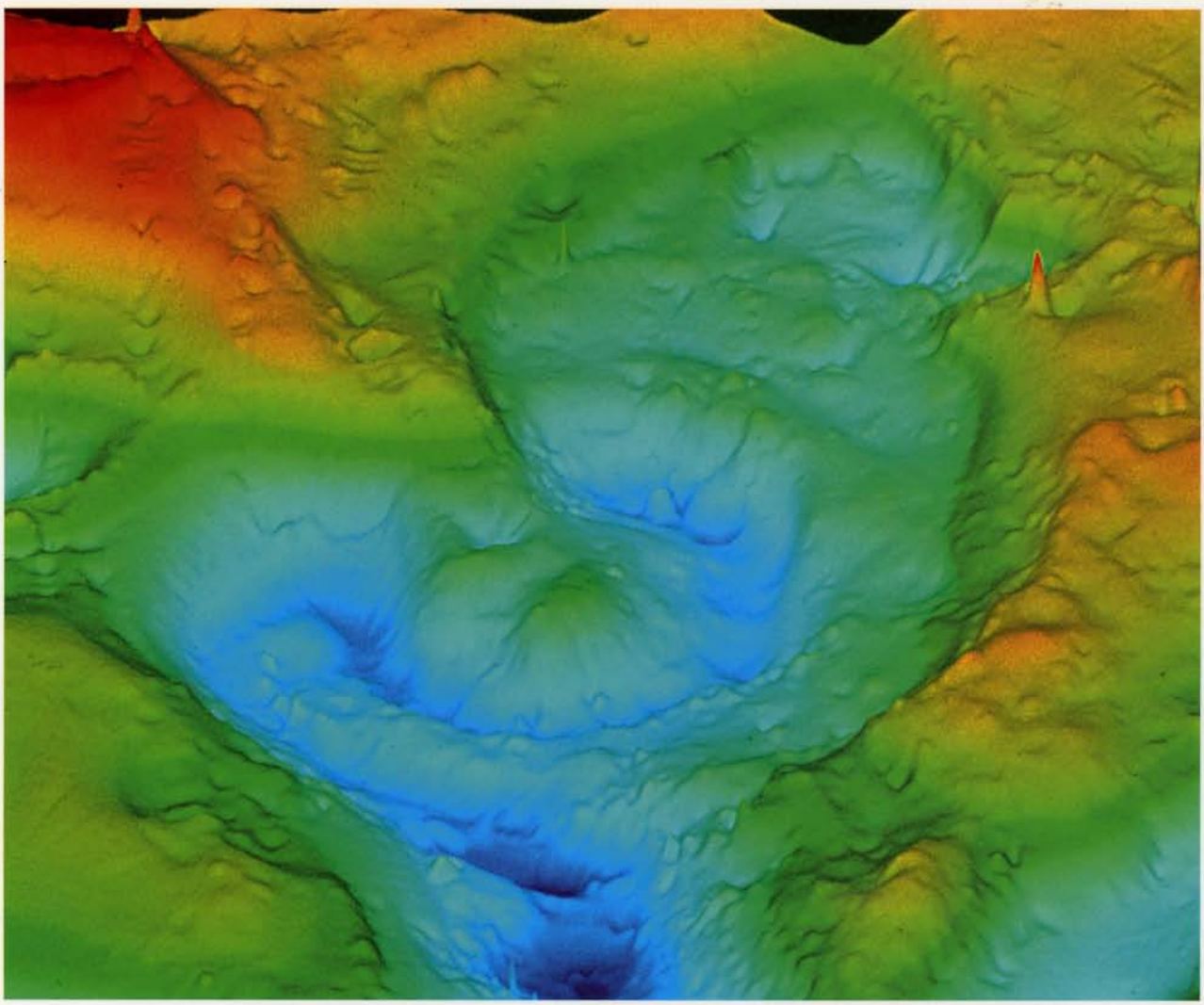
Scientific Rationale for Establishment of an International Program of Continental Scientific Drilling



International Lithosphere Program

Coordinating Committee Continental Drilling (CC4)

Mark D. Zoback & Rolf Emmermann

Scientific Rationale for Establishment of an International Program of Continental Scientific Drilling

Report of the International Meeting on Continental Scientific Drilling

Prepared by the Scientific Planning Committee
Mark D. Zoback and Rolf Emmermann, Chairs

Albert Autran
Sierd Cloetingh
John Eichelberger
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Robert Fournier
Karl Fuchs
William S. Fyfe
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Hans-Peter Harjes
Arthur McGarr
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Frontispiece:
Gravity signature of the Chicxulub impact structure at the edge of Yucatan Peninsula, Mexico (courtesy of V. L. Sharpton). This impact, one of the largest known in the inner solar system in the past 4 billion years, is widely suspected of having caused the major faunal and floral extinctions at the Cretaceous-Tertiary boundary. Scientific drilling has been proposed in the basin to better understand the impact process and the physical and chemical processes responsible for mass extinctions.

Back Cover:
Children's impressions of deep drilling in Germany. During the Continental Deep Drilling Program of the Federal Republic of Germany (KTB), a drawing competition was held in the small city of Windisch-Eschenbach, the location of KTB. The nicest pictures of these were printed on a calendar.

The International Conference on Continental Scientific Drilling, Aug. 30 - Sept. 1, 1993 in Potsdam was sponsored by:

Bureau de Recherches Géologiques et Minières BRGM
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U.S. Geological Survey USGS

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Forward

From August 30th to September 1st, 1993 approximately 250 Earth scientists and science administrators from 28 countries met in Potsdam, Germany to discuss the scientific rationale for establishing an International Continental Drilling Program (ICDP). The meeting, as well as the preparation of this report summarizing the discussions at Potsdam, were carried under the auspices of the Coordinating Committee for Continental Drilling (CC-4) of the International Lithosphere Program, a program jointly sponsored by the International Union of Geological Sciences (IUGS) and the International Union of Geodesy and Geophysics (IUGG). An introductory section of this report entitled „Deep Drilling and New Sustainable Technologies for the 21st Century" was prepared by IUGS President William S. Fyfe.

The scientific themes of the meeting were intended to be as comprehensive as possible, attempting to cover a broad spectrum of contemporary Earth sciences in order to discuss how scientific drilling could complement ongoing studies and make it possible to address fundamental, unresolved questions critically relevant to both societal needs and an improved understanding of Earth's lithosphere. These questions were discussed in detail at the meeting by the many experts listed at the end of this report. The chairs of the varied thematic sessions were primarily responsible for preparation of the different sections of this report.

On the last day of the meeting, each of the thematic chairs reported on the key scientific questions that were discussed in their sessions. There was a clear consensus at the meeting that establishment of an International Continental Scientific Drilling Program is critically needed to make substantive progress in a number of fields of the Earth sciences. As elaborated in this report, the many diverse scientific objectives of an International Continental Scientific Drilling Program strike at the very heart of fundamental problems being investigated throughout the solid Earth sciences.

The Potsdam meeting was hosted by the GeoForschungsZentrum (GFZ), an Earth sciences research institute founded recently in Potsdam. The meeting was held at the historic New Palais, originally built by Frederick the Great, and the new home of Potsdam University. The attendees wish to thank the many people with GFZ and Potsdam University who worked so hard to make this meeting an outstanding success.

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Executive Summary

We live in a geologically complex world where Earth scientists around the world are faced with tremendous challenges. Earth scientists must play a key role in satisfying society's ever-increasing dependence on natural resources, in meeting its needs to remediate existing environmental damage, in learning how to sustain human progress without causing further environmental degradation and in learning how to reduce society's ever-increasing vulnerability to natural hazards. At the same time, Earth scientists, like scientists in other disciplines, are motivated by an inexorable need to better understand our planet Earth. This report contains the scientific rationale for establishment of an International Continental Drilling Program to enable the international geoscientific community to complement on-going field, laboratory and theoretical studies with direct observations at depth in order to critically test current geological models. Without such observations, substantive scientific progress on problems of great importance will be essentially unattainable.

Participants of the Potsdam meeting expressed strong support for establishment of an International Continental Scientific Drilling Program to address a broad range of pressing problems critical to society and an improved understanding of Earth's lithosphere. The participants summarized this support by endorsing the following major points.

There is an Essential Role for Continental Scientific Drilling in the Solid Earth Sciences

As outlined in this report, a broad spectrum of research in the solid Earth sciences requires scientific drilling as an integral part of modern Earth science research. Only by drilling can the international Earth science community *i)* obtain critically-needed data on active processes and *ii)* possess the ability to directly test and calibrate hypotheses based on remotely sensed geological and geophysical field studies, laboratory measurements and theoretical modeling. An International Continental Scientific Drilling Program is critically needed to lead to a better understanding of such diverse problems as:

- *The physical and chemical processes responsible for earthquakes and volcanic eruptions , and optimal methods for mitigating their effects*
- *The manner in which Earth's climate has changed in the recent past and the reasons for such changes*
- *The effects of major impacts on climate and mass extinctions*
- *The nature of the deep biosphere and its relation to geologic processes such as hydrocarbon maturation, ore deposition and evolution of life on Earth*
- *How to safely dispose of radioactive and other toxic waste materials*
- *How sedimentary basins and hydrocarbons resources originate and evolve*
- *How ore deposits are formed in diverse geologic settings*
- *The fundamental physics of plate tectonics and heat, mass and fluid transfer through Earth's crust*
- *How to better interpret geophysical data used to determine the structure and properties of Earth's crust*

Full Realization of that Role Requires a Comprehensive International Program

Scientific questions such as those outlined above are global in nature and of international importance to society. The international geoscientific community needs to incorporate drilling in essentially the full range of solid Earth science disciplines at sites located throughout the world. Such activities can best be addressed by establishing an International Continental Drilling Program, in many ways complementary to the successful Ocean Drilling Program. While the details of such a program are not presented here, general requirements for an International Continental Scientific Drilling Program are that:

- *It addresses fundamental scientific problems of global importance as an element of integrated geological and geophysical research programs. Scientific drilling is neither an end nor a means unto itself.*
- *It seeks geological sites from around the world and it involves the international community of scientists to optimize the results from drilling.*
- *It involves both shallow and deep drilling, at sites chosen from throughout the world, to address specific questions. The program should be proposal-driven, peer-reviewed and operated on the basis that the scientific findings of the program should have broad impact on ongoing research throughout the world.*
- *It is organized in such a way that it will be possible, from both a managerial and technical perspective, to meet the varied needs of the Earth science community .*
- *It is a continuing program with an operational framework which fosters international collaboration and evolving technological capability.*

It is Timely to Grasp the Opportunity to Embark on an International Continental Scientific Drilling Program

A wide range of factors indicate that this is a critical time to begin moving forward toward establishing such a program. These include:

- *The widespread international recognition of the importance of scientific drilling to address problems critical to both societal needs and improved understanding of Earth's crust and lithosphere.*
- *The urgent need to assist in major development projects throughout the world and to participate in training geologists and geophysicists to minimize natural hazards, mitigate environmental damage and effectively discover, efficiently and responsibly utilize natural resources.*
- *The endorsement of the Organization for Economic Cooperation and Development of the need for international cooperation in scientific drilling.*
- *Political changes in the former Soviet Union, eastern Europe and elsewhere that provide important new opportunities for scientific collaboration and progress on outstanding problems.*
- *The need to maintain and build upon the outstanding scientific, technical and operational achievements of the KTB project (Kontinentales Tiefbohrprogramm der Bundesrepublik Deutschland).*

As we move into the 21st century, the role of Earth scientists is abundantly clear. Earth's ever-increasing population will continue to place a huge demand on natural resources. Almost all energy resources, mineral resources and most of the global water supply, come from the upper few kilometers of the Earth's crust. Further, the continuing trend for much of the world's population to be concentrated in „Mega-cities" creates enormous problems of resource distribution, waste disposal and vulnerability to natural hazards and fluctuations in climate. Thus, it is clear that the further development of humankind will depend largely on a greatly improved knowledge of the processes acting within the Earth's crust and lithosphere. Establishment of an International Continental Scientific Drilling Program is criticically needed to provide Earth scientists the ability to address the broad spectrum of challenges society will face in the 21st century.

INTRODUCTION

In this report we describe a large number of important research problems in the multidisciplinary branches of the Earth sciences. Many of these problems are of pressing societal importance and their resolution is critically needed for both immediate and long-term benefit to people around the world. The section of this report entitled „Deep Drilling and New Sustainable Technologies for the 21st Century" by W.S. Fyfe cogently summarizes some of the pressing problems that humankind faces-problems of energy, water, food and mineral resources, waste disposal and natural hazards. Throughout the body of this report, the societal relevance of the research being discussed is repeatedly stressed.

Other important research problems are discussed below which would seem to be more easily classified as being related to improving our fundamental understanding of the evolution of Earth's crust and lithosphere. It is important to realize, however, that many pressing societal issues are so closely related to a better fundamental understanding of these processes that any distinction between science applied to societal needs and more fundamental science is almost meaningless. For example, scientific drilling is important for a better understanding of the origin, composition, mobility and thermodynamic state of crustal fluids at depth. Solutions to many of these fundamental problems are needed before we can adequately address pressing societal questions such as the safe, long-term disposal of hazardous waste, understanding the role of fluids in processes which control earthquakes and volcanic eruptions, obtaining more efficient utilization of ground water resources and developing a better understanding of the origin and accumulation of hydrocarbons and mineral deposits.

As outlined below, scientific drilling is needed for application to problems that involve a better understanding of the history of short term climatic fluctuations and mechanisms of climate change. Advances in this field are crucial to better separate anthropogenic climate variations from naturally-occurring ones. Additional research in this field will provide fundamental guidelines for how society establishes policies to deal with real, or potential, consequences of global change. Scientific drilling is also crucial to obtain a better understanding of how to mitigate natural hazards. Greater and greater numbers of people are killed, injured and adversely economically affected each year by earthquakes, landslides and volcanic eruptions due to the combined effects of global population growth and the concentration of people in exceedingly vulnerable „Mega-cities". One illustration of the critical need for scientific drilling is that research during the past decade has shown that key aspects of the mechanics of crustal faulting and earthquakes (established earlier by extensive laboratory measurements and theory) are either incorrect, or inapplicable, to many major earthquakes. Scientific drilling of active faults is needed to build a firm foundation for earthquake hazard mitigation research based on an understanding of earthquake physics. A similar argument can be made for the processes that control volcanic eruptions.

While much is known of the structure, properties and workings of Earth's crust and lithosphere, many fundamental problems are not well understood. In the different sections of the report below, many examples are presented of how scientific drilling is needed to address some of these outstanding questions. While the modern theory of plate tectonics has revolutionized the geological sciences over the past 30 years, it is important to emphasize that we still do not understand the driving mechanism behind plate tectonics. We do not fully understand the origin of forces that drive the plates, how these forces are transmitted through the plates or how and why different parts of the lithosphere respond so differently to these forces. Inferences based on remote sensing of the lower crust using

geophysical methods and studies of isolated outcroppings of the lower crust and upper mantle have yielded incomplete, and often paradoxical, views of the inner workings of Earth's lithosphere. For example, the electrical resistivity of the lower crust is surprisingly low. This requires either the presence of substantial water at extremely great depth or pervasive carbon films coating mineral grains. However, neither hypothesis has been supported by direct observations nor found to be compatible with the chemical composition of most exhumed deep crustal rocks now exposed at Earth's surface. The discovery of ubiquitous „layering" in the lower crust has been revealed by seismic reflection profiles collected around the world. Yet the cause for this layering is mostly unknown and scientific drilling is needed to calibrate a number of hypotheses based on observations from surface-based geophysical techniques. While conductive heat transfer seems to be the dominant process within the lithosphere (in contrast to convective heat transfer in the asthenosphere) extrapolation of the conductive thermal gradients to the lower crust and mantle yield temperatures that imply ubiquitous melting at unexpectedly shallow depths. Finally, it is becoming increasing clear that the biosphere extends many kilometers below the surface of the Earth and that the nature, origin and evolution of the deep biosphere is very poorly understood. Scientific drilling has the potential, therefore, to contribute greatly to a better understanding of the deep biosphere and its role in a broad range of geologic and biologic processes, and perhaps even to a better understanding of the origin of life on Earth.

During the past decade there has been the recognition of the critical couplings between the solid Earth, the oceans and atmosphere and life on Earth. Research into the couplings among what was once considered diverse processes has come to be known as Earth System Science. It is clear that Earth System Science is rapidly becoming a new context for varied forms of research in the Earth sciences. While this development is long-overdue and quite welcome, one unfortunate consequence is that there is a tendency to lapse into a logic which suggests that only problems of global scale are of global importance. Some of the issues related to this were captured in a comment entitled „Rock System Science vs. Earth System Science" that appeared in the Dec. 1993 issue of *Geotimes*, by Thomas Jordan, Head of the Dept. of Earth, Atmospheric and Planetary Sciences at the Massachusetts Institute of Technology. Jordan wrote, „We need to recognize the importance of pushing forward a research program focused on the fundamental problems of local geosystems, for which the term *rock systems science* might be most appropriate. Many academics, including myself until recently, view global studies as more basic or pure than work done on smaller-scale geosystems, which is often marginalized as „applied geoscience." This mindset is certainly outmoded and perhaps even dangerous to the future of geology."

The scientific discussions at Potsdam were initially divided along topical lines into parallel workshops. The themes are listed below along with the name of the chair(s):

Earth History and Climate (J. Negendank)
Impact Structures and Mass Extinctions (V. Sharpton)
Evolution of Sedimentary Basins (S. Cloetingh)
Fluids in the Crust (R. Fournier)
Dynamics and Deformation of the Lithosphere (A. McGarr)
Origin of Mineral Deposits (J. Hall)
Volcanic Systems and Thermal Regimes (J. Eichelberger)
Convergent Plate Boundaries (B. Stöckhert)
Geophysics of the Crust and Upper Mantle (K. Fuchs, H.-P. Harjes)
Sub-Continental Upper Mantle (A. Autran, D. Mainprice)

Additionally, there was a separate meeting of engineers and technical specialists at Potsdam which is summarized by H. Rischmüller. A discussion of topics related to the deep biosphere is included below based on introductory material provided by W.S. Fyfe and extensive input from the U.S. Department of Energy plan for research of the deep biosphere. Thanks are due to Frank Wobber for making this material available. The section „Structure and Evolution of Basement Provinces" was prepared by R. Rutland, to provide background information for research in this important field of Earth science.

The most difficult task associated with organizing the scientific discussions was the appreciable degree of overlap between the different topics. For example, fluids in the crust is a topic related to most of the thematic groups, yet it would not have been possible to have an effective discussion with 50 people in a room. For this reason, there were initially 10 separate meetings of each thematic group and then combined meetings between thematic groups so as to have the opportunity to discuss points of common interest. Many of the „cross-ties" between the interests of the different thematic groups are illustrated in the discussion that follows. Also, during the deliberations at Potsdam, the participants were asked to refrain from making overly specific proposals. That is, the purpose of the Potsdam meeting was to discuss the types of problems which need to be addressed, not to review, rank and endorse specific proposals. Readers of this report should keep in mind that the projects listed here are included for illustrative purposes only.

The principal justifications for establishing an ICDP are twofold: to address pressing societal problems and to fundamentally improve our understanding of planet Earth. It is clear that the advancement of scientific knowledge depends on the interplay of observations of natural phenomena, generalization of these observations into hypotheses and testing these hypotheses by further observations and experiments. A common aspect of all the sciences is that true advances are almost always crossed as a result of new techniques yielding new data and observations not before available. A comprehensive International Continental Drilling Program uniquely enables Earth scientists to make important advances across a broad spectrum of studies in the Earth sciences. The global Earth science community should begin the process of establishing a scientifically, geographically and technically comprehensive program of continental drilling. Through the ICDP, there would be ample opportunities to obtain data to test key hypotheses which would lead to widespread progress in many fields of Earth science for decades to come.

DEEP DRILLING AND NEW SUSTAINABLE TECHNOLOGIES FOR THE 21ST CENTURY

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As we move into the 21st century the global situation is changing dramatically. With an increase of almost one hundred million humans each year we approach a potential world population of ten billion, which will place a huge demand on all resources. We tend to forget that at this time, almost 90% of our energy resources, almost all our metal-mineral resources, and a large part of the global water supply, come from the outer few km of the Earth's crust.

We also tend to forget that the Earth's land surface is invaluable and there are very few areas of our planet's surface not now invaded by humans. The massive influx of people to cities is creating vast problems of waste disposal in a situation where the cities are extemely vulnerable to natural hazards or fluctuations of the climate and geosphere, which must support the massive structures of urban and technological developments. We simply cannot afford careless technology and development or to be ignorant about the Earth.

Future global development will require exact knowledge of the structure and composition of the Earth's crust. The KTB deep drilling project (and others) have clearly shown that at this time our techniques for remote sensing this composition and structure are inadequate.

In the next few decades we need to develop new technologies for many of our support systems for providing:

- sustainable energy (perhaps 10 times the present levels)
- sustainable water resources
- sustainable use of soil and food production (perhaps 3 times the present levels)
- new technologies for the use, disposal or recycling of wastes
- improved knowledge of climate and natural fluctuations and anthropogenic influences
- increase in the production of mineral resources

These support systems all involve detailed knowledge of the lithosphere and the interactions between the lithosphere and atmosphere-hydrosphere-biosphere systems. Further, as we change technologies in the future, we must take extreme care to protect and preserve the land surface for its unique purposes.

Energy technology is one of the most basic components of the systems which have increased our quality of life and permitted the growth of population. Future energy technologies must be based on the almost infinite resources of solar energy (including wind, tide, biomass, etc.) some of which are now economically viable. For instance, solar electric systems will require new resource development for the supply of the special chemical elements for the new devices.

Geothermal resources, both high temperature (over 300°C) and warm (30-100°C) represent a vast source of potential energy but require a much improved knowledge of deep fluid transport mechanisms and techniques for permeability manipulation at depth. There is the potential for heating most of our cities from drill holes using recyled fluids at temperatures above 30°C. We now know that in all regions of heat flow, or high topography, regionally deep fluid flow cells exist producing warm springs . The energy potential in regions such as the Himalaya is vast.

One intriguing possibility is to use simple reactions like: ferrous silicates + H_2O Æ H_2 + ferric components + SiO_2 for hydrogen production (the ultimate fuel for mobile systems?). As we know that these chemical reactions more efficient at high temperatures, large scale hydrogen production at depth would require exact knowledge of deep permeability, hydrofracture techniques, etc. Could we use deep thermophylic bacteria to assist such processes?

Another area of great potential involves developing techniques for carbon dioxide disposal. There is no doubt that for decades to come, coal will be a major component of world electricity generating systems (*e.g.* India, China). We cannot afford to continue to play Russian Roulette with the atmosphere and climate. Can we develop the techniques needed to use very familiar mineral reactions (*e.g.* Ca Silicate + Mg Silicate + CO_2 Æ carbonates) to control the combustion products from stationary power facilities?

Finally, there is vast potential for energy production via nuclear processes. Here, however, one of the crucial problems is to find the technologies for safe containment of the radioactive waste products. I will return to this problem below.

Recent work by many different groups has clearly shown that in many regions there is now a critical shortage of usable water. The situation is almost desperate in forty nations. Ultimately, the management of our global water systems, will require detailed knowledge of the total water system, above and below Earth's surface. In many regions, water is being mined just as any other non-renewable mineral resource might be. We must have a precise inventory for deep water, quality and quantity in order to understand all the possibilities of removal and renewal of such resources.

Every year more dams are constructed on every large and small river system. By 2050, given the „wisdom" of our present practices, will any rivers flow unperturbed and regularly to the oceans? Will runoff be replaced completely by evaporation and evapotranspiration? We know that rivers clean the salt from the continents and supply nutrients to the ocean biosphere. We also know that the light water fluxes to the oceans strongly influence ocean current systems and have impact on energy transport and climate. Do we understand such systems? Do hydro-engineers know about the Younger Dryas cold event?

The need for exact knowledge of deep fluid systems is critical. We should not store water in surface reservoirs in hot climates. Can we use biomineralization by deep organisms to control and modify permeability? And can we use mineral waters rich in Ca-Mg-K to rejuvenate depleted soils? The possibilities are vast and may even include manipulation of N_2 - NH_3 systems.

Our global situation is desperately screaming for new technologies that involve the proper management of our waste products. A well-defined, very special case involves the world's nuclear wastes. Perhaps, some will be recycled in breeder reactors, but for most nations, geologic disposal is the only viable solution at present. Where is the best place on planet Earth to dispose of nuclear waste? What is the best depth, the best rock matrix? Can we find adequate stress-free domains? One thing is certain, before any major disposal

vault is constructed, we must have exact knowledge of the geologic structure above and below the vault and exact knowledge of fluid flow systems in the surrounding environment.

The future of waste disposal must surely involve waste reduction and waste recycling for maximum re-use of certain components. For metals, recycling will have an influence on future mining developments in regions of stable human population. But there will always be difficult wastes which require long-term disposal. For example I am intrigued by the situation with toxic organo-halogen compounds. At present the major techniques involve incineration at exceptionally high temperatures. But there could be other geo-possibilities. For most C-Cl, C-Br, C-F etc. compounds, reactions like NaSilicate + C-Cl —> NaCl + graphite are thermodynamically possible. Can such reactions be used, catalyzed, in deep zones where the water supply is protected?

At present, humans in the developed world use about 20 tons of rock per person per year to provide the mineral resource they need. For a population of 10 billion this amounts to about 100 km^3 of processed rock per year (it takes about a metric ton of rock to produce a standard 10 g gold wedding ring!), a mass exceeding all natural processes of natural rock movement.

There is no doubt that while recycling will increase and become increasingly more economically viable, there still will be massive need for new resources. Can we develop better techniques for providing the needed resources? Can we produce Cu, Zn, Ag, Au, Fe, Mn, Co... from „black smokers" along oceanic spreading centers or geothermal power plants? Can we use special thermophylic bacteria for in situ metal leaching? Can we use the same species operating up to 100°C for methane production in carbon-rich rocks? The possibilities for new, kinder, cleaner, technologies are endless.

Finally, for the elucidation of climate history, the recent history of erosion, the history of biomass and biodiversity, we require high technology, careful, clean drilling techniques and mobile systems which can be taken to any chosen site on the planet.

I conclude with a remark from Sir Christopher Ball of the U.K who recently stated „Success will come to those who are able to design strategies for research that recognize the realities of today and tomorrow, not of yesterday". We live on the crust of the Earth and obtain our resources from the lithosphere. We must understand the nature of our resource base. Given such knowledge, the possibility for intelligent use of Earth is greatly increased.

SCIENTIFIC THEMES OF CONTINENTAL SCIENTIFIC DRILLING

I. Earth History and Climate

Introduction

During the last two decades, knowledge of global climatic change and Earth history has been greatly enhanced through the study of marine sediments obtained through the Deep Sea Drilling Project (DSDP) and its successor the Ocean Drilling Project (ODP). These data are currently used to simulate and forecast climatic conditions with the help of general circulation models (GCM's). However, GCM's will not be able to predict abrupt and nonlinear shifts in climate which have been recorded by the fossil records. Therefore, forecasts must be based on information about actual changes in climate, as preserved in natural climatic records obtained from sedimentary basins, ice cores, corals and tree rings.

Investigation of long ice cores from both hemispheres, mainly from Greenland and Antarctica, provide new and convincing evidence for large gradual and abrupt changes in climate with a much higher resolution than available from the deep ocean sedimentary record (GRIP 1993, Dansgaard *et al.* 1993). This natural variability from one relatively stable climatic condition to another is independent of expected human-induced changes in climate which could add to, subtract from, or trigger natural changes. Previously, scientists assumed that extreme fluctuations in climate were related to an ice-bound Arctic and limited episodes of glaciation. Climate between major episodes of glaciation, during the interglacial intervals, was believed to be relatively stable, with small fluctuations in temperature and precipitation occurring over time spans of many thousands of years. This opinion was based on evidence for a stable climate state of the last 10,000 years. However, recent evidence from ice cores suggests that protracted intervals of stable climate, such as the one we are now living in, are an oddity and clearly do not represent the typical behavior of the climate system (Fig. I-1). Furthermore, we know that the shift from one quasi-stable state to another is typically abrupt, lasting no more than a few decades, *e.g.* within one human generation.

Most of the data obtained so far cover areas very remote from inhabited regions, *e.g.* the vast areas of the worlds oceans or the polar ice sheets. Much more direct and meaningful for the human interest are the continents-the places where we live-because they reflect climatic changes in inhabited geographical regions rather than in far distant mid-ocean settings.

Sufficient records exist on the continents to characterize regional and global changes in climate and their environmental responses. The best sites lie within the continents or in marine settings along continental margins where high rates of sediment accumulation permit the reconstruction of records with high temporal resolution. Lake basins are exceptionally integrated archives of regional dynamics which can help to resolve questions of environmental forcing on scales from tectonic through to orbital, solar, greenhouse, and catastrophic. The information needed includes a comparative network of long Quaternary cores which span the globe with decadal resolution over glacial/interglacial cycles in order to link these records with records of polar ice caps and ocean cores. In addition to the most recent parts of the Earth's history information from other selected parts of geologic time (*e.g.* Cretaceous) are necessary. To obtain long continuous and undisturbed records from continental sedimentary basins new coring techniques have to be developed and shared among scientists to provide optimal use of such a highly cost-intensive device. Just as the development of the hydraulic piston corer caused an explosion

of information from the marine environment a new coring device for shallow and intermediate continental drilling (range up to several 100 m in depth), to be developed through the International Continental Drilling Project (ICDP), will allow the recovery of sedimentary records spanning the whole Pleistocene and other time windows of the geologic past.

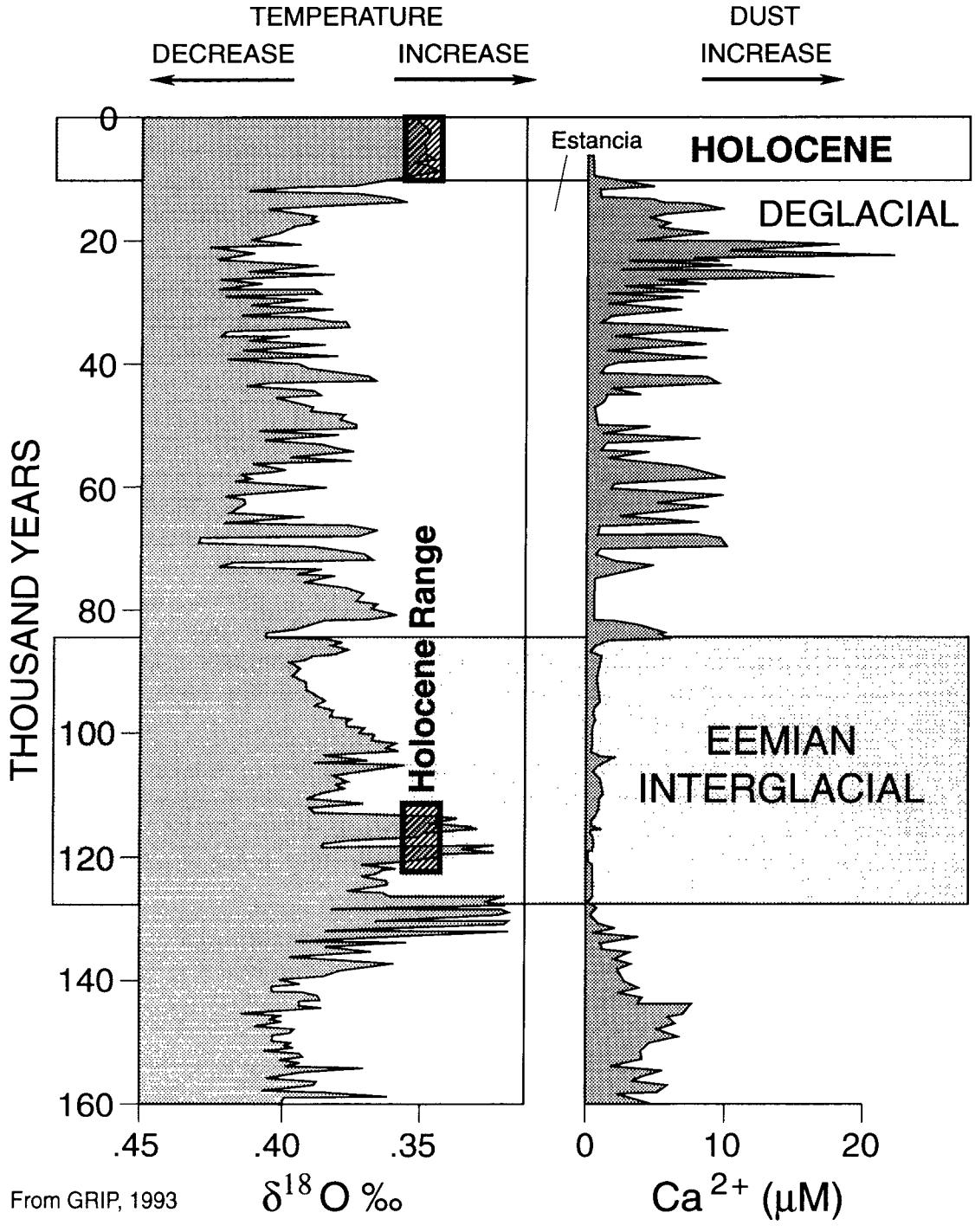

Figure I-1: Comparison of stable Holocene climate with less stable climate of Eemian interglacial (from Anderson, 1993).

Key Questions

Sedimentary records from the continent and from continental margins, when studied in the context of a basin analysis with multidisciplinary strategies (including sedimentology, stratigraphy, geophysics, geochemistry, paleolimnology, palynology and volcanology) provide data on a number of interesting scientific problems. The retrieval of high resolution archives with sedimentological, geochemical, geophysical and paleobiological signals devoted to both, large- and small-scale rates of climatic change will be the major goal in deciphering the history of terrestrial climate.

We need information that covers more than the last glacial/interglacial cycle. At present high resolution lacustrine records seldom go back as far as the Pleistocene. But the efforts of IGCP 314 (Glopals) demonstrate that presently uncored continuous sequences are much more widespread than previously described. Also, there are many sites with stratified anoxic deep waters, where varves have been formed and preserved. They provide an invaluable tool for geochronology and make available detailed rates of change.

Most of the marine records are poor in time resolution when compared with these lacustrine records. Only polar ice cores give such information but they are restricted to the last glacial cycle. The opportunity also exists to extend high-resolution paleoclimate analyses to geologic periods when continental configurations and ocean circulation differed from today, *e.g.* the Cretaceous, an ice-free period.

There are questions of events, like the Younger Dryas, Younger Dryas-like events at the termination of the last interglacials or the recently discovered event-like cold/warm fluctuations during the Eemian. Are these rapid changes catastrophic events or are they a result of a threshold overflow?

Medium- to long-term gradual changes also exist. These periods vary from the 11-year sunspot cycles via a multitude of orbital forced cyclicities to low frequency Milankovich cycles. If complete sediment sequences have been recovered these periodicities might be used to refine the time scale and establish a cyclostratigraphy.

Continental records are very effective traps for pollen grains. They are usually well preserved and can be identified to the genus making them very useful for detection of vegetational changes and the distribution of particular plants. Processes of plant evolution and phytogeography are the major results of palynology, useful for the reconstruction of paleoclimatic conditions like temperature, precipitation and drought stress.

High resolution magnetic records of susceptibility and laboratory implanted remnent magnetizations provide proxy information about paleoclimate. There is growing evidence that the geomagnetic signal is useful for correlation of sediment cores on a global scale including marine sediment sequences. If it is possible to recover undisturbed sediment cores (paleomagnetic directions of inclination and azimuthally oriented cores given) even geomagnetic declination can be obtained. This would also enhance our understanding of the Earth's magnetic field history.

Many sites for continental drilling are available and selection of locations will require prioritization in distinct time windows and along well-defined guidelines. Most important for the understanding of present and future climatic conditions is the paleoclimate of the last glacial cycles, available from sedimentary basins and from polar ice caps. Also, the opportunity exists to extend high-resolution investigations to older geologic records using sediments of Tertiary, Mesozoic and Paleozoic age. These sediment sequences might provide information about the climate system of the Earth when there were no polar ice caps, and to explore the mechanisms leading to exceptionally warm conditions, the so-

called „greenhouse", as opposed to the present day „icehouse" conditions. Furthermore, sediment sequences from geologic time intervals prior to the Jurassic provide information on paleoclimates and paleoenvironments not available from present day marine settings, as the oceans are generally younger than Jurassic.

Some possible guidelines include:

(1) Records with temporal resolution ranging from annual to decadal. High-resolution is needed for understanding rapid responses of climatic and environmental systems.

(2) Records should be obtained from sediment basins (polar ice caps) still accumulating sediment (ice). They allow the option of direct and indirect linkage to the modern climate system and environmental processes (not valid for records of Tertiary, Mesozoic, and Paleozoic age).

(3) Records of sufficient length to characterize millennial changes. Ideally records should range from 10,000 years to several hundred thousand years.

(4) Location of sites in important climatic transition zones.

(5) Location of sites in responsive environmental settings. Preliminary hydrologic and other information should be used to identify favorable sites.

(6) Availability of multiple measures (proxies) of climatic and environmental change. Preliminary paleontological and geochemical information should indicate favorable conditions for measuring climate and environmental changes.

In addition to the above guidelines imposed by the physical setting, the destructible nature of the core materials collected require that each project be backed up by a program that will assure that adequate subsampling, analysis, and research are completed in a timely manner. Cooperation with IGBP, PAGES, ODP, INQUA Commison of Long Quaternary Records, CLIP, Baikal, IGCP, and other international global change initiatives can be incorporated into a science plan under the auspices of the ICDP.

Target Areas

Lakes

The potential for long cores from lake basins relates to the lake type simplified to „small" lakes and „large" lakes. Small lakes, *e.g.* volcanic lakes (maar-, crater-, caldera lakes), impact craters or solution lakes, have the advantage of defined origin, small drainage area, a close approximation of atmospheric input, and relative technical accessibility. Recent drilling in maar lakes is providing some of the best quality, continuous paleoclimatic records across Europe (Negendank & Zolitschka 1993). Such lakes have potential in many regions of the world and might provide a global network of local to regional paleoenvironmental information.

Large lakes on the other hand can provide integrated, long, continuous records of climate and landscape changes for whole regions. Local effects are largely buffered, although abrupt events are reflected as well. The rates of accumulation are generally lower giving the potential of much longer records if compared to small lakes. Technological problems exist on large lakes, as big coring platforms or vessels are needed. The great water depth can be still another problem.

Small Lakes

Suggested coring sites are located along two transects. One along the western spine of the Americas (PEP initiative), the second from central Europe across the Mediterranean into the tropics of the African continent.

The western hemisphere transect from northern to southern America should include lakes like Clear Lake, Pyramid Lake, Mono Lake, Salt Lake, Peten Lake, Lake Nicaragua, Lake Valencia, Lake Titicaca, Lake Carl Laufquen and Lake Cardiel (Fig. I-2). The old world transect includes lakes like the Eifel maar lakes, the volcanic lakes of Massif Central, Lago Grande di Monticchio, Lake Ohrid, Lake Kinnereth, Lake Bosumtwi (Fig. I-2).

Large Lakes

Potential coring sites for large lakes are the East African Graben lakes of Malawi, Rukwa, Tanganyika, Edward, Albert, Victoria and Turkana, which are currently under study within the IDEAL (International Decade for East African Lake) program as well as Lake Biwa, Lake Baikal, the Black Sea and the Dead Sea (Fig. I-2).

Continental Margins

Marine settings on the continental margin off the west coast of the Americas, inaccessible to the large ODP drilling vessel because of shallow water, are very sensitive to climatic and environmental changes and, additionally, provide high-resolution records of sea level changes in response to orbitally forced climatic fluctuations.

Continental Basins with Ancient Marine or Lacustrine Sediments

- Eocene lake basins with annual resolution like the Green River Formation (USA) or the Eckfelder Maar (Germany). These sediments allow the study of the response of depositional systems to astronomic forcing on a potentially annual basis.
- The Cuyo Basin in Bolivia has a unique potential to contain a continuous lacustrine sediment sequence crossing the Cretaceous/Tertiary boundary.
- Cretaceous marine sediments as suggested by the Apticore-Albicore initiative, includes the study of climate and oceanic circulation models, of widespread anoxic conditions in space and time, of Milankovich cycles, of climatic-oceanic interactions resulting in sea level fluctuations and of the onset of Cretaceous „greenhouse" conditions that might be related to the immense extrusion of plateau basalts in south-east Asia.
- Recovery of Pre-Cretaceous marine sediments on the continents gives the opportunity to reconstruct the evolution of CO_2 in the atmosphere and sea water.
- Paleozoic evaporite basins of huge dimensions exist in North America (Permian Castile Formation) and Central Europe (Permian Zechstein salt-formation). These high resolution shallow marine deposits provide an opportunity to test the links between orbital forcing, climate and the corresponding response of the depositional system during an early period of Earth's history.

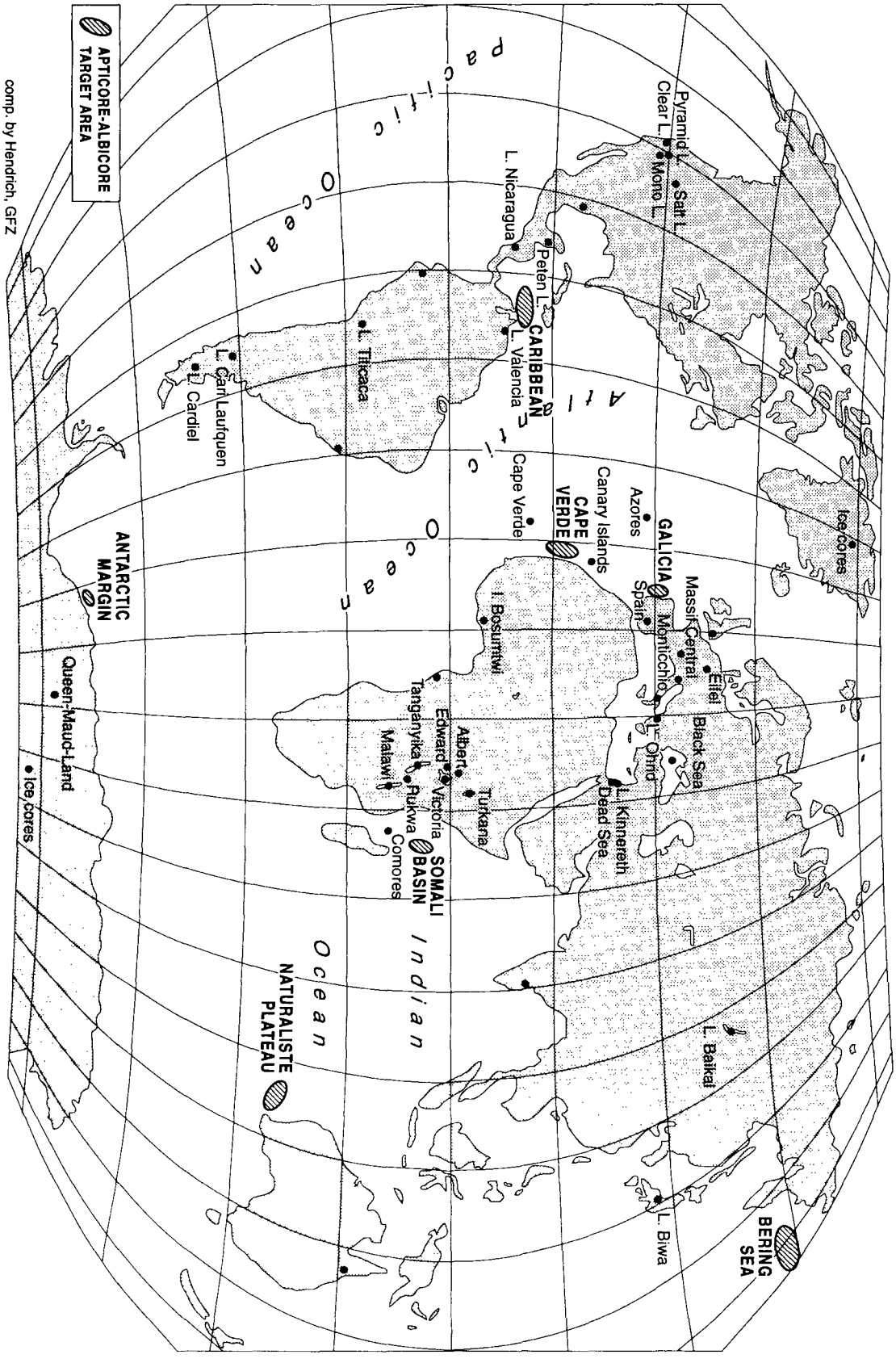

Figure I-2: Summary of all important continental drilling localities inclusive the proposed Apticore-Albicore target areas (After Larson *et al.*, 1993)

Polar Ice Caps

The study of ice cores has demonstrated that the polar ice sheets record an abundance of paleoenvironmental data. Future deep ice cores should be located in Antarctica (Dome C. Dome F. Queen-Maud-Land) and on north-central Greenland (Fig. I-2) to extend the presently available records to the last 3 to 4 glacial cycles.

Technological Issues

Scientific drilling is necessary to obtain stratigraphically more complete and better preserved (unweathered) sediment sections than available from outcrops. The early scientific cores from continents were not commonly studied in a multidisciplinary mode and have not been archived carefully. These drill cuttings provided core material which was disrupted with poorly constrained depth scales.

Recently precision soft sediment piston coring (Livingstone-type or Usinger-type piston corer) enables recovery of undisturbed sediments from water depths of up to about 50 m. Penetration into the sediment depends on the compaction of the sediment and on core vibration or percussion techniques when used to aid penetration. The maximum sediment depth achieved with the Usinger-type piston coring system was 52 m at 6 m of water depth. The length of individual core sections usually is 2 m. The Kullenberg gravity corer and the Selcor percussion corer are used for deep lakes. They can operate at water depths of several 100 m. Core recovery is 8 m. In some cases ultra-long core tubes may provide 12 m of sediment. Recently, the Lake Baikal drilling campaign used ODP expertise for an ice-based hydraulic piston coring system to core more than 100 m subbottom depth.

The new techniques that should be developed within the ICDP are light-weight hydraulic piston corers or remote reentry systems working from small ships or platforms. These devices would be able to penetrate to depths of several 100 m without damaging the micro-fabric of the sediment. Sediment distribution can be produced by grain rotation in response to fluid flow through the sediment pores at the high pressures generated during coring operations. It would be useful if core sections could be oriented azimuthally. Future coring techniques should stress the need for recovery in plastic liners and high-quality archiving. Ideally, such systems should be cheap, flexible, and convenient to use. For coring consolidated sediments further development of existing systems like Sedidrill and wire-line coring systems is needed.

Care should be taken to facilitate the exchange of cost effective coring developments and archiving technology, as well as documentation of basic lithological and sedimentological parameters. All data should be made accessible to the scientific community.

Conclusions

Recovered high resolution sediments will give new information on paleoclimatology, the influence of solar and astronomical (Milankovich) forcing on paleoclimate and the general aspects of global environmental change. Regional correlation of transient and abrupt climatic change can be tracked and explained. These data give background information for modeling past climatic conditions and, more importantly, for predicting future climates.

Our understanding of paleoceanography made a big jump with the advent of the

hydraulic piston corer in 1979 for the DSDP. For the first time undisturbed and continuous sections of the uppermost 100 m of ocean sediment were recovered. Investigations focused on the lithological signatures, delicate layering and cycles of sediment type, the abrupt and subtle changes of sediment transitions, by taking the opportunity to obtain samples for myriad analyses at well-constrained sample depths.

An advance in drilling technology during the last decade allowed continuous ice coring of the polar ice sheets. Important information on past climate and an abundance of paleoenvironmental data with high resolution for the last glacial cycle is now available, exceeding the resolution of marine sediment sequences.

Lake drilling, in both modern and ancient basins is just entering this realm. The prospects of recovering continuous, high resolution records of paleoenvironmental indicators over vast periods of the Earth's geologic history is a fascinating prospect. It will culminate in detailed correlations between marine, continental and ice core data finally providing a global network of sites from which a profound knowledge of the Earth's history and detailed predictions for future changes in the system Earth will be obtained.

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II. Impact Structures and Mass Extinctions

Introduction

Exploration of the inner solar system during the latter half of the twentieth century has shown that meteorite impacts played a major role in shaping ancient planetary landscapes such as those preserved on Mercury and the Moon. The large multi-ring impact basins, some over 1000 km in diameter, preserved on these small planets reveal an early period of intense bombardment in the inner solar system ending ~3.8 Ga. The steady-state crater production rate since that time is considerably lower, but appreciable nonetheless. For instance, the Earth experiences an impact event large enough to produce a 20-km diameter crater every million years on average. Although Earth's active surface processes quickly destroy the impact record, approximately 120 impact craters have been identified, with diameters aging from ~30 m to ~ 300 km, and ages from ~2,000 yr to ~2 Ga (Figure II-1). Analysis of these structures, combined with a better understanding of the dynamics and interactions of objects within the inner solar system, has led to an enhanced appreciation of large-body impact as a fundamental geological process occurring throughout Earth history.

The first evidence that large-body impacts can induce global mass extinction events came in 1979 when a geochemical signature of impact was discovered within the thin clay layer at Cretaceous-Tertiary (KT) boundary near Gubbio, Italy. Since that time, the case for a KT impact event has continued to strengthen; geochemical and physical evidence of meteorite impact is now established at KT boundary localities world wide. Recently, the Chicxulub structure in Northern Yucatán has been identified as a large impact crater linked to these KT boundary deposits. Although completely buried by Tertiary platform rocks, geophysical and geological data indicate a multiring basin with an outer ring diameter of ~300 km. Three exploration wells drilled into the center of the structure recovered melt rocks and breccias with diagnostic evidence of meteorite impact. Additional investigations of this basin could provide clues to the environmental and climatological consequences of large meteorite impact, and the response to those changes by the biosphere.

Scientific Drilling at Terrestrial Impact Craters

Over 50 impact craters have been drilled in the past 40 years. The information gained through drilling, combined with that from surface studies, analysis of planetary images, impact and shock experiments, and theoretical inferences provide a first order knowledge of the impact process and the resulting landforms.

Early studies focused on establishing structural, geophysical, chemical and mineralogical criteria for recognizing and reconstructing eroded or deformed impact structures. A principal element in distinguishing impact craters from endogenic features is diagnostic evidence of shock metamorphism, the irreversible or metastable changes produced when rocks are dynamically compressed beyond their Hugoniot-elastic limit, which for most silicate rocks is above 3 GPa. Diagnostic expressions of such deformation, observed in the natural environment exclusively in conjunction with meteorite impact structures include: *(i)* shatter cones, *(ii)* characteristic microdeformation features in several common rock forming minerals including quartz, *(iii)* stishovite and other high density metastable polymorphs, *(iv)* diaplectic mineral glasses including maskelynite, *(v)* fused mineral glasses and melts, and *(vi)* whole rock melts with evidence of superheating above the liquidus.

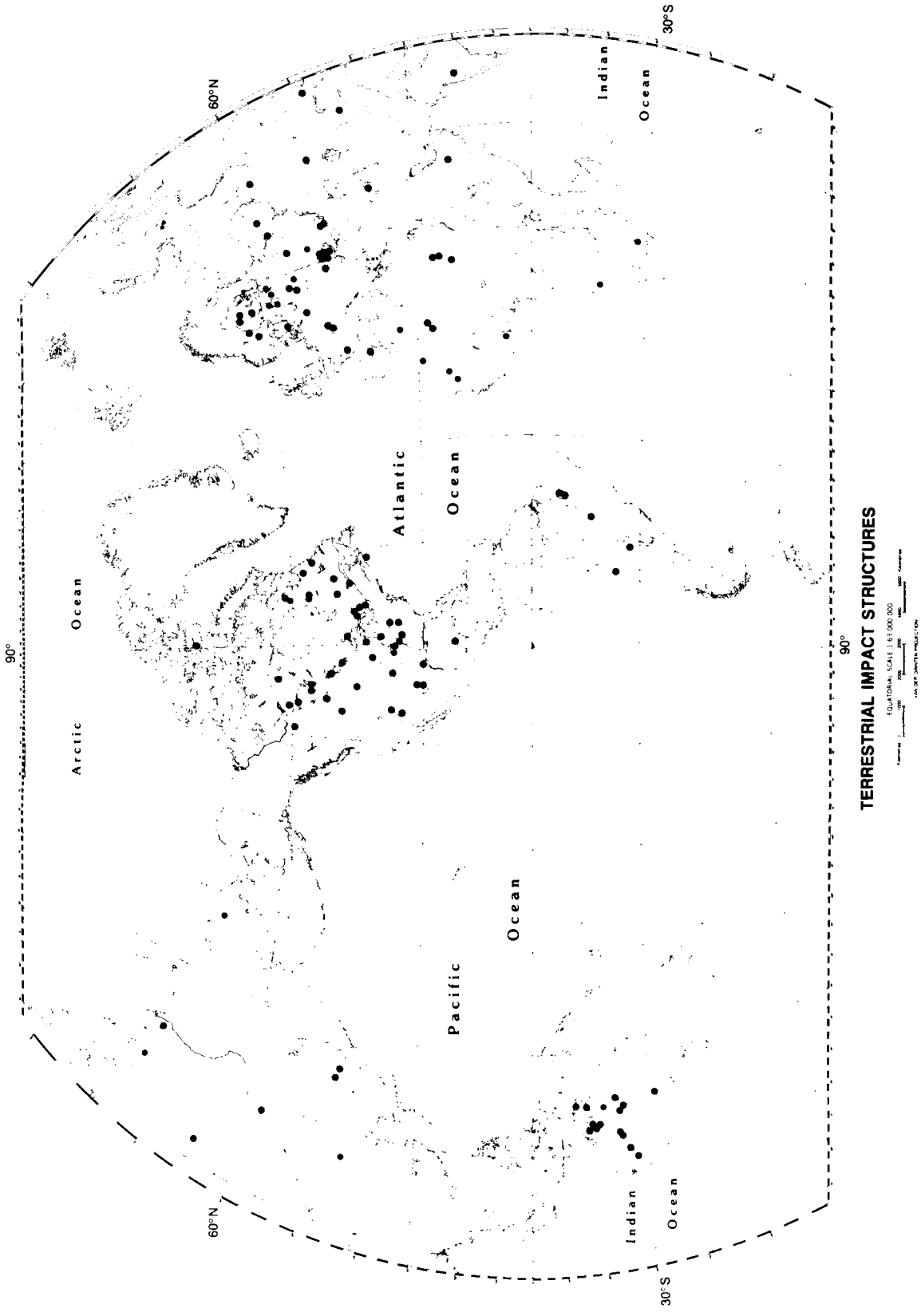

Figure II-1: Terrestrial Impact Craters identified as of 1992.

Considerable advances have been made in understanding the mechanics of the cratering process and the morphological elements of the final landform. Craters on Earth less than ~4 km in diameter have simple bowl-shaped cavities reflecting the original excavation cavity overlain by a thin lens of allogenic breccia and, in some cases, melt rock. Larger craters, however, have a complex morphology developed during the final stages of the impact process as the transient crater, the deep bowl-shaped cavity produced by excavation and downward displacement, laterally collapses under the influence of gravity. This late stage modification produces a broader, shallower final crater, typically with a central zone of uplifted rocks surrounded by a downdropped annulus and raised rim (Figure 2). Complex craters up to ~40 km on Earth have been studied in detail and correspond structurally to central peak craters on other planets. Scaling relationships have been developed to relate various morphological and structural attributes of these central peak craters. For instance, if the crater rim diameter is known, the amount of structural relief on the central uplift, the melt volume, or the impact energy (and in turn the projectile size or impact velocity) can be estimated. Conversely, if the crater rim is not preserved, its size can be estimated by knowing any one of the other parameters.

Data from planetary images show that crater morphology undergoes other discrete changes as final crater diameter becomes larger - from central peak craters to peak ring basins and finally to the largest impact basins characterized by multiple concentric rings. Attaining a detailed understanding of the nature and origin of these rings and other crater components in these large basins remains one of the outstanding problems in impact cratering. One important approach requires access to the substructure only available for the terrestrial craters. Craters >40 km are not common on Earth and are typically highly eroded or deformed. Consequently the link between surface appearances, as gained from planetary data, and structural expression rests on detailed evaluation of large, relatively unmodified craters.

The largest craters observed on planetary landscapes are impact basins with three or more concentric topographic rings such as the Orientale basin on the Moon (Figure II-2). There are only three terrestrial craters with diameters 150 km and appear to be associated with a multiring morphology. Two, Sudbury (Ontario, Canada) and Vredefort Dome (South Africa) are ancient features produced almost two billion years ago and are consequently highly eroded and tectonically deformed. The other is Chicxulub a buried impact crater on the Yucatán Peninsula that was produced ~65 Ma at the stratigraphic boundary between the Cretaceous and Tertiary Periods. Because very little is presently known about these large features and the extremely energetic collisional events that produced them, and as there is mounting evidence of their potential to effect geological and environmental change of global proportions, these large impact craters must be considered as the highest priority for future studies.

Key Research Directions for Future Scientific Drilling Activities

The scientific objectives of studying terrestrial multi-ring impact basins include topics of interest to many disciplines of the Earth sciences. The following list includes some of the fundamental goals that should be addressed in future terrestrial crater research. These objectives will benefit significantly from continued evaluation of the crater images from space missions to other planets in the inner solar system but they absolutely require the exposure to substructure and deep samples that only the terrestrial crater record can provide.

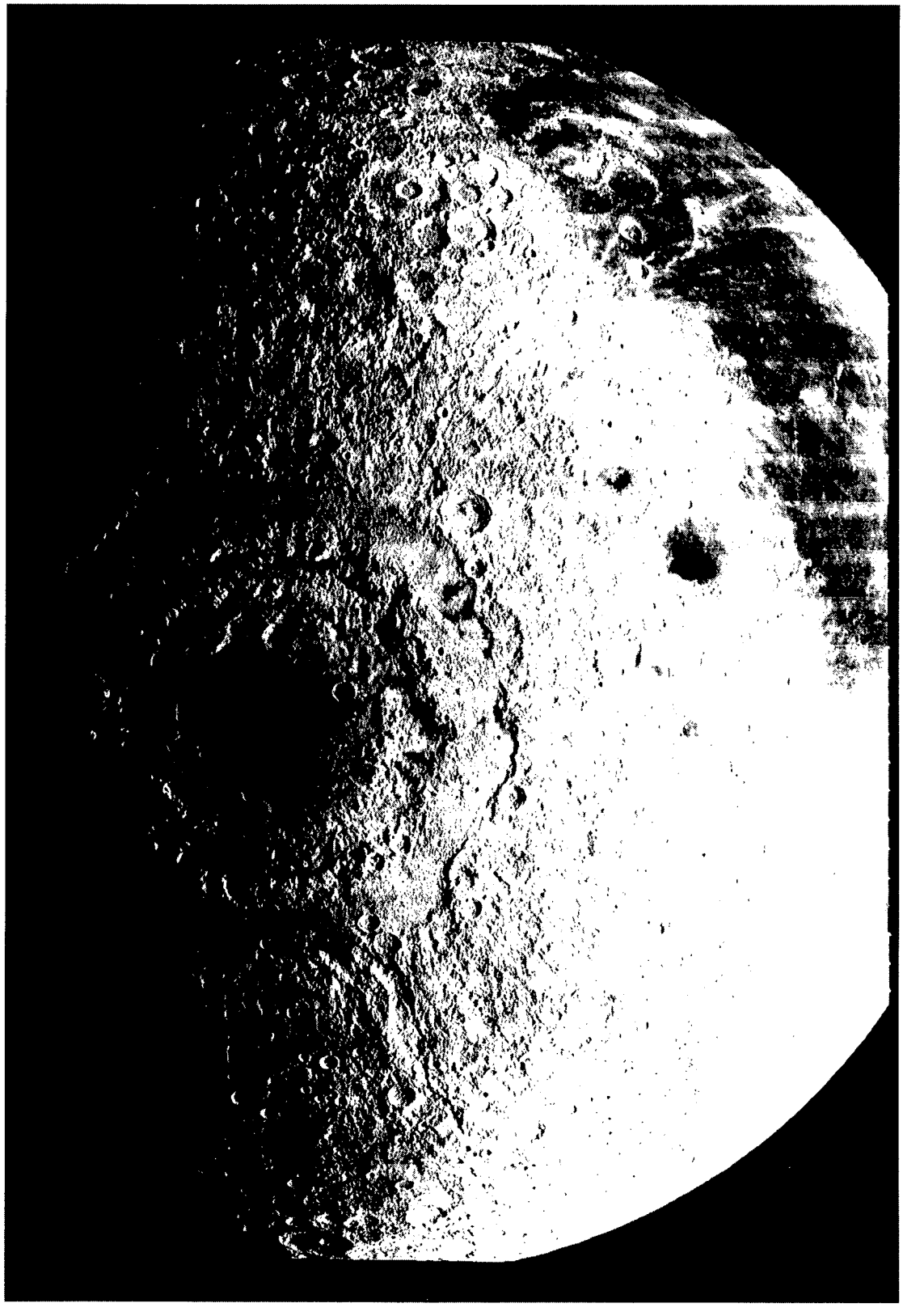

Figure II-2: Lunar Orbiter IV photograph of the 950 km diameter Orientale Multiring impact basin on the western limb of the Moon.

(i) *Improve constraints on scaling laws for large multiring basins and their implications for planetary evolution.* Because these large basins contain several topographic rings, there is considerable uncertainty as to the nature and origin of these rings, and particularly to which ring corresponds to the crater rim in smaller central peak and peak ring craters. This lack of basic control poses severe constraints on predicting the actual size of the modified crater and therefore the energy involved in the formational event. A clearer understanding of the controls over the final size and shape of these large basins can lead to scaling relationships that will, in turn, help scientists evaluate potential geological consequences of impact such as crustal erosion and weakening, initiation of volcanism from mantle uplift, thicknesses of ejecta and melt deposits produced during impact events on the early Earth and the other terrestrial planets. These same scaling relationships may provide critical information for reconstructing the original configuration of the Sudbury and Vredefort Dome structures.

(ii) *Evaluate the origin and evolution of uplifted crust in the basin center.* Currently, there is considerable uncertainty regarding the nature and extent of the structural uplift at the center of large ring basins. Large craters present two fundamental problems: they are rare on Earth, and they excavate through the sedimentary succession that provides stratigraphic depth information. Because, the underlying silicate crust is not stratified on a scale that typically permits the level of uplift in craters <200 km to be constrained, little is known about the amount of structural uplift and the depth of excavation in these large features. For the largest multi-ring basins, like Chicxulub, Sudbury and Vredefort, however, it is possible that relief on upper crust/lower crust and crust/mantle boundaries would be measurable and provide depth constraints necessary to extend the information gained from smaller craters to multi-ring basin scales. The nature and level of the deformation experienced by the rocks of the crater floor also provides clues that assist in evaluating crater efficiency and ring formation.

Regardless of the these uncertainties, multi-ring basin formation is clearly accompanied by considerable uplift of the crater floor during the final stages of the impact process. This uplift provides access to deep basement rocks that would otherwise be located beyond current capabilities of drilling and core recovery. For instance, extending the observed structural uplift versus crater diameter trend for craters between ~4 km and 25 km in diameter to the likely size of the Chicxulub basin (~300 km) suggests that the central uplift, located within a few kilometers of the surface, is composed of rocks that were originally 15-30 km deep within the crust. Access to such deep rocks would be of considerable importance to understanding the lower crust and perhaps the upper mantle of continental lithosphere.

(iii) *Assess the internal structure and evolution of the breccia and melt rock units within large multi-ring basins.* The large impact process produces a thick and complex sequence of melt rocks and various kinds of breccias which fill the modified crater cavity and form dike-like bodies in the surrounding rocks of the crater floor (Figure II-3). For instance, the ~100 km Manicouagan crater contains a melt sheet that is ~300 m thick and is estimated to have originally been about a kilometer thick. These melt rocks, composed of superheated melt produced near the point of impact that is driven outward and integrated with colder clasts, contain enormous amounts of thermal energy. Understanding the volume of melt rock and evaluating the melt rock samples can provide crucial constraints on the

magnitude and duration of a crater's thermal signature, and constrain post-impact processing of melt such as differentiation and hydrothermal alteration. No appreciable melt sheet has been identified at the Sudbury impact basin. However, the so-called Sudbury Igneous Complex, a sequence of melt-matrix breccias, quartz gabbro, norite, and granophyre ~3 km thick, recently has been reinterpreted as the original melt sheet that differentiated after implacement. Evaluation of melt rock sequences at other impact basins of comparable size will be an important test of this hypothesis.

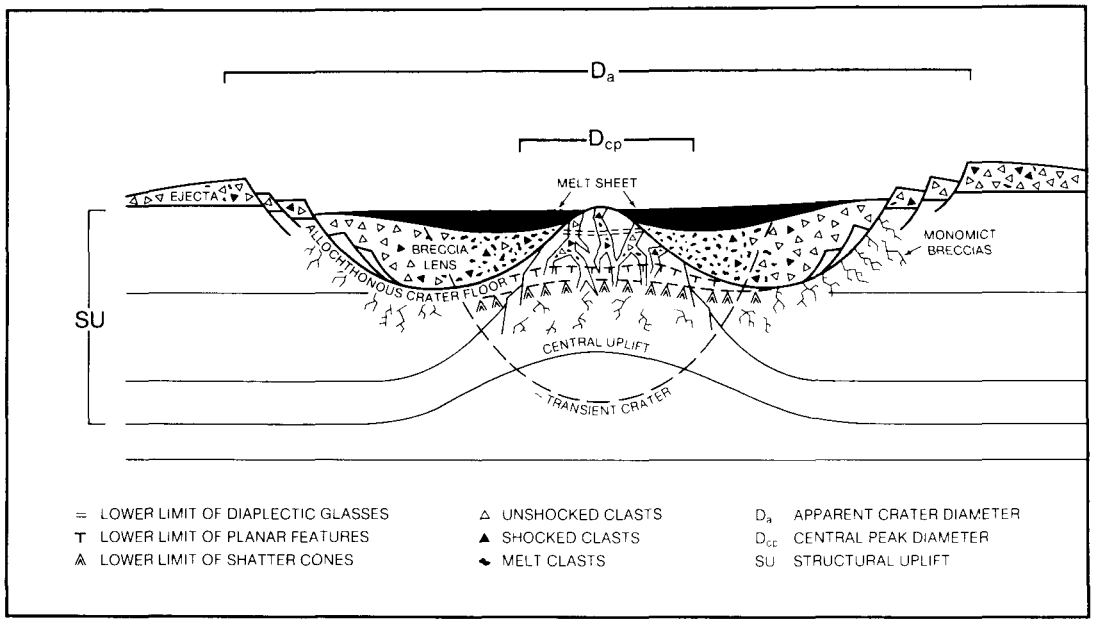

Figure II-3: Schematic cross section of a complex terrestrial impact structure showing major structural and morphologic relations and distribution of diagnostic shock features. This complex morphology represents considerable modification of the initial, or transient, crater shape. Thickness of the breccia lens and annular trough are exaggerated to illustrate clast and breccia relations. The size of the melt sheet is dependent on target properties.

Melts produced during meteorite impact are composed predominantly of the target rocks of the upper crust. The melt rocks at some central peak craters, however, show elevated siderophile element abundances that indicate 2-10 wt% is meteoritic material. The amount of impact melt and the proportion of meteoritic contamination at larger multi-ring basins is not well constrained. By identifying the proportion of projectile in the melt rocks, the process and efficacy of melt formation can be evaluated.

The allogenic breccias contain a wealth of information about the nature of the impact process as well as the lithologies involved. In particular, the breccias provide information on the depth of excavation and the distribution of materials within and around the crater during impact and collapse. In addition, these breccias and large down-dropped blocks within the basin preserve a record of target strata

that, outside the basin, may have been removed by erosional processes. In several cases, the impact basin provides an isolated depositional environment allowing the only record of the post-crater geological and enviromental conditions to be retained. The post-crater sediments immediately above the impact melts and breccias can also help constrain the nature of extended modification of the crater due to long term crustal readjustments of the weakened, cooling crust.

(iv) Constrain the environmental and geological effects of large impact events and evaluate the implications for anthropogenic change. Although there is compelling evidence to link the formation of the Chicxulub multi-ring basin with the global extinctions that characterize the Cretaceous-Tertiary boundary, the nature, extent, and duration of impact-induced environmental effects remain problematic. What was the killing mechanism? Global darkening/cooling from dust ejection, greenhouse warming, and acidification of ocean waters resulting from vaporization of sulfates or carbonates have been suggested. A better understanding of the target stratigraphy and the melt and breccias produced during impact is critical. Furthermore, assessment of the sediments deposited directly on top of the crater units in the Chicxulub basin could provide important isotopic, chemical, and paleontological insight into the modus operandi of the KT mass murders.

The KT boundary provides a link between paleo-climate studies and recent anthropogenic changes. Industrialization and deforestation result in considerable modification of the atmospheric CO_2 and SO_2 budget; recent estimates indicate a factor of two increase in CO_2 by the middle of next century and there are concerns that this may have catastropic consequences even if behavior patterns improve. Given current estimates of its size and the nature of the target rocks at the Chicxulub basin, there may well have been over 2×10^{13} metric tons of CO_2 (equivalent to ten times the total mass in the present atmosphere) and possibly a similar amount of SO_2 instantaneously ejected into the atmosphere by the impact. This can be compared to volcanic eruptions such as the 1982 El Chichon volcano which ejected approximately 3 million metric tons of SO_2 into the atmosphere.

While volcanism may initiate appreciable climatic responses, there is no known instance where volcanic eruptions are linked to a global extinction event. For the Chicxulub event and the KT extinctions we have a situation where a physical event initiated an enviromental change and the biospheric reaction was catastropic. An integrated study of the KT boundary and close examination of the sediments at the Chicxulub basin is essential to understanding the nature and degree of environmental change associated with this highly energetic but short time-scale event. In turn, this important new information will assist scientists in evaluating and predicting the future consequences of past and current human activity.

Specific Examples

The Chicxulub multi-ring impact basin

This 200-300 km diameter structure is one of the largest impact features recognized on Earth to date yet is geologically young and unmodified. The impact occurred within the Yucatán platform which at that time was an active environment of carbonate deposition. Because the region was covered by a shallow sea, the only exposure to erosion the basin has experienced was the wave action generated by the impact event itself, although, the high-standing rim facies may have remained a subaerial landform for a considerable time after the impact. The basin is now buried by up to a kilometer of Cenozoic sediments.

There is no topographic expression of the structure on the present land surface; geopotential studies provided the first hints that a large structure lay underneath. Test wells were drilled by Petróleos Mexicanos beginning in the early 1950s in which three wells, situated near the center, intercepted unusual occurrences of breccias and silicate crystalline rocks (Figure II-4a). An impact origin was suspected by Pemex geophysicists in 1981. Subsequent evaluation of samples recovered by these early drilling efforts reveal diagnostic evidence of shock metamorphism and strongly suggest that the crystalline rock sequence was produced in a large meteorite impact event and not by volcanic processes. Reevaluation of the geophysical and well log data divulges structural indications of a multi-ring impact basin approximately 300 km in diameter (Figures II-4 and II-5).

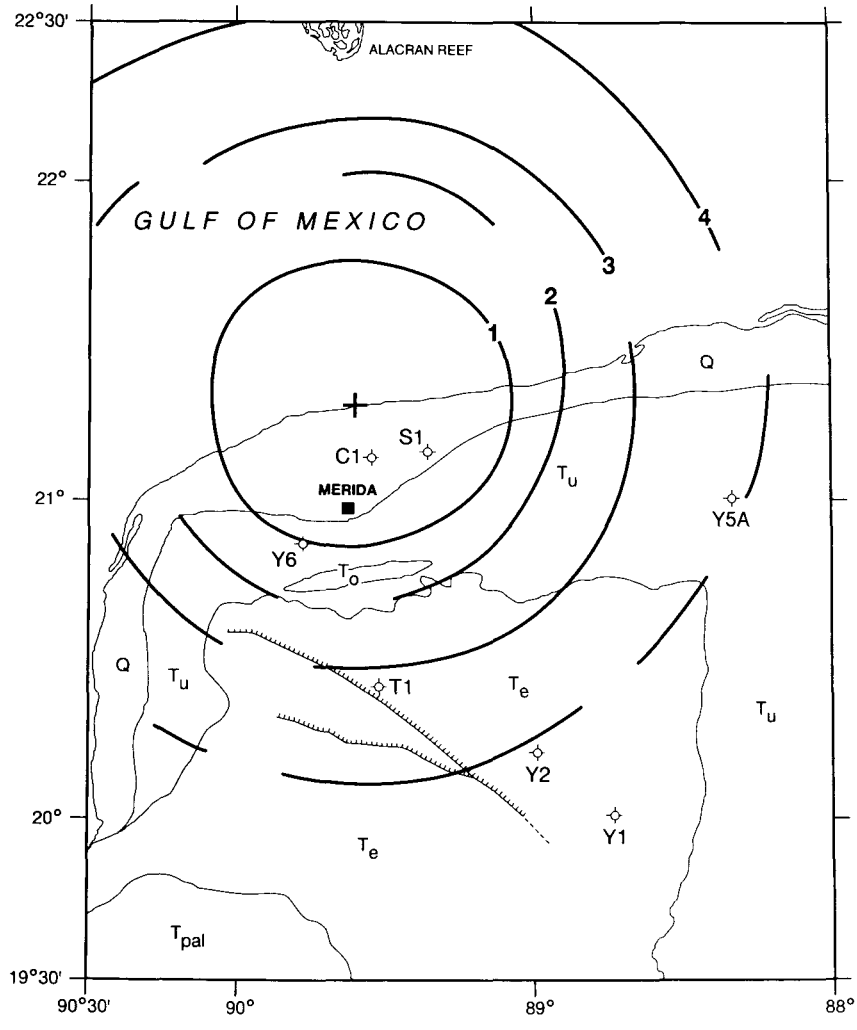

Figure II-4: (a) Surface geology and rings of the Chicxulub multiring basin, Yucatán, Mexico. The three wells that penetrated impact melt rocks and breccias beneath the carbonate cover rocks are C1 (Chicxulub 1), S1 (Sacapuc 1), and Y6 (Yucatán 6). Other well sites shown are: Yucatán 1 (Y1), Yucatán 2 (Y2), Yucatán 5A (Y5A), and Ticul 1 (T1). Carbonate units at the surface are Q (Quaternary; <2 Ma), Tu (Upper Tertiary; 2 to 35 Ma), Te (Eocene; 35 to 55 Ma) and Tpal (Paleocene; 55 to 65 Ma. Hatchured lines represent the Ticul fault system.

Figure II-4: (b) Relief-shaded gravity anomaly data for the region shown in Fig. 4a viewed obliquely from approximately 60° above the surface looking north. Artificial lighting is from the south. Gravity anomalies in the mapped region range from -16.4 mgal to +53.6 mgal.

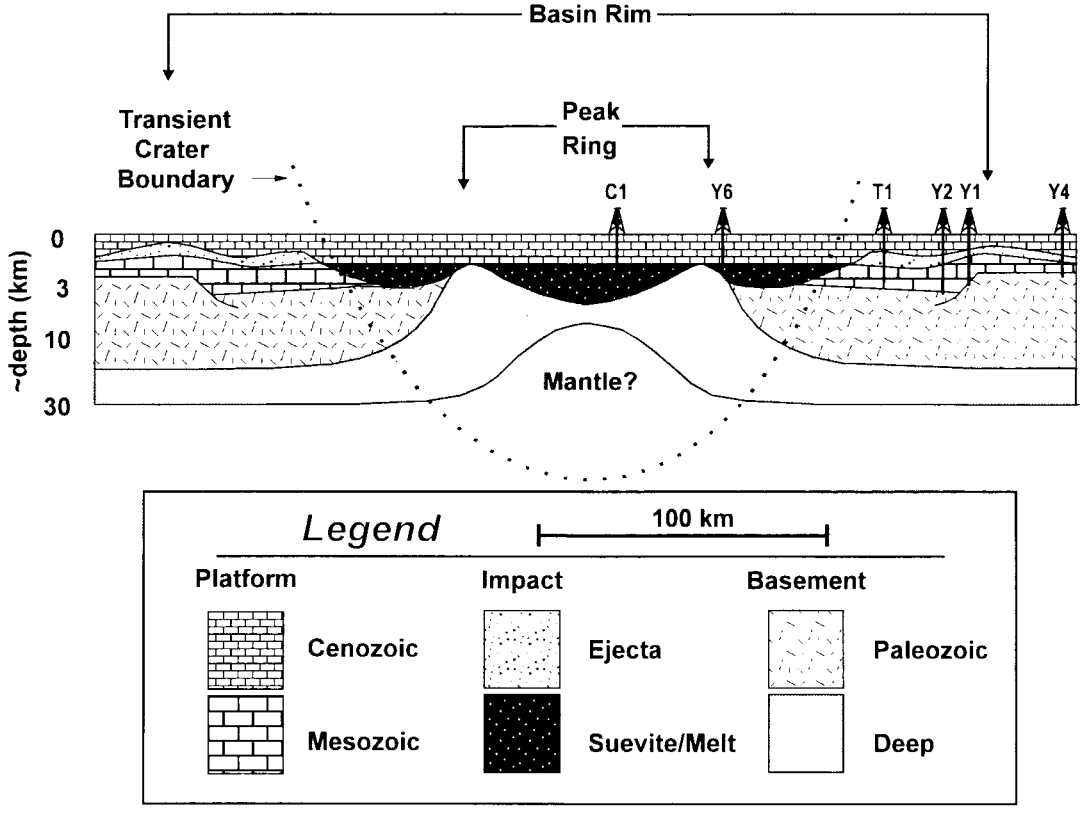

Figure II-5: A schematic model of the Chicxulub multi-ring basin derived from analysis of gravity and well logs. This simplified cross section shows the general configuration of the crater but does not consider erosion; erosion at the time of impact could modify the upper crater units significantly and reduce crater topography. Faults and unit boundaries are simplified.

There is compelling evidence linking the Chicxulub impact crater to the KT boundary layer. The crystallization age of the melt rocks recovered from the center of the structure is ~65 Ma and, within the limitations of the ^{40}Ar-^{39}Ar dating method, are coincident with the age of the KT boundary. The magnetic properties of the core samples indicate they cooled during an interval of reversed geomagnetic polarity, again consistent with a KT connection. The composition of the melt rocks within the Chicxulub structure match precisely the composition of the impact glass spherules found in the KT boundary sites in Haiti and Northeastern Mexico, in terms of major, rock trace elements, and isotopic properties. Fragments of unmelted silicate basement in the breccia samples from Chicxulub reveal a medium-to-high grade metamorphic granitic protolith consistent with the shocked lithic fragments found in the KT boundary worldwide. Age estimates based on U-Pb in zircons indicate that the age of the Chicxulub basement matches precisely the 545 Ma age of unmelted shocked debris from the KT boundary in the Western Interior of North America.

Exploration drilling activity initiated by Pemex in the Chicxulub area has provided the important access to core samples, which when analyzed, establishes a strong connection with a large meteorite impact crater and the mass extinctions at the KT boundary. But the amount of coring was quite limited and interest in drilling deeper into the structure wained

when crystalline rocks were intercepted. Consequently, the highly incomplete samples of the impact-generated lithologies cannot adequately address the fundamental issues listed above. Continued investigations of this structure, focused on a more precise understanding of large multiring impact basins and their environmental effects, will require an aggressive scientific drilling program designed to meet specific objectives. Because the crater is only shallowly buried, it seems reasonable to expect that the complete sequence of impact melt rocks and breccias, and the underlying shocked basement can be recovered by continuously coring to a depth of three to six kilometers near the basin center. To evaluate lateral heterogenieties in the impact units and underlying basement would require several sites located at various distances from the basin center. The nature of the ejecta and rim deposits can be addressed with much shallower drilling efforts located on the basin margins.

Other Important Meteorite Impact Structures

The Sudbury Basin, located in Ontario, Canada, is the eroded and deformed remains of a 150 km to 250 km diameter impact crater. It is also one of the world's largest supplies of nickel ore. This structure benefits from abundant industrial exploration activities and a strong interest from the Ontario Geological Survey and the Geological Survey of Canada. It has been the focus of several drilling efforts which provided lithological constraints for deep seismic profiling and other geophysical activities. Nonetheless the origin of the extensive sulfide mineralization and the unusual sequence of crystalline rocks filling the basin remain problematic. Although this feature has been studied in considerable detail, future scientific drilling efforts will require drilling to considerable depths if significant advances are to be achieved. Additional details of this structure and its potential benefits are found in another section of this report.

A number of craters in Russia have been explored through scientific drilling efforts by the former Soviet Union. The Puchezh Katunki structure is an 80 km diameter impact crater in Russia. Although smaller than the previous examples, a considerable amount of information on the distribution of shock deformation features and the chemical and physical properties of various impact lithologies has already been gathered by Russian scientists. Popigai crater is ~100 km in diameter with a configuration suggestive of a multiring basin. Like the Chicxulub structure, this structure is relatively young at ~35 Ma. Because it is not buried it presents access to deep structure through shallower drilling efforts. It is not clear what if any global biological consequences this impact might have produced and continual subaerial exposure has removed the uppermost units that would normally have provided information necessary to address this issue.

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III. Evolution and Physical Processes of Sedimentary Basins

Introduction

Sedimentary basins provide one of the most complete and fundamental long-term records of Earth's geologic history and house much of the world's hydrologic and hydrocarbon resources. Understanding the origin, evolution, and physical state of sedimentary basins is thus critical to understanding earth history and managing the wise use of our resources. Problems related to the origin of sedimentary basins can be divided into two categories: „large-scale" and „basin-scale". „Large-scale" factors involve the origin of sedimentary basins in terms of plate tectonic processes and „basin-scale" factors include subsidence, sedimentation, compaction and heat, fluid and mass transport within a given basin.

On the „large scale," virtually all modeling carried out so far has been in terms of lithospheric displacements, neglecting dynamic stresses. This is because stresses are very sensitive to adopted lithospheric rheologies and these rheologies have been, by convention, unrealistically simple. This is true of models for both extensional and compressional sedimentary basins. Moreover, changes in plate tectonic regimes and associated fields have been shown to be quite important in controlling the subsidence record and stratigraphic architecture of extensional basins (Cloetingh and Kooi, 1992; Kooi and Cloetingh, 1992).

At the „basin-scale", research questions are focused on understanding the mechanisms of heat, mass, and fluid transfer and how these processes interact to produce the observed conditions of sedimentary basins. A better understanding of the relationship between pressure, stress, and rock properties will reveal much about the structure and the evolution of the permeability in sedimentary basins. At the „basin-scale" also lies the question of how individual faults behave as conduits or seals and under what physical conditions displacement is possible across these faults.

Scientific drilling is an important direct observational tool that will complement ongoing observational and theoretical studies addressing these problems. Proposed applications of scientific drilling are: 1) boreholes in recent and ancient extensional basins to better understand the dynamics of rifting and the interplay of tectonics and climate. 2) Drilling into high heat producing granites beneath basins for potential energy sources; 3) Drilling active extensional faults to examine in-situ properties and address mechanics of fault orientation, fault property, and fault movement; 4) Drilling transitions from hydrostatic to geopressured strata to examine in-situ properties and understand mechanisms of geopressuring; 5) Drilling type location to understand how stratigraphy records sea-level change.

Key Large-Scale Questions

To understand the origin and evolution of sedimentary basins in terms of lithospheric dynamics we must understand what controls: (1) where and why sedimentary basins develop, (2) the rates and duration of subsidence and basin fill, (3) uplift and erosion, (4) structural style and changes of structural style with time, (5) salt tectonics and shale diapirism, and (6) heat transfer, fluid flow and rock/water interaction.

To quantitatively address these issues, the interplay between heat and mass transport, and strength and stress of the lithosphere are critically important as an overall constraint

on lithospheric deformation. In the context of the relationship between lithospheric deformation and basin development we need to address a series of fundamental questions:

How is the evolution of sedimentary basins tied to lithospheric dynamics?

Sedimentary basins provide the recorder for the spatial and temporal evolution of the lithosphere. The formation of these basins reflects the large scale tectonic processes operating in the plates as well as plate interactions. For example, the timing of initiation and abortion of rifts occurs in many cases in intervals too short to be explained by thermal processes in the athenosphere/lithosphere system, suggesting a strong control exerted by forces operating on the lithosphere plates themselves (Ziegler, 1989).

Examples include the abandonment of the Labrador spreading center in conjuction with a late tectonic reorganization of the stress regimes as a result of plate interactions and the formation of Mesozoic extensional basins in Central Africa. Similar patterns have been established for the inversion events in northwest Europe, following closely the changes in plate motions and reflecting the transmission of far field compressional stresses induced in the Alpine collision zones (Ziegler, 1990).

In other cases, such as the Tertiary East African rifts, processes such as thermal perturbations in the upper mantle may have provided the driving force for extensional basin formation. Rifted basin formation by gravitational collapse of over thickened crust is another example of a basin formation process not directly linked to plate motions. Interactions with superimposed far-field stresses induced by plate motions may, however, strongly influence the effectiveness of crustal collapse as a basin formation mechanism. As widely realized, it is often a combination of these mechanisms that provides the unique signature of the individual basin (Cloetingh *et al.*, 1993a and papers in Tectonophysics, v. 226, see for a location of the basins discussed Fig. III-1).

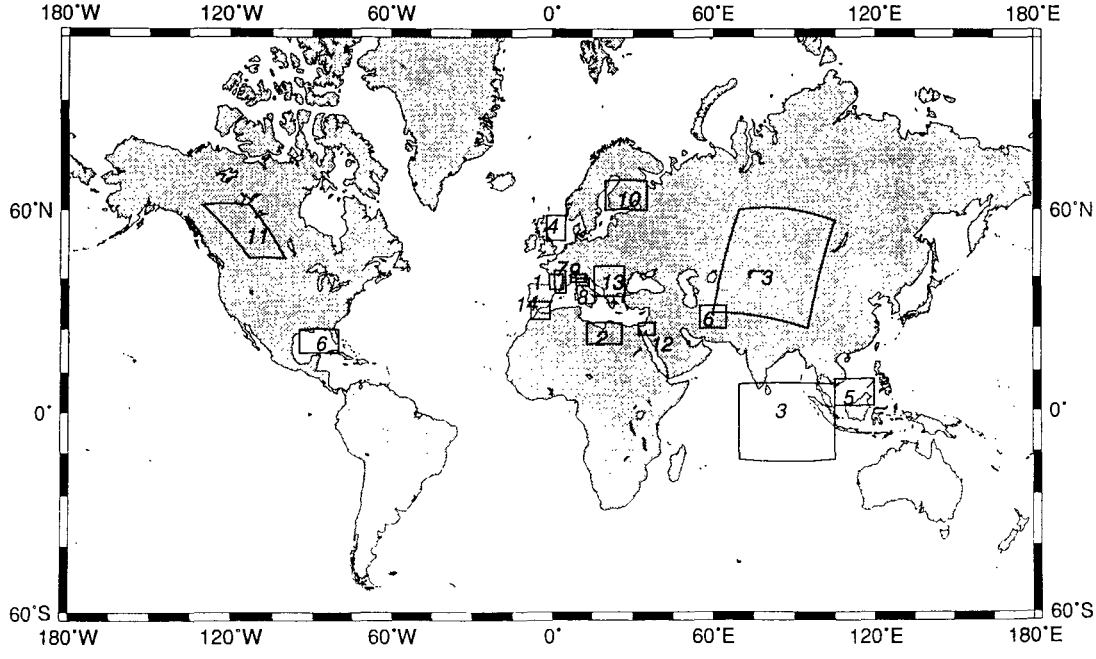

Figure III-1: Areas selected as natural laboratories by the Task force on Sedimentary Basins of the International Lithosphere Program and discussed in the special issue of Tectonophysics, v. 226, no. 1 4, 1993, S. Cloetingh, W. Sassi and F. Horvath, eds.

Many questions still need to be answered about the precise nature of the interplay of the stresses operating on the lithosphere and the mechanical structure of the lithosphere. We believe this interplay can strongly influence the location, timing, and style of basin formation.

What are the sources of stress that lead to formation of sedimentary basins?

The sources of stress in the lithosphere can be subdivided into several categories (see for a review Zoback, 1992 and Zoback *et al.*, 1993). These stresses vary in magnitude, ranging from several tens to as much as a few hundred MPa, comparable to the strength of the lithosphere. Stress concentration by geometrical focusing or local weakness zones can be a crucial factor in magnifying the level of the stresses to that comparable to lithospheric strength. The question of whether lithospheric stresses remain relatively constant over time, as has been suggested for the Proterozoic Australian lithosphere, or varies episodically, is of key interest for understanding the dynamics of basin formation. Recent studies of large scale plate tectonic processes complemented by structural geological field studies on a much smaller scale have demonstrated that in some places, lithospheric stresses undergo important temporal changes both in orientation and in magnitude. In particular, studies of the northwest European and Mediterranean stress fields have revealed temporal changes on a characteristic time interval of 2 5 Ma (Philip, 1987).

How does the interaction between internally and externally applied stresses affect the formation and evolution of sedimentary basins?

Time varying interactions of internally and externally applied stresses are probably of key importance in the explanation of migrating rift axes of extensional basins, as well as migrating depocenters in the foredeeps of foreland fold and thrust belts. The actual magnitude and the depth distribution of internally applied body forces and externally derived far field tectonic stresses depends on the rheological layering of the lithosphere. Stress concentrations caused by lateral variations in lithospheric rheology affect the spatial wavelengths involved in basin formation processes (Burov *et al.*, 1993).

Key areas to investigate the interaction of externally and internally applied forces in conjunction with rheological models are the Betic/Alboran Sea system (Cloetingh *et al.*, 1992) and the Carpathian/Pannonian basins. For both areas an intensive debate is going on regarding the relative importance of internal stresses and body forces associated with gravitational collapse versus far field tectonic stresses induced by changes in plate configuration and subduction zone dynamics. Both areas developed extensional basins in a compressive stress regime with a strong control exerted by the dynamics of the down-going African lithosphere (Wortel and Spakman, 1992). In these systems, a flexural coupling of foreland flexure (induced by thrust sheets of the Carpathian arc and the Betic nappes) occurs with shoulder uplift of the adjacent Pannonian and Alboran extensional basins (e.g., Cloetingh *et al.*, 1992; Morley, 1993) and thus reflect lateral variations in the mode of extension along strike of the Betic and Carpathian arcs.

How do space and time variations of rheology and pore pressure affect stress transmission, strain, vertical motions and stratigraphy during basin evolution?

The manner in which lithospheric stresses are distributed throughout a basin is a function

of the rheological properties of the basin and the surrounding crust. Within the brittle domain, the magnitude of pore pressure establishes a fundamental constraint on the magnitude of deviatoric stress in the crust and changes of pore pressure may have a profound effect on basin evolution. An important example of why is related to the observation that many basins are pervasively over pressured at depth (i.e., the pore pressure is essentially equal to the magnitude of the over burden stress). In such cases the effective strength of the rock is essentially zero; compressional deformation, or even basin inversion, can be induced by relatively minor changes of applied stresses, and, as regionally applied stresses could not be transmitted through the overpressured sections of the basins, they would be concentrated in stronger sections of the crust. Perhaps more importantly, application of compressive stress will generate appreciable fluid flow as pore pressure increases resulting from pore volume compression will result in natural hydraulic fracturing and fluid expulsion.

The extremely low strength and viscosity of salt and some overpressured shales also represent important examples of the manner in which rock rheology affects the evolution of deformation of sedimentary basins. Low angle normal faulting and detachments frequently occur along salt and shale layers, providing an important influence on the style of deformation within basins.

What factors influence spatial and temporal variations of rheology in, and around, different kinds of sedimentary basins?

The basic factors affecting rheology are temperature, lithology (perhaps more correctly, mineralogy, including the state of hydration or dehydration), the state of stress, porosity, chemical composition of pore fluids, and the possible presence of melts. Some of these factors change with time, especially as the result of vertical displacements producing temperature/pressure and stress related effects. Spatial variations of rheological properties are likely to be extremely important in controlling the localization and style of deformation. Of course, the primary control on spatial variations of rheological properties are the compositional changes associated with the geological evolution of an area. A widely observed geological phenomenon is the tendency for localized deformation to repeatedly occur in certain places over geologic time, often with different structural styles. For example, both the New Madrid rift and Rhine Grabens are Paleozoic intraplate extensional structures that are currently being compressionally reactivated with the predominant style of contemporary faulting in both areas being strike slip.

What is the role magmatism in basin formation and what deep seated processes does it reflect?

Volcanism is rare inside actively forming sedimentary basins. But magmatism can occur as intrusions (dykes, sills and plutons) at different depths, at different locations, and at specific times during basin development. When magmatism occurs, however, it gives important information about the relationship between heat, magma pressure and the development of stresses in the basin. This knowledge is only rarely utilized when studying the geological history of basins.

In the Oslo Graben the sills predate the time of greatest volcanic activity, occuring at a time when extensional stresses were increasing (Sundvoll *et al.*, 1992). The large extrusions of plateau lavas in the Oslo Graben mostly predate the major normal faulting activity impying that magma pressure declined when the extensional stresses were still

active. Frequently, the use of magmatism as a stress indicator is overlooked by geologists working in such areas. It should be noted that magmatism is in general easily datable and can also provide important additional information on the heat budget.

Although many of these observations are directly related to the thermal history of the rifted basin, some of the observations cannot fully be explained by this alone. Does the stress history of the specific basin explain aspects of basin formation that cannot be explained solely by temperature and heat flow alone? More examples of worldwide relationships with magmatism and stress in rifted basins, pull apart basins and passive margins are needed.

Key Basin-Scale Questions

Basins are complex systems comprised of a large number of individual components which interact to form the entire system behavior. Although sedimentary basins have been studied for years (driven by hydrocarbon exploration), it is remarkable how many fundamental questions remain both concerning characterization of the state and behavior of the individual components and descriptions of the complex interactions between the components. Below we present a partial list of these components and their controls on basin evolution.

Components of Basin-Scale Evolution

Sedimentation: The sedimentary evolution provides the basic lithologic framework which in turn controls the distribution of primary permeability and the distribution of hydrocarbon source rocks.

Subsidence: Subsidence controls the space available for sedimentation. It is fundamentally a large-scale problem in that large-scale tectonic processes provide an initial mechanism for subsidence. However, subsidence is strongly modified by intra-basinal processes. Listric growth faulting creates subsidence within sedimentary basins, and sedimentation magnifies subsidence by loading.

Faulting: Faulting can be both driven both by large-scale tectonic processes (i.e.. extensional growth faulting during rifting) and be a response of basin evolution itself (i.e., growth faulting in overpressured shales of passive margin basins (Worral and Snelson, 1989).

Temperature: The basal heat flow into sedimentary basins is a fundamental large-scale tectonic control. Yet the temperature field and the evolution of that field is fundamentally controlled by the thermal conductivity and the permeability distribution within the sedimentary basin.

Pressure: The fluid pressure within a sedimentary basin is fundamentally an intra-basinal phenomena. It is controlled by the large-scale permeability field, the subsidence history, and the generation of pressure sources during basin evolution.

Stress: The stress field is controlled both by the physical processes of deformation within the basin but also the extra-basinal 'tectonic stresses' applied to sedimentary basins.

Porosity: The porosity field is first controlled by the compaction history of the basin and second by the dissolution and or cementation processes due to chemical changes in the basin.

Research Approach to Basin-Scale Evolution

The analysis of basin-scale evolution can be approached at several levels that can be illustrated as follows:

Characterizing the Physical State of Basin-Scale Components:

Although sedimentary basins have been studied in great detail, there remains fundamental information without which the broader issues of basin-scale system behavior cannot be addressed. Further careful characterization of all the components described above, and many that were not listed, are necessary to address these problems. We list just a few examples below.

1) Lithostratigraphic and chronostratigraphic mapping by means of field observation, multi-channel seismic, or drilling is a basic characterization step that must continue. This approach yields the critical information upon which geologic interpretation can proceed.

2) Similarly, the characterization of pressure in the subsurface and its' relationship to lithology is of critical importance. Characterization question is what is the distribution of fluid pressure. Powley (1990) has proposed that pressure seals form at certain pressure and temperature conditions in the earth and these can be independent of lithology. Significant research effort must be expended to test this hypothesis. This approach attempts to document the distribution of fluid pressures and their relationship to stratigraphy and local chemical seals (*e.g.* Fig. III-2). Obviously, externally-applied stresses can also have a marked effect on the distribution of pore pressure within a basin as schematically illustrated in Fig. III-3.

Describing the Physical Behavior of the Components

In characterizing the present state of the basin system, we need to understand the physical behavior of the individual components. Below we list several examples:

How does a rock compact?

Porosity is observed to decrease with effective stress in sedimentary basins (Fig. III-4). This physical process can be inferred from direct measurements in boreholes of porosity, pressure, stress, and material properties (such as Poisson's ratio). A second approach to understanding the physics of this deformation is through direct laboratory experiments by subjecting sediment to deformation (e.g. Karig and Morgan, in press). The results of this approach have extremely important implications for our understanding of basin-system behavior. For example, the compaction due to sediment loading is one of the fundamental sources of fluid pressure in sedimentary basins (Palciauskas and Domenico, 1989). Different workers have chosen very different rheological models to describe this behavior. For example Mckenzie (1978) use a viscous model to describe sediment properties, while Bethke (1985a, 1986) and Palciauskus (1989) use an elastic model.

What is the relationship between pressure and stress in a sedimentary basin?

Two extremely different approaches have been used to predict the interrelationship between pressure and horizontal stress in sedimentary basins. On the one hand a simple uniaxial elastic strain model has been used to describe this relationship with the result that the ratio of effective stresses is a function of Poisson's ratio. In marked contrast, Zoback and Healy (1984) proposed a relationship based on the Coulomb failure criterion

where the ratio of principle stresses is controlled by the friction coefficient of the rocks and pore pressure. Once again, resolution of these problems has direct implications for our ability to understand large-scale system behavior. In the uniaxial strain example the stress field can be understood as solely a function of the vertical load and the fluid pressure. While in the latter case, the state of stress is controlled by the frictional strength of rock which is assumed to be in a state of failure equilibrium.

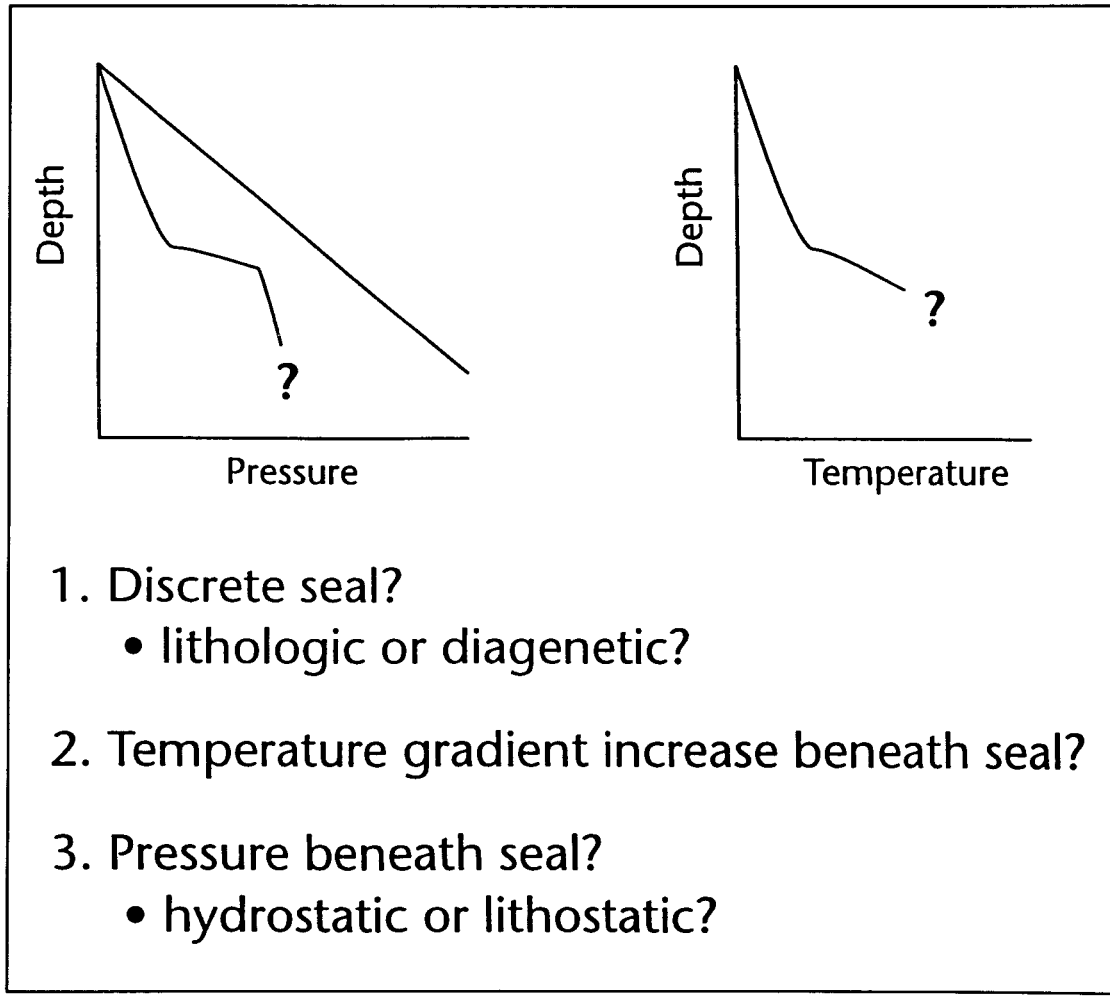

Figure III-2: A sketch of temperature and pressure field passing through a geopressure transition. Question marks illustrate that we do not yet understand the nature of the pressure and temperature field beneath the onset of geopressure.

Understanding Basin-Scale System Behavior

The final step of this approach is to integrate the behavior of the individual components to understand and predict the evolution of the basin system. Below we cite several examples of this approach at both the „large-scale" and the „basin-scale."

At the large scale, it is reasonable to start with the generally accepted idea that plate tectonic processes have determined the evolution of the Earth throughout Phanerozoic times (and possibly also during the Proterozoic). These processes involve continental extension and the opening of new oceanic basins, as well as the subduction of oceanic lithosphere and the collision of continental cratons leading to the formation of orogenic

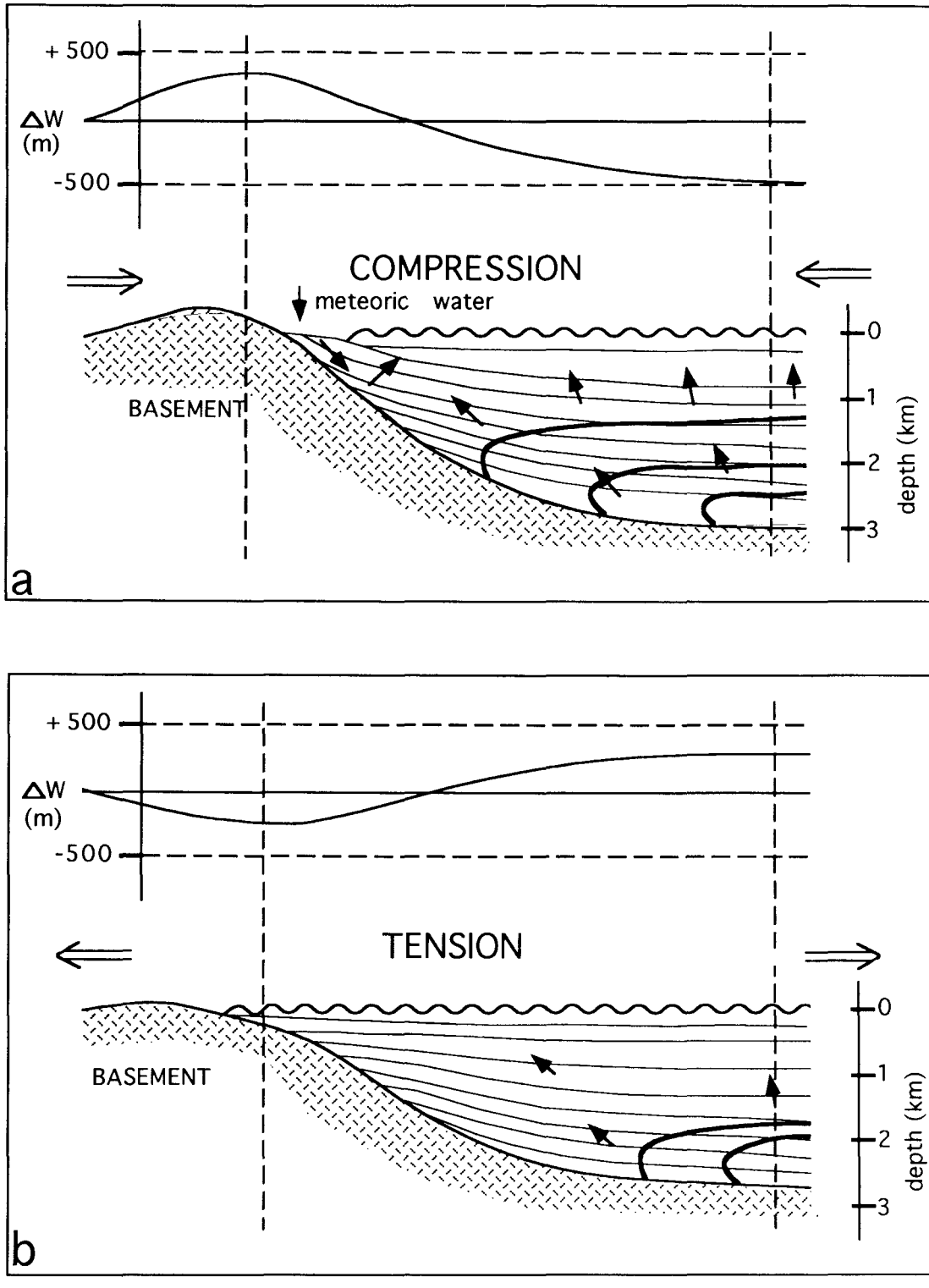

Figure III-3: Schematic illustratation of the relationship between stress-induced tilting of basin and perturbations in hydrodynamic regime.

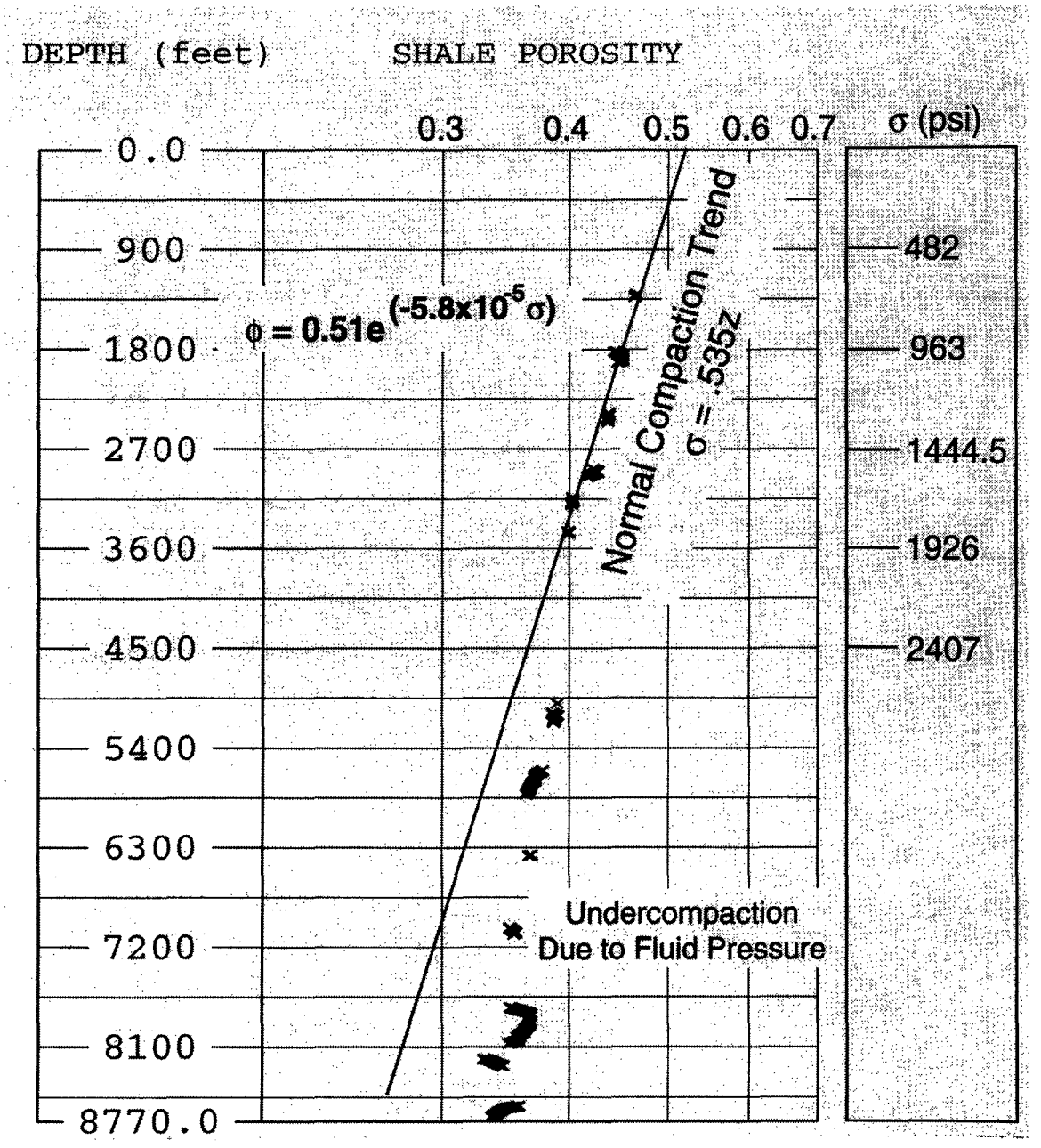

Figure III-4: Porosity vs. Depth in a Plio-Pleistocene offshore Gulf of Mexico well. Porosity is an exponential function of effective stress (s). with depth.

belts. As a result of this continuous history of plate movements and plate interactions, geodynamic processes determining the origin and evolution of sedimentary basins have changed through time and space. These changes may be reflected in the nature of the stratigraphic record and in distinct phases of basin deformation. It is important, therefore, to document and predict the spatial relations of plate interactions and associated intraplate paleo-stresses using computer programs that permit the construction of global palinspastic maps. For this purpose use could be made of the results of the Paleomap Project, a joint IUGG-IUGS programme whose goal is to produce a plate tectonic and paleogeographic synthesis of the Earth during the Phanerozoic, both through publications and by development of appropriate software packages.

The full incorporation of data on the mechanics of thrusting and faulting in basin

models is important as well as the collection of data on erosion rates and sediment transport in foreland basins. This is a must for a better understanding of the role of tectonics versus climate in these basins. The fill of foreland basins is characterized by a geometry and facies distribution which is continuously controlled by the structural development of the adjacent mountain chain. Plate collision, thrust sheet emplacement, and thrust propagation are directly responsible for the basin geometry, stratigraphic architecture, sequential partitioning, stepwise outward displacement of depocenters and facies distribution. Integration of these data forms an important step in the construction of a time-step model of the basin fill where thrust load, subsidence, sediment input and eustasy are incorporated.

Similarly, the sedimentary fill of extensional basins is to a large extent influenced by the type and geometry of the basement structure. The contact between the syn-rift fill and the basement and the lateral extent of infilling sequences is often fault-controlled. Sequence boundaries in extensional basins often involve erosion of the basin margins due to uplift of rift shoulders and reliable estimate of eroded thickness are, therefore, crucial in quantitative modeling. Integrated data bases on seismic stratigraphy, mapping of facies distribution, mapping and dating of extensional faults, good time control on the existing and missing record and accurate determination of the sequence-stratigraphic subdivision of the basin fill is required.

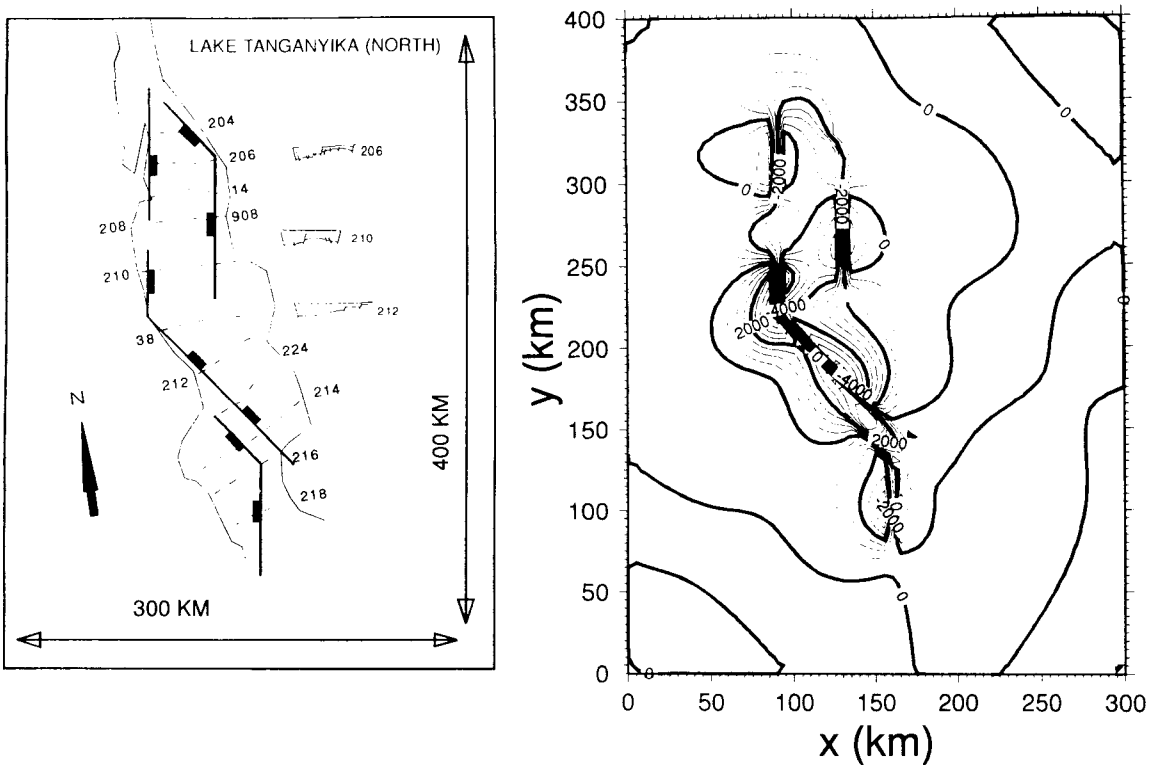

Figure III-5: Model linking 3D flexure and faulting and application to the Lake Tanganyika rift setting. (left) Basin configuration and location of faults. (right) Deflection contours (meters) calculated with numerical model incorporating basin faults and 3D flexure (after van Wees and Cloething, in press).

Perhaps one of the most effective ways to examine the interaction between the individual components of a basin system is to use quantitative modeling. At the „large-scale" this approach has been used to describe the structural evolution and stratigraphic evolution of

sedimentary basins (e.g. McKenzie, 1978; Jordan 1981; Flemings and Jordan, 1989; Lawrence, 1990; Cloetingh *et al.*, 1993). Recently developed modeling technology linking 3-D flexure and faulting (Van Wees and Cloetingh, 1994; Fig. III-5) will allow the full incorporation of the mechanics of basin formation in a new generation of basin modeling to be tested with drilling and seismics. A principal goal of a detailed study and modeling of sedimentary basins should be optimization of this type of information.

At the basin scale, it is important to realize that in most commercially-developed sedimentary basins (where sub-surface data from wells should be widely available) data on stress, pore pressure, temperature and heat flow are available in varying amounts. Unfortunately, many opportunities to obtain more complete and better data are not taken advantage of and relatively few integrated and complete data sets exist. A principal goal for the detailed study and modeling of sedimentary basins should be acquiring and managing large data-sets of basin systems. We emphasize that much data is being lost permanently as industry abandons high cost and declining fields. Much of this information is no longer proprietary, but does require considerable commitment of effort to rescue and manage this information.

A long-standing approach to understanding the complex interactions of a variety of components has been the use of physical models. An example of such an approach is a sand-box deformation experiment of fault deformation. Similar models have been made to describe the evolution of porosity and pore pressure. At the „basin-scale", this approach has focused on integrating the processes of heat, mass, and fluid transfer. Bethke (1985a,b) and Harrison and Summa (1991) have built on earlier work (e.g. Bredehoeft and Hanshaw, 1968) to predict the evolution of porosity, pressure and temperature using as constraints present-day observations of sedimentary basins. Quantitative modeling is now being extended to consider diagenetic processes within basin systems (e.g. Orteleva and Al-Shaieb, 1993; Moore and Orteleva, 1990).

Research Questions in Basin Systems

While significant progress has been made on understanding the dynamic behavior of basin systems, fundamental research questions remain:

- What are the principal mechanisms that cause fluids to be expelled from some formations and accumulate in others? Compaction-driven fluid flow is clearly quite important, but what are the other mechanisms and how do these mechanisms interact with stratigraphy, structure and in-situ stress?
- How do heat, mass and fluid transfer within the sedimentary section affect basin development?
- Is fluid flow continuous or episodic? What are the roles of faults in controlling fluid flow? What are the principal controls on geopressure and how does geopressure control the permeability of sedimentary basins.
- What are the principal chemical, biologic and thermodynamic controls on hydrocarbon maturation?
- How is cementation and diagenesis controlled by basinal fluid flow? Progress towards understanding the nature of these links is most likely to come from empirically establishing temporal connections between sediment diagenesis and features of basin evolution in a number of areas and then by modeling the effects these phenomena might have on fluid flow.

- What is the fundamental control on basinal fluid flow? Sedimentary processes, themselves strongly influenced by tectonics, largely determine permeability distribution and hence exert the initial control on the location of overpressured zones and permeable pathways. Basin tectonics may affect fluid flow in a number of ways. Rates of subsidence exert the second control on overpressuring in fine grained rocks and determine the pattern of fluid expulsion along more permeable sedimentary units. Faulting will affect flow paths by creating impermeable barriers or permeable conduits which did not exist in the unfaulted sequence and may also release overpressures. Margin uplift and erosion will subject portions of basins to artesian flow of meteoric water. Although these features of the evolution of sedimentary basins will have a major influence on fluid flow, the details of how they affect flow rates and paths remain poorly understood.

Key Areas/ Natural Laboratories

At the „large-scale" and the „basin-scale", the natural laboratory for the analysis of sedimentary basins is one where there is a sufficient data base to characterize the basin system. Such data might be provided within an ancient exhumed basin system, a modern rift system, or a sub-surface basin that is in the mature phase of hydrocarbon development. Cloetingh *et al.* (1993) presented a number of natural laboratories (Figure III-1) which include:

Passive margin basins

Norwegian and Greenland margins

Western Mediterranean extensional basins and the Pannonian Basin

Atlantic Margin (North America and Europe)

Foreland basins

Pyrenean and Betic foreland basins

Molasse Basin

Alberta Basin

Central Australian Basins

Rifted basins

North Sea

Sverdrup Basin

Strike-Slip related basins

San Andreas fault system

Dead Sea rift

Scientifc drilling in sedimentary basins is already operational in a number of countries including, France and Russia. A number of specific basins were proposed during the Potsdam meeting.

1. The Molasse basin of western Switzerland and southern Germany (Fig. III-6). The sites in the peri-Alpine Molasse basin falls also in the framework of the Peri-Tethys project (Vaslet and Dercourt, 1993) with a strong emphasis on the

calibration of models on thermal, subsidence and fluid flow and the quantification of the tectonic versus eustatic control on the sedimentary record.

2. The North German basin, extensively drilled by the oil industry.
3. The Baikal rift to study the dynamics of rifting and the interplay of tectonic and climate. A parallel study is proposed in the Lake Tanganyika region utilizing results from recently developed 3-D modeling of tilted fault blocks (Fig. III-5).
4. Drilling in the Newark basin to study the interplay of tectonics, climate and orbital fluctuations on the sedimentary record in rift settings. This approach is important to calibrate astronomically variations and to investigate the interplay of basin formation mechanics and high frequency control on sedimentary succesions.
5. A number of sites proposed in the framework of the Canadian drilling continental drilling program, including the southern Ontario drilling proposal Algonquin Arch transect (Drury, 1989; 1990)
6. Australian hot dry rock HDR geothermal energy targets, including drilling a high heat producing (HHP) granite beneath the Cooper basin of south Australia
7. Continental drilling through geopressure transitions. This will test the broad range of hypotheses on what controls geopressure. A borehole has the opportunity to directly measure fluid pressure, fluid and rock composition, porosity, and stress state. There are any of a broad range of sedimentary basins where this could be proposed. Two attractive basins are the Plio-Pleistocene Gulf Coast and the Viking Graben. These two sites are both heavily explored; hence there is an abundance of data available to characterize the site prior to drilling. They also are of very different ages. While one might expect Gulf Coast geopressures to be dominantly due to undercompaction and sediment loading; it is possible in an older basin the fluid pressure sources are due to other effects (such as thermal expansion or hydrocarbon generation).

Proposed Scientific Drilling Problems and Sites

Scientific drilling fits alongside a range of research tools in furthering our understanding of the basin system. Most importantly, drilling provides the opportunity to directly characterize active processes. Data on the state of stress, pore pressure, temperature and heat flow are critical for an improved understanding of the origin and evolution of sedimentary basins in two important ways. Knowledge of the state of stress and pore pressure provides insight into the nature of deformation and temperature and heat flow provide critical information about the nature of heat transfer and mechanisms driving fluid flow. These types of data proved fundamental information for both input and testing of dynamic models.

Measurements of stress, pressure, and rock properties across faults.

There are a huge range of questions possible concerning the mechanics of faulting, fluid flow along faults, and the orientation of faults. We use the recent Global Basins Research Network Pathfinder Well as an example of the potential of this approach (Billeaud *et al.*, in press) in which scientists from academia deepened an industry well to penetrate a growth fault to conduct a wide range of investigations, including measuring stress, pore pressure and porosity (Fig. III-7). A fundamental question remains how, when, and under what conditions do faults behave as permeability pathways. The growth

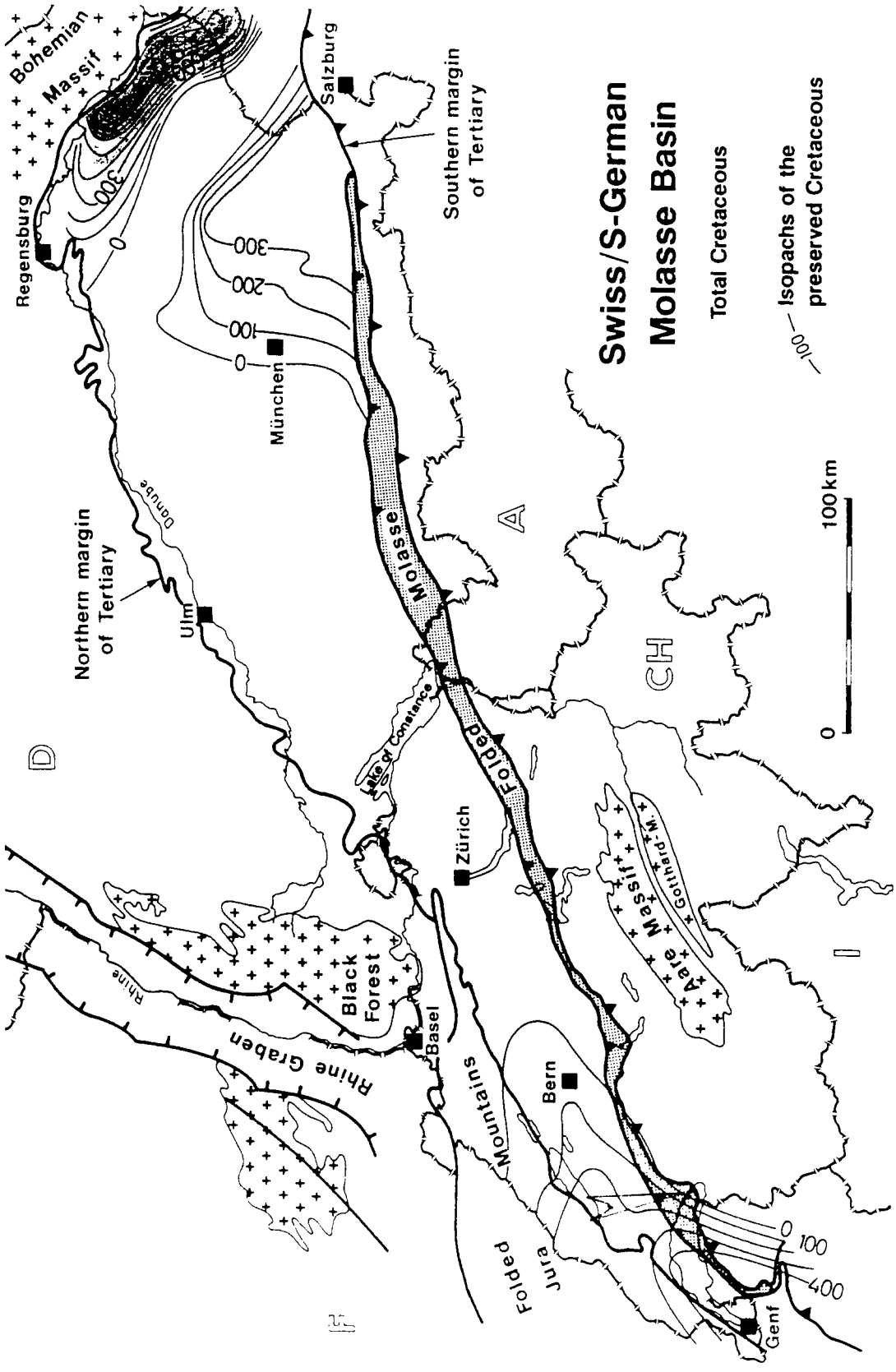

Figure III-6: Example of possible target for scientific drilling in foreland fold and thrust belt of the peri Alpine Molasse basin .

faults in the offshore Gulf of Mexico are thought to be the fundamental hydrocarbon migration pathway. In-situ measurements of temperature, pressure, stress, porosity and chemistry have the potential to answer how these faults behave as hydraulic conduits.

Drilling Strategy

As it has been demonstrated in other areas of sedimentary basin research (Cloetingh *et al.*, 1993a; Zoback *et al.*, 1993), close cooperation between industry and the academic research community can be very advantageous and cost-effective to both sides. On the topic of deep drilling in basins, such a link seems to be mandatory considering the cost-intensive nature of the proposed research and the need to avoid duplication of industry efforts in drilling in basins. Planning of drillholes in basins should therefore complement and utilize the industry drilling activity.

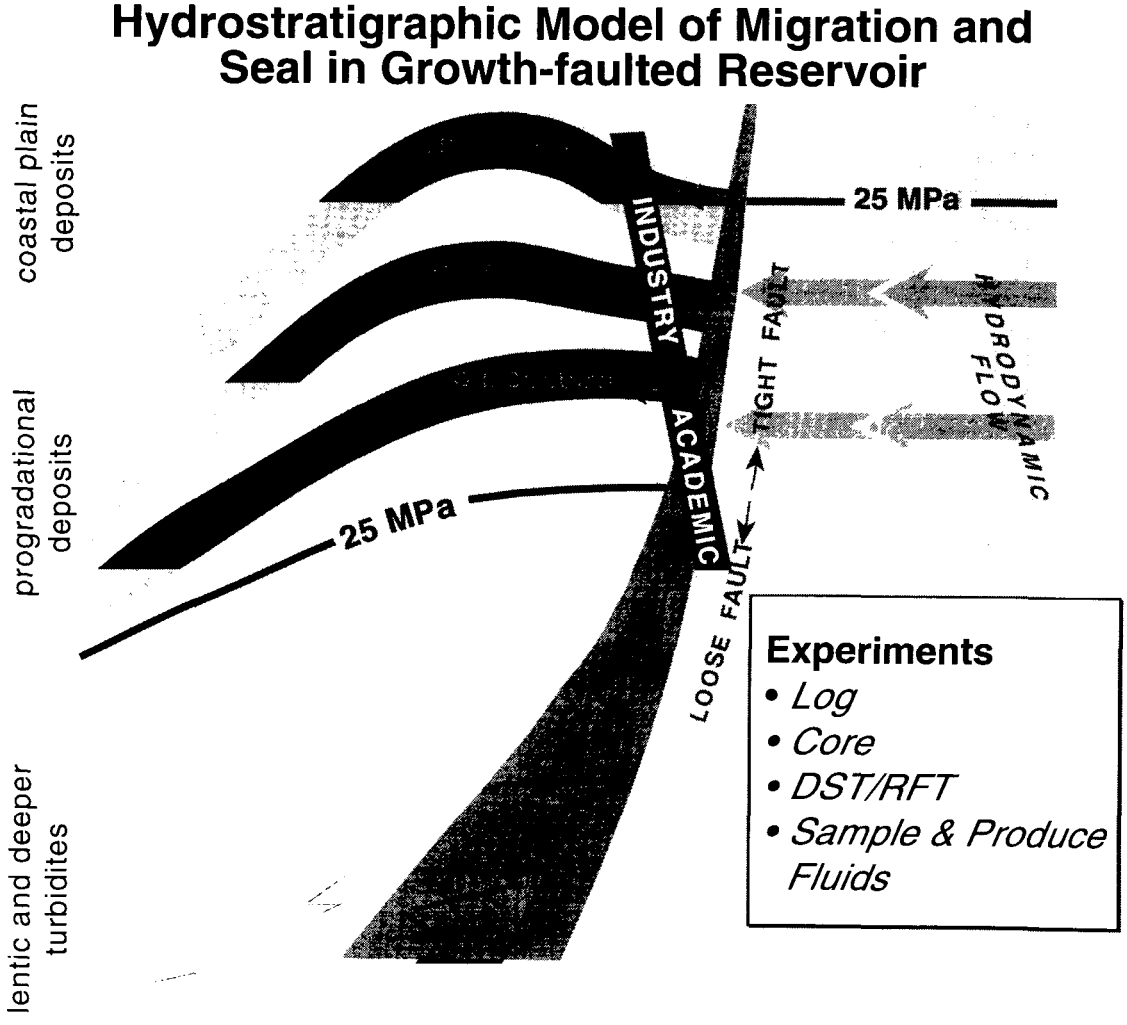

Figure III-7: Sketch of the GBRN Pathfinder experimental well (see text). In this well academia, government and industry collaborated to extend an industry well across a growth fault to examine physical properties across the fault plane.

A cost effective way to achieve scientific results will be to collaborate with industry boreholes. The Global Basins Research Network well is a good example of this. In this case, the GBRN (a consortium of 8 U.S. universities and 6 major oil companies)

collaborated with Pennzoil Corporation and its' partners to extend the industry borehole schematically shown in Fig. III-7. Industry thus paid for the shallow hole while academia paid for research in the borehole that was not deemed of sufficient economic interest to justify expenditures by the oil industry. We would propose this approach as one way of 'piggy-backing' critical research on top of ongoing drilling programs.

Drilling of shallow-water stratigraphic sequences to test fundamental aspects of sequence stratigraphic concepts is another fruitful approach of joint interest to industry and academia (e.g. Miller et al., 1993). This would be complimentary to ODP drilling as ODP cannot drill shallow-water stratigraphic sequences because of shallow water and shallow gas, leaving the shelf unexplored to drilling by the academic research community.

The construction of a series of drillholes through the same lithostratigraphic sequence at different stages of evolution (subsidence) in proto-type geologic-tectonic settings for the reconstruction of temperature history and calibration of basins modeling is also of importance. This approach is of broad interest for 1) basin modeling on all scales; 2) understanding the complex interplay of geologic processes; 3) understanding the process of compaction and pressure evolution; 4) fluid flow; 5) diageneis; 6) mineral deposits; 7) petroleum exploration; 8) seismic interpretation. The experiment should measure sensitive parameters: organic, (e.g. time/temperature integral, vitrinitte etc.), inorganic, fluid inclusions, fission track, petrophysical studies, logging, and seismics to be used in numerical simulation procedures to quantify the energy balance over time. Quantities to be calculated include the heat flow at the surface, the heat input, compaction and fluid flow.

Finally of vital importance will also be the interaction between basin modeling and seismic interpretation.

Conclusions

Continental scientific drilling has extraordinary potential to rigorously test a variety of developing models that are attempting to integrate the components of sedimentary basins. Drilling has the great potential to characterize in-situ conditions at the basin-scale. In particular, the interrelationships between pressure, stress, porosity, and temperature can be directly examined. Scientific drilling within sedimentary basins has an added advantage that it commonly occurs within basins that have extensive databases due to hydrocarbon exploration. Further, a proposed methodology for keeping costs low is to collaborate on these research problems with ongoing industry drilling programs.

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IV. Lithospheric Dynamics and Deformation

Introduction

Since the beginning of the plate tectonics revolution 30 years ago, it has been recognized that the outermost portion of the Earth is composed of relatively strong plates of lithosphere that move with respect to each other at rates of the order of tens of millimeters per year. Much of the deformation of our planet's outer shell is concentrated along the boundary zones between plates, with less focused strain distributed throughout the plate interiors. The key earth science efforts associated with the Plate Tectonics paradigm have involved unraveling the complex kinematics of this deformation, at first emphasizing interplate motion, but more recently, within the plate interiors. These multidisciplinary endeavors have been sufficiently successful in helping understand most aspects of the kinematics of both inter- and intra-plate deformation, especially in the ocean basins.

Not nearly so successful, however, have been our attempts to determine the forces acting on the lithospheric plates and the rheological response of the plates to these applied forces. Attempts to model these processes invariably lead to frustration because of the ambiguity of the results. That is, multiple hypotheses, involving various applied forces and rheological behaviors, can yield equally good fits between modeled and observed deformation.

Unlike lithospheric kinematics, which can be observed directly using numerous geological, geophysical and geodetic techniques, the dynamics are far more elusive and difficult to characterize using the established techniques of earth science. Neither the applied stresses nor the rheological response to these stresses are observable using surface-based instruments or techniques because of the depths within the lithosphere at which the critical processes occur. Thus, earth science has clearly reached the point at which *in situ* observations at depth are needed to gain substantial new insights regarding the deformational mechanics of the lithosphere.

Two mechanisms of stress release are competing in the lithosphere: brittle rupture and anelastic creep. Tectonic stress can only rise to the yield strength, the maximum stress supported by either mechanism. The transition between the brittle to the ductile mode of stress release, although mathematically defined as a point extends certainly over a range of several km where both modes are competing with each other. The presence of pore-fluid, their pressure, rock permeability, mineral composition are controlling the critical stress status in the upper and lower crust. The classic assumption that theoretical 'brittle-ductile' transition point coincides with the deepest seismicity has been challenged by occasional observation of hypocenters throughout the lower crust. This indicates that the brittle strength of the lower crust may fall below that supported by creep mechanisms. Such a reduction of brittle strength may be induced by the presence of fluid phases under near lithostatic pressure conditions.

The stress distribution with depth in the lithosphere is often assumed to reflect its rheological behavior. The upper crust is assumed to be brittle, basically in the frictional equilibrium in a manner often described as Byerlee's law because the stresses are predicted from laboratory-determined coefficients of friction. As temperature increases with depth, the brittle-ductile transition is passed and stress is limited according to the creep law for a given strain rate. Byerlee's law based on extrapolation from laboratory measurements has been successfully tested so far to a depth of 6 km in the KTB borehole (Fig. IV-1). Figure IV-1 also shows that the distribution of the forces carried in the lithosphere (as

defined by the capability of the crust and upper mantle to sustain differential stress) suggests the the brittle upper crust is essentially carrying all the force induced at the plate boundaries because, due to the relatively high heat flow in the KTB area, the lower crust and upper mantle is extremely weak.

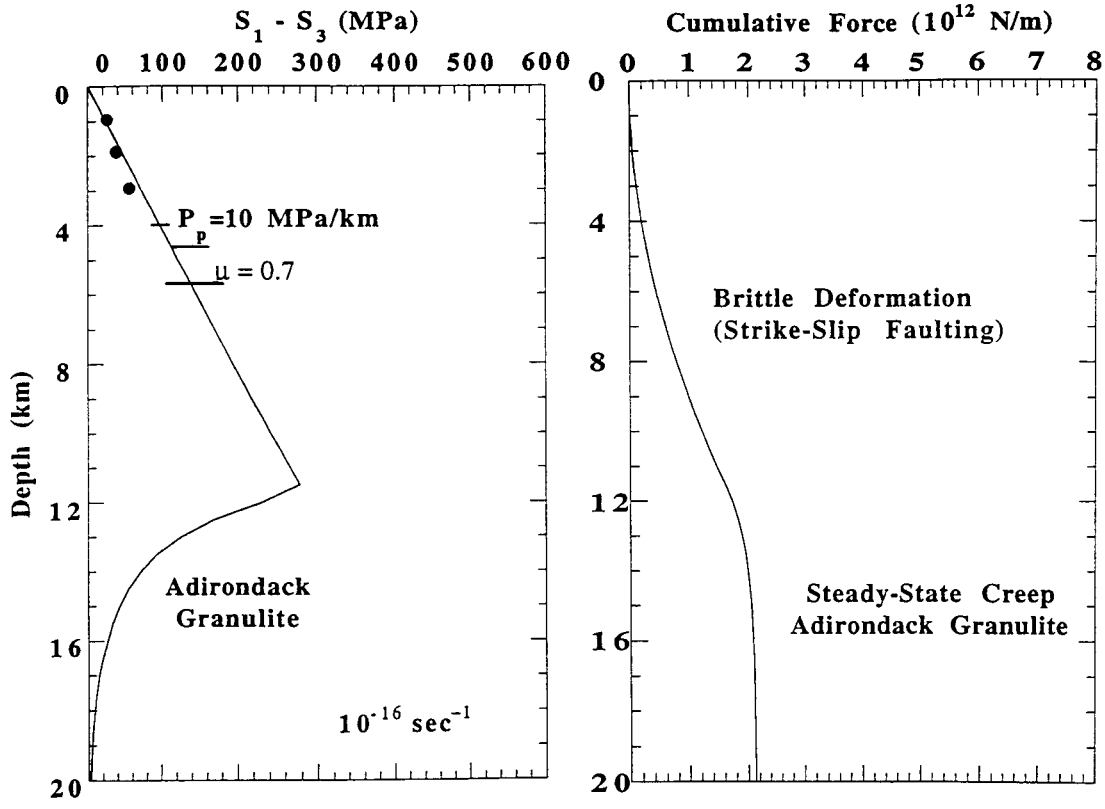


Figure IV-1: (left) In situ stress measurements in the KTB drillhole to 6 km depth showing agreement with theoretical predictions based on frictional faulting theory and laboratory derived coefficients of friction (Byerlee's law). (right) The force carried by the lithosphere in the region appears to be primarily concentrated in the upper crust because the high geotherm results in high lower crustal and upper mantle temperatures. The integrated force carried by the lithosphere in this region is compatible with theoretical estimates based on the magnitude of plate-driving forces (Zoback *et al.*, 1993).

However, while intraplate stress measurements support the validity of Byerlee's law, major plate-boundary faults appear not to. As major active through-going faults are the most dramatic expression of lithospheric deformation and because they produce destructive earthquakes these features are of particular concern to society. In spite of the importance of such faults, however, both with regard to our understanding of lithospheric dynamics and from the more practical viewpoint of societal hazard, our ignorance of their dynamics is profound. The importance of large-scale active faults to mankind and the first-order scientific questions concerning their mechanical behavior render them ideal subjects for an international effort to define the nature of their dynamics. Every nation on Earth is concerned with seismic hazard and thus, all societies have a considerable interest in a scientific program to advance our understanding of the dynamics of active fault zones in a meaningful way.

Key Questions

Although much progress has been made during the past several decades in defining the nature of crustal-scale active faults, most of this progress has involved kinematics issues. The questions regarding the dynamics of these features are much the same now as they were 20 years ago, major research efforts notwithstanding. The principal questions include:

1.) What forces, or stresses, are required to cause fault slip?

2.) Are major active fault zones weak? If so, why?

3.) What factors determine whether a fault zone is seismic (locked between earthquakes) or aseismic (creeping)?

4.) What fault features affect the nucleation, propagation, arrest, and recurrence of earthquake rupture?

5.) What factors control the size of an earthquake?

6.) What is the role of fluids in fault processes and where do they originate?

7.) How do fault zone geometry, composition, deformation mechanisms, and structure change with depth?

8.) What controls the depth of seismic activity?

9.) How do geophysical observations relate to fault zone properties? Do deformational features in ancient exhumed fault zones correlate with those in active zones?

10.) Are large earthquakes predictable?

11.) Are there fundamental differences in the applied stresses or the seismic response of large-scale faults in oceanic versus continental settings, and, if so, what causes these differences?

That several decades of substantial effort by a broad spectrum of earth scientists have not yielded definitive answers to any of these questions is, in itself, a strong indication that new „tools" are required to address these issues. In fact, these research efforts have resulted in a number of very specific and testable hypotheses regarding the nature of faults and their dynamics (*e.g.*, Sibson, 1977, 1983; Hanmer, 1988; Lachenbruch, 1980; Byerlee, 1990; Rice, 1992; Chester *et al.*, 1993). The testing of these hypotheses, however, can only be accomplished by *in situ* observation and sampling at seismogenic depths in the fault zone.

Need for Drilling

Clearly, the only way to sample the environment of an active fault zone at seismogenic depths (5 to 10 km) is by drilling. While all drilling to study earthquake processes would not have to be done to such great depth, a limited number of key drilling projects of this type will be necessary in different types of faults around the world. Such a drilling program would include the following experiments:

1.) Measure the stress state at the fault and in its vicinity. Currently, the debate regarding the level of stress required to produce fault slip involves an order of magnitude disagreement. Resolution of this debate in part entails comparing the stress acting on the fault to the regional state of stress.

2.) Sample the fault zone material. Neither the material nor its properties within fault zones at seismogenic depths is known with any great certainty. Much of what is currently conjectured about fault zone rheology is based on laboratory deformation experiments and fault rock studies from exhumed fault zones. Clearly laboratory results can be accepted with confidence only if they are performed on the appropriate materials and environmental conditions. Whether the fault zone consists of granite or serpentine, for instance, can affect dramatically its strength (*e.g.*, Fig. IV-2). Although studies of exhumed fault zones in ancient terrains have provided numerous insights regarding midcrustal rheology, such observations suffer an intrinsic disadvantage in that these terrains have been heavily modified over geologic time, especially by the processes that exposed them.

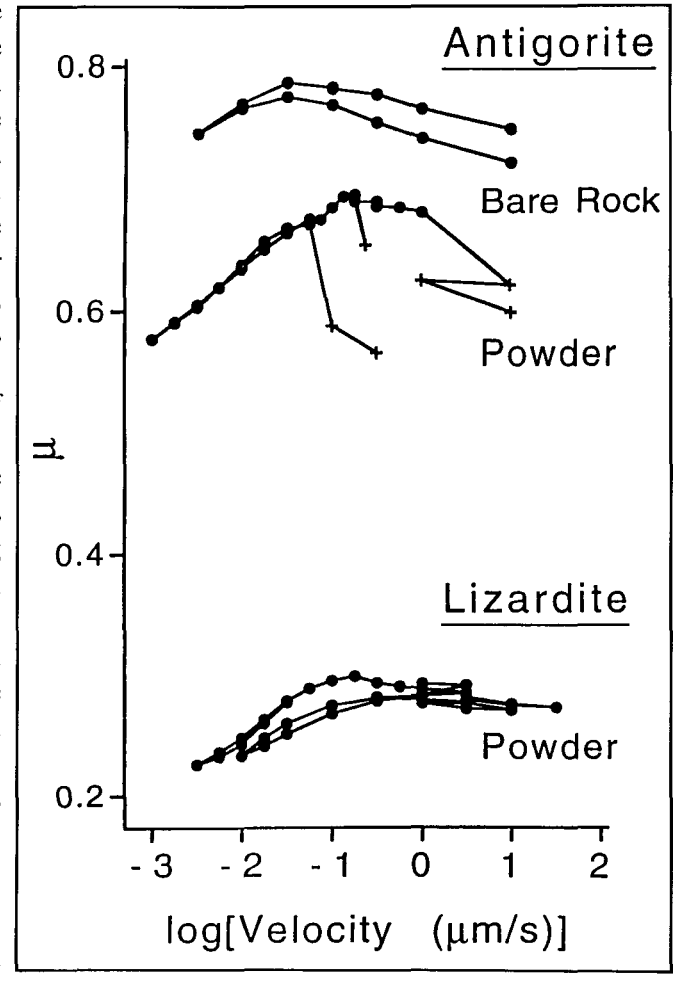


Figure IV-2: Coefficient of friction as a function of slip velocity for two types of serpentine. The dramatically different behavior seen here illustrates the need to sample fault zone materials from depth to do appropriate experimentsin the laboratory (from work of T. Tullis, Brown University).

3.) Measure the fluid regime within the fault zone as well as in the adjacent country rock. Such measurements include pore pressure, permeability, fluid chemistry, and isotopic character. The fault zone rheology is closely coupled to the fluid regime and, in particular, several of the most promising hypotheses, as already mentioned, invoke very high pore pressure confined to the fault zone to explain the low apparent strength of the San Andreas fault; such hypotheses can only be tested by drilling. Knowledge of the fluid regime is essential to performing realistic laboratory experiments to simulate fault behavior at seismogenic depths.

4.) Measure the thermal regime in and adjacent to the fault zone. These data provide an effective means of estimating the actual strength of the fault. Similarly, the depth to the brittle-ductile transition is a strong function of temperature. Moreover, a recent large earthquake is likely to leave a detectable thermal anomaly that can be interpreted in terms of fault zone rheology.

5.) Establish one or more downhole observatories to monitor fluid pressure and chemistry, temperature, strain, and seismicity over extended periods near an active fault zone. (This will require further developments in technology, as current technology limits the long-term operation of seismometers and strainmeters to temperatures of about 100°C, or less.) Such an observatory could be designed to allow periodic evaluation of the stress state so as to monitor possible changes in the state of stress during the earthquake cycle.

Past Drilling

Much of the progress toward a better understanding of lithospheric dynamics has been a consequence of drilling (or using holes of opportunity) to measure heat flow and *in situ* stress. Extensively distributed downhole measurements at depths ranging typically up to several hundred meters have helped to map out both heat flow and horizontal stress directions throughout vast areas of the continental crust around the world (*e.g.*, Lachenbruch and Sass, 1980; Zoback, 1992). Such measurements have provided considerable constraints on the environs of various fault zones, especially the San Andreas, which has been the subject of more geological and geophysical scrutiny than any other (Lachenbruch and McGarr, 1990). More recently the stress state and the geothermal regime near the San Andreas fault have been measured to greater depths in holes ranging from about 500 m to the 3600 m hole at Cajon Pass, in southern California 4 km from the fault (Zoback and Healy, 1992; Lachenbruch and Sass, 1992).

These various downhole measurements, sampling the uppermost crust in the vicinity of the San Andreas fault have provided the basis for our current conceptions regarding its mechanical nature. The fault has no detectable heat flow anomaly (Lachenbruch and Sass, 1980), an observation that has been interpreted in terms of conductive heat flow models as indicating that the strength of the fault must be very low compared to prior expectations (*e.g.*, Lachenbruch and McGarr, 1990). Indicators of horizontal stress, many of which have been measured in various holes (most notably in the Cajon Pass well), suggest a low fault strength also in that the shear stress resolved on planes parallel to the San Andreas fault is quite low, consistent, at least qualitatively, with the heat flow interpretations.

These observations, in fact, have motivated the development of the hypotheses, mentioned before, that the fluid regime within the fault zone is grossly different from that in the surrounding crust. Until the fault zone is actually drilled at seismogenic depths, however, our understanding of the fault zone mechanics will continue to be in terms of multiple hypotheses that generate much debate without resolution.

Specific Examples

Drilling projects designed to better understand the dynamics and deformation of the lithosphere fall into two general categories: Those addressing lithospheric dynamics by attempting to define better the forces responsible for inter- and intra-plate deformation, and those intended to investigate the factors that determine the rheological response of the lithosphere to the applied forces. Although projects in the second category typically involve high-risk drilling into deep seismogenic fault zones, such endeavors are deemed higher priority here because of their potential to answer the numerous profound questions already mentioned and also due to the considerable societal benefits they might ensue.

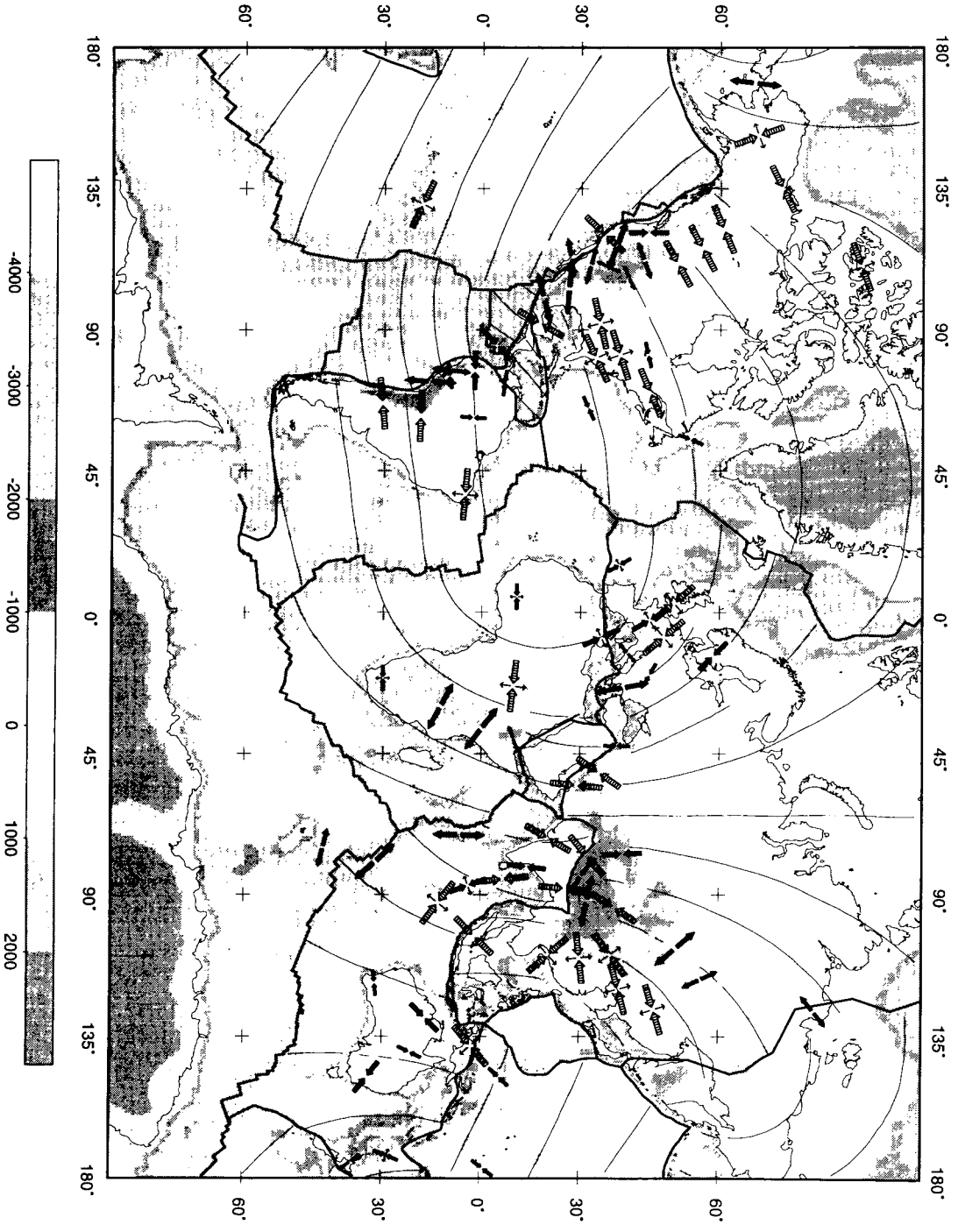


Figure IV-3: Generalized pattern of stress orientation and relative magnitude (modified from Zoback, 1992) and absolute plate motion directions (from DeMets *et al.*, 1990). Inward-directed large arrows indicate S_{Hmax} orientations in areas principally characterized by reverse faulting (S_{Hmax} S_{hmin} S_V). Inward-directed large arrows with small, outward-directed small arrows, indicate S_{Hmax} orientations in areas principally characterized by strike slip faulting (S_{Hmax} S_V S_{hmin}). Outward-directed large arrows indicate direction of S_{hmin} in areas of normal faulting (S_V S_{Hmax} S_{hmin}). The size of the stress symbols is proportional to the quality of the data. Shading indicates average topography in accordance with the scale at the bottom of the figure. .

Projects to Investigate Applied Tectonic Forces :

This category can be subdivided into three general types of projects:

1.) Investigate the driving forces of the plate tectonics by testing specific geodynamic models and filling in the major data gaps (Fig. IV-3) of the World Stress Map (Zoback, 1992). This work would entail the measurement of stress-induced wellbore breakouts in new or deepened holes, thus providing the horizontal stress direction data necessary to determine, or at least constrain, the directions of the tectonic forces affecting lithospheric plates. Such a project is currently underway in eastern Europe as a collaborative effort between GFZ, the University of Karlsruhe and Stanford University.

2.) Determine magnitudes of plate driving forces by using high mountain ranges as stress gauges. The topography of the Andes is observed to have offset the applied plate boundary forces that, in the absence of high topography, create a compressional tectonic regime. Where the topography is in excess of about 3000m the state of stress is observed to be extensional. Preliminary modeling (Richardson and Coblentz, 1993) suggests that east-west compressive stresses of 35 MPa, as averaged over the thickness of the lithosphere, are the result of „ridge-push" forces (see also Dalmayrac and Molnar, 1981). This modeling, currently poorly-constrained due to an absence of stress indicators in the zone where the stress state transition occurs, can be upgraded substantially by means of a series of 3000m deep holes. This drilling program, on the western flank of the Peruvian Andes, would define the transition in much greater detail, thus permitting better constrained modeling of the applied forces.

3.) Investigate the time dependence of the applied tectonic forces by (a) comparing present-day stress direction indicators to their paleostress counterparts and (b) analyzing the deviatoric stress as a function of depth in the lithosphere in search of evidence for temporal changes; modeling of the rheological response of the lithosphere to changes in the applied loads such that a „stressing history" may be evident in the stress field (N. Kuznir, written communication, 1993).

Projects that Investigate the Rheological Response of the Lithosphere to Applied Forces

Studies in this category involve drilling into either major active fault zones to investigate the rheological response of the upper (mostly seismogenic) crust or, where the geothermal gradient is exceptionally high and the bottom of the seismogenic layer shallow (*e.g.* less than ~6km), drilling into the ductile, aseismic substrate to investigate higher temperature modes of lithospheric deformation. The major active fault zones fall into three categories according to tectonic setting, compressional, extensional or transcurrent. We now describe, briefly, examples of drilling projects in each of these various categories.

Transcurrent Tectonics

1.) Alpine fault, New Zealand.

The Alpine fault, striking NESW across the South Island of New Zealand, is a major continental transform which has accommodated ~480km of dextral strike-slip since the mid-Miocene (Sibson *et al* ., 1979). Increasing convergence across the plate boundary in the last 5 Ma has led to adaptation of the fault zone and the development of a significant

reverse component of motion. At present, dextral-reverse oblique motion in excess of 25 mm/yr is accommodated across a fault zone that dips 45-55° SE, with the current interplate slip vector trending ~075° and a rake of ~30° NE.

Paleoseismic studies suggest that the Alpine fault is capable of producing ~M_w 8 earthquakes and that current seismic potential is high. „Characteristic" slip increments for the southern Alpine fault are ~8 meters, with the last major earthquake occurring at c.1700± 50 A.D. (Cooper and Norris, 1990).

In Central Westland (the area of most intense uplift) the fault juxtaposes well-foliated garnet-oligoclase Alpine schists on the hanging wall against a variably deformed late Mesozoic granitoid complex (the Fraser Complex) on the footwall. Discontinuous outcrops of a range of fault rocks (gouge, microbreccia, cataclasite, pseudotachylyte, mylonites derived from both the hanging wall schists and the footwall granites) in streams transecting the fault zone form the basis of provisional models for a fault zone about 1 km in width. Thermal modeling suggests that the rapid uplift of the hanging wall (< 10 mm/yr) in the central Southern Alps should have perturbed the thermal structure to an extent that temperatures of ~300°C may occur at only a few kilometers depth on the upthrown side.

Drilling into the Alpine fault (Fig. IV-4) would:

- Test provisional models on the structural geometry of the fault zone.
- Provide a continuous cored section through the fault zone (unaffected by surficial processes) as a basis for deformation mechanism studies, and compare with models of fault-rock distribution derived from surface mapping.
- Investigate the stress state associated with a major oblique-slip transform fault by means of downhole measurements, and compare with local earthquake focal mechanism studies.
- Explore the thermal structure associated with a major oblique slip transform fault and correlate with detailed studies of the depth distribution of microseismicity in the vicinity of the fault zone.
- Investigate active mineral deformation mechanisms within the fault zone. For example, there is the possibility of drilling into zones of active crystal plasticity in the hot uplifted rocks on the hanging wall.
- Investigate the role of fluids within the fault zone.
- Establish a borehole observatory for monitoring physical processes in a major fault zone that is close to failure.

Advantages:

- Seafloor spreading data from both the southeast Indian Ocean and the SW Pacific constrain the Late Cenozoic movement history of the AFZ to an unusual degree.
- The 45-55° SE dip of the fault zone allows a series of vertical drill holes to intersect the fault zone at different depths.
- Uniform hanging wall rocks (garnet-oligoclase Alpine schists) for > 300 km along strike allows extrapolation of information along strike, and correlation with fault rock studies.
- Because of the fast reverse component of slip across the Alpine fault zone through

the Quaternary, fault rocks and processes which would otherwise be inaccessible to drilling now occur at or near the surface. Rapid continuing uplift is likely to have distorted the thermal structure of the hanging wall such that the ~300°C isotherm, marking the onset of quartz plasticity and the base of the seismogenic zone, may occur at < 5 km depth.

Problems:

- Interpretation of thermal structure is made difficult not only by the rapid uplift and the possibility of shear heating, but also by the extreme topography, recent valley glaciation, the high degree of anisotropy in the hanging wall schists, and the high rainfall (5-10 m per year).
- The highly anisotropic, steeply SE-dipping Alpine schists on the hanging wall would make accurate directional drilling and downhole stress measurements difficult.

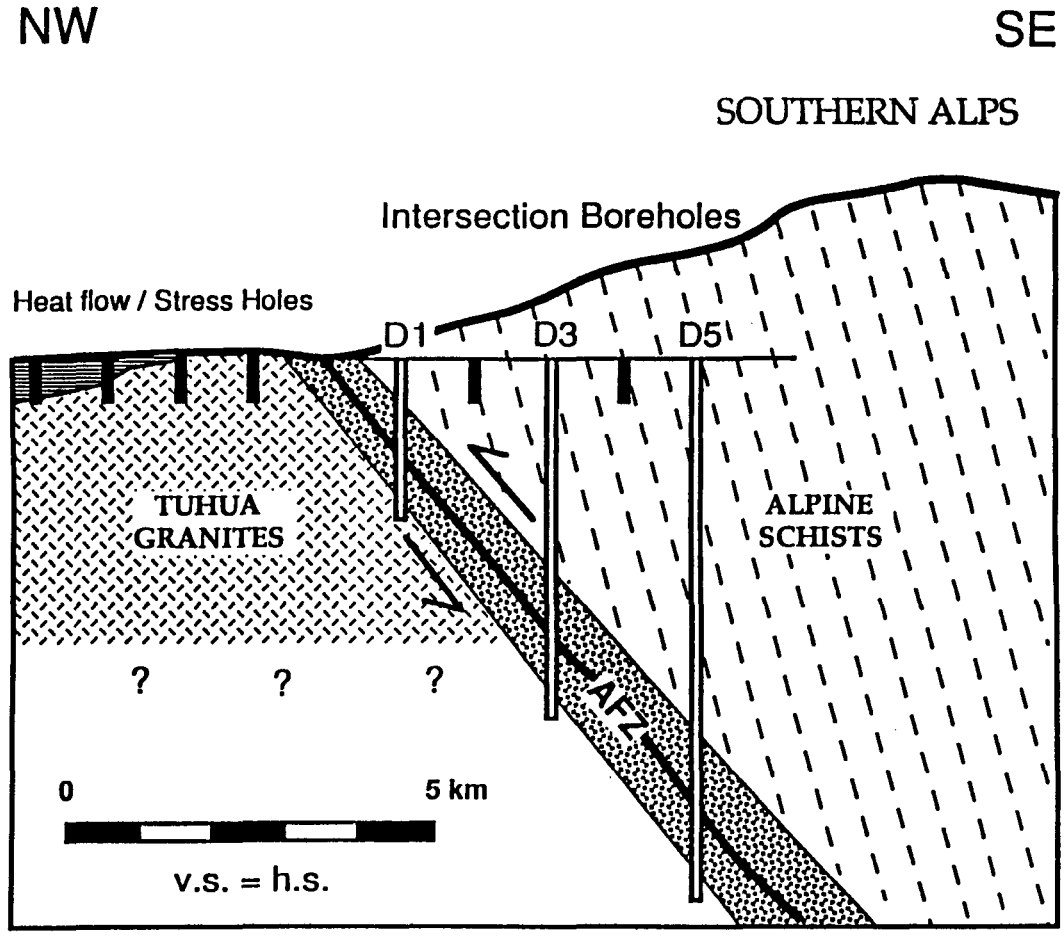


Figure IV-4: Cross section of Alpine fault zone illustrating possible configuration of drilling project there (from R. Sibson, Otago University, New Zealand.)

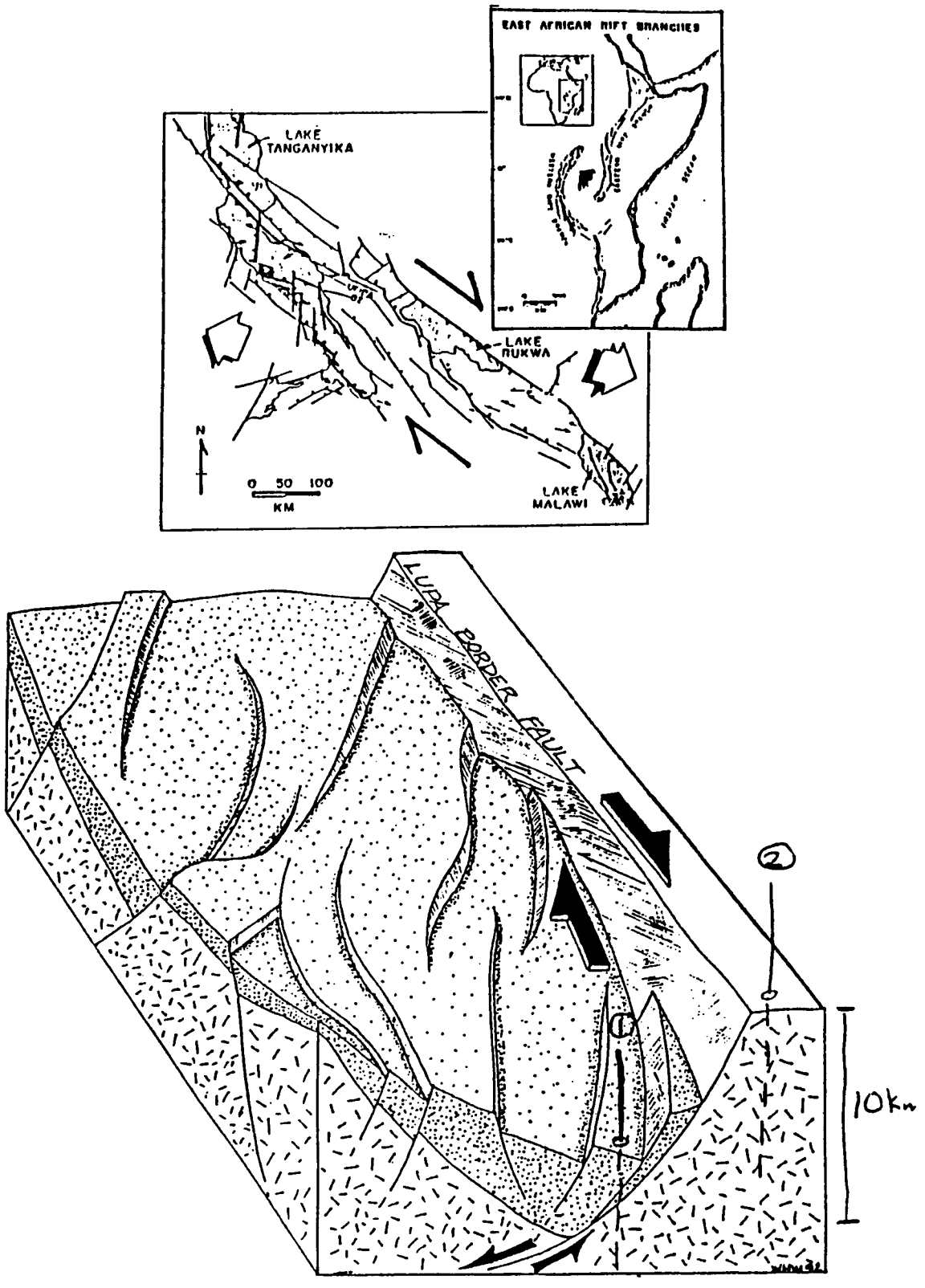


Figure IV-5: Lupa border fault, East Africa. Map location is shown above including Tankanyika, Rukwa and Malawi rifts. Below is a schematic block diagram of a portion of the Rukwa rift basin showing style and orientation of intra-basinal faults and striae directions on border fault (from J. A. Karson and W. H. Wheeler, Duke University.)

2.) Lupa Border fault, Tanzania-Malawi, East Africa.

This is an excellent example of a major transform fault with a substantial component of fault normal extension. Among the features of fundamental importance that can be explored along this system (Fig. IV-5), which extends between Lakes Tanganyika and Malawi, are continental rifts, continental margins and, possibly, oceanic transform faults.

Drilling into the hanging wall of the Lupa fault would provide important data regarding the history of sedimentation and subsidence, the fault zone material, the fluid-rock interactions within and outside the fault zone, and the stresses acting to cause fault slip. Drilling into the footwall would reveal the uplift history, the thermochronology and the regional state of stress. Much of what was said about drilling into the Alpine fault applies as well to this fault system except that the tectonic setting is transtensional instead of transpressional.

3.) Three Major-Earthquake-Producing Faults in Central Japan.

The large, active faults Neodani, Atotsugawa, and Atera (Fig. IV-6) are attractive drilling targets because they show individual characteristic features that may reflect different stages in the earthquake cycle. Each of these intraplate faults, 70-80 km in length, appears capable of producing earthquakes in the magnitude range 7-8. The Neodani fault last ruptured in 1891 when a M 8 event was associated with 4 m left-lateral slip and 6 m dip-slip; this was the largest earthquake ever in inland Japan.

The Atotsugawa fault shows right-lateral accumulated displacement of 2.7-3.5 km over the last 1-2 million years and a similar rate of vertical displacement. Major earthquake recurrence intervals seem to be 1000-2000 years, with the latest significant event being M 7 in 1858. This fault shows a high level of current seismicity.

The Atera fault shows left-lateral slip rates of 3-5 mm/y and much smaller dip-slip rates, with an average major earthquake recurrence time of 1700 years. The latest major event may have been 300-1800 years ago. Moreover, the current seismicity here is very low.

Along each of these faults, modest drilling projects into the fault zones, at depths up to several km, could provide valu able insights regarding faults at different stages in the „characteristic" earthquake cycle.

4.) San Andreas Fault, California.

As a major continental transform fault, the San Andreas is an especially attractive drilling target because, even though it has been the subject of intense scientific scrutiny for much of this century, our ignorance regarding its mechanical nature is almost complete. Measurements of heat flow, *in situ* stress, and rock strength (in the laboratory) have resulted in the so-called „stress heat-flow paradox" (Lachenbruch and McGarr, 1990), which represents several decades of frustrated, unresolved debate, regarding the dynamics of the San Andreas fault. Numerous sites along the San Andreas are well suited to the drilling program proposed by Zoback *et al.* (1993) (Fig. IV-7).

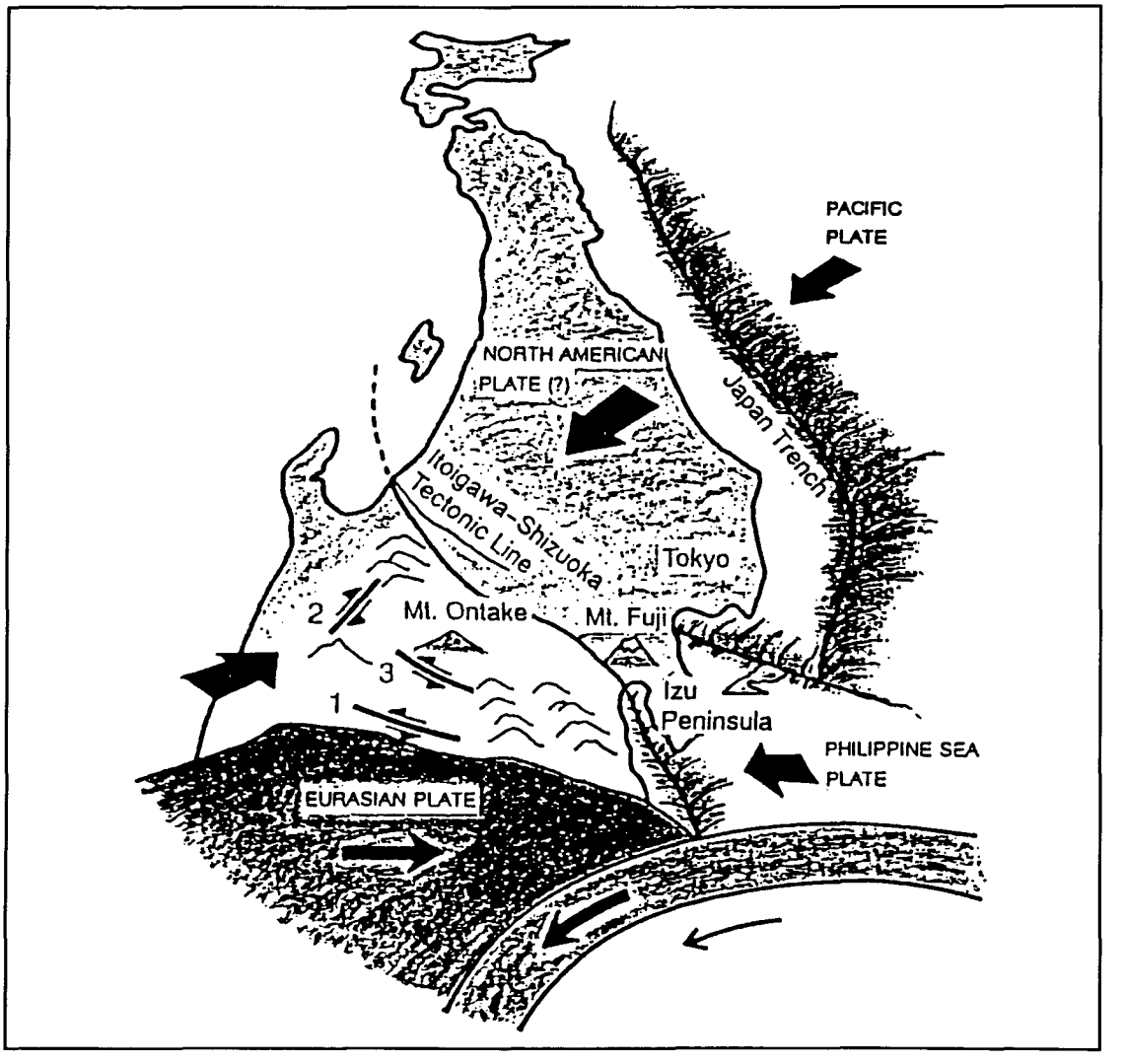


Figure IV-6: Schematic drawing of the plate motions around three large active faults in central Japan: (1) Neodani Fault: Total length 80 km, general trend N45°W, left-lateral strike slip, max displacement 4 m left, 6 m NE-up at Midori fault by Nobi Earthquake (1891, M=8.0, the largest earthquake in inland Japan), aftershocks are remarkable in the southern part of the epicentral area. (2) Atotsugawa Fault: Total length 70 km, general trend N60°E, right-lateral, accumulated displacements 2.7 - 3.5 km over the last 1-2 m.years, slip rates 1.0 - 5.7 mm/y (horizontal) and 1-4 mm/y(vertical) (large earthquake recurrence interval would be of the order of 1000-2000 years), latest event is Hida Earthquake (1858, M=7.0), high seismicity is concentrated with lineation. (3) Atera Fault: Total length 70 km, general trend N45°W, left-lateral slip rates 3-5 m/1000 years (horizontal) and 0.6m/ 1000 years (vertical) (average recurrence time 1700 years), very low seismicity, latest large event 300-1800 years ago. (modified after Gifu Newspaper, 1991).

The key questions that could be addressed through recovery of core from the San Andreas fault zone and downhole measurements directly within the fault zone are as follows:

Fault Behavior

- Why is the fault zone weak?
- Why are some segments of the fault creeping and some locked?
- What is the variation in fault creep with depth?
- What factors control the localization of slip and strain-rate?
- What factors determine the nucleation, propagation, arrest, and recurrence of earthquake ruptures?
- How is the fault zone loaded at different crustal levels?
- Can the frequency-magnitude relationship for earthquakes be extrapolated to smaller magnitudes?
- How does strain communication occur within the fault zone over different time-scales?
- How is energy partitioned within the fault zone between seismic radiation, frictional dissipation, grain size reduction, and chemical reactions?

Fault Structure & Materials

- How does the width and character of the active slip zone vary with depth?
- What is the thermal structure of the fault zone?
- How do mineralogy and deformation mechanisms within the fault zone change with depth, temperature and country-rock geology?
- What determines the maximum depth of seismic activity?
- At what temperature do mineral reaction kinetics operate at the time scale of an earthquake cycle?
- How accurate are inferences drawn from deformation microstructures, piezometers, and fluid inclusions and how might one assess their survivability?

Fault Zone Properties & Physical Parameters

- How does the stress tensor vary in the vicinity of the fault zone?
- How do pre- and post-failure stress states compare?
- What, if any, form of cyclical dilatancy operates in the vicinity of the fault zone?
- How do the physical properties relate to the fault zone fabric?
- What is the origin of low-velocity zones in the fault zone?
- How well and in what manner do physical properties and heterogeneity measured in boreholes correlate with geophysical observables?

Fault Zone Fluids

- What is the origin and composition of fault zone fluids?
- What are the permeabilities of fault-zone materials and country rock?
- What are the fluid transport mechanisms in and adjacent to the fault zone and what physical processes lead to fluid redistribution?
- What is the extent of water-rock interaction at different structural levels?
- What is the interplay between water-rock interaction and rheology?

Fluid Pressure

- What is the vertical and lateral distribution of fluid pressure regimes?
- Do fluid pressure compartments exist?
- If so, what is the nature of the seals between these compartments?
- What is the time-dependence of fluid pressure within the fault zone?
- What is the extent of vertical and lateral fluid migration during a seismic stress cycle?

Answers to the above questions will also prove critical to a host of other societal problems, including understanding the origin and distribution of mineral resources along faults and the role of faults as either conduits or barriers to oil and gas migration.

As many major plate boundary faults (both transform and subduction zones) seem to be slip at extremely low levels of shear stress, what is found by drilling the San Andreas is likely to have broad applicability to plate-bounding faults around the world.

Mechanics of Low-Angle Normal Faults Extensional Tectonics

These faults are quite enigmatic in that they are poorly oriented for reactivation in terms of the Coulomb failure criterion. At least three types of models have been proposed for such features (Wernicke, 1992).

1.) Special boundary conditions cause gradual stress rotations throughout the crustal column (Bartley and Glazner, 1985; Spencer and Chase, 1989; Lister and Davis, 1989; Yin, 1989; Melosh, 1990). These conditions, involving surface slopes, specific end loads and basal tractions may not be commonly satisfied. Moreover, these models generally entail higher shear stresses on the high-angle fault surfaces that probably require high pore pressure within the low-angle fault zones.

2.) Coulomb wedge models work well for growth faults with high pore pressure, but require substantial surface slopes (Xiao etal, 1991). Such models involve stress rotation throughout the crustal column.

3.) High pore pressure within the fault zone possibly causes local stress rotation (Hubbert and Rubey, 1959; Axen, 1992; Rice, 1992; Byerlee, 1990). For this type of model, no special boundary conditions are required other than an impermeable fault zone.

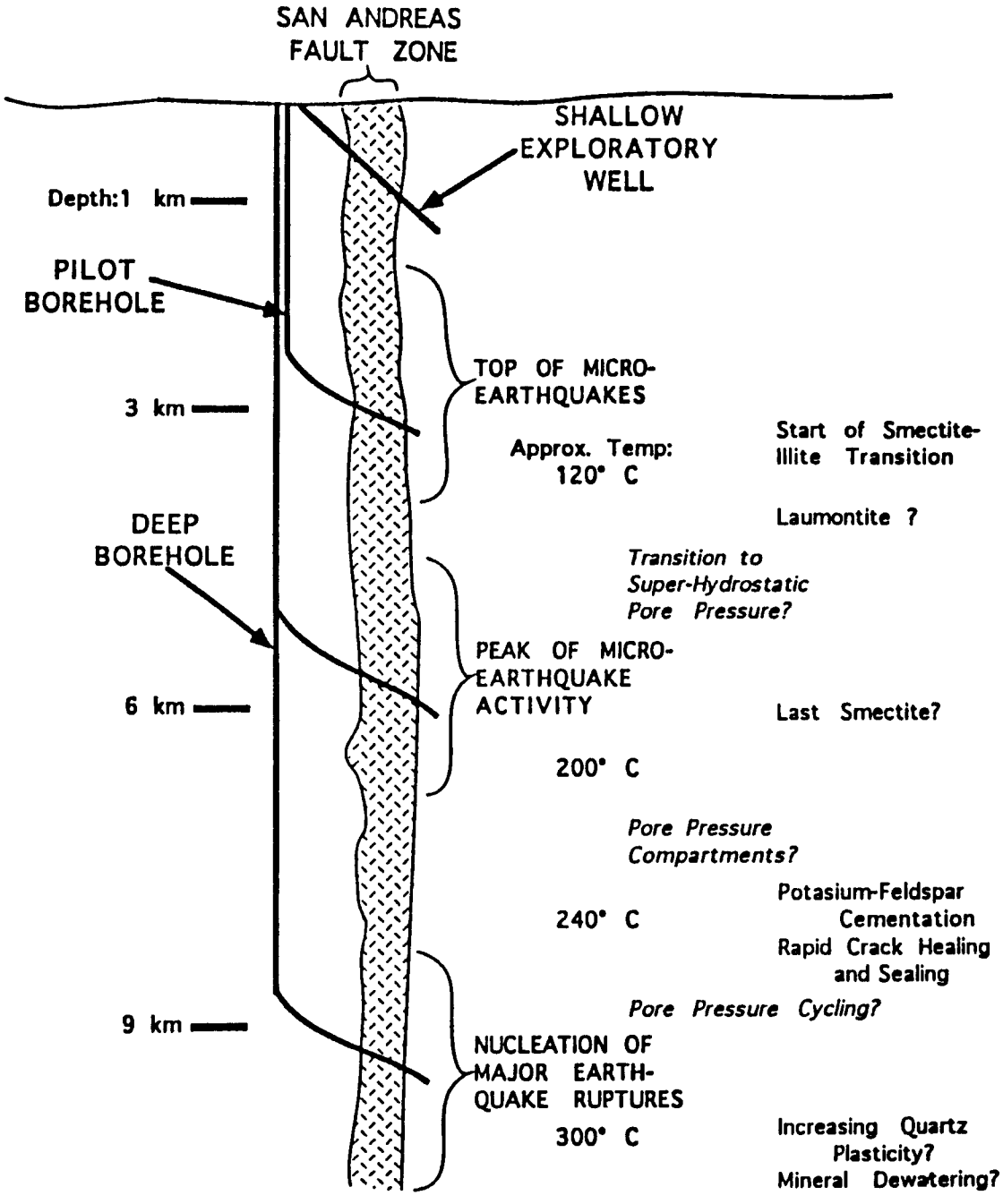
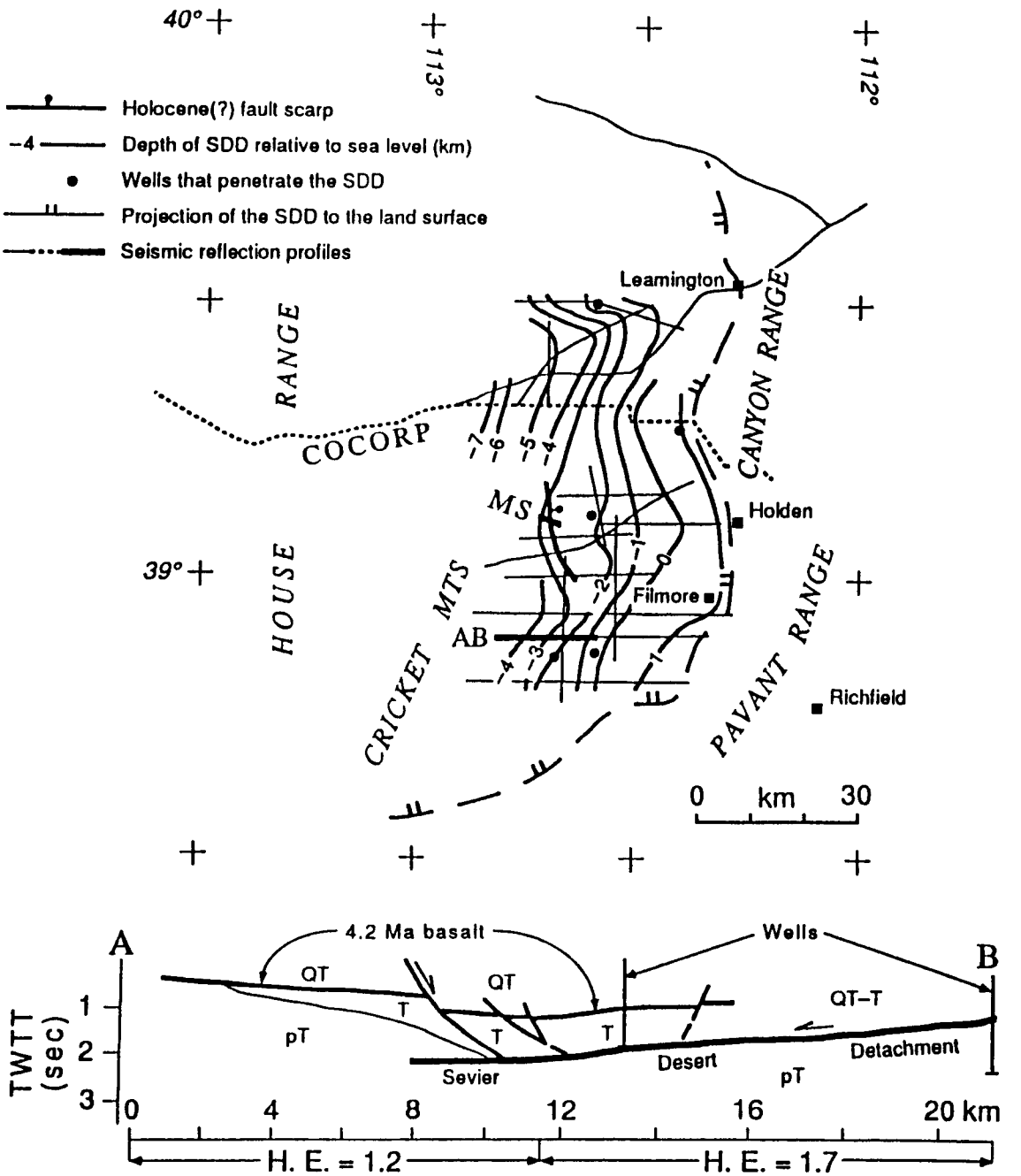


Figure IV-7: Schematic of proposed San Andreas fault-zone drilling project. An inclined, shallow exploratory core hole would penetrate the fault zone at a depth of about 1 km. Once the best location for the deep hole is selected, a 3-km-deep pilot hole and a 10 km deep main hole would be cited at a distance of about 300 to 500 m from the surface trace of the San Andreas fault and deviated (whipstocked) to intersect the fault zone at depths of about 3, 6 and 9 km. Use of two separate boreholes for deep drilling would allow for cross-hole tomography and ongoing experimentation in the pilot hole while the deeper hole was being drilled. Also shown are the approximate temperatures and mineral stability fields, deformation regimes and hydraulic phenomena hypothesized at depth along the San Andreas fault.


40°
113°
112°
39°
Holocene(?) fault scarp
Depth of SDD relative to sea level (km)
Wells that penetrate the SDD
Projection of the SDD to the land surface
Seismic reflection profiles
Leamington
Holden
Filmore
Richfield
COCORP
MS
AB
HOUSE RANGE
CRICKET MTS
CANYON RANGE
PAVANT RANGE
0 km 30
A
B
4.2 Ma basalt
Wells
QT
QT
T
T
T
pT
QT–T
Sevier
Desert
Detachment
pT
TWTT (sec)
1
2
3
0
4
8
12
16
20 km
H. E. = 1.2
H. E. = 1.7

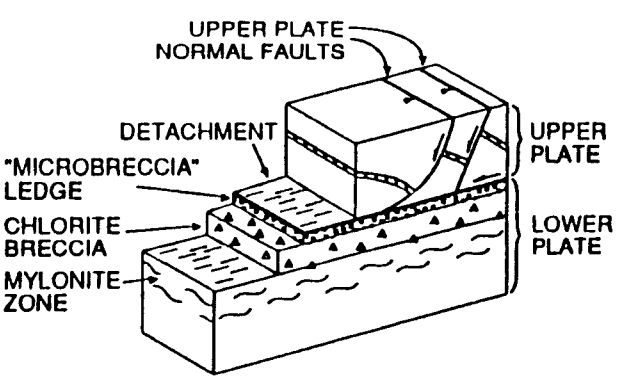

UPPER PLATE NORMAL FAULTS
DETACHMENT
"MICROBRECCIA" LEDGE
CHLORITE BRECCIA
MYLONITE ZONE
UPPER PLATE
LOWER PLATE

Figure IV-8: (Upper diagram) Structure contour map (contour interval = 1 km) of the Sevier Desert detatchment fault (SDD) in west-central Utah, showing locations of seismic reflection profiles, and interperetations of profile AB (both after Planke and Smith, horizontal exaggeation: TWTT = two way travel time. The SDD is inferred to underlie a minimum of 5600 km^2 and probably underlies > 9000 km^2. It can be traced confidently on the COCORP profile dipping between 8° and 16° for > 70 km across strike to depths of 12-15 km, and is nowhere offset by a high-angle fault (Allmendinger *et al.*, 1983). The SDD has had > 2.5 - 3.2 km of low-angle normal slip since since mid-Pliocene time, and probably has slipped tens of km since Oligocene time.

(Middle diagram) The Holocene(?) fault scarp crossed by profile MS formed over over a hanging wall fault (similar to the large E-down fault in profile AB), suggesting that the SDD is still active (Crone and Harding, 1984). The SDD affords a unique oppertunity to drill an active(?) low-angle normal fault at a variety of depths, using existing technology and possibly reoccupying existing wells. In situ data pertinent to fault and rock mechanics would be obtained at a variety of depths representing different deformation regimens, ranging from frictional sliding through cataclastic flow to „brittle-ductile" conditions.

(Lower diagram) Typical structural succession in Cordilleran metamorphic core complexes formed by large-magnitude slip on low-angle normal faults. Successively higher footwall passes through as it is unroofed by slip on the detachment. These are: frictional slip on the detachment itself (probably both seismic and aseismic), formation of the microbreccia (currently poorly understood), cataclastic flow during formation of the chlorite breccia, and combined grain-scale crystal-plastic and brittle deformation mechanisms during mylonitization. These regimes should be encountered laterally down the dip of an active low-angle normal fault such as the Sevier Desert detachment. (From G.J. Axen, Centro de Investigación Superior de Ensenada, Baja California, Mexico.)

Low angle detachment faults play key roles in active extensional terrains and, thus, it is important to understand their mechanics. Drilling into such fault zones at depth is clearly necessary to test the various proposed hypotheses just outlined.

Sevier Desert Detachment, Basin and Range Province: This is perhaps one of the best suited drilling targets to investigate the nature of these features (Fig. IV-8). Advantages of such a drilling project are:

- It has been well imaged seismically.
- It has been drilled before but for oil exploration.
- This is a high heat-flow area and so the brittle-ductile transition may be shallow enough to be accessible to drilling (~10 km or less).
- It is associated with very young fault scarps (Crone and Harding, 1984).

The most fundamental question is whether this feature, defined principally from seismic reflection data, is actually a fault (*e.g.*, Wernicke, 1992) or something entirely different

such as an unconformity (Anders, 1993). If this is a fault, the most essential questions to be addressed through drilling include:

- How do stress, pore pressure and fluid chemistry vary in the vicinity and within the fault zone?
- Where do breccia and microbreccia layers form?
- If the pore pressure is high within the fault zone what is the fluid source and flow direction?
- Similarly, if pore pressure is high, what are the sealing mechanisms at different depths?

The potential problems with such a project include:

1.) Even if this feature is a normal fault, it is possible that the Sevier Desert detachment is not currently active. Alternatively, it may be active but aseismic. Site investigations may resolve sone of these uncertainties.

2.) Similarly, strain rates along the Sevier detachment are poorly known.

3.) In order to obtain reliable stress state results it is necessary to avoid secondary faults in the upper plate (Fig. IV-8).

Compressional Tectonic Processes

Section VI, Convergent Plate Boundaries addresses a broad range of questions regarding drilling in compressional areas. The following list discusses several drilling projects specifically related to drilling active faults in compressional areas.

Super-deep drilling through the subducting plate boundary around the Izu Peninsula, Japan. This proposal has the long-term objective of predicting great inter-plate earthquakes and entails drilling a 15 km borehole through the plate boundary of the subsiding Philippine sea plate to explore the actual earthquake focal zone to gain insight into the physics of earthquake processes. The potential societal benefits are huge, especially in view of the tragic results of the 1923 great Kanto earthquake which destroyed much of Tokyo.

Continental collision zones in the NW Himalaya. A proposal to drill into the Himalya would address the neotectonics and the thermal, mechanical and fluid flow behaviors of actively thickening continental crust. The Nanga Parbat massif (Fig. IV-9) presents a superb opportunity to investigate thermal and mechanical properties of active fault zones associated with the substantial thickening of the continental crust and the ongoing creation of the highest mountain range. Among the questions to be addressed at this relatively accessible site are:

- How are basement rocks uplifted and exhumed?
- What is the relationship between denudation and uplift?
- What are the links between the deformation and thermal behavior of the crust?

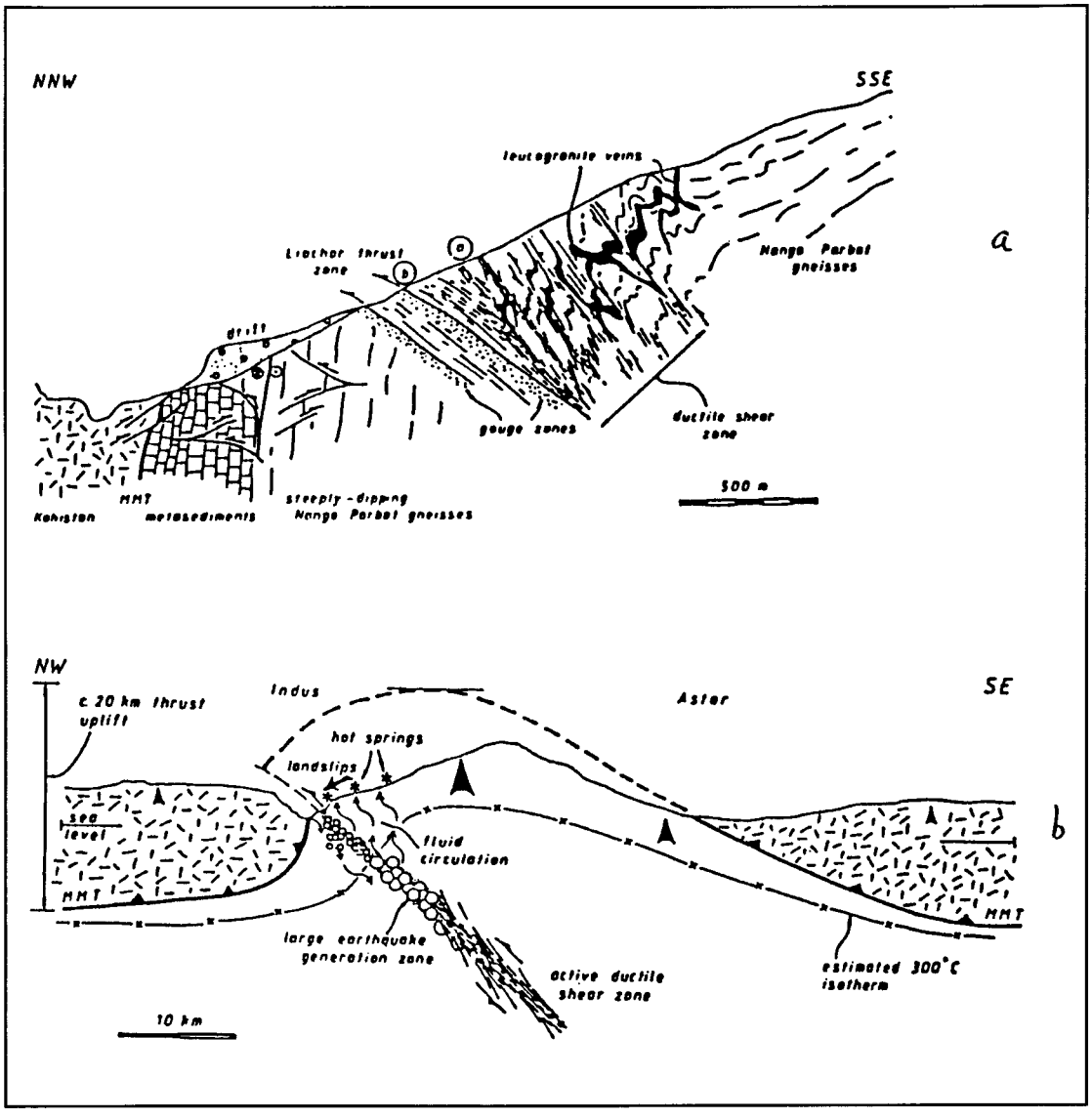


Figure IV-9: (Top) Sketch geological cross-section through the Raikhot part of the massif margin. a) site of ductile deformation, b).cataclastic deformation. After Butler *et al.* (1989). (Bottom) A model for the Liachar thrust zone and differential uplift (arrowheads) of Nanga Parbat. Cataclastic faulting is indicted by circles and stipple, ductile shearing by lines. Collectively this zone forms the Liachar thrust. MMT - Main Mantle thrust. After Butler *et al.* (1988).

Drilling can provide information on:

- Subsurface thermal structure together with cooling rates at different depths to establish temperature-depth relationships.
- Rates of textural reequilibration.
- Rates of diffusion of different isotopic species.
- Information on the resetting of apparent mineral ages.

- *In situ* stress states.
- Fluid flow regime.

Drilling to Investigate the Mechanics of Earthquake Swarms - Hypothesis: Earthquake swarms involve the migration of overpressured fluids through fault/fracture meshes. Hill's (1977) model for earthquake swarms involves migration of fluids through a „honeycomb" mesh of interlinked extension fractures and Coulomb shears. Geological evidence supports: (i) the existence of Hill fault/fracture meshes developed over a broad scale range through combined faulting and hydrofracturing, and (ii) their role as conduits for the migration of hydrothermal (and hydrocarbon) fluids (*e.g.*, extensional chimneys and normal faults in the Monterey formation, California).

Swarm activity probably required $S'_3 = (S_3 - P)$ approaching 0, allowing the fault/ fracture meshes to form effective fluid conduits. At other than shallow depths (top 1-2 km), swarm activity is therefore likely to be associated with fluid overpressures. In compressional regimes (*e.g.*, Santa Barbara Channel), swarms probably involve ~ lithostatic levels of fluid pressures. Fluid pressure fluctuations of the order of rock tensile strengths (DP~1-10 MPa) are likely to accompany swarm activity.

*Drilling Experiment*Kilometer-scale earthquake swarms form well-defined targets for investigatory drilling. Intersection of an active earthquake swarm at > 2 km depth would allow measurements of fluid pressure within the swarm and pressure gradients in adjacent regions. Attempts could be made to correlate fluctuations in fluid pressure with seismic activity within the swarm. Aside from the general relevance of swarm activity to fault mechanics, fluid passage through such mesh structures has important implications for processes of hydrothermal mineralization.

Drilling to Investigate the Brittle-Plastic Transition - Hypothesis: The cessation of seismic activity with increasing depth in continental crust is primarily temperature dependent and involves the onset of crystal plasticity in quartz at ~300° C. Thermal modeling suggests that temperatures at the base of the seismogenic zone in continental crust are ~300± 50° C. Microstructural studies of fault rocks from exhumed fault zones define the onset of significant crystal plastic flow in quartz-rich mylonites at similar inferred temperatures, under low greenschist facies metamorphic conditions.

Experimental rock mechanics has managed to duplicate the onset of quartz plasticity in this temperature range but only in „wet" quartz under high confining pressure-it is thought that the high pressure is needed to force „water" into the quartz lattice to induce hydrolytic weakening in the short time-span of laboratory deformation experiments. This raises an important question as to whether the base of the seismogenic zone, and the onset of quartz plasticity in fluid saturated quartz-rich crust are just temperature dependent, as is often assumed in rheological modeling, or whether some minimum value of pressure is also needed for the onset of crystal plastic behavior in quartz.

*Experiment*Investigate physical parameters (T, P_{con}, P) at the seismic-aseismic transition directly by drilling to investigate the boundary where it approaches the Earth's surface (*e.g.*, in geothermal fields at depths of ~4 km, or where tectonic transport has significantly elevated geotherms as in the Southern Alps on the hanging wall of the Alpine fault, NZ).

Conclusions

The emphasis here has been to illustrate how drilling can be used to better understand the the distribution of stresses in the lithosphere and constrain geodynamic models and the study of major active fault zones at seismogenic depths. Direct benefits to society include the potential for making major progress into the following problem areas:

- Earthquake hazard mitigation.
- Ore deposition processes. Many of the most important hydrothermal mineral resources are hosted within ancient fault systems.
- Geothermal processes.
- Hydrocarbon migration.
- Ground water circulation.
- Waste disposal.

In addition, there are numerous potential benefits to earth scientists including

- An improved understanding of ancient exhumed fault zones through calibration of geobarometry and deformation structures.
- Insights into plate boundary processes.
- Improved understanding of rock-fluid interaction. There is growing evidence for a link between active faulting processes and fluid redistribution in the Earth's crust.

Further Reading

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V. Volcanic Systems and Thermal Regimes

Introduction

The Earth's interior is still hot and the continued production of heat by radioactive decay within the Earth drives many geologic processes. The thermal state of the crust is an important consideration everywhere because of what it reveals about deeper conditions, the movement of crustal fluids (magma, water and gas), and even the past climate. Thermal regimes reach their most spectacular expression in volcanic systems and associated hydrothermal systems. Volcanism, the rise and emplacement of magma into the crust and onto the surface, is a fundamental planetary process responsible for the formation and evolution of the crust and, because of the volatile component of magma, the hydrosphere and atmosphere as well. In terms of their intrinsic scientific importance, their impact on society, and the opportunities they provide to study the active processes which shape the planet, Volcanic Systems and Thermal Regimes are among the most attractive targets for an international Continental Scientific Drilling Program. Many of these targets are specific volcanoes or hydrothermal fields, but temperature gradient and heat flow studies are an essential component of any scientific drilling project.

There is a pressing need to understand volcanic and hydrothermal processes (Panel on Continental Scientific Drilling, 1984). Volcanic explosions extend to energies that are orders of magnitude greater than nuclear explosions. Eruptions kill thousands to tens of thousands of people per decade and the threat of eruptions displaces hundreds of thousands

Figure V-1: Unzen Volcano and the devastated area viewed from the east-south-east, on the island of Kyushu, Japan. The summit dome has grown continuously during the past 3 years at ≤ 3 m^3/s. Its steepening sides repeatedly collapse to produce pyroclastic flows. The upper course of the devastated area (light gray in color) is occupied by the deposits of pyroclastic flows; the lower course consists of debris flow deposits. The current activity has killed 43 people, caused 5000 people to be evacuated, and resulted in 50 billion Y (400 million US$) in damage to property. The double-peaked mountain at right is Mayu-yama, a composite lava dome, part of which collapsed during the 1739 eruption of Unzen and produced a tsunamis that killed 15,000 people. Seismicity defines a magma conduit that dips obliquely west from the dome to a depth of 10 km at an angle of 40° from horizontal. Mixing of contrasting magmas at shallow depth apparently occurs just before surges in magma flux. Swarms of earthquakes migrate upward along the conduit just before the rate of effusion increases, and changes in this rate are reflected in tilt, EDM, leveling, GPS, and electromagnetic field data. Drilling through the volcanic edifice into the conduit would reveal valuable evidence of magma transport and eruptive mechanisms. Volcanism presents resources to human society as well as hazards. The vast energy in associated hydrothermal systems, and perhaps one day in magma itself, is available for use, with advantages over conventional power sources. Use of geothermal energy is growing exponentially world-wide, particularly in under-developed countries. In the future, this source of energy will play an even more important role as an environmentally benign alternative to the burning of fossil fuels. Volcanic processes also produce mineral deposits upon which society relies. Understanding the processes by which hydrothermal systems and ore deposits form will provide for informed evaluation, acquisition and use of these resources.

more, with attendant suffering and loss of livelihood (Fig. V-1). Volcanic ash clouds drifting across air routes pose lethal threats to international travel and commerce. These dangers are growing rapidly as cities expand around volcanoes and as air traffic increases over once-remote volcanic arcs. Evaluation, prediction, and consequent mitigation of volcanic hazards are now important safety concerns in many parts of the world. A less direct impact of volcanism on human activity is through its effect on the atmosphere. Release of large amounts of ash and gas into the atmosphere can cause climatic and pollution effects. Such events may sometimes result in meteorological catastrophes such as floods and crop failures. These effects should be understood in order to evaluate the importance of anthropogenically produced „global change".

Key questions

Volcanic systems span a great depth range, at least 100 km and perhaps in some cases essentially to the core/mantle boundary. Questions pertaining to these systems can be listed in ascending order:

- Where and how is melt generated and segregated in the mantle?
- How does magma rise into and accumulate in the crust?
- How does magma evolve chemically and thermally within the crust?
- How are heat and mass transferred from magma to associated hydrothermal reservoirs?
- How do hydrothermal reservoirs develop and how do the fluids within them behave?
- How does magma rise to the surface?
- What controls the eruptive behavior of magma as it approaches the surface?

In cooler areas of the crust where magma is not present, much heat transport is likely to be by fluid flow and we must ask how hot rocks and fluids interact mechanically, chemically, and thermally, as well as evaluate the interplay of thermal and fluid conditions with tectonic and metamorphic processes.

Much progress has been made in these areas over the past few decades through geological, geochemical, and geophysical investigation of both active and „fossil" systems. Thermal, chemical, and dynamical models have been developed for magmatic and hydrothermal fluid behavior. In recent years, attempts have been made to link such models for a fuller description of magma/hydrothermal systems. Models for the shallow subsurface structure of volcanoes, for the chemical evolution of melt and fluid, for cooling of magma/hydrothermal systems, and for the explosive eruption of magma have reached considerable maturity. New analytical techniques, particularly those involving isotopes and microanalysis, have yielded major advances in understanding the source of volatile as well as non-volatile components of magmatic and hydrothermal systems. Seismic monitoring of erupting volcanoes, together with geodetic, gravity, magnetic, seismic surveys, and new petrologic insights (*e.g.*, Pallister *et al.*, 1992) is providing view of where magma resides in the crust and how it is transported.

Role of drilling

Models based solely on the study of fossil volcanic or hydrothermal systems, or even on surface observations above active subsurface systems are hypotheses that, to be properly

used and further developed, must be tested through observation and sampling at depth. This is the role of drilling. Because of the great depth scale and extreme conditions presented by volcanic systems, not all of the questions listed above can be addressed through drilling observations. Except in special circumstances, drilling is presently limited to temperatures below 500°C, downhole logging and fluid sampling systems are limited to 300°C, and continuous coring, required to address most volcanic/hydrothermal problems, is limited to depths of less than 5 km. The combination of high temperature and coring requirements may limit depth further. Nevertheless, very important scientific advances can be made with drilling techniques now in hand. Drilling provides the only means by which models for active systems can be tested, and it is only at active systems where the full suite of geochemical and geophysical (and in the case of eruptions, visual) observations can be brought to bear on magmatic and hydrothermal problems. This is because drilling provides the only means to observe conditions and to take samples at depth in active systems. In addition, drilling can provide a continuous vertical sample of greater extent and/or quality than is afforded by natural outcrop in fossil systems.

There is already a considerable history of scientific results from drilling in volcanic regimes. Most of the drilling has been motivated by interest in geothermal energy. This has resulted in important understanding of hydrothermal reservoirs and, in so doing, in the structure of volcanic fields. A lesser number of projects motivated purely by scientific objectives have been undertaken. These include drilling basalt sequences in Iceland (Robinson, *et al.*, 1982), drilling into a hydrothermal reservoir in Yellowstone National Park (Wyoming, USA; Fournier, 1989), drilling into lava lakes on Kilauea Volcano (Hawaii, USA; Hardee, *et al.*, 1981) which directly observed shallow crystallization behavior of basaltic magma, and drilling at Inyo Domes (California, USA; Eichelberger et. al., 1986; Carrigan and Eichelberger, 1990), which elucidated degassing and chemical segregation phenomena associated with effusive eruptions. By drilling into the Salton Sea (California, USA) hydrothermal system, conditions of active formation of sulfide minerals were directly observed (McKibben *et al.*, 1987). A number of additional projects of this type are pending and are close to implementation.

Two aspects of drilling into thermal regimes should be noted. First, although volcanic systems extend to great depth, very important processes and extreme conditions are present at modest and readily accessible depth. For example, fragmentation of magma to tephra during ascent, the basic process of explosive volcanism, is believed to generally occur at depths of several hundred meters or less (Sparks, 1978; Wilson, 1980). Groundbreaking observations of basalt crystallization through lava lake drilling at Kilauea involved depths of less than one hundred meters. Second, simplicity of a system is critical for successfully interpreting drilling results in terms of the thermal, mechanical, and chemical behavior of magma and hydrothermal fluid (Panel on Volcanic Studies at Katmai, 1989). Often, a volcanic system represents the integrated effects of many similar, small-volume intrusive and eruptive events spanning tens or hundreds of thousands of years. This composite nature of most volcanic systems presents formidable obstacles to some kinds of interpretations. Where testing eruption models is the objective, it is essential that the identity of the subsurface conduit associated with an eruption can be unambiguously established in the drill core. Where rates of heat and mass transfer from an intrusion are of interest, it must be possible to isolate the thermal and chemical effects of the target intrusion from those of previous events. Thus, it is important to search worldwide, not merely within an individual nation's borders, for the best places to address magmatic and hydrothermal problems through scientific drilling.

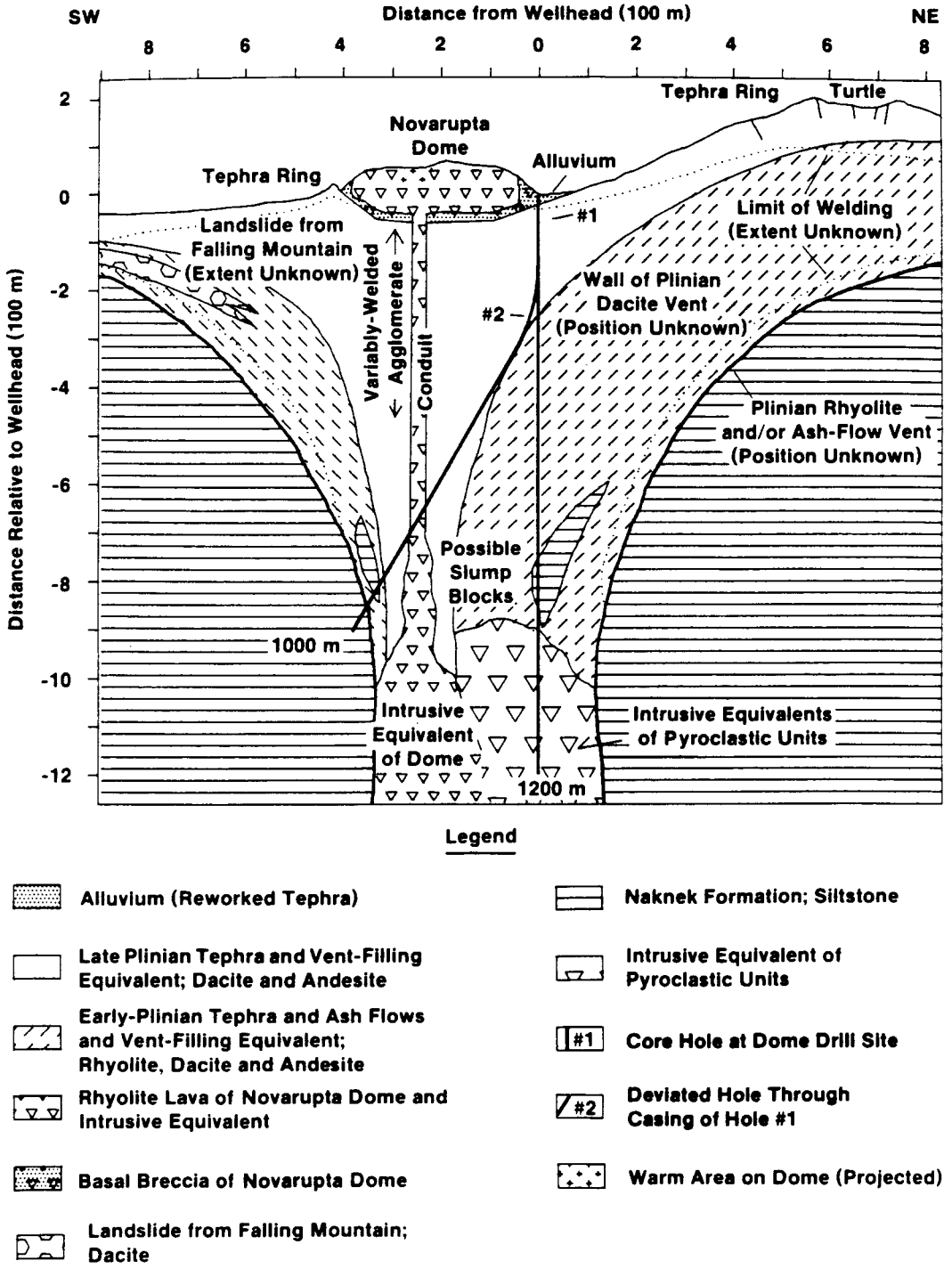
Recommended drilling investigations and suggested sites

Four key problem areas are ripe for immediate investigation by scientific drilling. Examples of where these problems can be addressed are cited. In some cases, multiple problems can be addressed by a single drilling program, and so some sites are mentioned repeatedly.

I. Eruption processes: flow, degassing by decompression, fragmentation

Perhaps no problem is as central to volcanology as the problem of why volcanoes behave as they do, at times erupting explosively with great violence and at times quietly oozing lava. Chemically identical magma batches can display both behaviors, often alternating between them in time. Knowledge of why this is so is of great practical benefit, as the hazards posed and the mitigating actions to be taken are entirely different. At present, models for explosive eruption and for the shallow three-dimensional structure of active volcanoes are reaching maturity. A logical next step is to drill into the vent and conduit systems of recent, well-described eruptions in order to test such models. Observations of vent and conduit geometry and structure and chemical zonation within them, together with mass flux observations from the eruption, will help constrain subsurface flow rates and their respective characteristics. Observation of how the retained volatiles and vesicles are distributed at depth will elucidate degassing behavior of magma. The character and distribution of fragmental material relative to the intact intrusive feeder will test ideas about explosive fragmentation of magma to tephra. This general approach was applied successfully to a cold system, Inyo Domes, during scientific drilling in the 1980's. Plans exist for such a project at the much larger and still-hot system of Novarupta, site of the largest eruption on Earth this century, on the Alaska Peninsula (USA; Eichelberger, 1989; Fig. V-2). Presently active volcanoes such as Unzen in Japan (Fig. V-1) will present attractive targets when the danger of eruption has passed. Plans also exist for this type of drilling in the Kuril Islands (Russia). These problems can be addressed at depths less than 2 km. Elevated temperature is not a prerequisite for these specific scientific goals but will normally be present at depth for systems young enough that the desired eruption information is available.

Figure V-2: Hypothetical cross section of the Novarupta Vent, Alaska, source of the largest eruption on Earth this century, showing proposed core holes. The volcano erupted 30 km^3 of tephra during June 6-9, 1912. Such drilling could investigate basic processes of explosive eruption, as well as intrusive conditions immediately after magma emplacement. The vent is thought to consist of two nested concentric funnels and a central conduit for the last-emplaced lava dome. A radially slanted hole would sample the entire stratigraphic section of the vent, providing a record of its development, and bottom in the vent wall where outward migration of heat and magma-derived chemical components could be measured. A vertical hole from the same well head would pass through intravent pyroclastic units, penetrate the fragmentation surface, and sample the main intrusive feeder. A third, shallow hole would provide a complete section of the associated ignimbrite sheet, providing an eruption record that could be tied to vent development.


SW
Distance from Wellhead (100 m)
NE
8 6 4 2 0 2 4 6 8
Distance Relative to Wellhead (100 m)
2 0 -2 -4 -6 -8 -10 -12
Tephra Ring
Turtle
Novarupta Dome
Alluvium
Tephra Ring
#1
Landslide from Falling Mountain (Extent Unknown)
Limit of Welding (Extent Unknown)
Variably-Welded Agglomerate
Conduit
#2
Wall of Plinian Dacite Vent (Position Unknown)
Plinian Rhyolite and/or Ash-Flow Vent (Position Unknown)
Possible Slump Blocks
1000 m
Intrusive Equivalent of Dome
Intrusive Equivalents of Pyroclastic Units
1200 m
Legend
Alluvium (Reworked Tephra)
Late Plinian Tephra and Vent-Filling Equivalent; Dacite and Andesite
Early-Plinian Tephra and Ash Flows and Vent-Filling Equivalent; Rhyolite, Dacite and Andesite
Rhyolite Lava of Novarupta Dome and Intrusive Equivalent
Basal Breccia of Novarupta Dome
Landslide from Falling Mountain; Dacite
Naknek Formation; Siltstone
Intrusive Equivalent of Pyroclastic Units
#1
Core Hole at Dome Drill Site
#2
Deviated Hole Through Casing of Hole #1
Warm Area on Dome (Projected)

II. Intrusive processes: injection, crystallization, degassing by second boiling, volcanic/ plutonic transition

During the 1970s and early 1980s, drilling into the 1959 Kilauea Iki lava lake (Hawaii, USA) provided significant new insight into the cooling and crystallization of basaltic magma. This represents a special case for the shallow cooling of magma, however, because all the magma „saw" one atmosphere pressure during eruption as a spray and the material cooled entirely within its own crust. A logical next step is to proceed to the more general case of a partially molten shallow conduit or sill. Observation of the distribution and character of crystals, retained volatiles, and vesicles will provide information on the coupled processes of crystallization and degassing. Observation of temperature, fluid composition, and hydrothermal alteration with time since emplacement and in space relative to the intrusive body will provide the first direct measurement of rates of heat and mass transfer in an igneous environment. In this latter context, selection of a simple system in which there was a single magma emplacement event of known age is very important. These goals can be readily combined with the eruption-process objectives listed above at young volcanic vents. Katmai (Novarupta) and Unzen Volcano are attractive possibilities. Although there is not a single, discrete emplacement event, White Island in New Zealand (Fig. V-3) offers the possibility of reaching a hot magmatic intrusion at shallow depth. It is highly desirable that such drilling reach the melt-present regime, or about 1000°C. Because the target is in this case concealed, deeper, and not fully degassed, this will pose greater design, technological and safety challenges than the lava lake situation. Nevertheless, it should be taken as a serious goal.

Although the fundamental processes can be investigated at shallow (1 km) depth, deeper drilling should be undertaken to investigate the volcanic/plutonic transition in magmatic behavior through continuous coring, and the dynamics of intrusion through stress measurements at depth near an active intrusion. These measurements could possibly examine the brittle-ductile transition at elevated temperatures. Among the attractive sites for such an approach are silicic calderas, such as Mt. Aso in Japan and Long Valley Caldera (Rundle and Hill, 1988; Fig. V-4) in the United States. Similarly, crystallization of basaltic intrusions in rift environments could be investigated by drilling in sites such as Krafla in Iceland and Salton Sea in the United States.

III. Magma/hydrothermal coupling

Ambitious drilling by the geothermal industry has substantially explored selected hydrothermal reservoirs. It has also brought us to the threshold of the important problem of the coupling, in terms of heat and mass transfer, between magmatic and hydrothermal systems. The zone where these systems are coupled may be one of concentrated brines, of ductile behavior, and of dominantly conductive heat transfer interrupted by transient pulses of volatiles released by second boiling of the magmatic heat source. It is desirable to select a system where the crystallized upper portion of the intrusive heat source can be sampled. Critical observations are the age, composition, and alteration of the heat source. Investigation of fluid pathways, transitions from water-dominated to vapor-dominated regimes, and evidence of sealing; the content, distribution, and age of veins; fluid inclusions; and the present fluid temperature, pressure, and composition will provide tests of models of heat and mass transport. The regime of interest is 300° to 500°C, at depths of 1-5 km. Drilling has shown that these temperatures and the intrusive heat source can be reached at the base of hydrothermal reservoirs at Larderello, Italy (Batini *et al.*, 1985; Cathelineau *et al.*, 1989; Fig. V-5), Sengan, Japan (Sasada *et al.*, in press) and the Geysers,

California, USA. In both of these vapor-dominated geothermal fields, below 3 km there is a transition to conductive geothermal gradients, giving rapid increases of temperature with depth. White Island in New Zealand (Fig. V-3) represents a special case where the interface between magmatic and hydrothermal fluids may be reached at substantially less than 1 km. Other attractive targets include the high-temperature hypersaline geothermal systems at the Salton Sea, several high-temperature magma-hydrothermal systems in the Philippines, and possible sites in the Aegean Arc of Greece. Geophysical evidence of magmatic intrusion and a shallow brittle/ductile transition supports the existence of such temperatures at drillable depths beneath the resurgent dome of the Long Valley caldera (Fig. V-4).

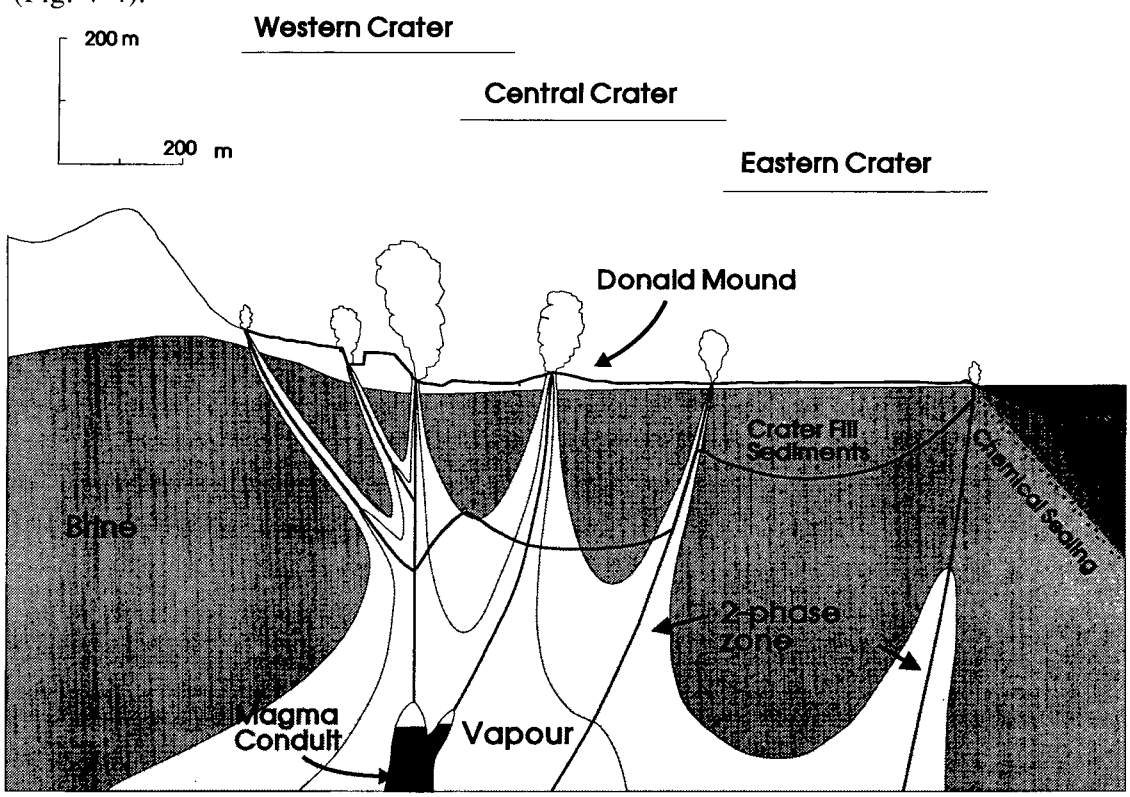


Figure V-3: Cross section of the vent of White Island Volcano, New Zealand. Almost continuous activity brings magmatic temperatures and the regime of magma/hydrothermal coupling to the near surface. This model for distribution of fluid characteristics has been drawn assuming conductive heat transfer from a magma at a depth of 600 m, a depth suggested by microseismicity. Fumarolic temperatures have varied between 100°C and 830°C, with up to 600°C variation in some individual fumaroles. Cyclic variations in discharge composition result from interaction between the magmatic emanations and the enclosing hydrothermal system. Cooling of the fumarolic conduits leads to encroachment of the enclosing brine envelope into the vent region, leading to removal of soluble magmatic gas components (*e.g.*, HCl, HF, and metals) from the vapor phase and the precipitation of elemental sulfur. During reheating, these condensed constituents are remobilized and expelled, after which the discharge returns to a more magmatic composition. Spatial variations of discharge compositions across the crater basin reflect the degree of interaction between condensed magmatic components and the host andesitic material. Core recovery and fluid sampling will assist in clearly delineating these reaction pathways.

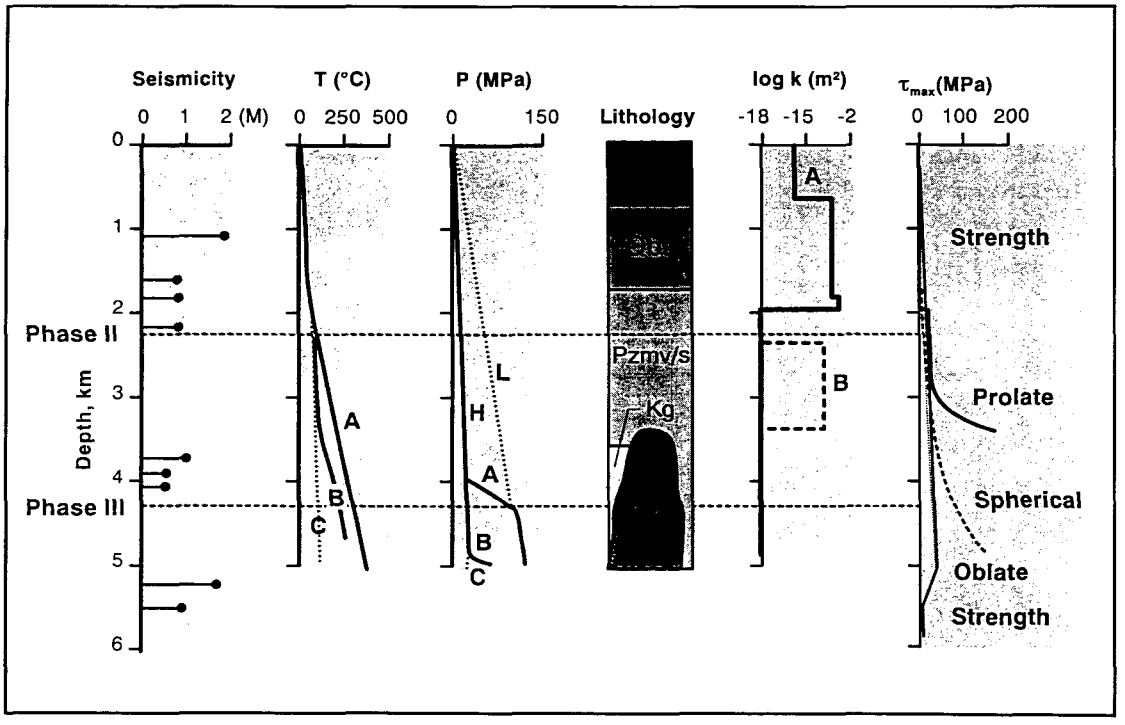


Figure V-4: Abundant geophysical evidence at Long Valley Caldera in the United States indicates that a reservoir centered at a depth of 7 km under the caldera's resurgent dome is receiving new magma. Deepening of an existing research hole, the Long Valley Exploratory Well (LVEW; current depth shown as Phase II), would test this hypothesis through measurement of physical properties with depth. If the hypothesis is validated, conditions above an active intrusion could be explored. Columns depict known or inferred conditions as follows: a) Seismicity observed during 1992 and located within a 2 km x 2 km square centered at LVEW; b) Temperature as a function of depth for A- magma at 7 km and impermeable pre-volcanic basement, B- magma at 7 km with a permeable zone in uppermost basement, C- no magma at depth. c) Calculated fluid pressure profiles for the three cases. The normal hydrostatic (H) and the lithostat (L) are also shown; d) Lithology as a function of depth (known to 2.3 km). Kg is basement consisting of Cretaceous granitic rocks of the Sierra Nevada Batholith; Pzmv/s is basement Paleozoic metavolcanic and metasedimentary rocks; Qbt is the Quaternary caldera-forming Bishop Tuff; Qer is subsequently erupted rhyolite flows and tephra; Qri is caldera-related rhyolite intrusions. e) Permeability as a function of depth, values below 2.3 km are not known, but are shown as used in the model calculations; f) Maximum shear stress as a function of depth for an inflating magma body centered at 7 km with the shapes shown and a volume, corresponding to post-1980 inflation, of 0.09 km^3.

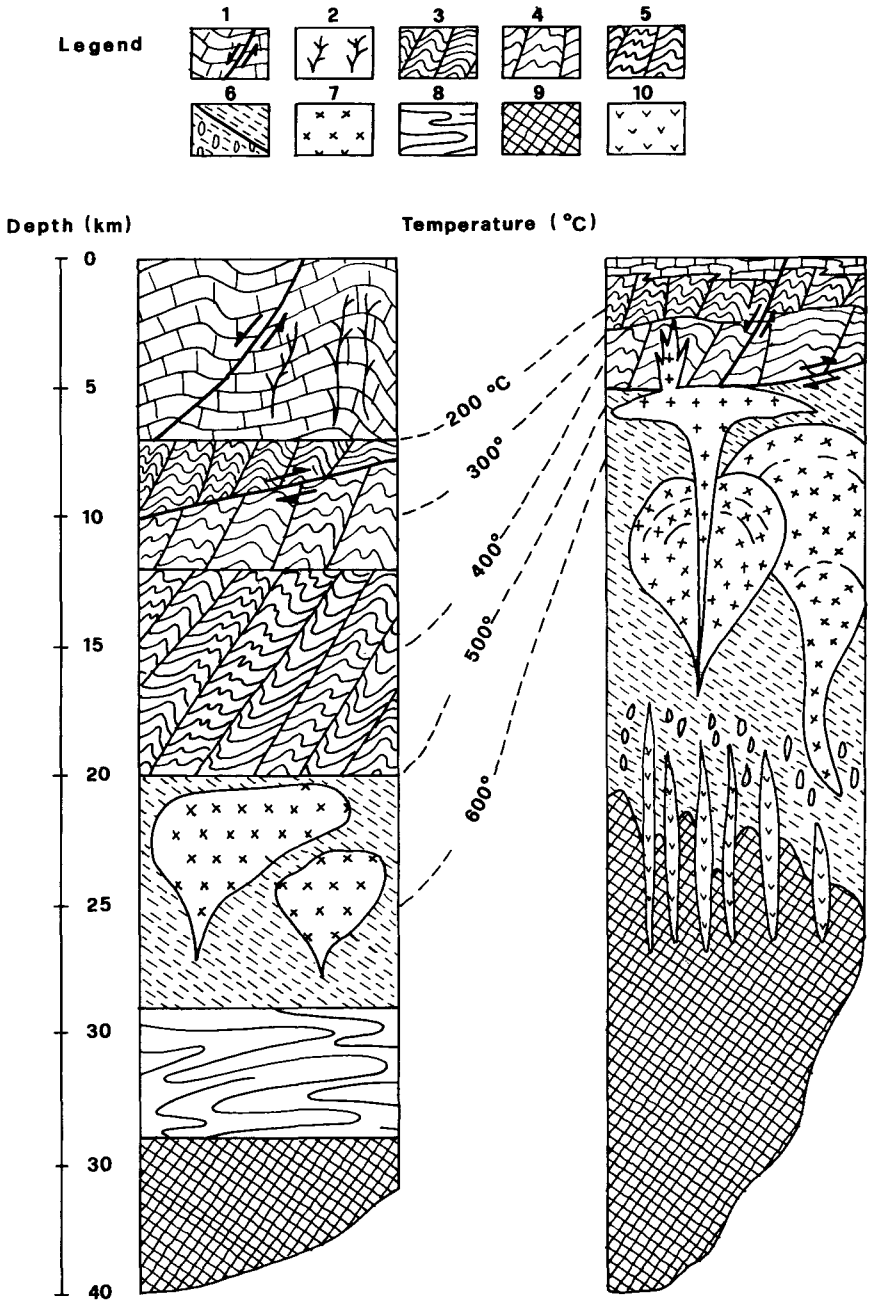


Figure V-5: Modest extension of drilling in geothermal fields, such as at Larderello, Italy, can access the regime of magma/hydrothermal coupling. However, these anomalously hot regions also provide relatively easy access to thermally controlled structure of broader extent, such as the brittle/ductile transition. Hypothetical crustal cross sections for normal (left) and high thermal gradient continental crust such as at Larderello. The model for normal crust is taken from Carter and Tsenn (1987). 1) non-metamorphic brittle regime; 2) hydrothermal fluids; 3) metamorphic brittle regime (zeolite facies); 4) low-grade metamorphic regime (semi-brittle or ductile normal crust); 5) low-grade to medium-grade metamorphic regime (semi-brittle or ductile in normal crust); 6) ductile regime in the medium to high metamorphic grade with partial melting; 7) granitic intrusions; 8) granulite; 9) upper mantle; 10) basalt.

IV. Magma emplacement to the lithosphere

The largest volcanic features on Earth are the oceanic intraplate volcanoes. They provide the purest record of deep melt generation, in the sense of minimal modification by shallow processes, presumably reflecting the decompression of rising mantle diapirs. As such, a continuous and vertically extensive suite of samples from a large volcanic edifice, yielding data on lava composition and volume as a function of time, would provide an important new constraint on models for magma genesis. Such drilling will also provide information on deformation of the lithosphere in response to loading, and on the transition from submarine to subaerial volcanism. Attractive sites are Hawaii, where a pilot research hole is underway (Thomas *et al.*, 1993), and Gran Canaria (Fig. V-6), which is advantageous from the standpoint of radiometric dating of the eruptive sequence. A program of multiple 3-4 km holes can be used to sample an entire edifice, rather than using a single deep hole.

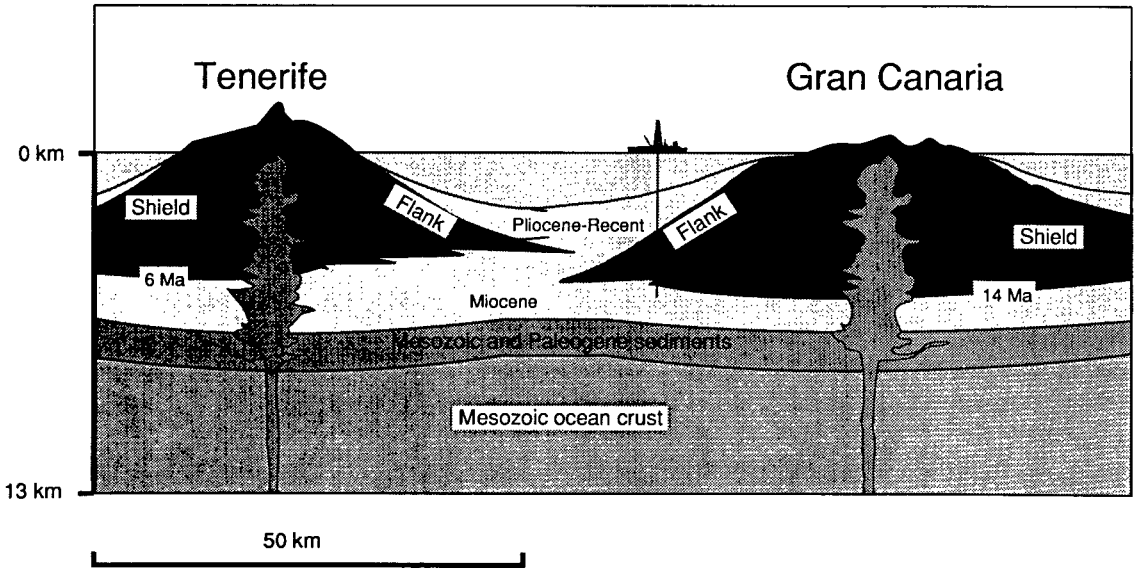


Figure V-6: Schematic cross section showing two large overlapping intraplate volcanic islands. The 3700-m-high Pico de Teide on Tenerife is the third largest volcano on Earth. Supra-aerial evolution of Gran Canaria is fairly well know owing to extremely good exposures. Nevertheless, more than 90% by volume of this, and other comparable oceanic volcanoes, are not exposed. The volcaniclastic apron, which extends 1000 km into the Madeira abyssal plain and represents materials shed from the island during its 15 million years of growth, will be drilled in 1994 during Leg 157 (MAP/VICAP within the Ocean Drilling Program). Together with the ocean drilling, drilling on land into the flanks of the island would provide an unprecedented record of the chemical, volcanological, and temporal evolution of a prototype hotspot volcano. Such data are fundamental to model the decompression rate of mantle plumes.

In terms of addressing magmatic problems, special note should be made of silicic calderas. These represent the largest and most chemically evolved volcanic systems on the continents. They are „windows into the tops of granitic batholiths" (Lipman, 1984). Drilling investigation of their deep structure and thermal and stress state will provide important evidence of the conditions under which large magma chambers exist in the crust. Although not within the realm of the technically feasible now, drilling into crustal

magma chambers beneath calderas will be needed if concepts of chemical differentiation of magma are ever to be rigorously tested. It is likely that such differentiation involves melt/crystal/bubble segregation in the high thermal gradient zone of the margins of magma bodies.

Thermal regimes are an important, ubiquitous, and non-site-specific aspect of the geology of the continental crust, thus other thermal regime targets deserve mention. Heat transfer by both conduction and fluid flow plays important roles in phenomena such as maturation of hydrocarbons, diagenesis of sediments, and ore genesis, and in changing the mechanical properties of rocks during tectonic deformation. Certain mid-crustal features, such as the base of the seismogenic zone or the brittle-ductile transition and laterally extensive seismic reflectors shallow toward volcanic centers, where they may be accessible to direct investigation by drilling (Fig. V-5). Drilling into subduction zones, where convergent plate boundary magma genesis occurs, should be considered in the future.

Conclusions

Volcanism is a fundamental planetary process that also presents both hazards to and resources for human activities. Shallow drilling into recently active volcanic vents and modest extension beyond energy-motivated drilling in hydrothermal reservoirs are two areas where there can be high expectations for research drilling to rapidly yield benefits to science and to society. In addition, thermal processes are an important aspect of general, non-volcanic areas of the crust, and should be fully investigated as part of any scientific drilling project, regardless of the primary scientific objectives of the project.

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VI. Convergent Plate Boundaries and Collision Zones

Introduction

Convergent plate boundaries and collision zones are the sites where the formation, deformation and destruction of continental crust occurs. Because an understanding of processes along convergent margins is fundamental to crustal evolution and continental dynamics the study of convergent plate boundaries deserves special attention.

Mountain belts are formed along convergent plate boundaries during continuous subduction, as in the Andes, or as a consequence of collision between continents, as in the Himalayas. Uplift is driven by isostatic rebound of crust undergoing thickening due to horizontal shortening or magma emplacement resulting in exhumation of deep crustal sections not exposed elsewhere. Intense upward transport of matter is coupled to the uplift, intrusion and extrusion of arc magmas. The volcanism most hazardous to civilization is bound to convergent plate boundaries. Denudation of elevated mountain belts provides the material for filling of adjacent sedimentary basins. Altogether, convergent plate boundaries are zones of extensive mass transport, sediments and other crustal material are subducted and recycled into the mantle.

The interaction between continental collision, buoyant features on the descending plate like oceanic plateaus, extinct island arcs and continental fragments with active continental margins or island arcs can often be explained within the kinematic framework of plate motion. Changes in velocity and relative plate motion may occur as a result of plate collisions. As such, understanding the processes at convergent plate boundaries critically depends upon our knowledge of the driving forces and how stresses are transmitted in the lithosphere. The weakness inherent to plate boundaries is poorly understood. Problems include understanding the inherent weakness of plate boundaries (see Section IV) and why the largest earthquakes are located in the shallow parts of subduction zones.

Active convergent plate boundaries provide insight in the boundary conditions and processes that lead to the formation of continental crust, as well as into mass transfer between crust and mantle. Due to the buoyancy of mountain belts and related denudation, sampling of deeper levels of the crust produced at historically active tectonic settings can be studied and interpreted.

Key Questions

There are a number of fundamental problems in Earth sciences related to or exclusively addressable in convergent plate boundary settings and collision zones. Many of these aspects are probably interrelated and cannot be treated independently. The following list accounts for most of the outstanding problems:

- Mechanics of plate motion
- Rheology of Earth materials
- Stress field in convergent margin settings
- Kinematics related to stress field and changes of stress field in space and time
- Time scales of stress field changes
- Localization of deformation and strain rate gradients (*i.e.*, mechanical properties of faults and shear zones)

- Thermal structure of the crust and relations to deformation, denudation and topography
- Role of mobile phases (fluids and melts) for the thermal structure and the rheological behavior of the crust
- Mass transfer budget in subduction zones and recycling of crustal material
- Processes involved in exhumation of (ultra)high pressure metamorphic rocks and boundary conditions for their preservation
- Crustal architecture and calibration of geophysical observations

Addressing these questions represent first-order goals for future scientific research.

Role of Scientific Drilling

Scientific drilling in convergent margin settings and collisional belts is the only means that provides direct access for in situ observations that determine the actual physical conditions as a function of depth and related variations. Knowlege of these in situ conditions gained through drilling makes it possible to infer the actual processes. Furthermore, only scientific drilling enables the continuous recovery of appropriate samples to constrain crustal architecture and to decipher the record of crustal evolution.

The principal objectives of a drilling project comprise:

(1) Measurement of the actual physical conditions, particularly

a) state of stress

b) geometry of pore space and permeability

c) pore fluid pressure

d) pore fluid composition

e) temperature field

and their mutual relations in terms of depth variations, composition, and heterogeneities of the crust,

(2) Study of the actual state of material and processes in active fault zones (thrusts, decollements, "interface" between plates or any type of faults in general),

(3) Recovery of continuous sections along gradients (*e.g.*, from ancient ductile shear zones)

(4) Recovery of quenched samples unmodified by near-surface alteration during exhumation on natural time scales

(5) Reconstruction of thermal history by fission track methods

(6) Three-dimensional analysis of large-scale crustal architecture and geophysical calibration.

Drilling projects can be designed with emphasis on currently active regions such as subduction or thrusting, as well as regions of relict zones of continental collision. Sites can be selected on the basis of the age of the slab under consideration and which "active process" is of interest. In many situations an attractive combination of studies is possible in which both fossil processes and currently active processes exist. These targets appear to be outstanding for economic reasons and because they provide access to more complex studies covering different time scales. In any case, efforts should usually concentrate on

geologically "young" situations constrained by the current plate tectonic framework. The scientific potential of deep drilling into continental crust in convergent plate boundary settings or in collisional belts is best illustrated using examples.

Specific Examples

A number of concrete proposals for specific drilling projects were presented at the Potsdam meeting including:

- Arc tectonics (Japan)
- Collision mechanics (Alps, Himalaya)
- Extension (Italy)
- Forearc (Hellenic arc)
- Neotectonics, thermal history, rates (Himalaya, Alps) Subduction zone (Japan, Chile, Hellenic arc) Suture zones (general)
- Thrust tectonics (Hellenic arc, Alps)
- Ultrahigh pressure metamorphics (China, Alps)

Generalized objectives of any scientific drilling project along convergent plate boundaries is illustrated for different regional targets in a number of the figures which are deliberately drawn to be as simple as possible. Note that nearly all the cross sections are intended to be generalized examples and that the position of the drilling rig does not infer any specific site. In the figure captions, reference is given to the regional setting and the original manuscripts from which the figures originated. The examples can be grouped as follows:

- Active subduction zones and accretionary wedges
- Active intracontinental large scale thrusts
- Thermal history of mountain belts
- Crustal architecture of mountain belts and post-collisional physical state
- Exhumation of (ultra) high pressure metamorphic rocks

Further subjects linked to convergent boundaries, such as arc magmatism and high heat flow areas with active volcanism, are not discussed in this section; but are covered elsewhere in this report.

Active Subduction Zones and Accretionary Wedges

The scientific benefits gained through direct access to the "interface" between converging plates is considered to be highly attractive. Designing a drilling experiment in this environment will provide precise information about the physical properties of the material within a large scale shear zone and the ambient conditions of the stress state, pore space, pore fluid composition, pore fluid pressure and temperature. On a larger time scale, information about the mass transfer between the plates (in terms of tectonic erosion versus accretion, and the extent of transport of sediments towards greater depths) is urgently required. Present day models are based on the interpretation of geophysical data, theoretical models and paleostructures which have been modified during exhumation, and a number of shallow drill holes through the outermost toe or into the uppermost level of the accretionary wedges (Fig. VI-1). The data base leaves ample freedom for

interpretation of the deeper levels. Abundant geologic information about the history of accretion over a larger time scale is already provided by penetration of the accretionary wedge in the hanging wall of the subduction zone.

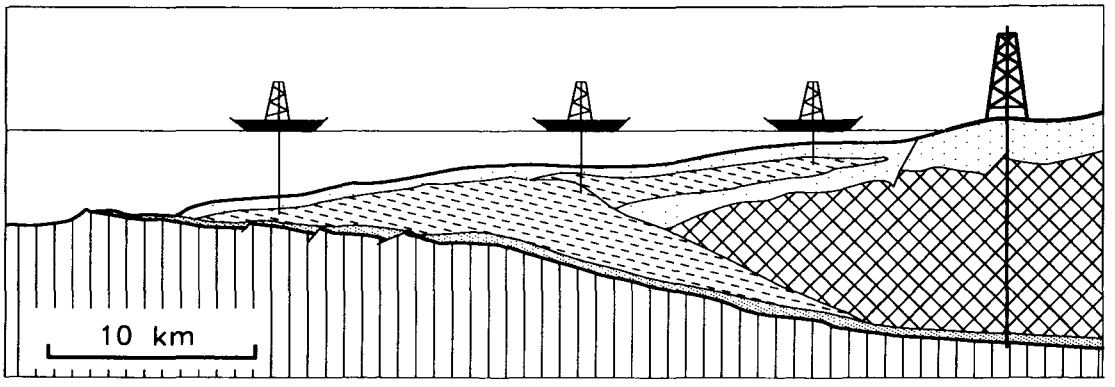

Figure VI-1: Cartoon showing a cross section through an accretionary wedge and the information gained by ocean drilling versus the range which could be covered by deep landbased drill holes.

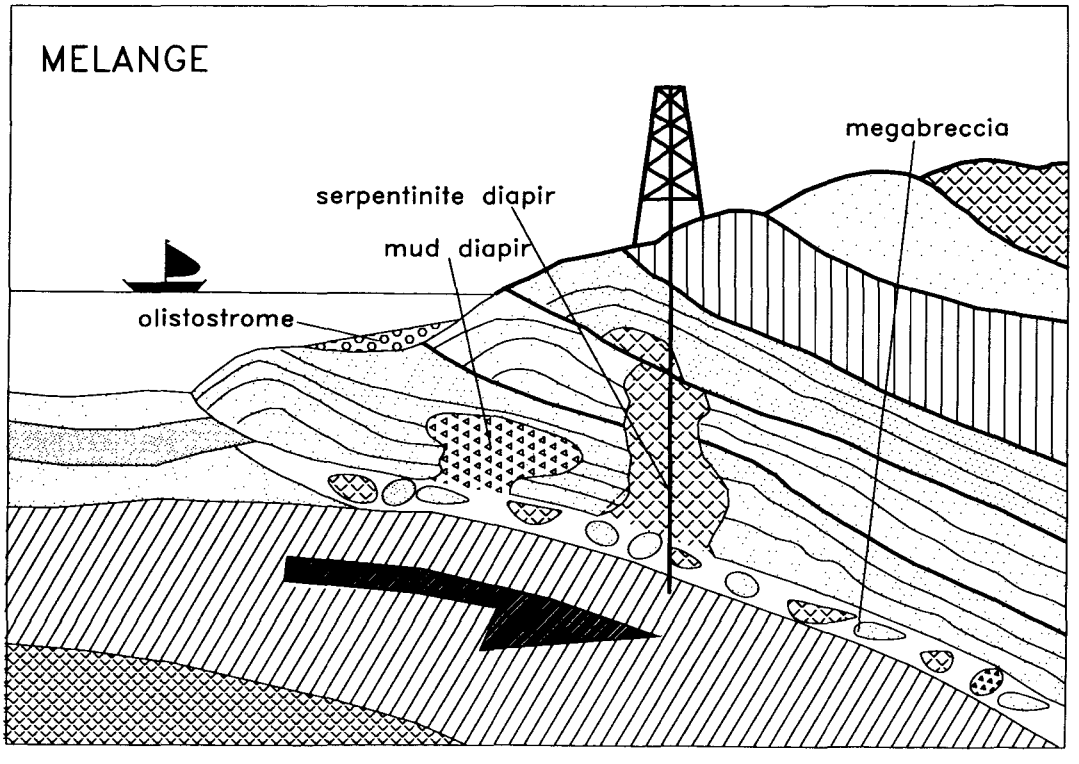

Figure VI-2: Various models inferred for the formation of melange complexes, from Rauche, 1993 (unpublished). Deep drilling would provide insight into processes in and on top of subduction channels.

Formation of melange complexes is linked to convergent plate boundaries, although the mechanisms involved and the placement of these boundaries are poorly understood (Fig. VI-2). Concepts of melange formation in the subduction channel or in diapirs could be tested by analysis of actual structures and conditions at depth gained by drilling.

Presently available technology allows for drilling to a depth of about 10 km. The low thermal gradient expected for forearc regions of active subduction zones may allow for even deeper penetration. In regions of high heat-flow, sites of primary importance remain out of range. In any case, deep drill holes can potentially extend our observations by an order of magnitude compared to the previous ocean drilling efforts along convergent margins (Fig. VI-1). For penetration of the "interface" between the plates by landbased deep drilling a special situation is required. This exists only in few places all over the world. One example is the Izu peninsula in Japan (Fig. VI-3), where the upper surface of a subducted slab is expected to lie at a depth of 10 km. Others are found close to the Chile triple junction where the forearc is underlain by continental crust (Fig. VI-4).

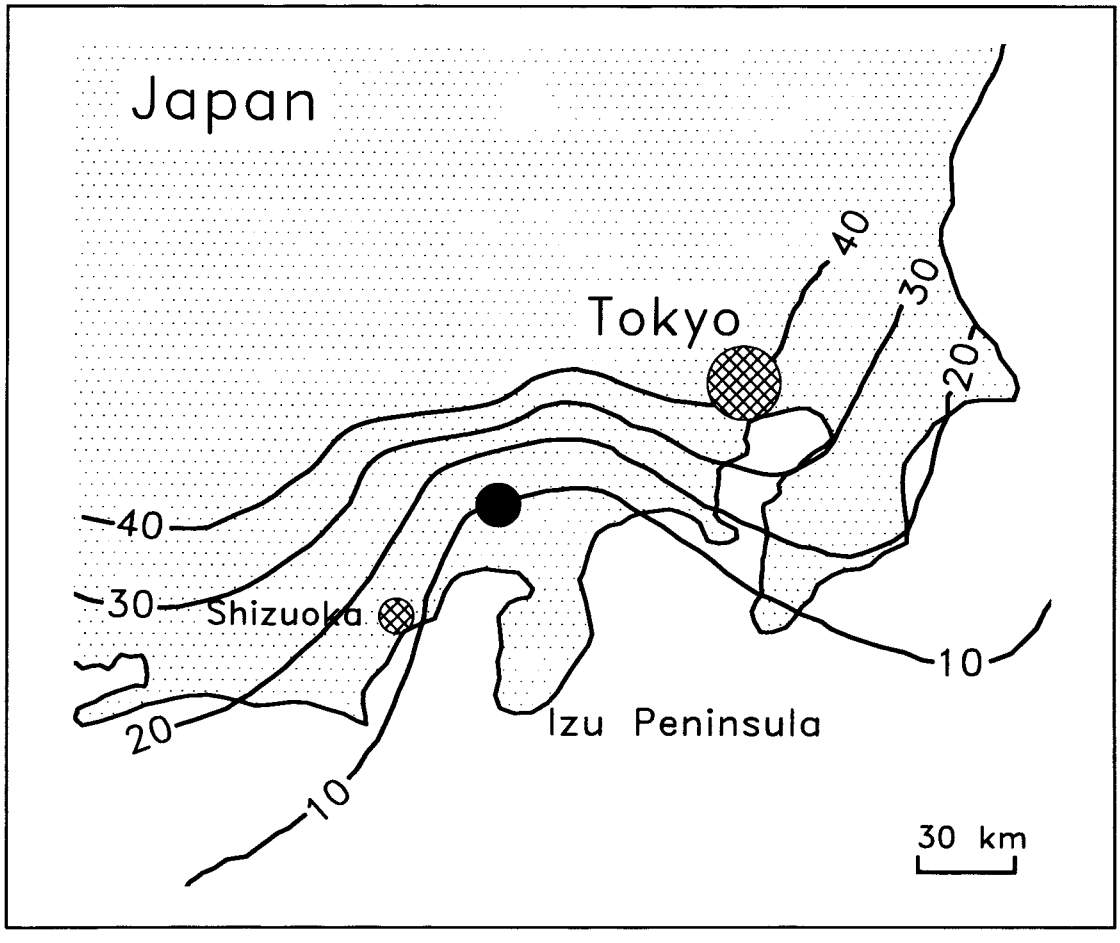

Figure VI-3: Depth contours for the upper surface of the descendig slab around Izu peninsula, Japan, simplified after Urabe et al. (1992). The subducted plate could be reached within 10 km from the surface.

Subduction of oceanic crust results in accretion of massive sections of its sedimentary cover associated with the downgoing plate into the upper plate, either by frontal offscraping or by underplating. A concept regarding the mechanics of accretionary

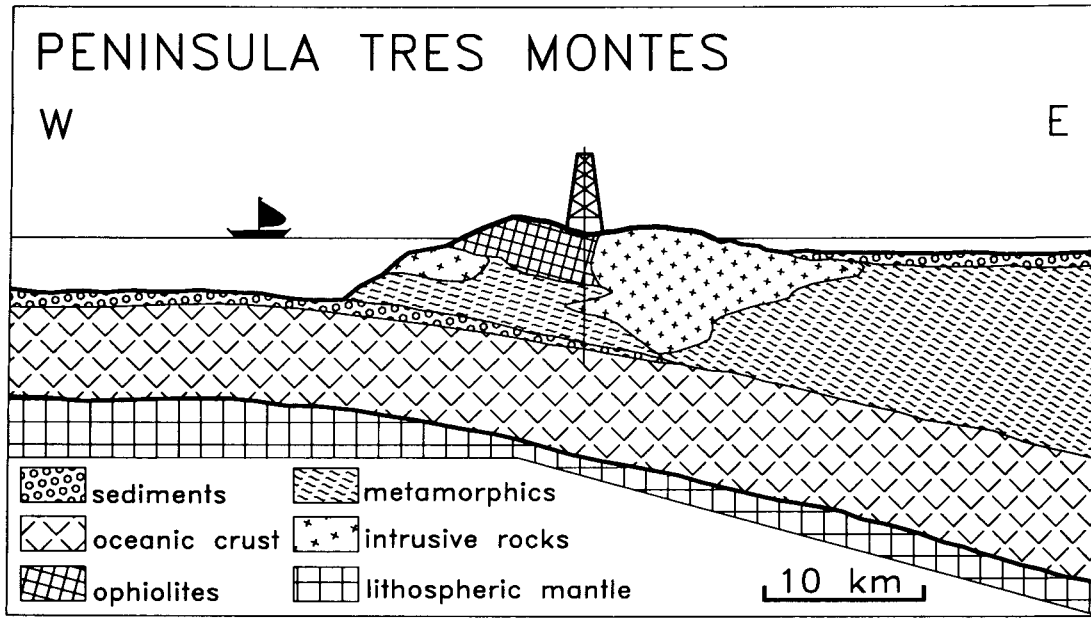

Figure VI-4: Schematic cross section through the southern Chile margin at Taitao peninsula, close to the Chile triple junction, simplified after Behrmann (1992, unpublished). The internal structure is inferred from seismic data. Land based drilling could reach the descending slab at a depth of around 10 km after transecting continental crust of the forearc.

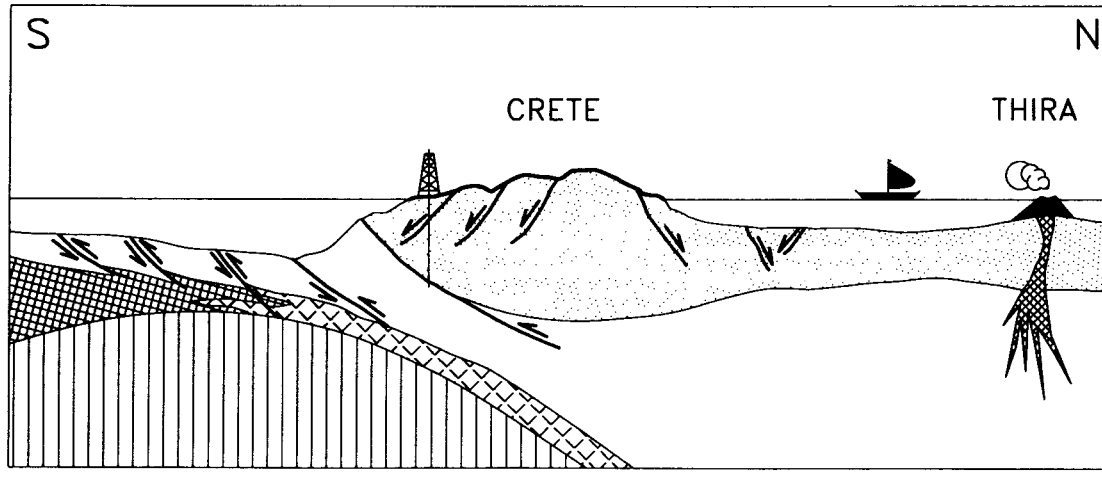

Figure VI-5: Cross section through the Hellenic subduction zone and the island of Crete, compiled and simplified after Le Pichon and Angelier (1981) and Finetti et al. (1991). The island of Crete is made up by a Miocene accretionary complex including high pressure/low temperature metamorphic rocks, which has suffered extension during exhumation (cf. Fig. VI-6). The rear part of the actual forearc is currently being extended. Determination of the actual stress state as a function of depth in the transitional region between the recent accretionary wedge and the frontal range of the extending upper plate would be one of the primary goals of a deep drill project.

wedges, the "critical taper" model (e.g., Dahlen, 1990), predicts horizontal extension in the rear upper part of the wedge in response to underplating that maintains constant geometry. This is an effective mechanism for the exhumation of once deep-seated crustal slices during ongoing subduction (Platt, 1986). The "critical taper" concept implies a specific stress field, which could be tested by deep drilling into the rear of an active wedge.

A transition from a compressional regime into an extensional regime in space and time is observed in forearc regions. The actual Hellenic subduction system in the Eastern Mediterranean serves as an example (Fig. VI-5). In the frontal part of the upper plate parts of a Oligocene/Miocene accretionary complex is composed of high pressure/low temperature metamorphic rocks (Fig. VI-6). During subduction, the stacked thrust sheets experienced extension during exhumation, while subduction continued. A three dimensional structural analysis of such a complex, including reconstruction of thermal history and kinematic framework, could provide valuable insight into forearc dynamics. A deep drill hole simultaneously allows the analysis of the actual physical state of the crust in the hangingwall of the active subduction zone and the evaluation of the record of ancient processes.

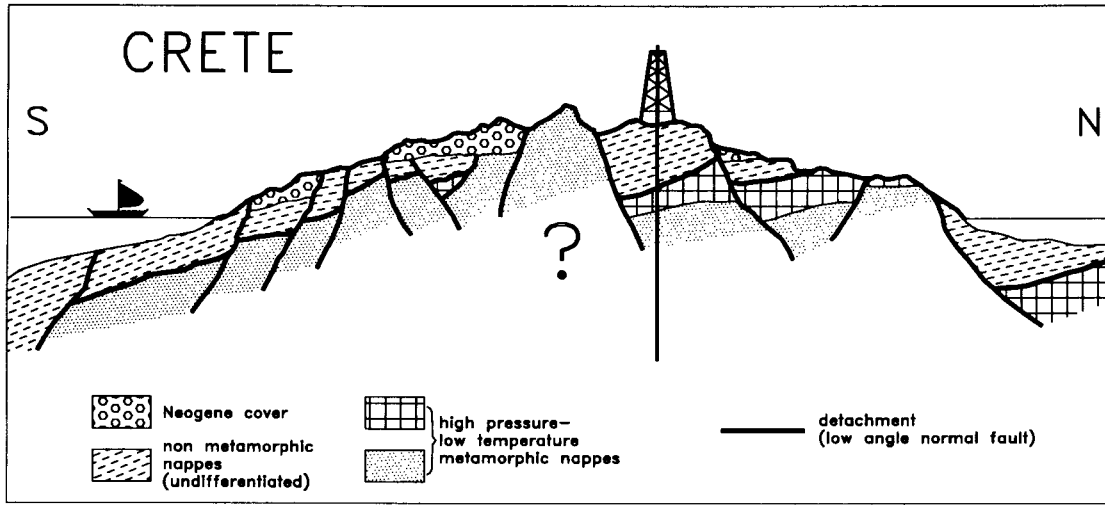

Figure VI-6: Schematic cross section through the island of Crete as an example for the exhumation of high-pressure metamorphic rocks in an active forearc. The Oligocene/Miocene nappe pile has experienced major extension. A large-scale low-angle detachment that developed during exhumation separates the upper unmetamorphosed rocks from the lower high-pressure metamorphic nappes, which are cut by a series of active normal faults. Reconstruction of the sequence of processes involved in exhumation requires kinematic and rheologic analysis of the fault zones correlated with the thermal history of the units. Appropriate samples and sufficient insight in the three-dimensional structure of the complex can only be gained by drilling.

Active Continental Large Scale Thrusts:

Deformation in convergent boundary settings is concentrated along thrust faults. The mechanical properties of fault zones as a function of depth and temperature are dealt with

elsewhere in this report. As a consequence of the denudation of their uprising hanging-wall, thrust faults provide samples of earlier active, more deeply buried segments of fault strands. It is possible to integrate the tectonic history as a function of depth along narrow cross sections, and to infer the mechanical behavior of thrusts on a crustal scale. This geologic mapping approach helps unravel records of ancient fault systems by sampling at all observational scales. Since surface exposure of thrusts is generally very poor, scientific deep drilling is essential (Fig. VI-7).

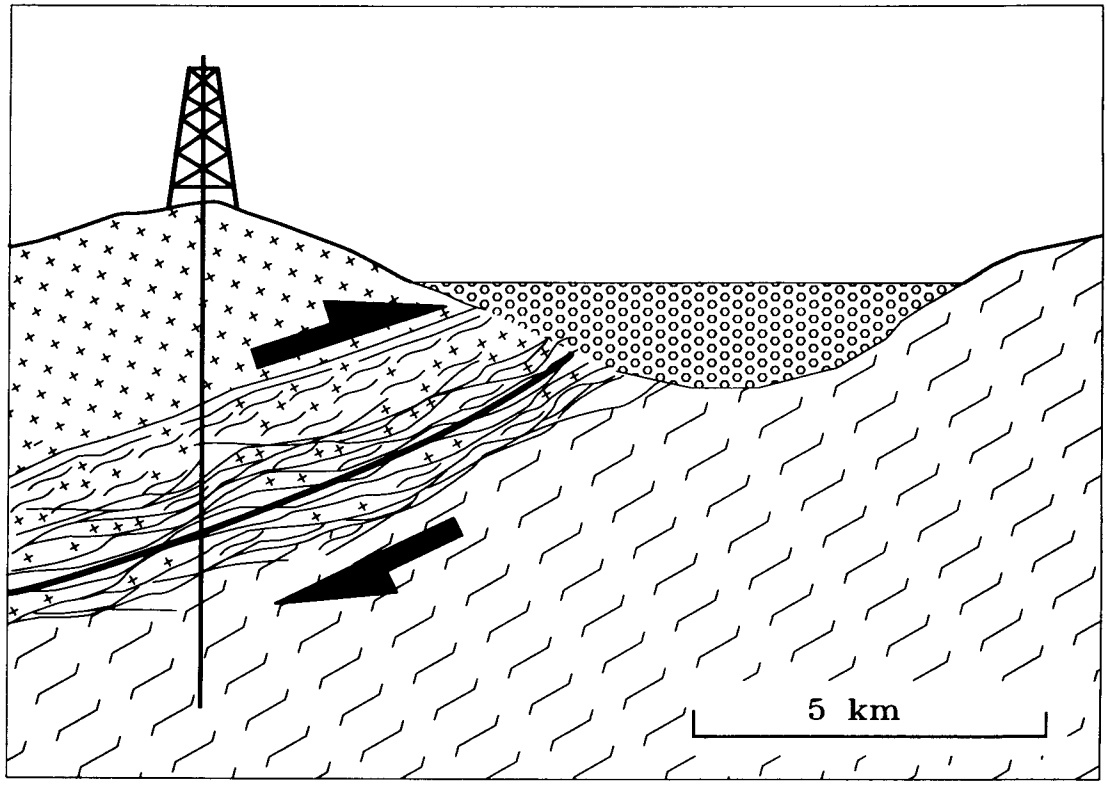

Figure VI-7: Exposure of shear zones is generally poor. Thrusts provide the unique opportunity to study the structural and microstructural record of displacements acquired in different levels of the crust along a single cross-section due to upward transport of material within the hanging wall and telescoping. Their detailed and quantitative analysis requires continuous sections readily provided by shallow drill holes.

The same holds true for large scale intracontinental thrusts still active in collisional belts, as in the Nanga Parbat region of the Himalayas (Fig. VI-8). Drilling through these faults or shear zones allows the determination of the actual state of stress, material properties, pore fluid pressure and composition as a function of depth. The thermal structure and its perturbation due to fluid flow, the mechanical consequences, and the effects of displacement rates on the thermal structure on a larger crustal scale can be investigated through drilling. The general question of heat transport and thermal structure of the upper crust is addressed in the following section.

Thermal History of Mountain Belts

An important aspect of the uplift of mountain belts is the thermal structure of the crust.

Advective heat transport to shallow crustal levels may be controlled by the rate of denudation, which in turn is controlled by the isostatic rebound in the lithospheric system. Rates of denudation and cooling in the low temperature range can be derived from fission track analyses in minerals like apatite and zircon (Hurford, 1991). Continuous age and track length distribution profiles along a deep drill hole, or an array of drill holes (Fig. VI-9), combined with data from surface samples related to elevation, yields a very attractive data base for the reconstruction of the interplay between uplift, denudation, thermal structure and resultant morphology. This should lead to a better understanding of continental convergent boundaries in terms of the modes of crustal heat transport and the long-term response of the crust/mantle system due to thickening.

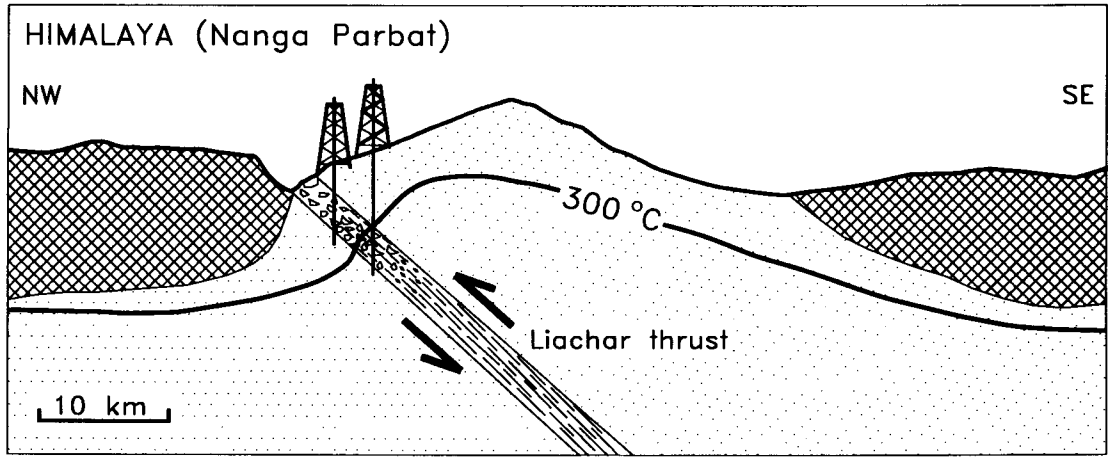

Figure VI-8: Cross section through an active intracontinental thrust in the Nanga Parbat region of the Himalayas, simplified after Butler *et al.* (1988). Drill holes through the fault zone at various depths provide data on material properties, fluid flow and state of stress, and allow for correlation with kinematics. Additionally, the thermal history of the adjacent blocks and the influence of the fault zone can be studied (cf. Fig. VI-9).

Crustal Architecture of Mountain Belts and Their Postcollisional State

Mountain belts are the result of isostatic uplift after crustal thickening due to subduction and collision. Dependending on the age of these processes, the present level of erosion provides access to one, and only one thin slab through the crustal bulge. The structural and metamorphic features in this esposed slab allow some inferences on the already removed overburden, as well as extrapolation into deeper levels of the crust.

The understanding of the crustal architecture of mountain belts requires a complete cross-sections through "tectonic slabs" to answer fundamental questions such as what a fossil plate boundaries look like at depth. In most cases, major crustal sections correspond to high strain zones and show progressive, or polyphase, tectonic evolution, the earliest characteristics of collision largely being overprinted by later structures. Moreover, even good outcrops are usually highly-weathered thus making tectonic analysis quite difficult. Therefore critical factors in such areas, like strain partitioning, the distribution of metamorphic gradients and the rheology of major crustal boundaries remain poorly constrained. For these reasons, a multi-site drilling program has been proposed for the

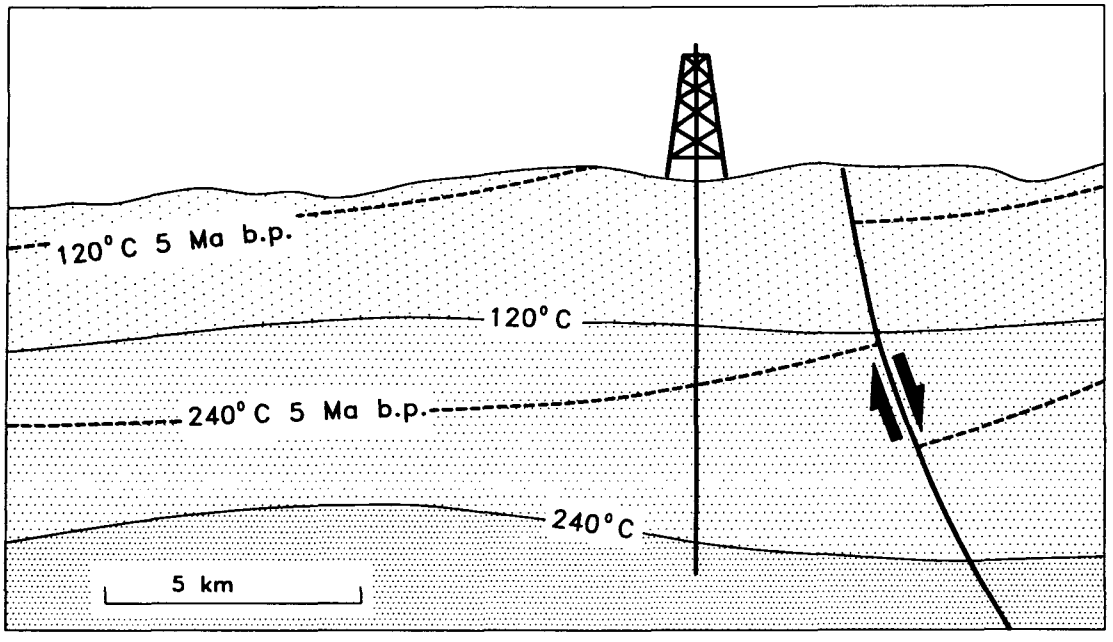

Figure VI-9: Thermal history of a mountain belt undergoing denudation due to uplift. The actual thermal structure is to be measured directly in drill holes. The thermal history can be derived from the determination of fission track ages and track length distributions on various minerals as a function of depth.

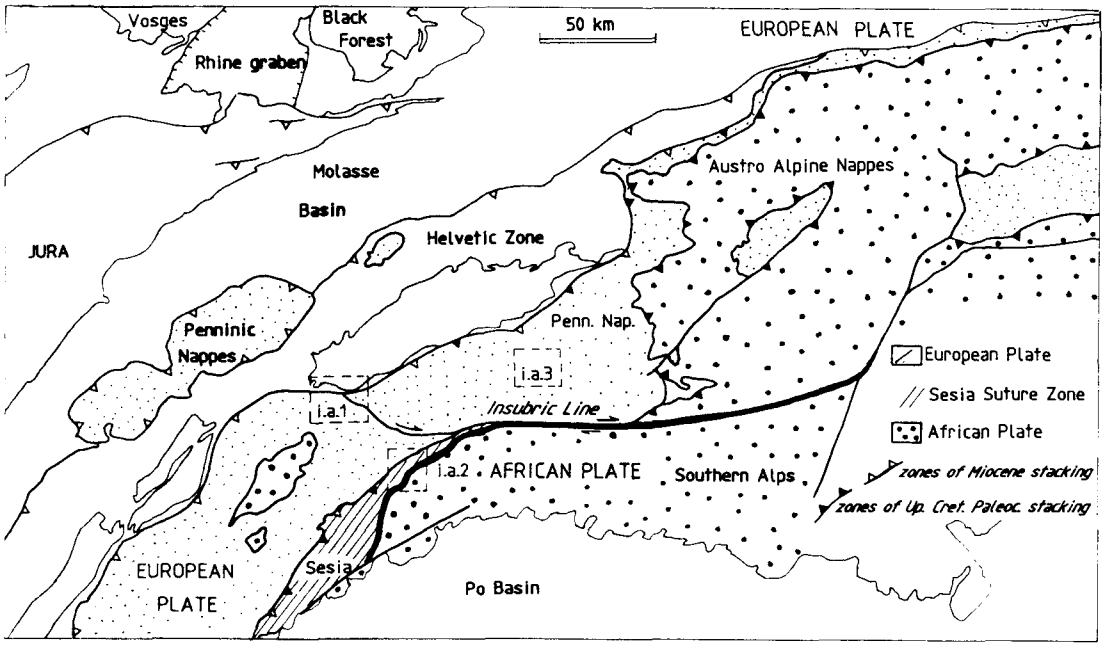

Figure VI-10: Location of the multi-site deep drilling project in the Alps (from Schönborn *et al.*, 1992). Areas indicated i.a. 1, 2, and 3 refer, respectively. to investigations in the area across the Simplon Line and the Pennine Frontal Thrust, the Insubric Line and the Leventina nappe.

Alps (to a depth of about 4 km at each site) based on existing detailed geologic maps and seismic profiles. Furthermore, as shown by the KTB and Couy scientific drillings, fluid circulation through tectonic zones can be characterized by multi-site drilling. Three main targets have been defined (Figs. VI-10, 11 from Schönborn *et al.*, 1992).

(1) The Simplon Line and the Pennine Frontal Thrust, across a recent detachment fault and an earlier major thrust zone (Figs. VI-11).

(2) The Insubric Line, across the border line between the Central and Southern Alps and the Ivrea zone (Figs. VI-11). This line represents the major medium-upper crustal recent collisional site for the European and Gondwana plate collission, post-dating the first stacking stages of Cretaceous-Eocene age. With site 1 on the Simplon line detachment, these two situations show how the tectonically-thickened crust has been reactivated by extensional processes.

(3) The Leventina nappe, across the deepest structural level of the Alps (Figs. VI-11).

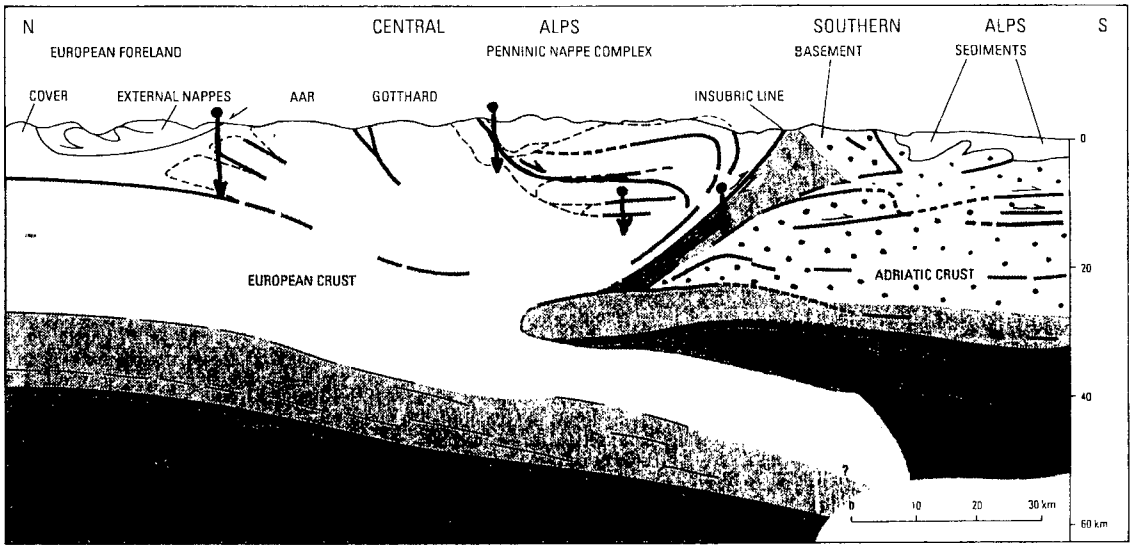

Figure VI-11: Crustal section across the Alps after the Swiss Programme PNR 20 (Frei *et al.*, 1989). This section shows the regular subduction of the European crust beneath the Alps. The crust is indented and scraped by the southern African plate with a wedge of mantle at its base. This configuration postdates earlier polyphase Alpine deformation which began in the Cretaceous (100 Ma). Exposures, laterally from this cross section give access to major structural lines at moderate depth which could be targets for deep drilling programs.

This multi-site program has been defined in close connection with investigations concerning the fit between geophysical and geological data. Geophysical models, in particular those derived from reflection seismics, are used in combination with extrapolation of surface structures to gain a three-dimensional picture. In many cases, these structural models seem to be satisfactory - but they lack any control. Moreover, the experience of the deep boreholes in crystalline rock complexes (Kola, KTB, Cajon Pass, GPF Couy) has shown that such correlations are hazardous. As such it is highly desirable

to check the interpretations in selected sites by deep drilling. Deep drill holes in areas where the structural models are very well constrained by surface geology and geophysical data (as shown in Fig. VI-12) could provide unique opportunities for calibration of crustal geophysics.

The actual mechanical state of the crust in an active mountain belt, where body forces cause extensional collapse due to steep elevation gradients (Dewey, 1988), is a fundamental question to be investigated in deep drill holes. Analysis of the state of stress as a function of depth would pose constraints on the respective models.

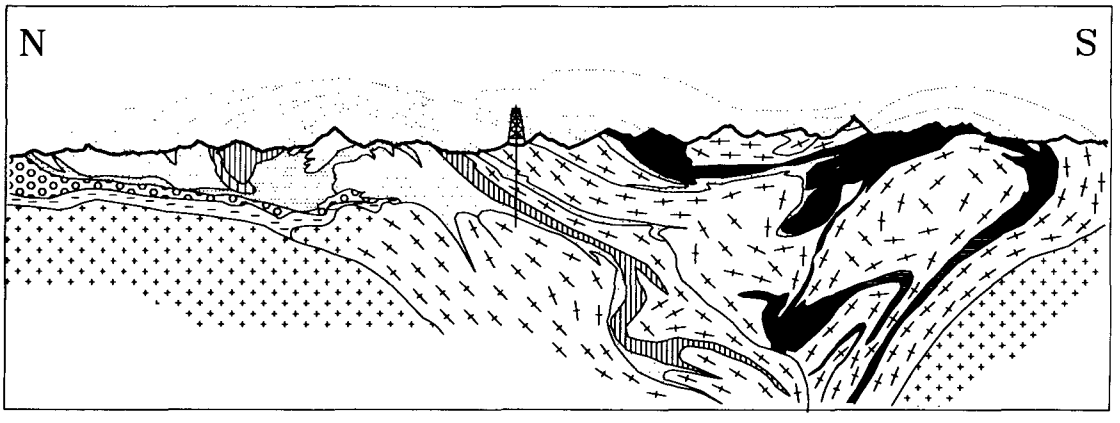

Figure VI-12: Schematic cross-section through a collisional orogenic belt (Example Western Alps, simplified after Escher *et al.* 1988). The structural relations inferred at depth are based on extrapolation of structures from the surfac and correlated with seismic data. The role of scientific deep drilling is to verify the inferred subsurface structure and to gain samples for studies of the material properties at depth, especially from the large scale shear zones. More important, ultradeep drill holes are the only way to calibrate crustal geophysics, which is essential to reduce the uncertainty in the interpretation of the data.

Exhumation of (Ultra) High Pressure Metamorphic Rocks

The recognition of ultrahigh pressure metamorphic rocks with coesite and diamond in Mesozoic and younger mountain belts (*e.g.* in the Western Alps, Michard *et al.* 1993, Schertl *et al.* 1991, and in China, Wang *et al.* 1992, Okay *et al.* 1993) has focussed attention on the exhumation processes of these continental crustal fragments that are believed to have been buried deeper than maximum known depths of actual crustal slabs. The particle paths and the kinematic framework during the exhumation of these ultrahigh pressure metamorphic rocks are as enigmatic as their preservation. They may be of paramount importance for our understanding of collision zones. The sites of formation and the larger portion of their exhumation path are clearly out of range for deep drilling. One approach to this problems is to delineate the three dimensional geometry of these extraordinary crustal slices in the orogen. Although a great deal can be achieved in this respect by detailed structural mapping,scientific drilling is necessary to obtain an unambigous three dimensional geometry and to study the contact zones with the underlying rocks. Drilling will also provide continuous and unaltered cores across these bodies and their respective interfaces (Fig. VI-13). The structural and petrological information from these drill holes may provide the clues for the development of concepts of large-scale continental crustal

behavior beyond the conservative structural approaches, which are, at least at depth, rather poorly constrained.

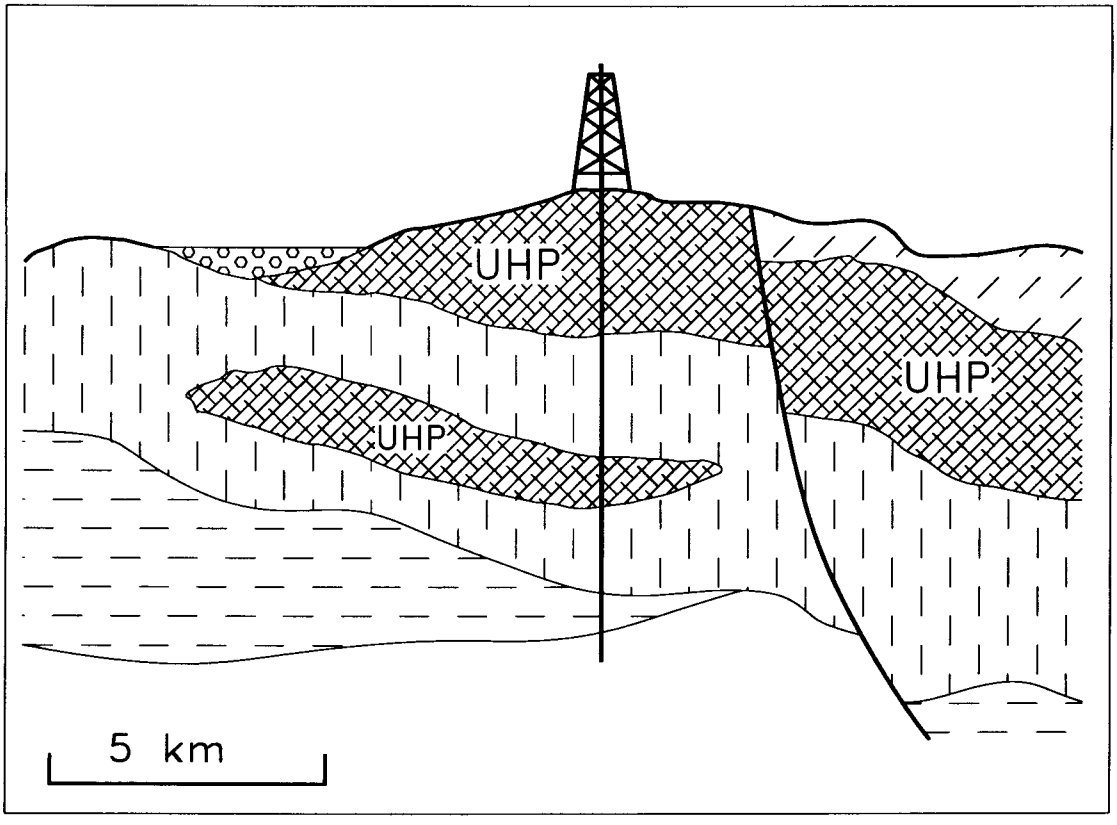

Figure VI-13: Ultrahigh pressure metamorphic slices embedded in material lacking any sign of deep burial. Scientific deep (or shallow) drilling can provide continuous sections required to study the transitional zones. These may provide the clue to reconstruct the exhumation history and hence crustal processes of paramount importance.

Technological needs

To address a number of the problems outlined above would require drilling to unprecedented depths. Thus, drilling systems capable of depths to about 15 km is required for the studies of subduction zones, the lower levels of accretionary complexes and deeper portions of active shear zones. Drilling in tectonically active zones may require technology for handling lithostatic pore fluid pressures. Clearly this will provide extraordinary technical challenges. A respectable depth of penetration is also desired in studies on the crustal architecture in mountain belts, but these are well within existing capabilities. Temperature hardening of logging and sampling tools to at least 300°C is essential.

Conclusions

Deep scientific drilling into convergent plate boundary settings, especially active forearc regions, and young mountain belts along collision zones would provide fundamental clues to outstanding questions of paramount importance. Direct access is the prerequisite and the only way to gain the badly needed data to understand the actual mechanical and thermal

properties of the crust as a function of depth and time. Adding the third dimension in studies on crustal architecture is as important as is proper calibration of geophysical methods to properly constrain interpretations. Finally, continuous recovery of high quality core samples is essential for many studies in mountain belts.

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VII. Fluids in the Crust

Introduction

Fluids are present throughout the Earth's crust and include dilute water, brines, gas, petroleum, and magma. The study of these fluids should constitute an important component of all scientific drilling programs. Mineralogical and mechanical properties of rock are influenced by physical and chemical properties of the fluid. A change that affects one property is likely to affect other properties (Fig. VII-1). Consequently, the physical and chemical states of fluids, and rates of fluid movement must be considered in the study and interpretation of geologic processes. An excellent overview of linkages of fluids in the crust with metamorphic processes and rock mechanics is provided by Fyfe *et al.* (1978).

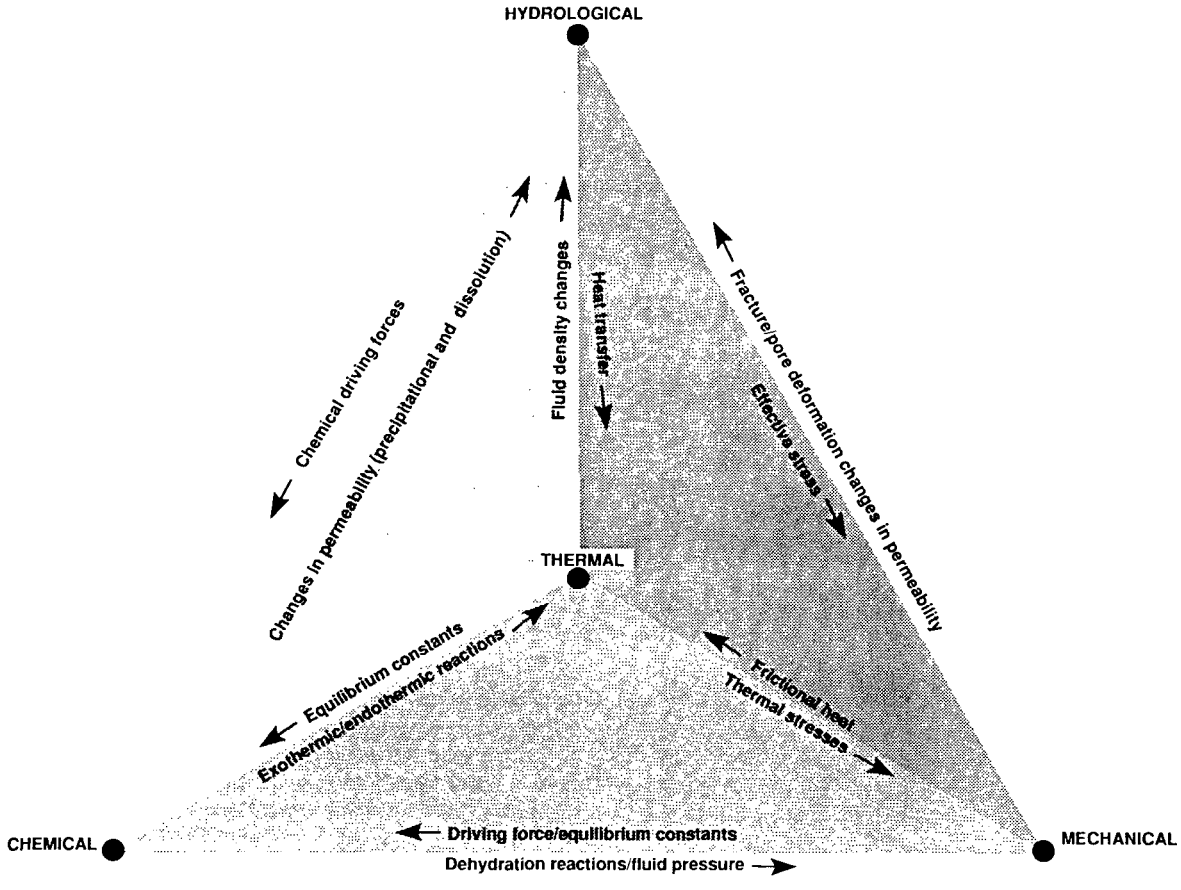

Figure VII-1: Diagram illustrating the coupling between thermal, mechanical, chemical, and hydrologic processes in the Earth's crust (from the workshop on continental scientific drilling, 1988).

Magma is a very important fluid in some parts of the crust. However, because magma is discussed elsewhere in the section of this report on Volcanic Systems and Thermal Regimes, it will be considered here only in regard to the role that its upward movement plays in (1) transporting dissolved water and gases from deeper to shallower levels of the crust where they are released by decompression or crystallization and (2) modifying the

thermal structure of the crust which may induce hydrothermal circulation and water-rock reactions that can affect large volumes of the surrounding rock. Figure VII-2 schematically shows several relations in a subduction environment where relatively siliceous material is carried downward to a sufficient depth that partial melting occurs (environment A). Water and other volatile components (particularly CO2, SO2, and Cl) dissolve in the magma and are transported upward along with the buoyant melt. During upward movement (environment B) the magma may gain additional volatile components from the surrounding host rock (particularly water) or loose volatile components, depending on their initial state of saturation. A magmatic body coming to rest at a relatively shallow level (environment C) will lose its volatile components as a result of a decrease in confining pressure and crystallization of the magma.

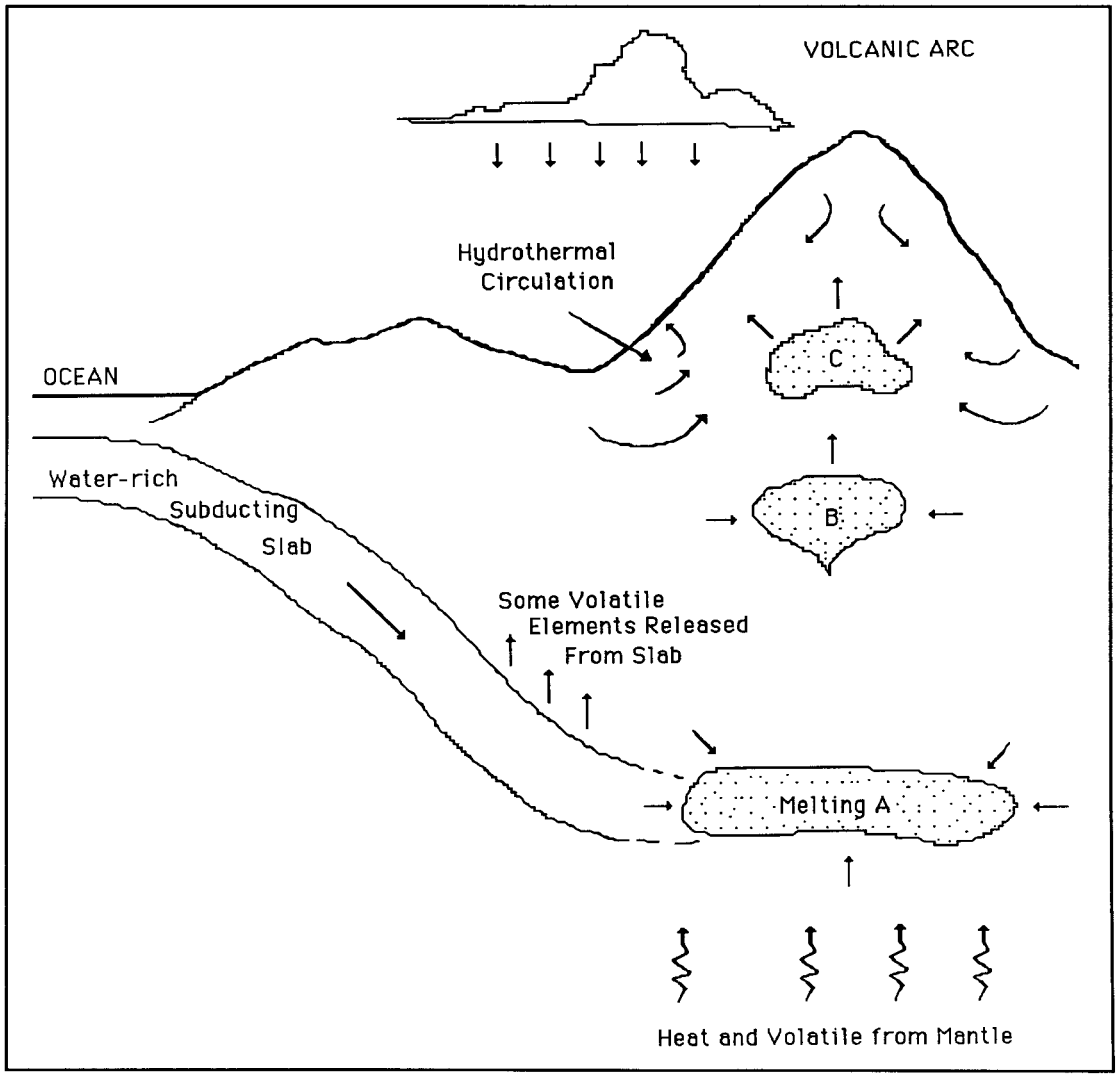

Figure VII-2: Schematic diagram showing the generation of melt in a subduction environment and transport of volatile components dissolved in the magma from deep in the crust to a shallow level where they art released. The heat brought to a shallow level by the intruding magma supplies the energy to drive a circulating hydrothermal system that may be dominated by meteoric water.

Information regarding variations in fluid composition in the crust are obtainable by direct sampling and the analysis of springs, gas vents, subsurface fluids from different depths in wells, and by analysis of fluids trapped as inclusions in minerals (Roedder, 1984). Indirect information about fluid compositions is obtained by calculating chemical and isotopic compositions necessary to obtain equilibrium with particular minerals or mineral assemblages.

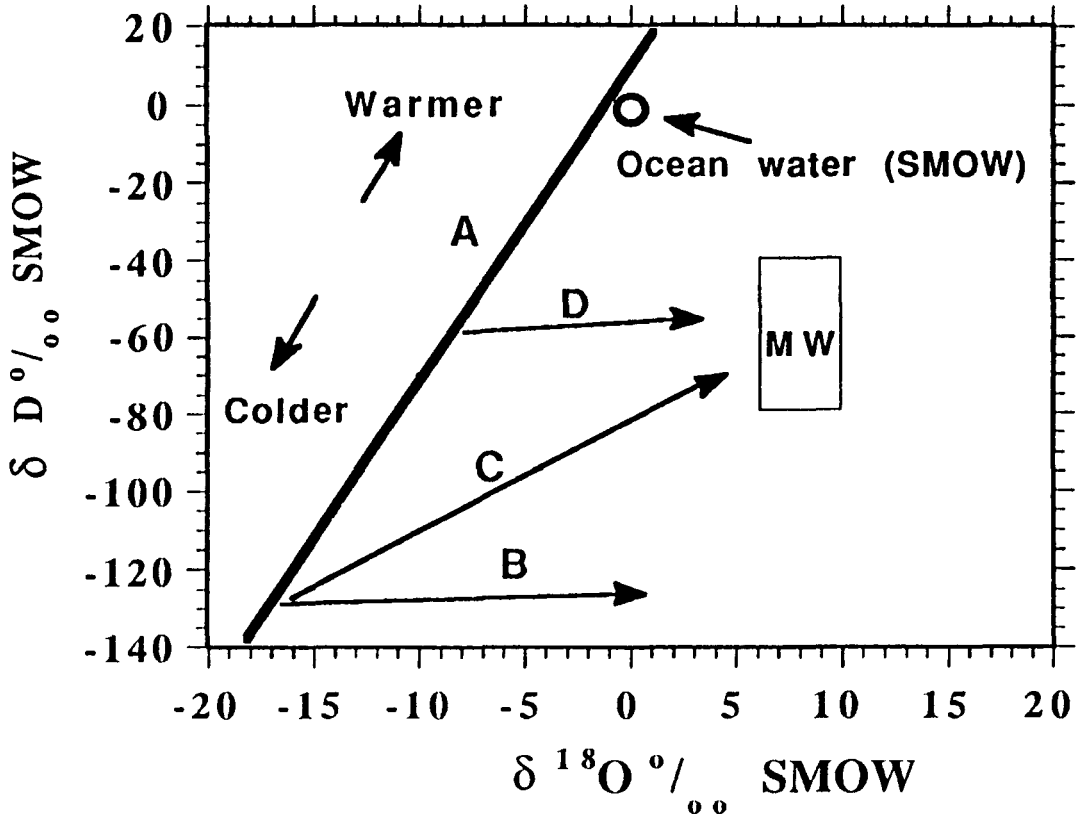

Figure VII-3: Isotopic composition of meteoric and magmatic waters relative to standard mean ocean water (SMOW). See text for discussion.

One very useful and powerful tool that is now widely used to help determine the source(s) of meteorically-derived groundwaters that have infiltrated into the crust, and for identifying possible magmatic and metamorphic water components, is the stable isotope composition of the water (Craig, 1961; Taylor, 1979). Figure VII-3 shows the world-wide trend in isotopic compositions for meteoric waters (line A). Most magmatic waters are expected to lie within the box labeled MW. Line B shows the change in composition that would result from reaction of meteoric water with rock at a relatively high latitude (colder average climate) region, and line D shows the change in composition for meteoric water in a warmer region. Line C shows variations in composition resulting from mixing of a given meteoric water with magmatic water. Note that it becomes increasingly more difficult in warmer climates to distinguish changes in isotopic composition resulting from mixing of meteoric and magmatic waters from those resulting just from water-rock interactions. Figure VII-4 illustrates the use of isotopes to show that waters sampled from fractures in

granite just 210 m apart in the Cajon Pass well were isolated from each other, and that they had different places of recharge and/or different times of recharge when climatic conditions were different.

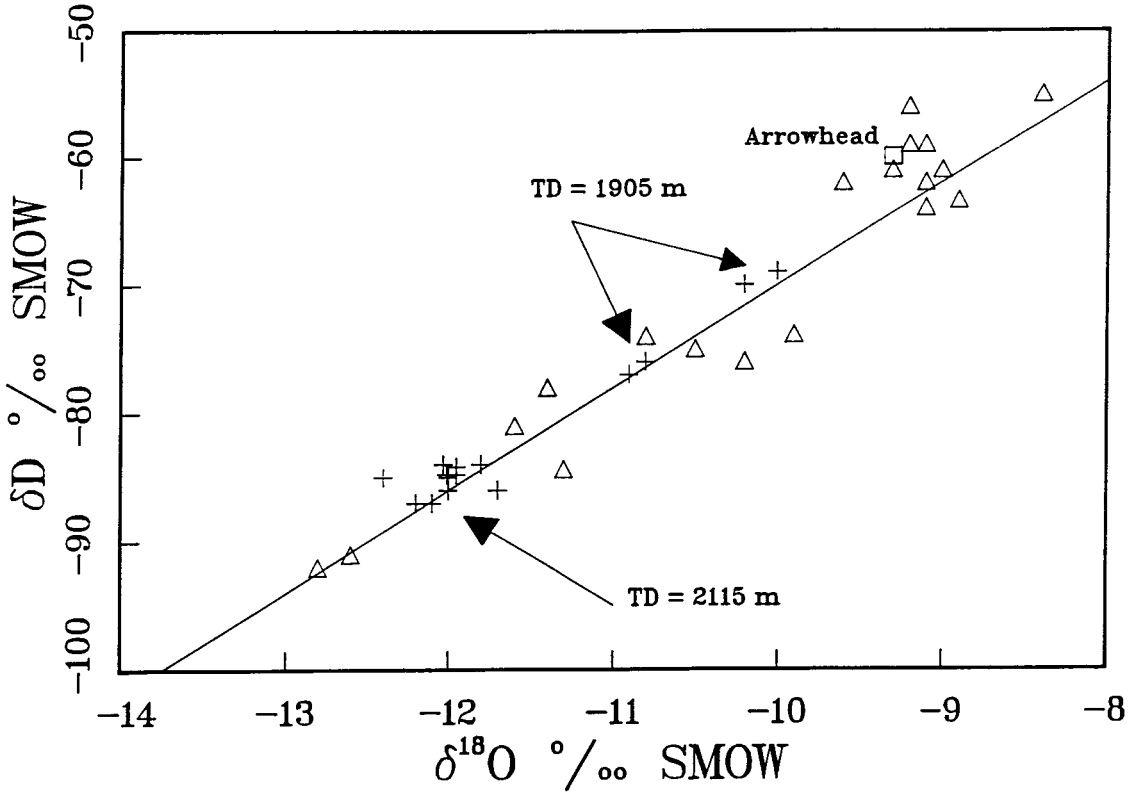

Figure VII-4: Isotopic composition of water from the Cajon Pass, California well (crosses), Arrowhead geothermal well (square), and groundwater in the area, from Kharaka *et al,* 1988.

Key Questions

Knowledge of the distribution and of the physical and chemical properties of fluids in the Earth's crust, and of rock properties that control the movement of these fluids is of vital importance for improving our understanding of tectonic processes, the genesis of ore deposits, the distributions of petroleum and geothermal resources, and mechanisms of explosive volcanic eruptions related to gas evolution and water-magma interaction. It also is vital for determining the availability and recharge of potable water in the Earth's crust, and for guarding against natural and man-induced pollution of that resource by unwise exploitation policies or poorly designed waste disposal practices.

The overall objectives of fluid studies are to determine the parameters and processes that control fluid movement and composition in different geologic and tectonic environments to ascertain (a) how geologic, tectonic and hydrologic processes are coupled in the Earth's lithosphere, and (b) how these nonlinear coupled interactions control the separation, concentration and redistribution of heat and mass in the crust. The nature of these coupled processes is reflected and recorded by the distribution, composition and flow of fluids in the Earth and the compositions and geometric relations of the precipitates and other solid phases with which they have interacted. The important questions of a general nature to be addressed directly by fluid studies in the Earth include:

- What does the chemical and isotopic composition of the fluid tell us about the end member sources and chemical interaction during fluid transport?
- What do the precipitates and solid phase products of fluid-mediated reaction tell us about the changes in fluid composition and sources over the time-scale of the hydrogeologic process?
- How do the compositions of the fluid and its coexisting solid phases reflect the continuity of fluid flow in space and time with changing pressure, permeability, and fluid/rock ratios?
- To what extent can the composition of the fluid-rock system and the geometric relations of veins be used to constrain specific hydrologic transport processes, including forced convective flow, free convective flow, and mechanically controlled fluid flow?

To answer the above questions it will be necessary to determine gradients in temperature, pressure, and fluid chemical and isotopic compositions, as well as compositional and textural information about the host rocks in many geologic environments. This information is required to constrain the magnitudes, processes, and directions of mass and heat transport that occur in response to particular styles of hydrogeologic processes. Because coupled chemical-physical-mechanical processes continually modify the conditions that govern flow, and changes in the flow conditions may occur episodically, there is a great need to determine the rates of fluid movement and chemical processes in three-dimensional space, and the rates of change of these movements and processes.

Outstanding Issues

Transition from hydrostatic to overpressured conditions

The transition from hydrostatic fluid pressure to overpressured conditions is an important factor that limits the penetration of surface waters into the crust. Hydrostatic fluid pressure is the pressure exerted by the weight per unit area of an overlying, free-standing column of water extending upward to near the Earth's surface. Fluid pressures approaching lithostatic (the pressure resulting from the weight of the overlying rock) have been encountered in many compacting sedimentary basins at depths as shallow as 1-2 km (Hubbert and Ruby, 1959), where relatively weak and impermeable argillaceous beds generally play a key role in the development of the "overpressure" (Jones, 1969). In contrast, the few deep wells drilled in crystalline rocks in "normal" thermal regimes (temperature gradients of 20-30°C km-1) have not encountered overpressures. They have, however, encountered fracture permeability to considerable depth (Kozlovsky, 1987; Fritz *et al.*, 1991). Rock strength and fracture permeability considerations (Brace, 1984; Clauser, 1992) suggest that downward circulation of surface waters at hydrostatic pressure through crystalline rock is likely to occur to the maximum depth at which seismic activity creates new fractures and reopens old fractures, commonly 10-20 km (Costain *et al.*, 1987). However, the depth of the transition from normal to overpressure may be transitory, slowly migrating upward with time as chemical processes decrease permeability along fractures (Walder and Nur, 1984; Byerlee, 1993). This trend may be reversed episodically as a result of renewed seismicity or hydraulic fracturing (Walder and Nur, 1984; Gold and Soter, 1985; Pollard and Aydin, 1988; Torgersen, 1991; Sibson, 1992; Byerlee, 1993).

An environment in which a transition from hydrostatic to near lithostatic pressure might be found at a moderate depth in the crust is where present-day low-angle thrust faulting is occurring. It is generally agreed that near lithostatic pore-fluid pressure is

required within the plane of the fault for low-angle thrust faulting to occur (Hubbert and Ruby, 1959, Sibson, 1990). Questions remain about pore pressures and fluid compositions in rocks above and below presently active low-angle thrust faults. Similarly, elevated pore pressure may explain fault activity along high-angle reverse faults which are also "poorly-oriented" to the stress field (Sibson, 1990).

Impact of the brittle-ductile rheologic transition on fluid flow

There is considerable evidence that free water is present throughout the crust (Table 1). The maximum depth at which this free water is at hydrostatic pressure is probably limited by the opening of shear fractures in brittle rock. The cessation of brittle fracture and onset of plastic rock deformation in the upper crust is likely to occur at about 300-400°C, depending on rock type and strain rate (Kirby, 1985; Scholz, 1988). Although shear fractures do not provide relatively open channel for the downward penetration of surface-derived water into the crust to depths below the brittle-ductile transition, mineral compositions and rock textures show that large volumes of fluid are present in, and moves through deep, hot rocks which behaved plastically (Etheridge etal, 1984; Walther and Wood, 1986; Newton, 1989; Bailey, 1990; Torgersen, 1990). Rocks metamorphozed at temperatures of 400-500°C commonly contain abundant hydrous minerals, and calculations of metamorphic fluid pressures generally indicate lithostatic values in these rocks during such metamorphism (Walter and Wood, 1986; Bredehoeft and Norton, 1990). In addition, comparison of parental and metamorphosed rocks demonstrates that fluid gain as well as fluid loss occurs during metamorphism. However, the distribution of fluid pressure, connectivity, and mechanisms of movement of pore fluids within the plastic region are uncertain.

In support of the above generalizations, fluid pressures significantly in excess of hydrostatic have been encountered at the bottoms of a few very hot (>370°C) geothermal exploration wells drilled to depths of 3.0-3.5 km in crystalline rocks above young, shallow plutons (Fournier, 1991). This environment presents an excellent target for scientific drilling to investigate the brittle to plastic transition region and its possible relationship to pore pressure changes from hydrostatic to lithostatic.

Fluids in the plastic crust may be derived from several sources, including (1) pore-waters in sediments that become deeply burried by compaction or tectonic movements, (2) in situ generation by metamorphic reactions that release water and various gases from hydrous minerals, carbonates, sulfates, and organic materials, (3) degasing of magmas that have moved from deeper to shallower levels in the crust, and (4) degasing of the mantle.

Relationship of pore fluids to seismicity

There has been much concern recently about the possible role of high pore fluid pressure in the initiation of seismicity on faults that are oriented at non-optimum angles with respect to the directions of the principal stresses (Raleigh and Evernden, 1981; Sibson, 1990; Rice, 1992; Byerlee, 1993; Zoback and Beroza, 1993). We know little about how fluid pressures in faults compare with pressures outside the fault, how high fluid pressures are generated, where overpressure fluids in fault zones originate, and how fluid pressures in faults evolve through the seismic cycle. There also is uncertainty about the effect of fluid pressure on total stress in the Earth, and about the relative importance of fluid-driven (hydraulic) fracturing compared to shear failure in different geologic environments.

Limits of potable water in different geologic-tectonic environments

As populations increase throughout the world, ground water pumping has increasingly been relied on to supply domestic and agricultural needs. Increased attention should be given to determining both the local and regional water supply by determining the extent, rates of recharge, as well as the depths at which the transition from potable to non-potable water in the crust, and the mechanisms and rates of mixing between various groundwaters.

Saline groundwaters commonly underly fresh waters at relatively shallow depths even in crystalline rocks (Fritz and Frape, 1992; Nurmi *et al.*, 1988). Figure VII-5 shows an idealized model of groundwater compositional zonations in crystalline rocks of the Fennoscandian Shield, based on a limited amount of data from wells (Nurmi *et al.*, 1988). Detailed studies of groundwater compositional changes to depths of 1-2 km also will provide a wealth of information to address potential waste disposal and contamination problems.

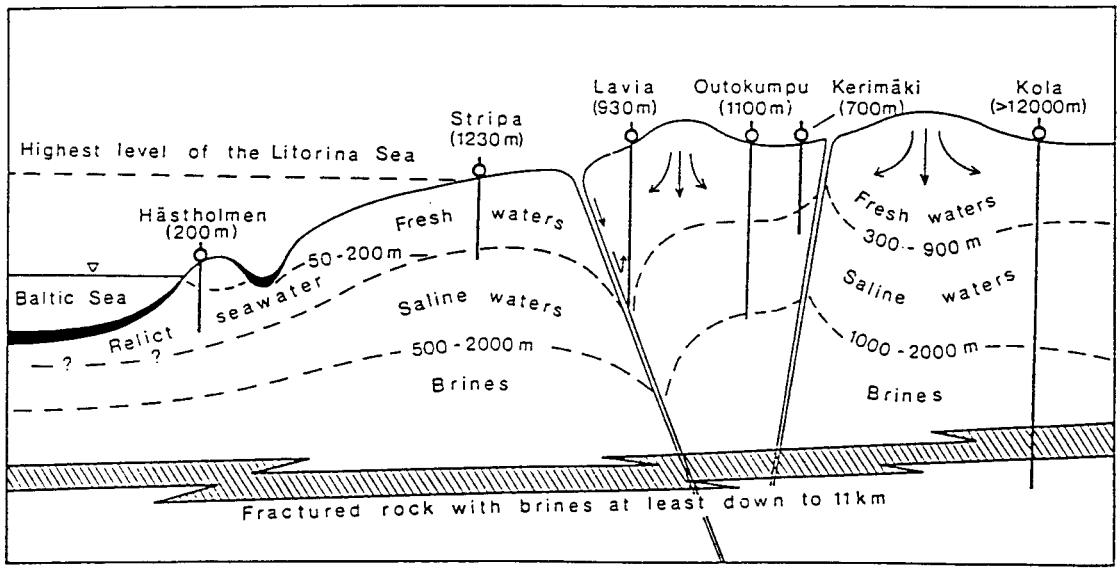

Figure VII-5: Idealized model of groundwater zonation in the Fennoscandian Shield. Adopted from Nurmi *et al,* 1988.

Degassing of magmas, explosive volcanism, and the genesis of hydrothermal mineral deposits

Explosive volcanism appears to occur both as a result of degassing of magma and as a result of magma coming in contact with groundwater and surface water. There is still much to be learned about degassing of magma, and about the movement and accumulation of fluids in and around bodies of magma. In addition, many ore deposits appear to have been deposited from aqueous-rich fluids expelled from crystallizing magmas (Hedenquist, 1992; Rye, 1993). The time, place, and extent of degassing of a magma are likely to depend on many factors, including the composition of the magma, the concentrations of volatiles (particularly H2O, SO2, H2S, CO2, Cl, F, and B) initially dissolved in the magma, the rate of upward movement of the magma, the depth at which degassing starts, and the permeability of the surrounding rock. Ore deposition is likely to depend both on the initial composition of the evolved magmatic fluid and on the pressure-temperature environment at which the fluid degasses from the magma (Fournier, 1987). Figure VII-6 shows

contrasting hydrothermal conditions that may occur above degassing magmas emplaced at different depths.

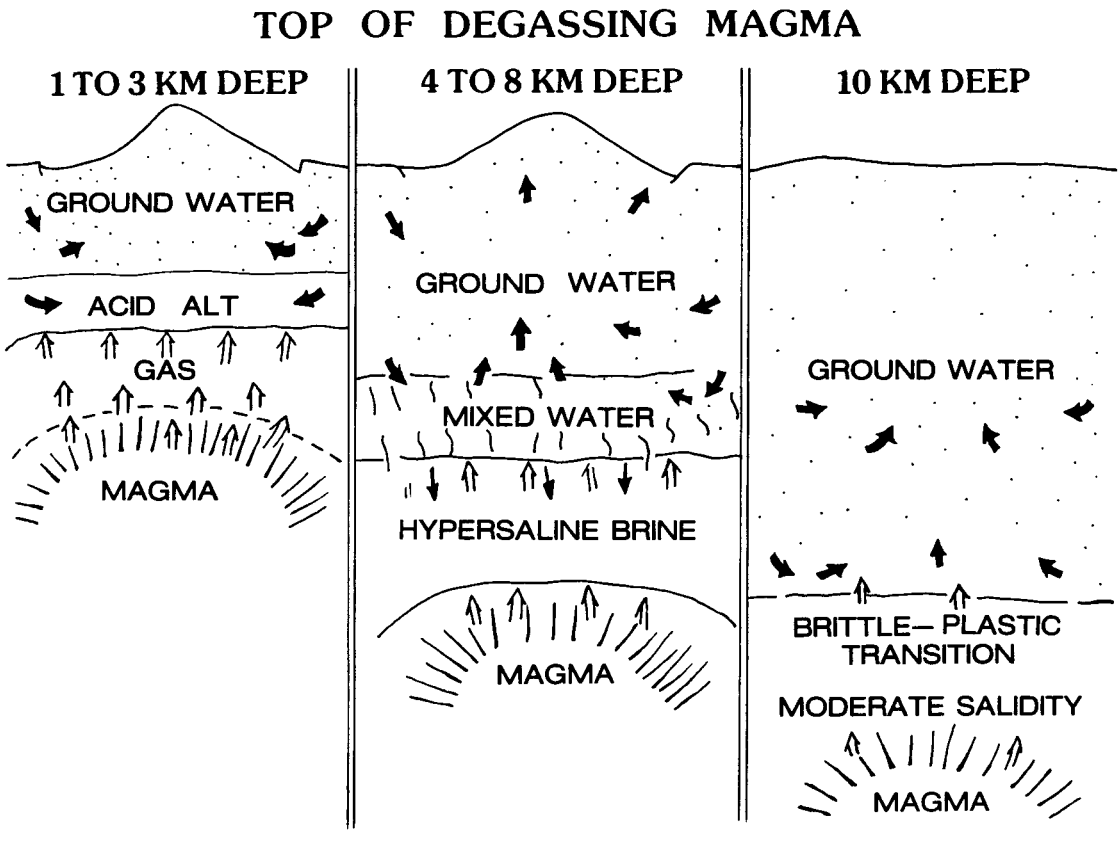

Figure VII-6: Schematic diagram of possible hydrothermal conditions above degassing magmas emplaced at different depths.

Dewatering of sedimentary basins, petroleum maturation, and fluid migration resulting from tectonic deformation

Much information has been provided about sedimentary basins by the hundreds of thousands of wells that have been drilled to exploit petroleum and hydrocarbon gas resources. However, there is still much to be learned about how sedimentary basins dewater while organic material is converted to petroleum. The relative roles of compaction, release of water from clay minerals by diagenic reactions, and deformation (squeezing) of the basins by external tectonic forces require further study (Oliver, 1986; Bethke and Marshak, 1990). Brines in some sedimentary basins carry high concentrations of metals (Carpenter, 1974), and important classes of ore deposits apparently have been deposited by the waters expelled from these basins (Hanor, 1979; Wright *et.al.*,1987). Figure VII-7 shows schematically how anthracite, gas, oil, and Pb-Zn deposits may be related to flow of brines expelled from deforming sedimentary basins by tectonic processes. Inferred brine migration paths in North America are shown in Fig. VII-8. There is uncertainty, however, about the degree to which these brines interact with crystalline basement rocks beneath the sediments, and about the factors that control the time and place of ore deposition.

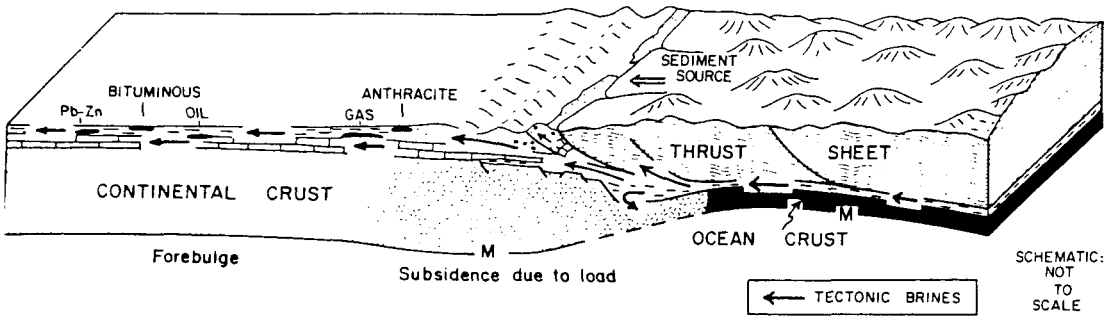

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Figure VII-7: Block diagram showing schematically the path taken by brines expelled from sediments during tectonic deformation and the geometric relations of anthracite, hydrocarbon gases, oil, bituminous material, and Pb-Zn deposits the oregen. continental crust is ~ 35 km thick; horizontal dimension of the diagram is ~ 500 km. From Oliver (1986).

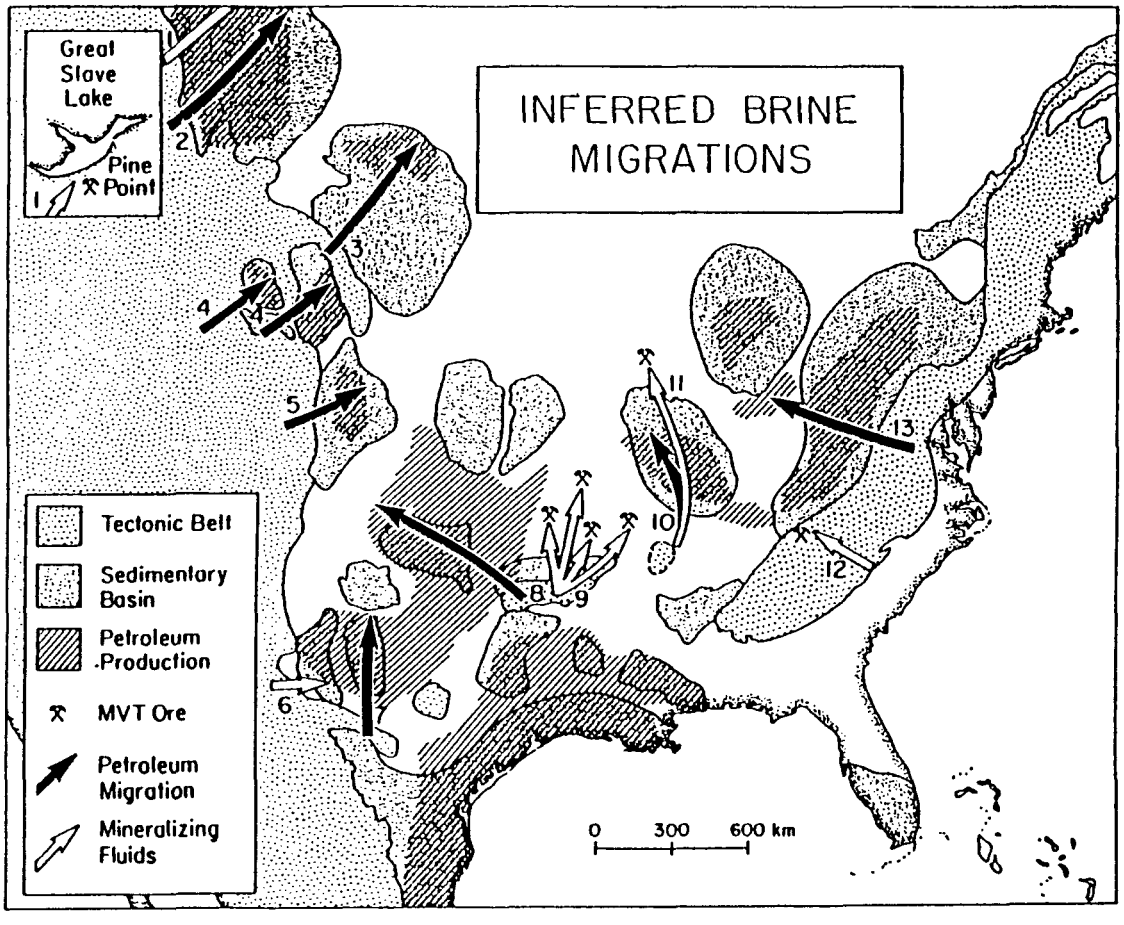


Figure VII-8: Map showing the inferred migration pathways of ore-forming fluids and petroleum across the continental interior of North America. From Bethke and Marshak (1990).

The contribution of pore fluids to geophysical anomalies at mid to deep crustal levels

Accumulations of pore fluids at near lithostatic pressure in sub-horizontal sheets and/or the alignment of platey hydrothermal alteration products may have formed as a result of passage of hot fluids that can be imaged as seismic reflectors and seismic velocity anomalies deep within the crust (Hyndman, 1988; Baily, 1990). In addition, interconnected sheets of brine can greatly enhance crustal electrical conductivity (Hyndman, 1988). It is vital to develop and test methods to distinguish between geophysical anomalies resulting from the effects of pore fluids and hydrothermal alteration, and those resulting from primary differences in rocks. Geophysical methods are and probably will remain the primary means for unraveling deep crustal structures. However, deep scientific drilling can become a useful tool for sampling these deep crustal rocks as well as calibrate our remote geophysical observations.

Recycling of fluid transported into the Earth by subduction

Fluids and hydrous minerals are present in rocks that are subducted deep within the Earth, well beyond the range of drilling (Fig. VII-2). The amount of fluid that is subducted in hydrated ocean floor basalt would probably be sufficient for major metasomatism of the overlying continental crust, depending on the release pattern (Fyfe, 1986). However, the nature of how these fluids in the subducted rock become heated and finally melted are not clear (Newton, 1989). There are still many questions about the amount and composition of fluid that is released from such rocks before melting occurs and the mechanisms and rates of transport of this fluid upward through the plastic crust and into the brittle crust.

The correlation of stress regime with hydrologic and geochemical parameters

The current state of knowledge suggests the following correlations of tectonic environments with styles of large-scale fluid circulation (Nesbitt, 1990). In extensional regimes there generally are widespread hot springs and exploitable geothermal resources that are related to subvertical faults or fractures (for example in the Basin and Range province of Nevada, USA). These faults apparently provide relatively open channels for vigorous convection of surface fluids, mass and heat transport, considerable alteration of the rocks, and vein formation. In uplifting, post-compressional regimes, progressive opening of fractures leads to the influx of fluids into rocks, convective cooling, and vein formation. Low dD, low-salinity, vein-forming fluids are expected. In compressional thrust regimes, the fluid systems tend to be relatively isolated and heterogeneous fluid pressures are likely to develop. Fluid flow may generally be confined to small scale systems. It is important for models of mass and heat fluxes, ore genesis, and many other geologic processes to test these generalizations.

Continued growth of crack-seal veins in terrains where vein filling greatly limits permeability during progressive metamorphism

Crack-seal veins apparently form by repeated fracturing and sealing of rock under "high?" fluid pressure (Ramsay, 1980). However, the details of the fracturing and vein filling remain enigmatic, particularly in light of the high water/rock ratios necessary to fill the veins.

to determine fluid compositional variations with depth.

The role of fluids in volume loss deformation over large regions of foreland fold-thrust belts

Another important tectonic problem that remains mysterious to date concerns the mechanism by which large masses of rocks, particularly in slate belts, can be removed (as much as 50% by volume in some places) by a process so pervasive that volume loss is found on the grain scale (Wright and Platt, 1982).

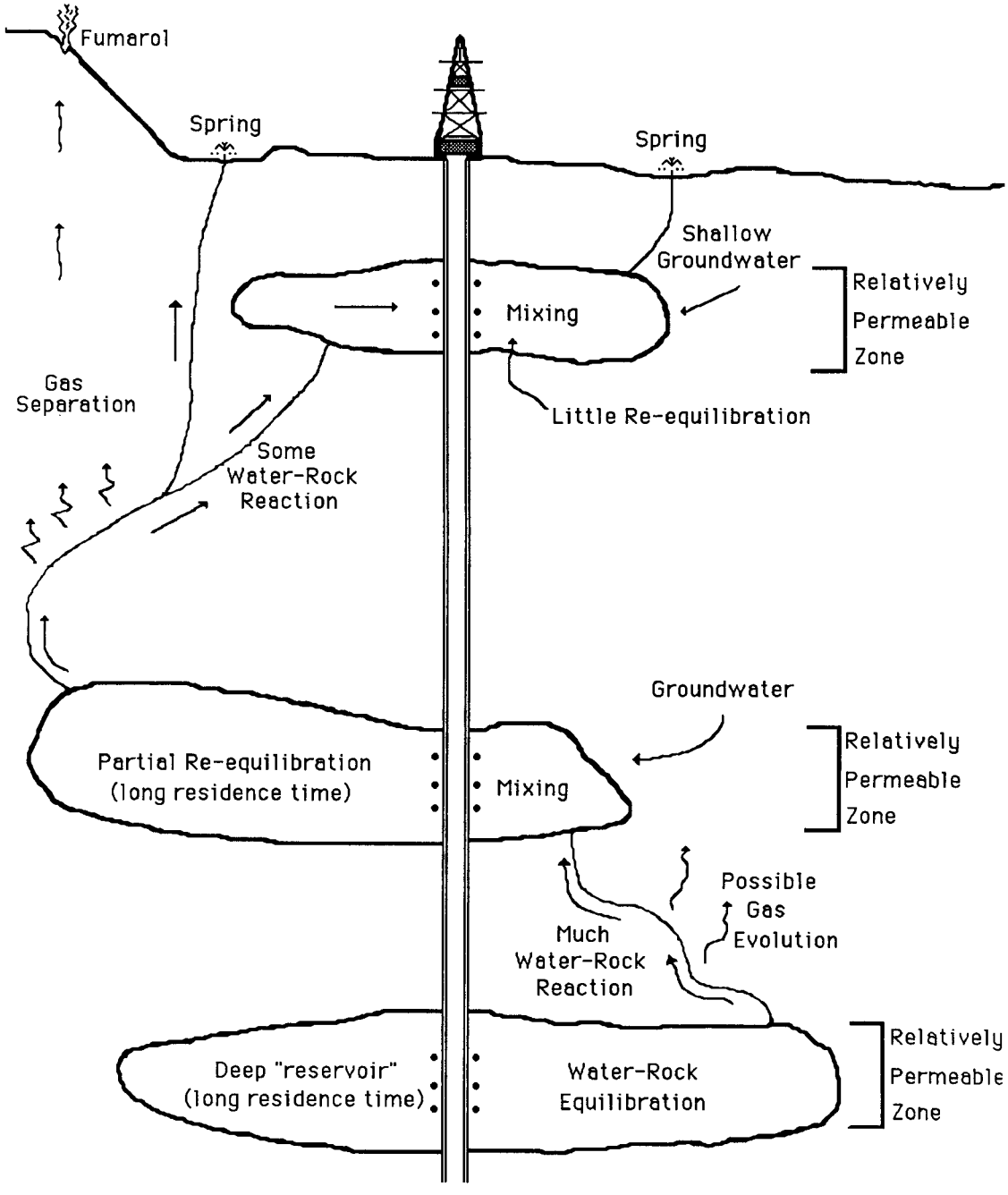
Episodic changes in the hydrologic state within the crust

Little is known about the constancy or time variability of fluid flow through different parts of the crust in different tectonic environments (Torgersen, 1990). Rates of movement and fluxes may change very slowly and continuously, brought about by regional changes in the general geologic environment in response to long-term crustal movements. Alternatively, there may be sudden and episodic changes in the hydrologic regime within parts of the crust that may last for short or long periods of time. An example is increased flow rates as a result of the creation of new fractures or the reopening of previously sealed fractures by major seismic events or hydraulic processes (Sibson, 1990). Episodic breaching of a chemically sealed region that separates lithostatically pressured magmatic fluid in or above a cooling pluton from surface-derived hydrostatically pressured fluid in the surrounding country rock could have major geologic consequences (Fournier, 1983; Dzurisin etal, 1990). In both cases the rock record may show mainly the results of water-rock interactions that occur during periods immediately following the onset of the episodic event because rates of flow are temporarily increased, moving fluids into new temperature-pressure and rock environments.

The nature of thermal transport processes in the continental crust

Most, if not all, dynamic processes in the Earth's crust are powered by thermal energy in one way or another. Understanding these processes therefore requires knowledge of the thermal regime and the nature of heat transport processes in the Earth's crust (Beck *et al*, 1989). Several transport mechanisms need to be considered because heat advected by moving fluids may supplement or even dominate conduction of heat. For example, when just the thermal data provided by the Kola and the KTB deep boreholes are considered, the relative importance of advective and conductive heat flow are ambiguous (Clauser and Huenges, 1992). At shallower depths, even downward diffusing thermal transients need to be considered. On the other hand, combined analyses of mass and energy transport can be used to produce independent data sets for the calibration of a specific flow system. Thus, a coupled approach using thermal and fluid composition data seems to be most appropriate for the treatment of this problem (Clauser and Huenges, 1992). This holds true both in respect to the acquisition of petrophysical and geochemical parameters and for the numerical simulation of flow and transport. These questions should be addressed at every location where scientific drilling is carried out.

Figure VII-9: Schematic diagram showing multiple zones of enhanced permeability (reservoirs) that ncontain fluids of different composition resulting from possible gas evolution, mixing with shallow groundwaters, and water-rock interations at successively lower temperatures. Drilling with provision for sampling uncontaminated fluids from multiple depths in wells is required


Fumarol
Spring
Spring
Shallow
Groundwater
Mixing
Relatively
Permeable
Zone
Gas
Separation
Little Re-equilibration
Some
Water-Rock
Reaction
Groundwater
Partial Re-equilibration
(long residence time)
Mixing
Relatively
Permeable
Zone
Possible
Gas
Evolution
Much
Water-Rock
Reaction
Deep "reservoir"
(long residence time)
Water-Rock
Equilibration
Relatively
Permeable
Zone

Role of Scientific Drilling

Fluids discharged at the surface as springs and fumaroles commonly have changed composition during ascent to the surface by mixing, by separation of gases, and by reactions with rock at changing temperature and pressure along the flow path (Fig. VII-9). Sampling from multiple depths in wells is required to overcome these problems. Drilling to exploit petroleum and geothermal resources in sedimentary basins and in volcanic environments has provided considerable information about deep fluid compositions and rock permeabilities to depths of a few kilometers. However, commercial drilling seldom provides core, so information about the history of fluid circulation is sparce. Also, relatively little is known about fluids in crustal rocks in geologic environments where petroleum or geothermal resources are unlikely to be found, especially below 1-2 km. Studies of veins, fluid inclusions, and compositional variations shown by metamorphic and mineralized rocks that have been exposed by uplifting or by mining provide an integrated view of water-rock interaction over the life of the system (Continental Scientific Drilling Committee, 1984b). However, such studies generally provide limited, if any, information about variations in the physical-chemical-hydrologic state of the rock-fluid system at any given time.

Scientific drilling that is designed to collect both core and uncontaminated pore fluids provides an opportunity to obtain information about variations in geochemical and hydrologic parameters at an "instant" in time, and also provides an integrated picture of what has transpired over a long period of time (Continental Scientific Drilling Committee, 1984a). Both types of information are required to gain an understanding of coupled fluid-rock interaction processes, rates of change of these processes, and the role of episodic events involving movement of fluids in nature.

The generic requirements for designing a scientific drilling project that would provide optimum information about fluids in the crust are:

- Continuously cored holes to obtain information about the history of fluid-rock interaction that is provided by cross-cutting veins, mineralized fractures, alteration of the surrounding rock, and fluid inclusions.
- Provision for sampling uncontaminated fluids from known depths.
- More than one hole or well in order to conduct cross-well experiments to determine bulk permeabilities and the initial gradients in the physical and chemical states of fluids in large volumes of rock.

The problem of sampling uncontaminated fluids from known depths is not trivial. Wells must be induced to flow or be pumped in sufficient volume to get rid of contamination by drilling fluids. If the produced fluid is a brine or contains toxic elements it may be ecologically and environmentally unacceptable to dump this fluid onto the ground or to discharge it into a nearby stream or river. Thus, a disposal well or a very large storage pit with an impermeable liner may be required to receive the discharge. The fluid or evaporated residue in the pit may have to be deposited elsewhere. Sampling from given depths can be accomplished by using packers and, if necessary, perforated casings.

The necessity of using two or more holes for cross-well experiments to obtain hydrologic parameters (permeability and gradient information) for large volumes of rock greatly adds to the expense and complexity of a project. One way to minimize this problem is to drill close to a pre-existing well that was drilled for another purpose. An alternative method of obtaining hydrologic information from deep scientific drill holes was suggested at the Potsdam meeting by Christoph Clauser, Ilmo Kukkonen, and Ladislaus Rybach in which

whipstocked side holes are drilled extending in different directions away from a "hole of opportunity", drilled for a different primary purpose (Fig. VII-10). Thus, a two- or three-dimensional picture of gradients can be attained. The different side holes are instrumented and isolated by packers so that cross-hole hydrologic experiments can be carried out. This scheme was inspired from the proposed San Andreas fault drilling project, in which a series of whipstocked holes would be drilled across the fault from a main hole that is drilled to one side. A second part of the strategy is to utilize a series of relatively shallow holes to gain additional hydrologic information where deep (> 4 km) scientific holes are drilled. These "shallow" wells would be drilled deep enough to get below the surface region of "fresh" ground water. Where there is latitude in the siting of a particular deep scientific drill hole, the availability of moderately deep monitoring wells in one locality and not in another should be a major factor in the final selection of the deep drill site.

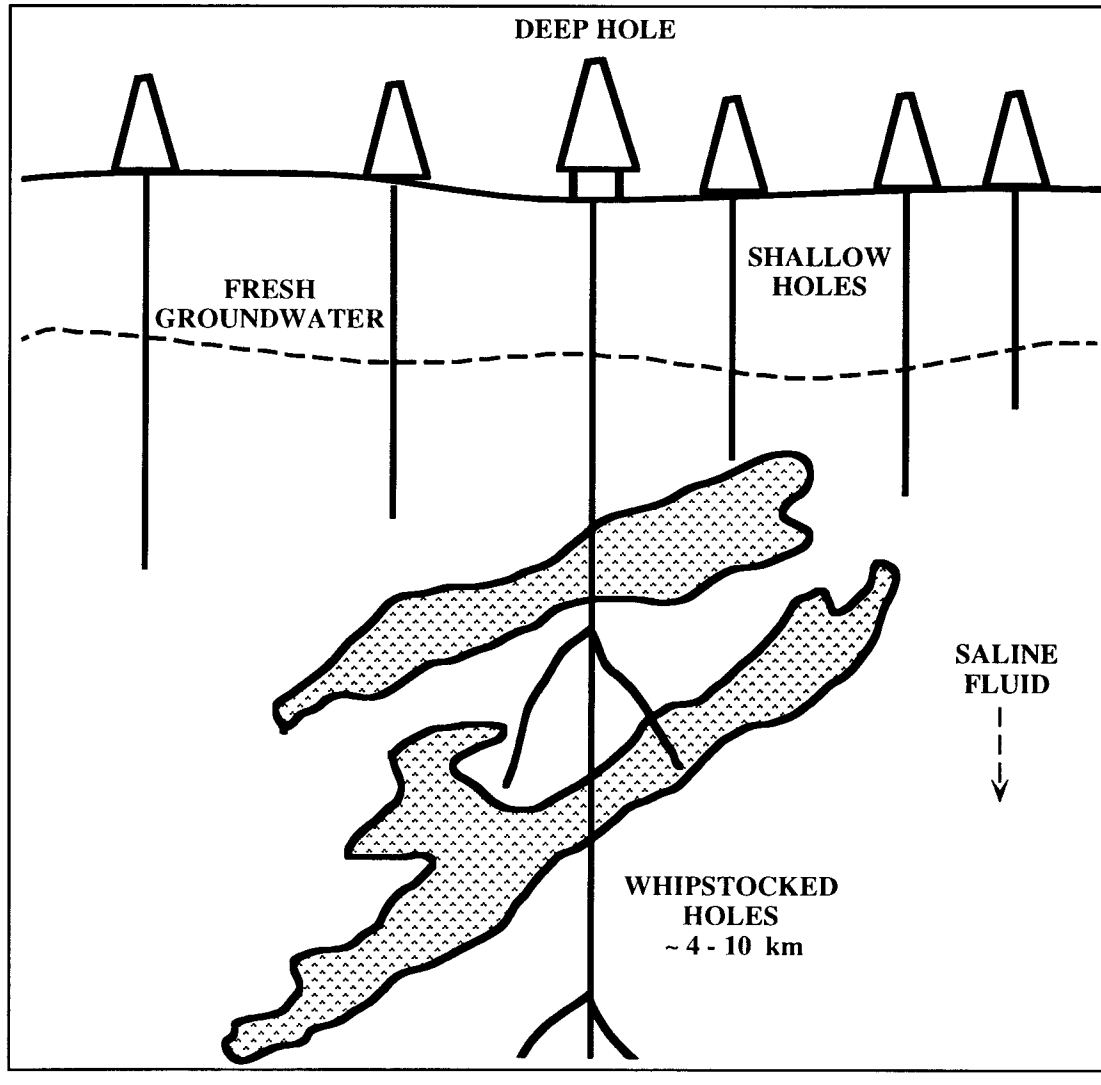


Figure VII-10: Scheme for obtaining two- or three-dimensional information on petrophysical, hydrologic, and geochemical parameters, such as permeability, thermal conductivity, and gradients of pressure, temperature, and salinity using a series of relatively shallow wells drilled to below the fresh ground-water interface, and whipstocked holes projecting away from a deep hole.

Examples of Specific Targets

The information required to assess fluid flow in the crust (variations in permeability and gradients in fluid composition, pressure, and temperature) cannot be obtained from exposed rocks and must be attained from drill information. Possible targets for studying the effects of fluids in different geologic-tectonic environments are listed below. The young, hot, shallow plutonic environment is the only one discussed in detail because examples of specific targets that address the other issues are provided elsewhere in this report.

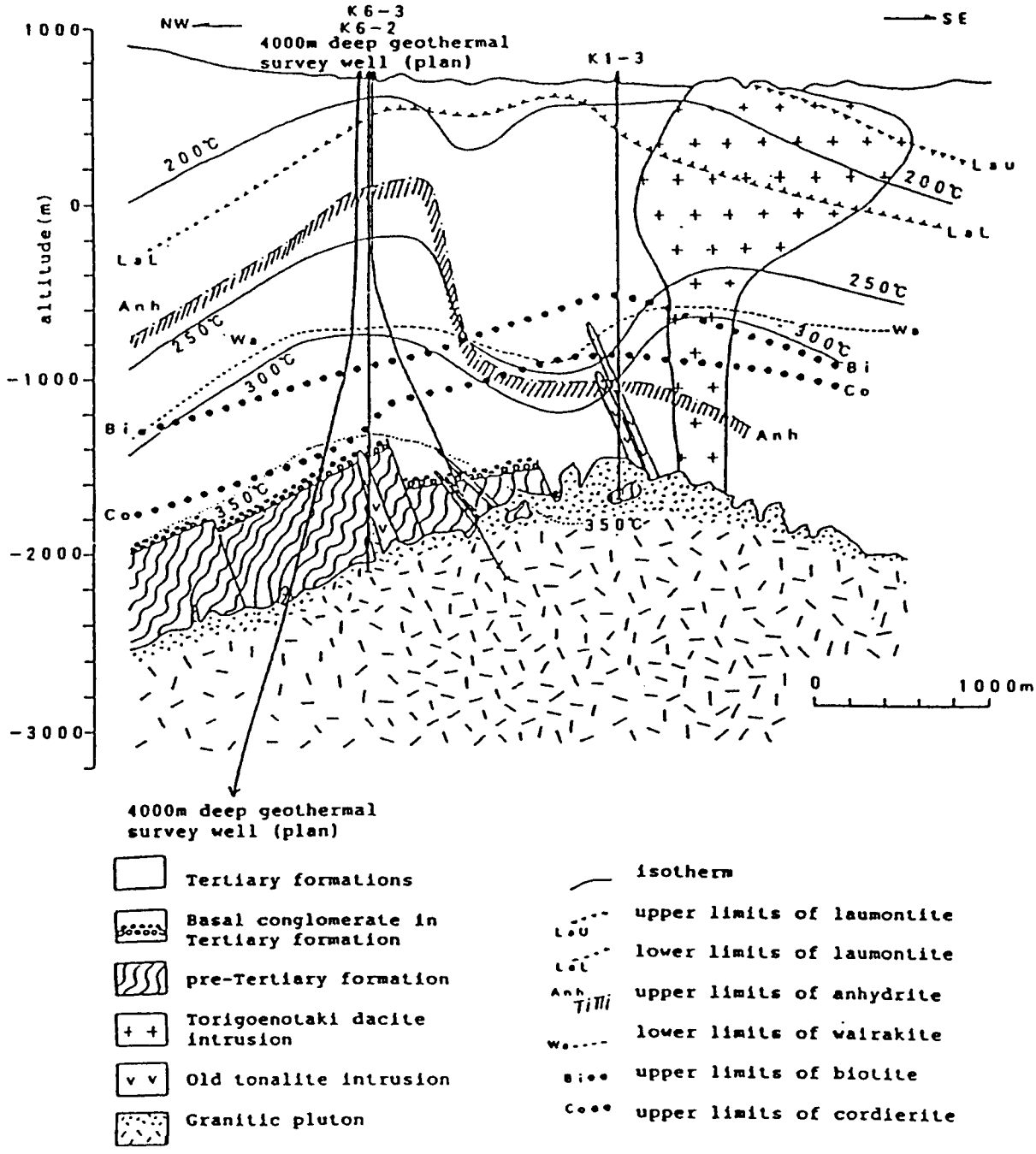
Young, hot plutons emplaced at relatively shallow depth

Drilling by continuous coring methods into hot (>400-450°C) shallow plutons that have been emplaced at depths less than about 5-6 km will provide a wealth of information about the limits of (a) hydrothermal convection at hydrostatic pressure and the transition to fluid overpressures, (b) the genesis of hydrothermal ore deposits, (c) degassing of crystallizing magma, (d) the generation of shear and hydraulic fractures in a brittle to plastic transition zone, (e) the contribution of pore fluids to seismic and electrical geophysical anomalies, and (f) metamorphic reactions and fluid and mass flux at high temperatures. Societal benefits would include gaining better understanding of processes affecting the distribution and magnitude of geothermal resources and ore deposits, the assessment of volcanic hazards related to gas evolution and water-magma interaction, earthquake mechanics, and the design of radioactive waste repositories. There are many possible targets in regions of young volcanism throughout the world. Two targets where young, shallow plutons at sufficiently high temperatures have been demonstrated to exist by extensive drilling for geothermal resources are at Sengan, Japan (Sasada *et al.*, 1993), and The Geysers, California, USA (Stone, 1992). There is evidence that a relatively shallow, hot pluton also underlies the Larderello region in Italy where extensive geothermal resources are being exploited (Batini *et al.*, 1985). A fourth exceptionally fine target, identified by geologic and geophysical observations, is in Yellowstone National Park (Yellowstone National Park Task Group, 1987).

Figure VII-11 shows a schematic geologic cross section at the Kakkonda geothermal field in Japan where a 4-km deep research well is planned for drilling in 1994-1996. Cores will be cut about every 100 m. In this area several wells about 3-km deep already have penetrated a young granitic pluton at temperatures >300°C (Sasada *et al.*, 1993). The proposed 4-km well may penetrate into rock where temperatures are near 400°C and plastic rheologic conditions prevail. There is much seismic activity in and around the Kakkonda geothermal reservoir to depths of about 3-4 km, but little within the underlying hot granitic pluton.

The Geysers vapor-dominated geothermal field north of San Francisco, California, is closely related to young silicic intrusive body (felsite) (Figs. VII-12 and VII-13). The main vapor-dominated reservoir (~ 240°C) is in greywacke, but it also extends downward into the felsite (Stone, 1992). In the northern part of the field deeper wells that have bottomed in greywacke have encountered temperatures higher than 300°C. There is a sharp decrease in seismic activity at about 4 km below sea level beneath the geothermal

Figure VII-11 Schematic geologic cross section showing relations expected to be encountered in the 4-km deep exploration well at the Kakkonda geothermal field in Japan. From Sasada *et al.* (1993).


NW
SE
K6-3
K6-2
4000m deep geothermal survey well (plan)
K1-3
1000
0
-1000
-2000
-3000
altitude (m)
200℃
250℃
300℃
350℃
Lau
LaL
Anh
Wa
Bi
Co
0
1000m
4000m deep geothermal survey well (plan)
Tertiary formations
Basal conglomerate in Tertiary formation
pre-Tertiary formation
Torigoenotaki dacite intrusion
Old tonalite intrusion
Granitic pluton
isotherm
upper limits of laumontite
lower limits of laumontite
upper limits of anhydrite
lower limits of wairakite
upper limits of biotite
upper limits of cordierite

reservoir (unpublished data of R. B. Julian and G. R. Folger). Presumably the seismic activity cuts off sharply because the rocks become too hot and plastic for shear failure to occur at greater depths. The temperature of this transition appears to be about 370-400°C in this region (Fournier, 1991). In addition, fluid pressures considerably in excess of hydrostatic were encountered near the bottom of a 3.6-km deep geothermal exploration well about 9 km north of The Geysers geothermal field (Fournier, 1991). The temperature at the bottom of this well is estimated to have been in the range 370-400°C and the transition from hydrostatic to considerably in excess of hydrostatic occurred within the depth range 3.4 to 3.6 km. The initial flow rate of the high-pressure fluid was in excess of 90,000 kg hr-1, but it later stabilized at about 12,700 kg hr-1. A large, relatively shallow, hot pluton, or several small intrusive bodies probably underlie the region north of The Geysers geothermal field. Evidence for this includes a broad heat flow anomaly and the bottoming of one deep exploration well in tourmaline-rich hornfels, which is typical of contact metamorphic rock found elsewhere in the district above shallow, silicic plutonic rocks. Drilling to depths of 4-5 km within The Geysers geothermal field or in the region to the north or northeast of the production zone would likely penetrate the brittle-plastic transition region and provide important information about the nature of fluids in and below the transition region.

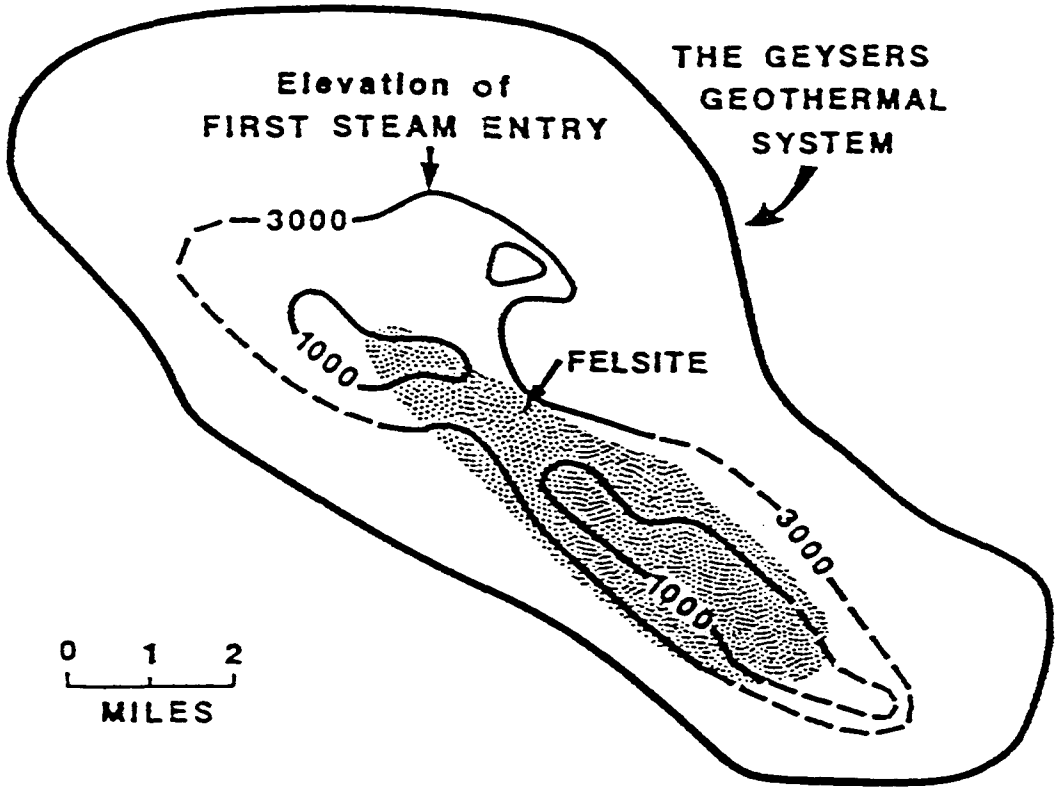


Figure VII-12 Map showing generalized elevation of first steam entry (countours in feet below sea level) and distribution of felsite intrusive body at 5000 feet beow sea level. From Thompson and Gunderson (1989).

One 3-km deep geothermal exploration well in the Larderello region of Italy (the San Pompeo 2 well) encountered very high temperatures (>400°C) and high pore-fluid pressures (Batini *et al.*, 1985). It also penetrated into tourmaline-rich metamorphic rocks that contain minerals and fluid inclusions indicative of temperatures in the range 325-600°C. It is very likely that the well bottomed in the contact metamorphic aureole above

a shallow pluton, and that the boron-rich minerals formed as a result of interactions of the country rock with magmatic fluids expelled from this pluton as it crystallized. Future scientific drilling in the Larderello region offers the opportunity to investigate not only the brittle-plastic transition region, but also sub-horizontal seismic reflectors and seismic velocity anomalies (Fig. VII-14).

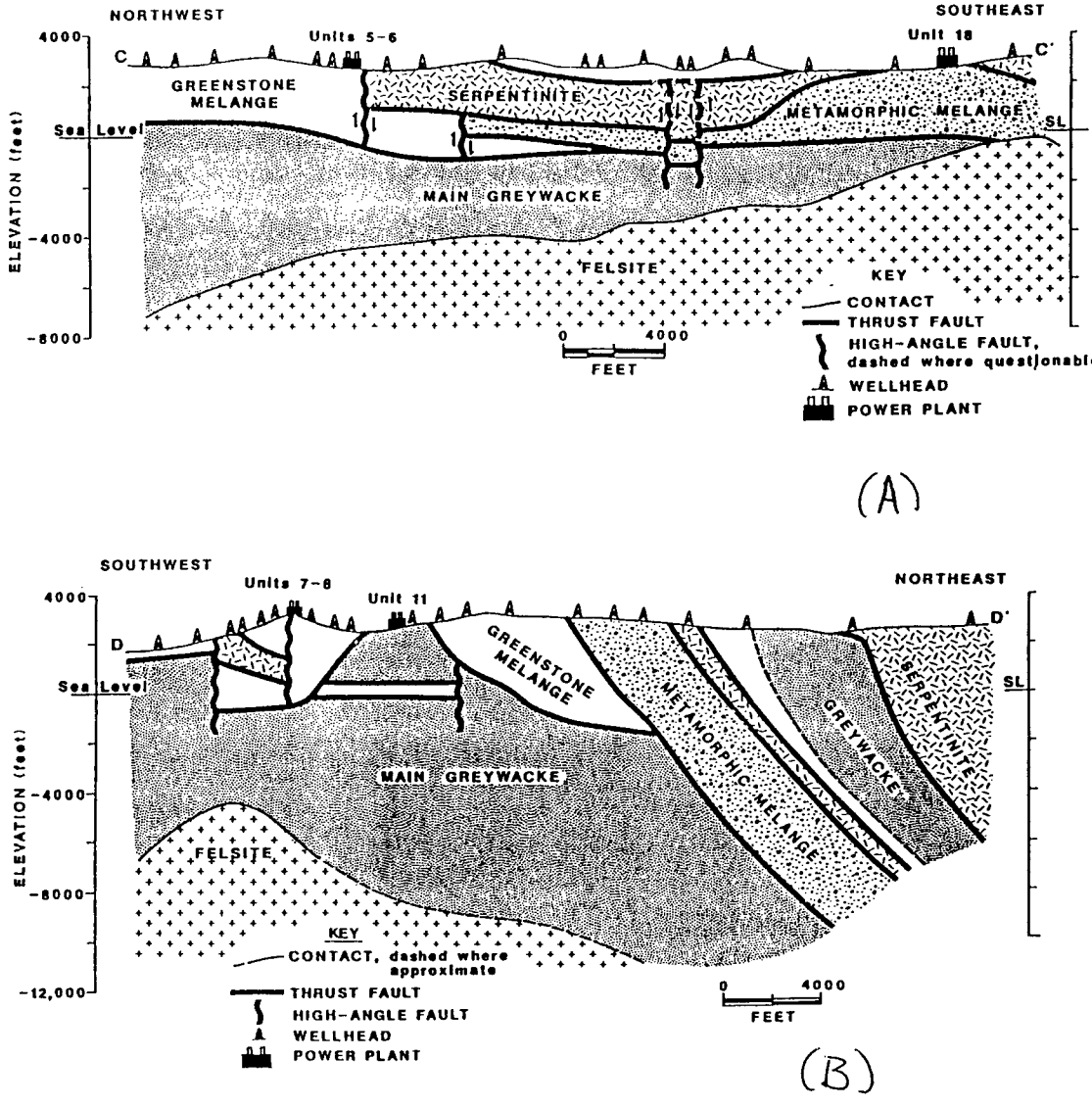


Figure VII-13 Cross sections in the central part of The Geysers geothermal field. (a) Northwest-southeast cross section along the axis of the felsite; (b) southwest-northeast cross section across axis of the field.

At Yellowstone National Park, Wyoming there is good geologic and geophysical evidence that a large, silicic magma body underlies the 1500 km2 Yellowstone caldera with the top of the magma (>700°C) at a depth of 4-5 km. Repeated leveling measurements

evidence that a large, silicic magma body underlies the 1500 km2 Yellowstone caldera with the top of the magma (>700°C) at a depth of 4-5 km. Repeated leveling measurements showed that the caldera inflated (the floor of the caldera went up) prior to 1985, and deflated (the floor went down) thereafter (Dzurisin *et al.*, 1990). Figure VII-15 shows two contrasting explanations for the inflation and subsidence of the Yellowstone caldera, the first involving changing rates of supply of basalt at the base of the crystallizing magma, and the second involving a lithostatically pressured brine above the magma. Recent analysis of data obtained from GPS surveys indicates that the uplift required a volumetric increase in the depth range 3 to 6 km, and the subsidence source is shallow, between the surface and a depth of 3 km (Meertens *et al.*, 1992). The source of the elevation changes can be modeled as an irregular shaped sill-like body at a depth of 3 km (Meertens *et al.*, 1992). This is at about the depth where there is likely be a transition from brittle to plastic behavior of the rock overlying the large magmatic body. The GPS model strongly supports the involvement of lithostatically-pressured hydrothermal fluids in the ground deformation. Thus, the Yellowstone caldera presents a very large and relatively shallow target for investigating hydrothermal processes within the brittle to plastic transition region above a batholith-sized degassing magmatic body.

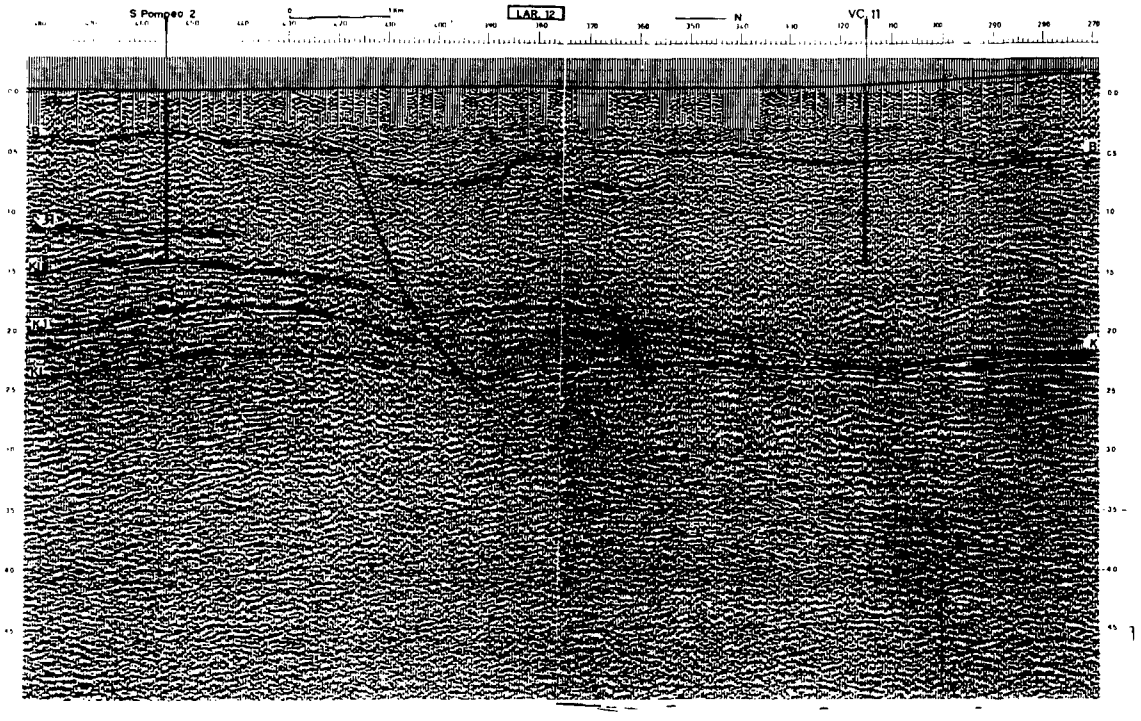


Figure VII-14a Seismic profile trending N. 12°E. and geologic interpretation in the Larderello region, Italy. 1) Neogene sediments. 2) Flysch nappes. 3) Tuscan Nappe. 4) Tectonic slice complex. 5) Filladi Inferior Group. 6) Micaschist Group. 7) Gneiss and amphibolite. 8) K-seismic reflecting horizon. Illustration from Batini *et al.* (1985).

Extensional, high heat flow regimes

Deep drilling in extensional terrains could supply important information on the maximum fluid fluxes in the crust, impact of the brittle-ductile transition, and the States, southwestern Canada, south central Slovakia, Papua, New Guinea, Rheingraben, Germany, and the East African Rift.

Table VII-1 Possible indicators of free water in the Earth's crust. The type of indicator and the depth range of relevance is indicated (From The Workshop on Continental Scientific Drilling, 1988).

FREE WATER IN THE CRUST

INDICATOR	DEPTH RANGE	REFERENCES
Water Table	0-2 km	-
Deep Wells	to 12 km	-
Reservoir induced seismicity	to 12 km	Bell & Nur (1978)
Crustal low velocity zones	7-12 km	Berry & Mair (1977) Jones & Nur (1984)
Crustal electrical conductivity zones	10-20 km	Nekut et.al. (1977) Skankland & Ander (1983)
Oxygen isotopes	to 20 km	Taylor (1977)
Metamorphism	> 20 km	Fyfe et.al. (1977) Etheridge et.al. (1984)
Crack healing & sealing	?	Richeter & Simmons (1977) Sprunt & Nur (1979) Ramsay (1980) Smith & Evans (1984)
Formation of hydrothermal ore deposits	> 5 km	Norton & Knight (1977) Cathles & Smith (1983)
Crustal Seismic attenuation zones	7-15 km	Herman & Mitchell (1975) Winkler & Nur (1982)

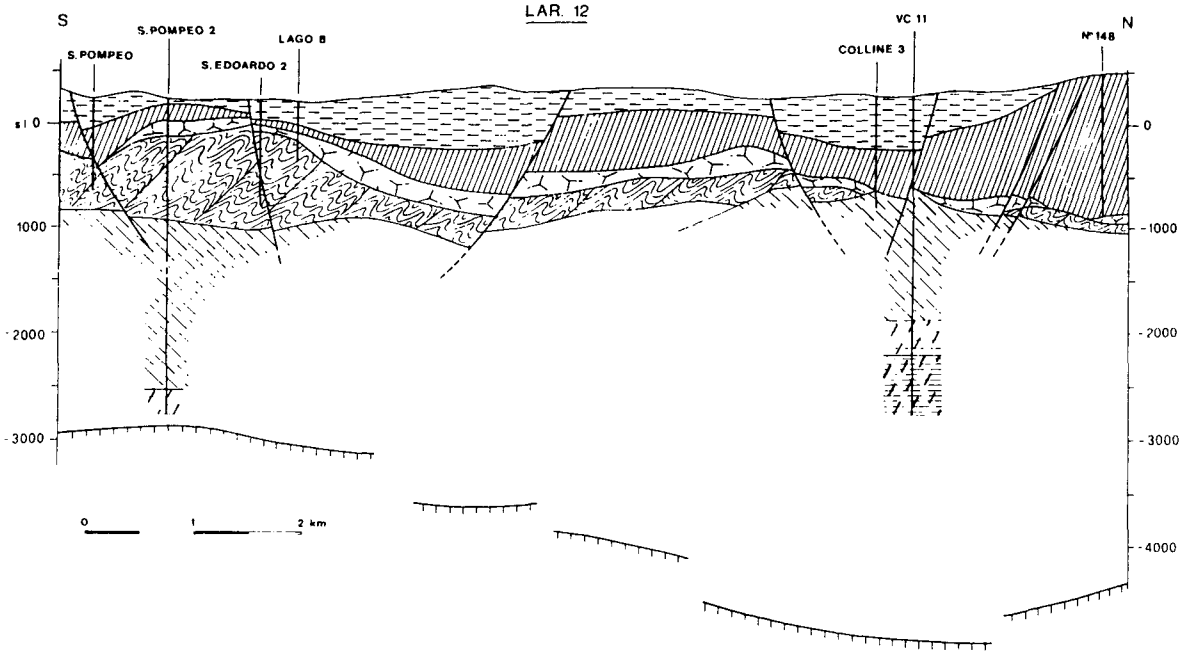


Figure VII-14b Seismic profile trending N. 12°E. and geologic interpretation in the Larderello region, Italy. 1) Neogene sediments. 2) Flysch nappes. 3) Tuscan Nappe. 4) Tectonic slice complex. 5) Filladi Inferior Group. 6) Micaschist Group. 7) Gneiss and amphibolite. 8) K-seismic reflecting horizon. Illustration from Batini *et al.* (1985).

Active uplifting regimes

Drilling in an uplifting regime will prove useful in characterizing the nature of fluid influx into such systems and the characteristics of transient flow regimes. An excellent target area would be the Alpine fault in New Zealand.

Active compression regimes

Drilling in this environment will yield information on the degree of continuity of fluid cells and the development of fluid overpressures where faulting tends not to result in increased vertical permeability along fractures. It also may provide information about tectonic expulsion of fluids from deforming sedimentary rocks. Possible targets are in the Himalayan Mountains and in Iran and Turkey.

Active foreland wedges

Drilling into active foreland wedges might supply some answers regarding the role of fluids in volume loss deformation. A possible target would be the Aleutian trench.

Dzurisin et al.: Recent crustal subsidence at Yellowstone Caldera

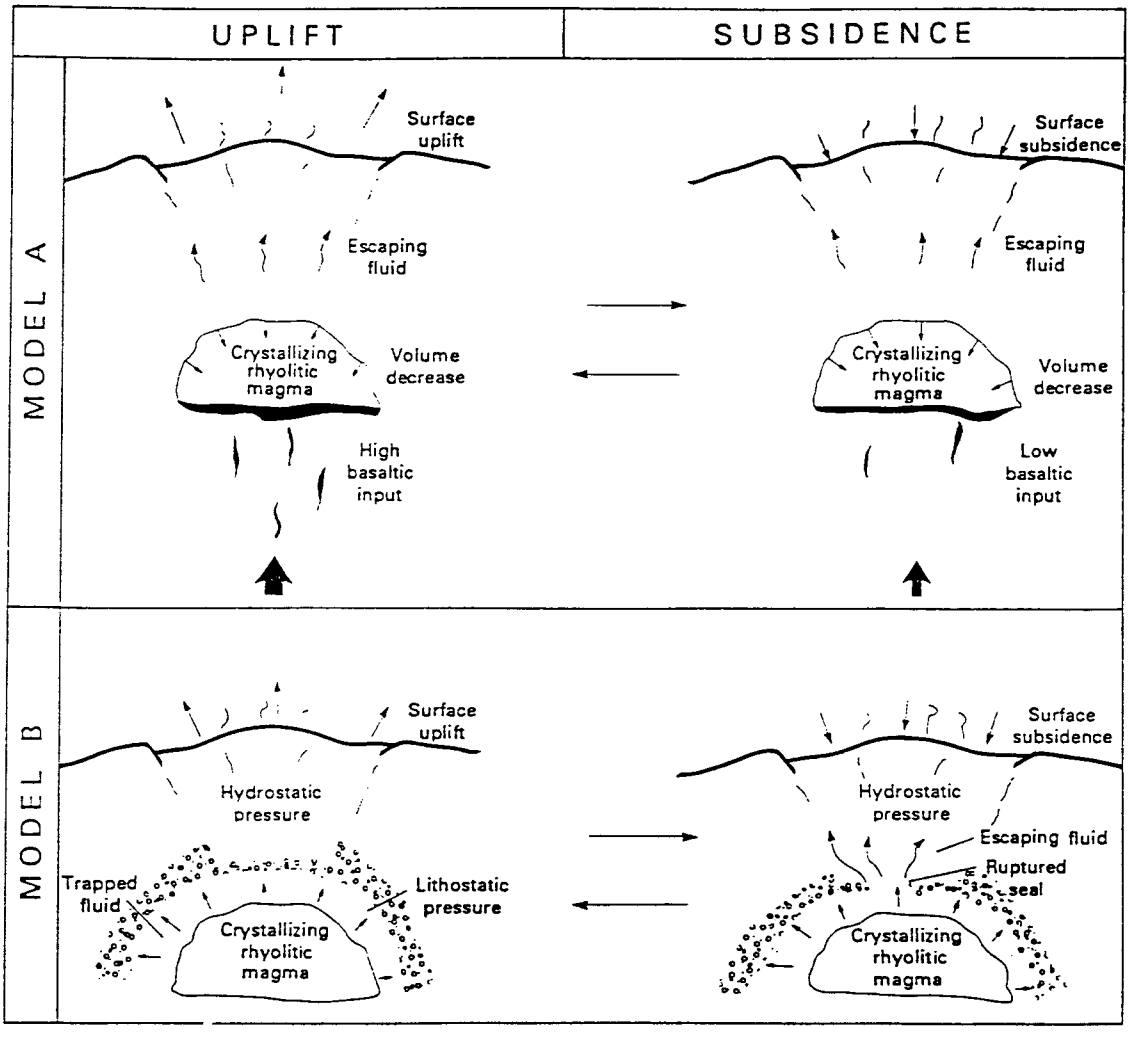


Figure VII-15 Alternative models for historic uplift and subsidence at Yellowstone Caldera. In model A (top) uplift and subsidence result from different rates of supply of basalt at the base of the rhyolitic magma system. In model B (bottom) uplift occurs when fluid released from the crystallizing magma are trapped at lithostatic pressure beneath a relatively impermeable zone and subsidence occurs when the impermeable zone ruptures, allowing escape of magmatic fluids. From Dzurisin *et al*, 1990.

Technological Needs

(1) A very high priority is to develop the capability of continuously coring into rock where temperatures are 400°C to 450°C at depths in the range 3 to 5 km. Not

only are there problems in regard to the present temperature limitations on materials used for drilling, but there also may be severe problems with explosive fluid-rock interactions at these temperatures if fluid pressure within the drill string drops too low when liquid is used as the drilling medium.

(2) Advances need to be made in our ability to isolate and instrument multiple whipstocked portions of wells. In particular, there is a need to measure temperature and fluid pressure very precisely in isolated compartments at moderate to high temperatures.

(3) Methods need to be developed to analyze accurately single fluid inclusions for a greater number of major and minor dissolved components than is now possible. This would be of tremendous value in deciphering how fluid compositions have changed with time. It also would allow the application of chemical geothermometry for comparison with fluid inclusion filling temperatures. Depending on the particular geologic environment and salinity of the inclusion, differences might provide crude to moderately good indications of pressure corrections for fluid inclusion filling temperatures. Alternatively, information about relative rates of fluid flow may be obtained by comparing the results of chemical geothermometers that react relatively quickly with a change in temperature (*e.g.*, Mg/K2) with those that react relatively slowly (*e.g.*, Na/K).

Conclusions

Scientific drilling projects should be designed to obtain information about fluid compositional variations and rates of fluid movement and chemical processes in three-dimensional space, and about the rates of change of these movements and processes. Fluids are present throughout the Earth's crust, and the possible effects of fluid-rock interactions and variations in physical state (temperature, pressure, specific volume, viscosity, etc.) and fluid compositions must be taken into account in the study and interpretation of geologic processes that occur within the lithosphere. This is because there is a general coupling of mineralogical and mechanical parameters of rock with physical and chemical parameters of the fluid that exists throughout that rock. A change that affects one parameter is likely to affect the other parameters to some extent.

Knowledge of the distribution and of the physical and chemical properties of fluids in the Earth's crust, and the rock properties that control the movement of these fluids is of vital importance for gaining an understanding of tectonic processes, the thermal regime of the continental crust, the genesis of ore deposits, the distributions of petroleum and geothermal resources, and mechanisms of explosive volcanic eruptions. It also is vital for determining the availability and recharge of potable water in the Earth's crust, and for guarding against natural and man-induced pollution of that resource by unwise exploitation policies or poorly designed waste disposal practices.

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VIII. Origin of Mineral Deposits

Introduction

Society's ongoing dependence on minerals is abundantly clear. It is also obvious that supplying this need in the future will depend on there being a much greater fundamental understanding than we have now on how several important classes of deposits are formed. It is with this intent for improving our understanding of mineral deposits that this segment of the Continental Scientific Drilling Program is aimed.

Our use and growing dependence on minerals, and in particular, metallic minerals, dates back 5000 yr when copper ores were mined by Egyptians in Sinai and, from the Troodos ophiolite, by the ancient inhabitants of Cyprus. Our large and fast growing Earth Population, and increased dependence on engineering and technology, now puts an increasing demand on those whose task it is to find mineral deposits. Over one hundred years of scientific study of ore deposits, with much three-dimensional information supplied by mining, drilling and geophysics, has led to a pragmatic classification of mineral deposits which is applicable on a world-wide basis. A widely acceptable descriptive classification scheme for metallic mineral deposits might start with those occurring within igneous rocks, such as crystal differentiate ores, and those derived directly from cooling igneous systems, such as volcanic massive sulfide (VMS) deposits, porphyry coppers and skarns. A second large group occur in metamorphic or sedimentary rocks, with the metals thought to derive increasingly indirectly from igneous sources. In this category are the important gold and base metal vein systems, SEDEX (sedimentary exhalative) and MVT (Mississippi Valley Type) deposits, and red bed copper deposits. Other important sources of metals, such as Archean banded ironstones and a variety of Placer-type deposits, are most naturally associated with their sedimentary environments.

Much of the more recent investigation of mineral deposits has been directed towards a better understanding the processes responsible for the formation of the different types of deposits. A very well known, and most successful step in this direction, is the unequivocal recognition that many VMS deposits were formed by the deep water venting of ore bearing fluids into cold seawater along active sea floor spreading centers.

The quest to understand processes of formation is a very reasonable one. If the process for the formation of a particular kind of mineral deposit is known, then it should be easier to predict where previously undiscovered deposits are likely to occur. To date, investigation of ore forming processes has been based on material from a wide variety of sources, ranging from outcrop, mine and drilling records to the results of sophisticated petrological, chemical, fluid inclusion and isotope work on ore material or on synthetic analogs.

Key Questions

With this plethora of information at hand, why then does scientific drilling play an important role in understanding the processes of mineral formation? The answer is in the fact that the transport of metals plays a necessary role in the formation of all mineral deposits, with the medium principally being aqueous fluids but in some cases that special fluid, magma. While this fact is well known, quantitative information on transport systems is not nearly so widely available. This is because the volumes of rock through which transport has taken place are generally not now mineral rich, and are hence not of interest to the explorationist. For example, the millions of diamond drill holes that explore ore bodies almost invariably stop where mineralization falls off. Even the few that extend further were rarely designed to recover the wide range of geological information that is

needed to define mineralization pathways.

The principal task, then, of scientific drilling in the area of mineral deposit studies is to provide key information to help complete the understanding of the processes that have led to the formation of a number of very important classes of mineral deposits. For most of these classes, transport, and indeed the original leaching of the metals from a source rock, has involved that most complicated of fluids, water. For this reason, the major part of the recommended program for this theme is aimed at identifying the sources of metals and aqueous fluids, and the pathways by which the fluids carried the metals to their final depositional sites. A wide range of changes, physical, chemical and temporal, must have occurred to both metals and fluids along these channelways, and the specific nature of these changes will also have to be sought. Demonstration of the value of this approach is already evident in, for example, the success of the Echassièrs project of the French scientific drilling program, GPF (Cuney and Autran, 1987).

A very important class of deposits where drilling can play this role is the *hydrothermal vein group,* seen here as encompassing a range of types, from gold-quartz to lead-zinc vein systems. In many cases, a strong component of vertical fluid transport, driven by buoyancy forces, is assumed, a situation well suited to study by vertical or steeply dipping drillholes to moderate, 1-3 km, depths. A more complete understanding of the processes of formation of these deposits will be gained by drilling into both active and ancient systems. Active systems are those in which primary ore transport is currently underway. Many of these systems are associated with active volcanism or with shallow igneous intrusion. Drilling into these systems will allow ore carrying fluids to be sampled from actual pathways. It will also be possible to look at variations in systems by installing long-term monitoring devices in drillholes where they intersect flow-ways. This approach is, however, limited in the information it can provide because of rapidly increasing subsurface temperatures, high fluid pressures, and other technologically limiting or hazardous conditions. We can only expect that the near surface, or generally more distal parts of pathways will be explored in active systems, leaving metal and high temperature fluid sources, and the proximal part of pathways, inaccessible. Information on these important parts of systems will have to be obtained from ancient systems, where temperatures and pressures are relaxed, or nearly so, to normal crustal values. The price of this necessary step will be less direct observation and more interpretation. It will be an advantage, as the program develops, to call for technical advances that will allow active systems to be explored more fully.

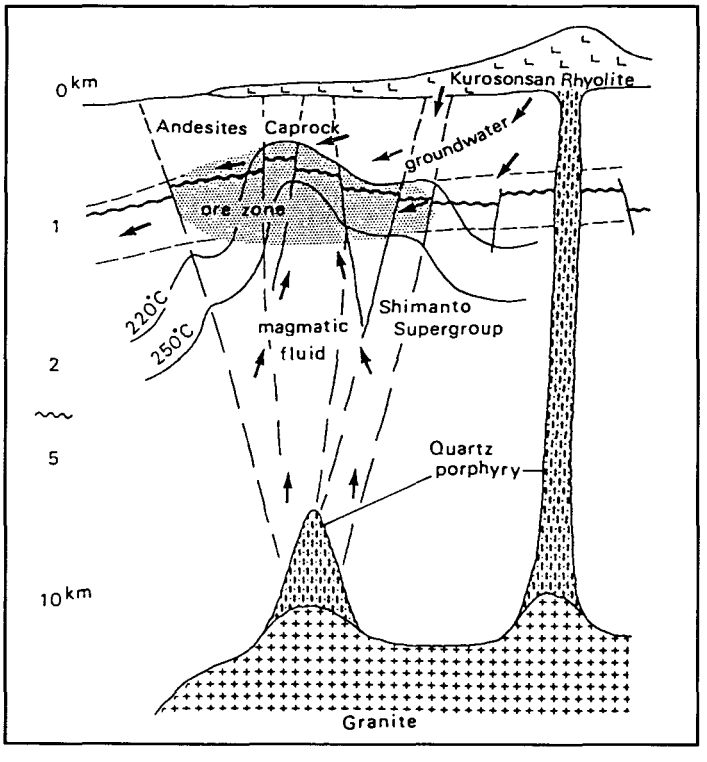


Figure VIII-1: Schematic model for the formation of Hishikari gold deposit (from Ishihara *et al.*, 1986).

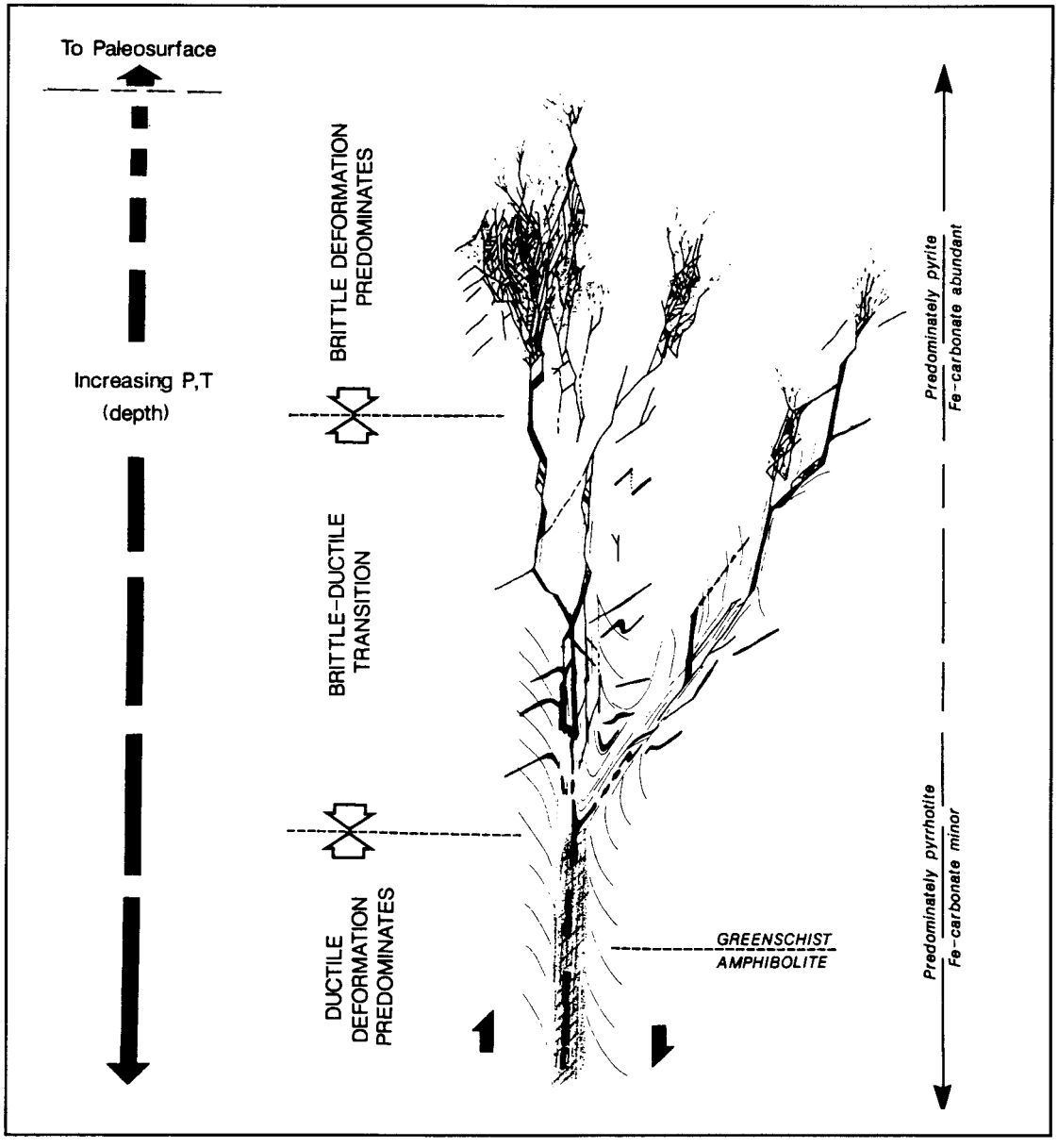


Figure VIII-2 Idealized composite depositional model for Archean lode gold deposits (from Colvine *et al.*, 1988). The vertical extent of the system is between 5 and 10 km. The shallowest levels of the system consist of breccia zones. Systematic, dilatant vein arrays occur at intermediate depths while a shear-parallel style without prominent veining occurs

The Role of ScientificDrilling

There is wide choice, worldwide, where active and fossil vein systems can be explored by drilling. Currently active systems are known, for example, at Satsuma-iwo-Jima in Japan, White Island, 50 km offshore in the Bay of Plenty, New Zealand, (Hedenquist *et al.* 1993) and the Salton Sea in the USA (Elders and Sass, 1988). Dying systems are found at locations such as Hishikari in Japan, where fluids at the level of the mining of the gold-silver-quartz veins are still at 60 to 70oC. Figure VIII-1 shows a proposed model for the system. Several key questions have been posed for this particular system, such as

whether the mixing of ground and magmatic hydrothermal fluids are responsible for the shallow, distal Au-Ag vein system and whether Au-Ag in veins is replaced by the assemblage Cu-Pb-Zn at depth. Fossil systems of all ages are known in all continents. Well known examples are the mesothermal gold-quartz vein systems of the Appalachians, the metal-rich vein systems of the Hercynides and the mesothermal gold-quartz systems of Archean greenstones (Colvine *et al.*, 1988) (Fig. VIII-2). Profitable overlap with the interest of other thematic areas are readily envisioned. Thus, valuable information on volcanic and general fluid history will be outcomes of drilling to test mineral formational processes. The presence of hydrocarbons, both as vein minerals and in the country rock, will provide information on the role and distribution of carbon in the crust. Intermediate depth drilling (3-7 km) in carefully selected locations will probably span large fractions of vertical fluid flow-ways. Site selection will need to take careful account of post-mineralization tectonism to ensure the original geological continuity of the sections drilled.

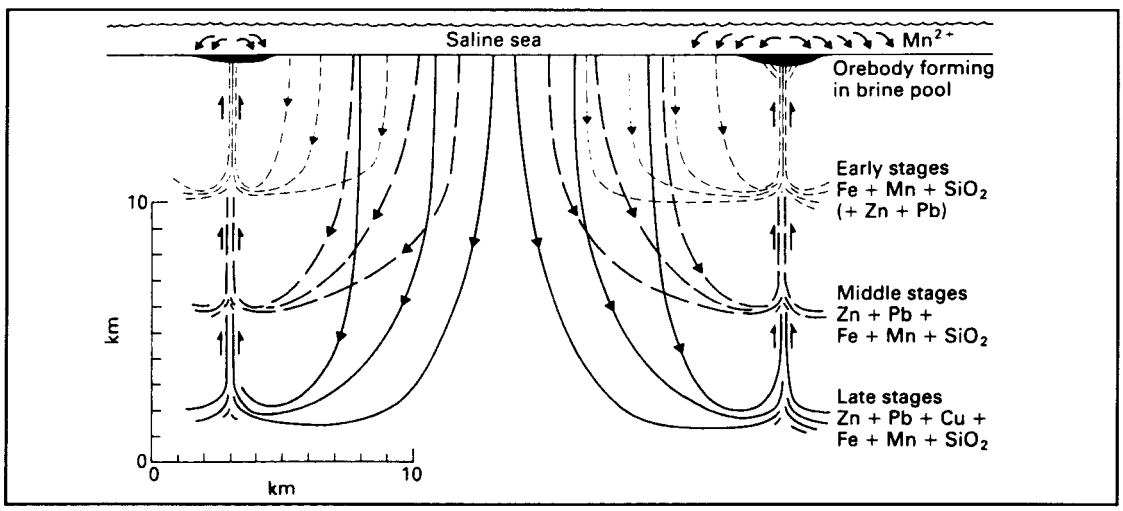


Figure VIII-3 Model for the formation of SEDEX type deposits (from Evans 1993 after Russell *et al.*, 1981).

The transport processes for metals that are at least one stage removed from original igneous sources gives rise to the important sedimentary-exhalative (SEDEX) and Mississippi Valley (MVT) type base-metal deposits. Here an immediate sediment source for the metals and fluids is likely, with the SEDEX deposits being of a proximal nature, located in the thicker, clastic part of basin sequences (Fig. VIII-3), and the MVT deposits in distal, carbonate platforms (Fig. VIII-4). Deposits of these types are typical features of large, marine sediment filled basins, and their study is appropriately described under the overall title of basin evolution and the formation of strata-bound mineral deposits. Transport of metals is likely to have a strong lateral component, possibly involving distances of up to hundreds of kilometers through both basin sediments and subjacent basement in the case of MVT deposits. This assumption is based in large part on the difficulty of identifying sources for MVT deposits. Scientific drilling, coupled with seismic and industry drilling, has the potential to identify fluid pathways, and the immediate sources of fluids and metals. This new information will contribute strongly to the answer to these problems, as well as providing information for generally improved understanding of basins and their contained fluids. Demonstration of the value of dedicated drilling at carefully located sites in sedimentary basin for the purpose of seeking mineralization pathways is already available through the Ardeche project of GPF (Megnien, 1993). Many

examples of both CEDEX and MVT deposits are potential targets for scientific drilling, such as the South Iberian Pyrite Belt and the Hohes Venn area (Fig. VIII-5), near the border of Germany and Belgium. Many areas already have extensive surface and underground geological and geophysical information useful for testing previously proposed models.

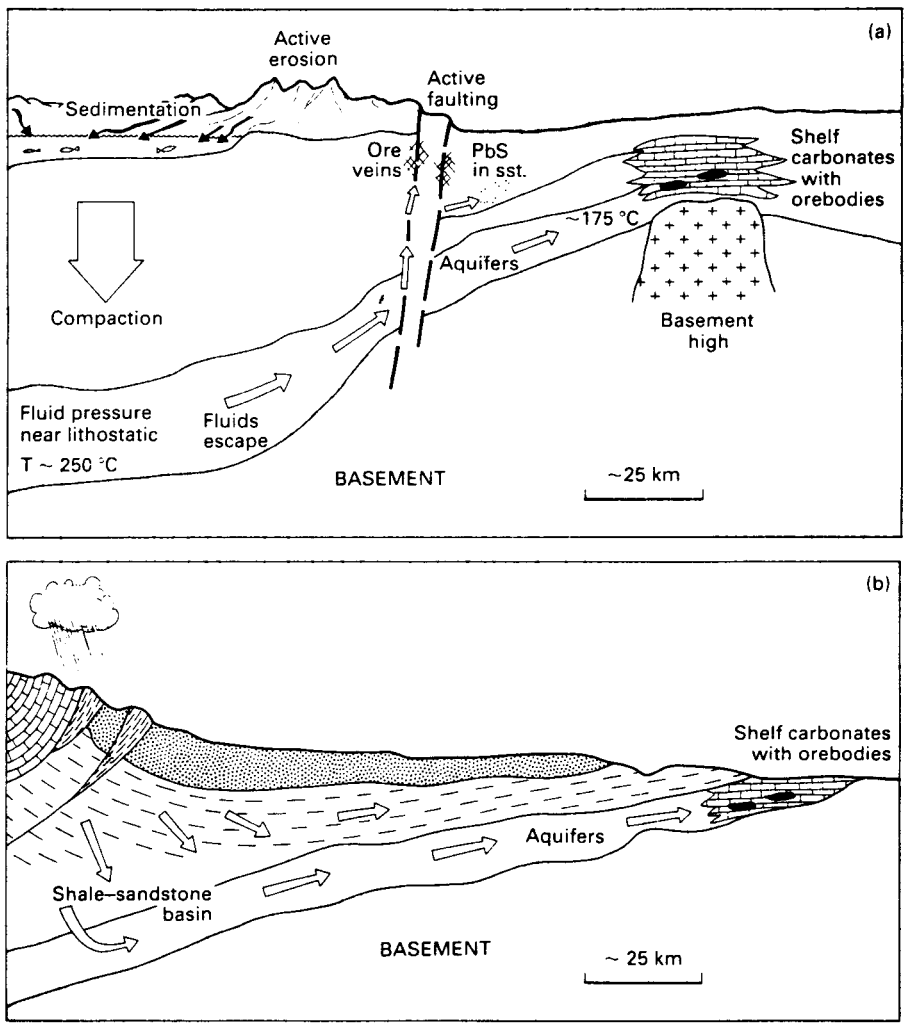


Figure VIII-4 Models for the formation of Mississippi Valley-type deposits. (a) Overpressured, hot pore fluids escape from a shale basin (perhaps aided by hydraulic fracturing) and move up aquifers to form deposits in cooler strata, filling fractures or forming other types of ore bodies. (b) Gravity-driven fluids flowing form a hydraulic head in a highland area flush through a basin driving out and replenishing the formation waters. The maximum vertical dimensions of systems is about 8 km. From Evans, 1993 based on the work of Garven (1985), Bethke (1986) and Ravenhurst *et al.* (1989).

Figure VIII-6 shows a geological interpretation of a seismic reflection section based on surface mapping and drill control in the GPF Ardeche program. Fluid-rock interactions on a well-preserved passive margin of the SE Basin of France near the Rhone Valley shows evidence of large-scale mass transfers during the diagenetic evolution of Liasic

(carbonate) and Triassic (sandstone) reservoirs. Sulfides (Pb, Zn, Fe, Ag) and sulfates (Ba, Ca) mineralizations are associated with extensive silicification and dolomitization phenomena (Largentiere mining district). Two drillings on the foot- and hanging-wall sides of a synsedimentary normal fault (offset about 1 km) showed the precise geometry of the two reservoirs. Horizontal gradients of diagenesis appears to have existed during two stages: First, prior to fault movement in Triassic/Liasic time. Second, during Jurassic-lower Cretaceous diagenetic evolution. Extensive mineralogical, petrological and geochemical studies of the cores and fluids trapped in diagentic stages from these boreholes have provided critical data for quantitative modeling of multistage diagenetic evolution of mineralized deposits.

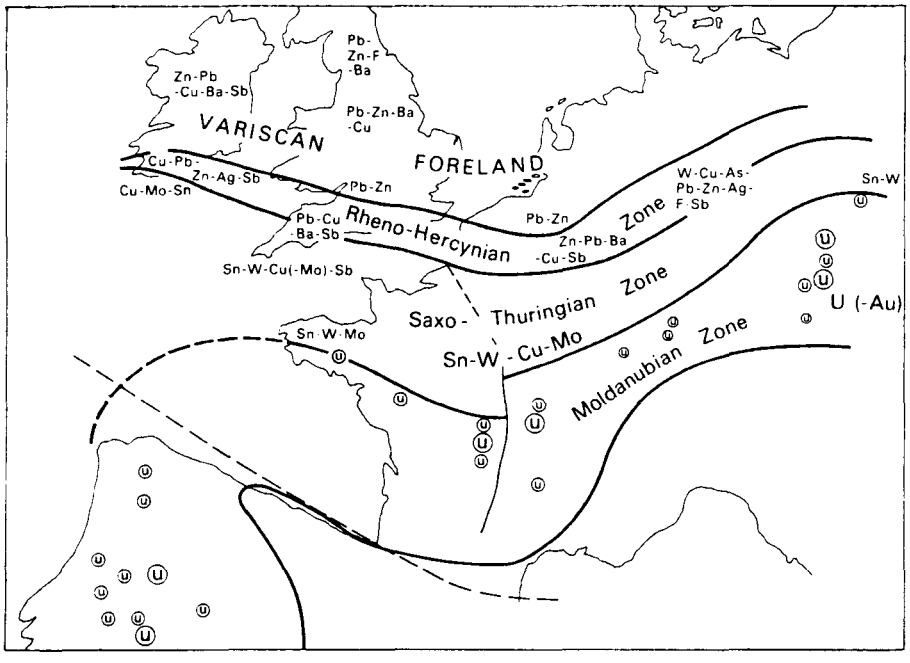
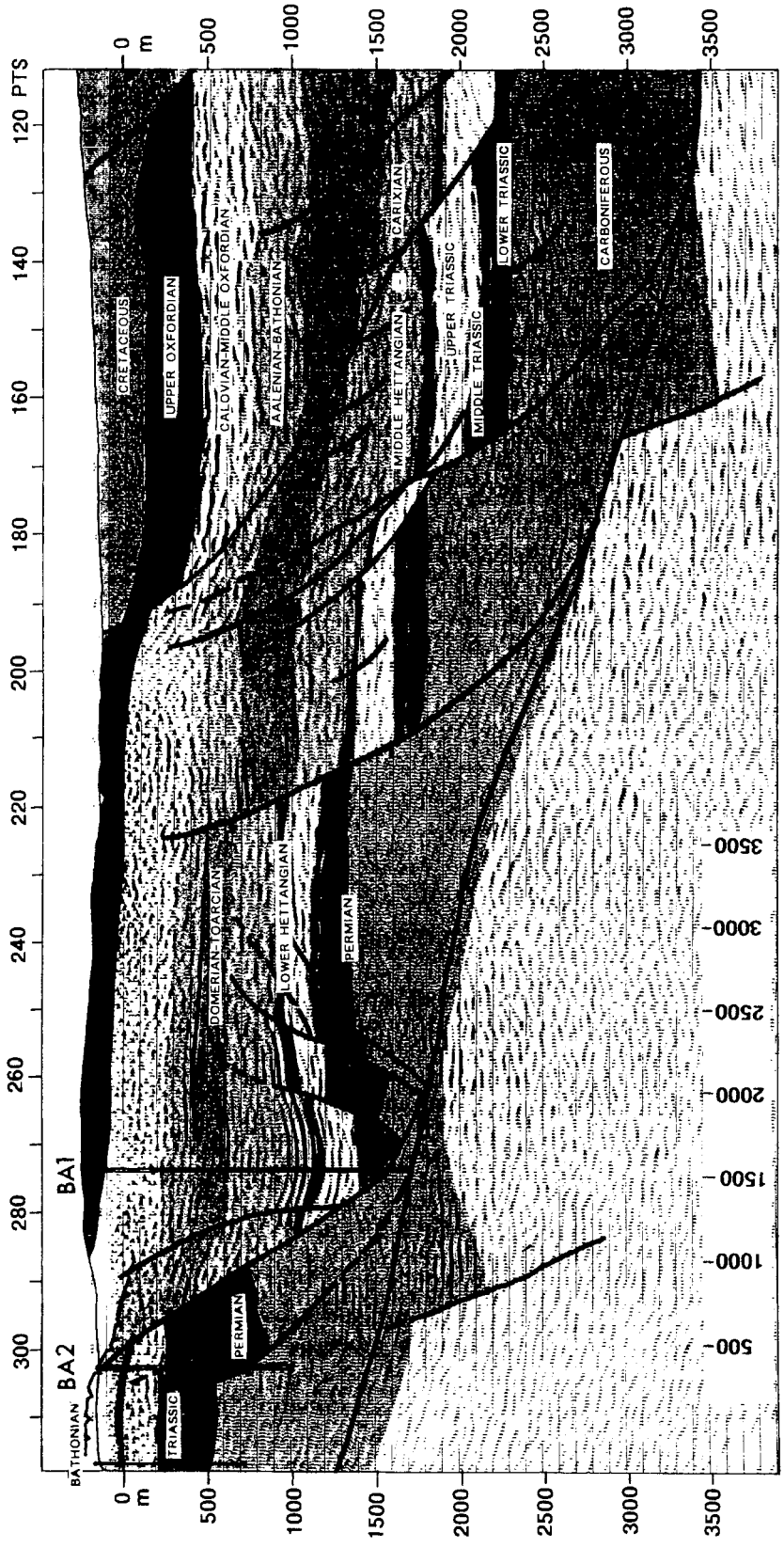


Figure VIII-5 Regional metal zonation of epigenetic deposits in the Variscan Metallogenic Province of western Europe (after Evans, 1976 and Cuney, 1978).

The South Iberian Pyrite Belt (IPB) is the largest massive sulfide province in the world (Leca and Leistel, 1993). Mining from chalcolithic to present times has resulted in the exhaustion of almost all outcropping and near surface bodies. Structural and seismic reflection studies suggest a thin-skinned tectonic setting and the presence of a major decollement at the base of the IPB terranes. Drilling of a carefully sited, 2 km hole would allow this structural model to be tested together with the exploration of the roots of the large-scale paleohydrothermal systems responsible for known and, perhaps, deeper polymetallic deposits.

The Hohes Venn area (Fig. VIII-7) is also located in an area of thin skinned tectonics, in this case on the Variscan Front. Deep reflection seismic and geologic mapping suggest sources of both vein type and MVT ores in relatively undisturbed foreland sediments beneath a regional detachment surface. One or more 5 to 7 km drillholes would be needed to test this prediction.

Figure VIII-6 Geological section based on surface geology, drilling and seismic profiling in the area of the Ardeche GPF program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MIDDLE HETTANGIAN
CARNIAN
UPPER TRIASSIC
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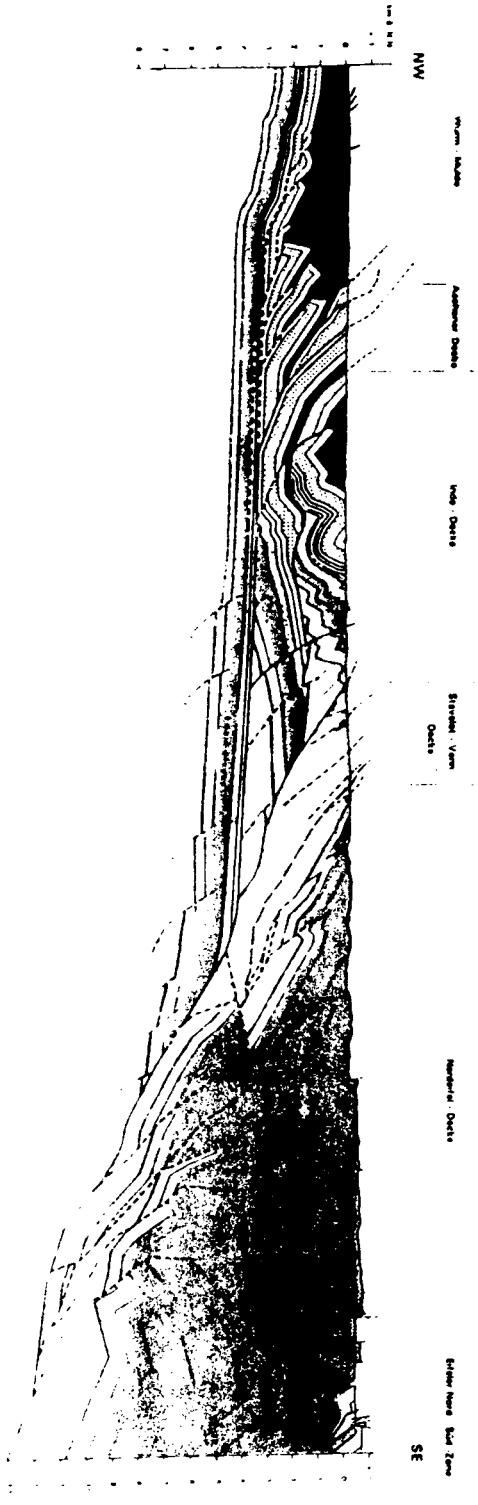

Figure VIII-7 Profile through the Variscan frost in the Hohes Venn area. The profile is about 60 km long and extends across part of the Rheno-Hercynian belt of Fig. VIII-5. (Taken from DEKORP Line 1A) (personal communication G. Friedrich, RWTH Aachen, Germany).

Within the strata-bound group of mineral deposits there is a group of copper and other metal bearing beds deposits for which drilling may be a valuable tool for testing models for formational processes. Examples are the Kupferschiefer of Central Europe and the White Pine deposit of the USA (Garven, 1985). For these deposits it has been suggested that their immediate source of the metals is igneous, but the link has often been hard to demonstrate. The economically very important Central African Copper Belt may also belong to this rather enigmatic group of deposits. Careful consideration of existing geological and geophysical information may show that scientific drilling can play an important role in determining the formation processes of this class of deposits.

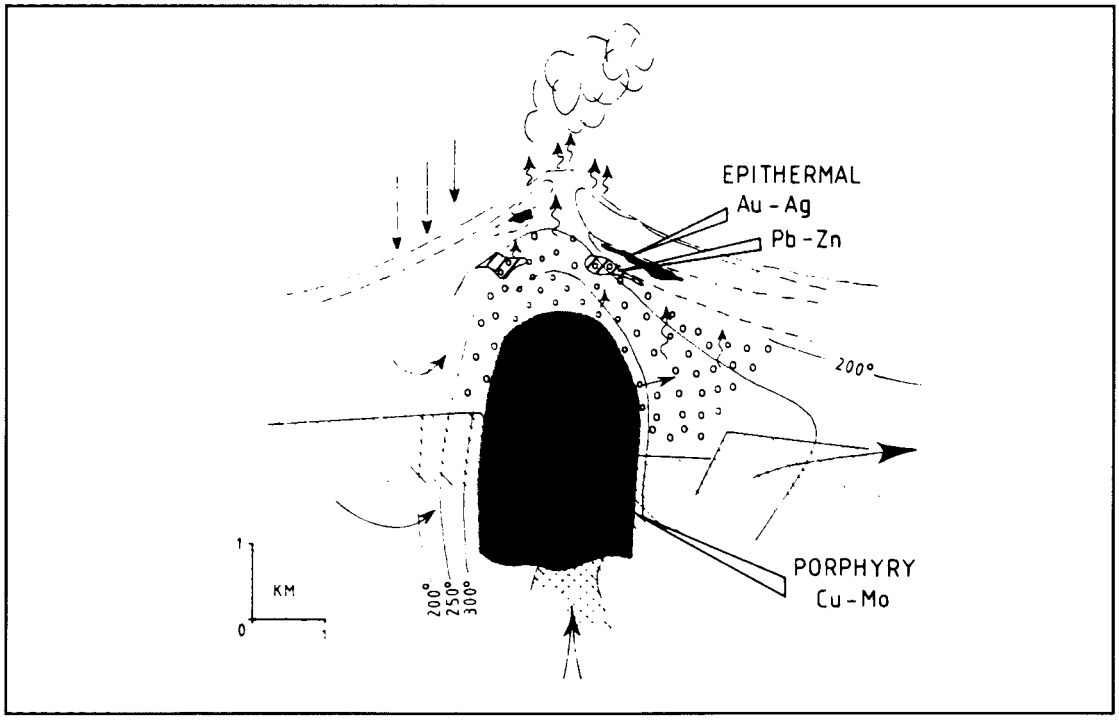

Figure VIII-8 Proposed environmental of hydrothermal ore deposition in a typical calc-alkaline stratovolcano (from Henley and Ellis, 1983).

Hydrothermal circulation is known to be critical to the formation of the important porphyry copper group of deposits, associated with the deeper parts of some andesitic volcanoes (*e.g.* Sillitoe, 1973; Henley and Ellis, 1983; Hunt, 1991). While a number of examples of this type of deposit are currently undergoing intensive study, scientific drilling is likely to have a strong bearing in settling a number predictions regarding the mineralizing veins, where the deeper disseminated mineralization may be part of the same overall system (Fig. VIII-8). This and other problems can be addressed by drilling at carefully selected sites of different ages and levels of erosion from the western parts of South and North America, Indonesia, the Philippines, and elsewhere (Fig. VIII-9). One well studied example would be the Tertiary volcanic-hydrothermal Maricunga area of Chile where native sulfur, precious metals in veins and porphyry type disseminations, as well as indications of copper minerals in some of the deeply eroded centers,.

Among the remaining classes of mineral deposits, one very specific class and example is a prime candidate for scientific drilling. This is the world class Ni-Cu mineralization of the Sudbury irruptive in Canada (Fig. VIII-10). It has been conclusively demonstrated

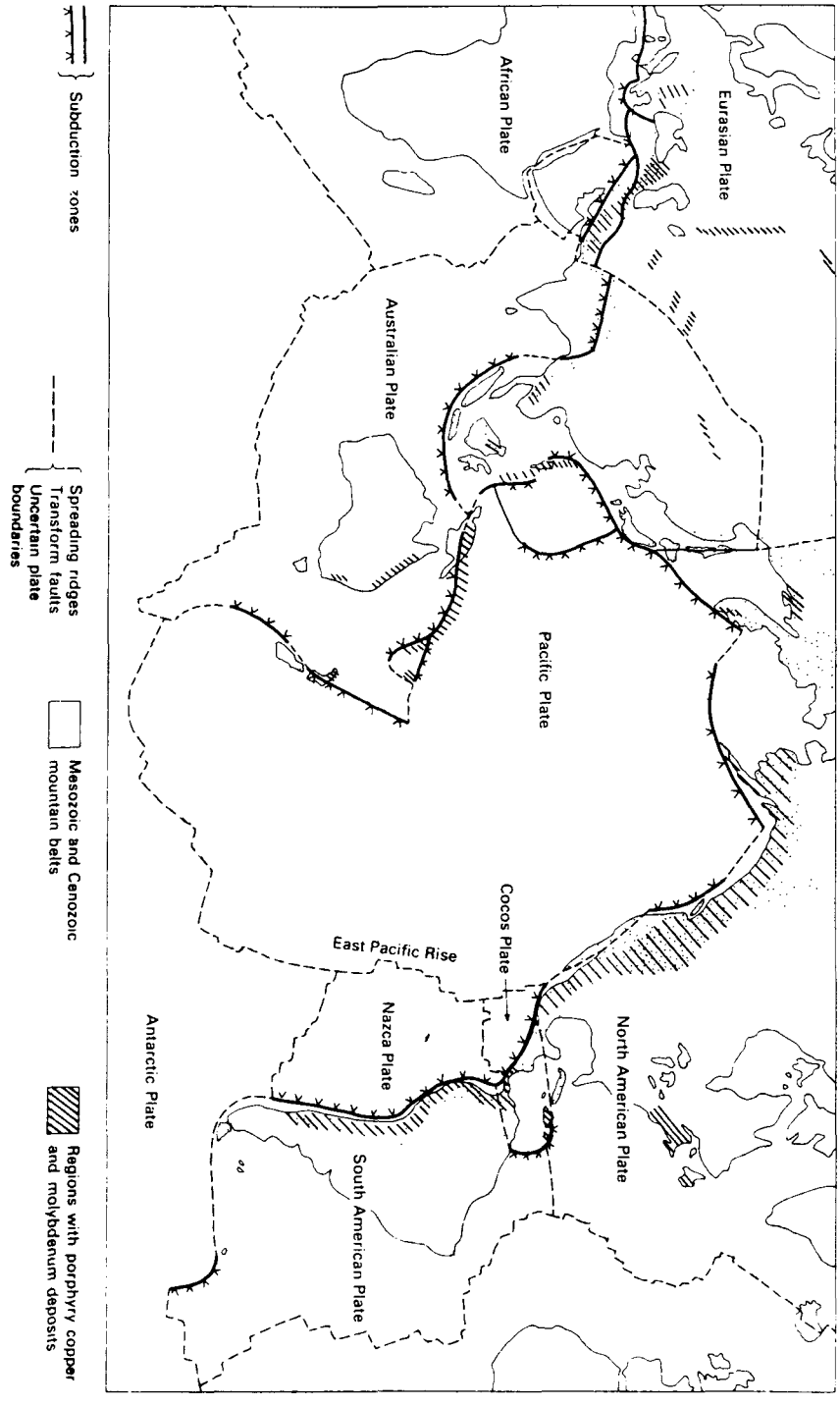

Figure VIII-9 The principal porphyry copper and molybdenum regions of the world (from Evans, 1993).

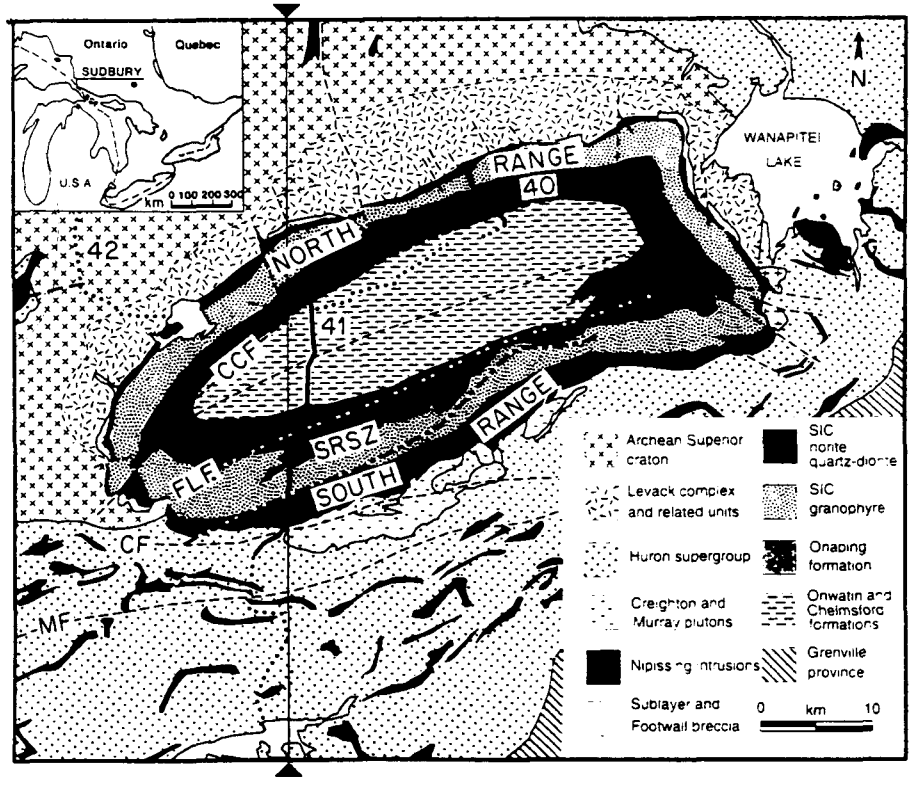

Figure VIII-10 Geology of the Sudbury region modified after Dressler (1984) and Milkereit *et al.*, (1992). Vertical line between triangles marks the location the density model-gravity profile shown in Fig. VIII-10. Thick solid lines are coincident high-resolution and regional seismic reflection profiles. Thick dotted lines are regional seismic reflection profiles. Dash-dot lines and SRSZ is the South Range shear zone. Dashed lines are faults: CCF - Cameron Creek fault; CF: Creighton fault, FLF: Fairbank Lake fault; MF: Murray fault.

that the Sudbury structure is of impact origin but what is not yet clear is the source of the metals or, the reasons for the segregation of so many rich sulfide deposits and particularly of the enormous quantities of sulfur involved (*e.g.*, Naldrett, 1984; Pye *et al.*, 1984). Ore-transport here is magmatic rather than aqueous, with ore bodies lying at the base of the Sudbury Igneous Complex (SIC). Understanding of the ore forming process is inextricably linked with the nature and origin of the impact structure as a whole. In turn, this could yield valuable information on the nature at lower constructional levels of other major impact structures on the Earth, in particular, the Mexican Chixulub, South African Vredefort and Russian Popigai structures. The wealth of existing knowledge of the Sudbury structure, including, most recently, a deep seismic reflection study, has answered some questions but has raised others (Milkereit *et al.*, 1992). It is now known that the elliptical shape at the surface is the result of overthrusting of the southern limb of a sheet-like body at least 120 km in diameter, on top of the north limb (Fig. VIII-11). The appreciation of the great size of the original structure means that the SIC can be interpreted as a sheet of impact melt. A major problem that is now before us, and must be addressed by drilling, is that the gravity, magnetics and seismics are best reconciled by

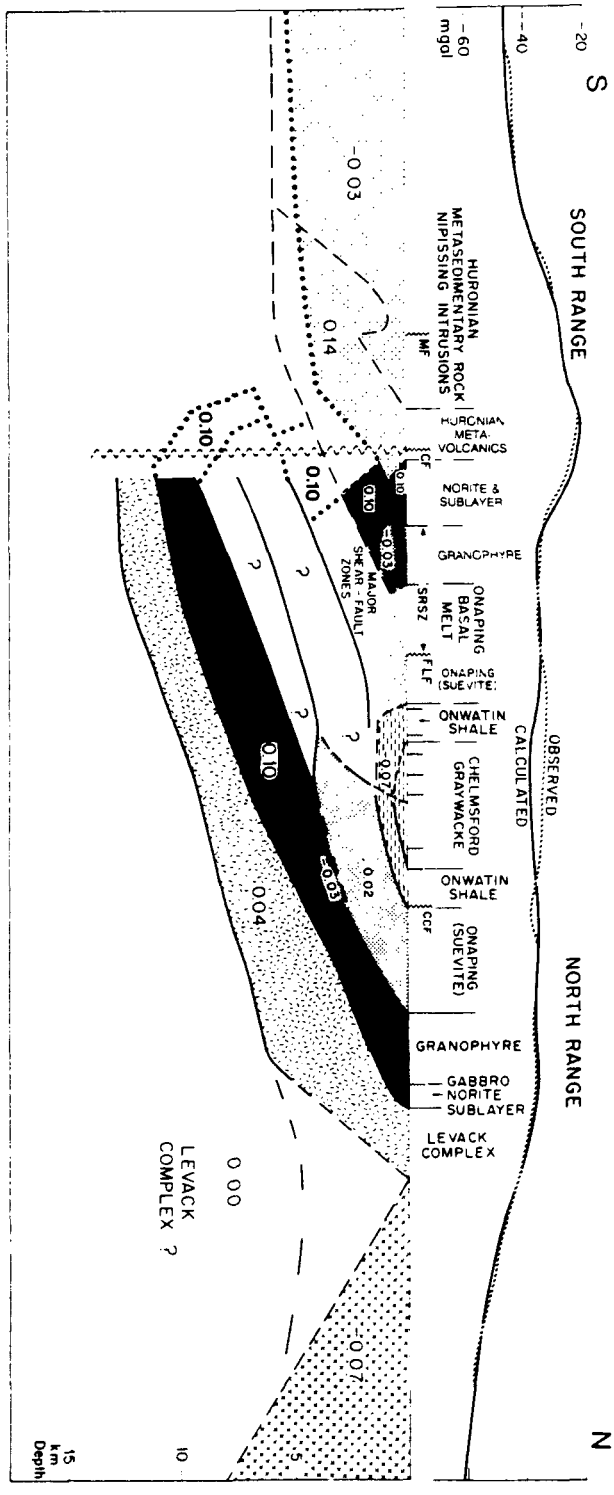

Figure VIII-11 Proposed deep geometry of the Sudbury structure. Most model boundaries are delineated by seismic reflection data. Density model and gravity data are for the north-south line are shown in Fig. VIII-10 (from Milkereit *et al.*, 1992).

assuming that the SIC and an underlying 2 km-thick sheet of granulitic gneiss continue together, with uniform southerly dip, beneath most of the structure. There is no evidence of a hidden mafic-ultramafic body at depth. This leaves completely open the question of the origin of the ores, and the closely associated suite of mafic/ultramafic inclusions. Other questions include: (i) does the present differentiated structure of the SIC imply two, incompletely mixed impact melts, possibly resulting from the impact-melting of country rocks that were originally stratified into an upper felsic and lower mafic layer? and (ii) was the precipitation of the sulfides caused by the mixing of these two layers (it is known that mixing of S-unsaturated mafic and felsic magmas can give rise to sulfide saturation) or did the impact trigger the rise of mafic magma from the mantle which mixed with an impact melt? A single 7 km hole, collared near the centre of the structure (Fig. VIII-10), will lead to an understanding of the geophysical results, and provide answers to some of the questions about the origin of the magmatism and the ores. It will also give a record of the substructure of a major impact crater, of the size of Chixulub in Mexico and Popigai in Russia, but collared at a level several kilometers below the surface of the original crater fill.

Technological Needs

In these suggested studies new approaches will be necessary to quantify the mobilization of metals by fluid-rock interaction and the amounts of fluids involved. A newly developed leaching method, which has already been applied to KTB drill core material, allows determination of the fraction of each element that is more soluble than typical rock-forming minerals. This fraction changes systematically with the intensity of alteration. The combination of leaching studies and isotope geochemistry will yield detailed insights into the process of metal release during alteration. Studies on drill core or cuttings will need to be supported by chemical analyses of carefully sampled and uncontaminated fluids.

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IX. Geophysics of the Crust

Introduction

Our understanding of the Earth's interior is largely inferred from geophysical measurements made at the surface. The formalized interpretation of surface measurements for crustal structure and composition is based on mathematical inversion which is inherently non-unique. Because of this non-uniqueness, drilling provides the ultimate test of geophysical interpretations. Additionally, calibration of crustal geophysics allows extension of direct information from a borehole into a larger crustal section. In sedimentary basins, this calibration procedure is well established in geophysical exploration for hydrocarbons. However, to effectively use surface-based geophysical data in crystalline rocks, it is clear that new geophysical analysis and interpretation techniques (and some new types of instrumentation) are needed which must be calibrated through the kind of "ground-truthing" provided only by scientific drilling.

One region where the correct interpretation of geophysical data is critical is the lower crust to upper mantle transition zone which contains major changes of physical and chemical properties. This region often governs the style of tectonic processes expressed at the surface as orogenies, sedimentary basins, rifting, plateau uplift as well as processes that form mineral deposits. Apart from exceptionally shallow cases, this transition zone will not be directly accessible to deep drilling in the near future. And yet, new and important insight into this region below the bottom of existing or future boreholes is to be gained since a whole spectrum of borehole techniques opens new windows which are closed to surface experiments alone. Remote observations of the lower crust, the crust-mantle boundary (Moho) and the uppermost mantle would be possible through new and critical experiments of higher resolution and signal to noise ratio than would be normally be obtainable from the Earth's surface.

Key Questions

Multi-Genetic Origin of Crustal Reflectivity

Since acquisition of the first crustal-scale seismic reflection sections, Earth scientists have been excited by the high-resolution images of otherwise inaccessible deep parts of the Earth. The pattern of deep crustal reflectivity has evoked many hypotheses of its origin which are still speculative and as diverse as composition, shear zones (Fig. IX-1) or fluid-filled fractures (Fig. IX-2). However, several types of reflectivity can be clearly related to tectonic structures and/or tectonic processes. In the seismogenic, brittle upper crust, reflections are often observed along shear zones, mainly as thrust faults in compressional regimes or normal faults in extensional regimes. The reflection polarity from shear zones is negative ($R < 0$), because many processes reduce the elastic moduli, and hence the seismic velocity, inside the fault zone. A major shear zone was detected at ~7.5 km depth in the KTB borehole that corresponds to a pronounced dipping reflector. Many zones of detachment in all continents have been inferred in recent or ancient compressional belts on the basis of sub-horizontal reflectors. However, all deep crustal reflectors are not shear zones (as proven by the Siljan boreholes in Sweden). This drilling showed that at least some Proterozoic areas where strong bands of reflections are observed over hundreds of square kilometers (*e.g.* Arizona or Sweden) correspond to diabase (dolerite) sills. In these cases the marked subhorizontal reflections had positive reflection coefficients ($R > 0$).

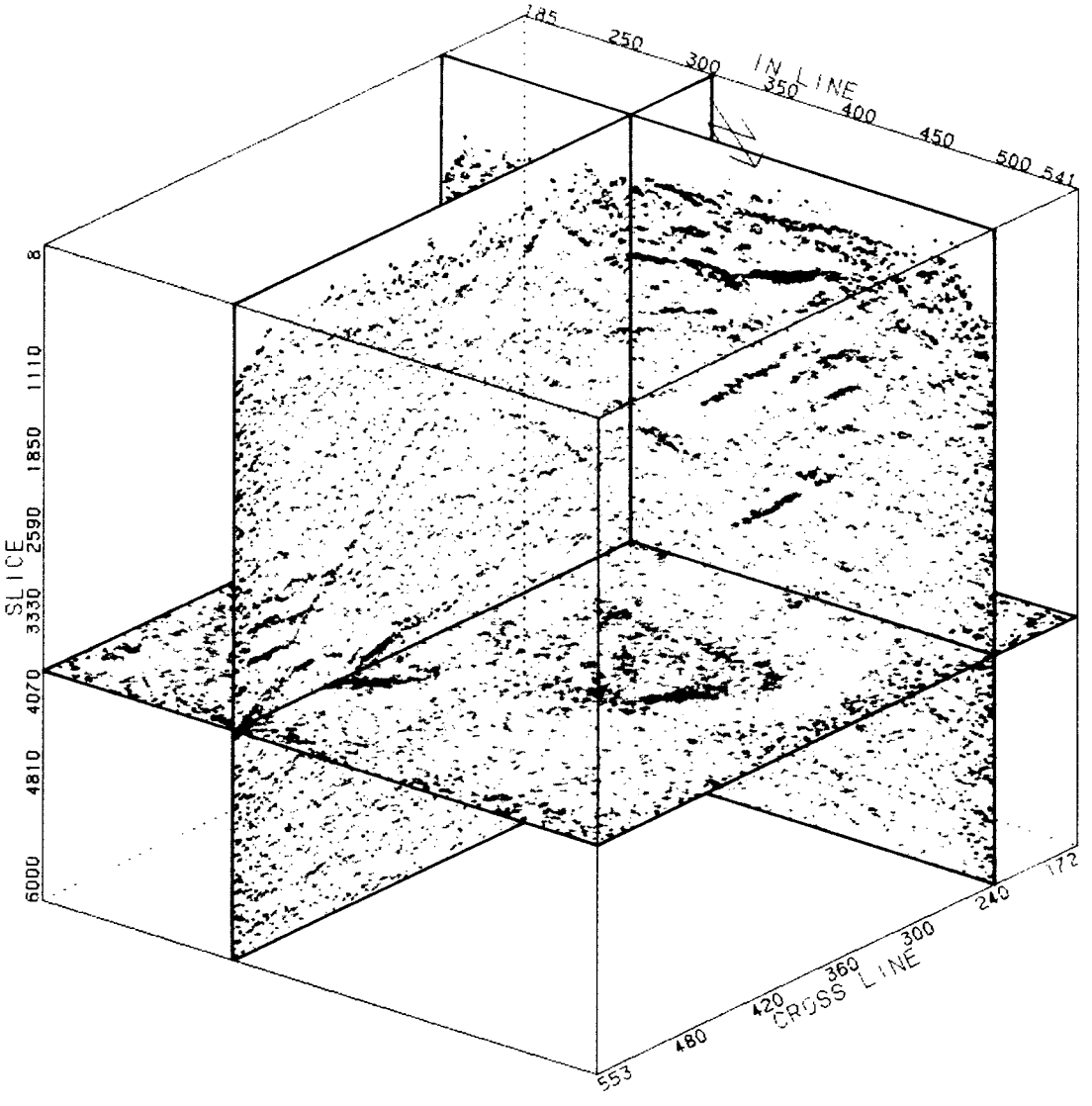

Figure IX-1: Three-dimensional image of the crust beneath the KTB borehole in southeastern Germany obtained through seismic reflection profiling. The reflector dipping across the image corresponds to a major shear zone encountered in the borehole at a depth of about 7.5 km.

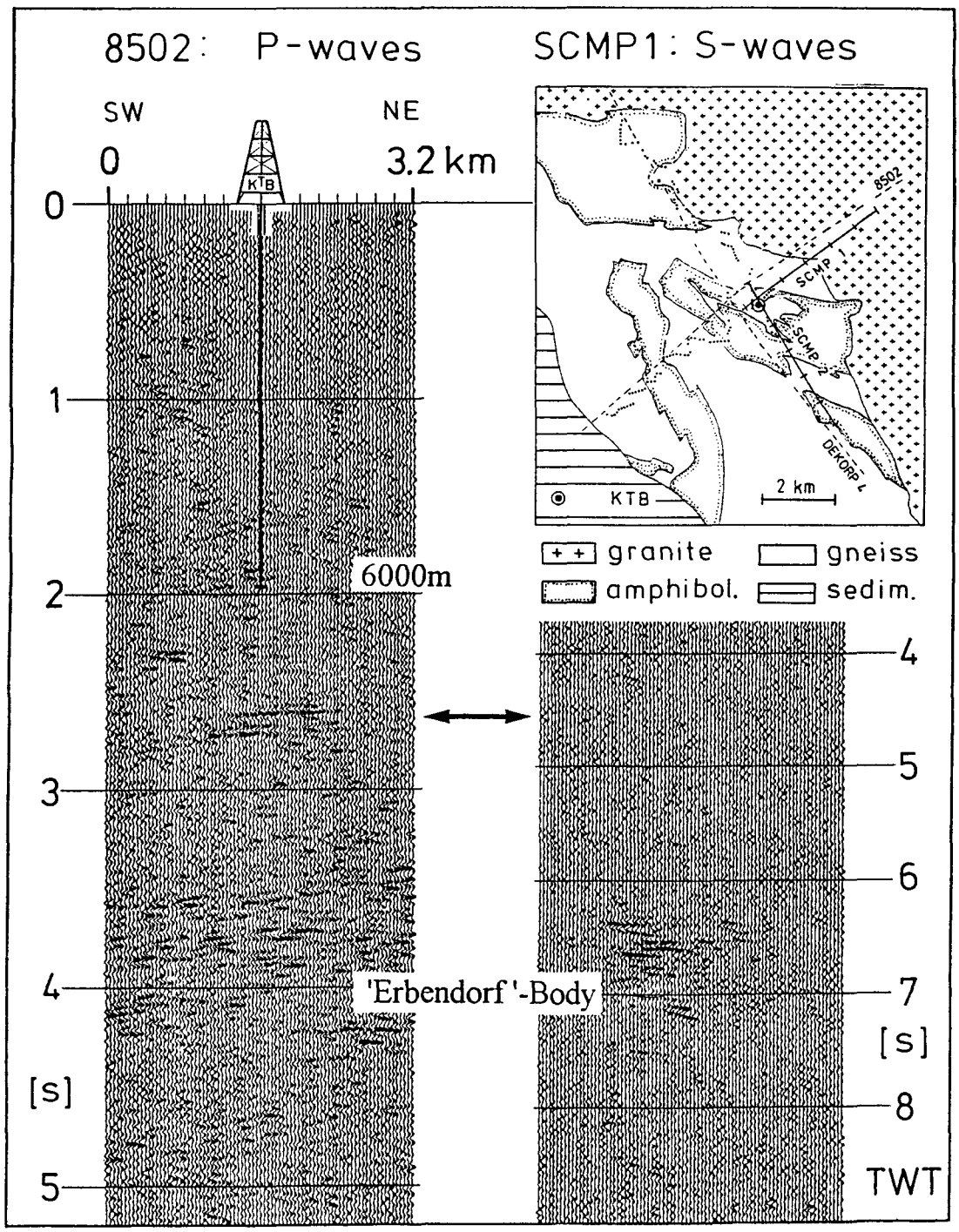

Figure IX-2: Comparison of seismic reflection sections at the KTB site collected with P-wave sources and receivers (left) and shear wave sources and receivers (right). The time-scale of the S-wave section has been compressed so that reflectors at the same horizontal position correspond to the same depths on both sections. Note that although reflectors from the the Erbendorf body (at a P-wave two-way time of 3.5-4.0 sec) is prominent on both sections at a P-wave time of about 2.7 sec (at a depth of about 8.5 km) there is a marked reflector on the P-wave section which is absent on the S-wave section. This has been interpreted to be the result of high pore fluid pressure at depth (E. Lueschen, written comm.).

Reflectivity in the lower crust, especially in its ductile part is also related to the tectonic and rheological history. In western Europe more than 75% of the studied reflection profiles show subhorizontal "lamellae" or bands of reflections whose origin is truly multigenetic. Probably, widespread post-Caledonian and post-Variscan collapse with extension has produced the elimination of former crustal mountain roots and the creation of lamellae. Hence, the ductile lower crust must be younger than the upper crust, a consequence which is also provided by the isotopic signature of xenoliths worldwide.

Composition is often inferred from "wide-angle" seismic refraction velocities. Most velocities reported for crustal regions generally originate from a wide variety of igneous and metamorphic rock types or, more realistically, from complex assemblages of several rock types. Anisotropy originating from preferred mineral orientation associated with extensional or compressional ductile flow undoubtedly complicates both crustal reflection and refraction data.

Clearly, the geological interpretation of crustal seismic data represents an important frontier in the earth sciences. Continental drilling and associated laboratory studies of physical rock properties will provide the calibration necessary to understand the origin of these seismic observations. Seismic reflections can serve as drilling targets in which continuous sampling and logging obtained at critical depths, provides the means of "ground truthing" the seismic observations.

Calibrating Seismic Reflectors from High-Grade Metamorphic Rocks

Rocks that normally are present at depths of about 20 km have been apparently thrust to the surface in the Kapuskasing uplift, located in the south central part of the Canadian shield. A wide spectrum of geologic and geophysical data have been accumulated and used to throw light on the nature of the rocks comprising the uplift, but verification can only be achieved by drilling. Geological field mapping in the Kapuskasing area revealed the presence of deep crustal rocks at the present day surface. However, detailed surface evaluation (and extrapolation to depth) is severely limited due to the scarcity of a continuous outcrop.

A seismic reflection transect across the Kapuskasing uplift was acquired as part of the Canadian Lithoprobe project. Three fairly prominent bands of reflected energy which are interpreted as representing the boundary of the deep crustal rocks with shallow crustal rocks, could be evaluated by the drilling of a hole to a depth of about 2000 meters at Kapuskasing.

Origin of High Electrical Conductivity in the Crust

The electrical conductivity in the lower crust of stable continents is two orders of magnitudes lower than the conductivity of dry rocks measured in the laboratory at the appropriate pressure and temperature conditions. Traditionally, these data were obtained from a combination of magnetotelluric experiments, but more recently, from controlled-source conductivity measurements it has been shown that the lower crust has a much higher electrical conductivity than one would infer from laboratory studies of presumably representative rocks. Various mechanisms have been proposed to explain this discrepancy. In the 70's and 80's, the existence of highly saline fluids at depth were postulated by many geophysicists to explain the observed high conductivity. But when thin films of graphite along grain boundaries were identified in exhumed rocks formed at mid- to lower-

crustal levels, a second mechanism, possibly operating in parallel with saline fluids (Hyndman and Shearer, 1989; Frost *et al.*, 1989) could be invoked to explain the surface observations. More recently, based on measurements on core samples to 4.6 km from the KTB borehole, a third mechanism has been proposed (Duba *et al.*, 1994) which argues for the importance of accessory minerals (such as Fe-Ti oxide and sulfides) on electrical conductance. They argue that such minerals can enhance, or even surpass, the importance of saline fluids.

With grain boundaries having a dominant influence on electrical properties of rocks in the crust, deep drilling provides the opportunity to obtain samples of rocks from various depths in the crust where grain boundary phases are being actively produced or destroyed. In order to test some of these metamorphic processes, the conductivity of similar rock-type cores from several depths can be measured in the laboratory. Petrographic and petrologic studies of the rock, particularly grain boundary phases is vital to this effort. Complementary to these measurements would be an in-situ measurement of the time variation of the electrical conductivity at a particular depth in the well as surface oxygen, mixed in the drilling fluid, reacts with these surface phases. Clearly, studies of deeper samples from the KTB borehole will be quite important in such studies as would be the study of samples from other deep boreholes.

One very interesting model put forward by Jones (1987) consists of a thin zone of saline fluids at mid-crustal levels overlain by an impermeable zone as suggested by Etheridge *et al.* (1983). The Hyndman and Shearer model is closely connected with the overall distribution of seismic reflectivity in the whole lower crust, whereas in the Jones model, the enhanced conductivity is confined to a rather thin layer in the middle crust. In the Frost model the whole lower crust possesses enhanced conductivity. In all of these cases, water and/or graphite are just accessory constituents of the rock mass because high conductivity structures cannot contribute essentially to the bulk composition of the lithosphere. This can be inferred from the (generally) poor correlation with seismic discontinuities, especially in cases where these represent compositional changes. Instead, the electrical anomalies seem to go with tectonic and/or petrological processes. There is evidence that the bulk resistivity in tectonic active regions is lower than in passive regions. While trapped fluids and partial melts could cause the electrical conductivity anomalies in recent tectonic processes, graphite is a candidate in fossil collision or strike-slip zones. In this way, drilling into a geoelectrical anomaly would not only address the fluid/graphite controversy but more importantly drilling would provide the opportunity to directly examine the processes responsible for the electrical conductivity.

Magnetization of the Deep Crust

Magnetizations calculated from very broad-scale (and thus apparently deeply-sourced) magnetic anomalies in crustal surveys (satellite airborne, ship borne, etc.) are often several times larger than magnetizations in upper parts of the crust (Toft & Haggerty, 1988; Wassilewski & Mayhew, 1992; Nolte & Hahn, 1992; Morley, 1991). Magnetic field measurements in the KTB borehole (Fig. IX-3) have scrutinized the analysis of airborne observations: the observed vertical gradient of the magnetic field is clearly stronger than predicted by the Earth dipole field (Fieberg, 1993). A corresponding discrepancy has been observed in laboratory measurements on rocks originating in the upper or lower crust, respectively. The reconciliation of this discrepancy is a significant challenge in crustal geophysics.

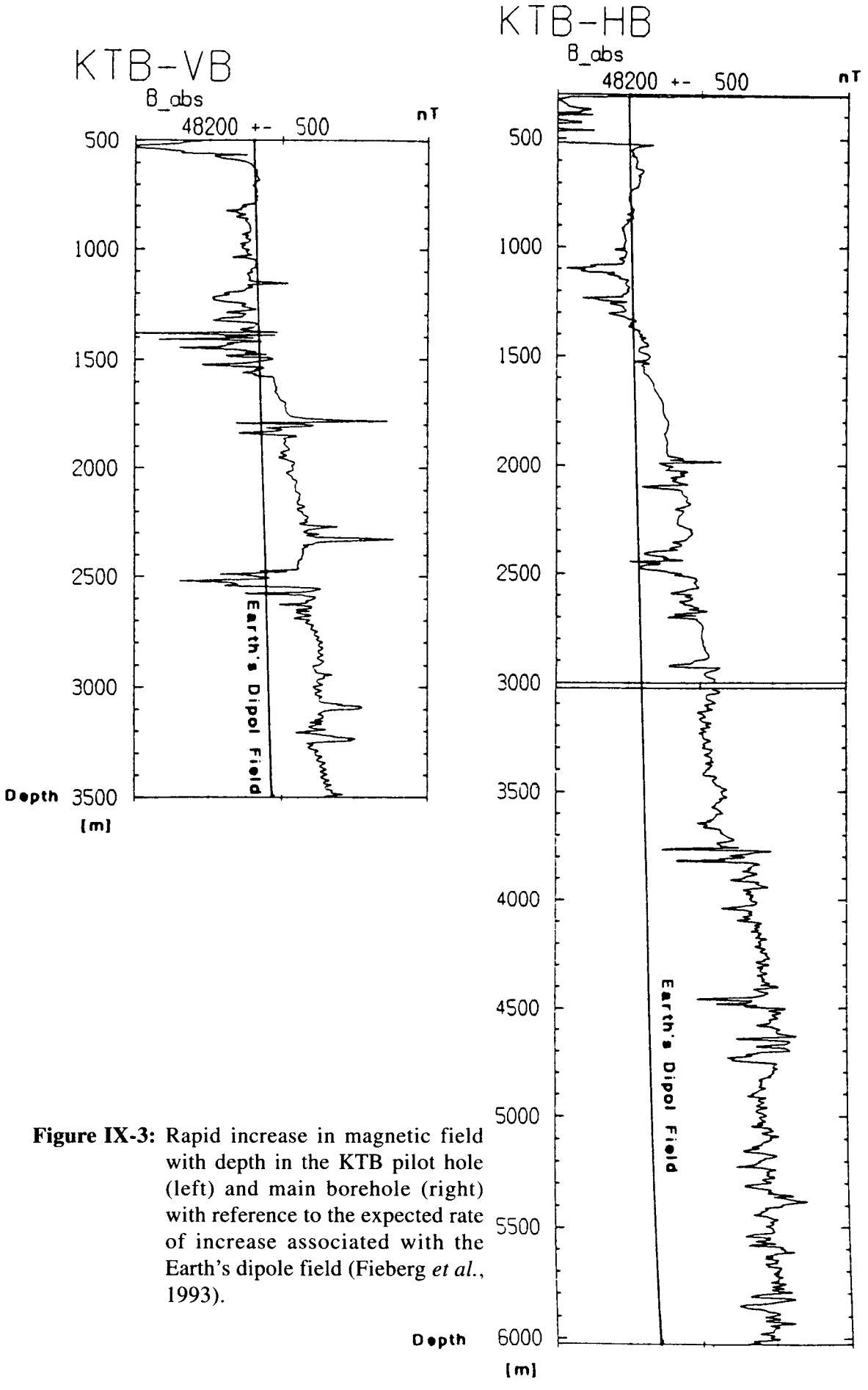

Figure IX-3: Rapid increase in magnetic field with depth in the KTB pilot hole (left) and main borehole (right) with reference to the expected rate of increase associated with the Earth's dipole field (Fieberg *et al.*, 1993).

Total magnetization is the sum of induced and remanent magnetization. Two types of remanence exist, stable and viscous. Stable remanence is in the direction of the Earth's magnetic field during cooling below Curie-temperature, whereas viscous remanence is in the present field direction and adds to the induced magnetization. Viscous change is probably thermally activated and therefore should become more important with depth. An enhancement of the induced magnetization may stem from the Hopkinson-peak in magnetic susceptibility of ferri-magnetic (magnetite, pyrohotite) and anti ferromagnetic (hematite, ulvite) minerals.

Crustal Thermal Regime

Although temperature is one of the most important parameters needed to understand geodynamic processes in the crust, the thermal gradient in the crust is not well known. Estimates of vertical heat-flow are determined from temperature gradients in shallow boreholes and thermal conductivity. These observations are, in turn, used to estimate the temperature at greater depths. The temperature gradient is altered by the effect of paleo-temperatures which can only be determined through scientific drilling. Paleo-temperatures yield important constraints for current climate models. Additionally, the depth extrapolation of the surface heat-flow is usually restricted to pure heat conduction models. Other mechanisms like fluid convection or refraction can be obtained from measurements of the magnitude and direction of the temperature gradient around a deep borehole.

Temperature in the transition zone from lower crust to upper mantle is the most important physical parameter controlling geochemical processes including mass and energy transport. Deep boreholes offer the possibility to improve present estimates of geotherms in this region which in turn lead to a more realistic modelling of these processes.

Key issues include the distribution of heat sources, mechanisms of heat transfer and the temperature field of the lower crust, specifically:

- the geotherm and heat flow and from the surface to the bottom of the hole,
- the seismic velocity structure of the lower continental crust,
- an estimated geotherm for the uppermost mantle.

With this information, the distribution of heat sources can be derived and the dominating heat transfer mechanism can be identified, from which the temperature field can be estimated. In addition, information about the petrologic nature (in terms of rock type) of the crustal realm in question can be obtained.

The flow of fluids at depth is critically dependent on the existence of sufficient permeability (see Section VII). It remains unclear, however, how long fluid circulation can prevail in the lower crust. As mineral deposition might seal existing permeability, it is unclear to what extent lower crustal seismicity (a rather rare phenomenon) can create new pathways for fluid circulation. In essence, the prerequisites for significant convective heat transfer in the lower crust are poorly known and great research efforts are needed to shed light on the many open questions.

A deep borehole offers the chance to obtain a more constrained estimate of temperature distribution through the lower crust and upper mantle than was previously possible from heat flow measurements at the surface alone. If sufficiently reliable P-wave velocities in the lower crust below the hole are available the relationship between P-velocity and radioactive heat production (Rybach and Buntebarth, 1982) can be used to estimate the degree of heat production in the lower crust. The temperature field in the crust between

the bottom of the hole (BH) and the Moho can be calculated on the basis of the BH temperature and gradient, the distribution of heat sources, A(z) and some estimates of the thermal conductivity. In the presence of a significant convective heat-flow component, coupled heat and mass transfer must be considered (*e.g.* Clauser and Huenges 1993b, Kohl *et al,*. 1993). The comparison of the calculated Moho temperature with independent estimates (*e.g.,* from xenoliths geotherms) provides a challenging check.

Comparison of the Moho temperature predictions from heat-flow observations and xenolith-geothermobarometry, the temperature across the Moho boundary can be estimated. Boreholes located in volcanic areas provide the possibility to compare geotherms derived from heat-flow measurements with those obtained from the analysis of temperatures and pressures of equilibration of mineral assemblages in xenoliths. An important part of this experiment is also the study of elastic wave velocities of xenoliths measured in laboratories using the technique of petrophysical modelling for the inversion of seismic data. This reduces the number of parameters involved in the inversion procedure giving an estimate of the special distribution of rock types and heat production in the lower crust. Xenoliths of lower crust and upper mantle rocks brought to the surface in basaltic and kimberlitic magmas provide direct information on the composition and physical properties of the deep lithosphere.

The Role of Scientific Drilling

A scientific drill-hole provides the opportunity to perform unique experiments that investigate geophysical parameters on different spatial and temporal scales.

Laboratory experiments on core samples. This provides microscale (cm) measurements of physical properties of rock samples under controlled thermodynamic conditions. That is, compressional and shear wave velocity, seismic absorption, density, electrical and thermal conductivity, magnetic susceptibility and magnetization can be measured under a wide range of conditions presumably representative of those at depth.

Borehole Measurements. This provides mesoscale (m) measurements using relatively conventional logging measurements and makes it possible to find physical properties under actual the in-situ conditions (and thus help constrain the laboratory experiments). Additionally special borehole surveys investigate properties available no other way such as *in situ* stress, temperature, pore pressure, permeability, etc. In this way borehole logging links rock physics measurements in the laboratory to larger scale geophysical surveys and the properties of the crust, in general.

Measurements between boreholes and the surface and crosshole experiments. Such measurements at the macroscale (km) allow sampling of large volumes of rock. Placing sensors in the borehole obviously opens a third dimension to geophysical surveys normally restricted to the Earth's surface. Seismic transmission and reflection tomography proved to be a very useful tool to detect anomalies within a rock volume. Geoelectric methods can also be used (*mise-a-la-masse*-experiment) to map conductive geological structures (faults) between the borehole and the surface.

Rock properties cannot only be measured at different scales but also under different ambient conditions, *i.e.*,

a) Undisturbed conditions of the crust by borehole-surface or crosshole measurements.

b) Under conditions disturbed by the existance of the borehole (borehole logging).

c) Under conditions at free surface or simulated subsurface conditions (drill cores).

In summary, quantitative relations between geophysical parameters at all scales and under different ambient conditions are to be established for a successful calibration of surface profiles.

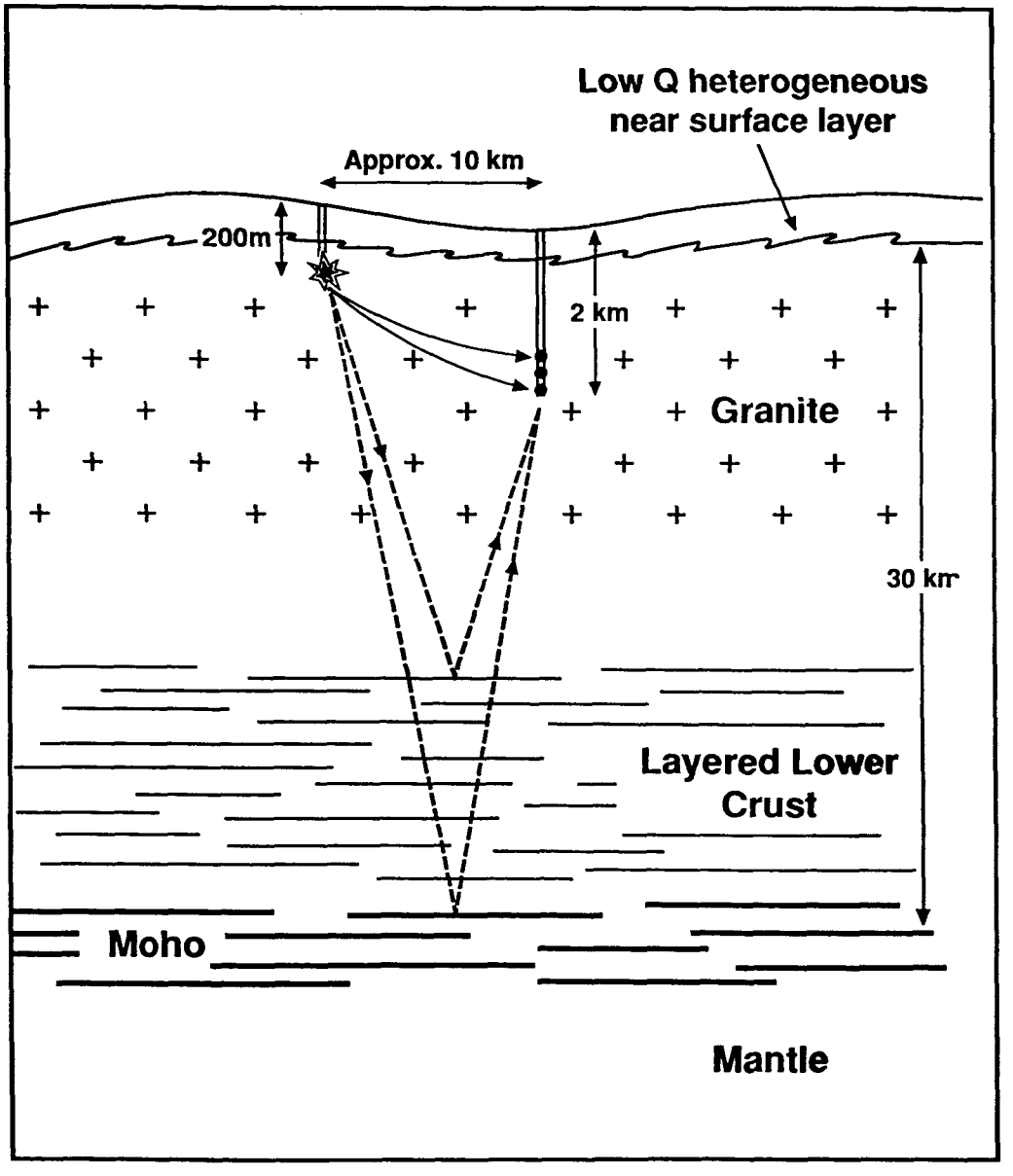

Figure IX-4: Schematic diagram illustrating that fact that seismic waves emanting from the bottom of a relatively shallow borehole (~200 m depth) and being received in a borehole at somewhat greater depth (~2km) permits the ray paths to avoid the highly attenuating rocks in the upper several hundred m of the crust (Warner, 1993). Note that this diagram is not drawn to scale.

High Resolution Images of the Lower Continental Crust and Crust-Mantle Boundary

Conventional crustal seismic surveys typically utilize frequencies in the range 10 - 20 Hz, corresponding to wavelengths of a few hundred meters and Fresnel zone diameters of several kilometers. Problems related to the scale of heterogeneities in the crust/mantle transition zone can only be answered by improving both, lateral and vertical resolution which is only possible if much higher seismic frequencies are used for imaging.

Seismic investigations of deep crustal and upper mantle structures utilizing surface measurements are constrained by the horizontal resolution (given by the Fresnel Zone, in near-vertical reflection studies typically several kilometers) and by the vertical resolution (given by 1/4 off the dominant wavelength, typically 50-100 m). This discrepancy in resolution (~1:10) results in long horizontally correlated phases in the observed seismic wave fields and therefore very often in one-dimensional crustal models.

Placing a seismometer (or seismometer array) deep in a borehole with seismic sources in dense intervals at the surface provides a unique opportunity to significantly increase both, the horizontal resolution (being closer to the target) and the vertical resolution (broad band signal). Additionally, the strong discrepancy between horizontal and vertical resolution will be reduced. Such a higher resolution is necessary in order to study fluid-filled layers, tectonic shear zones and magmatic intrusions.

Recently a borehole-borehole experiment was performed successfully (Warner, 1993). In this experiment P-wave near-normal incidence reflections from the lower crust and Moho with frequencies in the range 15-180 Hz were obtained (Fig. IX-4, IX-5). S-wave reflections were obtained with frequencies up to 70 Hz. This was achieved by placing 20 kg explosive sources in ca. 200 m deep boreholes in granite and recording using accelerometers, hydrophones and geophones in boreholes up to 2000 m deep. The data were simultaneously recorded on a surface geophone array. The maximum frequency observed with a deep source and surface receivers was 80 Hz. The maximum frequency observed with a surface source (~10 m) and surface receivers was 40 Hz. It is clear that much of the high frequency loss in conventional reflection experiments over crystalline terrains occurs within the top few hundred meters of the Earth. Seismic experiments, both near-normal incidence and wide-angle, performed in arrays of relatively shallow boreholes can obtain significant improvements in bandwidth.

Requirements:

The proposed high-resolution imaging method has the potential of even higher resolution by further development of source and receiver characteristics by using an array of shallow and intermediate depth boreholes and through development of high energy broad-band sources and receivers (accelerometers) and processing techniques.

Three-Dimensional Seismic Imaging of the Crust

Including a deep borehole into the configuration of seismic sensors at the surface offers the opportunity to utilize three-dimensional array techniques. With adequate source offsets, there is the possibility to observe refracted phases from midcrustal discontinuities as first arrivals which are difficult to detect in surface recordings because they are not only masked by background noise but also by coda waves from earlier phases. This is especially true for observations from the Conrad-discontinuity.

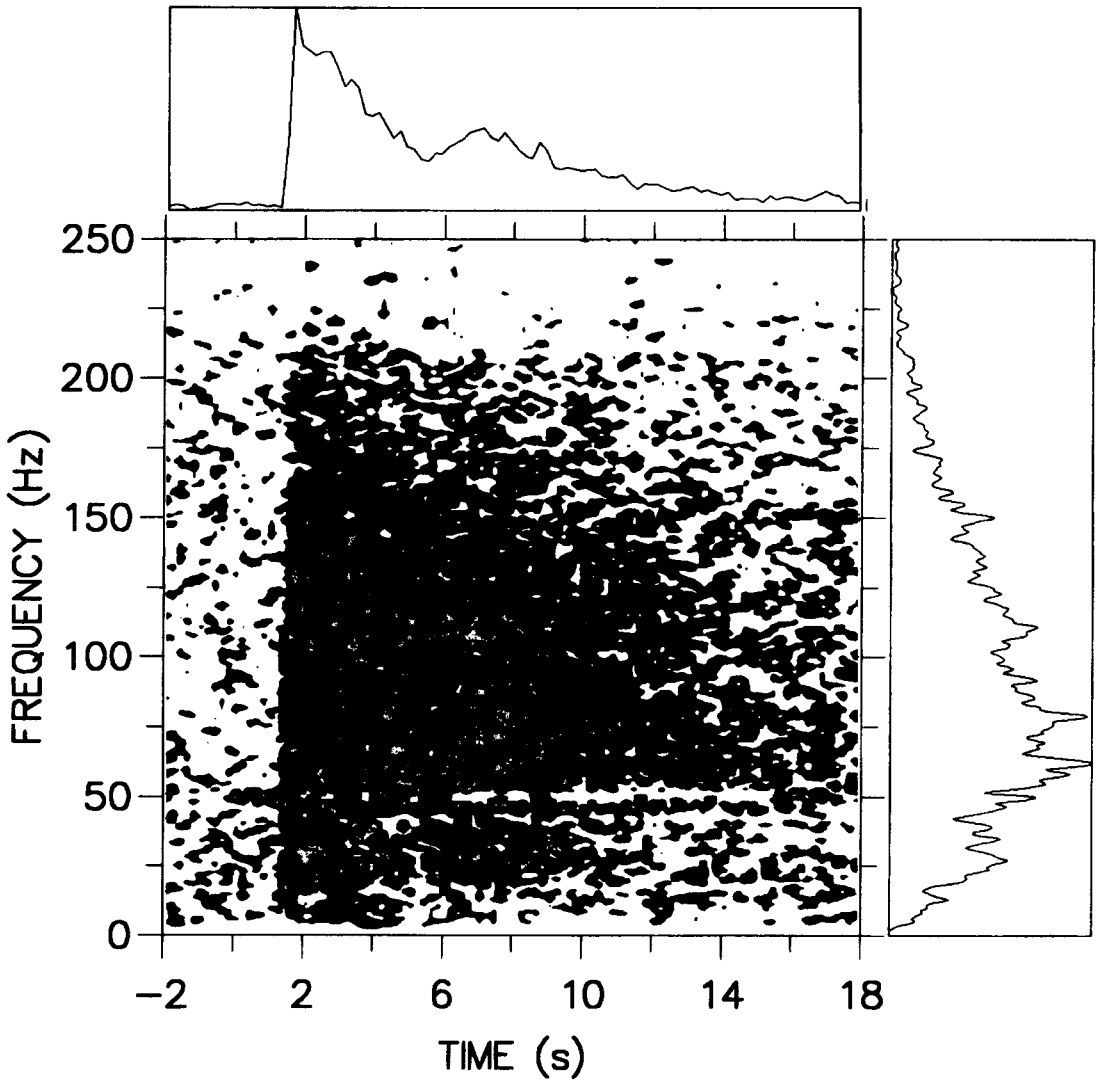

Figure IX-5: Frequency spectra as a function of time for seismic records obtained in the experiment pictured in Fig. IX-4. Note that energy with extremely high frequencies were obtained even from times corresponding to the lower crust and Moho (Warner, 1993).

The anisotropy of seismic waves travelling in the vertical direction usually cannot be resolved from surface measurements. From travel time observations at different depths one can determine the direction of the wavefront and the corresponding velocity. Finally, the vertical dimension of a seismic array can be used to receive direct information about the absorption of seismic waves. This information allows the calibration of seismic tomography results for the seismic quality factor Q, which have been published for many areas of the continental crust.

A 3D seismic reflection survey at the surface is certainly the backbone of geophysical interpretation of the borehole environment. It is suggested to use the borehole to integrate the Vertical Seismic Profiling (VSP) and Moving Source Profiling method (MSP) into this survey.

Requirements:

No special requirements for borehole conditions or instruments, except that the maximum depth should be no more than 8 - 10 km and that the temperatures should not exceed 250°C.

Improved resolution and calibration of lower crustal electrical conductivity through measurements in deep boreholes

The best way to get an improved image of the lower crustal conductivity distribution is to employ deep boreholes either as sites for probing deep sources and/or deep receivers (Fig. IX-6). Only in this way can we eliminate the screening effects of conductive overburden using deep holes in the range of 5-10 km and thus image more closely the transition zone between upper and lower crust, with a much better resolution than could be obtained through the surface measurements alone. Experiments can be performed as controlled source experiments or as natural source experiments. The experiments can be carried out essentially with existing techniques in deep boreholes as long as the temperature is not too high.

Requirements:

For controlled source measurements two experimental procedures are used: vertical electric current dipole source in the hole and horizontal electrical dipole source at the surface.

Magnetization of lower crust and upper mantle

Borehole magnetic measurements in continental deep drilling (KTB, Sancere Cuoy) have shown that the magnetic field strength growths stronger with depth than the Earth magnetic dipole field. Thus, available observations in deep boreholes further emphasize the hypothesis originally suggested by surface and airborne measurements, that the lower crust (and possibly also the upper mantle) contain more magnetization than was expected from consideration of only the Curie point of magnetite from metallic iron. It is strongly recommended that Earth magnetic field observations are carried out in existing and future super-deep boreholes, and if possible in regions of different strong magnetic anomalies with surface and airborne control.

It is essential that the borehole measurements are complemented by rock magnetic laboratory measurements to investigate the carrier of magnetization (FeS, Fe3O4, Fe/Ti Magnetite, Fe Curie-points), to study the dependence of induced and remanent magnetization of pressure and temperature, the magnetic viscosity and its dependence of pressure and temperature, anisotropy and its tectonic significance, homogeneity of magnetic parameters, thermoremanence and its relation to fluids, hydrothermal processes, alteration (effects of fluids), petrologic studies of xenoliths.

Requirements:

- Uncased borehole at great depth (approaching 10 km).
- Development of borehole magnetometer (temperature shielded) for measurements of magnetic field and susceptibility.
- Improved laboratory equipment (high P, high T conditions).
- Airborne and surface surveys of magnetic anomalies.

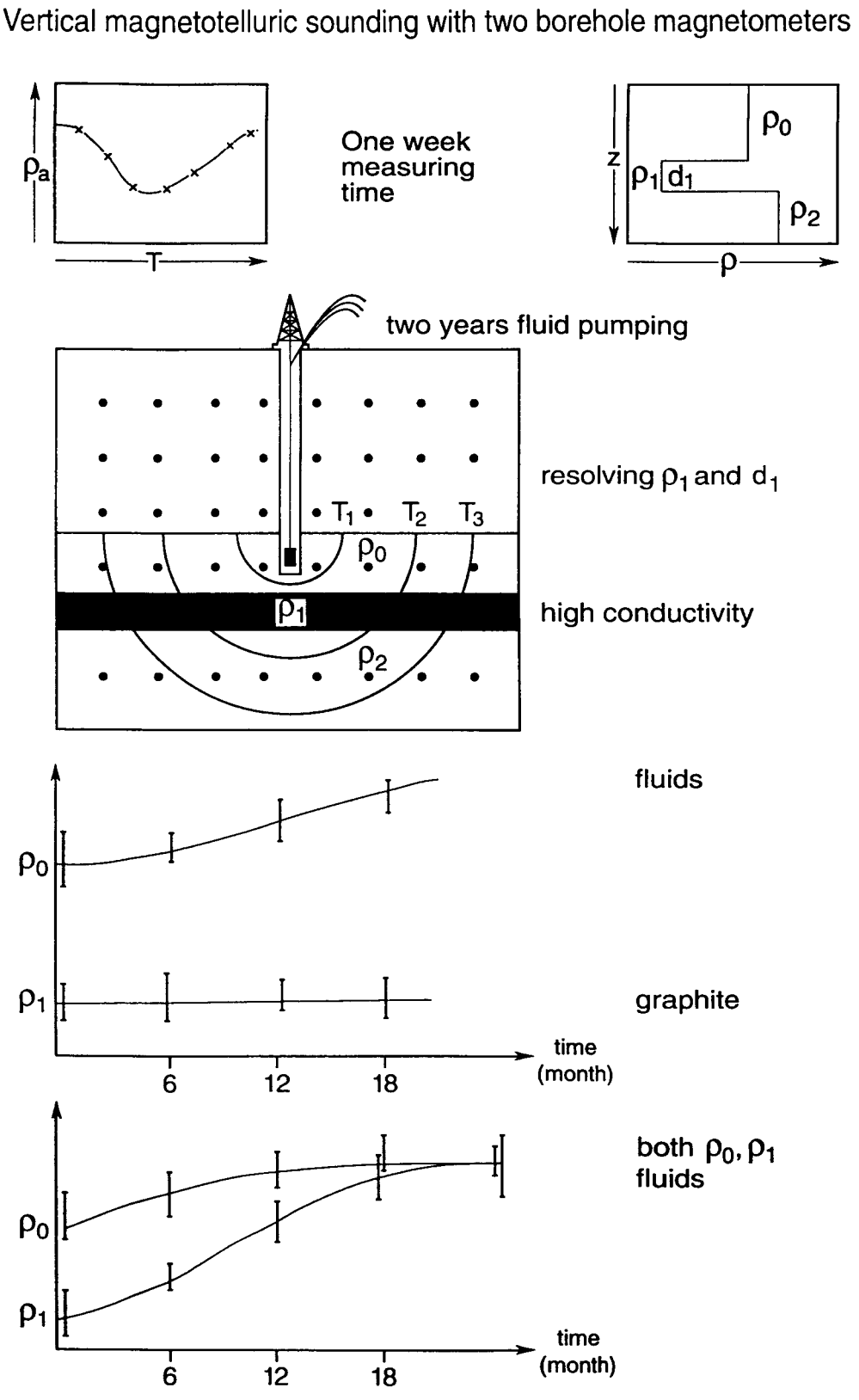

Figure IX-6: Schematic illustration of the fact that high conductivity zones at depth can be delineated using magnetotelluric sounding much more precisely if electrical sources (and/or receivers) were deployed in boreholes penetrating through the relatively high conductivity rocks near the Earth's surface.

Vertical Magnetotelluric Profiling (VMP)

Standard electrical logging experiments cannot investigate large-scale geoelectrical anomalies. Instead, specially designed methods have to be developed to resolve layers of low electrical resistivity which are thin but have a large lateral extent. VMP provides such a method which uses two magnetometers in the borehole. It yields the same apparent resistivity curve as the magnetotelluric method without measuring the electrical field. The experiment has been successfully applied in the KTB pilot hole.

Another experiment could connect a VMP-survey with a fluid pumping test in the deep crust lab. During the fluid pumping experiment, a continuous extraction and recharge of fluids will change the natural resistivity distribution in a range of about 1 kilometer around the borehole. A VMP experiment repeated every 6 months will reveal the temporal variations in electrical resistivity which could help to solve the fluid/carbon controversy.

Borehole Observatory

Continental drilling projects contain three phases which are essential for successful geophysical calibration:

- A detailed pre-site survey including a 3D-reflection profiling as the backbone,
- The main drilling phase with continuous logging and coring at critical intervals and
- Experiments after drilling using the borehole as a deep crustal observatory.

The deep crustal borehole can provide unique measurements on long-term variations of physical parameters including the reaction of the crust to natural physical fields (*i.e.*, tectonic stress, tidal forces. Borehole tilt measurements are used to study the time-dependent rheological behavior of the crust. It should also be possible to study the reaction of the crust to artificial sources of excitation (pressure change in borehole liquid, long-term pumping test, electrical current injection). Acoustic emissions can be observed in the borehole under natural conditions and by pressure-stimulation. Zones of weakness (shear zones or critical stress concentrations at the borehole wall) can be localized by high acoustic activity.

Fluid migration, transmissivity of the crust, and change in fluid composition can be studied by a long-term pumping test and in-hole and cross-hole observations of fluid flow, measurements of electrical conductivity, self potential and chemical analysis of borehole liquid. The deep crustal observatory also allows one to investigate the temporal changes in the temperature gradient and its relation to heat transport and the observation of temporal changes of the vertical gradient of the magnetic field to understand the origin of telluric disturbances at the surface. Finally, a number of seismic experiments and long-term seismological observations can be made under unprecedented favorable noise conditions. These should reveal high-resolution images of crustal reflectors as well as the depth dependence of seismic waveforms.

Technological Needs

One of the most important technological needs for deep scientific drilling projects (or those drilled in areas of unusually high temperature at depth) is to increase the temperature

at which borehole geophysical instruments can operate. At temperatures of 250-300° C, new electronic components and even completely new principles of instrument design are necessary. But it is exactly this combination of new instrumentation with exciting new scientific ideas which led to progress in science in the past.

A number of specific technical needs include those for data transfer from downhole instruments to the surface, logging units with a variety of new instruments, and the modification of conventional instruments to operate under high temperatures.

Use of Drill Bit Vibrations as a Seismic Source

The drill bit method is an excellent example to demonstrate the technological needs of promising new measurement techniques. Over the past few years this technique, often termed Seismic-While-Drilling, has been developed. The seismic signal produced by the drill bit is recorded by a sensor attached to the top of the drill string (named the reference or pilot signal) and also remotely by geophone arrays deployed on or near the surface. It is extremely important to incorporate the interactions of drillstring wave propagation with propagation in the rock to accurately model drill bit wavefields. No downhole instrumentation is required and the data recording does not interfere with the drilling operation.

The drill bit method includes some important new applications such as real-time seismic P and S velocity logs (inverse VSP), real-time reflection images (prediction ahead of the bit) and seismic images of features several wavelengths away from the wellbore. In addition, there are several uses of drill bit data that are still in the experimental stages, but could be of immense benefit to drillers, particularly in unknown crustal geology. These include real-time measurements of shear and compressional rock impedance, real-time measurement of downhole drilling efficiency and real-time indicators of anomalous vibrations which can predict cone failure, tooth wear, and impending stuck pipe.

Despite the promising aspects of the drill bit method, no applications of the drill bit method in crystalline rock and few examples in sedimentary rock have been published which is an indication of the technical problems involved in implementing the technique. A scientific drilling program offers the opportunity to overcome these difficulties by combining new drilling parameters with sophisticated data acquisition and processing concepts.

Conclusions

In general, geophysical surface measurements offer well-established, non-destructive remote-sensing methods to explore the interior of the Earth. However, the development of reliable calibration criteria from a representative set of scientific boreholes would shed new light on the geological interpretation of thousands of kilometers of existing crustal geophysical profiles thereby significantly increasing our confidence in the interpretation of future surface measurements.

Further Reading

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X. Composition and Properties of Sub-Continental Upper Mantle

Introduction

The composition of subcontinental upper mantle is well known from xenolith samples, but is poorly understood with respect to ist genesis, polyphase history, mechanical and thermal state in different geodynamic settings. This limited level of knowledge, in comparison with oceanic mantle, results from the scarcity and small dimension of outcrops. A better understanding of the nature and evolution of the continental upper mantle will have direct bearing on three major dynamical processes of the Earth:

- The late orogenic thinning (and initial stages of sedimentary basin formation) of continental crust which was initially thickened by collision processes.
- Mechanical coupling between the mantle and the crust during mountain building, especially at plate boundaries.
- The intense mass transfer of mantle materials to the lower continental crust and ist effect on heating of the crust. In turn, this causes melting of the lower crust, leading eventially to the presence of magmatic material in the upper crust.

Obtaining continuous samples of unweathered core from moderate-depth boreholes sited at critical locations can help address key questions about these processes.

Key Questions

Properties of continental upper mantle are deduced exclusively from geophysical observations (seismic, gravity, magnetics) which give only mean, bulk values. Some widespread geochemical and petrological information are obtained from the small samples transported to the surface by Kimberlite pipes and basalt lavas rapidly expelled from the matle to surface. Also, a few peridotite massifs, generally connected with a rift stage of crustal development, are expelled to the surface by later tectonic processes. They tive kilometer scale observations. Tectonic emplacement, weathering, and oxidation has generally transformed (or eliminated) some of the deep-seated properties of these mantle pieces. This is expecially the case for high temperature flow structures, deep fluids and primative gas content. Currently, these scarce pieces of mantle are the only place on Earth where we can make direct in situ and continuous observations, measure properties and calibrate geophysical observations to aid the interpretation of indirect observations made from the surface.

The major/present uncertainties concern:

- Heterogeneity within the mantle: ist nature (petrological or seismic, gradual or sharp transitions) and the dimensions of heterogenous domains.
- Ability of the mantle to record different stages in the history of the long evolution of continental lithosphere.
- The rheological evolution of the mantle: Homogeneous or localized deformations at different stages, different levels and thermal conditions.
- Trapping of deeper level anatectic melts (basalts) and diffusion, contamination process and transformation of upper mantle by these transfer.
- Fluids and gas trapped in minerals of the mantle: oxygen fugacity, permeability of the mantle.
- Differential transfer of elements assisted by fluids.

In complement to surface investigations boreholes are necessary tools for:

- Obtaining a continuously cored and logged section of mantle to study.
- Correlation between laboratory measured magnetic, electrical and seismic properties and their larger scale geophysical expression in the field by use of different penetration or directional measuring with logging tools, VSP, cross-correlated seismic experiments using the borehole and surface.
- In situ composition of fluids (volitles, melts) not contaminated or removed by metoric water and the oxygen fugacity of uncontaminated mantle samples.
- Study the geochemical gradient in "mobile" element (Li, Rb, Ba, Cu ...) transfer using samples not affected by surface alteration or interaction with a lava (volcanic) as in the xenoliths of basalts or kimberlites.

Strategy of drilling program

The outcropping Moho is a three dimensional surface which is tectonically transported to the surface of the Earth and is always tectonically sheared. It is a 'tektonic Moho'. Coring multiple boreholes in subcontinental upper mantle at different sites is desired to obtain 4 - 6 continuous sections of subcontinental mantle from different regions. The choice of these sites in 'fossil mantle' is controlled by identification of the structural position of the 'tectonic Moho' for each site. Several different geodynamical situations should be successively investigated.

Specific Examples of Possible Drill Sites

The Ivrea zone (southern Alps - Italy), Figs. 1, 2

Four outcrops of peridotites are known in this thick slab of continental lithosphere which (before ist exhumation during alpine collision), underwent an important tectonic extension at the end of Hercyian orogeny (290 - 270 Ma) (with an important thermal transfer associated with underplating of gabbro in the lower thinned hercynian crust). This famous and well-studied area is exposed in the Balmuccia, and expecially in Baldissero, massifs where very 'fresh' peridotites of subcontinental mantle in a well-defined structural position and lower-Paleozoic age (500 - 280 Ma).

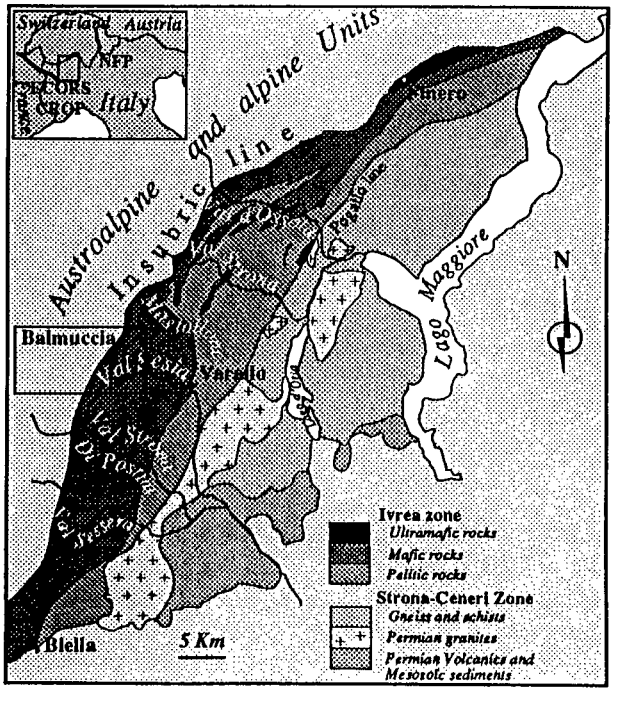

Figure X-1: General map of Ivrea Zone (Barruaol and Mainprice 1993)

Southern Spain and North Morocco, Fig. 3

The Betic-Rif alpine chain presents sections of mantle thrusts of older age than in the Alps with transition from spinel to garnet peridotite. The Ojen massif in Betics (Spain)

and the Beni-Bouchera massif in Rif (nothern Morocco) are the thickest and best preserved slabs.

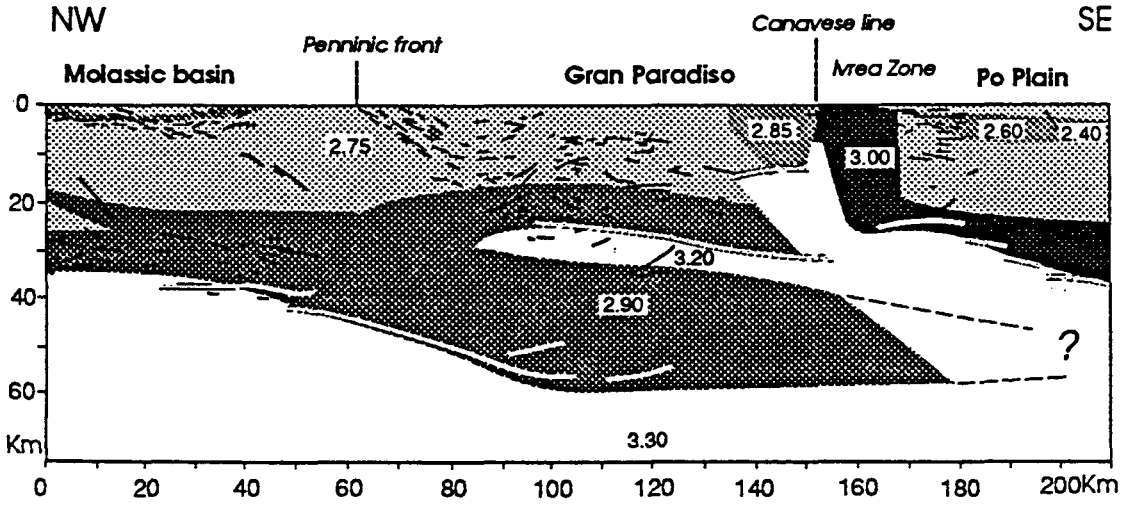

Figure X-2: Tectonic section of the Western Alps based on the ECORS-CROP seismic profile and gravity data (Nicolas et al. 1990). Numbers are density in g/cm3

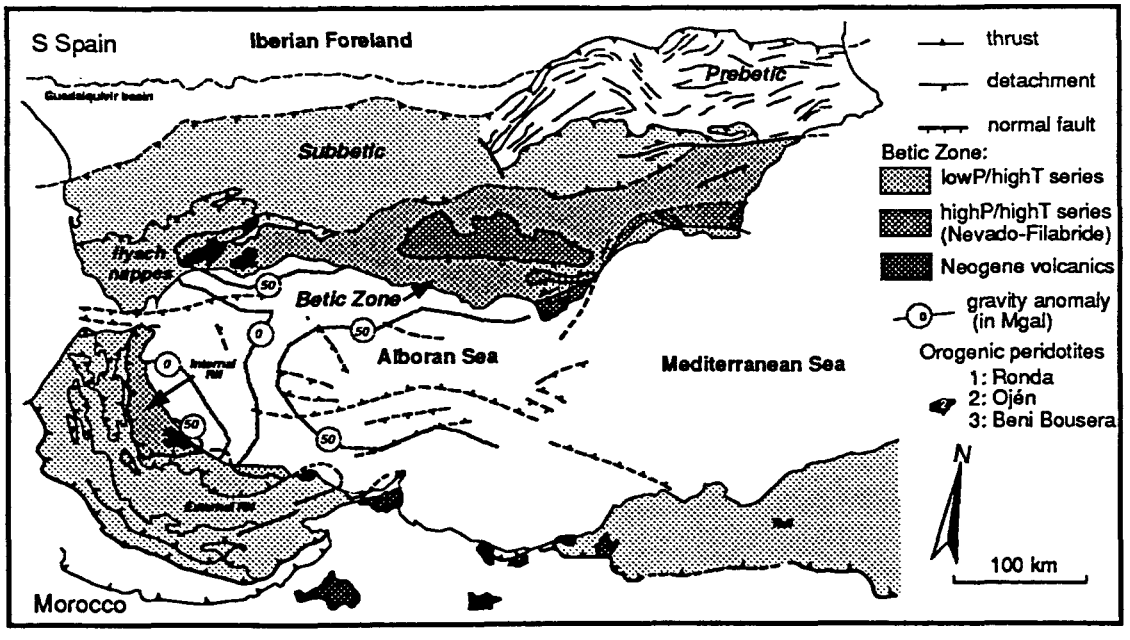

Figure X-3: Tectonic map W Mediterranean (Van der Wal, 1993)

Zabargad Island, Red sea, (Egypt), Fig. 4

Here there are exposures of new mantle intruding a very attenuated crust, (and driving the rifting event at 20 Ma) preceeding the opening of the Red Sea opening. It could be a

good site for extremely "fresh" peridotites in a well controlled rifting geodynamic context, of very recent age.

Hokkaido Island (Japan), Fig. 5

Peridotites of the Horoman massif in the western part of Hidaka metamorphic belt (Horoman massif) could represent the mantle rocks at the floor of a Tertiatry island arc or active margin arc. Ist thermal and magmatic connection with the gabbros and metamorphism which affect the deep part of this crustal arc section, offer a possible site with different geodynamic situation and extremely "fresh" periodotites of more than 3000 m of thickness.

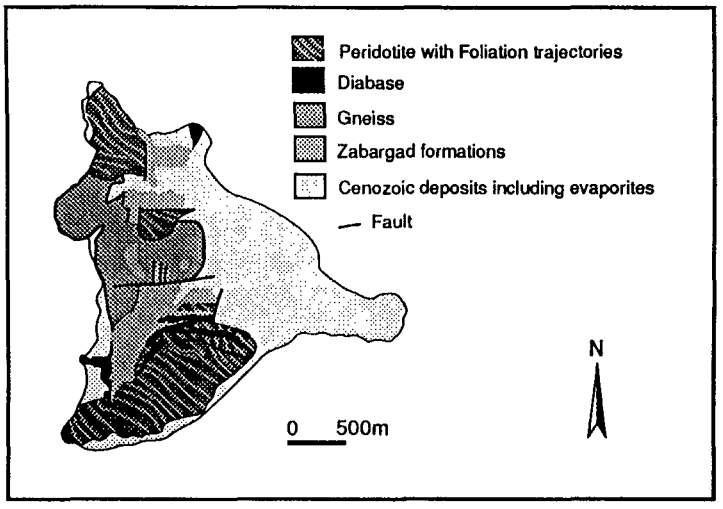

Fig. X-4: Zarbargad Island, Read See (Nicolas et al. 1987)

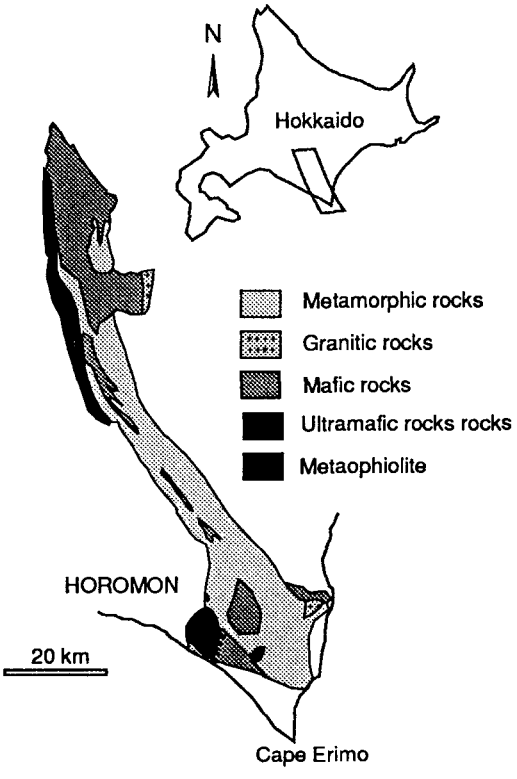

Figure X-5: Horoman peridotite complex (Komatsu et al. 1968)

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XI. The Deep Biosphere

Introduction

Although thermophilic bacteria have long been known to exist in hot springs, fluids exhumed from depths up to 2 km have revealed the existence of subsurface bacteria in a suprising number of environments. Over the past decades we have begun to appreciate the ability of organisms, particularly microorganisms, to adapt and develop in extreme environments (Wilson, 1992). Pedersen (1993) stated the situation as follows: "Some 50 years ago it was generally anticipated that microbes in the sea only could survive in the uppermost meters. Now we know that the microbial ecosystems of the seas extend down into the deepest sea. Approximately ten years ago, it was generally proposed that microbes only could thrive in the uppermost meters of the ground. It now seems that we have to update our knowledge about the subsurface in the same way as for the sea. This review presents an array of independent reports suggesting that microbial life is widespread at depth in the crust of Earth - the deep subterranean biosphere. The obvious consequence is that microbes may be involved in many subterranean geochemical processes, such as diagenesis, weathering, precipitation, and in oxidation or reduction reactions of metals, carbon, nitrogen and sulfur - just as they are in most terranean environments."

One of the ultimate questions of all science is where and how did organic life originate on planet Earth and what are the physical conditions (pressure and temperature) that can sustain life. Following the classic work of Brock (1978) it became clear that organisms could survive to temperatures up to 100°C. These are the thermophilic organisms found in surface and near surface thermal water. Lowenstam and Wiener (1989) first showed the vast array of biological processes in the surface environment which promoted the formation of common minerals. Often such minerals are not in thermodynamic equilibrium with their macroenvironment but reflect conditions in the living cell (see Fyfe, 1986, 1987). For many years, petroleum geologists, recognized that deep diagenetic processes involving organic debris might involve subterranean organisms. Very recently, Stetter *et al.* (1994) reported the discovery of hyperthermophilic archea at depths to 3 km in hydrocarbons from the North Sea and North Slope, Alaska. Some of these bacteria were found to be quite similar to those found in thermal vents. Stetter *et al.* suggest that these thermophiles may play an important role in mioconversions of crude oil fractions at relatively high temperatures.

Most near surface rocks have significant (5-20%) porosity. Almost all deep rocks contain aqueous fluids and increasingly we discover deep flow of surface fluids (to 8 km depth in the KTB borehole, for example) and there have been spectacular discoveries of such deep flow with associated cooling processes, in ocean ridge environments. If there is porosity and flow of fluids with some appropriate nutrients (it is almost impossible to avoid!) and if temperatures are appropriate, why should there not be deep microorganisms?

This question became critical when it was suggested that there might be bio-corrosion processes in deep nuclear waste repositories. These ideas initiated a number of drilling projects to search for such bacteria. This work has recently been reviewed by Pedersen (1993) with spectacular conclusions. In many such drilling studies, from depths of a few hundred to a few thousand meters, life, often prolific, has been discovered. The most spectacular case at present is from a drill hole in Gravenburg, Sweden, where, at a depth of 3900-4200 m, thermophilic and fermenting bacteria were discovered.

At this time the temperature limit observed for life is about 110°C. Thus, in any crustal region the possibility of life must exist to depth of 4-5 km depending on thermal gradients or in subduction zone environments with very low thermal gradients to even much greater depths. Thus, the biosphere has become much deeper. Biomineralization and bio-processes may thus operate over a depth range never before investigated. These discoveries lead us to ask two fundamental questions:

- What is the temperature limit of life?
- Could life have originated in the sub-surface during the early history of the planet when the surface environment must have been extremely turbulent?

Research Program of the U.S. Department of Energy

The United States Department of Energy's Office of Energy Research has, since 1985, tested and applied aseptic sampling protocols in hydrogeologic systems that include the Atlantic Coastal Plain, Snake River basalts and interbeds in Idaho (Fig. XI-1), Tertiary sediments in Washington State, and the Taylorsville Triassic Basin in Virginia. Sampling has ranged from depths of a few hundred to several thousand meters. To date, this research is probably the most comprehensive international scientific effort in the deep biosphere. DOE's deep microbiology research program, which is a part of the DOE Subsurface Science Program, is now addressing what is the most challenging question about the deep biosphere: the origins of bacterial communities. DOE seeks to determine whether deep microbial communities are the progeny of communities that have been isolated in the geological past, or whether they have been transported more recently to the sites where they are found. These questions, since the early 1900's, challenged the geological and biological sciences. For example, Bastin (1926) questioned the origins of subsurface bacteria and whether a satisfactory answer could ever be realized. Over sixty years later, Sidow *et al.* (1991), while examining DNA in Miocene sediments at Clarkia, Idaho questioned whether the sequences they found were derived from bacteria isolated since the Miocene, or whether they had more recently "penetrated" the sediments.

To address such questions, DOE's Office of Energy Research has organized a multi-institutional team of about 30 geologists, molecular biologists, geochemists, and microbiologists. Following exploratory studies in a Triassic Basin in Virginia, DOE is now conducting studies at two sites in the Upper Colorado River Basin. DOE's research plan is currently the most definitive effort to examine deep microbial origins. This research effort systematically addresses important questions about the origins of deep microbiota, the product of nearly two years of work by DOE, university and national laboratory scientists. This research is attempts to better understand the paleoenvironments and geological controls in order to test hypotheses regarding long term in situ survival and regional transport and microorganisms. Extracts of the DOE plan (Wobber, 1992) have been used extensively to develop this chapter.

To date, studies of deep microbiology have demonstrated the presence, abundance, diversity, and metabolic characteristics of subsurface microorganisms at a variety of sites. In summary, what has been found in research carried out by the U.S. Department of Energy at various sites around the U.S. include:

- Unexpectedly high populations (nearly equivalent to surface soil of culturable microorganisms were present in the aquifers of the Southeast Coastal Plain. Biochemical analyses demonstrated the presence of additional viable, but nonculturable, microorganisms.

- A strong relationship exists between population densities of chemoheterotrophic bacteria and porosity (bulk density) of the sediments, with the highest populations present in the sandy aquifers and the lowest in the less permeable aquitards.
- Some clay aquitards contained microorganisms that may have been the progeny of organisms associated with the sediments at the time of deposition.
- Molecular analyses, including restriction fragment mapping and ribosomal RNA (rRNA) sequencing, revealed some deep subsurface bacteria that were related to, but distinct from, characterized surface strains.
- The microbial community was very diverse, as determined by physiological and genetic characterization methods. High diversity was apparent both between and within geological formations.
- The greatest microbial diversity and highest in situ respiration rates were associated with relatively young groundwater, whereas the lowest estimated respiration rates were associated with groundwater ages calculated to be greater than 10,000 years.
- Chemoheterotrophic isolates and communities degraded a variety of organic contaminants, and some of the microorganisms had novel catabolic capabilities.
- The presence of aerobic heterotrophs, Fe(III)-reducing bacteria, and sulfate-reducing bacteria in core sediments suggested the occurrence of anaerobic microsites throughout the Middendorf aquifer, even though water analyses indicated that the aquifer is predominantly aerobic.
- Microbial populations and metabolic activities are, in general, much lower in unsaturated subsurface sediments and rocks as seen at the Idaho National Engineering Lab (INEL) (see Fig. XI-1), the Hanford, Washington site, and the Nevada Test Site, than in Southeast Coastal Plain saturated sediments.
- Populations of microorganisms and levels of metabolic activity were higher in sedimentary interbeds than in basalts at INEL, and were higher in paleosols than in pedogenically unaltered fluvial deposits at Hanford.
- Numbers of culturable microorganisms were three to four orders of magnitude lower than the total number of cells visualized by microscopy, indicating a high proportion of nonculturable cells in unsaturated sediments.
- Relatively higher microbial populations and activities in some of the calcic paleosols in the Ringold formation [4 to 10.5 million years before present (myBP)], coupled with the low vertical moisture recharge and low populations and activities in the overlying Hanford formation (13,000 to 790,000 yBP), suggest that the organisms in Ringold sediments may be survivors or progeny of microorganisms transported downward during the last flood event (13,000 yBP).
- The geochemical composition of confined aquifer groundwaters from Hanford indicated that biological sulfate reduction and methanogenesis dominated in different strata and were reflected in the compositions of the microbial communities.

In summary, significant microbial populations have been detected in a range of subsurface sediments and lithologies. However, microbial abundance, diversity, and physiological types varied considerably, depending upon environmental conditions (e.g., moisture content and sedimentology). Investigations of the origin of microorganisms in

deep subsurface environments is an exciting scientific challenge that should be vigorously pursued - focusing on the seminal issues of microbial transport, in situ survival, and interactions between microorganisms and their environment. These issues are considered critical to advancing understanding of the nature of microorganisms as they may have evolved over geologic time.

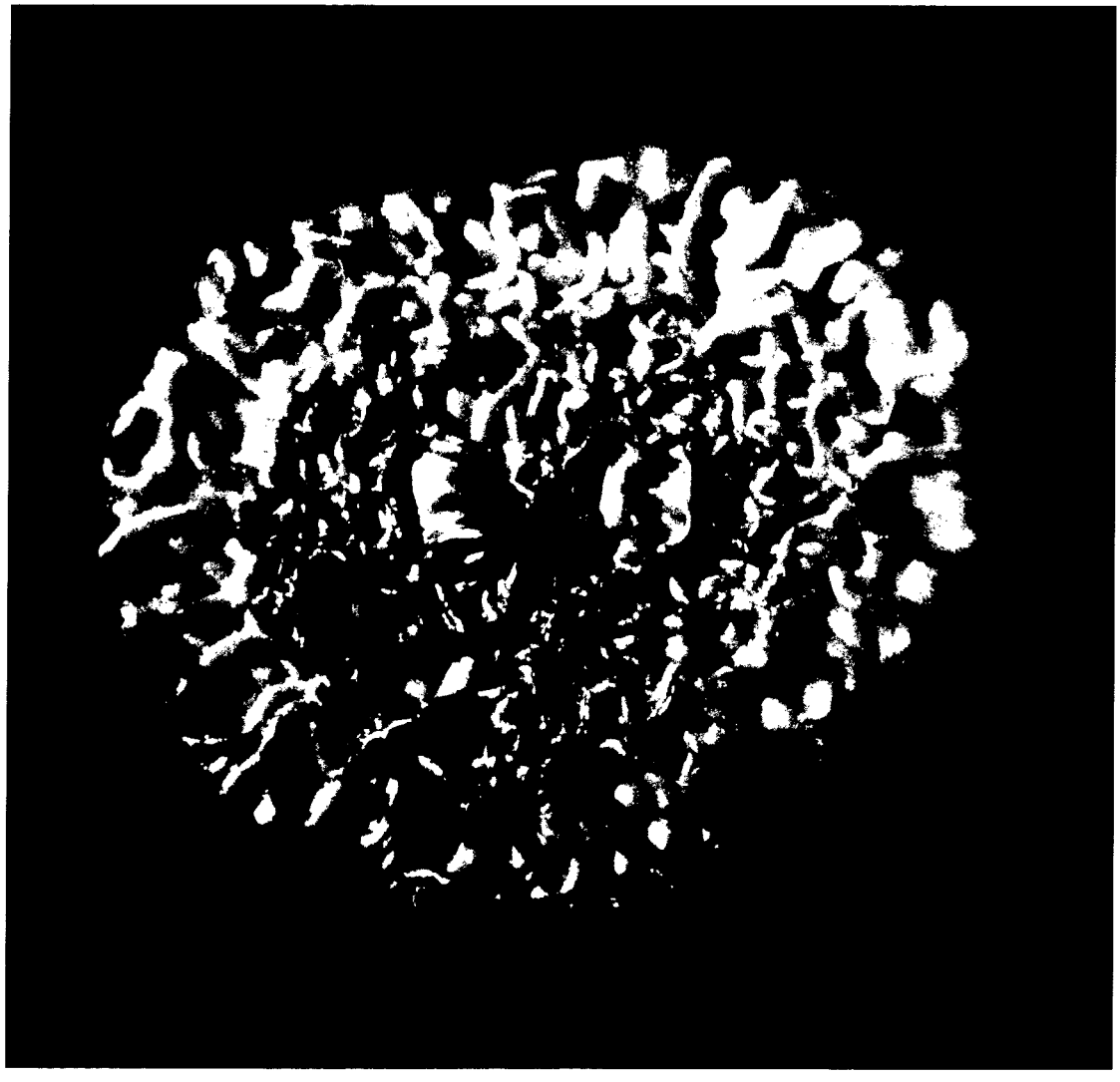

Figure XI-1: Colony of an actinomycelelike bacterium isolated from unsaturated sediment situated 122 m beneath the Earth's surface at DOE's Idaho National Engineering Laboratory.

Key Questions

When considering the existence of microbial life far below the Earth's surface there are a series of questions with large scale, far-reaching consequences. These include:

- Where is the bottom of the biosphere?
- What is the size and distribution of the subsurface biomass?
- How do subsurface bacterium live, evolve, migrate with time?

- Do subsurface bacterium interact with life forms at Earth's surface?
- What was the role of subsurface bacterium in the evolution of surficial life on Earth?
- What is the role of subsurface bacterium in geologic processes such as hydrocarbon generation and ore development?

Of course, these "mega-scale" questions are related to a series of more direct questions such as:

- Are subsurface microorganisms well adapted to conditions in the subsurface, or are they persisting despite a relatively hostile environment?
- Do subsurface microorganisms reflect evolutionary pressures exerted over millions of years?
- Are subsurface microorganisms different from microorganisms on the surface that have adapted over geologic time in response to different and changing environmental conditions?
- Were they transported by water flowing from recharge areas in the recent past, or were they buried when the sediments were deposited millions of years ago?
- Have they persisted in sediments that have changed little since the time of deposition?
- If not, what are the environmental conditions and physiological mechanisms that have allowed them to survive.

Any comprehensive research program of the deep biosphere must begin by addressing the following issues:

- Are deep subsurface microorganisms the survivors or progeny of organisms that were associated with the sediment or rock at, or shortly after, the time of deposition?
- Were deep subsurface microorganisms transported to their current location? If so, by what mechanisms were they transported and what environmental and physiological conditions contributed to their survival or colonization of subsurface media?

Long-term Persistence of Microorganisms

The Middendorf Formation of the Southeast Coastal Plain contains abundant and diverse microbial populations and consists of a series of fluvial, deltaic, and marine sediments. These sediments probably contained extensive microbial communities when deposited, and it may be possible that microorganisms in the deep formations may be descendants or survivors of microorganisms associated with the original sediments. Dense confining layers with high clay content may contain microorganisms that are relict populations, because significant transport of microorganisms into these materials is unlikely, assuming compaction occurred soon after deposition.

Some marine and soil bacteria are known to be extremely well adapted for survival under extremely low-nutrient (starvation) conditions, and stable biological macromolecules, such as DNA, can persist in some environments for extended periods. However, the length of time that a microbial cell can maintain the capacity to metabolize and divide is still unknown. Related research questions are:

- How long can microorganisms survive?
- Are they physiologically active?
- What environmental conditions are conducive to microbial cell survival?
- What physical and chemical conditions promote metabolism and reproduction after extended periods of dormancy?
- How have microorganisms adapted or evolved in over geological time changing environmental conditions ?
- Are some subsurface microorganisms optimally adapted to subsurface conditions and not particularly stressed by their austere environment?

The techniques of molecular biology are rapidly advancing the fields of bacterial systematics and evolutionary biology. New knowledge about the composition and diversity of biological macromolecules (*e.g.*, ribosomal RNA, DAN, fatty acids) leads to insights into the relationships among various groups of microorganisms and between microorganisms and higher organisms. Thus, molecular techniques have potential not only for identifying subsurface microorganisms but also for determining phylogenetic relationships and establishing the evolutionary history of specific organisms. Knowledge of rates of evolution of genetic determinants in the subsurface, combined with genetic analysis, may permit the development and use of "molecular clocks." Thus, the time in the evolutionary past at which a given subsurface organism diverged from known groups of microorganisms may be established.

However, phylogenetic relationships and the utilization of molecular clocks alone will not establish the time of deposition of subsurface microorganisms. This must be established in the context of the hydrogeology, geochemistry, and paleogeography of a particular site. Information on ground water age, sediment age, and the mechanisms of microbial transport must be closely integrated with molecular biology to successfully calibrate molecular clocks. In addition, it may be necessary to assess the rates and mechanisms of gene transfer among microorganisms in deep subsurface environments.

Research questions related to biologic longevity are:

- Can the molecular biology of subsurface microorganisms, in concert with companion scientific methods such as isotopic dating, be exploited to provide insights into whether microorganisms have evolved recently or in the geological past?
- Can "molecular clocks", such as ribosomal RNA and other conserved macromolecules, be used to evaluate the age of microorganisms?

Transport of Microorganisms in the Subsurface

Microorganisms in the Holocene, near-surface aquifers of the Southeast Coastal Plain, where the groundwater is of modern age, may have been transported from surface aquatic or terrestrial environments. Microorganisms in the deep Cretaceous aquifers also may have been transported from surface environments to their current locations, but over longer periods of time. Various mechanisms can affect the transport of microorganisms in porous media: (1) advection, (2) dispersion, (3) mechanical filtration, (4) sedimentation, (5) growth/decay, (6) chemical adsorption, (7) chemotaxis, and (8) adhesion to surfaces. The relative importance of these mechanisms tends to be organism-specific. It can also vary with the properties of the porous media and the scale of the observation, which is critical to examining the long-term transport of microorganisms over regional distances. For

example, the geochemistry of the subsurface or groundwater, including the availability of nutrients, changes over long groundwater flow paths. Cell survivability, size, shape, and physiochemical properties are expected to be among the principal determinants of microbial transport over regional scales.

Research questions related to microbial transport include:

- What are the bacterial survival characteristics necessary for transport?
- How do community dynamics along a groundwater flow path affect transport?
- Do microorganisms undergo morphological and/or physiological changes along a flow path? Do these changes affect transport? If so, under what conditions, and over what time and distance scales?

The origin of deep subsurface microorganisms is an exciting and provocative question that can be answered only by drawing on and integrating the disciplines of geology, hydrology, geochemistry, geophysics, sedimentology, microbiology, ecology, biochemistry, and molecular biology. Answers will require interaction and cooperation among scientists from different disciplines using a variety of innovative approaches.

In Situ Evolution/Survival Hypothesis

1. Have microorganisms been trapped in soils and sediments during their deposition: What types of depositional environments prompted entrapment? What types of microorganisms can be trapped or survive entrapment?
2. If microorganisms are trapped, how long can they survive? What geochemical and microbial characteristics favor survival?
3. To what extent is the rate of evolution influenced by entrapment and by what in situ geochemical conditions? The subsurface environment may be relatively stable, but it is also relatively "hostile," presumably imposing a selection process. Does evolution occur at a different rate here than it would in stable, less hostile environments? What is the relationship between "stress" and adaptation?
4. Can the limits and validity of "molecular clocks" be established? To use molecular phylogenies to determine the evolutionary age of organisms, the "clock" rate must be known. Although there are estimates of molecular clock rates, there is little assurance of accuracy.
5. What is the potential for preserving particular functional groups of microorganisms, based on modern analogs? What geological environments are likely to foster or bias conservation of certain functional groups?
6. Are there "antiquity markers", that behave as chemical biomarkers that relate to periods in the geological past?
7. What are the rates of in situ metabolism? How can they be measured?
8. What sites are likely to contain only (a) microorganisms persisting since time of deposition, or (b) microorganisms transported from the surface? Can studies of isolated environments provide information on bacterial survival, adaptation, and evolution?

Technological Requirements

Scientific drilling clearly plays a critical role in the study of subsurface microbes and careful drilling and sampling will be required to resolve the many questions listed above. While it is possible to begin to address some of these research questions with current techniques, others will require development or refinement of approaches for characterizing microorganisms and transport phenomena. For example drilling with unusual fluids such as argon gas and using perflurocarbon tracers must be experimented with and perfected as well as the different types of technology available for core recovery. New tools, particularly in the area of molecular biology, are rapidly evolving, and some will be extremely useful for elucidation of bacterial survival, evolution, and adaptation processes. Critically important to research on bacterial origins is the interaction and collaboration among researchers from different areas, including microbial physiology and ecology, geochemistry, molecular biology, hydrology, and paleontology. Microorganisms have persisted in the deep subsurface after prolonged exposure to an array of geochemical and geological factors. Only through consideration of the complex interplay between the microorganism and its geological surroundings can the questions of microbial origins be fully answered.

Acknowledgements

As mentioned above there was no detailed discussion of the study of the deep biosphere via scientific drilling at the Potsdam meeting. The material above was included in this report for completeness. Thanks are due to Frank Wobber, U.S. Department of Energy for making the plan available. Contributors to the plan are Frank Wobber, Madilyn Fletcher, Ellyn Murphy, James Fredrickson, R. Wildung, P. Long, T. Phelps, T.C. Onstott, David Balkwill, Brent Russell and Tim Griffin. The DOE plans includes the proceedings of a workshop that lists other contribuitors. International progress in subsurface microbiology is outlined in the Proceedings of the 1993 International Symposium on Subsurface Microbiology.

Further Reading

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XII. Structure and Evolution of Basement Provinces

Introduction

The mineral potential of the Earth is largely in the exposed basement provinces and in their extensions beneath thin sedimentary cover. A better understanding of the global resource base for sustainable development is therefore highly dependent on improved understanding of the structure and evolution of these basement provinces. This will permit the assessment of the potential for various mineral deposit types in space and time, and also provide the basis for more effective and efficient exploration. At present interpretations of the three-dimensional structure of the crust, and of the evolution of that structure through time are highly model dependent. Continental drilling offers a unique approach to the solution of fundamental problems of crustal evolution and of associated metallogenesis.

This chapter provides a very brief outline of the potential value of this approach. The discussion is limited to basement provinces because the Evolution of Sedimentary Basins and Origin of Mineral Deposits is dealt with in separate chapters. Likewise we limited the discussion of structural and tectonic models since discussion of continental drilling in relation to geophysical models is dealt with in other sections.

Much of the proposed continental drilling program is directed at improving our understanding of contemporary geological processes such as lithospheric deformation, volcanism and fluid migration. Consequently, drilling targets will be largely located within areas related to Ceno-Mesozoic Megasutures in Fig. XII-1. The knowledge gained through drilling will be of direct value for environmental management, and natural hazard mitigation, as well as contributing to the understanding of resource distribution in these areas. It is also essential for the interpretation of the geological record in the older basement provinces which form the greater part of the continental areas (Fig. XII-1). Indeed the interpretation of the structure and evolution of basement provinces depends largely on the application of our understanding of present day global dynamics.

These basement provinces have developed over the past four billion years. The interaction of a range of geological processes has produced provinces of complex structure. Moreover there has been secular change in tectonic processes related to the secular change in radioactive heat generation. Thus, while actualistic interpretations are appropriate strict uniformitariarism cannot be assumed (*e.g.*, Rutland, 1982). It is therefore not possible to provide reliable interpretations of the structure and evolution of basement provinces, and assess their resource endowment on the basis of models derived from surface observations and remotely sensed data of younger tectonic systems. Drilling is required to test both geological and geophysical models.

Key Scientific Questions

The broad range of research questions regarding Continental Dynamics has been well summarized in a report to the U.S. National Science Foundation (Phinney *et al.*, 1993). Among the goals of a research program (*op. cit.* p 8) the first relates to „Origin and Evolution" of continents:

„How do continents form, deform, and break up? What are the roles of arc-continent collisions and backarc extension in the evolution of continents? How do continents behave when intersected by active plate boundaries? How do we recognize these phenomena in surface geological and in geophysical data?"

The answers to these questions are pre-requisites for a full understanding of metallogenesis and the distribution of resources in space and time, especially in the Precambrian Shield areas of the Earth.

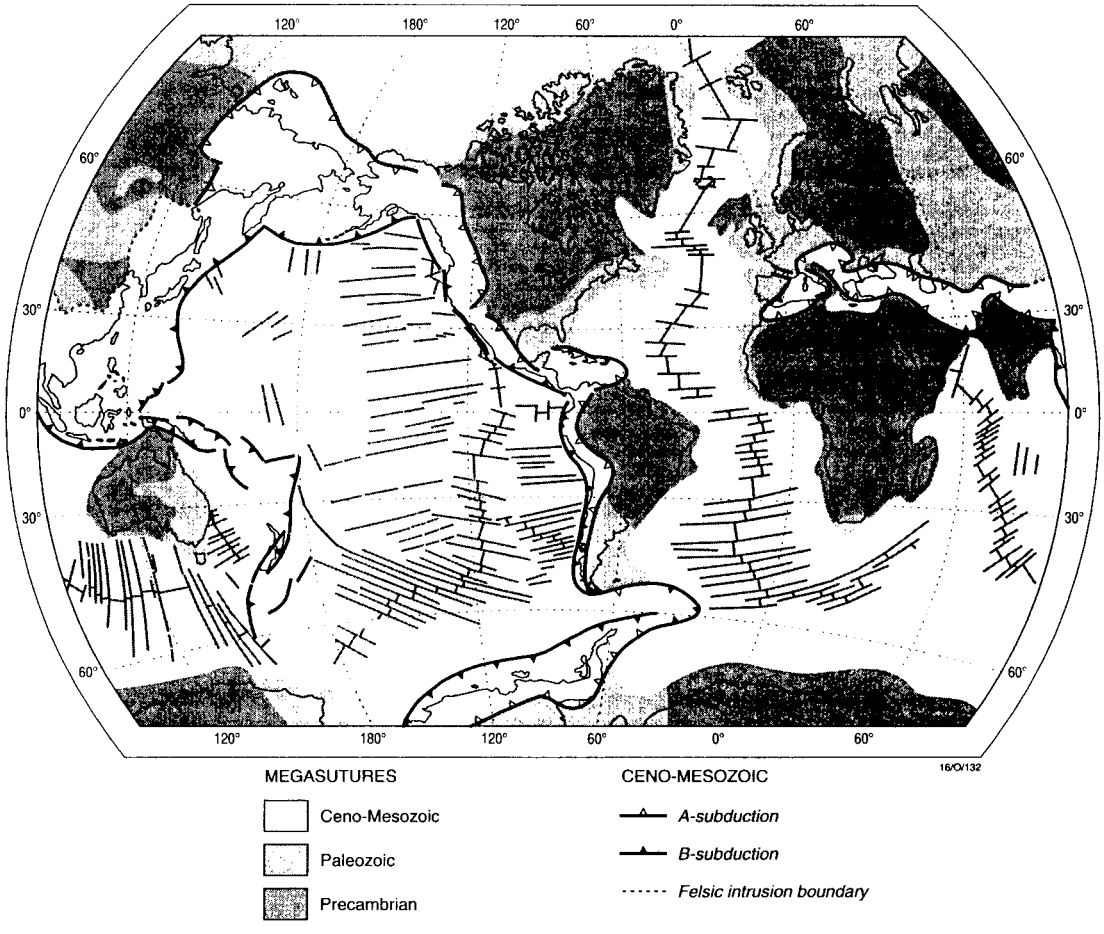


Figure XII-1: Megasutures around the world defined on the basis of geologic age.

The first and critical step in the assessment of resource potential, or in the identification of highly prospective areas, is the delineation of tectonic environments which are permissive for particular deposit types. This requires an understanding the deposit types themselves, such that drilling can be used as a tool in developing this understanding (see chapter in this volume on the Origin of Mineral Deposits).

The relationship between mineral deposit models and tectonic environment (*e.g.* Cox and Singer 1986) are best understood for deposits related to active margins in the Mesozoic-Cenozoic plate tectonic systems. The relationships are less well understood for deposits in intraplate environments and in older systems, especially the Precambrian, where plate tectonic interpretations are less firmly based. In particular, Precambrian basement provinces are associated with distinctive variations in deposit type compared with those in younger systems.

Scientific drilling, as part of a multidisciplinary scientific approach has a key role to play in providing an exact knowledge of the three dimensional structure and temporal evolution of these basement provinces, and consequently, of the regional controls on the development and distribution of particular deposit types. The benefits of drilling will be greatest where the multidisciplinary approach incorporates seismic reflection profiling. This greatly enhances the value of drilling in interpreting regional structure and evolution. An example for Archaean greenstone belts is discussed below.

Fundamental questions of continental structure and evolution will be best answered by careful selection of the best sites world-wide (see closing comments in this volume by K. Fuchs). This can ensure that the results have widest possible applicability, as well as bringing the intellectual and cost-sharing benefits of international cooperation.

Significant differences have been recognized between Archaean, Proterozoic and Phanerozoic basement provinces and it will therefore be appropriate to seek drilling proposals to elucidate the structure and evolution of provinces in each of these categories. In all provinces, however, key questions relate to the nature of the basement to the exposed litho-tectonic assemblages and to the nature of contacts between assemblages. Where contacts are tectonic it is necessary to determine the geometry of the contacts and the nature of movements along them.

The Role of Scientific Drilling

In Phanerozoic mountain belts, which have often been subject to Cenozoic morphogenesis, the surface relief of several kilometers may provide the necessary information on three-dimensional structure. Even in these areas however the fault zones are often not well exposed and drilling can provide critical information.

In contrast, Precambrian Shield areas, generally exhibit very low relief, and drilling is correspondingly more important for establishing the three-dimensional structure. It is also crucial for establishing relationships beneath areas of extensive, but relatively thin, younger Precambrian cover. In all areas, the various tectonic models carry implications about the nature of the lower crust which is generally beyond the reach of drilling. However, careful documentation of the composition and physical properties of the upper crustal elements in the various provinces using drilling and geological and geophysical models can assist in determining whether these elements also form buried components in the lower crust of other provinces.

It has been argued that drilling is unnecessary to study the deeper parts of basement provinces since a variety of tectonic processes have acted to exhume the deeper levels to the surface for direct examination (*e.g.*, metamorphic core complexes). This is undoubtedly true in some cases. However, it is also true that the in the process of elevating lower crustal rocks considerable re-working of the lower crust has occurred such that original characteristics and contact relations have been destroyed. Drilling, in areas which have not suffered tectonic re-working, is often the only way to test hypotheses about the earlier tectonic characteristics and relationships.

Phanerozoic Provinces

Phanerozoic basement provinces are essentially the product of processes operating at convergent plate boundaries and associated marginal basins, and in collisional zones. A separate chapter (Convergent Plate Boundaries and Collison Zones) focuses on the direct study of tectonic processes in the contemporary plate tectonic framework. Such studies

provide the basis for the interpretation of ancient provinces in earlier plate tectonic situations. Drilling is also required to test the interpretation of these tectonic assemblages.

The Qinling orogenic belt in China provides a key example of an older collisional orogeny where drilling has been suggested to elucidate tectonic relationships (Zhu Zhiqin *et al.*, 1993). Drilling would also be invaluable in testing models for the emplacement of inferred exotic terranes in accretionary processes.

In various areas of the Western Pacific (*e.g.* Luzon, Philippines) relatively flat lying lavas of oceanic affinities rest on crust of unknown character and are also associated with ophiolite assemblages which are inferred to have been obducted. Drilling is essential to the full understanding of such terranes and associated mineralization. In the Canadian Cordillera where classic seismic profiling studies have been undertaken (Clowes *et al.*, 1987) a range of proposals have been made to study the major fault systems and associated mineralization. (Canadian Continental Drilling Program Reports 88-3 and 90-1).

In the broad continental flysch-dominated Paleozoic terranes of the Lachlan Belt in eastern Australia, proposals have been made to test models of continental accretion by testing the nature of inferred crustal detachment zones and the underlying crust (Gray et al, 1991). It may be noted that Paleozoic relations are better tested in regions, such as eastern Australia, where there is little re-working by younger orogenies, rather than in areas of the East Pacific margins where Paleozoic provinces have been strongly modified by Mesozoic and Cenozoic processes.

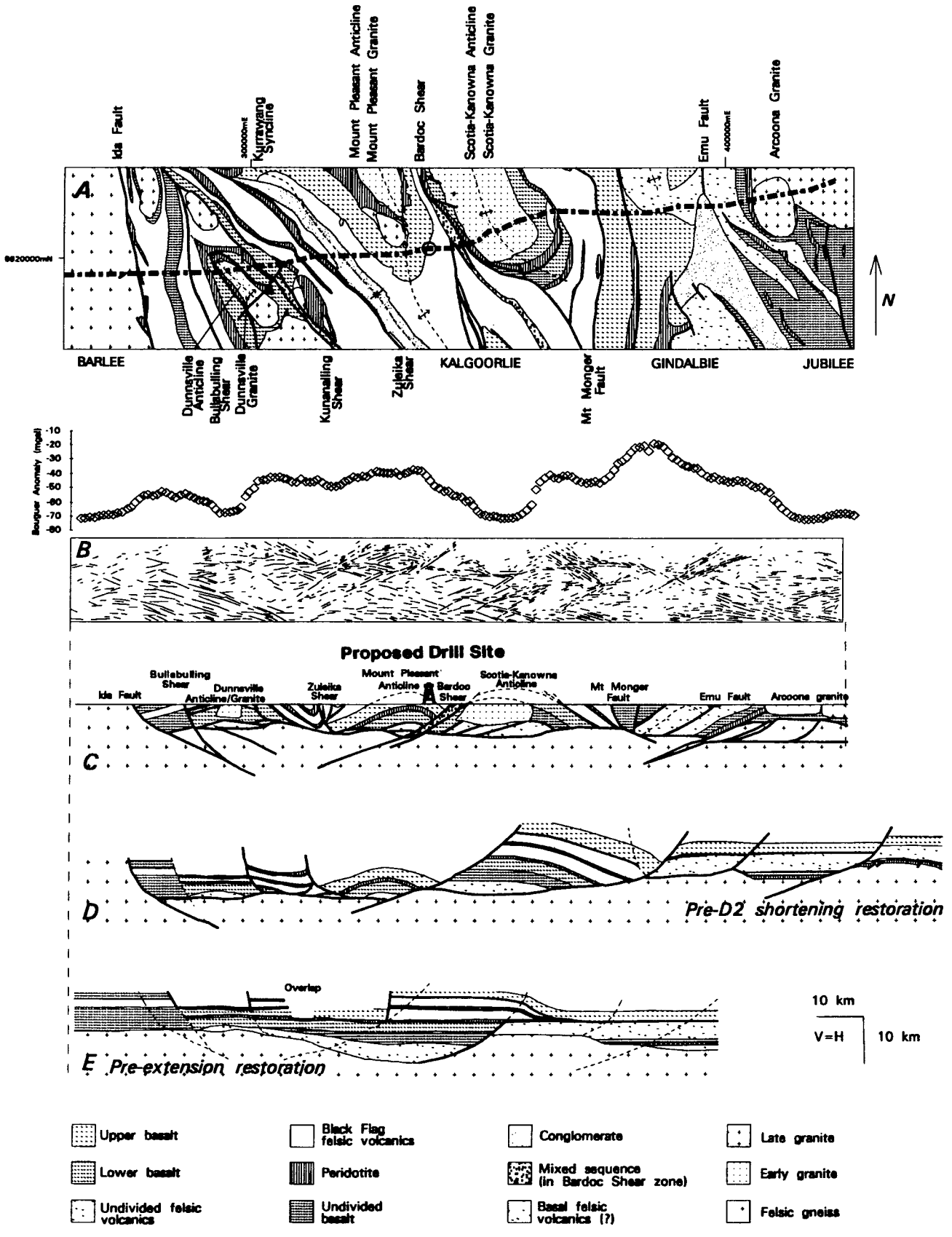
Proterozoic Basement Provinces

In the study of Proterozoic basement provinces, questions of secular change in tectonic processes become important. For example, early Proterozoic orogenic domains have broadly similar characteristics and chronology in Canada, Fennoscandia and Australia but the respective tectonic interpretations vary widely (*e.g.*, Hoffman, 1988; Gaàl and Gorbatschev, 1987; Etheridge *et al.*, 1987). Again, drilling can provide crucial information on tectonic relationships between supracrustal complexes and their present basements. Workers from these and other regions could cooperate in developing an appropriate international drilling program. Similarly, a program could be developed for the study of major mid-Proterozoic (Grenvillian) belts which have been inferred to form a global network of collision of intracontinental character.

Archaean Basement Provinces

Archaean provinces also exhibit very similar characteristics world-wide and the solution of fundamental problems of interpretation of these provinces could be greatly assisted by an international drilling program. It is likely that a small number of sites could be selected which would provide crucial information for the interpretation of all Archaean provinces. For example, in Australia, there may be a site particularly favorable for study of the tectonic relationships of the earliest greenstones. These sites have been interpreted as autochthonous deposits on proto-continental crust or as obducted oceanic complexes emplaced by plate tectonic processes similar to those which have operated in the Phanerozoic (Hill *et al.*, 1992; Kusky and Kidd, 1992; Kimura *et al.*, 1983).

In the North Pole region of the Pilbara province of Western Australia, Archaean greenstones dated at 3460 Ma are preserved as a thin undeformed carapace over a major dome. Drilling would therefore permit detailed studies of the nature of the oldest members


Ida Fault
Kurrawyang Syncline
Mount Pleasant Anticline
Mount Pleasant Granite
Bardoc Shear
Scotia-Kanowna Anticline
Scotia-Kanowna Granite
Emu Fault
Arcoona Granite
A
N
BARLEE
Dunnsville Anticline
Bullabulling Shear
Dunnsville Granite
Kunanalling Shear
Zuleika Shear
KALGOORLIE
Mt Monger Fault
GINDALBIE
JUBILEE
Bouguer Anomaly (mgal)
-10
-20
-30
-40
-50
-60
-70
-80
B
Proposed Drill Site
Ida Fault
Bullabulling Shear
Dunnsville Anticline/Granite
Zuleika Shear
Mount Pleasant Anticline
Bardoc Shear
Scotia-Kanowna Anticline
Mt Monger Fault
Emu Fault
Arcoona granite
C
D
Pre-D2 shortening restoration
Overlap
10 km
V=H
10 km
E
Pre-extension restoration
Upper basalt
Lower basalt
Undivided felsic volcanics
Black Flag felsic volcanics
Peridotite
Undivided basalt
Conglomerate
Mixed sequence (in Bardoc Shear zone)
Basal felsic volcanics (?)
Late granite
Early granite
Felsic gneiss

of the greenstone sequence, the nature of the contact between the greenstone sequence and the basement, and the nature of the unmodified pre-3460 Ma basement complex. In most regions these relationships are obscured by later deformational, metamorphic or plutonic events.

The poorly-exposed weathered peneplane of the younger Archaean Yilgarn province of Western Australia provides an excellent example,where scientific drilling can be of maximum value as part of a multidisciplinary program. A new generation of maps, based on high resolution airborne surveys and on careful structural mapping of available exposures has been combined with seismic profiling to produce a new model of greenstone structure and evolution (*e.g.*, Goleby *et al.*, 1994). Figure XII-2 illustrates the main features of this model which can be tested only by drilling. Drilling at the site indicated in Fig. XII-2 would allow the testing of this hypothesis in respect of overall thickness of greenstones, nature of detachment surfaces and character of shear zones. Drilling would also assist in developing models of fluid migration in relation to mineral deposit genesis. These examples provide indications of proposals which would need to be evaluated along with proposals from other Archaean provinces (see *e.g.* Canadian Continental Drilling Program, 1989).

Conclusions

There seems little doubt that international cooperation in the selection and execution of drilling projects to enhance understanding of the structure and evolution of basement provinces and of their mineral resources would bring great scientific benefits.

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Figure XII-2: Proposed drill site in the vicinity of Mount Pleasant Anticline, western Australia where it would be possible to use drilling to test new models of greenstone structure based on geophysical profiling.

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Technological Considerations

Scientific drilling provides indispensable information for understanding the processes in the Earth, derived from cuttings, cores, exhumed fluids, downhole geophysical measurements, surface-to-hole and hole-to-hole geophysical measurements, mud logging, geochemical analysis, and hydrologic testing. Moreover, instrumentation such as seismometers and pressure sensors can be installed in boreholes for long-term monitoring of the Earth's crust. The need to continually improve the performance and the efficiency of drilling and coring operations at depth and continued improvements in measurement and instrumentation capabilities provides ongoing challenges to engineers and scientists alike.

Over the past 20 years scientists (and the funding agencies providing the research funding) have become increasingly aware of the fact that specialized drilling, coring and downhole measurement technologies are usually required for nearly any scientific drilling project. To date, there are more than 50 publications to technical topics in CC4 conferences held in Tarrytown, New York 1984, Seeheim, Germany 1985, Mora, Sweden 1987, Yaroslawl, Russia 1988, Regensburg, Germany 1990 and Paris, France 1992. Further efforts to be mentioned are the 1986 „Engineering Foundation Conference" at Sky Valley Resort, Georgia, as well as a „Deep Drilling Workshop" held in 1990 on behalf of ODP in College Station, Texas. A large number of reports have been published on downhole measurements, new logging tools and log evaluation in ODP- and KTB-Reports and in scientific and technical journals. Additionally a number of thematic workshops, national and international, have been performed. These efforts must be continued, to find out the constraints, but also the challenges of technology for hopefully ongoing scientific drilling.

The depth ranges in scientific drilling may be subdivided as follows:

Shallow drilling	< 2000 m
Intermediate deep drilling	2000 - 5000 m
Deep drilling	5000 - 8000 m
Ultra deep drilling	8000 - 14000 m

An overview of available drilling rig capacities shows, that in the conventional depth range down to 8000m, a feasible arrangement of rigs is commercially available. Mining rigs and hybrid rigs are cheaper than rigs for the oil industry and are preferred for continuous coring to shallow and intermediate depth. Rigs for ultradeep targets require special design and are singularly very expensive. For example, the daily operating cost of the KTB ultradeep drilling rig is equivalent to 4.3 „mining type" coring rigs with 5000 m capacity.

Despite the overall decline in the petroleum industry over the past decade there is still a competitive market for drilling and services, including contractors for shallow, intermediate and deep drilling and a wide range of downhole services such as:

Directional drilling

Coring and sampling

Wireline logging and evaluation

Measurement while drilling (MWD) and logging while drilling (LWD)

Mud logging

Cementing, fracturing and well treatments

Well completion and testing

For hostile environments or very great depths, four major questions have to be addressed:

- Availability of recommended technology
- R&D needed for improvement of conventional operation (optimization)
- R&D demand to perform a special task
- The need for very new drilling technologies like coiled-tubing and slim hole drilling

The major components and equipment for the majority of scientific drilling projects exist and are available commercially with further development being necessary for improvement and special applications. In many of the previous chapters, special attention was drawn to the need for new technologies to achieve the desired scientific objectives.

Current drilling technologies involves the following:

Drilling technique

Rotary

Downhole motor

Wireline coring

Slim hole drilling

Horizontal drilling

Coiled tubing drilling

Drilling rig

Rotary, hook load 100 - 8000 kN

Mining rigs

Hybrid rigs

Drillpipe and casing

Sizes and programs

Tool joints and connections

Material and handling

Downhole Motors

Positive displacement motors

Turbines with or w/o reduction gear

Directional drilling with MWD
- Horizontal Drilling
- Vertical Drilling
- Side drilling
- Closed loop and geosteering

Drilling fluids
- Water based
- Oil based
- Air

Drill bits and core bits
- Roller cone
- Diamonds, PCD
- Anti whirl

Coring technology
- Continous and discontinous
- Wireline, counterflush
- KTB and ODP coring systems
- Side-wall coring

Downhole measurement and sampling
- Logging
- Fluid sampling
- Hydraulic fracturing, microfracs
- Completion
- Tests

Safety
- Blowout prevention
- Lost circulation
- Inflow
- Overpressure
- Environment protection
- Disposal (cuttings, mud, etc.)

The key issue is to choose the most feasible, economic and technically appropriate option for each individual scientific drilling project. This means that it is necessary to describe and qualify the scientific targets, to quantify the related data as much as possible,

to forecast the geology, to establish alternative technical design options including judging the risk and establish a procedure by which detailed engineering, procurement and contracting can be outlined.

While most of the drilling objectives discussed in this document can be carried out using currently available technology, in many cases new technology is needed (to varying degrees) to meet the scientific objectives of these projects. For this reason, it is useful to consider in overview the general areas where technology development is necessary.

Improved performance and efficiency in essentially all areas of drilling and coring technology are needed at great depth and high temperature, including:

- Long life bits
- Retractable bits
- Drill string design and materials
- Straight hole drilling
- Advance pipe handling
- Measurements While Drilling (MWD)
- Completion technologies
- Upgrading current technology to higher temperature

Many of the problems that need to be addressed require near-continuous coring. Continued improvement of coring systems is necessary to fully realize the scientific goals of many of the projects. This also applies to the drilling of relatively shallow holes, designed for example, to study climate changes, where drilling requirements are not met by currently available technologies.

Scientists need to drill and core and make downhole measurements often under difficult circumstances. These include high pore pressure, unstable rock with poorly consolidated materials. Drilling and completion in such environment will be required to meet the objectives of several projects, with major developments in:

- Special well design and completion
- Drilling and completion fluids
- Blow-out prevention and safe operation
- „Casing While Drilling“

Directional Drilling and Coring

While appreciable technological advances have been made in this area in recent years, still further advances (such as directional coring) will be needed to satisfy the objectives of many proposed projects.

- System hardware to start and guide slant holes
- Capability to re-enter deviated or horizontal holes
- Long-reach drilling, coring and completion
- Systems and technologies for downhole measurements, selective testing and isolation for hydraulic fracturing (such as coiled tubing)

To obtain a precise and accurate record of the rock formations penetrated in a scientific borehole downhole measurements are essential. Discontinuous data are gained from core and cutting analysis, depending on the percentage of core drilled, core recovery problems, sampling frequency and mixing of cuttings due to cavings. Nearly-continuous in situ measurements and borehole logs and therefore indispensable for scientific drilling projects. The limitations of downhole measurement, testing and sampling technologies are governed by the temperature and pressure range of the tools deployed:

< 125°C (military standard)	103.4 MPa
< 175°C (service company standard)	137.9 MPa
< 260°C (hostile environment)	172.4 MPa

Two different means to convey these tools are in use:

- logging cable for wireline logging, test and sampling
- drill pipe for „Logging While Drilling" (LWD), drill stem testing (DST) and sampling.

Although all standard tools have been developed by industry for the exploration and exploitation of hydrocarbon and mineral resources, specialty tools („Third Party tools") have been designed and manufactured by scientific agencies, laboratories and university institutes engaged research within the Earth sciences.

To satisfy the technological requirements of scientific drilling projects, the following groups of measurements and mineral services are available and can be contracted:

- Resistivity and/or conductivity measurements
- Acoustic and seismic recordings
- Natural or induced nuclear measurements
- Gravity measurements
- Temperature, pressure and flow measurements
- Borehole caliper and trajectory
- Formation and drill stem testing
- Sidewall coring
- Fluid sampling

These measurements can be recorded either in water-based or oil-based muds, in vertical, deviated or horizontal wells and holes that range from 5" up to 17 1/2" in diameter. Certain services are available for slim boreholes with less than 5" bit size.

Critical boreholes may be best served utilizing MWD methods, as data are recorded while drilling is in progress. Data with reduced sampling frequency are recorded in real time via mud pulsing and through high density data storage to be evaluated after retrieving the drill string.

Wireline logs are recorded after drilling and need to be corrected for such effects as mud invasion and borehole geometry, etc. Techniques for corrections and detailed log evaluation (lithology, stratigraphy, porosity, saturation, mineral composition) are available. Scientific drilling projects in shallow, intermediate and deep holes can draw on expertise present in the industry. For ultra deep projects in crystalline rock, experience has been gained mostly from the Kola and KTB boreholes.

As is the case with drilling technologies, downhole measurement technology needs to be improved by further development in cooperation with industry:

- Measurements at temperatures >260°C (logging, testing, sampling, cables, data transmission systems)
- Projects requiring long-term data recording systems (sensors, memory, transmission systems)
- Slim and difficult hole projects requiring high temperature equipment (logging, testing, sampling, wet connectors)
- Testing, sampling and HT-fracturing equipment (inflatable packer, fluid sampler)

Conclusions

The ultimate success of a scientific drilling project will depend on the realization of the borehole to target depth, the condition of the borehole for safe re-entry, sufficient cores, samples and good quality downhole measurements and tests. Every scientific drilling project needs the cooperation of the scientific institution in charge of the drilling and service industry. This is intended to take advantage of their expertise and to make the developed technologies available for immediate use in private enterprises.

General Considerations for an International Continental Scientific Drilling Program

As discussed above there is a strong consensus among Earth scientists from different countries (and a diversity of disciplines) enthusiastically supporting the development of a coordinated International Continental Scientific Drilling Program (ICDP). In many senses this program can be seen to complement the Ocean Drilling Program (ODP), which is widely recognized as being one of the most successful international collaborations in science. The development of a comparable land-based program to the ODP is a logical next step in the development of the earth sciences. After all, it is on the continents where most of the Earth's history is recorded, most of our resources are found, and most of the world's population lives. In considering establishment of an ICDP it is valuable to review some of the reasons why ODP has been so successful. The ODP (and its predecessor the Deep Sea Drilling Project):

- Addresses fundamental science
- Is proposal driven and priorities are established on the basis of peer review
- Serves the entire marine earth science community
- Undertakes well-received proposals in a timely manner

The ICDP and the Ocean Drilling Program

There is no question that any program of continental scientific drilling that is established should have close ties to the ODP. These ties are technological, scientific and perhaps managerial. The scientific ties are most important to discuss and this is most clear in the area of research related to studying continental margins. Much of the world's population lives along continental margins. Significant geological hazards associated with earthquakes and volcanic eruptions are faced at many continental margins and much of the world's hydrocarbon resources are found there. Equally important, continents evolve at their margins and thus the processes responsible for the creation of continents are occurring today along continental margins around the world. Yet our understanding of many of the processes that shape continental margins is poor and many fundamental questions about these processes have gone unanswered. Because the study of continental margins literally lies between those areas normally considered in ocean drilling and continental drilling, it is hoped that cooperation between ODP and ICDP can address the many important outstanding scientific questions that need to be addressed along continental margins.

International collaboration in continental scientific drilling is necessary because individual nations have neither a monopoly of worthwhile drilling targets nor an unlimited budget for drilling. However, it is obvious that the environment of the ICDP differs from that of the ODP in a number of significant ways. These differences are cultural, political, geological, and societal, as well as technical.

The obvious cultural difference between the practice of geology on land and at sea is due to their different traditions based on their different logistical requirements. Early pioneer geologists went forth with little more than a hammer and a notebook, whereas from the beginning, marine geologists needed to organize a ship, a crew, and a dredge-haul. Whereas the practice of geology or geophysics on land tended to be diverse, individualistic and relatively inexpensive, geology at sea required more standardized

methods, more team work, and more money. For example, operation of the ODP drillship costs more than ten times the cost of operating a drilling rig with comparable depth capacity on land. Even this lower cost of drilling on land seems too high to some geologists accustomed to the level of budgets of „notebook and hammer" science. However, the debate about „big science" versus „small science" is heard much more among land based geologists than among their sea-going colleagues. Today geologists and geophysicists ought to emulate the mutual cooperation of astronomers and astrophysicists. Where would their science be if, for budgetary reasons, astronomers and astrophysicists each had to build their own telescopes? Mutual cooperation does not mean dividing the resources between an increased number of individuals, but using available resources more effectively and, hopefully, increasing the total resources available to all. Thus, one answer to the ever-present problem of funding relatively expensive ICDP projects is to carry them out through international cooperation.

The obvious political difference between the oceanic and continental drilling is the ODP drill sites are mostly located in international waters, thus emphasizing the global aspects of the programs being investigated. Whereas ICDP drill sites will be situated in individual countries and so may be perceived as primarily benefiting the scientific endeavors of the host nation. The answer to the problem of justifying the funding of drilling in foreign countries is to choose „world-class" problems to investigate, that is, to drill at sites which are the best world-wide examples of general geological and geophysical problems. The results obtained would then be of wide-spread significance, far beyond the confines of the individual country where the borehole is situated. Thus, the projects chosen should have global significance.

The obvious geological difference between the ODP and the ICDP is that the former deals with only the last 180 million years of Earth history, whereas on land rocks as old as 3.8 billion years are exposed. Perhaps the most significant result of the Deep Sea Drilling Project (DSDP), the predecessor to the ODP, came when it showed that the stratigraphy and distribution of marine sediments in a transect across the Atlantic Ocean was exactly as was predicted from the hypothesis of „sea floor spreading". Subsequently, ocean drilling and geophysical studies have unraveled the plate tectonic and climatic history of the ocean basins and have given enormous insight to the processes involved. In contrast, the geological history of the land masses is not only an order of magnitude longer, but is also far more diverse and complicated than that of the ocean basins. Continental geology has been painstakingly reconstructed by detailed geological field mapping aided to a lesser degree by surface geophysics than is the case in the oceans. Investigation of the major tectonic units of the continental crust is chiefly done by judicious choice of locations with good outcrops. In order to justify individual continental scientific drilling projects, or even the ICDP itself, we must first show clearly that we have exhausted the possibilities of further outcrop studies and surface geophysics in solving first-order, geological problems. Thus we must convince the funding agencies, and the public at large, that the projects chosen have a clearly demonstrated need for drilling.

The obvious societal difference between drilling in the oceans and on land is exemplified by the fact that we find it necessary to append the word „Scientific" to the title of the continental drilling program. The ODP is so obviously a scientific program that it does not need stating in its title. However, both the public and science administrators are so conditioned to the fact that drilling on land is normally done by the petroleum and mining industries in the search for hydrocarbon and mineral resources that it is necessary to remind them that our aims are scientific rather than strictly economic. The ICDP should actively seek to obtain access to boreholes, samples and data obtained by industry.

Similarly, although the ICDP should not attempt to carry out the work of industry by becoming unduly involved in applied projects, the funding of expensive drilling projects is likely to be easier if the problem investigated is not entirely academic. Thus, preference in selecting major drilling projects should be given to those which help to advance the scientific basis for addressing one or more important societal needs.

The obvious technical difference between ocean drilling and drilling on land is that the latter involves a much greater diversity of drilling targets, and drilling depths which, in turn, require a much greater diversity of drilling technology. The heart of the ODP is a single, dynamically-positioned, drillship. The requirement there is for a platform which can drill in deep water in all the world's oceans. There is no equivalent requirement for a similar single drilling platform on land. Continental drilling targets may range in depth from a few tens of meters in the Quaternary saline deposits of a dry lake, to 12 km in the Archean granite gneisses of the Kola Peninsula. These different depth ranges require widely different technologies and have widely different costs associated with them, as the cost of drilling increases exponentially with depth. Although ultradeep drilling truly represents a new scientific frontier, unfortunately it also represents a new funding frontier in the Earth Sciences to meet the major engineering challenges required in drilling, sampling and downhole measurement. The high temperatures encountered at more moderate depth in active volcanic and thermal regimes also represent a new scientific frontier and difficult engineering challenges, albeit at a much lower cost penalty. Similarly, as the history of the Mohole and the DSDP demonstrated, a number of shallower boreholes may be more scientifically productive, and certainly more cost effective, than a single ultradeep borehole. Given these inescapable facts, we must remind ourselves that our aim in the ICDP is to maximize the scientific yields of the drilling projects selected rather than to perform difficult feats of engineering or to set new records on levels of science funding. Thus, sites for ICDP projects should be selected specifically to minimize the depth and difficulty necessary to obtain the critical data and samples required to attain the scientific goals of the project.

The obvious differences between the rates of geological processes which can be more readily investigated on land then at sea perhaps provides the most compelling reason for the creation of an ICDP. As mentioned above, ocean drilling has been extraordinarily successful in investigating the last 180 million years of plate tectonics. On land the history of the Earth's continental crust has been laboriously unraveled by fitting together the scattered and very incomplete pieces of a four-dimensional jig-saw puzzle. However, many targets for the ICDP are active processes which act today to shape the continental crust of the planet and which operate on a time scale suitable for investigation by drilling. These include targets such as active faults, sedimentary basins, volcanic and hydrothermal regimes and places where the deep biosphere can be studied in detail. Only by drilling into such areas can we gain appreciable knowledge into the workings of critical geologic processes.

Close and intensive cooperation between any newly established ICDP and ODP is essential. Many of the scientific objectives of the two programs are similar and often drilling both on land and at sea is needed to address programmatic objectives.

Selecting ICDP Targets

The preceding remarks lead naturally to the following succinct statement of criteria for organizing the ICDP and selecting its drilling projects:

- International Criterion - The ICDP projects should be international in scope in order to choose the very best targets, to optimize scientific yields, and to pool technological and financial resources.
- Global Criterion - The ICDP should select drilling targets which are „World Class", and represent problems of global significance, rather than just local problems.
- Need-for-Drilling Criterion - The ICDP should only choose drilling projects where it can clearly be shown that the necessary information is not otherwise obtainable than by drilling, or which exploit the unique environment of the borehole.
- Societal-Needs Criterion - The ICDP projects, where appropriate, should strive to collaborate with industry, and not only be concerned with purely academic issues. Where possible it should give preference to projects which have some relevance to societal needs, such as energy and mineral resources and geological hazards, etc.
- Depth-and-Cost Criterion - The ICDP projects should try to be cost effective by minimizing the depth, difficulty, and hence cost, of the drilling targets selected, by judicious choice of the best possible locations world-wide for the classes of phenomena being investigated.
- Active-Processes Criterion - The ICDP should put special emphasis on the study of active rather than ancient systems. Drilling projects should focus on projects where drilling provides crucial information, not otherwise obtainable, including rock and fluid composition, temperature, pore fluid chemistry, state of stress, etc.

EPILOGUE

Continental Drilling and World Geological Targets

Remarks by Karl Fuchs
Past President, International Lithosphere Program
Closing of the Potsdam Meeting

At the end of this International Conference on Continental Drilling at Potsdam I would like to draw to mind the spirit experienced at the OECD Megascience Forum on 'Deep Drilling' captured in the OECD report published in time for this conference (OECD, 1993). Let us ask ourselves what we are up to scientifically and how we should proceed in the solid Earth Science community to survive as a discipline at the forefront of natural sciences.

Consider our planet Earth in space. We live at the interface of the outer and inner space of this planet. Astronomy and space research during the last 100 years and especially the last 30 years have strived to the very limits of their technical capability in their investigation of outer space.

There was a turning point in astronomy which Berthold Brecht, a well-known German Poet, caught in words in his play on the life of Galileo "I tell you astronomy did not progress for a thousand years because astronomers did not have a telescope". But once it was there, they used it. The question can be asked whether the solid Earth Science community has made comparable efforts using available technology to its limits in reaching for goals of Earth's inner space. The Earth sciences are facing the task and responsibility of exploring inner space with the same ingenuity and the same effort as space researchers, however, this task is much more difficult.

„Scientific Earth drilling" must be taken in the wider context of a sophisticated multi-component megascience research tool which comprises not just the drill rig, but all tools providing remote sensing information, especially geophysical and geological surveys, in short all geoscience information. This definition of „Scientific Earth drilling" implies, therefore, that scientific drilling is a sophisticated system in which the components are mutually controlling each other, as developed so successfully in the oil industry for the exploration of hydrocarbons. Methods were developed mutually: Geophysical remote sensing provided the image to which the drill bit was directed and the information from the hole in turn led to the improvement of the geophysical acquisition and imaging methods which provided better predictions for the drillers and vice versa. We must take it as a system, this message came through very clearly during the Megascience Forum.

Solid Earth sciences, especially Earth drilling, has always been at the forefront of Earth science using the best possible technology available at that time. We should ask ourselves today if we are using the best available technology and if we are willing to work at the forefront of our science or are we satisfied with something less? Here are some examples of high technologiy: conventional ships adapted for the purpose of ocean drilling and on the continent, the drill rig adopted to conditions which are expected here at depth. The ship, and the drill rig on the continent, are embedded in an environment of remote sensing technologies and information. The remote sensing observations comprise

all information from satellites, from airplanes and ground based methods in order to select the drill site locations because they can help to identify the geological problem which has to be solved by drilling. All components are of equal importance: pre-site surveys, drilling, logging and scientific experiments in and around the hole. We must insist that for every scientific objective the highest technology available is used. While the engineers are going to the technological limits in developing new instruments, the solid Earth scientist must do likewise in remote sensing and logging, otherwise they will lose their credibility as scientists. Experience has proofed that engineers are really willing to go to the limits of their technical possibilities and are even developing new tools while drilling. It is of utmost importance that scientists do the same in cooperation with the engineers. I must confess that it is fun to work with drilling engineers. They are not just involvd with drilling a hole, they are, like scientists, full of splendid ideas. They also bring us back to Earth and thus our ideas are brought back to feasibility. This is one of the most fascinating experiences which we have here in Germany during the KTB operation.

Apart from engineering accomplishments in deep drilling, there are also quite a number of socio-economic aspects. We should not be shy as Earth scientists to say that we contribute in an essential way to the immediate need of our civilization. We have to understand processes in the Earth for safe waste disposal, heat flow, and geothermal energy. It is one of those components which probably will give us visibility also in the present political situation.

Scientific Challenges

Our main goal for the advancement of the solid Earth sciences is our perpetual drive for a better understanding of the processes which shape the outer shell of our planet. What are the scientific challenges of Earth drilling? We have learned a lot on this subject during this conference at Potsdam, especially in the session summaries by the various chairs. Many times I have been asked the followin question by friends from physics and other fields: it is very impressive what the KTB in Windischeschenbach has achieved; but just tell me in 5 sentences or so what are the achievements in the deep drill hole which are of global scientific significance, not just locally for Bavaria. I will try to provide an answer, although it may be a very subjective view with the risk of leaving out important items. For a comprehensive list please consult the KTB-reports. Here are those five key topics on my list which are breakthroughs in the solid Earth sciences:

Estimating the Temperature in the Lower Crust

Calibration of Surface Geophysical Observations

Fluids in the Crust

Stress at Depth

Magnetization of the Lower Crust

Either explicitly or implicitly these have been discussed during this conference. Emphasizing them at the end of this conference should help us all to recognize the power of the tool 'Scientific Earth Drilling'.

Estimating the Temperature in The Lower Crust

Estimating the temperature in the lower crust and at the Moho is considerably constrained by information obtained in and around the borehole. The observed temperature gradient in the KTB mainhole is 30°C/km - a fairly standard gradient already known to

miners - but becomes a powerful constraint to temperature predictions since it is astonishingly constant to more then 6 km when most of the heat producing part of the upper crust has been passed. If this gradient continues, temperatures at the Moho would be 900°C and at 40 km depth, at 1200°C and basalt would start to melt, which seems extremely unlikely. Therefore we ask, what causes a decrease in the temperature gradient below the bottom of the hole? Since the influence of radioactive heat production beneath 6 km decreases, fluid convection in the lower crust seems to be the most realistic possibility. If the geotherms are known in a hole at a depth of 10 km, temperature estimates for the lower crust and Moho will have even smaller error bars.

Calibration Surface Geophysical Observations

Next topic is the calibration of surface geophysical observations. There are literally thousands of km's of seismic reflection profiles collected by scientists around the world, not to mention the industry reflection profiles, beautifully imaging the crystalline crust. We generally see a transparent upper crust and a reflective lower crust, we see „crocodile" patterns and other animals in the reflectors - a whole zoo. But if we are honest, so far we do not understand the physical meaning of these reflectors. Therefore, it is so very important that we drill into these reflective patterns to calibrate them and even try to predict what is awaiting us at depth before the drill bit has reached the imaged reflectors. There is one very exciting prediction to be tested in a few weeks, namely the prediction of the possibility of fluids present at a depth of 8.5 km (Lueschen *et al.*, 1993). This is inferred from joint P- and S-reflection experiments where at this depth only P- and no S-waves were observed. This will be a direct test on the nature of the reflectors at depth.

Fluids in the Crust

Another exciting topic is fluids in the crust, which is closely connected with both previous topics (as well as the one that follows). Clearly, one of the most exciting observed phenomenon in the KTB for the whole Earth science community is the increased presence of fluids with depth. Everybody who has thought about this before would have predicted that cracks should long have been closed at 6-8 km depth. The experience gained from KTB is quite the opposite. This is one of the strongest lessons of the borehole: as you go deep you get wet!

Stress at Depth

Stress at depth has been discussed sufficiently at this conference. The main message is that the hypothesis that the differential tectonic stress at depth raises to the rock strength according to what is often referred to as Byerlee's-law has now been confirmed to a depth of 6 km (Zoback *et al.*, 1993) - about half way through the brittle thickness of the crust in this area. As the borehole approaches 10 km we would expect to approach the brittle-ductile transition as at temperatures near 300°C quartz should begin to flow. Surely, many surprises are to be expected!

Magnetization of the Lower Crust

One of the big problems in Earth sciences is understanding the 'magnetization of the lower crust' at the big magnetic anomalies on continents. Morley (1991) who was not successful in submitting his paper on the reversal of the magnetic field to *Nature*, worked

on this phenomenon in an attempt to understand big magnetic anomalies in Russia or Canada. From the strong anomaly at the Tornquist Teisseyre suture zone the magnetization of the lower crust was deduced. This prediction from surface and satellite observations has never been tested so far . The magnetic field measured in the KTB-borehole shows that the observed gradient is clearly stronger than that of the Earth's dipole field. This means that some magnetization must be located below the borehole extending well into the lower crust. This is a stronger constraint because 6 km of upper crust have been penetrated already. It must be below 6 km and if 10 km are reached we will have even tighter constraints. One of the critical questions now for the lower crust is what is the Curie point under high P, T conditions or the presence of iron? The fact is that as KTB is deepened, borehole measurements will provide more constraints on existing models than have ever been available before.

Once a deep borehole is finished, be it KTB, the existing Russian holes or future deep holes, we have to make wise use of the holes and the opportunities they offer. There is an enormous number of ideas which have been discussed during the sessions of this conference and I would like to encourage colleagues who are seriously thinking of doing research in a deep laboratory to contact the KTB management. KTB offers such an opportunity if there is sufficient international interest but we should also look for the use of Russian boreholes as well as that of future boreholes. I think it is very important for all future boreholes to be used as deep laboratories.

The boreholes in the former Soviet Union are available for experiments, and their use has started already. There have been reflection surveys and VSP by David Smythe and Scott Smithson and others at the Kola borehole. There have been loggings of borehole deformation measurements by the joint group from Potsdam, Karlsruhe and Stanford at the boreholes Vorotilov and Uralskaya. Here are the first results obtained from the Vorotilov well with the deformation pattern with clear breakouts which give the direction of the maximum horizontal compressional stress. The survey was a fantastic teamwork and I can really say the Russian partners (ROSGEOLCOM, the Academy of Sciences, and NEDRA) are very willing to co-operate.

Small vs. Big Science

Whether we like it or not the question of „Small vs. Big Science" is either loudly or silently frequently raised at (or following) meeting like this: „Are the big projects eating the funds for the smaller projects". My experience is quite to the contrary. I speak from experience, because I have suffered from the decision to take the site for KTB from the Rhinegraben area to its present location in the Oberpfalz. However, in retrospect, there were all together five such sites, each one with an intense presite survey. The number was reduced to four and finally to two places: one was Windischeschenbach and an other was Haslach in the Black Forest. On both places we had a complete set of comprehensive site surveys from wide angle refraction, reflection seismics, magnetotelluric, heat flow, gravity, magnetics, stress, $^3He/^4He$, structural geology and mineralogical investigations. Site surveys should be taken as seriously as possible because it helps to make the best decision. This is not a zero-sum game, whoever loses is actually a winner, because in fact he has gained more than without it. Take the Black Forest. We have learned in the 2 years of site surveys more than in 20 years of small-scale science before the negative drilling decision. Before we did not know anything of laminated lower crust in the Rhinegraben area. All the details which we did not understand before, Conrad, low velocity layer, its relation to the earthquake hypocenter distribution began to fit and we have to ask the question why

is the lower crust so thin in the graben proper? Now we can start to discuss and test the model of differential thinning between upper and lower crust in the Rhinegraben rift system in a stress field changing with time. This is something which was only possible because of this intense presite investigation, because big science was on its way, only because big science attracts the small sciences. This is a general experience also here at the KTB. The notion that the small projects are eaten by the big ones is simply contradicted by experience. On the contrary, the big projects are generating new possibilities for the small ones. We need the small science investigations. On the other hand work at the frontier of science with big or small projects is only possible if we go to the limits with our technology. We have a lot to learn from physicists and astronomers.

We must also emphasize that an adequate computer capacity for simulation and modelling is available in a continental drilling program. 3D-seismics which will be a standard tool in narrowing down sites requires the best and strongest computers, as well as modeling in other fields such as stress and strain, tectonics, heat transport, and fluid transport models. We should not be shy, otherwise we may lose our credibility.

World Geological Targets

We held a continental drilling conference in Potsdam, but many solid Earth scientists were not represented here. How are we going to convince them that continental drilling is really an important issue? We have simply to face the situation that for big projects we have to get an international consensus. As a first step, it is important that the solid Earth science community should agree that work at world geological targets attacking critical geological or geoscientific problems over a very broad range of disciplines is attractive. Let me just mention a few - continental tectonics, continental rifting, collision zones, and evolution of sedimentary basins. The geological community should agree on targets of world-wide interest. These world geological targets should be considered as presite surveys in a much wider sense than those for a drill hole.

I must come back to this very interesting and exciting OECD Megascience Forum on Deep Drilling in Brest . The Earth science experts were together two weeks after a similar OECD meeting on astronomy. In the evening we were, in effect, asked by the chairman, „you are doing pretty well in the Earth science, you probably have the capability for megascience projects but you are so different from the astronomers. When they address the public, they speak with one voice in spite of all the controversies which they have as well. But you quarrel about ocean and continent, shallow and deep, etc.“ This was the immediate observation which he made as the meeting chairman (a nuclear physicist). We decided fairly quickly that there should be only one report on Deep Drilling. In the future there should be a very close connection between the two programs of drilling into the continents and into the ocean floor. I think this is very important - not only for engineering but also for scientific reasons.

My personal conviction is that we have to reach a consensus on big international projects very soon. Our solid Earth science discipline has become distorted in its planning by the growing pressure of limitations in funding. We are hesitant to work on the crucial issues at the forefront of our science ready to be attacked with today's or tomorrow's tools which are expensive. Instead solid Earth scientists develop a tendency to limit their ideas and ambitions according to restricted funds. We hope for survival by proposing small projects fitting the limited budgets. We do not notice that this is the way to endanger the future of our discipline. In such a situation we ought to reach a consensus in the solid Earth Sciences about the priorities of the most important research goals towards and

beyond the year 2000. We must take care not to end up in a vicious circle: if we let our ideas be constrained by limitations in funding, we should not be surprised if funding becomes even more limited for us in the future and will turn to other disciplines which have reached a consensus about their priorities. If we are not striving to the frontiers of the solid Earth sciences with all our curiosity, ingenuity and determination we will not attract the most brilliant students of our time. We will lose them to other science disciplines which will satisfy their curiosity. This will lead to the decline of the solid Earth sciences. If we continue to satisfy ourselves by playing with nicely polished „marbles", solid Earth sciences will end up as a highly useful survey but it will lose its traditional place at the leading edge of natural sciences.

I would like to finish with one brief story. When you are leaving this university building you see the beautiful New Palais. Remember it as a symbol for our situation in the solid Earth sciences. It was built by Frederick the Great after he came home as the winner of the Seven Years War. His country and his economy were completely ruined. He decided at that time that the first and most important task to do is to „show to the world that this country is still alive". This story is not only interesting for historical reasons, it carries also a lesson for the solid Earth sciences, especially in times of crisis, we have to identify our priorities! Let us show the world that solid Earth scientists are not only alive but are willing to go to the frontier of natural sciences, *as in the past*, to address the critical questions facing mankind!

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