetrate to depths between 5 and 10 km in order to sample the frictional/quasiplastic transition within the fault zone. Specific problems to be investigated include determining 1) the insitu stress state, 2) seismic reflectivity of the fault zone, 3) mineralogical and chemical composition of fault rock, 4) fault zone geometry, 5) fluid chemistry and pressure, 6) thermal and hydrological characteristics of the fault zone, 7) relation of the normal fault zone to older crustal structure. Downhole instrumentation will be required to monitor changes in stress, strain rate, fluid pressure and chemical properties in the fault zone. This data will provide direct evidence for the rheologic processes and geometric properties of contemporary crustal extension and earthquake generation.
PROPOSAL TO DRILL IN THE BAY OF ISLANDS OPHIOLITE COMPLEX,
WESTERN NEWFOUNDLAND

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5401 EOB
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Newfoundland: T1
Well Drilling
Plate Tectonics: A1
Stress Analysis
Igneous Rocks
Geochemistry
Research Programs: A2

Petrology
Seismic Surveys: A2
Seismic Arrays
Magnetic Surveys: A2
Paleomagnetism
Mineralogy
Geothermal Fluids
Rock Mechanics
Chemical Properties
Thermodynamic Properties
Geologic History: A2
Mohoole Project
Drill Cores
Oceanic Crust: A1, T2
Proposal to Drill in the Bay of Islands Ophiolite Complex, Western Newfoundland

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During the last two decades, the deep sea drilling program has played an essential role in accumulating data from the deep ocean basins that have allowed confirmation of many of the fundamental postulates of the theory of plate tectonics. While the ocean drilling program has been extremely successful in most aspects, one of the important initial goals of oceanic drilling has remained unfulfilled. "Project Moho", as originally formulated, proposed continuous sampling of the oceanic crust and penetration of the Mohorovicic Discontinuity within the deep ocean basins. To date, ocean drilling has penetrated oceanic basement to a depth of only about one kilometer and penetration in most holes is significantly less. The attempt at direct sampling of the deeper parts of the oceanic crust and uppermost mantle (1-6km) within contemporary oceanic basins has largely been abandoned because of technological difficulties. Marine geological studies of the oceanic crust are, therefore, inherently limited because the information on deep crustal portions is available only through indirect geophysical methods. For this reason, land-based studies of ophiolites have become particularly valuable because they provide an otherwise unavailable view of the sequence of lithologies and structures comprising oceanic crust and upper mantle.

Ironically, the proposed Continental Scientific Drilling Program in North America presents a unique opportunity by drilling within an on-land segment of intact oceanic crust and upper mantle, to achieve the initial goal of the oceanic drilling program, i.e., to continuously core the oceanic crust and penetrate the oceanic Moho.

The authors propose this drilling be conducted within the Bay of Islands Ophiolite Complex in western Newfoundland, Canada. Ophiolitic rocks in the Bay of Islands region consist of a discontinuous belt of mafic and ultramafic massifs approximately 100 km long and 25 km wide. Ophiolitic rocks represent the highest structural slices in the Humber Arm Allochthon emplaced in the middle to late Ordovician during the Taconic Orogeny in the northern Appalachians. Below the ophiolitic slices, the lower structural slices of the Allochthon consist of early Paleozoic seamount alkalic volcanic rocks, melanges, a flysch sequence, and continental rise and slope deposits. The allochthon, in turn, rests on an autochthonous flysch sequence, a stable margin carbonate shelf sequence, and a rift-related clastic sequence that unconformably overlies Grenville basement. Transport of the Allochthon is estimated to exceed 100 km.

The significance of the drilling is discussed.

There are several important reasons for choosing the Bay of Islands region as a possible drill site.

1) Detailed maps at a scale of 1:15,000 are now available for the entire Bay of Islands Complex and detailed maps of the surrounding sedimentary allochthon and autochthon have or are about to become available.

2) The Bay of Islands Ophiolite Complex represents one of the largest and best preserved ophiolites in the world and the most intact in North America.

3) Petrological studies of the ophiolites show that the basalt
chemistry is typical of that found at contemporary spreading centers. This suggests that the Bay of Islands complex is an especially good analogue for present-day oceanic crust. This factor alone distinguishes the Bay of Islands Complex from many ophiolites which appear to contain volcanics with island arc or uncertain affinities.

4) Recent studies of the Bay of Islands Complex indicate strong structural and geophysical similarities between contemporary oceanic crust and upper mantle.

5) The full and intact ophiolitic stratiform sequence is developed on two of the ophiolite massifs (North Arm Mountain and Blow-Me-Down Mountain) and palinspastic reconstructions of the map view and cross-sectional geometry of accretion are well constrained by detailed mapping and petrologic studies.

6) The remnants of shallow to deep levels of an oceanic fracture zone have been recognized within the Coastal Complex which has an autochthonous relationship with the Bay of Islands Complex in the Lewis Hills.

7) The North Arm Mountain massif is characterized by the largest gravity anomaly in Newfoundland and modeling suggests that the ophiolite extends to approximately six kilometers depth, suggesting that fairly continuous sampling of a full section of oceanic crust is possible.

8) The ophiolite has escaped any significant sign or post-emplacement metamorphism that is characteristic of many ophiolites in North America.

9) Deeper drilling below the base of the ophiolite would allow continuous sampling of the allochthon and autochthon and allow detailed examination of the continental rise, slope and shelf facies of the early Paleozoic stable continental margin of North America and further constrain its sedimentological and structural evolution.

A drilling program in the Bay of Islands region offers a fairly unique opportunity to study in detail the processes that lead to the generation and evolution of oceanic crust and upper mantle as well as the evolution of a stable continental margin and collisional processes that result in large overthrust sheets. If approved, we envision participation in this project by many members of the scientific community. The preliminary phase would involve geologists, geophysicists and engineers from the University of Houston, Memorial University, Woods Hole Oceanographic Institution and the Newfoundland Bureau of Mines and Energy as well as other interested parties. The following represents examples of specific proposed research projects that could be completed if drilling proceeded.

1) Core analysis and documentation of the igneous petrology through the entire oceanic crust and upper mantle using whole rock major element, trace element, isotopic and mineral chemistry studies. Petrogenetic models established for the evolution of oceanic basalts through detailed examination of cumulate sequences to determine the scale of cryptic chemical variations and the number of magma pulses into the ridge-axis magma chamber.

Determination of the composition of primary mantle-derived magmas that lead to the development of MORBs by establishing the bulk composition of the magmatic portion of the ophiolite.

2) Documentation of hydrothermal metamorphism through the oceanic crust using mineral chemistry and oxygen isotope studies. Also establish the depth of seawater penetration in the ocean crust.

3) Downhole seismic velocity measurements using multichannel full-wave seismic velocity logging tools to provide detailed P and S wave velocity profiles through the oceanic crust. Such velocity information will enable marine seismologist to better interpret marine reflection and refraction data.
These data will be coupled by laboratory velocity measurements and physical property measurements on segments of core.

4) Downhole magnetometer logging to determine magnetic susceptibilities with depth and direct core analysis to determine the contribution from various sources to marine magnetic anomalies.

5) Downhole logging of density, porosity, permeability and fractures as well as core analysis of alteration state, fracture density, fracture fill and age relationships to determine the extent to which the crust at various depths has accommodated hydrothermal circulation.

6) Ore petrology of sulfide systems encountered in the upper part of the ophiolite and of chromitites and platinum group minerals encountered in the ultramafic sections of the ophiolite.

7) Deeper drilling below the basal thrust contact of the ophiolite to sample various facies of the stable margin of North America that developed in the early Paleozoic. Such sampling is possible due to tectonic imbrication in the allochthon. Detailed logging, geophysical, petrologic, paleontologic, sedimentologic, isotopic, and structural studies may be facilitated by deeper drilling and would lead to a more coherent view of the evolution of stable continental margins, in general, and their ultimate destruction upon continental collision.

8) The integration of drill hole data and detailed surface geological and geophysical data in terms of subsurface geologic structure and lithology will provide a sound basis on which to interpret regional aspects of ophiolite obduction and the emplacement and the structural history of large overthrust sheets.

9) Isotope and geochemical studies of pore waters; determination of pore pressures and formation permeabilities at various depths; and diagenetic studies of sedimentary rocks encountered.

10) Downhole in situ stress measurements using hydraulic fracturing methods and the analysis of open microfractures in recovered core.

11) Laboratory measurements of the mechanical behaviour (including time dependent deformation) of deeply buried rocks to estimate the state of stress that existed during the overthrust episode.
SIGNIFICANCE OF ULTRA-DEEP BASEMENT ASTROBLEMES

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Significance of Ultra-Deep Basement Astroblemes

Impact cratering rates on the terrestrial land surface for the past 3 billion years predict over 150,000 craters (astroblemes) having diameters of 1 km or larger. Accumulating evidence suggests that impacts have been one of the dominant forces which shaped the terrestrial surface.

The extensive fracturing, hydrothermal alteration and structural modification of the target rock following hypervelocity impact places astroblemes in a unique area for research. Most cratering studies have been limited to exposed and eroded areas of the Canadian Shield. Little is known about the significance of crystalline basement astrobleme anomalies in deep sedimentary basins.

In August 1984, AGR Inc., operating with private capital and a grant from the U. S. Department of Energy, detected an astrobleme anomaly in the Black Warrior Basin. Geochemical surveys revealed C and nine distinct trace element halos at the surface directly above the central uplift believed to be developed in crystalline rock at a depth of 10,000 ft. Subsequent drilling to this depth followed by a velocity survey indicated that bottomhole velocities in the lower Paleozoics were approaching 25,000 feet per second. This significantly changed the time/depth curve and placed the Precambrian between 18,000 and 21,000 feet. This was beyond the capability of the rig and operations were suspended.
The revised depth of the anomaly most likely precludes commercial hydrocarbons—the original intention. It is now proposed that the existing borehole be deepened into the central uplift for research purposes and a thorough study of the target Precambrian be undertaken. Diameter of the crater is about 10 miles. The central uplift has a diameter of about 4 miles with over 1,200 feet of closure. The feature is overlain by approximately 15,000 feet of tight Paleozoic carbonates. This could be an excellent test for detectible amounts of primordial methane, trapped and sealed in fractured crystalline rock. An attempt is being made in Sweden to recover abiogenic methane from the Siljan impact structure, but this crater is exposed and appears to lack an efficient seal. ACR, Inc., is participating in the Deep Gas Project at Siljan, but the U. S. at present has no comparable research effort.

Drilling results may assist in determining the exogenic or endogenic origin of these circular uplifted basement areas and may provide better knowledge of the following:

4 The effect of basement astrobleme anomalies on geochemical emission profiles of crystalline rock overlain by sediments of Cambrian and younger age. This includes trace element concentrations.
Variations in the geothermal gradient within such structures and comparison with known endogenic crustal features.

The operation of interstitial fluid processes and mineralization in ultra-deep shock-fractured continental crust.

The role of astroblemes in subsiding basins. On a much larger scale, some impacts may initiate basin formation.

The presence of primordial methane and other gases.

It is proposed that ultra-deep basement astroblemes be made an integral part of the research features for the Continental Scientific Drilling Program. If the suggested site proves to be unsuitable for continued study, then a search should begin for an appropriate location.
DIRECT OBSERVATION OF VERY YOUNG IGNEOUS INTRUSIONS

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Direct Observation of Very Young Igneous Intrusions*

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Most large thermal regimes in the earth's crust are sustained by the convective transport of heat by magmas derived at deeper levels. Silicic magmas are of special interest because they accumulate at relatively shallow depths as plutons, and thereby form a characteristic feature of continental crust. In addition, silicic magmatism is the cause of most of the explosive eruptive activity on the earth's surface.

Outstanding problems in understanding this type of thermal regime are the mechanisms of upward migration of magma, the composition of magma and conditions during storage at shallow levels, and the processes of transfer of heat and mass from intrusions to associated hydrothermal systems and to the surface. Considerable progress has been made through geologic studies of active and eroded fossil volcanic systems, evaluation of geochemical and geophysical data concerning conditions at depth, and laboratory replication of inferred conditions. However, a number of critical questions can best be solved by direct observation; that is by drilling. These include the physical and chemical relationship of active volcanism to subsurface intrusion, the relative importance of conduction and convection in the cooling of intrusions, and the temperature and volatile content of melt at depth.

Much interest has focused on major silicic calderas, which represent the surface expressions of very large granitic intrusions. Because these calderas represent the integrated effect of intrusive events over a period of >10^7 y, many magmatic problems and the problem of how hydrothermal circulation develops in response to intrusion are better addressed by coring into very young intrusive environments of known age and surface volcanic expression. The north end of the 600-year-old Inyo Domes chain in eastern California was a logical first choice for such an investigation, because of lack of igneous events in the immediate vicinity during the last 3 my, presence of relatively uniform granitic basement at shallow depth, and surface evidence that delineates the geometry of the subvolcanic intrusion. In addition, the intrusion was young enough to give the hope of finding a residual thermal anomaly, without being so young as to pose costly technological challenges due to high temperatures.

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Three research holes cored during 1983 and 1984 have provided continuous samples and observations in the following parts of the northern Inyo system: 1) The distal (far vent) zone of Obsidian Dome. 2) The proximal (near vent) zone of Obsidian Dome. 3) Part of the underlying intrusion which forms the conduit of Obsidian Dome. 4) Part of the underlying intrusion which did not vent to the surface. The targets were defined entirely on the basis of surface volcanic features and were intersected within 10 m of their predicted positions, indicating that the intrusion beneath the domes is vertical to at least 700 m. A major portion of the funding was supplied by the Office of Basic Energy Sciences of U. S. DOE. Substantial additional support in the form of principal investigators' time was provided by the U. S. and Canadian Geological Surveys.

Results indicate that the Inyo event was fed by a dike of rhyolite magma which reached shallow depth beneath the vicinity of Glass Creek (1 km south of the Obsidian Dome vent) and was greatly enlarged by explosive activity where it vented at Obsidian Dome. Dike propagation was accompanied by fracturing and injection of fragmental magmatic material into the host rock over a broad zone. Crystallization behavior of magma emplaced at depth differed dramatically (poor in glass) from even slowly cooled extruded magma (rich in glass), probably as a consequence of retention of magmatic water in the melt at depth. A substantial thermal anomaly is associated with the conduit, suggesting that residual magmatic heat remains in the larger portion of the intrusion (other interpretations may be possible and are being evaluated). If so, hydrothermal circulation was limited. These holes provide the first direct link between a young volcano and a shallow intrusion.

The southern part of the Inyo trend lies within the Long Valley Caldera, providing an opportunity to determine the response of the same magma to different conditions of emplacement. For FY86, the Inyo consortium, which currently consists of investigators from 10 universities, 3 national laboratories, and the U. S. and Canadian Geological Surveys, is proposing to drill into the Inyo dike just south of Inyo Craters in the central western moat of the caldera. The position of the target is defined by the alignment of nearby phreatic craters and the trend of associated normal faults. Principal anticipated differences within the caldera are the much greater thickness of volcanic rocks traversed by the dike magma and the existence of an active hydrothermal system prior to the dike emplacement event. The surface expression of the dike suggests that there is indeed a substantial difference in magmatic behavior. In the segment to be studied, there are no magmatic vents but there is spectacular development of phreatic craters and extensional faulting. Ascent of the dike apparently stopped a short distance below the surface, perhaps due to rapid cooling as it entered the caldera hydrothermal system.

For the future, two attractive paths are apparent. One is to probe deeper into the Inyo system. We now know that the intrusion is a planar target, and therefore relatively easy to intersect. We do not know whether the dike remains essentially vertical to great depth and whether it increases significantly in size as the parent reservoir is approached. Defining the deeper portion of the system for future scientific drilling will depend on geophysical investigations to be carried out during the coming year. By intersecting the system at approximately 3 km depth, we can
expect to be below the region of extensive magmatic degassing and fragmentation and to observe important differences in structure, crystallization, and induced hydrothermal activity as a result.

A second path is to continue in the 1 km depth range but move to an even younger and therefore hotter intrusion. There are several advantages to this course, which may be an appropriate intermediate step between the type of drilling now underway and the deep thermal regimes drilling being contemplated. First, by drilling a younger system, we investigate an earlier point in time in the evolution of such systems, perhaps early enough so that melt is still present at shallow depth. Second, by staying relatively shallow, we can use surface geology to define drilling targets, as was done successfully at Inyo. Third, we maximize sample recovery (coring), a primary concern in scientific drilling. Fourth, we minimize costs, which increase very rapidly below 1 km depth. Finally, we can hope to carry drilling to its frontier in terms of temperature without dealing with great depth at the same time. There is little to be lost scientifically by staying shallow at this stage, as many of the processes critical to understanding silicic volcanism take place in the upper kilometer. Clearly the outstanding young silicic vent in the world is Novarupta Caldera at the head of the Valley of Ten Thousand Smokes, Alaska. The intrusion responsible for this event, which was two orders of magnitude larger than Inyo and is little more than a tenth the age, is an ideal shallow target for scientific drilling.
THE ILLINOIS SUPERDEEP DRILLHOLE:
A COMPREHENSIVE CENTRAL U.S. LITHOSPHERE STUDY

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A Collaborative Proposal by the Illinois State Geological Survey

A 30,000-foot superdeep hole in southern Illinois would provide new and vital scientific information for virtually every major category of geologic investigation on the continent. The site, in southern Gallatin or northern Hardin County, IL, is a tectonic and structural focal point critical for understanding both the Midcontinent Rift System and the development of the Illinois Basin and its deep, previously untested, sedimentary succession. Such a Midcontinent hole is necessary to gain further evidence of the incipient continental pull-apart and interior cratonic sag.

The Reelfoot Rift extends northeastward beneath the Mississippi Embayment to an intersection of a structurally complex quadruple point in southernmost Illinois formed by the geophysically defined and tectonically active Reelfoot Rift, Rough Creek Graben, St. Louis Rift and Indiana Rift. The intersection of the Reelfoot Rift with the 38th Parallel Lineament, an east-west trending series of fault zones, igneous intrusions, cryptoexplosive structures, gravity and magnetic anomalies, and mineralized districts, can best be investigated by a superdeep drillhole in the Eagle Valley Syncline (west Moorman Syncline). At this location, north-northeast of the Hicks Dome breccia and its adjacent magnetic anomaly, the 38th Parallel Lineament and the north edge of the Rough Creek Graben are represented by the Shawneetown Fault Zone. The proposed drillhole would test the hypothesis that the southward dipping Shawneetown Fault flattens at depth.

A superdeep drillhole will provide the first continuous suite of thermal, permeability, stress, and vertical seismic profile data, plus resistivity, potential, gamma, density and neutron logs, a sonic televiewer log and the opportunity to emplace a permanent seismometer, all of which will characterize the tectonic focal point and refine the Midcontinent model. A continuous core will provide a unique sample set for geochemical, stratigraphic, and hydrologic investigation.

The proposed borehole, the first Precambrian test in the Rough Creek Graben, will penetrate 10,000 feet of Precambrian basement complex, thereby exploring the pre-Mt. Simon layering indicated by reflection seismic profiling in the region and the nature of the upper crust in one of the most structurally complex areas of the U.S. Hypotheses include sills, mylonites, and a granite-rhyolite veneer overlying significantly older gneissic terrane of 1.6 to 1.8 b.y.o. The determination of the nature of the layering can only be determined from core. An understanding of the layering will greatly enhance Midcontinent seismic interpretation. The possibility of sidetracking the hole and drilling the Hicks Dome magnetic anomaly following completion of the vertical hole is being investigated.

U-Pb and Rb-Sr isotopic studies will be carried out on all basement units and used together with trace-, minor-, and major element analyses to model Midcontinent geochronology, petrogenesis and to discriminate among tectonic environments. These data will provide the first Midcontinent examination of approximately 8,000 feet of the Precambrian. Deeper penetration may be possible.
The weakened crust of the rift intersection subsided more rapidly than adjacent shelf areas and was filled with an estimated 20,000 feet of Paleozoic sediments and some lamprophyric intrusions. About 4,000 feet of previously untested Illinois Basin layered rocks will be intersected. The site is located near the superimposed depocenters of the latest Precambrian through middle Cambrian rift (Rough Creek Graben) and upper Cambrian-lower Ordovician (Reelfoot Rift) sediments as well as the general area of all post-Knox Paleozoic depocenters. Due to erosion on the Pascola Arch to the southwest, the most complete preserved section of Paleozoic rocks can only be penetrated at the Illinois site.

Coring of the complete Illinois Basin stratigraphic succession will provide an opportunity:

1. to obtain oriented cores for paleomagnetic determinations that will aid in interpreting the history of the North American Plate during Paleozoic and Precambrian time.

2. to study clay mineralogy, fluid inclusion studies and Rock Eval analyses that will all aid in interpretation of the thermal history of the Paleozoic rocks.

3. to carry out provenance studies of pre-Mt. Simon (Upper Cambrian) sediments including the pyroxene-bearing Mermet Sandstone and the Middle Cambrian shale drilled in Grayson County, Kentucky, plus additional sediments never before encountered.

4. to evaluate the rate of basin subsidence, depth of burial and sediment diagenesis at the optimum location for a complete Paleozoic history.

5. to study the Sub-Tippecanoe unconformity, and the overlying Everton Formation that is often mistaken as Knox (Lower Ordovician). Conodont biostratigraphy will be developed for the first time in a complete core. Evaporites in the Knox Megagroup ranging from upper Cambrian through lower Ordovician would provide new environmental and paleoclimatic information. The most favorable locale in Illinois for the occurrence of organic-rich shales in the Eau Claire Formation (upper Cambrian) would be cored, and geochemical studies would provide previously unavailable source rock and maturation data.

6. to study a potentially uninterrupted Silurian-Devonian column near the depocenter of the Devonian-Silurian carbonate sequence (Hunton Megagroup). The Tioga Bentonite (Devonian), and an unnamed bentonite near the Devonian-Silurian boundary will be "fingerprinted." Collection of the arenaceous foraminifers and chitinozoans will provide crucial biostratigraphic control.

7. to examine a nearly complete lower Pennsylvanian section thereby gaining a knowledge of the early Pennsylvanian history of sedimentation in the Evansville Paleovalley (a post-Mississippian fluvial channel) which extends across eastern Hardin County, Illinois. The core will be useful in evaluating depositional environments in one of America's largest coal fields.
The information gained from these and related investigations will be used to construct an integrated Illinois Basin analysis. For example, the core will provide the first evaluation of source rock potential in Middle Ordovician and older strata. Organic maturation studies will provide insight to source rocks that when coupled with deep hydrocarbon relative permeability data will provide new insight for petroleum exploration companies. Continuous measurements of porosity, permeability, and frequent pressure determinations as well laboratory determination of hydrocarbon relative permeability coupled with the complete sedimentologic analyses will allow refinement of hydrodynamic models for the basin. To date modeling of present and paleohydrologic conditions has relied on estimates of rock properties in the deep basin. Brine sampling and trace and major element analyses above and below aquitards will be carried out to determine the relative importance of reverse osmosis and interaction with evaporites in concentrating deep brines. Evaporites that would explain the brines have not been encountered to date. C, H, O and S stable isotopic studies will be used to determine the source, temperature, and history of the fluids responsible for modification of the sediments and to determine the degree of hydrologic continuity between the Paleozoic and basement rocks.

The core will also provide the first deep examination of the northern edge of the Fluorspar District of Illinois and Kentucky. Fluid inclusions in transparent and opaque phases from Paleozoic and basement rocks will be examined for paleotemperature, depth indicators, and fluid composition data in order to study the possible origin of Mississippi Valley-type mineralization.

Design of the hole and core curation will be discussed. A preliminary budget will be presented.
DEEP OBSERVATION OF CONTINENTAL CRUST AND FOSSIL HYDROTHERMAL SYSTEMS
AT YERINGTON, NEVADA AND RED MOUNTAIN ARIZONA

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Past studies of porphyry Cu-Mo systems, limited to crustal blocks on the scale of 1 or 2 km, have emphasized the highly anomalous ore zones and have identified their common alteration-mineralization features and deduced the general physiochemical environment and sources of hydrothermal fluids. However, in order to model the overall processes of heat and mass transport related to large magma-hydrothermal systems and to investigate their potential links with near-surface epithermal precious metal deposits, an interdisciplinary effort must be launched at a scale of crustal observation that is 5-10 km in vertical and horizontal dimension. We have identified two field sites that are ideally suited for such studies: Yerington and Red Mountain.

The Yerington district contains several different types of hydrothermal mineral deposits genetically related to a quartz monzodiorite to granite batholith of Middle Jurassic age. Rotation during Tertiary extensional faulting, and erosion, resulted in the virtually continuous exposure of the hydrothermal system from the volcanic paleosurface to paleodepths of 9 km. The batholith, approximately 10 km in diameter and occupying a major subsidence structure, intruded Middle Triassic andesite-rhyolite at depth, Lower Triassic to Early Jurassic shale, volcanioclastics, and carbonates, and Early Jurassic evaporites and sandstone near the paleosurface. The intrusive contact is continuously exposed over paleodepths from 1 km to 5 km. The roof of the batholith is located within 1 km of the paleosurface, where it intruded cogenetic volcanics. Deposits include three major porphyry Cu-(Mo) deposits associated with granite cupolas and dike swarms within the batholith, numerous Cu-Fe skarns in peripheral limestone, and Cu-Fe-(Au) veins in overlying volcanic rocks. Detailed field mapping, petrographic and analytical studies, combined with phase equilibria and preliminary fluid inclusion and O and H/D isotope analyses suggest that magmatic water was involved in upward flowing fluids that formed potassic alteration and bornite-chalcopyrite-magnetite at the apices of dikes (1.5 to 3 km depth) at the same time that seawater or isotopically heavy meteoric water was involved in inward flowing fluids that leached metals and formed sodic alteration in the root zone (3 to 6 km depth). The potassic-sodic couplet was cyclic with each successive intrusive event, and finally was overprinted by sericitic-pyritic alteration along structural conduits overlying the dike swarms. Near the volcanic surface, late hydrothermal fluids coalesced to form a regional pyritic-argillic alteration zone 10 km in diameter, but without major known metal concentrations.

Red Mountain, Arizona, serves as an excellent compliment to Yerington because it contains a better exposed hydrolytic alteration pattern in the uppermost volcanic portion of the system and higher concentrations of Ag, Pb, Zn, Mo, and As. The present surface at Red Mountain lies approximately 2.5 km below the paleosurface; numerous deep drill holes provide exposure of the structurally undisturbed mineralized system to a paleodepth of approximately 4 km. The deposit is located within flat-lying intermediate to silicic volcanic rocks of Cretaceous and early Tertiary age. Dikes and irregular bodies of granodiorite and quartz monzonite porphyry are present in outcrop and drill core, but no deep pluton has been recognized. At the surface, a zone of sericitic and argillic alteration (in part supergene), 4.5 km in diameter, lies within an arcuate pattern of porphyry dikes, intrusive breccias, and subsidence structures. Propylitic alteration extends beyond hydrolytic to form an overall alteration halo 12 km in diameter. Pyrite-enargite-(galena-sphalerite?) of the sericitic environment passes at depth to pyrite-sphalerite-chalcopyrite associated with lesser hydrolytic alteration. At greater depth, ore zones are characterized by pyrite-chalcopyrite-magnetite and local chalcopyrite-bornite associated with potassic alteration. High concentrations of chalcopyrite, molybdenite, and minor tennantite(?)
occur in the margins of a partially sericitized breccia pipe that extends from an elevation of 530 m (1.2 km below the surface) downward to at least sea level. The breccia pipe contains a matrix of orthoclase, quartz, anhydrite, chalcopyrite and pyrite.

Access to surface outcrops and surface/subsurface data is virtually assured at both sites. The first phase of research, conducted on the basis of surface exposures and existing drill holes from industry, is designed to test hypotheses discussed below and to acquire data necessary for the selection of drilling sites.

Regional petrological setting, geometries of plutons, and magma genesis.- Exposed margins and floor(?) of the Yerington batholith will be sampled for isotopic tracer studies designed to elucidate magmatic evolution and wallrock sources of components; results will be contrasted with similar studies of the Shamrock batholith, a barren system 3 Ma younger than the Yerington batholith. Two drill holes 1.5 to 2 km deep will be required to further constrain the geometry and geological characteristics of the floor of the batholith, and to test for the presence of underlying zones of diapiric mobilization, basaltic dike injections, and basement assimilation at paleodepths of 8 to 10 km. These two drill holes could be sited within the first few months of the project.

Regional mapping and petrographic studies at both Yerington and Red Mountain are required to establish the geometries of caldera-like subsidence structures, their age relative to the mineralized plutonic systems, and their role in both volcanic and hydrothermal processes. An early Tertiary age is inferred for the magma-hydrothermal system that generated the porphyry Cu-Mo deposit at Red Mountain; extensive radiometric dating will be required to establish its precise age and to correlate it with coeval volcanic rocks. At Red Mountain, detailed studies of the ore zone and its peripheral and overlying areas, discussed below, will allow selection of deep drilling sites to sample the root zones of the system and to test for the presence of a deep intrusive system; we anticipate that 2 drill holes 3 to 5 km deep could be sited in the 2nd or 3rd year of the project.

Physical processes of magma emplacement, breccia pipe formation, fracture propagation, and heat flow.- Past physical models (both analytical and numerical) of the thermal-mechanical evolution of magmatic intrusive systems have been hindered by the lack of constraining data and as a consequence have been general in nature. We will focus on developing models for the Yerington system which provide improved resolution of: 1) the consequences of the development of secondary intrusive centers (cupolas) on the overall patterns of heat and mass transport; 2) the consequences of multiple intrusions (in time and space) on thermal evolution; and 3) the role of advective heat transport. Morphology and physiochemical evolution of hydrothermal system in space and time.- Emphasis at both field sites will be placed on studies of hydrothermal alteration-mineralization on a regional scale above, below, and peripheral to, zones of maximum metal concentration. Deep alteration assemblages and related breccia pipes are of particular interest because of the probability of direct links to magmatic-hydrothermal processes. Analytical studies at Red Mountain will be preceded by mapping and petrographic studies aimed at establishing paragenetic sequences of veins and alteration assemblages in space and time; several 1 km deep holes will be required in the 2nd year of the project to sample the outer portions of the system. A variety of analytical techniques will be employed to establish a data base from which we can evaluate intensive thermodynamic variables (T, P, & chemical potentials of thermodynamic components). For some mineral associations, oxygen isotope analyses of mineral pairs (e.g., quartz-magnetite) may yield the only precise temperature estimates possible; however, we anticipate that the bulk of the thermal data will be based on fluid inclusion measurements and mineral equilibria, as these studies are necessary for evaluation of other intensive variables. Fluid inclusions will be: 1) mapped petrographically to establish limits of boiling zones; 2) analyzed by microthermometric techniques to estimate temperatures and bulk salinities of fluids; and 3) analyzed by Raman spectroscopy to determine types and amounts of volatile components. The results of these studies will be integrated with results of heat flow calculations and trace element/stable isotope analyses in order to model the overall mass and energy transport in these deposits. Sources and sinks of components and mechanisms of metal cycling.- Bulk and trace element distribution patterns will be determined for rock types and superimposed alteration facies in order to characterize the net alteration reactions as well as sources and sinks of elements. Sources of H, O, C, and S will be investigated by isotopic analyses of rocks, minerals, and fluids.
Preliminary O and D/H studies at Yerington indicate that the contrast between Jurassic meteoric/sea water and "magmatic" water is sufficient for tracking the sources of water in the hydrothermal system. Potential sources of C at Yerington include the carbonate and carbonaceous host rocks and magmatic carbon; potential sources of S include magmatic assimilation of pyritic volcanic rocks and shale, hydrothermal leaching of sulfides from earlier phases of the batholith, and hydrothermal "assimilation" of Jurassic sea water sulfate and Triassic evaporites. All of these sources will be tested by regional sampling and evaluated in the space-time context of water sources and alteration-mineralization events. *Uplift/cooling rates and reconstruction of paleoheatflow:* The present exposures of deep structural levels at Yerington are the consequence of extensional faulting and uplift that is largely bracketed between 17 and 11 Ma. Further refinement of the timing and rate of this uplift and an approximate reconstruction of paleoheatflow during faulting can be accomplished by detailed cooling studies of deep-seated granitic rocks using 40Ar-39Ar on hornblende, muscovite, biotite, and K-spar, and fission track on zircon and apatite. *Surface modification of primary sulfides:* Oxidative weathering in the Tertiary at Yerington and Red Mountain will be studied using mass balance methods in order to determine the: 1) location of the surface at the time of initiation of chemical weathering; 2) amount and rate of pre-enrichment erosion; 3) magnitude and direction of lateral fluxes transporting copper; and 4) extent of late destruction of the chalcocite enrichment blankets by oxidation and downward transport. *Normal faults and their relation to deeper crustal structure:* Repeated episodes of imbricate high-angle normal faulting and tilting at Yerington during the Miocene have more than doubled the width of this region. Well constrained palinspastic reconstructions indicate that the earliest faults penetrated at high angles to depths of 6 to 7 km; their behaviour at deeper structural levels is not known and remains one of the key tectonic questions here and elsewhere in the Basin and Range. Did these faults originally bottom into a subhorizontal ductile-brittle transition zone beneath which extension was accomplished by plastic flow, or did they bottom into a "detachment" or low-angle normal fault above a relatively rigid lower plate? What is the role of Miocene plutonism at depth? The large differential uplifts and rotations at Yerington make it an ideal area to address these questions; a 2-3 km drill hole that could be sited in the first year of the project would penetrate to paleodepths of 10-12 km, analogous to the maximum depths of recent faulting in the Basin and Range as inferred from seismic reflection and seismicity studies. *Regional structural reconstructions:* Extensional strain is highly heterogeneous across the Basin and Range province; greatly extended regions marked by multiple generations of high-angle normal faults and large stratal rotation alternate with less extended domains comprised of large, gently tilted fault blocks. The geometry and kinematics of deformation within the boundary regions between these domains is not well understood. We propose to map in detail the transition between the highly extended Yerington district and the nonextended Sierra Nevada to the west and less extended areas to the south. Ultimately, we expect to compile regional maps and cross sections that illustrate the magnitude, timing, and rates of extension of continental crust across this portion of western Nevada.
SALTON SEA SCIENTIFIC DRILLING PROJECT (SSSDP)
STATUS REPORT, APRIL 1985

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ABSTRACT

Salton Sea Scientific Drilling Project (SSSDP) Status Report, April 1985

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In October 1982 the Salton Sea Geothermal Field (SSGF), in California, was selected as a site for research drilling. The SSGF is one of the largest, hottest and most saline geothermal fields in the world. It is one of a number of high intensity hydrothermal systems within the Salton Trough, a depression partially filled with the Tertiary to Recent detritus of the delta of the Colorado River. The Trough represents a tectonic transition between the ocean rift systems of the East Pacific Rise and the Gulf of California to the south, and the San Andreas transform fault system to the north. Drilling into the SSGF is of interest both from the point of view of study of thermal regimes and of mineral resources, as the concentrated brines in the SSGF are actively forming hydrothermal ore minerals.

After learning that a commercial geothermal well was to be drilled in the SSGF to 3.6 km depth, where temperatures up to 300°C were anticipated, we requested funds to deepen it to 5.5 km in order to study the deeper hotter parts of the system. In response $5,900,000 was added to the 1984 budget of the U.S. Department of Energy to carry out this research project.

The purpose of this paper is to review the scientific goals, the plans, and achievements of the project to date. The original concept has been modified to drilling and coring a dedicated well to a depth of 3.1 km, some 4 km closer to the center of the hydrothermal zone. We anticipate reaching a temperature of 300°C at a depth of about 1.3 km at this new site. Because current estimates of the cost of this new plan exceed the funds available, we have provisionally reduced the scope of work by, among other things, eliminating the cost of
drilling a disposal well. Although this would limit the opportunity for brine sampling and reservoir testing, it still permits a minimally acceptable scientific program. We are therefore proceeding with this plan and expect drilling to begin in July 1985. At the same time we are also exploring sources of additional funds to permit a more extensive program of testing and sampling which a disposal well would make possible.

An interagency committee representing the National Science Foundation, United States Geological Survey and the Department of Energy is coordinating the scientific program. It will soon be making awards of funds in response to the sixty proposals received from the science community.

Although this project has suffered various vicissitudes during its short history, it remains an important and exciting step in the national program of Continental Scientific Drilling (CSDP). Even at this early stage important general findings from the SSSDP experience are clear:

(i) The way SSSDP was funded is not the ideal way to fund the CSDP.

(ii) The CSDP is less likely to be successful as a small program in a large bureaucracy. Instead it needs an efficient, technically-competent, and fiscally responsible, small organization to manage it.

(iii) The scientific goals of a CSDP project must be explicit from the outset and must play a key role both in the funding and in the engineering design.

(iv) Rotary drilling without wireline retrieval is an inefficient way to obtain core. Development of wireline systems which operate at high temperatures and with blow-out preventers is needed.

(v) I still believe in the concept of holes of opportunity. We must use our best efforts to get industry involved in the CSDP to our mutual advantage in supporting this exciting initiative in the earth sciences.
DEEP CONTINENTAL SCIENTIFIC DRILLING IN YELLOWSTONE NATIONAL PARK

DEEP CONTINENTAL SCIENTIFIC DRILLING IN YELLOWSTONE NATIONAL PARK

by

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ABSTRACT

The silicic volcanic complex at Yellowstone is one of the largest in the geologic record. It is related to an even larger igneous system that has been active for at least 15 million years (a slowly migrating hot spot), and shows signs of continuing igneous activity. These signs include: (1) an exceptionally high conductive and advective heat flux (the largest known natural discharge of thermal water in the world), (2) geophysical data consistent with the presence of magma in a large subcaldera chamber, (3) current uplift of the central part of the caldera floor at the rate of 1.5 to 2.5 cm/yr, and (4) isotopic compositions of helium in the hydrothermal system that are indicative of a mantle or magmatic source. Many geological, geophysical, and geochemical studies conducted in and around Yellowstone National Park have provided a large data base upon which to construct models that can be tested by drilling.

A major objective of drilling at Yellowstone would be to investigate the transition from seismic to aseismic conditions that occurs about 3 to 4 km beneath the caldera. Drilling to 5 km at Yellowstone would provide information about the following processes and how they relate to ore deposition: change in mode of rock deformation from brittle fracture to quasi-plastic flow, mechanisms of heat transfer in coupled hydrothermal-magma systems, limiting factors of meteoric water circulation, evolution of fluids in crystallizing magmas, flux of rare gases from the mantle, and formation of
brines at high temperatures and moderate to low pressures. Drilling also would provide information about rock and fluid properties at depth, required to improve caldera-wide models. Core drilling the entire hole would be necessary to achieve many of the above objectives.

There are social, political, and environmental constraints that would be imposed on a scientific deep-drilling project in Yellowstone National Park. However, these should not be insurmountable if it can be shown that (1) the scientific information obtained would be truly vital to understanding important earth processes, and (2) the drilling can be conducted safely with proven technology at a location in the Park where it would not have adverse ecological effects. Scientific drilling would have to be conducted near an existing major road and in a part of the Park that is not devoted to the preservation of endangered and diminishing species. A specific drill site has not been chosen, but several sites have been identified within the Yellowstone caldera that should satisfy the scientific objectives, while remaining within the political, social, and environmental constraints.

Deep continental scientific drilling at Yellowstone would provide a unique opportunity to study present day "hot-spot" activity within a continental crustal environment. The significance of hot-spot activity in the evolution of basaltic islands is well documented. Similar processes, active beneath the continental crust, may have played a key role in the evolution of many of the larger, silicic volcanic complexes containing genetically related plutons and ore deposits.
NAVY GEOTHERMAL/GEOTEC ENERGY R&D PROGRAM DRILLING PLANS

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ABSTRACT

The United States Navy, under the Navy Energy R&D Program, is actively developing plans for scientific drilling projects on the island of Adak in the Aleutian Arc and the island of Oahu in the Hawaiian island chain. The Navy hopes that the results of these drilling programs will provide needed information on the geothermal resources beneath these islands and the applicability of using geothermal fluids to provide power and space heating to Naval installations located on those islands. The Navy believes that if the fluid temperatures are greater than 180°C and of sufficient quality and quantity then direct use of the fluids for power production is possible; if the fluids are of moderate temperature (between 120°C and 180°C) and of sufficient quantity then the use of the Geothermal/Ocean Thermal Energy Conversion (GEOTEC) concept for the production of power is a viable geothermal utilization concept. GEOTEC uses the geothermal fluids for the topping cycle and the cold ocean water as the bottoming cycle using OTEC technology. Value from the drill holes for the scientific community could be as follows:

ADAK, ALASKA - The selected site is near the north coast of the island among the remnants of three volcanoes (Andrews, Moffett, and Adagdak), the youngest of which (Adagdak) has been dated at 140,000-340,000 years. Geophysical surveys on the island indicate an abrupt and steep drop in the gravitational field in the northern third of the island, as well as high electrical conductivity beneath the Adagdak volcano. Geochemical analysis of hot springs in the area indicate a reservoir temperature of 180°C with perhaps a slight magmatic component to the water. In addition, the island is continuously shaken by small to moderate earthquakes. Research opportunities associated with this hole could include: (1) geological, petrological, and geochemical analysis of cores and cuttings from the three possibly overlapping volcanoes; (2) exploration and modeling of the mechanics and thermal processes associated with an island in the Aleutian Arc; and (3) methods for determining the existence of a possible near-surface magma chamber.
OAHU, HAWAII – The site is located within Laulaulei Valley which itself lies within the eroded caldera complex of the 3.3 million-year-old Waianae volcano. Research in this hole might include: (1) downhole seismic studies of the structure of the Waianae caldera complex and nearby submarine flanks; (2) geochemical analysis and modeling of low temperature fluid compositions from a moribund basaltic island hydrothermal system; (3) geological, geophysical, petrological, and geochemical analysis of cores and cuttings of late stage subaerial caldera filling lavas, intrusive formations, and hydrothermal and retrograde alteration mineral suites; and (4) modeling of thermal and mechanical processes associated with an extinct, basaltic island volcanic system.

In a programmatic sense, the Navy proposes through the Interagency Coordinating Group to offer specific sites along the Atlantic Coastal Plain during fiscal years 1988-1992 for consideration as predrilling programs. These drilling programs could provide the geologic, geophysical, and geochemical data for the scientific community to support advance drilling targets. Again Navy would offer these sites as holes of opportunity.

ATLANTIC COASTAL PLAIN – Research opportunities in these holes could include (1) conformation of the Atlantic Coastal Plain stratigraphy, including lithology, thickness, age, and physical properties such as porosity and permeability; (2) testing of local Atlantic Coastal Plain structure: joint systems, faults, and solution caverns; (3) confirmation of depth to crystalline basement; (4) Sampling poorly-known basement rocks beneath the sediments of the Atlantic Coastal Plain to yield rock type, age (isotopic dating), petrology, local structure, radiogenic heat production, and thermal conductivity; and (5) determination of the origin of seismicity in the Southeastern United States.
CONTINENTAL SCIENTIFIC DRILLING PROGRAM—SOUTHERN OKLAHOMA AULACOGEN

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Introduction:
The Southern Oklahoma Aulacogen has been considered by many as the North American type of this structural class (Hoffman, Burke, and Dewey, 1974; Milanovsky, 1981). This feature apparently developed during the late Proterozoic-early Cambrian rifting of the continental margin. It is representative, as well as the best exposed, of a series of rifts along the southern and eastern margin of the North American plate during this time period. Pronounced Pennsylvanian structural inversion has lifted the igneous basal sections of this rift to shallow crustal levels and exposed parts of it. The following discussion lays out a rationale for the commitment of a scientific drilling program within this inverted, structurally high but stratigraphically deep, zone of the continental crust.

Geologic Setting

The Wichita Mountains of southwestern Oklahoma and the Arbuckle Mountains of south-central Oklahoma are an exposed part of what has come to be known as the Southern Oklahoma Aulacogen. This Cambrian age feature underwent inversion in the Pennsylvanian resulting in prominent WNW-trending structural axes commonly known as the Criner Hills-Wichita Mountains-Amarillo "high", the Arbuckle Mountains, and the Muenster Arch, which run from the southeast in south-central Oklahoma toward the west side of the Texas panhandle. The aulacogen is most prominently displayed on basement maps [e.g. Bayley and Muehlburger, 1969]. The aulacogen includes the uplifted blocks and various interior or adjacent basins, such as the Ardmore and Anadarko. The basement floor of the aulacogen is predominantly an Early to Middle Cambrian suite of layered gabbros, sheet granites, and rhyolites, strikingly anomalous in age compared to surrounding, mostly middle Proterozoic, basement. An overlying sedimentary column developed during the Upper Cambrian to Mississippian and has been estimated to have achieved about 45 km thickness before structural inversion began in late Mississippian to early Pennsylvanian. During inversion, about 5 to 6 km of Pennsylvanian "tectonic" sediments accumulated in the Anadarko Basin, the deepest of the basins. Subsequently, a final 2 to 3 km of Permian "post-tectonic" fill was generated. This Permian section buried the eroded arches so that a prominent paleotopography was preserved and this is now being exposed in the Wichita Mountains.

Sporadic movements along the arch continued through the Mesozoic and Tertiary as recorded in the Texas Panhandle. Movements in the Quaternary (including Holocene), as evidenced by the surface Meers Fault, have recently been recognized.
The Frontal Fault Zone [Harlton, 1963; 1972] is the structural boundary between the Anadarko Basin and the Wichita Mountain uplifted block. Considerable debate exists as to the exact nature of the offsets along the faults within the zone. There is no doubt, however, that the Cambrian basement was offset by at least 12 km vertically during the Pennsylvanian deformation. The most prominent, and northerly, of the faults is the buried Mountain View Fault. The upper 5-8 km of this fault plane is well-configured in many places because of numerous penetrations by wells [e.g. Harlton, 1963; Takken, 1968] and shows a consistent 40° dip to the south. The COCORP line [Brewer et al., 1983] was interpreted to show this surface continuing downward with a 40° dip to 20-24 km.

The most southerly of the faults, where the Frontal Fault Zone is widest, is called the Meers Fault. Brewer et al [1983] also interpreted this fault as a thrust at a dip parallel to the Mountain View. This is currently unresolved and many workers believe the Meers is steep to vertical as indicated by its surface trace. Donovan et al [1982] have argued for substantial left-lateral offset along parts of the Frontal Fault System.

The basement bordering the aulacogen on the north and west is 1.35-1.40 by in age and consists primarily of shallow-seated granites and rhyolites [Denison et al., 1984; Thomas et al., 1984]. The basement on the south is apparently younger and consists of a variety of rock types including a prominent metasedimentary unit known as the Tillman Group whose age may be ≤ 1.2 by [Brown et al., 1981]. This unit has been interpreted to be the top of a large, deep Proterozoic basin (10 km of existing section) beneath the Paleozoic Hardeman Basin [Brewer et al., 1981]. What floors the Proterozoic basin is unknown. Farther to the south in the Llano region basement ages are 1.0-1.2 by.

The Paleozoic sedimentary record is very well documented because of the tremendous amount of drilling over the years in the basins. What is least known and what could be determined from deep scientific drilling is the early (mostly pre-Upper Cambrian) character of this important rift. At least 4 terranes of the aulacogen are worthy of consideration for placement of deep scientific drill holes:

<table>
<thead>
<tr>
<th>Terranes</th>
<th>Objectives</th>
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<tr>
<td>1) Wichita Mountains Uplift</td>
<td>Development of aulacogen: igneous, host rock, structure, and deeper cratonal crust.</td>
</tr>
<tr>
<td>2) Hardeman Basin</td>
<td>Strong lateral seismic layering; deep Proterozoic basin</td>
</tr>
<tr>
<td>3) Anadarko Basin</td>
<td>Character, movement and maturation of fluids, esp. hydrocarbons; documentation of basin development with both thermal and loading character, basement rock.</td>
</tr>
<tr>
<td>4) Frontal Fault Zone</td>
<td>Nature and style of major Pennsylvanian cratonal faulting (thrusting, strike-slip, reactivation, listric character).</td>
</tr>
</tbody>
</table>
Both 3) and 4) have already been penetrated to a variety of depths so that a vast amount of sedimentary and structural Paleozoic history is known, although some of the supporting data are not public. It must be emphasized that there is much more to be known from deeper drilling beyond economically-based targets in 3) and 4). However, this proposal concentrates on terranes 1) and 2) but with expected contribution from previous studies and other on-going research efforts.

Terranes Targeted For Scientific Drilling

Terranes A) and B) offer compelling arguments for scientific drilling that are in many ways interrelated. Terrane B) includes some of the strongest horizontal seismic reflectors ever noted within the upper basement. Such reflectors have also been found farther west in the Texas panhandle. Their origin is unknown but suspected to be mafic layers in a vast metasedimentary or silicic volcanic host basin. Resolution of this enigma would solve many problems of southern Mid continent geology.

Terrane A) is particularly attractive because it is

1) Part of a class of rifts heading into the continental interior from a continental margin.
2) Unique in exposure of the igneous basal zone of a rift.
3) Developed at the Proterozoic-Cambrian boundary allowing extension of plate tectonic modelling into the Proterozoic from the Paleozoic.
4) Athwart fascinating gradients in basement age and character: a) basement youngs to the south, from \( \sim 1.4 \) by to \( \sim 1.26 \) by and b) changes from a granite-rhyolite dominated terrane to a mixed rock terrane with abundant tectonites and metasedimentary units.
5) Possible to unravel the structural character of the Wichita province igneous units.
6) Situated where deeper crust is exposed at shallow levels.

Strong logistical arguments can be raised which include:

1) Availability of detailed studies of the aulacogen's later evolution, providing good context for integration of new information on its earlier and unknown history, including a) a new seismic line by G.R. Keller and G.A. McMechan completed in 1985, b) a COCORP line, c) abundant oil company data in some locations, and d) new studies of the igneous basement outcrops.
2) Accessibility is good.
3) Reasonable costs because the study area is located in the center of the drilling industry ensuring ready availability of personnel and equipment.

In summary, major questions involving formation of the southern part of the North American plate can only be answered by drilling. A program of site study and shallow drilling can lead ultimately to a proposal for a 10 km hole.
INVESTIGATION OF MAGMA–HYDROTHERMAL SYSTEMS:  
CSDP PROPOSAL FOR THE VALLES CALDERA, NEW MEXICO

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Investigation of Magma-Hydrothermal Systems:
CSDP Proposal for the Valles Caldera, New Mexico

by

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Valles caldera in northern New Mexico is considered by many scientists to be the world's "type" resurgent caldera and is presently the most thoroughly studied of the three major young caldera complexes in the United States. Formation of the caldera and its associated post-caldera eruptives (1.09 to 0.13 Ma) represent the culminating episode of volcanism in the Jemez volcanic field which has been continuously active during the last 13 Ma. A 240 to 300°C neutral chloride hydrothermal system characterized by meteoric recharge, a vapor cap, and lateral outflow presently circulates beneath the resurgent dome. The understanding of caldera processes demonstrated in this magma-hydrothermal system are critical for the effective development of hydrothermal, hot dry rock, and magma energy resources. Hydrothermally altered rocks and mineral concentrations associated with the Valles are recent analogs of the epithermal mineral deposits mined from exhumed calderas.

Because of vigorous private and U.S. DOE-sponsored geothermal efforts and active DOE-sponsored investigations related to the CSDP, over 35 geothermal wells have been drilled both inside and outside Valles caldera from which almost all data are in the public domain. The cumulative known stratigraphic section in the caldera area approaches 7 km consisting of 1950 m of Quaternary caldera fill, 300+ m of Tertiary pre-caldera rocks, 800 m of Paleozoic sedimentary rocks, and 3700 m of Precambrian basement. Maximum bottom-hole temperatures (BHT) are 341°C at 3.2 km inside the caldera (Baca #12) and 325°C at 4.5 km just outside (EE-2).

The U.S. DOE, Office of Basic Energy Sciences has already initiated a CSDP drilling/coring program at Valles caldera (EOS, Nov. 20, 1984; GEOTIMES, Feb. 1984). Valles caldera #1 (VC-1), a 856-m continuously cored hole was completed just inside the topographic rim of the caldera on Sept. 3, 1984 (Fig. 1). The primary objective of this corehole was to penetrate a high-temperature hydrothermal outflow plume near its source, while secondary objectives included acquisition of important structural/stratigraphic data and acquisition of continuous core through the youngest volcanic unit in the caldera. VC-1 is deeper, hotter, and more scientifically interesting than originally conceived; BHT = 160°C, at least two hot fluid entries were encountered and the hydrothermally altered rocks contain concentrations of molybdenite and chalcopyrite as well as anomalous Pb, Zn, and U. Besides physical-chemical properties and mineral studies, information from VC-1 and other nearby wells is being used to study rates of flow, mixing patterns, and rock-water interactions in a lateral flow environment.

A comprehensive CSDP proposal has now been submitted to DOE/OBES. It is a joint effort involving seven universities, four national laboratories, one private company, and the U.S. Geological Survey. Our proposal is to drill and core six additional wells at four sites over the next nine years (Fig. 1). The overall objective is to explore the caldera from near-surface processes into the roots of the magma-hydrothermal system. At Sulphur Springs, a pair of coreholes 500 and 2000 m deep (VC-2a and VC-2b) will
investigate the evolution, dynamics, and ore deposit ion mechanisms of the vapor-dominated zone, the underlying 200+°C hydrothermal system and the boiling interface between them. Within the resurgent dome, we propose to deepen Baca #12 from 3.2 km (340°C) to 5.5 km (about 500°C) to study (1) the structure and evolution of the resurgent dome, (2) the physical-chemical properties of the heat transfer zone between magma and convecting hot water, and (3) the crystallized magma in the upper portion of the Valles pluton. At Valle Grande, two holes 1 and 6 km deep (VC-4a and VC-4b) are proposed to study (1) the tectonic character of the eastern ring-fracture zone, (2) the evolution of overlapping trap-door caldera structures, and (3) a major recharge zone to the hydrothermal system(s). Within the Toledo embayment we propose to core VC-5 (2 km) to investigate the volcanic and tectonic relationship of this parasitic structure to the Valles caldera and Jemez lineament. The present proposal involves drilling, management and preliminary scientific characterization. Numerous proposals have been initiated by collaborating investigators to carry out research on specific topics which require the samples to be provided by drilling. These proposals will be submitted to the appropriate funding agencies through normal channels.

The Valles CSDP is designed to investigate the roots of a classic caldera-type magma-hydrothermal system, its energy budget, and associated tectonic and ore deposit environments. It will provide a natural laboratory for the testing and calibration of surface and borehole geophysical techniques. It will lead to improvement of geological and geochemical models of magma-hydrothermal systems and it will generate technological advances in drilling procedures in high-temperature environments.

Figure 1. Sketch map of Valles caldera showing locations of existing and proposed CSDP wells; VC-5 is not shown but would be located somewhere in the Toledo embayment. VRF = Valle ring fracture; TRF = Toledo ring fracture; RCG = Redondo Creek graben.
A CONTINENTAL SCIENTIFIC DRILLING PROGRAM BASEMENT TEST BOREHOLE IN THE VALLEY AND RIDGE OF TENNESSEE

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Current CSDP plans allow for a deep borehole to be drilled in the Blue Ridge-Piedmont region of the southeastern Appalachians. To enhance the interpretation of structural and stratigraphic data obtained from that project, we propose that an additional deep basement test borehole be drilled in the Valley and Ridge province of eastern Tennessee. The proposed borehole will penetrate multiple thrust sheets of deformed middle to early Paleozoic strata, as well as autochthonous late Precambrian to early Cambrian sediments and Precambrian crystalline basement. Such a borehole would serve as a valuable reference point for strata penetrated by the first CSDP hole and is at a locality removed from intensive Blue Ridge deformation and tectonism. In addition, a Valley and Ridge borehole would provide an important stratigraphic reference point for future boreholes under consideration by CSDP in the southern Appalachians. Together with planned and possible future CSDP basement drilling projects, the Valley and Ridge borehole in Tennessee would provide an important link in a transect from the North American craton into the Appalachian orogenic belt.

In addition to the primary objective as a reference for current drilling projects, a CSDP borehole in the Valley and Ridge province would provide numerous unique opportunities for research on strata and structures of the province. Comparison of structures within individual thrust sheets, between separate thrust sheets, and at the master decollement will provide information on deformation styles, deformation mechanisms, strain partitioning and amount of strain for these strata. Regional Appalachian tectonic problems may be addressed by characterizing the nature of the autochthonous sediments and the underlying crystalline basement in the Valley and Ridge borehole and by comparing these characteristics with results from the current CSDP borehole in the Blue Ridge-Piedmont region.
A CSDP borehole in the Valley and Ridge would provide an opportunity to conduct important hydrological and geochemical research on the fluids throughout the thrust sheets above the master decollement and within the autochthonous sediments and crystalline basement below it. Hydrological problems that can be addressed with data from the borehole include: (1) chemical and isotopic composition and the age of fluids associated with various stratigraphic units within a thrust sheet, (2) variation of fluid composition within and between thrust sheets, (3) importance of faults and major structures as fluid migration pathways or barriers, (4) the effect of the master decollement on deep fluid migration pathways, (5) the fluid compositions associated with autochthonous sediments beneath the master decollement, (6) the chemistry and amount of fluid migration into or out of the crystalline basement, (7) chemical and isotopic composition of the sediments and basement strata, and (8) analysis of fractures and fracture-filling minerals within all strata penetrated to determine the pathways and mechanisms for fluid migration.

A CSDP Valley and Ridge borehole would be located after detailed examination of available geological and geophysical data. The proposed borehole should be located reasonably close to the borehole that will be drilled into the crystalline terrane of the southern Appalachians. The location, however, should be distant enough from the frontal fault system that separates sedimentary and crystalline rocks to ensure that the sediment sequence that is penetrated above the basement offers a realistic reference section. The location should also be along a line that can be tied to COCORP seismic surveys and that projects to possible future CSDP drilling sites closer to the cratonic interior. Ideally the site should be penetrated by other deep boreholes that provide a reference geologic framework for preliminary structural and stratigraphic interpretation of the area.

Based on the above selection criteria, we propose that the U.S. Department of Energy's Oak Ridge Reservation be considered initially for the location of the borehole. The Oak Ridge locality is at the locus of several recent deep test wells. Three boreholes (3400–, 2400–, and 2100-m-deep) are within 40 km. Data and geophysical log packages from these wells provide a structural and stratigraphic framework for this section of the Valley and Ridge province superior to that for any other nearby area. Several seismic transects have been run within 15 km of the site and can be tied into existing borehole data and surface geological data. The site would be on U.S. Government property, eliminating access problems and would be near Oak Ridge National Laboratory (ORNL) which would facilitate establishing and maintaining long-term experiments.
within the borehole and core storage. In addition, current plans call for
the drilling of a 1800-m borehole at ORNL that would allow for the
development of initial data framework for the upper portion of the CSDP
borehole. Finally, ORNL has the necessary expertise and analytical
facilities to coordinate the drilling project and to undertake extensive
preliminary sample analysis as a prelude to long-term research aimed at
resolution of the questions discussed above.

The borehole would be cored for its entire extent (borehole depth is
estimated at approximately 7.5 km). A complete geophysical log package
(including gamma/gamma spectral/compensated neutron/compensated
gamma-gamma/acoustic velocity and waveform/electric - SP, resistivity,
induction, guard/temperature) would be obtained for the entire borehole.
Preliminary lithologic and stratigraphic logs would be prepared from the
drill core immediately upon recovery and the core would be archived for
future sampling and analysis. A complete investigative approach will be
undertaken, including standard elemental and isotopic chemical analyses
of rocks, waters, and dissolved gases and microscopic (petrographic, SEM,
TEM) examinations. Plans also will be made to conduct long-term
research projects within the borehole such as hydrologic monitoring and
determination of in situ stress patterns. Analysis of the core, water
samples, geophysical logs, and other data obtained from the borehole
would be undertaken by scientists from academic institutions, national
laboratories, and other pertinent research institutions.
SCIENTIFIC DRILLING OF THE MANSON, IOWA, STRUCTURE

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The Manson, Iowa, structure consists of stratigraphically uplifted granitic basement rocks surrounded by a roughly circular region, about 30 km in diameter, where the normal section of sedimentary rocks is missing and replaced by "disturbed Cretaceous shale." The entire structure lies under one to several hundred feet of glacial deposits. Manson was recognized as a crypto-explosion structure based on studies of limited core and cuttings from drill holes into the central granite and the surrounding "shale." The structure was found to be an impact crater following identification of shock features in quartz from the granite. Recently, the "disturbed shale" has been interpreted as a suevite-like fall-back breccia.

Manson is the largest crater recognized in the United States and the only one to involve granitic basement material on a large scale. Its age is known only to be younger than middle Cretaceous, based on the presence of poorly preserved fragments of fossils found in the fall-back breccia. Positive gravity anomalies near the center of the structure are interpreted to correspond to granite of the central uplift. A decrease in wave length and amplitude of magnetic features occurs over the structure compared to the surrounding region. A refraction seismic survey undertaken to delineate the boundary between the fall-back breccia and the overlying glacial deposits was made difficult due to the lack of a velocity contrast between the two materials. Nevertheless, the pattern of pre-glacial drainage was established based on this study.

The first objective of the proposed research is to learn what happens during an impact of this magnitude. Our understanding of the formation mechanics remains incomplete. A single drill core from the somewhat smaller Ries crater yielded inconclusive results. We would hope to be able to establish the pre-impact location of rocks, including those of the continental basement, encountered in several drill holes and thereby learn what movement must have occurred during the impact. This research would provide input to the broader problem of what the role of impacts is in the formation of the Earth's continental crust.
Another objective which requires a drilling program is to learn the age of the Manson structure. The time of the Manson event could be related to the Cretaceous-Tertiary boundary and the corresponding mass extinction which marks the end of the Mesozoic Era. No material suitable for radiometric dating of the impact has been found among available core and cuttings and at the one known outcrop of fall-back breccia. The size and youth of the Manson crater are consistent with the formation and preservation of a large amount of melted material which would be appropriate for radiometric dating and which could be reached by a modest drilling program.

Recovery of drill core from two to four locations spaced radially outward from the center of the structure are required to satisfy all of the objectives of the proposed study. The required depth of the drill holes is about 5000 ft (1500 m). Research activity using material from the drill core will include the following:

1. Logging of the drill core;
2. Petrographic study of the different distinct units recovered;
3. Geochemical analysis of impact melt rocks and "country" rock;
4. Argon 40-39 and Rb-Sr age measurements of impact melt rocks and "country" rock; and
5. Synthesis of data to establish the nature and chronology of events related to the formation of the Manson structure.

Research work will be accomplished by a consortium of investigators from the Iowa Geological Survey, the U. S. Geological Survey, and various university geology departments.
APPALACHIAN ULTRADEEP DRILL HOLE:
SCIENTIFIC OBJECTIVES AND GOALS OF THE SITE STUDY

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APPALACHIAN ULTRADEEP DRILL HOLE: SCIENTIFIC OBJECTIVES AND GOALS OF THE SITE STUDY

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The principal goal of drilling an ultradeep hole in the southern Appalachians is to test the hypothesis of thin-skinned thrusting of large sheets of crystalline rocks. Other goals of drilling this hole include study of the petrology of Grenville basement rocks, stratigraphy and deformation of platform cover beneath the thrust sheet, determination of the state of stress in the crust at seismogenic depths, development of logging and drilling technology in a deep hole in crystalline rocks, studies of the petrology and geochemistry of core, comparison of P-T conditions of metamorphism in similar assemblages in surface Blue Ridge exposures and core from 4-6 km, and opportunities to study both brittle and ductile fault rocks at several depths in both the Brevard fault zone and the master detachment.

The site study which has just begun has several specific goals: 1) precise location of the deep hole site to maximize the scientific results from intermediate depths and to estimate the subsurface structural geometry at both intermediate and bottom hole depths. 2) provide critical data on in situ stress, heat flow, and petrology and anisotropy of rocks for engineering design of the hole. 3) Geologic and geophysical data from research should provide part of the basis for initiation of major research projects in the deep hole. To accomplish these goals additional studies of surface geology are being undertaken to complete detailed geologic mapping, 200 km of seismic reflection profiles along with high resolution and expanding spread profiles for velocity determination, petrology and geochronology, potential fields, and four shallow (300m) boreholes to provide in situ stress and heat flow data as well as a suite of representative rock types that should be encountered above the detachment.

A long term goal of this project is for this area to become an International Laboratory for Geologic and Geophysical Studies of Orogenic Belts. The data to be gathered during the site study alone would make this one of the most (perhaps the most) intensively studied areas in the interior of an orogen. Drilling this hole will add an immense body of knowledge to our knowledge of the anatomy of mountain chains and the evolution of continental crust.
DEEP DRILL HOLE ON THE CENTRAL BASIN PLATFORM OF WEST TEXAS

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Drilling has just been completed for a deep hole on the Central Basin platform of West Texas. This hole encountered basement at about 4600 ft and bottomed at 19,100 ft. Very preliminary analysis of samples from this well suggests that the igneous section drilled (approximately 14,500 ft) consisted almost entirely of a layered mafic intrusion. Downhole geophysical logs are in agreement with this interpretation and a vertical seismic profile type experiment indicates the average velocity of these igneous rocks is approximately 6.7 km/sec. A combination of air and mud drilling was employed and no cores were taken. However, several hundred pounds of hand-sized samples were recovered during drilling operations. Clearly a great deal can be learned from this hole, but it does appear that re-entry is feasible. Thus, further studies would be possible.
A PROPOSAL FOR DEEP SCIENTIFIC DRILLING AND ASSOCIATED EXPLORATION AND RESEARCH TEXAS GULF COAST

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The Texas and Louisiana Gulf Coastal provinces are characterized by an array of scientific dilemmas ranging from the origin of the Gulf itself and the nature of the subcrust to the causes and effects of long-lasting and continuing circulation of thermobaric waters throughout the thick sedimentary section.

The Gulf Coast is correctly classified as a "passive margin", as attested by the scarcity of seismic activity. Plate tectonics theory requires that the Gulf originated by rifting related to continental drift. From the little information concerning deep structure lithology that is available, this theory is appropriate, but by no means conclusively demonstrated. The nature of the underlying crust and its superadjacent sediments and their contained waters; the precise timing of the rifting; the fluid dynamics, geochemistry, diagenesis and early depositional history of the sedimentary sequence; the thermal history and the unusually high thermal gradient; and the fluid pressure regime in the deep sedimentary section are all too poorly known to permit quantitative analysis of processes which are of enormous scientific and practical importance.

In our opinion, the San Marcos arch is the best location for investigating these important phenomena and problems. The arch, extending southeastward from exposed Grenville basement rocks of the Llano uplift, is situated in an area of both lateral and vertical convergence of the sedimentary cover of the Gulf Coast Basin. Seaward of the Llano Uplift, highly deformed and slightly metamorphosed rocks of the Ouachita-Marathon orogen have been intersected at depth beneath Cretaceous sediments. The inferred edge of continental crust underlies an extensive Lower Cretaceous reef trend a few miles to the southeast of the known Ouachita rocks. Rapid thickening of Tertiary and possibly of Cretaceous sediments southeast of the reef, together with geophysical indications of a relatively shallow Moho suggest that a transitional continental crust underlies sediments basinward of the reef trend. This transitional crust could be rifted Grenville basement, buried rocks of the Ouachita trend, an island arc related to the Ouachita trend, or exotic continental basement related to a proto-south American continent.

On the basis of our present understanding of deep structure, it appears possible to locate a drill hole southeast of the reef trend which will penetrate a thick sequence of abyssal sediments, sample sediments in an underlying rift, and enter the "transitional crust" beneath the sediments.

Of equal importance to structural problems are questions related to diagenesis, lithification, and hydrodynamics of Tertiary and underlying Mesozoic sedimentary fill of this basin. Recent application of new techniques,
including stable isotope, trace element and fluid composition analysis have shown that both the diagenetic and the hydrologic systems are dynamic, and that fluid and mass transport within the basin are much more extensive and complex than previously assumed. Mass flux from the Mesozoic or older basement and convective recycling of deep waters are increasingly appealing as explanations for observed pervasive diagenetic features and for deposits of ore minerals and hydrocarbons found in shallow sediments.

The Cenozoic section contains three ground water regimes: an active meteoric regime, extending to depths exceeding one kilometer, a regime at intermediate depths, characterized by normal to moderately elevated hydrostatic gradients, and a deep system in the lower portion of the basin fill, including the Mesozoic section, containing highly overpressured, thermobaric waters, apparently derived in part from mineral dehydration reactions and thermal alteration of organic matter. Evidence exists that these deep thermal waters are still escaping to the surface along structurally controlled channels, and that the diagenetic changes and deposition of ore minerals continue today. Isotopic evidence indicates that at least some of the oil being produced from Cenozoic rocks is derived from deeply buried anoxic Cretaceous sediments. The penetration and study of these deep rocks is obviously of great scientific and practical importance.

The causes of the abnormally high thermal gradient present in much of the Gulf Coast is a matter of controversy. Undoubtedly circulating thermobaric waters play an important part. However, the nature of the "transition basement" and the structure at the basement-sediment interface may also be important, particularly as the rifting process might involve emplacement of large volumes of igneous material. Data derived from preliminary seismic and heat flow studies and from deep drilling will facilitate the modeling of the deposition rates of sediments and hence of subsidence rates related to cooling and loading of the transition crust. Furthermore, if the observed thermal gradients are essentially linear, then the planned deep drillhole should reach into the zone of greenschist metamorphism, thus providing an opportunity to collect rocks and associated fluids in a place where metamorphism and the formation of new crust is actively taking place.

The approximate locations of the proposed deep seismic reflection profile to be shot as a first stage of exploration are indicated on the enclosed figures. To achieve the best results the borehole should penetrate a relatively thin succession (100-3000 ft) of synrift, graben fill sediments at depths of less than 35,000-40,000 ft. For this reason a detailed seismic grid will be shot in the proposed drill site area to more clearly define the geometry and depth to basement. The detailed work may be done simultaneously with or after a deep sounding "COCORP type" profile has been run which will define the major framework of the Gulf Coast along the San Marcos Arch.

Additional research leading to selection of the most propitious drill site would include use of the abundant shallow to intermediate depth (5000 m) drill data to refine our knowledge of fluid and diagenetic regimes of the upper part of the basin fill, analysis of the thermal regime and heat flow along the crustal transition zone, and expanded geochemical and isotopic studies to better define the extent and importance of vertical flux of fluids and elements through the sedimentary fill.
DEEP DRILLING NEAR PARKFIELD, CALIFORNIA TO INVESTIGATE THERMOMECHANICAL PROCESSES LEADING TO A MAGNITUDE 6 EARTHQUAKE

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DEEP DRILLING NEAR PARKFIELD, CALIFORNIA
TO INVESTIGATE THERMOMECHANICAL PROCESSES LEADING
TO A MAGNITUDE 6 EARTHQUAKE

This abstract summarizes a proposed scientific program prepared by a
group of 22 investigators.* The forecast of a magnitude 6 earthquake to occur
in 1988 (±5 years) near Parkfield, CA, and the "characteristic" nature of
similar events, which have had typical interval times of 21-22 years since
1857, provide a unique opportunity to improve our understanding, by means of
in situ measurements at depth, of (1) the nature of the processes responsible
for medium-sized earthquakes, (2) the detectability of changes in fault zone
properties before such events, (3) coseismic changes in the crustal state
within and adjacent to the fault zone, and, finally, (4) the general thermo-
mechanical nature of the forces causing interplate motion. Because the
Parkfield Prediction Experiment is currently the centerpiece of the National
Earthquake Hazards Reduction Program, this portion of the San Andreas fault
system has been far more thoroughly studied and instrumented than any
comparable region. Thus, in situ measurements made in deep holes would be
particularly significant in view of the massive data base acquired at or
closer to the surface. As the characteristic earthquakes at Parkfield have
been shown to be nearly exact copies of preceding events, it is known in
advance where the rupture will initiate and terminate, the approximate
distribution of fault slip along strike and as a function of depth, and the
locations of major energy release during the mainshock. It is especially
interesting that we know the extent of the "preparation zone" where there is
the greatest likelihood of discovering significant changes in the fault zone
state before the next magnitude 6 earthquake.

Aside from the impending Parkfield earthquake, there are some specific
tectonic features here that render this a region of exceptional interest from
a geodynamics viewpoint. First, this reach of the San Andreas fault accounts
for most of the motion between the Pacific and North American plates. Second,
the Parkfield earthquake rupture zone coincides with a major transition in
fault behavior from creeping to locked; to date, no satisfactory explanation
for these contrasting modes of fault behavior has been forthcoming. Third, it
is believed that the rupture of the 1857 Fort Tejon earthquake initiated near
the southeastern end of the Parkfield zone of faulting. Are hypocentral
locations of great interplate earthquakes conditioned by unusual crustal
states or material properties?

The problems we hope to attack by means of deep drilling fall into three
categories. First, and least specific to Parkfield, there are the questions
associated with the nature of interplate driving forces and, in particular,
the state of stress and temperature in the environs of major, active through-
going faults. The second category includes questions about the state and
rheology of fault zones that give rise to large earthquakes and changes in

*The Parkfield Drilling Group is coordinated by A. McGarr and W. Thatcher and
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these factors from before to after an earthquake. The final set of problems involves the extent to which geophysical parameters that can be continuously monitored in the seismogenic zone itself show temporal variation before, during and after a "characteristic" earthquake.

The measurements most relevant to elucidating our understanding of plate driving forces are those of in situ stress and heat flow. Interpretation of in situ stress and heat flow data in the Mojave desert, adjacent to the San Andreas fault, have led to substantially different conclusions regarding levels of deviatoric stress responsible for interplate motion there with estimates from the stress data being approximately three-fold those inferred from heat flow. Although this discrepancy is as yet unexplained, it was clear from the measurements, which extended, in the case of stress, to 850 m, that a suite of stress and heat flow observations to depths of 3.5 to 4 km would suffice for resolving the current controversy between heat flow interpretations which argue for an upper bound on average shear stresses in the top 14 km of the fault of 20 MPa and the inference from the stress data of a corresponding average value closer to 60 MPa. In each case, doubt exists as to the appropriateness of the extrapolation of the results below the deepest measurements. Heat flow and stress data would also bear on the role of basal tractions acting on the plates below the seismogenic zone. Presently, we have almost no idea of either their magnitude or sense, relative to plate motion. Interpretations of the heat flow and stress measurements are linked directly to the fault zone rheology which can only be determined by obtaining data on composition, texture, density, pore pressure, and permeability. Such data are also relevant to the issue of the two contrasting modes of fault behavior, creeping and locked.

With more specific regard to earthquake mechanics, measurements of crustal state and material properties within the "preparation zone," elsewhere along the rupture zone, as well as in the adjacent crust exterior to the fault zone, are essential to diminishing the gaps in our understanding of how earthquakes work. We know almost nothing, for example, of the role, if any, played by the contrast in the material properties of well-developed fault zones and less-deformed adjacent crust in the generation of large earthquakes; in fact, even our knowledge about the nature of this contrast is scanty. Some of the most interesting results, however, would involve measurement of changes in the state, and possibly the rheology, of the fault zone due to the next Parkfield event. Thus, we advocate measurements of in situ stress, temperature pore pressure, and permeability both before and after the earthquake. Although coseismic stress changes are commonly estimated using seismic data, such estimates depend strongly on idealized models of the rupture process and so direct measurements of the coseismic stress changes would clearly not be redundant. If the seismically-inferred stress changes are indicative of the approximate magnitudes of these effects, however, then, based on experience with the stress data measured in the Mojave desert, it seems likely that the analysis of in situ stress data obtained before and after the earthquake will allow the resolution of the coseismic stress change. Measurement of coseismic frictional heating may also be feasible if measurements can be made very close to zone of fault slip. With regard to the other types of measurements proposed here, such as pore pressure, and remote thermal effects, we do not know what sort of coseismic changes to expect. Such comparisons, however, would certainly serve to constrain our notions of earthquake mechanics.

Continuous monitoring of geophysical and geochemical variables downhole are clearly the most relevant types of observations in terms of earthquake prediction, but they are also the most difficult to perform and could pose a
substantial risk to the integrity of the hole. Accordingly, we propose monitoring only temperature and pore pressure as a function of time before, during and after the earthquake because these measurements are each feasible with existing equipment, which can be extracted readily. The measurement of a temperature anomaly during the earthquake would provide the means of estimating the average strain within the zone of fault slip, information which is critical to our understanding of rheological changes associated with earthquakes. Time-dependent pore pressure is also important to the analysis of the faulting process but, in addition, the formation pore pressure is essentially a large strain gauge.

To address these problems, we propose three sites for deep drilling along the Parkfield break. The seismicity of the 1966 Parkfield sequence, as well as that recorded in the meantime indicates that the seismogenic zone extends to within about 4 km of the surface. Thus, we advocate drilling at least one of the holes to a depth of 5 km so as to sample the topmost portion of this zone. Each of the three sites has its own particular advantages in the context of the questions posed here.

Site A at Middle Mountain is within the "preparation zone" adjacent to the epicenters of the 1934 and 1966 events. Moreover, both creeping and seismic fault slip are known to occur here. On the one hand, no drilling problems have been encountered at this site in holes extending to about 300 m but, on the other hand, no intervals suitable for in situ stress measurements, using the current methodology, were found. In brief, the Middle Mountain site appears to be advantageous with regard to measuring fault zone properties, possibly excluding stress state, in the preparation zone where both creep and seismic slip occur.

Site B at Gold Hill, just to the northeast of the San Andreas zone, is attractive for a number of reasons including the quality of rock found in the course of drilling the top 200 m, its location at the southeastern terminus of the Parkfield rupture zone, the intensity of the 1966 aftershock distribution nearby, and its proximity to the point where the 1857 earthquake is thought to have initiated. It seems likely that in situ stress measurements can be made to depths of at least 1 km in this gabbroic formation, but the final results of site investigations, currently in progress, may indicate that the relatively high quality rock found near the surface does not extend much beyond 1 km in depth. Additional information is necessary to decide whether drilling into the seismogenic zone is warranted here.

Site C above the Salinian granites to the southwest of the fault zone is proposed partly because such a hole would be a more straightforward engineering proposition than those next to, or within, the fault zone but also for the purpose of acquiring data outside this zone, for direct comparison. A hole drilled into the Salinian block will almost certainly be well suited to in situ stress measurements, in contrast to the other sites for which stress measurements may require changes in current procedures.

For each hole we propose to make measurements to determine the crustal state and material properties within or adjacent to the fault zone during the course of drilling including stress, fluid pressure, porosity, temperature, fluid and rock composition, permeability, density, magnetic susceptibility, remanent magnetization, and seismic velocity. Measurements would be repeated, as appropriate, after the next Parkfield earthquake. Finally, we wish to monitor continuously temperature and pore pressure in the bottom portions of the holes within or immediately adjacent to the fault zone.
RECENT GEOLOGICAL & GEOPHYSICAL INVESTIGATIONS
IN THE SOUTHERN APPLACHIANS AND THEIR RELATION TO DRILL SITES
FOR THE CONTINENTAL SCIENTIFIC DRILLING PROGRAM


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Westerly transported thrust sheets have been known for many years to be the dominant structural feature in the Valley and Ridge province of the Southern Appalachian orogen. Recent work has shown that the same structural style dominates much of the crystalline terrane east of the Valley and Ridge as well. Ongoing field studies by the U.S. Geological Survey in the Greenville 1 x 2 degree quadrangle, Ga.-S.C., show that at least five westward-transported crystalline thrust sheets underlie the eastern Blue Ridge Mountains northwest of the Brevard fault zone, an area previously believed to be underlain only by the Great Smoky and Hayesville thrust sheets. In ascending order, these are the Great Smoky, Helen, Young Harris, Tallulah Falls, and Richard Russell thrust sheets. The Hayesville, Shope Fork, Allatoona, Dahlonega, and Brevard faults form the exposed tectonic
boundaries of these sheets. Large bodies of Grenville-age basement rocks are present in several thrust sheets. Exclusive of the basement, rocks of the thrust sheets were derived mostly from sediments deposited in various environments, during the Late Proterozoic.

Southeast of the Brevard fault zone and extending to the Lowndsville shear zone, a stack of four, and possibly five, additional thrust sheets is exposed in the Inner Piedmont belt. Several extensive klippen of the largest thrust sheet are also present. Distinct rock assemblages compose each of these thrust sheets, and each sheet probably contains rocks formed in a different depositional environment. Rocks forming these thrust sheets range from Late Proterozoic(?) to Ordovician(?) in age; Grenville basement has not been identified in the thrust sheets of the area studied in the Inner Piedmont.

Recently acquired gravity and aeromagnetic data include digital 1/2-mile-spacing aeromagnetic data northwest of the Shope Fork fault. One-mile-spacing aeromagnetic data are available for a large part of the quadrangle northeast of the COCORP line, whereas only three-mile-spacing N.U.R.E. aeromagnetic data are available southwest of it. Gravity data with approximately 1-km-spacing are available for a distance of 25 km on either side of the COCORP line, and Geotronix Corp. magnetotelluric data have been acquired along the COCORP line as well.

If a Continental Scientific Drilling Program drill site were
chosen near to the COCORP line, this geophysical data could be used in drillsite selection and later interpretations. Geologic considerations also suggest several drillsite options. A hole drilled northwest of the Brevard zone would yield much information on the thrust sheets comprising the Blue Ridge, penetrate more of the probable Paleozoic sedimentary section beneath the crystalline rocks, and intercept the autochthonous basement at higher levels than would sites drilled southeast of the Brevard zone. A drillsite southeast of the Brevard zone would yield more information in the upper few kilometers by intercepting the less well known thrust sheets underlying the Inner Piedmont in addition to the Brevard zone itself. A drillsite properly located southeast of the Brevard zone, but no more than 15 km from it, could intercept as many as four Inner Piedmont thrust sheets if located southwest of the COCORP line or as many as three if located northeast of it.

This paper then presents options on the location of these drill sites based on the thrust sheets which each would provide information on.
MIDDLETON ISLAND, GULF OF ALASKA:
A POSSIBLE SITE FOR DEEP DRILLING INTO AN ACTIVE SUBDUCTION ZONE

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Abstract for Workshop on Continental Scientific Drilling

Middleton Island, Gulf of Alaska: A Possible Site for Deep Drilling into an Active Subduction Zone

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We propose that Middleton Island, near the eastern end of the Aleutian arc, be investigated as a candidate site for deep drilling to examine processes and physical conditions within an active subduction zone.

Middleton Island sits on the upper plate of the Aleutian megathrust, at the edge of the continental shelf, 50 km landward of the trench (figure 1). A petroleum well, drilled 3 km southeast of the island to a depth of nearly 4 km, indicates a normally stacked sequence that bottoms in early to middle Eocene strata. Elevated wave-cut terraces on the island record a sequence of at least six major episodes of tectonic uplift in the past 4200 years, the most recent of which accompanied the magnitude 9.2 Mw earthquake of 1964. This uplift is the consequence of near-orthogonal plate convergence at a rate of 5.8 cm/yr.

A single 24-fold seismic reflection line across the continental margin, passing 15 km northeast of Middleton Island, shows Quaternary and late Tertiary marine sediments subducted subhorizontally, with no apparent disturbance, beneath the Tertiary rocks of the continental slope (Plafker and others, 1982). Based on extrapolations from the seismic reflection data and from regional earthquake data, the top of the subducted plate may be shallower than 10 km below Middleton Island. If so, this may be the only onshore location in the world where it is possible to drill into an active zone of subduction.

Better control on the depth of the subduction zone beneath Middleton Island may become available within the next 2 or 3 years. As part of the Trans-Alaska Lithosphere Investigation, the USGS hopes to obtain a state-of-the-art multichannel reflection profile across the continental margin at Middleton Island with the objective of tracking the subducted oceanic plate beneath the continental shelf. Selection of a specific site for drilling will require additional lines surrounding the island to map the configuration of the subducted plate.

A broad range of problems could be addressed with a deep hole beneath Middleton Island, among which are the level of pore fluid pressure in the subduction zone and the role of pore pressure in faulting and subduction, the state of stress in the vicinity of the megathrust and in the overlying plate, and the constitutive properties of materials in the megathrust. Sampling within the subduction zone would document the physical and chemical alteration of marine sediments subducted about 1 million years ago. A deep hole would also provide a quiet observatory for monitoring seismicity and acoustic emissions in the vicinity of the megathrust as well as changes of pore pressure, strain, fluid chemistry and temperature during the earthquake cycle.

Reference

Figure 1. Tectonic setting of proposed Middleton Island drilling site. Heavy lines, contours on upper surface of Aleutian and Wrangell Benioff zones; medium lines, major faults with known and suspected Cenozoic motion; light lines, bathymetric contour marking edge of continental shelf. Light shading, upper Tertiary to Quaternary volcanic rocks. PWS, Prince William Sound.
SCIENTIFIC DRILLING IN THE CASCADES VOLCANIC ARC

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SIGNIFICANCE OF THE CASCADE VOLCANIC ARC

The Cascades volcanic arc is of world-wide significance. It represents a unique end member in the spectrum of subduction-related volcanic arcs. Cascade volcanism is related to slow subduction of a small, young oceanic plate beneath a major continental plate. Development of a comprehensive geologic model for the evolution and dynamic processes operative in the arc will provide a general predictive model when combined with data from continental volcanic arcs related to rapid subduction of old oceanic lithosphere. The great size of the active portion of the arc, over 1,300 km in length and 40 to 60 km in width, probable high potential for geothermal resources, and record of violent volcanic eruptions underscore the importance to the nation of understanding the Cascades.

Additional detailed surface and subsurface studies are needed to quantify the geologic evolution and rates of mass and energy transfer in the arc. The studies should be focused on representative east-west transects where there is access to drill and a large data base. The following four areas have been proposed: Mount St. Helens-Mount Adams in the southern Washington Cascades, the Willamette Pass and Santiam Pass in the central Oregon Cascades, and the Mount Shasta-Medicine Lake area of Northern California (Priest and Blackwell, 1984).

RATIONALE AND METHODOLOGY FOR THE DRILLING PROGRAM

The Cascade Range consists of the volcanically inactive Western Cascades and the currently active High Cascade volcanic arc. If further progress is to be made in understanding the active part of the arc, the carapace of young volcanic rocks in the High Cascades must be penetrated. Extensive geophysical surveys have been
The 2.5 km-deep well near Breitenbush Hot Springs intercepted a major hydrothermal aquifer which dips toward the active High Cascade arc (Waibel, 1985). This industrial well can be reentered to sample fluids and rock and to conduct geophysical measurements. The well could also be deepened to examine pre-Cascade crust. Drilling at least one intermediate-depth (2.7 km+) well in the High Cascades at nearby Santiam Pass will help to characterize the deep hydrothermal system and lithology under the Quaternary volcanic pile. A minimum of three slim holes drilled to depths of at least 1 km will be necessary to determine the form and amplitude of the regional heat flow anomaly associated with the currently active volcanic arc at Santiam Pass. Additional seismic, electrical, and gravity studies must also be completed to help site the wells and resolve structural and stratigraphic details.

FUTURE WORK

The investigation should be expanded to include east-west transects in the other three transects. Ultimately, a 7-10 km well should be drilled to test the hypothesis of Blackwell and others (1982) that much of the High Cascade Range and eastern part of the Western Cascade Range may be underlain by a zone of partial melting and magma accumulation at depths of 7-10 km. Penetration of this zone would offer unparalleled opportunities for examination of magmatic and metamorphic processes in the roots of an active volcanic arc.

REFERENCES CITED


completed on the Cascade Range, but the high resistivity, low seismic velocity, and structural complexity of the young volcanic rocks of the High Cascades have made geophysical sounding difficult. Whereas shallow drill holes have successfully measured deep conductive heat flow in the older volcanic terrane of the Western Cascade Range, the high porosity and permeability of the High Cascade volcanic rocks have made shallow heat flow measurements impractical. Experience at Newberry Volcano and Mount Hood indicates that drilling to at least 1 km is necessary to obtain meaningful heat flow data. Drilling to greater depths is generally necessary in order to reach hydrothermal aquifers and pre-Quaternary volcanic units.

Lithologic sampling and geophysical measurements in drill holes are critical for three-dimensional modeling of the structure and stratigraphy. Geophysical and lithologic logs of the holes constrain geophysical models and determine stratigraphic thicknesses of units. The thicknesses, when combined with estimates of areal extent from detailed surface surveys, allow calculation of volumes of volcanic units. When this is combined with estimates of age from radiometric dating, the rate of volcanism can be calculated and related to contemporaneous rates of subduction, heat flow, hydrothermal convection, and crustal deformation to examine causal relationships.

PHASE I

The proposed first phase of the investigation is to apply the above methodology to one of best studied parts of the Cascades, the Santiam Pass-Breitenbush area of the central Oregon. The Santiam Pass area in the High Cascades has a relatively well-defined volcanic axis and a high overall rate of volcanism. The deepest well in the Cascades in the U.S., a 2.5 km geothermal well near Breitenbush Hot Springs, is located in the Western Cascade part of the study area. A number of 152-600 m temperature-gradient holes have also been drilled in the Western Cascade part of the area. Most of the area is covered by detailed geologic mapping and moderately detailed gravity and aeromagnetic surveys. A COCORP line crosses the Cascade Range a few km south of Santiam Pass and extends to the coast.
DRILLING TARGET: HARNEY PEAK GRANITE:
EXPLORATION OF THE ROOT ZONE OF AN S-TYPE GRANITE SYSTEM

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Anatetic S-type granites are one of the most typical representations of continental processes operative during the middle Proterozoic. They are common in structural and age provinces such as the Churchill Province of Canada and in areas such as the Michigan Superior Province. Although probably most of the vertical stages in the evolution of S-type granite complexes are available for study somewhere in the world, the manner in which those evolutionary levels fit together is not well-understood. Consequently, it is of great scientific interest to sample a vertical sequence through such a granitic system providing the means of correlating concepts derived from mapping of surface exposures elsewhere.

Direct sampling through drilling is a method to use in the determination of the vertical evolution of the granitic system. The site chosen for the drilling should be one which is well-exposed but not eroded to great depths, thus preserving an intact vertical sequence. Ideally, it should be a unit that is recognized as a typical S-type granite with a minimum of complexities. The Harney Peak Granite Complex of the Black Hills of South Dakota meets these qualifications. It is a domal structure in metasedimentary rocks, which resulted from the intrusion of many discrete granitic bodies. The granitic bodies range in size from small room-sized masses to bodies approaching one-half square kilometer in areal extent. Thermal metamorphism accompanied the dome formation and resulted in the superposition of high temperature metamorphism at approximately 3.5 Kp pressures on earlier higher pressure regional metamorphism and deformation. The latter events may have culminated in the formation of the granitic melts that moved upward to produce the dome.

In addition, the proposed Black Hills site is a classic location illustrating the intimate spatial and genetic relationship between a parent granite and associated pegmatites. Approximately 20,000 pegmatites are distributed in the country rock surrounding the Harney Peak Granite. A majority of the pegmatites are unzoned and are similar in composition to the Harney Peak granite. Large zoned, rare-element (Li, Be, Cs, Rb, Nb, Ta) enriched pegmatites make up approximately 1% of the total pegmatite population. The zoned pegmatites exhibit regional mineralogical and geochemical distribution with the barren pegmatites commonly occurring near the Harney Peak Granite and Li-enriched pegmatites commonly occurring on the periphery of the pegmatite field. Superimposed on the country rock surrounding the granitic pegmatite complex and presumably related to the intrusion of the complex is an apparent large alkali element exomorphic aureole. The aureole undoubtedly reflects the hydrothermal system which evolved in the country rock either during granite emplacement and crystallization or during the metamorphism accompanying granite formation.

The proposed hole in the Black Hills of South Dakota has four main objectives. 1) To drill a vertical column of granite through its root zone and to its protolith to investigate the vertical evolution of an "S-type" granite and its associated pegmatite field, 2) To investigate the fluid evolution during granite development and emplacement, which relates to
various types of ore deposits and pegmatite development, 3) To test the hypothesis of Archean protolith beneath the Black Hills, and 4) to provide an early opportunity to gain experience in drilling using the techniques that will be necessary for the extremely deep holes planned for future DOSECC operations.

A number of problems concerning the generation (melting, source material, melt-source separation) and evolution (compositional distribution, system plumbing, and hydrothermal system) of a granite-pegmatite system have been identified and may be addressed by a vertical sampling of the Harney Peak Granite-pegmatite system. Dehydration accompanied by partial melting of a metasedimentary material is the most likely mechanism for the generation of S-type granites. Detailed geochemical studies of the Harney Peak Granite suggest that the sedimentary source material for the granite is variable in both composition and age. A drill hole through the Harney Peak granite-pegmatite complex into its "root zone" would allow us to define the sequence of dehydration-partial melting reactions within the metamorphic country rock and to identify source rock compositions and spatial distribution. The efficiency of melt-restite separation and melt segregation dictates whether a coherent granite pluton or migmatitic layering will be the product of the melting reactions. Are the processes forming migmatites and coherent granitic intrusive bodies part of a melting continuum within the the same crustal block or reflections of different tectonic environments and episodes of melting? If part of a melting continuum, what are the spatial relationships between migmatites and zones of extensive melt formation? After-melting and segregation of the melt, what are the processes controlling melt composition? Do melts change drastically between segregation and intrusion? Variation in the mineralogy and chemistry of the granite in the third dimension may allow us to address these additional problems.

The Proterozoic terrain of the Black Hills is uniquely situated between major Archean provinces (Superior and Wyoming Provinces). Small areas of Archean age granites occur in the Black Hills, and we believe that Archean basement underlies the Proterozoic terrain. Because the Black Hills Proterozoic rocks are probably underlain by Archean rocks, they would be the source terrain for the Harney Peak Granite. However, an alternate model suggests that fabrication of Proterozoic rocks may have resulted in appropriate conditions to form the S-granite magma and that the core of the dome was either cross-folded nappes or allochthonous thrust plates. The data derived from the vertical sampling will provide constraints regarding these possibilities and may be applicable to similar problems encountered in other age/structural Precambrian provinces which involve massive remobilization of older terrains by pervasive intrusion and heating due to younger Proterozoic events. Because of low melting temperatures associated with the Harney Peak intrusions, zircons may prove to be useful for determination of the original ages of source materials.

Finally, the proposed drilling target will provide an excellent opportunity to test and refine technologies for the drilling of deeper targets anticipated during the DOSECC program. This area would be an excellent test of the deep exploration methods using slim-hole drilling. It would involve drilling, coring, and logging of a mixed sequence of schistose and gneissic metasedimentary units, as well as both thick and thin granitic bodies. Such a test should be made before commitment to the deeper projects is made and should be made in a target with substantial scientific interest such as the classic "S-type" granite represented by the Harney Peak Intrusions.
In summary, we propose to drill, sample, and log a target in a well-known, classic intrusive complex in order to gain insight into the vertical evolution of the magmatic system. The surficial geology of the area is well understood and credible models of the three-dimensional aspects of the granitic systems exist. These models are now testable given the state of drilling technology and are well within the capabilities of the CSDP program. It is appropriate that this target have a high priority because it may represent continental processes that shaped a significant portion of the Proterozoic continental crust.
INVESTIGATION OF ACTIVE TECTONIC AND MAGMATIC PROCESS IN LONG VALLEY, VIA SURFACE AND BOREHOLE TECHNIQUES

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Investigation of Active Tectonic and Magmatic Process
in Long Valley, via Surface and Borehole Techniques*

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Since October 1978, the Long Valley caldera has been rocked by a series of 7 M ≥ 5.5 earthquakes, indicating a renewal of activity after about 40 years of quiescence. Coincident with the seismic activity, as much as .7 m of uplift has developed over the southern margin of the old resurgent dome, indicating renewed magmatic injection as well. And finally, extensive changes in the hydrothermal system indicate that the physical properties of the shallow crust are being altered as well.

In order to gain a deeper understanding of the location and extent of magma within the caldera responsible for these changes, a group of scientists from Sandia, USGS, LBL, UCSB, USC, and the University of Wyoming, jointly initiated a plan to conduct a unified seismic imaging program across the central resurgent dome. The program revolved around use of a .9 km deep temperature gradient well (OLV-1) loaned to us by Santa Fe Geothermal, Inc. The project was begun in July 1984 with a P-wave reflection profile through the northwest part of the caldera, and continues to the present with passive recording of earthquakes via telemetry by the University of Nevada-Reno. We have also proposed to use the well for measurements of in-situ stress and stress changes, as well as drilling two other wells in the south central portion of the caldera for the same purpose. These data are vital to understanding the rapid evolution of physical processes in this magmatically-driven system.

In addition to a program of shallow drilling to measure stress data, we have also begun to provisionally plan a deep hole on the south central part of the resurgent dome. This well might be drilled in collaboration with an industry group to share the cost. Preliminary well designs have been worked out in consultation with industry sources, and projected cost for a 5 km well is about $4.5 million.

To better locate and define the magma, as well as to aid in siting of a potential deep well, an extensive series of reflection profiling is anticipated.

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A wide-angle walk-in P wave profile is planned for this summer, starting at OLV-1 and continuing south along the resurgent dome. This profile will pass over the 5 km deep magma body hypothesized by Sanders (1984) and Rundle and Whitcomb (1984) to lie under the southern edge of the resurgent dome. Thus, by the time a deep well is drilled, we expect to have a fairly detailed seismic "image" of the central part of the caldera as a model to test via drilling. In addition, we expect by then to have a model for stress and stress changes within the shallow caldera that can only be extended to greater depth by deeper drilling.
A CRUSTAL DRILLING EXPERIMENT NEAR THE SOUTHERN MARGIN OF THE COLORADO PLATEAU AND THE SAN FRANCISCO VOLCANIC FIELD

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Among the fundamental scientific questions raised by previous work on the Colorado Plateau are: What is the nature of the thermal and mechanical transition between the Sonoran Desert (Basin and Range) and the Colorado Plateau? Are the locations of volcanic fields controlled by the regional stress field? How is the transition from a cool interior to a warm rim (Figure 1) related to the stress field? What is the heat flow at depth? Why is the near-surface heat flow from the southwestern Colorado Plateau low, and how does it relate to the regional hydrologic regime? Is the Colorado Plateau margin being thermally eroded, or is it a quasi-stable feature controlled by lateral variations in properties of basement rocks? How (and why) did the late-Tertiary tectonic basins form on the Plateau margin?

The USGS recently initiated the Pacific to Arizona Crustal Experiment (PACE), involving geologic and geophysical studies along a transect from coastal southern California to west-central Arizona, reaching the Colorado Plateau south and east of Flagstaff (Figure 1). COCORP has scheduled a vibroseis reflection profile along the Arizona portion of the transect. Heat flow and stress direction studies (using well breakouts) in shallow (100-200 m) wells are planned for the Mojave-Sonoran segments of the profile. To anchor the eastern edge of the transect by such studies, and to obtain data pertinent to the questions raised above, suitable drill holes will be needed.

The authors propose to drill two continuously cored holes to depths of 2-2.5 km.

*Representing a group of investigators from the following institutions: California Institute of Technology, Northern Arizona University, Stanford University, United States Geological Survey, University of Maine (Orono) and University of Utah.
(6600 - 8200 ft) using available heavy duty wireline coring technology. The holes will be drilled at Longyear CHD 134 or equivalent, resulting in a minimum hole diameter of 13 cm (5.25 in), sufficient to accommodate downhole logging and packers for in situ stress and hydrologic testing. One hole is proposed near the eastern terminus of the PACE transect, 40 km from the Mogollon Rim and about 50 km southeast of the San Francisco Peaks (Figure 1). This well is off the volcanic field and reasonably far away from the nearest young volcanic center, and should provide a core undisturbed by late Tertiary and Holocene volcanic and hydrothermal activity. The hole will be spudded in the Paleozoic Kaibab Formation and should enter Precambrian crystalline basement at about 1 km depth. The expected near surface stress field here is extensional and oriented roughly east-west. This site will provide the first reliable background heat flow and stress magnitude for the southwestern Colorado Plateau.

The second well will be collared in late Cenozoic basaltic material, within the youngest silicic volcanic rocks (50-200 ka) of the San Francisco field (Figure 1). Precambrian crystalline basement should be entered between about 1.2 and 1.5 km depth. The expected stress field here is compressional or transitional between the Basin and Range and Colorado Plateau regimes. Heat flow and geochemical measurements will provide vital information on the existence (or otherwise) of a geothermal resource and indicate the magnitude of the thermal anomaly relative to the regional value, obtained from the well 40 km to the south.

Apart from studies of the coupled thermal, hydrologic, tectonic and geodynamic processes, the continuous core from these sites will allow detailed studies of the physical properties as well as the geochemistry and petrology of the entire geologic section.

Regional geologic mapping and geophysical coverage in the study area is complete at 1:250,000 with considerable detailed coverage at scales up to 1:24,000. Apart from the obvious relation of the proposed drilling to the PACE transect and related COCORP profile (Figure 1), predrilling site Survey activity will include detailed gravity and ground magnetic surveys, and use of shallow wells to study the coupled thermal-hydrologic system. A thorough investigation of known water discharge points will be conducted to calculate the regional thermal budget.
Figure 1. Map of northeastern Arizona, showing the San Francisco (SF) and White Mountain (WM) volcanic fields, approximate transition between the interior cool zone and the warm outer rim of the Colorado Plateau (65 mWm$^{-2}$ contour) and modes and directions of regional stress (arrows). Proposed drill sites are shown as triangles. Inset: Major tectonic-physiographic provinces of Arizona, and USGS PACE transect and scheduled COCORP reflection profile. SD, Sonoran Desert; TZ, Transition Zone; CP, Colorado Plateau.
PROJECT UPPER CRUST: A PROGRAM FOR SHALLOW TO INTERMEDIATE DEPTH
SCIENTIFIC DRILLING AND ASSOCIATED STUDIES IN THE CONTINENTAL INTERIOR

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PROJECT UPPER CRUST: A PROGRAM FOR SHALLOW TO INTERMEDIATE DEPTH SCIENTIFIC DRILLING AND ASSOCIATED STUDIES IN THE CONTINENTAL INTERIOR

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Scientific drilling can be used to investigate crustal structure in the vertical or the lateral direction, or both. In the continental interior of the United States, large portions of the crystalline basement are covered by Phanerozoic strata, and the answers to major questions regarding the growth and evolution of this part of North America are obscured because of this cover. Studies of samples returned through oil, gas, and mineral exploration and through limited holes of opportunity have helped substantially in some areas, but many problems remain, particularly where there has not been extensive drilling. In addition, knowledge of the stratigraphy of the overlying Phanerozoic strata is poor due to lack of drilling and (or) to lack of cored drill holes.

Principal needs in the midcontinent region are for (a) better lateral distribution of good samples of the crystalline basement, (b) detailed petrologic, geochemical, and geochronologic study of the Proterozoic crust, (c) geophysical measurements, and (d) regional stratigraphic analysis of the Phanerozoic cover. We recognize a three level approach to selecting drilling targets. First, propose to maximize the lateral coverage needed by emphasizing drill holes with total depths of 1 to 2 km. Second, targets relating to vertical structure of the crust and petrogenesis, requiring penetration of 2 to 5 km, are an important aspect of a longer term drilling program in the continental interior. Third, there are some problems for which deeper drill holes (up to 10 km or more) will be essential. The latter two types can be developed as individual projects or delayed until a good data base is built up from shallower holes and detailed geophysical surveys.
After considering the state of current knowledge, major questions that exist regarding overall evolution of the Precambrian crust in the midcontinent, and areas where basement is within 1 to 2 km of the surface, we have identified several priority targets for the first phase of drilling. These targets were chosen to answer major questions associated with (1) the transition from Archean to Proterozoic crust in the north-central midcontinent, (2) the boundaries (or transitions) between various Proterozoic provinces or orogens within the buried basement, (3) correlation of these provinces with similar provinces exposed to the west in the Rocky Mountains or to the east in the Great Lakes region, (4) the processes of generation of felsic magmas within older continental crust, and (5) development of rift basins in the cratonic interior. Secondary, but still major, objectives include regional stratigraphy, characterization of geophysical anomalies, regional heat flow and crustal stresses, and regional uplift history.

The initial drilling program includes a) a series of holes SSE from the Black Hills into Nebraska, b) a series of drill holes eastward from the Black Hills across southern South Dakota to the Sioux Uplift in SE South Dakota - SW Minnesota, c) a series of drill holes southeastward from the Sioux Uplift into northwestern Iowa, and d) a series of drill holes southward from the Sioux Uplift into eastern Nebraska and eastern Kansas, along the Nemaha Uplift. In addition to providing good regional control of the subcrop geology, these traverses (which should cross major crustal province boundaries) will help substantially in defining the third dimension of the crust in the region through better understanding of the origin, age, and composition of the various crustal blocks sampled. Later traverses are recommended for eastern Iowa, southern Wisconsin, southern Missouri, and the eastern midcontinent region into the Grenville Province.
Deeper, second phase, targets include a) a drill hole in the Black Hills to study genesis of anatectic granites, b) a drill hole through the 1.37 Ga epizonal granite layer in the southern midcontinent region, c) a drill hole through the Baraboo Syncline in Wisconsin, and d) drill holes into the Reelfoot Rift and Rough Creek Graben rift zones of the Mississippi Embayment.

For many of the proposed drilling projects there are sufficient geophysical and geological data available to locate specific drill sites (on or away from anomalies, etc.). In some regions, where geophysical data are sparse, preliminary surveys may be necessary to select optimum drill sites. In order to minimize drilling costs, the shallow drilling should be carried out with small rigs capable of taking 2-inch (NQ) core. An initial annual budget of $2 million would allow several holes to be drilled per year, cover a substantial part of the scientific investigations associated with each hole, and cover management costs. Essential studies would include petrology, chemistry, geochronology and isotopic studies, and physical properties. Essential in-hole studies would include heat-flow measurements and logging; stress measurements would be carried out as needed to provide a good regional data base. All core would be logged and distributed to other investigators. Remaining core would be stored in a CSDP core repository (preferable, if available), in local state geological surveys (if available), or at one of the institutions participating in the project.

THE OUACHITA FOLDED BELT, A SITE FOR DEEP CONTINENTAL DRILLING

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The Ouachita orogenic belt begins in the subsurface of Alabama near the southwestern terminus of the Appalachians and extends for approximately 1800 km across the southern United States and probably into Mexico. The two major areas of outcrop are in the Marathon uplift of western Texas and in the Ouachita Mountains of Arkansas and Oklahoma where the belt may be divided into several tectonic provinces (Viele, 1973). Of these the northernmost is the Arkoma Basin, a region in which Pennsylvanian clastic strata grade southward from shallow to deep water facies. These strata thicken abruptly across south-dipping, normal faults, which extend downward into the basement, and they are broken by slightly younger, northward-moving thrust faults. Lying farther to the south is the Ouachita thrust fault belt, a region of deep water deposits of flysch, broken and imbricated by numerous thrust faults and containing especially along its northern margin, structures and fabrics identical to those found in modern accretionary wedges. The deposits of flysch surround two uplifts, the Benton and Broken Bow, composed of multiply folded, lower and middle Paleozoic strata that were deposited in slope-rise and abyssal settings. The entire complex has been interpreted in terms of a complete Wilson cycle comprising an early rifting and spreading phase followed by a southward-subducting, closing and collision phase (Viele, 1979).

Geophysically, the Ouachitas constitute a region in which the aeromagnetic anomalies of the North American craton abruptly end and are replaced by the more homogenius magnetic signature of the basement beneath the Gulf Coastal Plain (Viele and Zietz, 1981). In addition, a major gravity gradient is present ranging from negative Bouguer values of as much as 100 millegals on the north of the folded belt to slightly positive values on its southern side. A COCORP profile across the Ouachitas in western Arkansas revealed beneath the Benton uplift a broad arch of reflections having a travel time as short as 3 seconds. A southward-dipping wedge of reflections flanked the arch on its southern side. Farther south a layered stack of reflections had a maximum travel time of about 7 seconds (Lillie and others, 1983).

These reflections have been interpreted via a model of southward subduction of the southern edge of the North American craton beneath the rocks and structures of the Ouachitas. The broad arch is viewed as an uplift of North American crystalline basement carrying intact on its southern flank the continent-ocean boundary wedge, all lying beneath the over riding thrust sheets (Lillie, 1985). The layered reflections to the south are viewed as the signature of a fore-arc (?) basin as deep as 20 km lying above the oceanic crust. Thus the Ouachita Mountains represent the surface trace of a complex suture joining the North American and a southern Llandorian plate.

A deep drill hole on the Benton uplift would be ideally situated to investigate a zone of continental accretion formed by subduction and collision. Specific questions to be addressed by deep drilling would include: are discussed.

1. The composition and origin of the lower Paleozoic rocks of the Benton uplift. How thick and how old are they? Are subducted Carboniferous strata present beneath the uplift.
2. Do platform carbonate rocks of the North American craton underlie the Benton uplift.

3. What is the structure of a collision zone? A deep hole would add a third dimension to our view of the Ouachitas.

4. What is the nature of the basement beneath the Benton uplift. In terms of its nature, may we interpret and explain the gravity and magnetic fields and the seismic reflections.

5. What is the nature of the transition zone between the North American basement and the possible oceanic crust to the south?

Potential preliminary studies include:

1. Detailed surface mapping of about two 7½ quadrangles within the Benton uplift. We already have much of this work finished and have a good understanding of the composition and structure of these rocks and their contained fossils. Over 20 theses and dissertations have been finished.

2. Continued surface investigation of structural fabrics along the northern margin of the thrust fault belt at the base of the accretionary (?) prism.

3. Detailed gravity studies across the Ouachitas. Relatively new filtering techniques of digitized data appear to hold much promise for interpretation of the gravity field.

4. Several shallow drill holes are needed to provide velocity control for shallow (above 3 seconds) reflection surveys.

5. To determine crustal velocities as accurately as possible, three, reversed refraction lines should be run: one on the north of the Benton uplift; one along it; and one on the south of it.
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CORE DRILLING TECHNOLOGY FOR ULTRADEEP SCIENTIFIC HOLES

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CORE DRILLING TECHNOLOGY FOR ULTRADEEP SCIENTIFIC HOLES

Report of the Ad Hoc Panel on Core Drilling Technology
Matt Walton, Chairman

Abstract

Continuous core recovery has been identified as a major requirement for scientific drilling if the goals of the Continental Scientific Drilling Program (CSDP) are to be achieved. The powerful rigs, tools and drilling methods developed by the petroleum industry for drilling to depths approaching 10,000 m in sedimentary basins are not well adapted to continuous core drilling and high-percentage core recovery, especially in the moderately hard to hard crystalline rocks which are expected to characterize some of the primary targets for ultradeep drilling. On the other hand, continuous core drilling, as practiced by the mineral exploration industry has had no economic incentive to go much beyond the practical limits of mining at depths of less than 5,000 m. There is growing interest on the part of both the petroleum and mineral exploration industries to adapt and combine their skills and technologies to develop continuous core drilling systems for soft as well as hard rocks at all drilling depths up to the ultradeep range of 10,000 to 15,000 m. The CSDP can provide a major impetus and incentive to this effort. This, in itself, will be a valuable spin-off of the CSDP.

The technical feasibility of continuously core drilling an ultradeep hole in moderately hard to hard crystalline rocks can scarcely be doubted in view of the fact that the Russians have done it. The fact that it has taken 14 years to reach 12,000 m depth in the Kola hole does not detract in the least from this remarkable achievement. Instead, it presents a challenge to develop and improve on the methods, materials and tools needed to bring ultradeep drilling into a cost-effective time frame and at the same time achieve maximum scientific results. An ad hoc panel was established by the Continental Scientific Drilling Committee (CSDC) to review the state of the art and to recommend steps needed to advance this technology to the point where the goals of the CSDP can be achieved. Members of the panel are listed below.

The ad hoc panel has met twice (January 8 in Minneapolis and March 5 in New Orleans) and reviewed written submittals from each member. The following preliminary conclusions and recommendations are made.

Conclusions

1. A number of holes have been drilled with slim-hole diamond core drilling tools to depths approaching 5,000 m in crystalline rock, and several systems are now in use which are rated to about this depth. The ultimate limit to which such systems might be pushed has not been tested. It is likely to be significantly deeper than 5,000 m, but it is not likely to extend into the ultradeep range. To drill into ultradeep range will require significant additional development.
2. The down-hole hydraulic motor for ultradeep drilling has been proven in the Kola hole and in deep sea drilling. This concept is currently undergoing rapid development to adapt it to slimmer holes, wire-line or pump-out core recovery, steerable bit drives, a variety of bits and coring and reaming configurations, and several types of motors. The concept has clear advantages for the vexing problem of drilling straight holes to great depth and allows the use of light-weight alloy rods, mitigates drill-string vibration and wear, and permits optimum bit load and rotation speed.

3. A fusion of large oil rig technology with slim-hole continuous core drilling tools is mandatory. A highly versatile rig with a lifting capacity of about 700 tons will be required with power swivel top-drive for rotary drilling, high pump capacity for down-hole hydraulic motors, automated rod handling and large rod storage capacity.

4. Rock disintegration due to stress release may be a major problem, and pressurized coring and core recovery may be important.

5. Further development of instrumentation is needed for monitoring dynamic parameters and hole conditions while drilling and for the automated control of bit load, rotation speed, coring efficiency, fluid flow and hole deviation.

6. The fundamental parameters from which the specifications for all other components of the system flow are:

   a. The desired diameter of the core at total depth.
   b. The target depth.
   c. The experimental protocol.
   d. The anticipated rock conditions.

Bits, motors, rods, fluids, hole sizes, drilling plan, casing program, and rig must all be optimized to these parameters in an integrated system. The first three are arbitrary, based on scientific needs and objectives. The fourth depends on the geology, much of which, in the nature of the quest for new scientific knowledge, is now speculative and will remain so until the hole is drilled, but "best guess" design assumptions must be provided by earth science.

Recommendations

1. The top priority is to establish a full-time, highly qualified, professional engineering staff in DOSECC to develop and evaluate detailed drilling plans and system designs for CSDP projects. This staff should be supported by a broad-based engineering advisory committee (EAC) drawn from both the industrial and scientific drilling communities, including the deep sea and geothermal drilling programs.

2. A trailblazer hole should be drilled as soon as possible at the prime CSDP target site to the total depth limit of presently available heavy-duty continuous core-drilling systems. This hole will have a dual purpose. During the substantial period of time it will take to design and procure an ultradeep drilling system, it will be used to test the limits, identify
problems, define rock conditions and test drilling systems and components (such as bits and down-hole motors) under realistic field conditions to significant depth, starting with proven core-drilling technology. At the same time, it will provide for the timely start of scientific investigations and an early output of scientific results. The ultradeep hole can then be designed on the basis of site-specific data with an optimum drilling plan to go to full target depth. The upper part of the ultradeep hole can then be drilled and constructed to trailblazer depth, using the most rapid and cost-effective methods without holding up the ultradeep drilling rig for core recovery and scientific experiments. Meanwhile the trailblazer rig and string will become available for other intermediate depth (5,000 to 10,000 m) CSDP targets or trailblazer operations.

3. Scientific demands and constraints on the drilling system must be identified, defined and evaluated early in the design process. Down-hole experimental protocols and logging procedures must be laid out in detail, and such constraints as allowable compositions and properties of drilling muds must be spelled out. Anticipated rock conditions must be defined within reasonable limits. The DOSECC Science Advisory Committee (SAC) should give high priority to providing these data.

4. A substantial budget for engineering, design, prototype development and testing must be a high-priority, early component of the program. At the same time, a vigorous program of joint venturing and cooperating with industry must be pursued in order to spread the cost, enhance technology transfer and develop the resources and the market for ultradeep core drilling technology.


A PROPOSAL FOR A TECHNOLOGICAL AND GEOLOGICAL DRILLING EXPERIMENT IN THE MINNESOTA RIVER VALLEY

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A PROPOSAL FOR A TECHNOLOGICAL AND GEOLOGICAL DRILLING EXPERIMENT IN THE MINNESOTA RIVER VALLEY


Scientific drilling depends on the ability of drills and drillers to reach the desired target, to recover adequate samples, to perform or assist with required down-hole measurements, and to do these tasks at sustainable cost within a reasonable time. Holes have been core drilled with conventional slim-hole diamond core-drilling equipment to depths of more than 4.5 km in sound crystalline rock. Tools with this rated capacity are available and capable of exploring the many geologic targets that lie within that depth range. Deeper targets present severe technological as well as geological challenges. The diamond drilling industry has been responding to these challenges with developmental research, but has lacked the economic incentive to drill beyond the practical depth of mining.

If the geologic research community is to accomplish continuous core drilling at acceptable costs and rates to depths of 5 to 10 or more kilometers, it has the obligation to work with industry to develop the required technology. Moreover, it has the further obligation to require demonstrated proof of deep-drilling capability under realistic geologic conditions before expensive, long-term commitments are made. We propose that this development be pursued in a hole approximately 5 km deep in Archean gneiss in the Minnesota River Valley. The hole would serve as a test for state-of-the-art drilling technology and would be designed to accommodate the newest developments in down-hole drilling motors and coring bits, core and motor retrieval systems, high-strength light-weight tapered rods, down-hole monitoring-while-drilling instrumentation, etc., as well as conventional rotary core drilling systems. Drilling fluids, reaming and casing, rig design, automation, and the coupling of large oil-field type rigs to deep continuous core drilling systems are other areas where innovation and development are needed.

The primary geologic requirements for the demonstration site are relatively homogeneous lithology and relative sparsity of fractures and altered zones. The vexing technical problem of maintaining a vertical hole is mitigated where steeply dipping, monotonal contacts between rock units of contrasting hardness are not common. The objective is to reach considerable depth as quickly and as cheaply as possible, and to confront those technological problems caused by depth rather than those caused by bad ground at shallow levels. Many sites meet these criteria among the batholiths and gneiss complexes of North America, but few can match the concomitant geologic insights that would come from deep penetration into some of the most ancient rocks in the continent. We propose that an appropriate drill site near Morton, Minnesota, the type locality of one of the best-documented Archean gneiss units, would provide valuable new data "in depth" on problems of early crustal genesis.

The gneiss terrane in the Minnesota River Valley forms the stratigraphic floor of the known continental basement, but whether it survives as a large roof pendant in younger granitoid plutons (3,000 Ma or
2,500 Ma), or passes downward into more primitive and perhaps more mafic crust is unresolved. Furthermore, it is not known whether the open dome and basin structure of these rocks at the surface continues to depth, or if the structure consists of stacked, refolded nappes. Of the four quasi-stratigraphic units in the Morton area, the lower three are quartzofeldspathic gneisses delineated on the basis of downward increase in the abundance of amphibolite inclusions or "rafts", which are komatiitic to tholeiitic in composition. The middle of these three units has been named the Morton Gneiss. Where not migmatized, the quartzofeldspathic gneisses are tonalitic or granodioritic in composition and are 3,500-3,600 m.y. old. Where migmatized, the neosome is granite and locally pegmatite, formed during two separate episodes -- a deformed granite at about 3,000 Ma and an undeformed granite at about 2,550 Ma. The latter age corresponds to the time of emplacement of granitic batholiths elsewhere in the Minnesota River Valley.

A ~ 5 km-deep hole would document the vertical changes in lithology, composition, isotopic age, metamorphic facies, and structural relationships, all of which bear on these fundamental questions of Archean crustal genesis and structural environment. In addition, such a hole would yield fundamental data on heat flow, in situ stress, fluid phases, fracture density, and seismic parameters in a very old and stable part of the continent.

We propose that DOSECC negotiate a joint venture with leaders in the drilling industry to design a hole and drilling program to meet the need for technical development. Management of earth-science investigations would be provided by the University of Minnesota. Proposals for research would be invited, through DOSECC, from the earth-science community.
STRUCTURE AND TECTONIC HISTORY OF THE CALIFORNIA COAST RANGES:
TESTING AN OBDUCTION MODEL OF FRANCISCAN EMLACEMENT INFERRED FROM
SEISMIC REFLECTION PROFILES AND OTHER GEOPHYSICAL DATA


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STRUCTURE AND TECTONIC HISTORY OF THE CALIFORNIA COAST RANGES—TESTING AN OBDUCTION MODEL OF FRANCISCAN ENPLACEMENT INFERRED FROM SEISMIC REFLECTION PROFILES AND OTHER GEOPHYSICAL DATA


Structural relations between the Mesozoic Franciscan assemblage and Great Valley sequence have long been considered a type example of subductive accretion of trench and oceanic sediments against a continent. Surface relations indicate that Franciscan rocks of blueschist grade are thrust eastward beneath coeval, but unmetamorphosed, miogeoclinal strata of the Great Valley sequence (GVS) along the Coast Range thrust (CRT), which is exposed for 600 km along the length of the eastern Coast Ranges. In the context of plate tectonics, this thrust has been assumed to continue eastward down into the mantle.

A distinct alternative to this subduction model is raised by recent geophysical studies. Seismic reflection profiling, in concert with refraction, gravity, and magnetics, suggests that the Franciscan was obducted as a tectonic wedge that overrode the continental margin and peeled up the overlying GVS. Scientific drilling to 8-10 km (see figure) can test these alternative models and shed light on the problem of accretionary tectonics.

![Diagram showing structural relations between Franciscan and Great Valley sequences.](image)

Tentative drill holes (vertical bars) on a cross section along seismic reflection line CC-1 (lat. 37.25 N). Subhorizontal boundaries are mainly from the reflection section; the solid CRT beneath steeply dipping GVS is from gravity modeling and the short dashed boundaries are from magnetic modeling. The serpentininite lens is the preferred, shallowest of a series of possible lenses that all satisfy the magnetic data. Queried lines are inferred. Velocities are from seismic reflection and refraction data.
Geophysical profiles at three latitudes all suggest similar obductive relations. The top of crystalline basement (6.2-6.5 km/s) dips westward from Sierran exposure across the Great Valley beneath Cretaceous and Cenozoic strata to depths of 5-10 km at its west side and then extends on to depths as great as 15 km beneath the eastern Coast Ranges. Near the east margin of the Coast Ranges this basement is overlain by an eastward-thinning wedge of material that, from its intermediate velocity (5.6-6.0 km/s) and structural relations, is probably Franciscan rock. The wedge is overlain by GVS (3.5-5.0 km/s), which increases abruptly in stratigraphic thickness from the nearly flat-lying section beneath the west edge of the valley to the steeply east-dipping GVS exposed in the Coast Ranges. A subsurface lens of serpentinite, inferred from magnetics to lie within the Franciscan mass, seems to extend nearly continuously along the CRT for the whole length of the Coast Ranges.

The possibility of wedge tectonics and associated thrusting suggests an important style of deformation that may be widespread in the Coast Ranges and elsewhere. Surface relations near the Klamath-Coast Range-Great Valley junction, for example, suggest that such wedge thrusting in front of the Franciscan mass has carried Coast Range ophiolite eastward onto Klamath-Sierran basement, has telescoped the GVS along thrusts that break over into major lateral faults at their northern ends, and has offset a Cretaceous shoreline about 100 km. The abrupt westward steepening and thickening of the GVS at the west side of the Great Valley implies eastward-directed thrusting, as does the large serpentinite lens beneath Franciscan rock. At Coalinga, wedge movement 2.0-0.6 m.y. ago was followed by related thrusting that is still underway; timing of most recent thrusting farther northwest is uncertain, although uplift of the Coast Ranges in the Pliocene and Quaternary has occurred.

Structure along the length of the CRT is nearly two-dimensional. Potential drilling sites to test the obduction model thus exist at many places along the eastern Coast Ranges, although local structural complications detract from many of them. At Coalinga, where extensive geophysical control exists, basement is too deep for the drill (16 km). A reasonable depth to basement (no greater than 8-10 km) does seem to exist north of Pacheco Pass at reflection line CC-1. This reflection line frames the problem and is supplemented by refraction, magnetic, and gravity data, surface mapping, and oil
test wells in the Great Valley. A drill site just west of the valley margin on CC-1 has multiple structural and lithologic targets that extend from near the ground surface to basement beneath the Franciscan. Rotary drilling with core taken at 150-m intervals, supplemented by sidewall sampling, should suffice. A preliminary 2-km hole to test drilling conditions and constrain geophysical and structural interpretation in the Franciscan and GVS would be highly desirable, as would a refraction line and a short reflection line parallel to strike.

In addition to testing the obduction model, the proposed drilling will provide subsurface information for a rich complement of ongoing Coast Range investigations. These include studies of: (1) structural relations at all scales, particularly those related to possible faulting at the range front and thrusting in and between the GVS and Franciscan assemblage, (2) petrology and isotopic ages of igneous and metamorphic rocks of the Franciscan assemblage, serpentine/ophiolite sequence, and basement complex, (3) stratigraphy, biostratigraphy, petrology, sedimentology, and organic thermal history of GVS and Franciscan rocks and their petroleum source-rock potential, (4) rock and fluid compositions and isotopic ratios in relation to diagenesis/metamorphism and production of high fluid pressures, (5) heat flow as a function of depth and evaluation of recency of wedge emplacement and degree of frictional heating, (6) physical rock properties such as seismic velocity, density, permeability, fractures, remanent magnetization, and magnetic susceptibility, (7) fluid pressure, and (8) in situ stress.
SCIENTIFIC DRILLING AND EXPERIMENTATION AT CAJON PASS,
A SITE NEAR THE SAN ANDREAS FAULT IN SOUTHERN CALIFORNIA

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This is a proposal for deepening a 2-km deep well at Cajon Pass, California to a depth of 5 km, conducting extensive downhole measurements and core analyses, and utilizing the hole after drilling as an ultraquiet seismic and strain observatory. The Cajon Pass site is located 4 km from the San Andreas fault, in the eastern Transverse Ranges. Nineteen investigators representing six universities and the U.S. Geological Survey are currently participating in the proposed research.

One of the primary objectives of this proposal is to attempt to resolve the 15-year old debate concerning the level of shear stress on the San Andreas fault. The uncertainty about whether the average shear stresses resisting plate motion are of the order of 100 or 1000 bars fundamentally limits our understanding of the forces that drive lithospheric plates, the nature of deformation at transform plate boundaries, and the mechanics of crustal earthquakes. Extensive heat flow data show no discernible effects of frictional heating near the San Andreas fault and suggest that the upper limit for average shear stress on the fault is less than 200 bars. Near surface (0-1 km) stress measurements, however, show an increase of shear stress with depth of about 90 bars/km. While consistent with stress estimates based on laboratory friction experiments, the near surface stress measurements can not be extrapolated to depths greater that 3-4 km without clearly violating the heat flow constraint. Deepening the well to 5 km would not only permit measuring the change in stress with depth, but also by measuring the thermal gradient, we could straightforwardly test pore fluid convection models that have been proposed to explain the low heat flow near the fault. Hydrologic testing in the well and geochemical analyses of core samples will also shed light on the role of pore fluid convection near the San Andreas.

A number of intriguing geological questions will also be addressed through deepening this well. For example, geological mapping, seismic studies, and regional gravity data suggest that low-angle thrust and/or detachment faults may underlay the eastern Transverse Ranges at relatively shallow depth. Such a hypothesis might be tested by deepening this well. Interestingly, such low-angle detachments are predicted by one thermo-mechanical model for low heat flow on the main fault trace. In this model, the low-angle detachments would be the principle sources of resistance to plate boundary motion.

The core exhumed from the well will also make possible a wide range of petrologic, petrophysical, and geochemical studies. One of the principal attributes of the Cajon Pass site is the fact that considerable geologic, geophysical, and seismological research has been going on in the region. For example, in the inset of the attached figure, some of the sites in the region are shown where in-situ stress, heat flow, and seismological measurements have already been made to depths of 1 km. Thus, it will be possible to interpret the data we propose to gather in the Cajon Pass well in the context of already existing regional data.

The existing well at Cajon Pass is 1.9 km deep and extends 1.0 km into fairly intact granodiorite below 0.9 km of Miocene sedimentary rock. The granodiorite has a minor cataclastic overprint. The relatively large bottom-hole diameter (8.75 inches), the good quality of the granitic rock in the lower part of the hole, and the proximity of the hole to the San Andreas fault make it an excellent opportunity for deepening. A preliminary cost estimate for continuously coring the existing hole to a depth of 5 km (and maintaining at least a 5 inch hole diameter) is approximately $2.5 million. The proposed downhole measurements and core analyses would obviously increase this cost.

The section of the San Andreas fault extending northwestward from Cajon Pass last broke in a great earthquake in 1857. Several lines of evidence suggest that this section of the fault has about a 50% probability of producing another great earthquake in the next 30 years. There is also a considerable probability that the section of the San Andreas to the south of Cajon Pass could break in a great earthquake in the next few decades. Thus, this hole has significant potential for use as an ultraquiet seismic and strain observatory for fault zone monitoring related to earthquake prediction. Other utilizations of the hole after drilling include conducting experiments aimed at improved imaging of crustal structure near the San Andreas fault. These experiments include using active seismic sources (VSP types of experiments) and passive detection of local earthquakes (travel-time inversion and tomographic types of experiments). As these activities would need to go on for an indefinite period, and be closely integrated with other fault zone monitoring activities, we suggest that at the completion of the proposed experiments, the hole be managed by the earthquake prediction program of the U.S.G.S.
of California and Nevada showing earthquakes of magnitude 1.5 and greater in the year.

The Cajon Pass drill site is 4 km from the San Andreas fault, at the southeastern
of the section of the fault that broke in the magnitude 8, 1857 earthquake. The
shows the location of the Cajon Pass well with respect to faults in the area, as
as some of the shallow wells where in situ stress, heat flow, and various
ological measurements have already been made.
SCIENTIFIC DRILLING IN THE SEVIER DESERT BASIN, UTAH:
INSITU STUDY OF THE INTERACTION BETWEEN HIGH AND LOW ANGLE NORMAL FAULTS

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Currently available in situ stress measurements indicate that the state of stress near active faults is consistent with predictions of classic frictional faulting theory. The mechanical interaction between slip on steeply-dipping and low-angle normal faults, both of which are observed geologically in the Basin and Range province, remains unexplained by this theory. For example, recent industry and COCORP seismic reflection data from central Utah reveal a regionally extensive (lateral extent of about 70 km) low-angle detachment fault (average dip = 12°) into which steeply-dipping normal faults with known Quaternary movement can be seen to merge, without offsetting the detachment fault (Almendinger et al., 1983, GEOLOGY). The proposed target area (see Figure) is in the western part of the Sevier Desert Basin, Utah where, based on reflection data, it should be possible to drill through a high-angle normal fault and then intersect the detachment at a depth of less than 6 km. The heavy vertical lines in the figure represent petroleum exploration wells. The well near the far western edge of the figure would have intersected the detachment at about 5.75 km depth. The rocks above and below the detachment in this area are probably well-indurated Paleozoic sediments which would be ideal for down-hole measurements. The objectives of the proposed hole would be to determine the conditions of the in situ stress field (and possible...
variations with depth), temperature, values of frictional coefficients and composition of the respective fault zones, and magnitudes of the in situ pore pressure that could explain the observed fault interaction. The location is especially favorable because of Quaternary faulting activity and an abundance of subsurface data, including petroleum exploration wells and several hundred kilometers of seismic reflection data.
Heavy arrow shows proposed drill site in the Sevier Desert Basin in west-central Utah. The proposed location would penetrate two high-angle normal faults as well as the detachment plane. The main basin-bounding fault (more eastern of the two penetrated) has been linked, through shallow high-resolution seismic profiling to a Quaternary scarp (Crone and Harding, 1984, GEOLOGY). Fault interpretation shown is after McDonald (1976, RMAG).