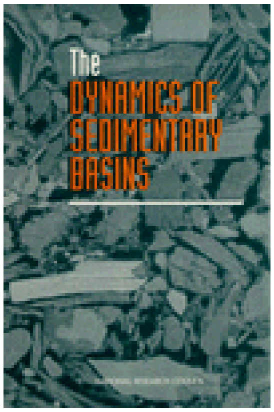

The Dynamics of Sedimentary Basins

Panel of the Geodynamics of Sedimentary Basins,
National Research Council

ISBN: 0-309-59001-9, 56 pages, 6 x 9, (1997)

The Dynamics of Sedimentary Basins

Panel on the Geodynamics of Sedimentary Basins
U.S. Geodynamics Committee
Board on Earth Sciences and Resources
Commission on Geosciences, Environment, and Resources
National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C. 1997

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

Support for this study by the Panel on the Geodynamics of Sedimentary Basins was provided by the U.S. Department of Energy and the U.S. Geological Survey, Department of the Interior. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government. Research supported by the U.S. Geological Survey, Department of the Interior, under USGS Agreement No. 1434-95-A-01313, and by the U.S. Department of Energy under DOE Grant No. DE-FG22-95BC14823. U.S. DOE patent clearance is not required prior to publication of this report.

Copies of this report are available from:
U.S. Geodynamics Committee
Board on Earth Sciences and Resources
National Research Council
2101 Constitution Avenue, NW
Washington, DC 20418

Printed in the United States of America

0-309-05679-9

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Preface

On behalf of the Board on Earth Sciences and Resources of the National Research Council, the U.S. Geodynamics Committee (USGC) examines the health and efficacy of geoscience research programs important for the national interest. As early as 1992, the USGC had identified basic research on the genesis and evolution of sedimentary basins as a crucial arena because of its value for reconstructing vertical movements of the lithosphere and varied environmental changes through geologic time, its impact on understanding the scope and distribution of vital resources of fossil fuels, and its implications for ground-water management and waste disposal. The USGC also perceived that needed advances in the field were at potential risk for two reasons: (1) changes in funding practices by governmental agencies and industry groups have called into question traditional patterns of research support, and (2) salient opportunities for future research entail interdisciplinary collaboration among groups of geoscientists not accustomed to close coordination.

In early 1995 the National Research Council appointed the Panel on the Geodynamics of Sedimentary Basins of the USGC. The panel was charged with identifying and evaluating significant research problems that can and should be addressed by multidisciplinary studies of sedimentary basins, new techniques and approaches that could be brought to bear on aspects of the required research, and the cross-disciplinary ties and collaborative efforts essential to attack key questions in the field. The panel met twice over six months. The present report incorporates the findings and recommendations of the panel from its detailed appraisal of the current status and future prospects for research on the origins and development of sedimentary basins. In all its deliberations the panel adopted a firmly integrative approach to the subject, embodying the dual vision that studies conducted within basins have broad implications for geodynamic relations outside basins and that studies about basins include insights derived from knowledge of general geodynamic relations in the world as a whole.

Mindful of the severe fiscal constraints currently faced by research managers both within and outside government, the panel's report does not call for infusions of new funding to pursue needed avenues of research. Instead, it attempts to outline strategies whereby available support can be used more efficiently within a context of collaborative efforts designed to achieve more integrative analysis of the dynamics of sedimentary basins by researchers in government, industry, and academia. From the perspective of the panel, professional societies also have a key role to play in fostering joint work with a total impact greater than the simple sum of its parts.

The report is thus intended for a double audience. On the one hand, it calls to the attention of individual researchers ways in which their particular expertise can be applied effectively to outstanding questions in a collaborative context. On the other hand, it calls to the attention of research managers and other professional leaders ways in which a more integrative approach to basin analysis can lead to enhanced dividends from research expenditures. The advice that the panel offers is intentionally not phrased in overly specific terms, which would not be appropriate for a wide audience. The panel believes that the fresh perspectives it presents have the potential to stimulate innovative research design and programmatic arrangements that can improve the net intellectual yield from future research efforts. Because of the centrality of basin analysis to many fundamental and practical aspects of geoscience, basin studies have the potential to exert a powerful integrative influence on future geoscience research. Our report attempts to show how.

WILLIAM R. DICKINSON, PANEL CHAIR

Contents

Executive Summary

Over geologic time, depressions on Earth's surface are filled with sediments and organic materials that have been transported by wind, rivers, and ocean currents. Known as sedimentary basins, these features come in many shapes and sizes. They are pervasive on Earth and form in response to complex geologic processes. At their largest, sedimentary basins can be hundreds to thousands of kilometers in horizontal dimensions and contain more than 10^{15} m^3 of buried materials. This basin fill is important in two respects. First, it preserves unique information regarding the history of tectonic, biologic, oceanographic, and atmospheric events during Earth's evolution. Second, basin fill contains most of the fuel and water, and many of the mineral resources, that are critical for society and industrial civilization.

For intellectual and economic reasons, research on sedimentary basins is at a watershed. First, basin research is poised to reap the benefits of decades of disciplinary research that has amassed a vast data set on basin properties. Utilizing this information in the broad context of plate tectonics, there are now great opportunities for multidisciplinary research on sedimentary basins touching on a wide range of fundamental problems in the earth sciences. Unfortunately, these opportunities come at a time of intense financial pressure on the funding sources for research on sedimentary basins. Cutbacks in industrial support for research, coupled with declining federal budgets, present significant challenges for developing a strong research agenda for basin studies. At this time of transition, this report by a panel of the National Research Council's U.S. Geodynamics Committee (USGC) assesses the status, opportunities, and goals for multidisciplinary research on the formation and evolution of sedimentary basins.

Through its survey of current research, the USGC's Panel on the Geodynamics of Sedimentary Basins identified a broad range of research topics focusing on the tectonics of sedimentary basins, the historic record of climate and oceans preserved in basin materials, and fluid and chemical transport in sedimentary basins. In part, this research is driven by the development of new technologies for studying and modeling sedimentary basins. The panel finds that there is an emerging research agenda incorporating the concerns of resource identification and extraction together with the issues of global climate change, fluid flow, and geodynamics.

Today, multidisciplinary research teams are common in basin research. Much of their effort is focused on understanding and predicting

- basin formation within the framework of plate tectonics and mantle convection;
- hydrocarbon generation and migration during basin evolution;
- present and historic ground-water flow and chemical transport;
- changes in basin fill and thermal evolution with tectonic environment;
- spatial and temporal variations of subsurface porosity and permeability; and
- the record of tectonics, climate, and sea-level change preserved in sedimentary basins.

To address these topics, it will be important to develop a broad and integrated research agenda for basin studies because advances in one research area will often rely on advances in distant fields and because of the extreme heterogeneity of basins and basin materials. For this work the panel makes the following recommendations.

Development of a Comprehensive Set of Basin Models. The panel recommends that a focused effort be made to develop a comprehensive set of models for studying the origin and evolution of sedimentary basins. In detail, such models would provide improved understanding of such diverse processes as fluid flow along fractures, the history of mineral and fluid reactions with basin subsidence, and the record of global climate change preserved in basin materials. Linked together, such models would contribute to a new integrated understanding of sedimentary basins with broad implications for research across the geosciences, for identifying and extracting mineral and fossil fuel resources, and for preserving the quality of vital water resources for society. Strategies for this modeling effort should focus on

- improved characterization of basin materials over all length scales;
- strengthened efforts to collect and archive subsurface data on sedimentary basins;
- refined theoretical understanding of the processes that modify basins through geologic time, including mantle convection and plate tectonics, subsurface porous flow of fluids, and the thermodynamics of reactions among fluids, minerals, and biomass at depth; and
- synthesis and linking of existing models to form a comprehensive yet flexible set of models for describing the formation and evolution of sedimentary basins.

Supporting this effort will require innovative funding mechanisms that emphasize collaboration among federal agencies, industry, and the academic community and that link disciplinary research programs related to sedimentary basins.

Data for Basin Research. To provide primary data to constrain the modeling effort on basins, the panel recommends continued funding for efforts to preserve, archive, and disseminate data on sedimentary basins. A diverse and substantial body of information was collected through massive investments by the petroleum industry, and it is unlikely that data gathering on this scale will ever be repeated for sedimentary basins in the United States. If adequately preserved, these data sets will sustain continued advances in basin research for many years.

Role of Scientific Societies. Finally, the panel recommends that the broad range of geoscience societies take an active role in facilitating progress toward the development of a comprehensive set of models for sedimentary basins. Examples of important efforts would include collaborative special sessions and research conferences, joint industry-academic-government roundtable discussions on critical organizational issues for strengthening multidisciplinary research on sedimentary basins, and increased liaison with existing international programs.

1

Introduction

Sedimentary basins are places where subsidence of Earth's crust has allowed sediment to accumulate on top of a basement of igneous and metamorphic rocks. Over geologic time these sediments and associated fluids are chemically and mechanically transformed through the compaction and heating associated with basin subsidence. The buried materials constitute the sedimentary stratigraphic record and contain both unique natural resources and information regarding the history of tectonic, biologic, oceanographic, and climatic events during Earth's evolution. Sedimentary basins and sedimentary materials cover most of Earth's surface. Understanding the evolution of sedimentary basins, and the reasons for their existence in particular places at specific times, can provide fundamental insights into a wide range of Earth processes. The imprint of geologic events left on the materials of sedimentary basins is the most detailed record of the history of Earth's outer shell, the lithosphere.

Basins come in many shapes and sizes and form in response to a variety of processes that influence the elevation of Earth's surface. Some are filled with strata deposited entirely in terrestrial environments, others with strata deposited below sea level in marine environments; many basins include both kinds of sediment. Sedimentary basins also develop in many different geodynamic settings, and their geohistories are diverse. To define the nature of basin-forming events, it is essential to understand how and where sedimentary strata have been deposited and preserved during Earth history.

The formation of sedimentary basins is ultimately controlled by topography that defines the surface depressions that receive the sediments, the elevated regions that provide sediment sources, and the topographic and bathymetric gradients that transport sediments from source to basin. Topography is ultimately governed by lateral variations in the thickness and density of crustal rocks coupled with global-scale flows in Earth's mantle. Through these geodynamic links to regional topography and sediment transport, research on basins overlaps almost the entire spectrum of earth sciences and thereby provides a unifying focus for research efforts in a wide range of subdisciplines.

BASIN FILL

The rock sequences that fill sedimentary basins can be viewed as a structural framework for exchange reactions among sediments, organic matter, and fluids, mainly water. These transformations yield the energy resources of petroleum, natural gas, coal, geothermal energy, and uranium and they lead to the precipitation of a wide range of ores for important metals such as copper, lead, zinc, iron, and mercury. The rock sequences are also the framework for aquifers, the most porous and permeable geologic units in the crust and the major reservoir for fresh water on Earth. Increasingly, these deposits are subjected to anthropogenic impacts because basins are the predominant repository for wastes from resource development and industrial production.

Because the characteristics and settings of basins are varied, research on sedimentary basins cuts across a wide range of scientific and engineering disciplines. Amidst these differences, however, two central themes emerge. First, the historic record of sedimentary basins has wide application for fundamental studies across the full span of the earth sciences. In recognition of the importance of basin data, there has been considerable effort to develop new technologies for measuring and interpreting the geochemical, tectonic, climatic, and biologic record of Earth history as preserved in basin fill. Second, sedimentary basins host many key natural resources, including fossil fuels, ground water, industrial minerals, and metallic ores. Consequently, there has been great interest in developing new multidisciplinary approaches for studying the generation and evolution of these resources in fluid-rock systems.

For as long as fossil fuels continue to be the main energy source for the world, knowledge of the modes of occurrence and distribution of hydrocarbon resources in sedimentary basins will remain key background information for public policy in both the domestic and international arenas. The fruits of this facet of basin research are critical now that imported petroleum accounts for roughly half of domestic consumption. The time is long past when the United States could meet domestic petroleum demand by simply expanding production from internal sources.

FUTURE RESEARCH

With diverse areas of focused interest, the opportunities for research on sedimentary basins are currently at a watershed. Decades of disciplinary research across earth sciences and engineering have amassed a vast data set of basin properties and settings. Worldwide campaigns of drilling, seismic imaging, and fieldwork have elucidated global patterns of basin fill and history. Over the same period, the development of plate tectonics has created a theoretical framework that integrates basin studies into the broad spectrum of earth sciences. With this perspective, and utilizing these data, there are now great opportunities for multidisciplinary research on basins to address fundamental problems in earth sciences. These include the relationship between plate tectonics and deep mantle convection, the causes and consequences of global climate change, the scale of fluid flow and chemical transport through the continental crust, and the distribution of mineral and fossil-fuel resources through the stratigraphic record.

These opportunities unfortunately come at a time of intense financial pressure on funding sources for research on sedimentary basins. Historically, research on basins has been financed primarily by the petroleum industry and secondarily by the federal government. Since 1985, however, falling oil prices and corporate restructuring have resulted in significant reductions in the work force and research expenditures by international and domestic oil companies. Between 1989 and 1993, for example, research expenditures by the 15 largest oil companies decreased from $2.3 billion to $1.9 billion (in current dollars) (Oil and Gas Journal, 1995), and this continuing decline in research investment was superposed on a level of expenditure already reduced from its peak of 10 to 15 years ago. Over the past 10 years employment in the petroleum industry has decreased by more than 400,000 jobs (Oil and Gas Journal, 1995). For the past five years the major oil companies have devoted approximately 0.5 percent of their revenues to research expenses. By comparison, oilfield service companies invest a larger fraction of their relatively smaller revenues (about 5 percent), while the research expenditures of environmental remediation companies appear to be significantly lower, although estimates are not available.

The implications of these funding cuts on the broader scientific community have been severe. For example, membership in the American Association of Petroleum Geologists has decreased by approximately 30 percent since its peak in the early 1980s. Industry support for university research programs also has declined significantly. Consequently, several university programs related to sedimentary basins have broadened their emphasis beyond the traditional focus of petroleum geology. Widening research perspectives is a potentially valuable strategy but cannot alone compensate for reduced funding without better coordination of continuing efforts. Throughout the research community, changing research arrangements have sparked considerable interest in preserving and disseminating the results from a half century of proprietary research on sedimentary basins that was carried out by petroleum companies.

CHARGE TO THE PANEL

At this budgetary and intellectual transition, there is a need to evaluate opportunities for multidisciplinary research on sedimentary basins. Given the continuing challenges of tight budgets and a shrinking scientific work force, effective strategies are critical to allow continued advances in basin research. To this end, this report by a panel of the National Research Council's U.S. Geodynamics Committee (USGC) assesses the status of multidisciplinary research on the formation and evolution of sedimentary basins. In carrying out this study, the National Research Council appointed a study panel of 14 members with expertise across the broad range of basin studies representing academia and industry. For this work the panel's charge was to

- identify scientifically important research problems that can be addressed by multidisciplinary studies of sedimentary basins,
- identify new techniques and/or data sets that can be brought to bear on these problems, and

- identify the cross-disciplinary ties that are essential to addressing these problems.

This report summarizes the panel's deliberations on these questions. It presents a brief summary of important topics in basin research and a description of the critical issues and requirements for developing a unified process model for basin initiation and evolution. Finally, conclusions and recommendations are presented.

2

Emerging Multidisciplinary Research Opportunities

The challenges of basin research are to understand why sedimentary basins formed where they have and subsided when they did, to characterize the properties of basins and their fill, and to identify the processes that have modified basin materials and their contained fluids. This work addresses both fundamental and practical issues regarding plate tectonics, fossil fuels, water resources, and global change and has incorporated diverse approaches from stable-isotope geochemistry through field geology to reflection seismology. Because of the broad scope of basin science, there are tremendous opportunities and potential rewards from multidisciplinary basin research. This section provides a brief overview of those opportunities. The purpose is not to be comprehensive but to illustrate the basic nature of the research questions and the breadth of the collaboration required for effective studies.

TECTONICS OF SEDIMENTARY BASINS

Sedimentary basins are created by vertical depressions of the surface of the lithosphere associated with tectonic processes. These topographic and bathymetric lows are subsequently loaded by the influx of sediment, leading to further subsidence and sediment accumulation.

Within the framework of plate tectonics, it has been long been recognized that this subsidence is a consequence of the much larger horizontal translations of the plates. As Dickinson (1974, p. 2) wrote:

> Plate-tectonic theory as a geometric paradigm to explain tectonic patterns lays special emphasis . . . on grand horizontal translations of the lithosphere with its capping of crust. However, major vertical motions of the crust and lithosphere are required to accompany the horizontal motions by any feasible geologic interpretations of the mechanisms of plate motions and interactions. The vertical motions are related to changes in crustal thickness, in thermal regime, and in conditions for isostatic balance. These three facets of plate-tectonic theory postulate inherent vertical motions of an order that no previous tectonic theory can match in overall scope.

Basin Subsidence

Geologic observations and modeling studies have identified seven processes that can initiate and sustain basin subsidence (Dickinson, 1974, 1976, 1994; Ingersoll and Busby, 1995) (see Table 1). Most basins involve several of these processes working together. The mechanisms of basin subsidence are complex because the forces operate on a wide range of length and time scales, and they interact with the heterogeneous properties of Earth materials in subtle ways. With few exceptions, the exact pathways of basin subsidence cannot be predicted from a general knowledge of the distribution of forces, energy, and material properties. Understanding the subsidence of specific basins requires a comprehensive approach involving both theoretical and experimental work complemented by diverse geologic observations. New theoretical concepts and technologies suggest that there are large opportunities for intellectual advances. Addressing the processes of basin initiation and evolution over the broad scale of the mantle and crust is the ultimate key to understanding the thermal history of the lithosphere and the economic potential of basins.

To this end, there has been considerable effort to classify sedimentary basins based on their affinity with particular tectonic provinces and processes. With this approach, Ingersoll and Busby (1995) have identified 26 basin types associated with seven subsidence processes and five plate-boundary environments (see Figure 1). The authors emphasize that such detail is required by the range of tectonic processes and note S. J. Gould's admonition that "classifications are theories about the basis of natural order, not dull catalogues compiled only to avoid chaos" (Gould, 1989).

TABLE 1 Mechanisms of Basin Subsidence

- Thinning of the crust due to stretching, erosion, or magmatic withdrawal.
- Cooling of the lower crust and upper mantle.
- Sedimentary and volcanic loading of the crust and lithosphere.
- Tectonic loading of the crust and lithosphere.
- Subcrustal loading caused by underthrusting of the lithosphere.
- Dynamic flow of asthenosphere penetrated by descending lithosphere.
- Densification of the crust due to high-pressure phase transformations.

Basin Modeling

The goal of basin modeling is to integrate the understanding of orogenic and subsidence processes to make predictions of paleotectonic reconstructions, basin evolution, and the distribution of potential resources such as aquifers and hydrocarbons. With sufficient data, such models should be feasible (e.g., Lawrence et al., 1990; Fouquet et al., 1990). The architecture of sedimentary basins is controlled by the rates and nature of sediment inflow and erosional and tectonic processes. Developing predictive models will require integrative studies to couple the history of erosion, mountain building, paleoclimatology, and paleo-oceanography to details of sediment accumulation and facies distribution. Groups of researchers have worked on portions of this problem, yet interactions to develop deeper understanding have been limited. Future work will require cross-disciplinary teams of paleogeographers, paleoclimatologists, stratigraphic modelers, paleontologists, geochemists, geophysicists, physical oceanographers, sedimentologists, and field geologists.

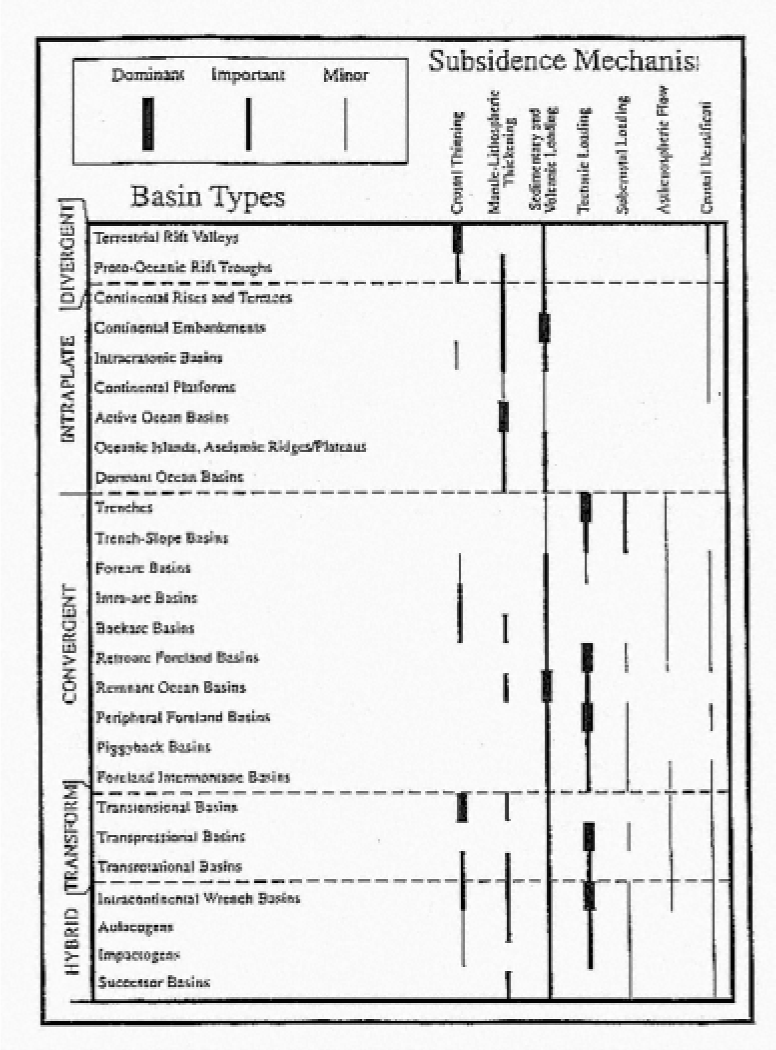

Figure 1
Suggested subsidence mechanisms for 26 types of sedimentary basins. SOURCE: Ingersoll and Busby (1995).

In these models it will be important to distinguish between a basin and its fill. As undeformed entities, individual basins are often destroyed by plate tectonic processes, but basin fill can be preserved for much longer periods. For example, some of the largest sedimentary accumulations form in complex tectonic settings, where the presence of thickened continental crust adjacent to a remnant ocean basin results in voluminous sedimentation, independent of tectonic subsidence of the ocean crust or sea-level fluctuations (e.g., the Bengal Fan). Some types of basins that are common today are rarely found in the ancient record because they are prone to uplift, deformation, and erosion (Ingersoll et al., 1995). In contrast, much basin fill is often accreted into orogenic belts to form reconstituted continental crust (e.g., Mutti and Normark, 1987; Sengor and Okurogullari, 1991). Although the preservation potential of such basins is low, the probability of preserving their strongly modified fill is moderately high. Considering these issues for a wide range of basins, there is significant variation in the preservation potential for tectono-stratigraphic elements (see Figure 2) (Veizer and Jansen, 1979, 1985). Studies of ancient deformed basin fill offer a means to test whether basin-forming processes have changed in a time-dependent way over the course of Earth history.

Integrating geologic observations into a global perspective has important implications for studies of mantle convection and plate tectonics. Because sedimentary basins arise from deformation of the lithosphere, the cold thermal boundary layer of mantle convection, sedimentary basins are an indicator of the coupled stresses and strains in the crust-mantle system. Deformation of the lithosphere, driven by mantle convection, produces vertical motions on scales ranging from compression of continental margins to broad intracratonic subsidence. A central goal for multidisciplinary studies of sedimentary basins is to use the sedimentary record of vertical motions as a fundamental constraint for global geodynamic models.

Research Perspectives

Future research should link models of basin formation over a wide range of scales (from the global to local). In this effort, global formulations of tectonic forces, subsuming global observations of stress magnitudes in the lithosphere, must be successively refined to match the observations of regional basin subsidence. New modeling techniques will

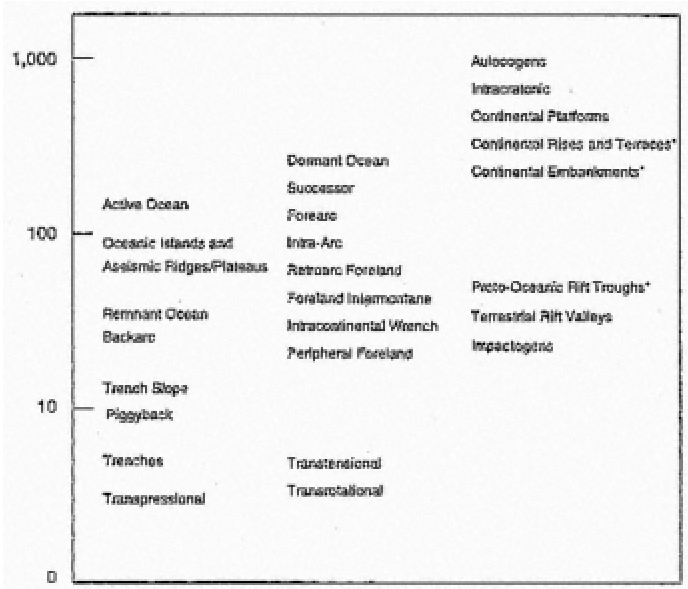

Figure 2
Typical lifespan for sedimentary basins in different tectonic environments compared to the preservation potential for the sedimentary fill. "Preservation potential" refers to the average survivor time before uplift, erosion, or tectonic destruction. Basins with asterisks are preserved in the sense that their basements are retained, but they are difficult to recognize in the ancient record. SOURCE: Ingersoll and Busby (1995).

be driven by continuing advances in computational power and new numerical algorithms for describing multiple subsidence mechanisms and complex geologic materials.

Past models have utilized simple approximations of basin geometries, tectonic driving forces, and material properties (e.g., Allen and Allen, 1990). This work has illustrated general principles of basin formation, but its applicability to specific cases has been limited by the range of interacting tectonic mechanisms that are known to be common in many basins (Figure 1). In particular, these models have not resolved the nature of sea-level changes through geologic history. As preserved in the sedimentary record, it is often difficult to determine whether changes in relative sea level arise from vertical motions of the crust (epeirogeny) or from changes in the volume of water on Earth's surface (eustasy). In cases of epeirogeny, the vertical motions may be driven by several processes. For example, in foreland basins linked to orogenic belts both supra-crustal and subcrustal loads influence basin subsidence (Beaumont, 1981), but the relative partitioning in the strength of these processes is difficult to constrain (Royden, 1993). Similarly, thermal subsidence and in-plane stresses may jointly influence subsidence both along intraplate continental margins and within intracratonic basins (Kooi and Cloetingh, 1989).

To address these complexities, there is a need for new research strategies that combine advanced geodynamic and stratigraphic modeling techniques with geologic observations. The goal of this effort will be to describe mantle and lithosphere processes, and their stratigraphic response, in a self-consistent manner so that the theory of mantle convection is fused with kinematic models of plate tectonics, basin formation, and basin filling. Successful backward modeling of well-known basins can be used as a springboard for forward modeling of unstudied basins.

For this effort the observed history of plate tectonics could be imposed as velocity boundary conditions in dynamic calculations of mantle convection using a spherical geometry and realistic constitutive relations for geologic materials. In such models, plate tectonics would evolve with a complete history of vertical motions, sea-level change, and paleogeography (e.g., Gurnis, 1992). Basin formation would result from vertical and horizontal forces on the lithosphere and basin filling from resulting patterns of sediment generation and transport (see Figure 3). Using realistic plate boundaries of thrust, transform, and normal faults breaking a thermo-chemical lithosphere, the perplexing history of

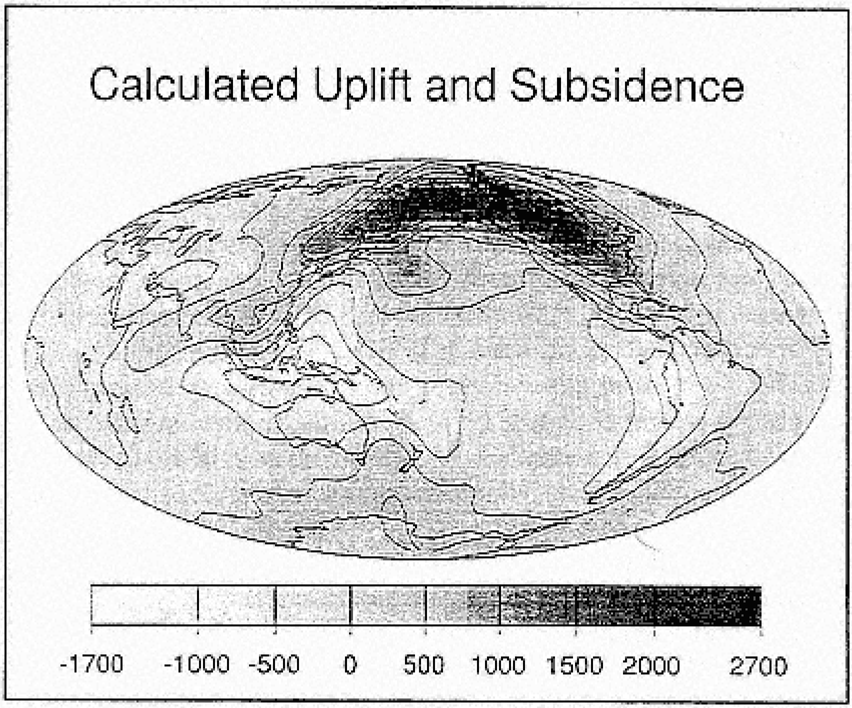

Figure 3
Map showing model calculations of the global distribution of uplift and subsidence over the past 64 million years (indicated in meters). The vertical motion arises from the change in dynamic topography resulting from viscous flow in Earth's mantle. The geodynamic model was constrained by the history of subduction since the middle Mesozoic. The model calculations provide a first-order approximation of the relative uplift of North America and the subsidence of Indonesia (courtesy of M. Gurnis, California Institute of Technology).

intracratonic subsidence also could be addressed. Ultimately, these models can be constrained by a wide range of geophysical and geologic observations regarding lateral and radial seismic structure, topography, heat flow, gravity, magnetic anomalies, borehole stress measurements, geodetic strain measurements, and stratigraphic sequences. Successful models ought to differentiate eustatic sea-level changes from the epeirogenic effects of vertical crustal motions.

Summary Overview

Tectonic appraisal of basin initiation and evolution in time and space has the intellectual scope to point always in two directions. On the one hand, knowledge of tectonic settings and global geodynamics improves interpretations of the origin and history of basin fill and the resources it contains. On the other hand, the detailed record of lithospheric subsidence and deformation represented by the stratigraphic sequences of sedimentary basins provides an incomparable template to constrain geodynamic theory. Basin research is thus a primary tool for reconstructing the history of the lithosphere as a whole.

HISTORICAL RECORD OF THE CLIMATE AND OCEANS IN SEDIMENTARY BASINS

As sedimentary basins subside, they preserve a geochemical, mineralogical, sedimentary, and paleontological record of evolving depositional environments. Given the ephemeral nature of the biosphere, hydrosphere, and atmosphere, proxy sedimentary data provide the only information regarding past climatic and oceanographic conditions on Earth's surface, as well as the rate and magnitude of natural fluctuations. These data are important because investigation of the present climate system yield only a limited understanding based on a mere snapshot of Earth history. In contrast, geologic studies document past global climate changes that are complex and that have occurred over long periods of time compared to the span to date of human history.

The sedimentary record of climatic change is critical because of the possibility that human industrial development is altering the global climate system. The rapid increase in carbon dioxide, as well as other greenhouse gases such as methane, may have significant impacts, but the magnitude of the changes and the actual variations in key climate parameters (in space and time) are difficult to predict with accuracy (Sundquist and Broecker, 1985). Climatic changes in past geologic epochs, as inferred from the sedimentary record, provide important insight and understanding for developing, calibrating, and testing numerical climate models that strive to predict future climate change. Because climate changes result from dynamic interactions between the oceans and the atmosphere, collaborations between sedimentologists, geochemists, marine geologists, paleontologists, planetary scientists, and physical oceanographers will be necessary to develop, test, and calibrate reliable models using the sedimentary record (e.g., Kutzbach, 1987).

Paleogeography and Paleoclimate

Over the past 10 to 15 years there have been numerous compilations of lithologic and geochemical data of climatic significance (e.g., coals, evaporites, phosphorites) and paleogeographic reconstructions of geologic time slices (Ziegler, 1982; Parrish et al., 1982). More powerful computer systems, robust and varied data bases, sophisticated mapping and visualization software, and detailed paleogeographic reconstructions can lead to more accurate paleoclimatic maps and interpretations. Although important products in their own right, these maps are the basis for other investigations in the areas of climate modeling and global geochemical cycles.

Paleogeographic and paleoclimate modeling investigations will be important for two reasons. First, there is a need to test and validate paleoclimate models using the climate record stored in sediments (Moore et al., 1992). Second, because the geologic record has both temporal and geographic limitations in terms of coverage, more accurate climate models could provide paleoclimate interpretations where sedimentological data are limited (i.e., in frontier exploration areas). Integrated interpretations and maps of past climatic conditions on Earth's surface could be used for many applications, including stratigraphic modeling, petroleum source-rock prediction, and geochemical-cycle studies.

The geochemical record of sediments and organic matter, when integrated with precise chronostratigraphic constraints, defines secular changes in global ocean and atmospheric chemistry. An exciting new line of research in this area is focusing on the climate record that may be embedded in the cyclicity of the stratigraphic record (e.g., Herbert et al., 1995; Hilgen, 1991). For example, quasi-periodic variations in Earth's orbit about the sun and the tilt of Earth's axis have been calculated as a time series for the past 10 m.y. (Berger and Loutre, 1990), and the main periods have been estimated back to the beginning of the Paleozoic (Berger et al., 1992). It has been shown that these variations strongly affected the Pleistocene glacial/interglacial climate (Imbrie et al., 1992), and they are called on as a possible source of climatic variations in ancient cyclic strata (Fischer, 1986). The goal for future work is to refine the tests for correlations between cyclicity in the geologic record and climatic variations and to utilize this information to further the understanding of climate change and sedimentation through geologic time (e.g., Fischer, 1986).

Paleo-Oceanography and Biogeochemistry

For paleo-oceanographic and climatic studies the most direct record of ancient ocean composition is found in the bedded evaporite minerals (chiefly halite and gypsum) associated with many sedimentary basins. For older geologic periods a chemical record of the past is only available from sedimentary basins where salts can be directly sampled. There is increasing interest in using this record of evaporated seawater to determine potential variations in seawater elemental and isotopic compositions. Evaporite samples could yield direct information via elemental analysis of individual fluid inclusions in halite and through elemental and isotopic analyses of halite and gypsum crystal growth layers. This record could be compared with the records stored in coeval carbonates to derive integrated signals of ocean chemistry through time.

Studies of the fundamental couplings among tectonic processes, sedimentary cycling, and atmosphere and ocean composition can be developed with global-scale biogeochemical modeling (Berner et al., 1983; Berner, 1994). The ground truth for integrated models is improving because of developments in trace-elemental and isotopic microanalytic tools that permit characterization of minerals, organic phases, and fluids at extremely fine scales. For example, determinations of U/Pb and Rb/Sr systematics for single detrital grains are becoming routine. Continued acquisition of detailed data sets should allow the development of biogeochemical models that can be used to better understand the processes that modulate Earth's climate and biosphere. This understanding, derived from the study of sedimentary basins, can strengthen the ability to interpret the past and to forecast changes in Earth's surface environment.

To this end, there is also great interest in using chronostratigraphic techniques to link the geologic record of the near past to modern processes. For example, coastal sediments deposited during the past few thousand years in bays, estuaries, and marine shelves contain a unique physical and chemical record of the interactions between terrestrial and marine ecosystems in response to tectonic activity, climatic fluctuations, ocean histories, and human impacts such as deforestation, hydrologic modification, and pollution. They also record, in part, the fluxes and sinks of terrestrial weathering products, biomass changes in coastal regions, and ocean-atmosphere-lithosphere interactions through time. Such information is necessary for establishing quantitative estimates of biogeochemical cycles as well as for assessing the impact of civilization on coastal environments over human history.

Summary Overview

The sedimentary record preserved in basins is a principal proxy indicator of paleoclimate and paleo-oceanography and the key basis for reconstructions of paleogeography. In this realm of paleoenvironmental concerns, as for basin tectonics, basin research points always in two directions. Even as the sedimentary record establishes the nature of past global and regional environments with implications for hydrocarbon and other resources, it also builds valuable insight for predicting future environmental conditions. The old rubric that the present is the key to the past is no stronger than the parallel rubric that the past is the key to the future.

FLUID MIGRATION AND CHEMICAL MASS TRANSFER IN SEDIMENTARY BASINS

Fluid flow that is ubiquitous within the crust and sedimentary basins has left fingerprints as chemical patterns of diagenesis, ore formation, and petroleum migration. Significant advances have been made in quantifying the nature of ground-water and petroleum migration in basins over geologic time scales and relating these flows to varied geochemical processes and tectonic forces (Garven, 1995). Improved techniques for mineral exploration and for dealing with environmental contaminants will be the fruits of continued and accelerated study of basin-scale flow systems. Applications to noninvasive mining by subsurface leaching will also be strengthened (National Research Council, 1995a).

Economically important fluid flow in sedimentary basins includes ground-water flow, hydrocarbon generation and migration, mass transfer between crustal reservoirs, development of geothermal reservoirs, and formation of hydrothermal ore deposits. Detailed understanding of ground-water flows and chemistry is critical for protecting the quality of drinking water supplies from waste products that may be stored in sedimentary basins. Circulation of subsurface fluids in sedimentary basins plays a central role in geochemical diagenesis and in forming the framework of sedimentary rock as it is compacted, cemented, modified, and lithified.

Flow Patterns

Recent work is yielding clearer ideas about characteristics of fluid flow in sedimentary basins. Field-based measurements of physical and chemical parameters such as pore pressures and fluid compositions are now being integrated with numerical simulations of flow systems. This combined approach is being applied to foreland basins, intracratonic basins, passive margins, and accretionary wedges, quantifying the crucial role of subsurface fluids in a wide range of geologic settings (see Figure 4).

Fluids migrate in sedimentary basins as a result of externally and internally generated forces. Most flow is driven by hydraulic gradients created by topographic relief in subaerial continental basins, by subsidence and compression in submarine basins, and by tectonic processes in varied types of basins. Under conditions of convergent tectonics, accretionary wedges of sediments are subjected to great deformation, and fluid flow is focused through décollement zones and thrusts. Flexural relaxation of the lithosphere creates regionally extensive gravity-driven flow systems. Fluid density gradients caused by temperature or salinity also drive fluid flow in both continental and marine basins, but they appear to be of only local significance.

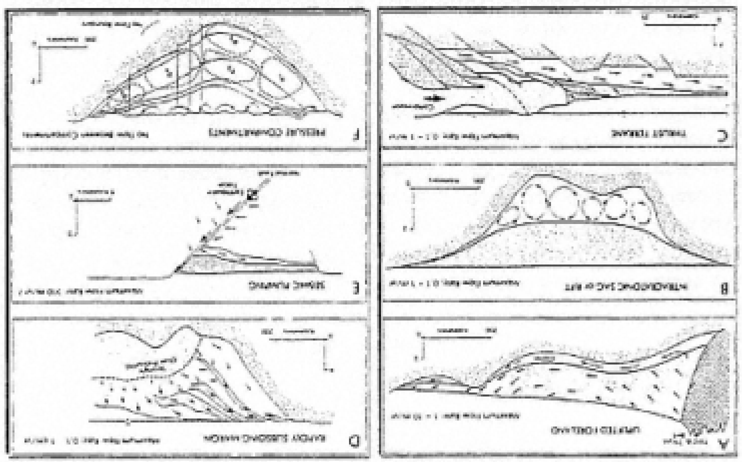

Figure 4
Hydrologic and tectonic regimes for continental-scale ground-water flow. Arrows depict general flow directions. (A) Gravity- or topography-driven flow in a foreland basin. (B) Thermally driven free convection in an intracratonic sag or rift basin. (C) Tectonically driven flow in a fold and thrust belt. (D) Overpressuring during compaction of a continental margin. (E) Seismic pumping of deep fluids in a rift. (F) Compartmentalization of a basin with no deep regional flow. SOURCE: Garven (1995); figure reproduced with permission from the Annual Review of Earth and Planetary Science Volume 23, © 1995, by Annual Reviews Inc.

In sedimentary systems, flow patterns, temperature fields, and fluid-rock interactions are all interdependent. The transport process itself modifies the physical characteristics of the rock matrix through which flow occurs; the porosity and permeability are changed as minerals dissolve and precipitate during diagenesis and hydrothermal vein deposition. Chemical reaction and transformation of organic compounds also are an integral part of the transport of heat and mass in sedimentary basins. For these reasons comprehensive models of fluid flow, tectonics, and chemical processes in sedimentary basins are critical for understanding the evolution of mineral resources and hydrocarbons.

Flow Constraints

Because of uncertainties in subsurface permeabilities and pressure regimes, direct observations are essential for understanding the coupled physical-chemical system of sedimentary basins. For example, combined elemental and isotopic measurements on formation waters and diagenetic minerals can provide direct information regarding the history of fluid migration, mobilized elements, and fluid temperatures. Oxygen-and hydrogen-isotope measurements on subsurface fluids and diagenetic mineral fluid inclusions can be used to identify water sources and the relative timing of meteoric recharge. The geochemical evolution of waters in sedimentary basins places important constraints on the relative importance of deep and shallow burial processes in shaping the physical and chemical framework of basin fill. In a few well-known basins it has already been possible to integrate the entire range of elemental and isotopic data on diagenetic minerals, waters, gases, and petroleum adequate to underpin hydrogeochemical models of mass transfer at different spatial scales in the subsurface environment.

At present, there is great reliance on subsurface measurements because porosities and permeabilities of heterogeneous basin fill cannot be predicted by theories or indirect observations. Even common rock types are difficult to model. For example, sandstones are usually porous and permeable. Locally, however, the porosity may be reduced by cementation or enhanced by fracturing. The permeability for the flow of hydrocarbons is complicated further because it depends on the local saturation level of petroleum. Faults and unconformities display as much variability in permeability structure as sediment layers. Either may be conduits, barriers, or seals. For these reasons the permeabilities that control subsurface flow are both time-dependent and spatially dependent properties of sedimentary basins. A major goal of sedimentary basin research is to develop models that are able to predict the permeability and storage capacity of specific sediment layers, unconformities, and faults.

Recently, there has been enhanced development of numerical methods for hydrologic modeling of flow in sedimentary basins (Person et al., 1996). New hydrologic research is focused on the geologic mechanisms of deep fluid flow, with the aim of improving exploration for metallic ores and petroleum reservoirs. Two-dimensional models of coupled fluid and heat transport have met with the greatest success in developing quantitative pictures of ore-forming processes, geothermal histories, and regional oil migration for ancient basins. Recent hydrologic models are also providing a better description of diagenesis and structural deformation, and they are valuable for evaluating deep disposal of hazardous wastes in low-permeability shale and salt. Field observations and simulation of pore pressures within accretionary wedges and thrust belts have documented the role of tectonically driven flow.

Transient fluid flow and heat transport in basins can be modeled with a continuum approach, though there are limitations in the representation of fractured rock, the scale effects of heterogeneities, and the availability of reliable data on permeability and other rock characteristics. Multiphase fluid flow and heat transport are described by the conservation equations for fluid mass and thermal energy. The flow equations are coupled by their common dependence on water density and viscosity, which must be specified by suitable equations of state. Nonlinearities arise because of the dependence of permeability on the saturation contents of the respective fluid phases. Further complications arise if deformation is strongly coupled to the flow pattern as additional equations for stress and strain are needed to conserve solid mass (Neuzil, 1995).

As part of the federal High Performance Computing and Communications Initiative,[1] consortia of computer scientists, hydrologists, and geologists are working to develop algorithms and codes to model flow in porous media on massively parallel computers. These

[1] The High Performance Computing and Communications Initiative coordinates federal research on computer technology across a wide range of agencies with the goals of extending U.S. leadership in high-performance computing and networking; disseminating new technologies to serve the economy, national security, education, health care, and the environment; and to spur gains in U.S. productivity and industrial competitiveness. See National Research Council (1995a, 1996).

simulations are applied to multiphase, multicomponent, reactive flow in complex ground-water, root-soil, and petroleum systems. For petroleum reservoir engineering these models have been used to simulate tertiary oil recovery in systems with a million grid blocks and thousands of wells. The models can also be applied to ground-water remediation strategies for contaminated aquifers (Sudicky and Huyakorn, 1991).

Efforts are under way to develop a new generation of models for describing fluid migration at the basin scale over geologic time intervals. These models will have the capability to predict the ancient hydrologic history of a sedimentary basin together with the related processes of organic maturation, hydrocarbon migration, rock alteration, and mineralization.

Important goals for this work include

- the development of integrated hydrologic-geothermal-geomechanical models with applications to the formation of sedimentary basins, diagenesis, ore formation, and petroleum migration;
- the use of stochastic theory to characterize heterogeneities in the permeability of porous and fractured sediments; and
- new quantitative models to predict sealing or leaking across faults based on stratigraphy and deformation.

Summary Overview

Frontier research efforts are now under way to develop a new generation of coupled hydrologic, chemical, thermal, and mechanical models to predict basin-scale fluid (aqueous and hydrocarbon) migration together with tectonic and chemical processes over geologic time scales. Further development of such models is critical for understanding basin evolution, diagenesis, deep crustal fluid circulation, fault zone permeability, petroleum and ore formation, and options for waste disposal. Obtaining ground-truth data via geologic, geochemical, and geophysical observations is equally important to the success of these innovations.

NEW TECHNOLOGIES FOR MULTIDISCIPLINARY STUDIES OF SEDIMENTARY BASINS

The opportunities for multidisciplinary research on sedimentary basins are driven in part by technological advances for data acquisition and analysis. The technological challenge for this work is to devise new methods to chart the subsurface of basins, to characterize the chemical and physical complexity of basin materials, and to model basin processes over a broad range of time and spatial scales.

New chemical analytical techniques for rocks and pore fluids continue to improve the understanding of sedimentary processes and phenomena through geologic time. For example, laser microsampling now provides detailed stable-isotope and trace-element data for fluid inclusions, authigenic mineral layers, and microfossils. Coupled with paleontological analyses of marine microfossils in deep-sea sediments, these stable-isotope and trace-element microanalyses provide quantitative measures of global climate and ocean behavior over diverse time scales. In organic geochemistry, compound specific isotope analyses and new biomarker methods are valuable for interpreting depositional environments, tracing fluid flow patterns, and understanding oceanic processes (Cubitt and England, 1995; Waples and Machihara, 1991; Schoell et al., 1994). Finally, recent measurements of ^{3}He variations in marine sediments may reflect variations in cosmic dust influx that are possibly coupled to orbital variations that influence climate (Farley and Patterson, 1995).

Sophisticated time-temperature models of basin history are now practical, based on innovations in the fields of fission-track dating and high-resolution $^{40}Ar/^{39}Ar$ thermochronology (Gleadow et al., 1983; Zeitler, 1987; Lovera et al., 1989). Over the past decade, apatite fission-track analysis has developed into a highly useful technique for studying low-temperature thermal histories of rocks. It has particular utility in oil exploration because its range of temperature sensitivity (20°–125° C) overlaps the window for oil formation (Corrigan, 1991; Ravenhurst et al., 1994). By comparison, $^{40}Ar/^{39}Ar$ analyses of potassium feldspars document thermal histories in the range of 150°–300° C, thereby complementing the apatite results. From these combined data sets, erosional events can be documented, unconformities in sedimentary sequences can be explained (e.g., Arne, 1992; Krol, 1996; Shaw et al., 1992), and the understanding of thermal controls on basin formation and evolution and their possible links to mantle processes can be advanced (e.g., Dumitru, 1988).

Tools and methods from a wide range of disciplines have been developed for innovative applications in the study of sedimentary basins. For example, nuclear magnetic resonance and advanced borehole imaging tools are providing unparalleled pictures of the deep subsurface. Paleontologists are utilizing DNA sequencing techniques to investigate the historical record of evolutionary processes. Satellite images from Landsat and SPOT are used by the petroleum industry to aid exploration of unstudied basins. Also, ground-penetrating radar and high-resolution magnetic surveys utilizing precise positioning are finding new applications for remote sensing of the subsurface.

Advances in high-performance computing have stimulated increases in the capabilities of seismic reflection techniques for subsurface imaging. Currently, it is possible to obtain accurate depth images over large three-dimensional regions of the crust (1,000 km^3) (National Research Council, 1996a). Combined with advanced visualization technologies and ancillary data sets (e.g., porosity, electrical conductivity), these methods have significantly improved interpretations of subsurface structures. Similarly, recently developed algorithms for processing and comparing three-dimensional seismic reflection surveys from different times have provided dramatic images of subsurface fluid flow.

FUNDING MECHANISMS FOR BASIN RESEARCH

Federal support for basin research is provided by several agencies, most notably the National Science Foundation (NSF), the U.S. Department of Energy (DOE), the U.S. Geological Survey (USGS), the Environmental Protection Agency (EPA), and the National Oceanographic and Atmospheric Administration (NOAA). For university scientists the private sector has provided significant support in the form of research funds, samples, and proprietary data.

Within the NSF, the Earth Sciences Division supports research on the continental and coastal record of sedimentary basins, while the Ocean Sciences Division supports ocean basin and deep ocean water research. Fundamental sedimentological, geochemical, and tectonic processes that shape modern and ancient sedimentary basins fall within the domain of the Earth Sciences Division. In the past several years, new initiatives with a strong multidisciplinary approach to scientific research have been successfully advanced at NSF. These initiatives are also innovative in that they straddle not only disciplinary divisions but also the division between "pure" and "applied" research. For example, the Geologic Record of Global Change Program was initiated to place proxy sedimentary records into a climatic and oceanographic framework that transcends Directorate boundaries. The Environmental Geochemistry and Biogeochemistry Program stresses integration of hydrologic, biologic, and geochemical processes. The Active Tectonics Program aims to support work on lithospheric processes that shape the human surface environment and are active on moderate-to-short time scales. Recently, a joint Water and Watersheds Program was established between NSF and the EPA. The program was set up to be jointly funded and administered by both agencies, with the proposal review and evaluation process utilizing available NSF infrastructure. Fundamental research on sedimentary basins deserves a similarly broad gauge and discipline-linking approach.

DOE supports several programs with active elements of basin research. Within the Office of Basic Energy Science, the Geosciences Research Program supports basic research at universities and the national laboratories on the geochemistry and geophysics of fluid-rock systems. It is intended that this basic research has applications to the extraction of oil, gas, coal, and geothermal energy; restoration of contaminated sites; and disposal of hazardous materials. By comparison, the Office of Fossil Energy supports a wide range of collaborative, cost-shared research projects among industry, national laboratories, and universities, with the goal of increasing the discovery rate and improving the recovery of petroleum resources. This program has developed many jointly funded projects with industry on reservoir characterization and secondary and tertiary hydrocarbon-recovery schemes, as well as cooperative drilling ventures that permit access to samples and data that would not be possible without industrial liaison (National Research Council, 1996b). The Advanced Computing Technology Initiative (ACTI) supports collaborative, cost-shared projects between the national laboratories and industry. A significant fraction of ACTI supports the development of new computational methods for processing and analyzing reflection seismic data of sedimentary basins. It has also launched a project to disseminate existing oil and gas production data from the United States over the Internet. Finally, DOE provides support for Grand Challenge activities within the High Performance Computing and Communications Initiative (National

Research Council, 1995b). As discussed in the section on Emerging Multidisciplinary Research Opportunities, this program funds the development of new algorithms for a wide range of porous flow problems.

The USGS conducts basin analysis in support of national and global energy resource assessments and environmental investigations. Much of this work is performed by the Energy Resource Surveys Program to assess the energy resources of the United States and the world; to predict the occurrence, distribution, and quality of energy resources; and to provide scientific knowledge for minimizing the environmental impacts of energy extraction. Publications from this program have provided broad data sets (oil production histories, seismic reflection data, mineral assessments, and geologic maps) for studies of sedimentary basins throughout the world. Much of this work is carried out by USGS employees.

Finally, the U.S. Global Change Research Program coordinates the research budgets among a broad range of federal agencies and departments related to global change. For 1995 these funds totaled approximately $1.8 billion. Through this program, NSF, DOE, NOAA, and the National Aeronautics and Space Administration (NASA) provided some $42 million for research on tectonics, coastal carbon cycles, sea-level change, and the historical record of climate and biological change.

3

Conclusions and Recommendations

The panel's survey of multidisciplinary research on sedimentary basins demonstrates a broadening beyond the traditional questions of identifying and extracting nonrenewable resources. By preserving a record of vertical motions of the lithosphere through time, sedimentary basins provide unique leverage for reconstructing the geodynamic history of Earth. Because of growing interest in environmental issues and global climate change, sedimentary basins also have become the crux for studies of interactions among the solid Earth, its hydrosphere, atmosphere, and biosphere. At the same time, important practical concerns regarding the quality of water resources and the disposal of industrial wastes are shaping the future of research on the hydrologic properties of basins. Minerals and fossil fuels are still important research issues, but there is a growing effort to integrate these questions into a more comprehensive agenda for basin research.

To address these problems, there has been increasing interest in multidisciplinary research strategies for basin studies. For example, research teams of geologists, geophysicists, geochemists, and petroleum engineers are now common throughout the petroleum industry. Industry-academic-government consortia have combined modeling, fieldwork, and laboratory measurements to develop an unprecedented understanding of subsurface fluid-rock systems. And scientists from diverse fields such as mantle geodynamics, oceanography, sedimentology, stratigraphy, paleontology, and hydrology are working together to study and interpret the historic record of geologic processes stored in sedimentary basins. The panel believes that continued efforts to encourage such collaborations among a wide range of geoscientists is a critical goal for strengthening basin research in the future.

Today, multidisciplinary research on sedimentary basins is focused on understanding and predicting

- basin formation within the framework of plate tectonics and mantle convection;
- hydrocarbon generation and migration during basin evolution;
- present and historic fluid flow and chemical transport;
- changes in basin fill and thermal evolution with the tectonic environment;
- spatial and temporal variations of subsurface porosity; and
- the record of tectonics, climate, and sea-level change preserved in sedimentary basins.

Developing a broad research agenda for basin studies will be important because there is considerable overlap among these topics. For example, predicting hydrocarbon formation and migration requires information on porosities and thermal and tectonic histories. Models of fluid and chemical transport depend on the distribution of rock types in a basin as well as the variations in porosity. Models of basin formation utilize a broad range of information to constrain the historical record of subsidence, fill, and chemical evolution. And patterns of subsidence through time help constrain geodynamic theories of Earth behavior.

Because of these interrelationships, advances in one research area may rely on advances in distant fields. For example, accurate interpretations of the paleo-oceanographic record in sediments may require advances in the subsurface visualization of basins obtained through reflection seismology and high-performance computing. Similarly, hydrologic flow models could be improved through enhanced understanding of fault distributions and rock properties in basins.

Future basin research will also be challenging because of the extreme heterogeneities of basins and basin materials over a range of length scales from the micron scale of the mineral-fluid interface of a particular grain to variations in sequence stratigraphy over distances of hundreds of kilometers. Moreover, geologic observations document that basins form in many different tectonic settings (Figure 1). This complexity suggests that accurate modeling of basin processes will require extremely fine spatial resolutions; large volumes of observational constraints derived from subsurface, field, and laboratory measurements; and a comprehensive understanding of the physical and chemical processes governing basin formation and evolution. As is common in the study of complex systems, the greatest challenge of this work will be to generalize modeling results to develop unified understandings and theories (e.g., Kauffman, 1993). To this end, the panel makes the following recommendations.

DEVELOPMENT OF A COMPREHENSIVE SET OF BASIN MODELS

The panel believes that there should be focused effort to develop a comprehensive set of models for studying the origin and evolution of sedimentary basins. In detail, such models would improve the understanding of diverse processes such as fluid flow along fractures, the history of mineral and fluid reactions with basin subsidence, and the record of global climate change preserved in basin materials. Linked together, such models would contribute to a new integrated understanding of sedimentary basins with broad implications for research across the geosciences, for identifying and extracting mineral and fossil fuel resources, and for preserving the quality of vital water resources for society. Strategies for this modeling effort should focus on

- improved characterization of basin materials over all length scales;
- strengthened efforts to collect and archive subsurface data on sedimentary basins;
- refined theoretical understanding of the processes that modify basins through geologic time, including mantle convection, subsurface porous flow of fluids, and the thermodynamics of reactions among fluids, minerals, and biomass at depth, and
- synthesis and linking of existing models to form a comprehensive yet flexible set of models for describing the formation and evolution of sedimentary basins.

Supporting this effort will require innovative funding mechanisms that emphasize collaboration among federal agencies, industry, and the academic community and link existing disciplinary research programs related to sedimentary basins. As an example, the panel believes that there would be significant benefit in establishing collaborative programs among the National Science Foundation and the U.S. Department of Energy's Office of Fossil Energy and Office of Basic Energy Sciences, with appropriate liaison with efforts by the U.S. Geological Survey (USGS) in basin research and relevant programs of the National Aeronautics and Space Administration, National Oceanic and Atmospheric Administration, and Environmental Protection Agency. Such an effort would strengthen communication among industry, government, and academic scientists and would enhance the dissemination of subsurface data collected by industry through drill cores and reflection seismology.

DATA FOR BASIN RESEARCH

Basin models are critically dependent on accurate and complete data sets describing the subsurface environment. Petroleum companies have recognized the economic value of such information and have spent billions of dollars over the past 40 years collecting reflection seismic data, well cores, borehole logs, and production data from oil fields. While much of this information is still proprietary, there has been recent interest in releasing, preserving, and archiving much of these data partly because of the great value for a wide range of applications beyond petroleum geology. These include environmental protection, waste disposal, water resource management, global change studies, and seismic hazard mitigation. There has also been concern that these data may be lost through the process of corporate downsizing and from degradation of the storage media (e.g., magnetic tapes).

To address these problems, the American Geological Institute (AGI) has initiated a project to establish a national system of publicly available repositories for data from the oil and gas industry (termed the National Geoscience Data Repository System). This project has identified data sets that corporations would transfer to the public domain for such a repository (approximately 25 percent of the reflection seismic data and 50 percent of the well cores collected in the United States). Detailed planning for this effort is under way. At the same time, the Shell Oil

Company has donated its core and sample repository to the Bureau of Economic Geology at the University of Texas. These data were obtained from wells in 40 states and include 670 km of core. The USGS is also playing a key role in the overall effort to preserve data in accessible formats (e.g., widely distributed compact disk data archives), and the AGI is developing a geographic browser for improved access to data on a national basis.

The panel recommends continued funding for efforts to preserve, archive, and disseminate data on sedimentary basins. This information was collected through substantial investments by the petroleum industry, and it is unlikely that data gathering on this scale will ever be repeated for sedimentary basins in the United States. If adequately preserved and archived, these data sets will sustain continued advances in basin research for many years. The panel emphasizes that the value of these data will be enhanced by appropriate dissemination (and processing) activities to increase access and provide additional information regarding the content, scope, and quality of the data.

There have been efforts to assemble data archives that synthesize the extensive multidisciplinary data sets that have been collected from petroleum-producing regions. Because much of this information is proprietary, these efforts rely on the public release of data. One such archive has been constructed by the Global Basins Research Network for a 60 km × 40 km × 10 km volume of Plio-Pleistocene Gulf Coast sediments. Referred to as a "data cube," the archive synthesizes measurements of surface heat flow; gravity; reflection seismic profiles; well logs; and subsurface temperatures, pressures, and fluid and mineral compositions.

The panel believes that these types of comprehensive data archives represent an invaluable source of information for multidisciplinary studies on sedimentary basins and that there should be continued efforts to develop additional data cubes for basins throughout the United States and the world.

ROLE OF SCIENTIFIC SOCIETIES

Research on sedimentary basins concerns the membership of several scientific societies in the United States, the largest being the Geological Society of America (GSA), the American Association of Petroleum Geologists (AAPG), and the American Geophysical Union. Additional societies that are active in this area include the SEPM

(Society for Sedimentary Geology), the Society of Exploration Geophysicists, the Society of Economic Geologists, the American Institute of Hydrology, the Soil Science Society of America, and the Paleontological Society.

On an international scale, there are analogous organizations, such as the International Association of Sedimentologists. Currently, the International Lithosphere Program of the Inter-Union Commission on the Lithosphere coordinates some of these activities through its task force on "The Origin of Sedimentary Basins." This project is focused on strengthening international collaborations between industry and academic scientists in an effort to develop multidisciplinary models of sedimentary basins. Since 1990, the project has sponsored five workshops at scientific meetings in Europe and the Middle East (e.g., Cloetingh et al., 1994).

In the effort to develop a comprehensive set of models for sedimentary basins, the panel believes that scientific societies and unions will play an important role. For example, through their meetings and special workshops, societies can shape and focus the research agenda on sedimentary basins. To this end, collaborative efforts between particular societies (e.g., between AAPG and GSA) can facilitate new research strategies. Because societies represent a wide range of scientists from university, government, and industry, they are in an ideal position to coordinate many of the difficult issues in developing collaborative research programs. These include facilitating access to proprietary data, developing industry-academic-government research consortia, developing innovative mechanisms for joint industry-government funding of basin research, and encouraging increased research efforts by the environmental remediation industry.

The panel recommends that the broad range of geoscience societies take an active role in facilitating progress toward the development of a comprehensive set of models for sedimentary basins. For this effort, both special sessions at regular meetings and cosponsored symposia or research conferences could be particularly effective. The panel believes it would also be useful for scientific societies to convene joint industry-academic-government roundtable discussions on critical organizational issues for strengthening multidisciplinary research on sedimentary basins. Finally, the panel stresses that it is important for U.S. scientific societies to strengthen their collaborations with ongoing international programs regarding the origin and evolution of sedimentary basins.

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