North American Continent-Ocean Transects Program

U.S. Geodynamics Committee, Board on Earth Sciences and Resources, National Research Council

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U.S. Geodynamics Committee
Board on Earth Sciences and Resources
Commission on Physical Sciences, Mathematics, and Resources
National Research Council

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IN MEMORIAM

Edward A. Flinn

(1931-1989)

From 1980 to 1986, Edward A. Flinn served with dedication and effectiveness as the first secretary-general of the Inter-Union Commission on the Lithosphere which was established to develop and oversee the International Lithosphere Program (ILP).

During this period, he was an *ex officio* member of the U.S. Geodynamics Committee. Thereafter, as Vice-Chairman of Working Group I and Past Secretary-General, he served as one of the USGC-ILP reporters.

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PREFACE

The Continent-Ocean Transects Program was initiated by the U.S. Geodynamics Committee (USGC) early in 1979, as a study of the structure and Phanerozoic evolution of the transitional region between the craton and oceanic lithosphere.

The USGC appointed Robert C. Speed as reporter of the USGC to coordinate the Transects Program. On behalf of the USGC, he provided leadership in developing and carrying out the program. Transect groups were organized for a series of corridors on the margins of the United States. Specific plans were developed for the conduct of the program and for presentation and publication of the results. Within two years after its initiation, the program expanded to include Canadian and Mexican corridors; thus it became a North American Continent-Ocean Transects Program. It is regarded as a contribution to the International Lithosphere Program.

The resulting maps, sections, and text of the North American Continent-Ocean Transects Program are being published by the Geological Society of America as part of its program on the Decade of North American Geology.

Comparison of the transition zone around the continental margins, and development of plans for future research were basic objectives of the transects program. Accordingly, initial planning for the Transects Program called for a report by the USGC giving an overview of the results of the program and guidance for the future—the present report.

This report on the North American Continent-Ocean Transects Program consists of two parts: Part I—Overview and Recommendations; Part II—North American Continent-Ocean Transitions (general and detailed discussion of the transects).

Part I is the responsibility of the USGC, which acknowledges the substantial contribution of Robert Speed to its preparation.

Part II is the responsibility of the indicated authors: Robert Speed, coordinator of the North American Continent-Ocean Transects Program, and 23 leaders of the individual transect teams. The USGC notes that Part II is based on both published and unpublished material associated with the transects. The USGC decided that this consolidated discussion of the transects should be made available as part of its report on the North American Continent-Ocean Transects Program.

The U.S. Geodynamics Committee is pleased to acknowledge the continuing support of the the Department of Energy, the National Science Foundation, the National Aeronautics and Space Administration, and the U.S. Geological Survey for the various activities of the committee, and the specific support of the National Science Foundation and U.S. Geological Survey for the North American Continent-Ocean Transects Program.

Expansion of the original Transects Program to become a North American Continent-Ocean Transects Program was welcome. A broader, unforeseen result was the launching in 1985 of the Global Geoscience Transects Project (under the International Lithosphere Program), modeled in large part on the successful North American Continent-Ocean Transects Program.

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PART I

OVERVIEW AND RECOMMENDATIONS

1

Overview

INTRODUCTION

The North American Continent-Ocean Transects Program is a study of the structure and Phanerozoic evolution of the transitional region of the North American hemisphere between its craton (Figure 1, zone 1) and bordering oceanic lithosphere (Figure 1, zone 5).

The U.S. Geodynamics Committee (USGC) places strong emphasis on the importance of the transition zone between continental and oceanic lithosphere. In 1978, the USGC recommended that a series of transects be prepared to set forth existing geological, geochemical, and geophysical data along a series of corridors around the U.S. coast—from the continental craton across the transition zone to the oceanic lithosphere.

The USGC initiated the Transects Program early in 1979. The USGC appointed Robert C. Speed as reporter of the USGC to coordinate the Transects Program. On behalf of the USGC, he provided leadership in developing and carrying out the program. Transect groups were organized for a series of corridors on the U.S. margins. Specific plans for the conduct of the program and presentation and publication of the results were developed. Within two years after its initiation, the program expanded to include Canadian and Mexican corridors; thus it became a North American Continent-Ocean Transects Program.

The program includes about 200 geologists and geophysicists from Canada, Mexico, and the United States. It is jointly sponsored by the U.S. Geodynamics Committee, the Canadian Committee for the International Lithosphere Program, and the Institute of Geology, University of Mexico. The Transects Program has received direct support from the National Science Foundation, the Geological Society of America, the University of Mexico, the Geological Survey of Canada, and the U.S. Geological Survey and indirect support from the many institutions represented by the participants in the program. The written and graphic products of the Transects Program are published mainly by the Geological Society of America within the *Decade of North American Geology* series (see Appendix A).

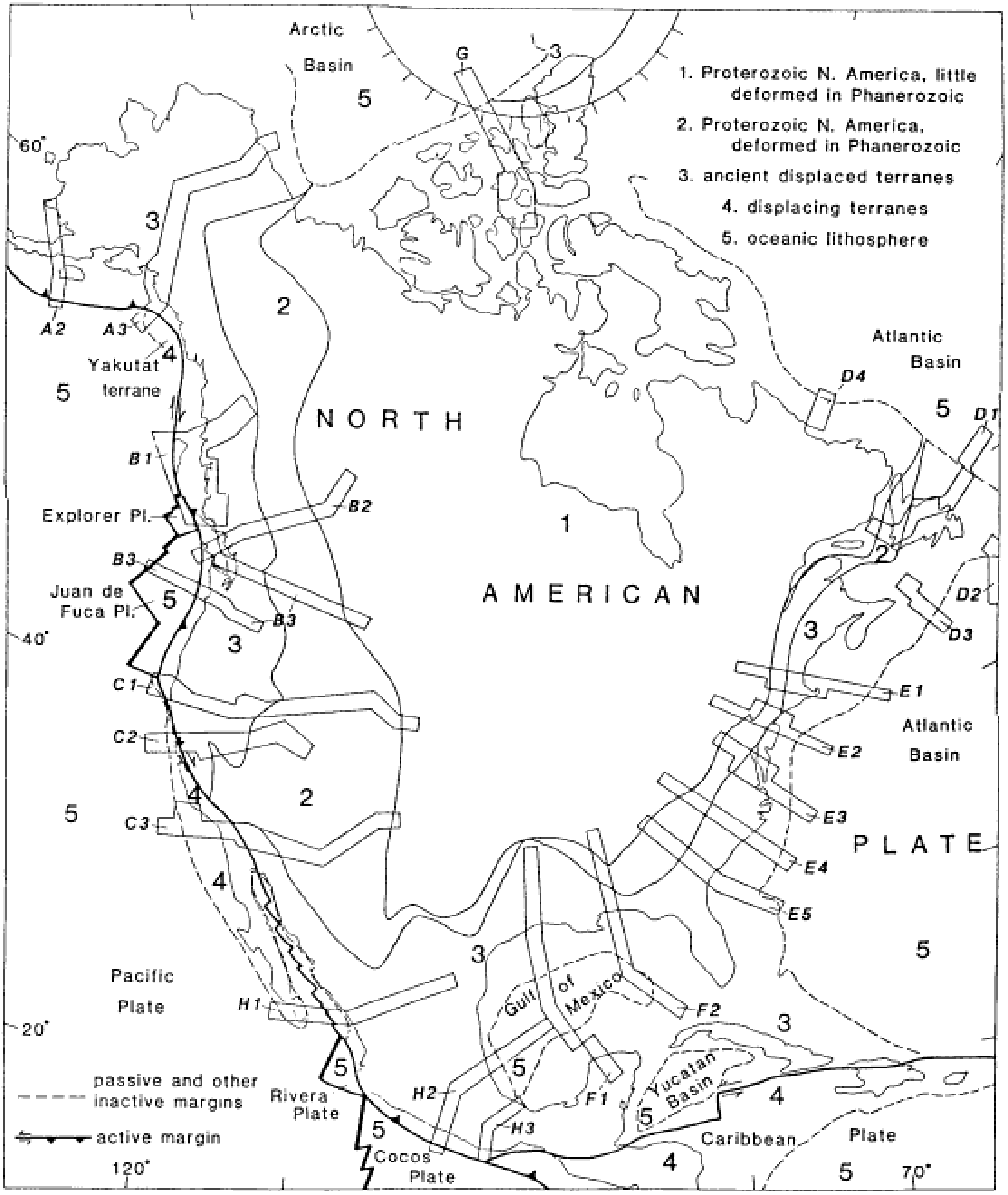


Figure 1
Map of North American continent and plate showing positions of 23 corridors of the Transects Program.

PROGRAM OBJECTIVES

The objectives of the Transects Program are threefold:

1. To analyze the structure, motions, and processes of the transitional zone between the North American continent and adjacent oceanic and other lithospheres and the evolution of that zone over Phanerozoic time (approximately the last 700 Ma).

The analysis is concentrated in 23 corridors that cross the transitional zone between oceanic and cratonal lithospheres where possible (Figure 1) and employs existing data. The analysis includes requirements for common presentation formats, with a goal of effective comparison of continental margin structure around North America.

2. To recognize the major gaps in understanding the character and origins of the North American continent-ocean transition, to identify the problems and avenues of study most likely to lead to breakthroughs, and to recommend to the scientific community and government the priorities and nature of research programs that can effectively solve such problems.
3. To provide coordination among major ocean- and land-based scientific programs.

In partial fulfillment of these objectives, especially the second and third, the USGC is issuing the present report.

PROGRAM ACHIEVEMENTS

The Transects Program achieved certain ends prior to the publication of its products. The program has demonstrated the ability of diverse earth scientists to collaborate successfully in the pursuit of new, broader, and more fundamental definitions of problems and interpretations of the structure and evolution of North American continental crust between the craton and oceanic lithosphere. This collaboration, together with new data, has extended former limits of thought in such topics as downward continuation of structure from surface to mantle; compatibility of motions between the oceanic terranes and the continental foreland; and event correlations around the continent's edge. Further, the Transects Program has conceived new display techniques to enhance comparability among the transects so that all members of the earth science community can recognize the important similarities and differences of continental structure and evolution around the entire margin.

Perhaps most important, the interpretations of crustal structure of the Transects Program have already stimulated the acquisition of new data by geophysical and geological profiling along several transects with the goal of testing hypotheses.

Completion and publication of many of the transects by the mid-1980s led to two unforeseen, but related, developments: recognition of the importance of digitization of future transects and the development of a Global Geoscience Transects (GGT) Project as part of the International Lithosphere Program. (See Chapter 4, "New Developments.")

NORTH AMERICAN CONTINENT

For the Transects Program, the North American continent is defined as the region currently bounded by oceanic lithospheres of the Atlantic, Arctic, and Pacific basins and by the North American-Caribbean plate boundary (Figure 1). The continental edges adjoining the Atlantic and Arctic oceanic lithospheres are passive margin types; they occur within the North American plate. Greenland and an undefined region offshore of western Alaska belong to the North American continent under this definition, but the Transects Program has not included them in its study. The edge of North America bordered by the Pacific basin is mainly a series of active margins between the

North American continent and a number of oceanic plates. In fact, the continent occupies the Pacific plate at two places; thus, today's North American continent contains plate boundaries.

The southern edge of the North American continent is less clearly delineated because much of it is below sea level and because of the two closed oceanic basins, the Gulf of Mexico and the Yucatan basin. The Transects Program has arbitrarily assigned to the continent all regions of the North American plate not floored by oceanic lithosphere as far south as its boundary with tectonic borderlands of the Caribbean plate (Figure 1).

PRESENT AND PAST CONTINENT-OCEAN TRANSITION

Today's transitions of the North American continent to adjoining oceanic lithosphere mark the sites of the most recent plate boundary tectonics to have shaped the continent in each region. At active margins, such tectonics are ongoing, whereas at passive margins, they range from modern (Gulf of California) to as old as mid-Mesozoic (central Atlantic). Much is learned at existing continent-ocean transitions regarding instantaneous relative motions, earthquake-derived kinematics, and concurrent geophysical expressions of the way continental and oceanic lithospheres interact. Such studies show, moreover, that relative motions between plates are widely distributed and heterogeneous and that a broad zone spanning the continental edge must be studied to address the interactions fully.

It is now well known that most oceanic lithosphere is returned to the mantle after a brief residence (`200 Ma) at the surface whereas continental and other types of nonoceanic lithospheres survive, at least in some proportion, at the surface. It is also now evident that continents, their shapes and volumes as well as positions, have evolved markedly through time. Plate boundary motions have transferred small and large fragments from position to position within a continent and probably from continent to continent; moreover, they may have caused some loss of continent to the mantle by subduction and addition of mantle to continent via magmatism and underplating. The history of these and other processes associated with continent-ocean interactions, therefore, is recorded within the continents. A full understanding of the evolution of the North American continent requires a synthesis of the structure and processes across the continent-ocean transitional zones as a function of position and time over geological history.

The Transects Program addressed this sizeable task by studying the structure of 23 corridors around the North American continent, each 100 to 200 km wide and aligned normal to, and crossing, the local modern margin. The analysis is carried to depths that include (as a minimum) the top of the mantle. The historical duration adopted is Phanerozoic time, loosely defined as about 700 Ma. This choice was based on the occurrence of widespread plate tectonic events near the end of Proterozoic time that gave rise to the general size and shape of cratonal North America today.

North American Continental Zonation

The present North American continent can be divided into four tectonic zones (1-4, Figure 1). Zones 2-4 constitute what is here called the transitional region—the part of the continent that has been shaped by continent-ocean tectonic interactions in Phanerozoic time. The transitional region lies between cratonal and oceanic lithospheres except in southernmost North America (Figure 1). Some of the boundaries and tectonic components of zones of Figure I are not yet well documented or agreed upon; it has been a goal of the Transects Program to improve regional tectonic divisions and delineations. The following paragraphs define the tectonic zonation.

Zone 1: Cratonal North America: This is the undeformed sialic nucleus of North America, which has behaved as a continuous, nearly rigid unit at least since the Proterozoic. Cratonal North America is a single tectonic unit, and it provides the reference frame for the history of relative motions of units in the tectonically active outboard zones in the last 700 Ma. The periphery of zone I is a post-Precambrian deformation front.

Zone 2: Deformed North America: This zone contains Proterozoic North America and its cover, which has undergone significant deformation related to Phanerozoic continental margin tectonics. Unlike zone 1, zone 2 consists of multiple tectonic units, which presumably reflect different loci, times, and mechanisms of plate boundary events that affected the margin of Precambrian sialic North America. Although zone 2 is probably well fragmented, the pieces have probably not moved great distances with respect to one another or to zone 1. However, zone 2 may have been the source of continental fragments that have undergone large displacements and now exist in zones 3 or 4 or among accreted terranes of other continents. Examples of tectonic units in zone 2 are the nappes of the Valley and Ridge province and Blue Ridge province, and the Rocky Mountain fold and thrust belt. Of special interest are the reactivation of old discontinuities by new phases of margin tectonics and the correlation of style of structures with type of margin tectonics.

Zone 3: Ancient Displaced Terranes: Zone 3 comprises terranes that are tectonic units that have certainly or probably undergone large transport but that are now fixed with respect to cratonal North America. Terranes include fragments of continents, arcs, oceanic lithospheres, deformed oceanic strata, and rocks of uncertain origin. Zone 3 also includes cover strata and igneous rocks that formed in place after attachment of displaced terranes to North America or earlier accreted units. Examples include the Avalon and Meguma terranes of the Canadian Appalachians, the Pericu and Zapoteco terranes of Mexico, and Stikinia and Wrangellia of the Pacific Northwest. Important considerations are the sources of such terranes, transport histories, times of attachment, coalescence with other displaced terranes before accretion to North America, internal tectonic history, and deep structure.

Zone 4: Displacing Terranes: The modern continent of North America incorporates parts of the Pacific plate as well as the North American plate. These parts (zone 4, Figure 1) are evidently moving with respect to zone I and are joined to the rest of North America by active margins. Displacing terranes are Baja and Alta California west of the San Andreas fault system and the Yakutat terrane west of the Queen Charlotte fault.

To understand the structure, tectonics, and Phanerozoic evolution of the continent-ocean transition of North America, the Transects Program has proceeded as follows: (1) analyzed tectonic zones 2-4 in terms of their constitutive tectonic units, which reflect past or present relative motions, (2) synthesized an evolution of these units into their current configuration as North America, and (3) interpreted the processes involved.

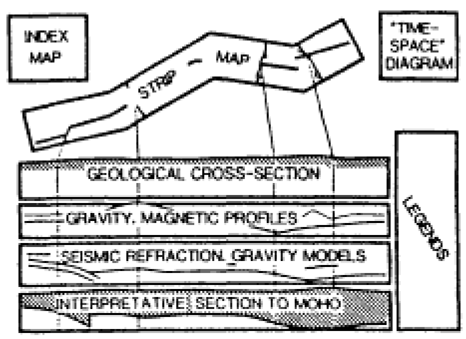
Corridors

Study corridors have been chosen to transect the tectonic zones from cratonal North America to oceanic lithosphere (zones 1 to 5). The exceptions are Mexico and Alaska, where the transects do not intersect Proterozoic North America (zones 1 and 2). The 23 corridor locations are selected to provide hemispheric representation of North American continent-ocean transitions, but more important, they incorporate the most significant examples of modern and ancient continental margin structures.

An important element in understanding the evolution of the transition is the ability to compare its structure corridor by corridor. To achieve comparability, corridor displays and discussions in the Transects Program are standardized by the inclusion of mandatory entries and formats (Figure 2). The mandatory entries include:

1. A tectonostratigraphic strip map of the corridor, colored according to protolith age.
2. A cross section depicting tectonic units that are colored according to a standardized hemispheric code; this section goes at least to the Moho.
3. Factual geological cross section that depicts rock stratigraphic units that are colored according to protolith age.
4. Geophysical profile data.
5. A tectonostratigraphic event diagram that shows kinds of tectonic events as functions of corridor position and age.

Preparation of the transects was predicated on the use of existing data. Cooperation among academia, government, and industry was an important element in the success of the program. There was coordination with other major geoscience programs. In particular, the results of deep seismic reflection profiling were integrated into the transects.



Legend for Figure 2.

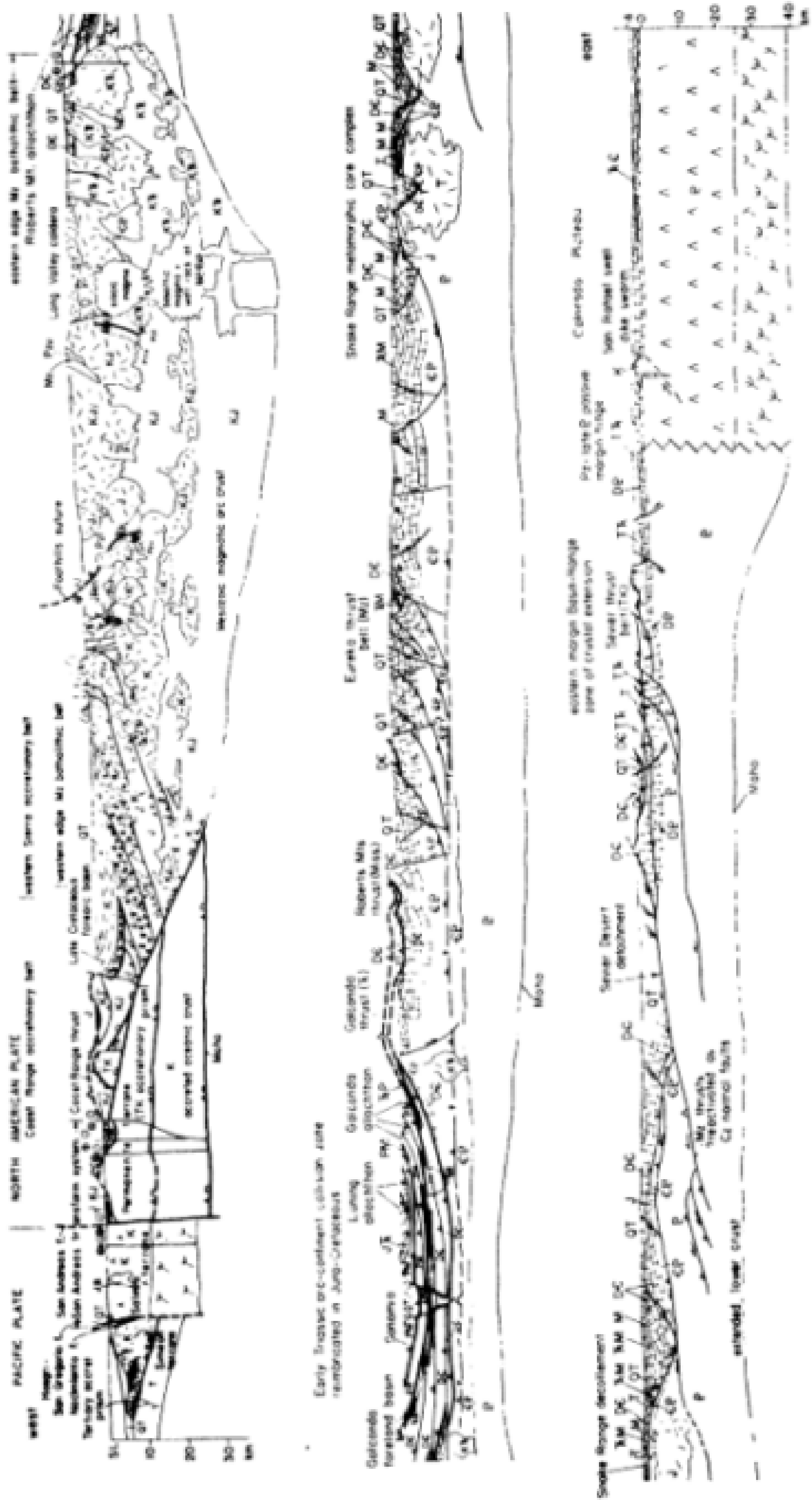


Figure 2
Diagrammatic layout of common format items on transect displays and example of interpretive (tectonic) cross secti on from Transect C2. (See legend, page 8.)

2

Major Scientific Problems

A fundamental goal of the Transects Program has been the identification and description of the major problems in understanding the tectonic evolution of North American continent-ocean transitions.

That goal is addressed in Part II of this report, in which 12 general problems of continent-ocean transitions are discussed: processes of active margins, processes at passive margins, tectonic heredity, tectonic significance of magma types, identification and processes of terrane boundaries, kinematics of orogenic belts, implications of high-grade metamorphic rocks in orogenic belts, event dating, foreland-margin tectonic coupling, diagnostic geophysical expressions of tectonic units, deep continental structure and origin, and Phanerozoic changes in Proterozoic North America.

Consideration of these general problems led to identification of four specific problems that are most fundamental to an improved understanding of continent-ocean transitions:

1. Underplating and tectonic attrition: The transfer of sediment, rock, and fluid from a downgoing plate to the base of a forearc and/or crystalline lithosphere of North America at active margins.
2. Origin of the Moho and lower crust: The nature, age, and origin of protoliths of the lower continental crust and mantle immediately below the continental Moho, the processes affecting those regions, and the times over which their evolution occurs.
3. Absolute chronology of tectonic events: The absolute timing of stages of kinematic and tectonic activity in orogenic events at the North American margin, such as durations of steeply versus shallowly dipping subduction, foreland versus hinterland contraction, collision, and major unroofing.
4. Strike-slip components of terrane displacement paths: The components of terrane displacement and velocity that parallel the margins of the continent during oblique convergence that may not be recorded in the contemporaneous structures of the adjacent continental foreland.

3

Needed Investigations

There are many gaps in our understanding of the structure and evolution of North American continent-ocean transitions. The gaps and uncertainties have been translated to problems whose solutions will cause major progress in the science of the evolution of North America and of the growth and destruction of continents in general. Focused investigations are necessary to achieve the solutions in a timely and efficient manner. Moreover, they are required to bring together the broad spectrum of scientific backgrounds and resources that must be pooled to address these complex problems. Studies of continent-ocean transitions must bring together terrestrial and marine scientists from varied disciplines: geologists, geophysicists, and geochemists for observational, data processing, theoretical, and laboratory approaches.

Four principal avenues for focused investigations are outlined below: syntheses, topical investigations, processes, and techniques.

SYNTHESES

Transect analyses show the value of regional synthesis and interpretation of existing data by scientists of diverse background acting in concert. The gains in perspective, problem definition, and in many cases, new ideas of continental margin evolution, have been enormous. Equally important, each transect has conceived and displayed graphically a model of the continent-ocean transition to Moho depths. Such models should be tested by new data gathering, which in turn will lead to improved models and further refinement in our understanding of continental evolution.

The USGC advocates continuing syntheses of North American continent-ocean transitions in two modes: (1) with existing data as in the Transects Program, and (2) with new data acquisition.

1. Syntheses with existing data: There are many regions of the North American continent-ocean transition that have not been sampled by the 23 transects of the Transects Program. Studies of such regions comparable to those of the Transects Program would produce a significantly more comprehensive understanding and problem definition than exist now. Such regions contain features that may be unique and vital

to continental science and that are fundamental to analysis of lateral gradients and discontinuities in orogenic belts.

Candidate regions for a new phase of transect studies are: Aleutian Islands, northwestern British Columbia, Santa Barbara-southern Sierra Nevada, northern Labrador to Greenland, northern Mexico across Gulf of California, west Texas to the Gulf of Mexico, Florida across southern Blake Plateau, Yucatan to Cayman Trench, Bahamas to Puerto Rico, Mackenzie Delta to Canada Basin, and the eastern Baffin Islands.

2. Syntheses with data acquisition: Some or all of the models of the 23 transects should be tested and refined by acquisition and synthesis of new, comprehensive datasets that are profiled along the transects. The new investigations should include seismic profiling with source-receiver parameters designed for penetration and resolution that can maximize analysis of model features: potential field data with uniform high- and low-frequency contents; isotopic dating that will resolve protolith ages and tectonic events; detailed analyses of kinematics and conditions of deformation in displacement zones and strained rocks; and determinations of latitude anomalies and rotations of well dated magnetizations. Data from scientific drilling on land and at sea should be incorporated.

TOPICAL INVESTIGATIONS

The USGC recommends new investigations that focus on problems in three broad tectonic divisions of North American continent-ocean transitions: (1) forearcs, (2) lower crust and Moho in transitional regions, and (3) terranes and forelands of the orogenic belts.

1. Forearcs: There should be concentrated data acquisition that will lead to greatly enhanced understanding of the deep structure and processes of forearcs of North America, both those active today and those in the Cenozoic. The objective is to evaluate what may be the prime sites of tectonic progradation and/or attrition of the continental edge and at which the continental edge appears to thicken. A prime technique is seismic profiling, which may reveal the characteristics of underplated packets, underthrusting sediments, basement reliefs, ramps and sites of change of detachment level, out of sequence faults, diapirs, duplexes, lateral velocity changes indicating rheologic gradients, and the downdip length of sediment cover on the downgoing plate below the forearc and into the crystalline subduction zone. Other important studies of forearcs should include seismicity, fluid and heat fluxes, progressive deformation, and deflection of the downgoing plate.
2. Lower crust and Moho: The scientific objectives to be addressed include the origin of reflector sets in the lower crust of the transitional region, nature and thickness of the Moho, existence of motions along and mass transfer across the Moho, protoliths on both sides of the Moho, and age of the Moho. Also included here are the structures of the deeply buried, greatly extended North American crust of the Mesozoic and Cenozoic passive margins and the nature of specific features such as the outer ridge, possible mantle protrusions at the continent-ocean join, continental microplate structure (Orphan Knoll, Flemish Cap, Blake Plateau), rift basin configurations, and estimation of amount of magma added to the crust.

   Investigations of this problem may follow several lines, which should be coordinated: (a) geophysical studies, chiefly seismic, that are tuned to desired depths, are set out in three-dimensional arrays so as to determine true dips and velocity anisotropies and are flexible enough to track deep structures to shallow depths; (b) studies of magmas and xenoliths derived from lower crustal or upper mantle levels; (c) tracking to the surface of plunging lower crustal structures, and (d) study of greatly exhumed rocks that were once at depths equivalent to today's Moho in transitional regions.

3. Terranes and forelands of orogenic belts: There should be continuing study of the orogenic belts of North America with traditional goals of defining basic tectonic units and dating their times of movement and attachment. Added emphasis should be placed on analysis of kinematics of orogenic belts, on the relationships between motions in the zone of terranes and those of the continental foreland, and on subsurface structure in the zone of terranes. Further goals of this topical study are a comprehensive picture of the closure history of Laurasia and Gondwana to form Pangea and the losses of Precambrian North America in tectonic interactions at active and passive margins since the Precambrian. The reconstruction of terrane migration in Mesozoic Mexico and western North America is also a goal. Also included here is the objective of understanding the widths of modern and ancient boundary zones of the North American plate over which boundary-related motions occur.

The methods to be employed in this investigation include all those for kinematic analysis: brittle and ductile fault slips, strain to displacement calculation, satellite geodesy, paleomagnetics, seismic parameters, and barometry of metamorphism. They include extensive dating by multiple techniques, and identification of protolith kindred by isotopic signatures (Nb, Nd, Sm, Sr, Pb, etc.). They also include geophysical studies, mainly seismic, and drilling to identify and track subsurface horizons that may be terrane boundaries, especially those horizons that lead from the zone of terranes onto the edge of sialic North America.

PROCESSES OF CONTINENT-OCEAN TRANSITIONS

Aside from the areal investigations of the synthesis and topical types discussed above, studies of certain basic processes have been recognized to play major roles in tectonic zones. Examples of such processes are detachment, unroofing, reactivation in fault zones, underthrusting and wedging, accretion, attrition, diapirism, intrusion, foliation generation, defluidization, extensional failure, anatexis, initiation of subduction, onset of drifting, predrift elevation, and transform faulting. Another process that requires extensive research is continental separation and the definition of the rift-drift transition from sedimentary successions and tectonic structures.

The objectives are improved comprehension of the conditions under which each process occurs and the mechanics and kinematics. The study of processes should include observational, theoretical, and experimental means.

TECHNIQUES

Major advances in understanding come not only from the recognition of new problems or new insights, but also from the development or improvement of techniques that yield new data. The study of the continent-ocean transitions has benefited greatly in the twentieth century from new techniques, such as paleomagnetism and isotopic dating. Therefore, research on improvement of techniques is an important component of the study of continental evolution.

Specifically, advances in techniques in the following areas would be important: dating of protolith ages; dating of thermal and straining events and of unroofing times; resolution of displacement components, especially of rotations and margin-parallel and latitude-parallel components; measures of bulk finite strain and small-domain strains; barometry and thermometry; detections of major rise of fluids and fluid sources; methods of delineating structures in and tracking displacement zones to mid- and lower crustal depths; improved analysis of the structure of the Moho; and more precise geodetic analyses. Advances should be made in techniques of digitization of data and in software that are compatible with commonly used computers and that allow combination and manipulation in three dimensions.

4

New Developments

GLOBAL GEOSCIENCE TRANSECTS PROJECT

As the transects of the North American Continent-Ocean Transects Program began to appear in print, it seemed clear to the USGC that the program was quite successful in terms of its intended goals. The USGC then strongly supported the recommendation that the International Lithosphere Program undertake an international program of transects across major geological/geophysical structures.

The International Lithosphere Program is an ongoing, international program of studies of the solid earth, under the joint sponsorship of the International Union of Geodesy and Geophysics and the International Union of Geological Sciences. Guidance for the Lithosphere Program is provided by the Inter-Union Commission on the Lithosphere (ICL).

The Inter-Union Commission on the Lithosphere approved a new program—the Global Geoscience Transects (GGT) Project—at its meeting in August 1985. The planners of the GGT Project drew upon the experience of the North American Continent-Ocean Transects Program and requested assistance in specific matters. At the request of ICL, the USGC organized the preparation of a draft map of some 200 potential transects (prepared by Muawia Barazangi) and provided major assistance and support for organization and sponsorship of the Pilot Meeting on the GGT Project, held in San Francisco, 10-11 December 1985.

Planning for the GGT Project moved rapidly. ICL established a Coordinating Committee for the GGT Project, headed by James Monger (Vancouver, Canada), one of the leaders of North American Transect B2 (Juan de Fuca Ridge to Alberta Plains). Monger spearheaded organizational meetings (see below) and plans for the GGT Project.

The ICL recognizes the importance and inherent difficulty of combining the results obtained from geological investigations with geophysical data. The GGT project has thus stressed workshops and special meetings. In the period from 1986 to 1988, at least 20 workshops and meetings on GGT were held (national, regional or part of international gatherings). They include 2 in Africa, 5 in Asia and Australia, 6 in South America, 3 in North America, and 4 in Europe. Major guidelines were developed at the GGT meetings during the General Assembly of IUGG, Vancouver, August 1987. Refinements were made at the ICL meetings during the Latin-American Geological Congress in Belem, Brazil, November 1988.

The transects—positioned to cross major crustal features—range up to a few thousand kilometers in length and up to 100 km in width. Standardization of graphics (regarded as essential for the North American Continent-Ocean Transects Program) was adopted as a key principle of the GGT Project (with appropriate adaptations to accommodate a greater diversity of geological elements). The GGT displays will have common formats, scales, and color schemes. As with the North American transects, the GGT sections will extend at least to the base of the crust. In addition, GGT sections will also include detailed tectonic interpretations of Proterozoic and Archean crust (the North American transects encompassed only the Proterozoic). In general, the GGT will be based on existing data, but it is clear that newly acquired data will be needed for some of the most important transects in the GGT Project, especially in Antarctica.

The GGT Project is guided by Coordinating Committee 7 of ICL. The project is divided into twelve regions, including the Arctic and Antarctic. By the end of 1988, 168 transects had been proposed, in all 12 regions (Figure 3).

The North American sector is guided by a subgroup under the leadership of W.R. Van Schmus. Twelve transects have been accepted for the North American sector. This includes the Quebec-Maine transect (discussed below). This number does not include the recently initiated transcontinental transect along the Canadian-U.S. border and other transects in the formative stage.

From the outset of GGT planning, it was agreed that the first major international presentation (symposia, poster sessions, and workshops) of results of the GGT Project from all parts of the world would take place in July 1989 at the 28th International Geological Congress, in Washington. The GGT sessions at the Geological Congress manifested remarkable progress in the project.

DIGITAL DATA

The USGC has a long-standing interest in the utilization of geological/geophysical data in digital and computer graphic form. The USGC recognizes that digitization of geoscience data is likely to become standard practice in the relatively near future. The USGC organized an ad hoc task group under the leadership of William Hinze to investigate this issue generally, with specific reference to the problems of digitizing the North American transects. A principal objective is to make the transects more useful—in terms of changing scale and projections, viewing and analyzing the data in different ways, editing, and updating.

In July 1986, that ad hoc task group recommended a two-track plan—to digitize an existing North American transect (B2, Juan de Fuca Plate to Alberta Plains) and to develop a plan for digitizing the Quebec-Maine transect. The U.S. Geological Survey (in cooperation with the Geological Survey of Canada) implemented the first recommendation within a year and set in motion the implementation of the second. Both efforts involve the cooperation of U.S. and Canadian scientists. The Quebec-Maine transect was under way prior to 1986—in a new generation of transects. It extends from the interior of Quebec, across Maine and into the Gulf of Maine; it is a joint undertaking of Canadian and U.S. groups under the coordination of David B. Stewart. In 1987, the Quebec-Maine transect was formally included in the GGT

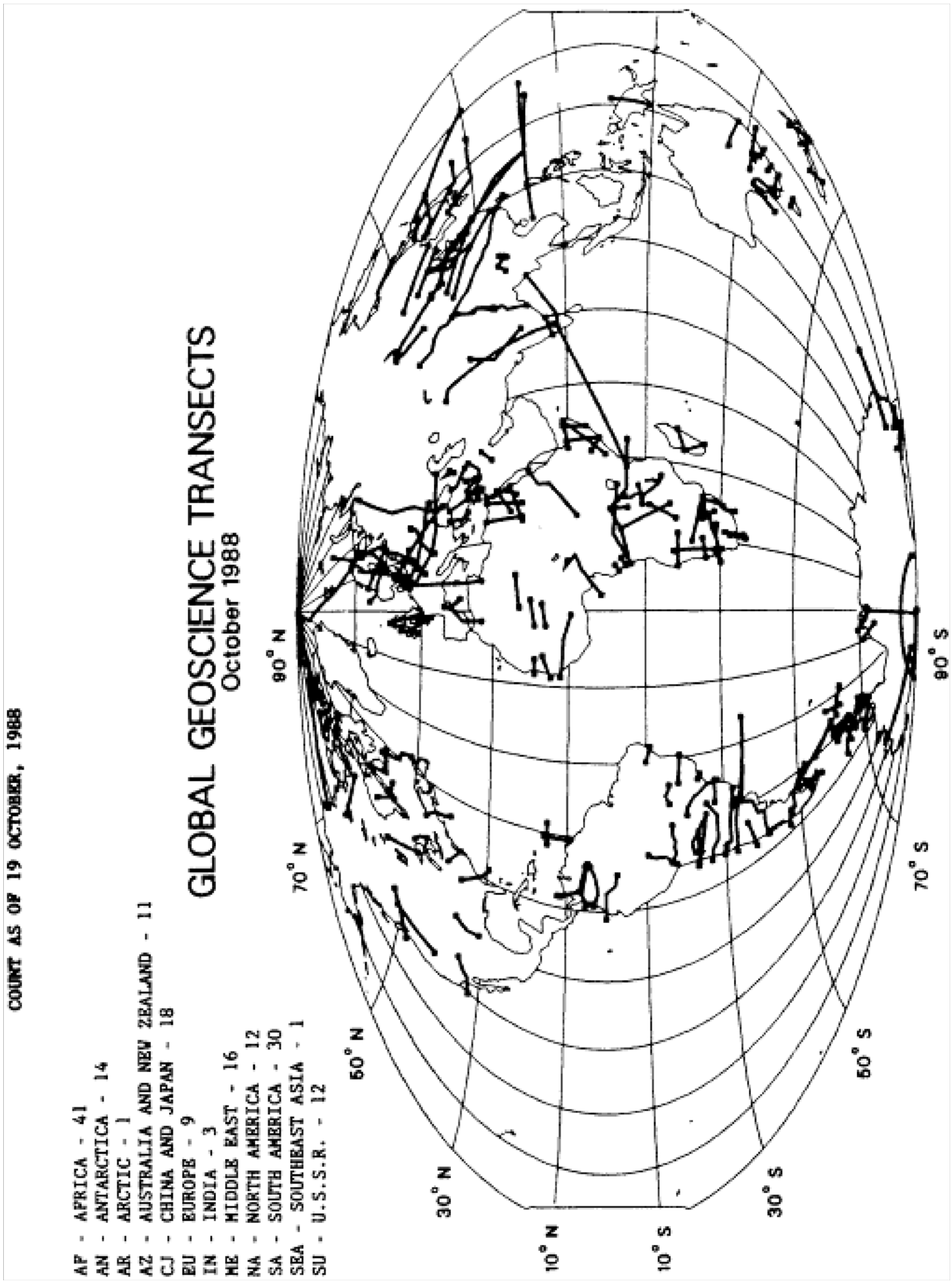


Figure 3
Global Geoscience Transects Project (world map).

Project. The leaders of the Quebec-Maine transect agreed to prepare their results for publication following GGT guidelines. The Quebec-Maine transect is providing a *de facto* model for ways to use digitization in studying deep crustal and lithospheric structure.

By the end of 1987, the importance of digitization for the GGT Project was well established: (1) to facilitate analysis of diverse types of data—and reinterpretation (interpretation is never final); and (2) for storage of the immense amount of data. The ICL Coordinating Committees on Data Centers and Data Exchange (CC-5) and on GGT (CC-7) recommended that steps be taken to define the needs, problems, and appropriate actions regarding digitization of the GGT.

A second meeting of the USGC Task Group on Digitization of Geological Data was held 19-20 May 1988 in cooperation with the two ICL Coordinating Committees (CC-5 and CC-7). That meeting dealt with many issues, including long-term preservation of GGT data and convenient availability for users. For example, CD-ROMs are favored for archiving large amounts of data. CD-ROMs have efficient and large storage capacity and long shelf life; they are cheap to duplicate; and their use involves relatively inexpensive equipment.

The need to plan for digitizing from the beginning of a transect project was emphasized by the USGC. The Quebec-Maine transect has provided pilot experience for digitizing transects. The task group recommended creation of advisory groups on digitization to assist CC-7 and the leaders of specific transects in the GGT Project.

Steps are being taken by ICL to implement the recommendations of the task group. It is the stated intent of the GGT Project to develop digitization by example. For the North American sector of the GGT, a subgroup on digitization is being organized by W.R. Van Schmus. The leader of the subgroup is John Harbaugh; the group will include members from Canada, the United States, and other countries participating in the North American sector of the GGT. This subgroup will prepare practical guidelines for digitization of GGT projects ranging from those involving relatively simple data sets and digitizing capabilities to those involving more complex data sets and computer capabilities.

PART II

NORTH AMERICAN CONTINENT-OCEAN TRANSITIONS

Part II has been prepared by Robert C. Speed (Department of Geological Sciences, Northwestern University), Coordinator of the North American Continent-Ocean Transects Program, and the following working group leaders: Clark Blake (C1), Richard Buffler (F1), Darrell Cowan (B3), Avery Drake (E2), Lynn Glover (E3), Arthur Grantz (A3), Robert Hatcher (E5), Richard Haworth (D1-4), David Howell (C3), Charlotte Keen (D1-4), Kim Klitgord (E1-5), Ray Martin (F2), Luis-Miguel Mitre-Salazar (H), James Monger (B2), Fernando Ortega-Gutierrez (H), Douglas Rankin (E4), Jaime Roldan-Quintana (H), Jason Saleeby (C2), Gerardo Sanchez-Rubio (H), John Sweeney (G), James Thompson (E1), Roland von Huene (A2), Harold Williams (D1), and Christopher Yorath (B1).

5

Major Topical Problems

Tectonic syntheses of the North American transects have allowed participants of the Transects Program to recognize many fundamental problems in understanding the Phanerozoic evolution of North American continent-ocean transitions. A comprehensive survey of such problems is presented below under 12 titles. These general problems (listed below) form the basis for developing new, coordinated investigations aimed at major strides in understanding continental-margin tectonics.

1. Processes of modern active margins.
2. Processes of passive margins.
3. Tectonic heredity.
4. Tectonic significance of magmas and magmatic rocks.
5. Identification and processes of terrane boundaries.
6. Kinematics of orogenic belts.
7. Implications of high-grade metamorphic rocks in orogenic belts.
8. Dating of events in orogenic belts.
9. Foreland deformation and tectonic coupling.
10. Diagnostic geophysical expressions of tectonic units.
11. Deep continental crustal structure and origin.
12. Phanerozoic changes in Proterozoic North America.

These general problems include certain common themes, the most frequently occurring of which are four specific problems (listed below). These specific problems are considered (by the majority of authors) to be priority problems for new investigations.

1. Underplating and tectonic attrition.
2. Origin of the Moho and lower crust.
3. Absolute chronology of tectonic events.
4. Strike-slip components of terrane displacement paths.

These 12 general problems and 4 specific problems are discussed in the sections that follow.

GENERAL PROBLEMS

1. Processes of Modern Active Margins

This problem addresses the relative motions and material transfer along the Pacific and Caribbean edges of North America where the continental margin and North American plate boundary are more or less coincident. Material transfer concerns the sites, processes, rates, and controls of the tectonic transfer of rock and sediment across the plate boundary zone (either way). Accretion of material to the continent may arise by attachment at a subduction trace, overthrusting above the continental edge, and underplating of material below the continental margin. Underplating is the attachment of rock from the downgoing plate to the underside of the overriding plate. Attrition (also called tectonic erosion) of active continental margins occurs by the transfer of continental material to adjacent displacing plates, whether in strike-slip, divergent, or convergent mode.

Tectonic accretion at the toe of the continental foreland (offscraping) is moderately well understood, with some exceptions. First, the factors that control the vergence of offscraped packets, whether arcward or oceanward, are not clear. Further, conjugate asymmetric structures exist at some places, implying the absence of systematic vergence. This problem needs solution in order to interpret subduction polarity in ancient offscraped rocks. Second, it has recently been discovered that in some forearcs upper intervals of the incoming sediment are offscraped whereas lower intervals pass with oceanic crust below the forearc. What controls the partition of the incoming sediment column between offscraping and underriding intervals? Third, some margins have undergone accretion over substantial durations but attrition at other times. What are the long-term conditions that favor the dominance of one process over the other? Fourth, the process of underriding of sediment and rock below the continental forearc is poorly understood. Undeformed sediments have been tracked in seismic sections at least 27 km below the fore arc in the Aleutians and over 100 km in other forearcs of the world. What controls the extent of underthrusting, and what happens to underthrust sediment? Ideas on the latter question are: (a) accretion to the base of the forearc or more landward regions of the continental margin (underplating); and (b) subduction into the mantle. It is vital to understand the fate of underthrust sediment to evaluate the degree to which continents have thickened at their margins from massive under-plating, and how much sediment is transformed to magma in continental arcs. How commonly does the underplating process attach ophiolite to the base of the forearc and what process generates ophiolite diapirs?

Another aspect of accretion that remains a problem is the path and magnitude of progressive deformation of material during its initial transfer at a deformation front, and afterward, within the forearc. What are the tectonics of continental forearcs that cause progressive landward thickening (such as imbrication, continuum contraction, and underplating) but without deformation of upper slope cover? What tectonics cause the commonly seen progressive contraction between the forearc basin and accretionary prism and antithetic wedging in the inner forearc zone? How much of the deformation in rocks of ancient orogenic belts was acquired during early accretionary phases?

Tectonic attrition at active North American margins is poorly understood because the material removed—presumably by strike slip, rifting, or subduction—is no longer present locally. Attrition has been recognized from the great volumes of missing material and by massive subsident events in the Aleutian and Mexican forearcs. The existence of old continental rocks now fronted by recently accreted oceanic sediment implies that materials are missing. Subsidence is implied by the depression of erosional unconformities to depths of 5 km and by the recovery of in-place neritic faunas from great water depths. The subsident events indicate a withdrawal and presumed further landward transport or total subduction of a large tract of the base of the forearc.

The kinematics of modern active continental margins are also a fundamental ingredient with which to interpret the development of ancient orogenic belts. Over what range of widths of continental plate boundary zones are horizontal displacements taken up relative to cratonal North America, and what parameters control the width: slab age and/or dip, lithospheric thickness, material strengths, inherited continental structure, obliquity of convergence?

Further, how does contemporary active margin structure relate to obliquity and velocity of convergence? What controls partitioning of displacement components into spaced strike-slip zones and continuous margin-normal contraction? How much plate boundary motion is taken up within the displacing terranes and within oceanic lithosphere?

Finally, how do rigid rotations occur within active margin zones? What sizes of fragments undergo rotations? What controls the size-frequency? What determines the rotation sense? How does the rotation continue with depth?

2. Processes of Passive Margins

This major problem concerns the processes and kinematics of passive margin generation. Solutions require improved resolution of the architecture and constitution of the deep region between the continental hinge and oceanic lithosphere with normal crustal thickness in the Canada Basin, Labrador Trough, Atlantic Basin, Gulf of Mexico, and Gulf of California.

Especially interesting topics are: (a) the nature, origin, and post-rift history of outer ridges; (b) the origin and uniformity of occurrence of anomalously thick oceanic crust and/or diapiric mantle at the juncture with continental crust; (c) whether brittle structures of rifted crust are predominantly half graben, symmetric graben, low-angle detachment fault nappes, or other extensional structures and whether the predominant structures vary with position; (d) deformation mechanisms and distribution of displacements in the ductile zone; (e) crustal strain and strain gradients during rift phase tectonics; (f) roles of magmatism and sedimentation in rift phase tectonics; (g) the volume of mantle material added to the rifted continental crust; (h) controls on siting of oceanic ridge development and the occurrence of ridge jumps that lead to isolated continental plateaus within oceanic lithosphere.

3. Tectonic Heredity

The idea that earlier structures influence the distribution of displacements and structures developed in a later deformation has long been appreciated but has gained greater importance in geological thinking with the maturation of plate tectonic theory. Early structures yield rheologic anisotropy to rock masses and extensive surfaces of discontinuity or weakness (contacts, faults). In principle, these guide the types and orientations of later structures that might occur during rifting, collision, or transcurrent events. One result of this inheritance is that brittle failure may occur first on reactivated rather than virgin fault planes such that the causal stress field may not be resolved without a very large data set of fault orientations and slip directions. Second, the width of new tectonic zones may be dictated by the distribution of initial discontinuities in the crust. Third, strain rates in the ductile zones may be controlled by inherited anisotropy, and finite strains may be difficult to interpret in terms of orientations of successive tectonic events.

The problem of reactivation of old faults is crucial. Why do some fail whereas others that seem to have been in a propitious orientation for reactivation do not? To what degree do normal faults become reactivated as thrust faults and vice versa in sequential deformation?

Some examples illustrate the point. Triassic/Jurassic grabens in the eastern United States commonly exhibit initial extensional failure by reactivation of thrust and ramp faults of the Paleozoic Appalachian orogen. No magmatism accompanied this initial phase of deformation. Subsequently, Jurassic movements created swarms of vertical diabase dikes oriented at high angles to the normal faults in the southeastern United States and fanning into near parallelism with the normal faults in the northeastern United States. Thus, the early brittle failure seems strongly guided by a pre-existing fabric, whereas the later comagmatic failure appears to have been independent of structural fabric control.

Similarly, thrust surfaces established during an early orogenic event may be reactivated as thrusts during subsequent orogenic events. An example is the mylonite of the Brevard zone of the southeastern Appalachians. Here mylonitization occurred in the Taconian event (ca. 450 Ma) and again in the "Acadian" (ca. 350 Ma in the southern Appalachians). The mylonites may be part of the Piedmont sole fault brought to the surface during Late Paleozoic brittle ramp faulting. The major Piedmont/Blue Ridge allochthon itself probably experienced intermittent reactivation during the Taconian, "Acadian," and Alleghanian orogenies. Also, early thrust faults appear to have reactivated as strike-slip faults. Examples are the Huntington Valley and Martic faults of Pennsylvania.

An example of a normal fault on a rifted margin guiding later thrusting during subsequent collision appears to be the Precambrian(?) Rockfish Valley fault of the Virginia Blue Ridge, which became active as a thrust fault during the Taconian and younger deformations.

Rifted continents tend to break along the grain provided by the last major orogeny (as in the North Atlantic) but not always (as along the southern Atlantic margin). In either case, available anisotropies serve to guide the details if not the major pathways of rifting.

4. Tectonic Significance of Magmas and Magmatic Rocks

It is a goal to interpret uniquely the tectonic environment of the generation and emplacement of magmas from their composition and the physical characteristics of magmatic rock masses. For example, how can ophiolites and basalts of midocean ridge, offridge oceanic, island arc, and continental sites be discriminated? Do calcalkaline magmatic rocks uniquely indicate a contemporaneous subjacent slab, or can such rocks be generated in other tectonic circumstances? What range of chemical and isotopic modifications do igneous rocks undergo in oceanic environments and under multiple metamorphic events in orogenic belts? What are the principal magma sources: base of lithosphere, base of crust, within crust, subducted slab, subducted ocean floor sediments?

Another question is the volume addition to the crust by magmatic rocks. How is stretching taken up in rifted crusts between constant volume on the one hand and constant (or increased) thickness due to magma addition on the other; what controls the proportionation and spatial variation of these two stretching modes? Do island and continental magmatic arcs emerge from a line source of magma or as spaced point sources, and, if the latter, what is the evolution of the lithosphere in between the points?

Contamination and/or assimilation affects the composition and physical properties of magmas at active continental margins. It is important to discriminate contamination at the magma source and by fluids from the downgoing slab from that within the lithospheric column above the magma source.

5. Identification and Processes of Terrane Boundaries

Orogenic belts of the North American continent contain displaced terranes that make up much if not all of zones 3 and 4 (Figure 1). Moreover, the deformed margin of Precambrian North America (zone 2, Figure 1) is partly overlain by terranes. Terranes are tectonic units that have been displaced or are displacing with respect to North America and to one another. Some terranes may be nappelike and underlain by other terranes, whereas others probably have deep lithospheric underpinnings and are thus microplates. At least 100 terranes have been identified to date in North America by gross differences in tectonostratigraphic histories. Of identified terranes, however, many are almost certainly composites of two or more smaller terranes with more subtly different tectonostratigraphic histories. In general, the resolution and delineation at the surface of discrete terranes remains a major tectonic problem in need of additional criteria. Moreover, the subsurface resolution of vertically stacked terranes is a problem hardly touched upon.

A major advance in terrane identification as well as in understanding terrane kinematics may come from study of terrane boundary phenomena. In general such boundaries must be considered zones of major displacement. What determines the width of terrane boundary zones and the types of structures developed with position across and with depth in the zone? What are the relative roles of total displacement, displacement gradients and rates, initial rock types, and fluid activity and permeability?

Processes at terrane boundaries may create unique structural imprints in the rocks involved that inform us about the physical environment which dominates the process during the formation of the boundary. This imprint goes even beyond transforming pre-existent rocks but also may create rocks of its own (anatectites) or create avenues for the emplacement of ascending magmas and mineralizing fluids.

The kinematic study of mylonite belts which may identify important sutures is capable of establishing the sense, type, and even amount of displacement and distortions that occur along many of these boundaries.

The analyses of individual fault zones at terrane boundaries in areas where differential uplift has created structural relief of, say, 10 km or more, should be considered extremely important in establishing probable changes in structural behavior or major faults as they descend into the crust. The presence of fragments of mylonite within mylonite, the complex microfolding of mylonitic foliation, and the involvement of granites during the process of mylonitization indicate complex evolution and changing conditions during the process of accretion. Furthermore, it seems that once established, the structurally weakened zone at a terrane boundary will be the locus of later breakup under completely different tectonic environments.

6. Kinematics of Orogenic Belts

The orogenic belts that nearly envelope cratonal North America and include most if not all of Mexico and Alaska have been studied for many years as to their constituents and the relative motions among them and North America. Current study of North American orogenic belts indicates that they have arisen by a combination of processes: extensional rifting, parautochthonous accretion and magmatism, attachment and removal (attrition) of displaced terranes, and parautochthonous deformation (that is, deformation of marginal North America and attached terranes). Although understanding is accelerating, the sequence of processes and associated motions with place and time remains the key to an accurate Phanerozoic history of North American continent-ocean interactions.

Some questions of particular importance within this topic are as follows:

Paleomagnetic and other data show that margin-parallel displacement components of thousands of kilometers have occurred between North America and some terranes in western Canada and the United States. Moreover, some terranes have moved relatively north and some south (but not at the same time). Have large strike slip components been similarly important in the evolution of the orogenic belts of Mexico, Florida, the Appalachians, and the Arctic? If so, what were the timing, senses of movement, and magnitude of displacement?

What are the kinematics of terrane migration and emplacement within orogenic belts? Did each currently attached terrane migrate as a discrete entity on an oceanic conveyor? Or, were terranes chipped off and stuck to North America from a passing coherent ensialic plate, either as slices at strike-slip boundaries or as nappes at collisional boundaries? If terranes were mainly discrete, were they strongly amalgamated to one another before attachment to North America? How much fragmentation and further displacement by strike-slip faults have terranes undergone after first attachment to North America? For example, did the terranes in the assemblage that constitutes most of Alaska arrive unit by unit at their current positions, or at the other limit, did the assemblage migrate as a unit? Are the many arc terranes in the Appalachians derived from a now-fragmented single arc, or do they represent mainly diverse original arcs?

What are the kinematics of continent-continent collisions? Did many discrete microplates exist in the collision zone, or do the continents maintain coherency? How is the obliquity of collision taken up in underriding and overriding continent? How much of North America was subducted in collisions? What arrests the convergence? What was the precise history of closure of North America with other continents that led to Pangea? Last, the timing and effects of superposed deformations must be clear at all positions.

How much of Precambrian North America was removed between the times of Late Proterozoic passive margin formation and the present edge of sialic North America that is mainly below the orogenic belts? Were the losses, if any, mainly by rifting and ridge jump, strike-slip plucking, or by collisional subduction?

What are the vertical motions in the development or orogenic belts? Do these reflect ramping over pre-existing declivities, thermal/magmatic doming, regional homogeneous contraction, or other phenomena?

What is the origin of the regional heterogeneities of deformation in orogenic belts? Are they due to attachment of terranes, rotation of allochthonous or parautochthonous units, different vertical displacements, initial paleogeographic complexities, rheologic changes, or to complexity of superpositions?

7. Implications of High-Grade Metamorphic Rocks in Orogenic Belts

Relatively narrow belts of anomalous high-grade metamorphic rocks occur in most North American orogenic belts. What were the vertical and horizontal motions that brought these belts to their current positions, and what tectonics caused the motions? There are many hypotheses for such metamorphic rocks: (a) roots of magmatic arcs exposed by deep erosion, (b) suture-generated rocks in zones of thickened crust, (c) nappes of either North American continental basement or collided continents, and (d) unroofed regions of large crustal extension.

By far the most widespread development of Phanerozoic metamorphic rocks now exposed in the North American continent is in the Appalachian mountain system. A close temporal and spatial relationship may exist between the timing of accretion of large terranes and the three major orogenic episodes that were at least locally accompanied by regional high-grade metamorphism and in some instances by anatectic magmatism.

A similar model has been recently proposed for two metamorphic belts in British Columbia. Metamorphism is attributed to the doubling of the continental crust by the overthrusting of two superterranes onto the North American continental margin.

In the Klamath Mountains of northern California and southern Oregon, it has recently been proposed that four tectonostratigraphic terranes were imbricated and accreted to the continental margin, producing a tectonic stack ~18 km thick in which there is an upward increase in metamorphism through the prehnite-pumpellyite and greenschist facies into highly deformed garnet-bearing schists and gneisses.

A special case concerns the Cordilleran metamorphic core complexes which all appear to lie within the deformed portion of sialic North America from Arizona to British Columbia, well east of the zone of displaced terranes (zone 3). The metamorphism is dated in several areas as Middle Jurassic (~160 Ma) and all the core complexes were subsequently involved in Cenozoic detachment faulting that resulted in their tectonic deroofing.

8. Dating of Events in Orogenic Belts

It has been commonplace in geological sciences to consider that events in orogenic belts occurred in distinct periods separated by durations of little activity and that events occurred uniformly over wide areas. Critical analysis indicates, however, that existing data are commonly insufficient to justify these long-held views. In fact, deformation at some places could have been continuous over hundreds of millions of years and heterogeneous over distances of 100 km or less.

The Appalachians provide a conspicuous example. The old view of Ordovician Taconian orogeny, Devonian Acadian, and Pennsylvanian-Permian Alleghanian has been questioned by age data. For example, Cambrian and Late Proterozoic Appalachian extension are recognized in the central Appalachians and Maine, and a deformation continuum from Cambrian to Mississippian may occur in displaced terranes of the southern Appalachians.

The need for precise knowledge of dates of orogenic events with age and position is evident, both to comprehend orogenic processes and to detect times of collision of exotic terranes that may no longer exist locally. Good resolution of ages of an orogenic phase at a given place would include ages of onset of movements, of maximum depth penetration/metamorphism, of rapid uplift, of attachment to North America, and completion of deformation. It is also important to resolve the timing of superimposed deformations.

9. Foreland Deformation and Tectonic Coupling

We consider the foreland as the peripheral region of Proterozoic North America that has undergone deformation in Phanerozoic time (Figure 1, zone 2). Foreland deformation includes the following effects: (a) parautochthonous contraction or extension of the type that has long been recognized in thrust and fold belts (e.g., Huastacan, Valley and Ridge, Rocky Mountain belts) and rift provinces (e.g., Mesozoic Atlantic coastal plain, Basin and Range); (b) superimposition on the foreland of terranes with major individual displacement (e.g., Ouachitas, Roberts Mountains allochthon); and (c) the tectonic attrition of the foreland.

Each of the three foreland deformation processes can be viewed as related to the tectonic coupling of North America to displacing terranes and/or oceanic lithospheres. It is a major question in foreland thrust and fold belts, however, whether such tectonic coupling is the sole driving force, and, if it is, the character of stress transmission. It is vital to evaluate this because such belts record much of the early continental margin deformation of North America.

The cratonward sides of foreland thrust and fold belts are well studied and contain many common structures: unmetamorphosed shelf cover strata that are detached on a weak sedimentary horizon or the basement unconformity; imbricated or duplexed thrust packets with cratonward piggyback propagation; and bulk volume-conservative subhorizontal shortening of about 50 percent. The structure and motions of the ocean-ward side of foreland thrust belts are markedly less clear. What are the transitions across the belt in the depth distribution of contractile motions and deformation mechanisms? What happens to the sole fault—does it climb section to the oceanic side, discharge into the continental arc, or root in ductile basement partway across the belt? If the cover is brittlely detached all across foreland thrust belts, how is displacement taken up by the crystalline crust, and what is the fate of the basement at the oceanward margin? Are nappes of crystalline basement on the oceanward side exotic terranes, or are they North American and a product of thick-skinned tectonics, or both? How strongly does earlier structure at the edge of North America influence the architecture of succeeding foreland thrust belts? Do crystalline nappes such as the Blue Ridge arise from initial declivities such as a passive margin hinge? Are major frontal and lateral ramps in thrust belts mainly inherited or mainly virgin structures?

It is reasonable to suppose that the shove that causes foreland contraction is supplied at the active plate margin by displacing terranes. If so, the long durations (50 to 100 my) and mainly margin-normal direction of shortening of thrust and fold belts suggest more or less steady normal convergence at most active margins through the Phanerozoic. These interpretations are not, however, in harmony with the apparently episodic collision of terranes or with the evidence of major obliquity in terrane displacement relative to North America. As example, how can the Eocene Laramide contraction in Wyoming be related to the concurrent highly oblique Kula plate motion at the active North American margin? How does the apparently margin-normal contraction of the Appalachians relate to the diachronous closure of Africa and North America from Ordovician to Pennsylvanian times? Perhaps foreland contraction arises by intracontinental stress systems.

10. Diagnostic Geophysical Expressions of Tectonic Units

It is important to be able to identify the tectonic units that constitute most of the outer zones of the North American continent between the Proterozoic craton and the ocean basins. Many of these units can be delineated by surface structure and tectonostratigraphy, but geophysics provides the necessary data for determining their vertical extent, their areal extent (where submarine or buried by younger cover), and possible evidence for their deformation history. Most units are constructed of a number of specific geological and structural elements, and therefore each unit has a number of geophysical signatures which together identify the particular tectonic unit. Examples of tectonic environments are: mid-ocean ridge, island arc subduction zones, continental edge subduction zones, passive rift and continental margins, continent-continent collision zones, and continent-continent transform zones. Island arcs, with their subducted oceanic crust, accretionary sedimentary wedge, volcaniclastic sedimentary deposits mixed with intrusives in the magmatic arc, and backarc basins, provide distinctive tectonic megaunits. Passive rifted continental margins have continental crust and oceanic crust separated by a rifted crust of faulted blocks and intrusives, overlain by evaporite, carbonate, and clastic sedimentary rocks deposited in shelf, slope, and rise paleoenvironments.

Many geological features have characteristic geophysical signatures based on seismic, magnetic, gravity, and heat flow studies. For example, oceanic crust has a characteristic seismic P and S wave velocity structure. Peralkaline granitic (magnetite-bearing) bodies usually produce positive magnetic anomalies and negative gravity anomalies, whereas calcalkaline granites (ilmenite-bearing) produce magnetic and gravity lows. Granitic bodies are generally associated with zones of high heat flow. Rhyolitic and gabbroic intrusives also have distinctive magnetic and gravity patterns. Island arc sedimentary-volcanic units produce a chaotic short wavelength magnetic signature that is clearly distinguished from that of zones of plutonic rocks and lineated patterns associated with foliated rocks.

On a regional scale, there are prominent magnetic, gravity, and seismic signatures that mark major crustal boundaries. For example, the East Coast Magnetic Anomaly is a linear feature that appears to separate oceanic from rifted continental crust. Foreland basins have a characteristic seismic structure due to sediment distribution. Fault plane geometries are important characteristics for identifying foreland-hinterland relations and the distinction between shear zone and collision zones. Distribution of plutons, batholiths, block-fault structures, etc., are important indicators of collision types and subduction directions.

Other examples are: (a) the steep gravity gradient that runs the length of the Appalachian orogenic belt and (b) the correspondence of positive gravity anomalies with basement exposures in New England. It is important to evaluate fully the interpretation that the gradient reflects the eastward-thinning wedge of continental crust at the Atlantic passive margin. Example (b) points up the need for careful evaluation of geophysical signatures because, although they are associated with positive anomalies, the basement rocks are less dense than their tectonic and sedimentary cover.

The erosion and metamorphism of units change their geophysical signature, often producing signatures characteristic of a particular event. The uplift and erosion of plutons gradually expose more mafic material, changing the geophysical signature of a magmatic arc. Compressive tectonism will alter random magnetic patterns into more lineated patterns as rocks are reheated and foliated.

To analyze orogenic belts by means of geophysics, it is vital to have comprehensive and spatially dense data sets: gravity, magnetics, heat flow, seismic refraction velocity structure, and seismic reflection layering and velocities. Geophysical surveys of North American orogenic belts are necessary to develop a coherent geological model of the tectonic evolution of the continent in Phanerozoic time.

11. Deep Continental Crustal Structure and Origin

Deep seismic reflection profiling shows that the continental crust contains reflectors at all depths above the Moho, but with varied characteristics and concentrations. Such reflectors occur in the zone of deformed sialic continent as well as in the cratonal crust, and moreover, in displaced terranes. Individual reflectors are commonly discontinuous, subhorizontal, and in sets that are extensive laterally and vertically over tens and several kilometers, respectively. Variations include sets of discontinuous dipping reflectors and, locally, a long continuous reflector or set of reflectors. At some places, sets of reflectors occur densely throughout the crust, whereas at others, they are uniformly but sparsely recorded, and at yet others, they are concentrated in the lower crust below a nonreflective upper crust. The base of reflector sets seems to be a laterally continuous surface that can be called the reflection Moho.

These crustal reflectors are at the same time a prime control and a puzzlement in the formulation and interpretation of deep geological structure. What are the nature and origin of the velocity layering that causes them? Some candidates for the nature are little deformed strata, compositionally differentiated metamorphic rocks, mylonite and nonmylonite zones, intrusions or anatectites, and thrust zones. It is essential to learn what gives rise to the reflectors before the origin and tectonic history of the continental crust can be interpreted.

The reflection Moho may be coincident with the more commonly known refraction Moho at most places, but at some sites the two differ in depth with any reasonable velocity structure employed. By definition, the reflection Moho is the maximum depth of finely scaled velocity layering, below which exists a more homogeneous upper mantle. In some regions, young structures deform the reflection Moho whereas in others (for example, Basin and Range), Late Neogene throws at the free surface of up to 5 km are apparently absent at projected positions of the reflection Moho.

Are the reflection and refraction Mohos in fact due to the same structural phenomenon? What is the continental Moho? Is it a compositional boundary preserved from early continental formation? Or, at the other extreme, is it a modern densityrheology boundary above which tectonics cause zonal impedance contrasts? The problem of the nature and origin of the continental Moho is inextricably linked to studies of the tectonic evolution of North America.

12. Phanerozoic Changes in Proterozoic North America

Current theory suggests that near the end of Proterozoic time, North America was located completely or mostly within a supercontinent. The Late Proterozoic breakup of the supercontinent and growth of oceanic lithosphere led to the isolation of a protocontinent of Phanerozoic North America. A Phanerozoic tectonic history therefore must account for the changes in extent and configuration between the Late Proterozoic protocontinent and the part of today's North American continent cored by Precambrian rocks that have remained contiguous or nearly so (Figure 1, zones 1 and 2).

Necessary ingredients to approach the problem of Phanerozoic changes in Proterozoic North America are the size and shape of the protocontinent and an accurate picture of the extent of Precambrian North America today. The latter (outer edge zone 2, Figure 1) is uncertain because today's edge of Precambrian North America is tectonically buried by displaced terranes at most places, and its subsurface locus has been inferred by inexact techniques. It is reasonable to suppose that Phanerozoic tectonics have reduced the girth of the protocontinent, and this is supported by locally truncated Late Proterozoic passive margin structures. Conceptual mechanisms for removal of Precambrian material are rifting and plucking out of chunks of the edge of North America during oblique convergence (as with Baja California) and subduction during collision, with loss via sinking of a detached slab, and/or by melting. A complete history of the changes should incorporate times, places, and tectonics of removal of fragments of Precambrian North America.

Another basic question is how far south (into what is now Mexico) Precambrian North America once extended and how this continental salient, if it existed, related to the confluence of the Appalachian and Cordilleran orogenic belts in northern Mexico.

It is generally assumed that the zone of Precambrian North America deformed in the Phanerozoic (zone 2, Figure 1) incorporates no large internal displacements (e.g., > 100 km). The assumption may be incorrect and should be tested. The existence of such Phanerozoic displacements within the Precambrian would be an important factor in models of the dynamics of continental deformation.

SPECIFIC (PRIORITY) PROBLEMS

From consideration of the 12 general and comprehensive problems set forth above, the following four specific problems are identified as the most fundamental to an improved understanding of the Phanerozoic evolution of North American continent-ocean transitions. Part I of this report deals with investigations needed to solve these and other problems.

1. Underplating and Tectonic Attrition

Underplating is the process of transfer of sediment and/or rock from a downgoing plate to the base of the forearc and/or crystalline lithosphere of North America at active margins. Questions are: What are the mechanics that cause sediment to underride the fore arc and be attached to the base of the forearc or continental crust? How important has this process been in the thickening and outgrowth of North American transitional crust over Phanerozoic time? What are the structures and material changes (strengthening, metamorphism, fluid release) that occur during underplating and how do these affect continental margin tectonics and magmatism? How can the existence of modern and ancient underplate be identified and characterized at depth by remote techniques and at the surface in orogens by geological and geophysical study? An important counterpart is the negative of underplating, that is, tectonic attrition of the base of North America above a downgoing plate. Attrition should be considered a part of this highest priority problem. Questions are: Is the overriding plate eroded by protuberances on the downgoing plate? Is the process controlled by migration of overpressured fluids or by the thickness of underriding sediment? How is attrition related to obliquity and velocity of convergence?

2. Origin of the Moho and Lower Crust

The evolution of the transitional region (and North America as a whole) will remain in part a mystery until we have much improved understanding of its deep, remotely observed reaches. Specific questions are: What material changes cause the acoustic impedance and density contrast across the Moho in the continent-ocean transitional zones? What are the protoliths? What are the age and age variability of the boundary, and is it a continually evolving surface or one that forms mainly during or before major tectonic events? What is the material flux across the Moho? What causes the deep reflection events in lower crusts of the transitional regions (major displacement zones, intrusions, strata processing, etc.)? What are the origins and transport paths of lower crustal rock—mainly from the surface, underplating, the mantle, or from primeval processes (autochthonous)?

3. Absolute Chronology of Tectonic Events

The times of major events in the evolution of North American continent-ocean transitions are generally known to the first order. These provide a glimpse into the complexity of the development of the transitional region: the superpositions of processes, temporal variability of processes along the margin, large and rapid vertical motions of 30 or more km, and the enigmas of origins of terranes and their approach and attachment to North America. A well understood Phanerozoic evolution of the North American margin requires both more widespread and more highly resolved dating that will indicate ages of deposition, magmatism, maximum depth penetration, uplift times and rates, fluid passage, and the superpositions of these and other effects. More important, the elucidation of major processes of the continental transitions demands vastly greater quantity and improved resolution of dates.

4. Strike-Slip Components of Terrane Displacement Paths

The terranes that constitute a nearly encircling zone around Precambrian North America (Figure 1) have generally unknown provenance. It is currently a major debate whether terranes emerged from sites near their present one, for example, either by extraction from the continent or the local arc and marginal basin development, or on the other hand, whether they have undergone displacements of thousands of kilometers, perhaps with large margin-parallel (strike-slip) components. An understanding of the evolution of the transitional region, of which terranes make up a sizeable proportion, requires knowledge of displacement paths of terranes into and within that region. The relative motions of terranes with respect to North America and to one another provide one of the primary means with which to determine obliquities in ancient convergent margins of the North American plate, ancient global plate reconstructions, and paleobiological excursions. The detection of major strike-slip components has proved to be elusive thus far, and different techniques sometimes yield greatly conflicting results. This difficulty must be rectified in future research.

6

The 23 Transects: Synopses, Findings, and Problems

TRANSECT A2 KODIAK TO KUSKOKWIM, ALASKA

Synopsis and Findings

Transect A2 (Figure 1) extends NW from oceanic lithosphere of the Pacific plate across the convergent plate boundary of North America at the Aleutian Trench. Landward of the trench in western continental Alaska, A2 contains two tectonic regimes of sequential development (Figure 4). The Chugach-Prince William terrane is an amalgam of displaced terranes with Cretaceous and Paleogene ages of attachment to one another. The peninsular terrane includes the modern Aleutian arc which dates as far back as 42 mybp and comprises magmatic arc and forearc zones that are constructed partly on the older terrane assembly. The magmatic arc is on the Peninsular terrane, and part of the forearc is on the Chugach-Prince William terrane (Figure 4). Cratonal North America does not exist in A2.

Recent studies of the Aleutian forearc in A2 have led to major strides in understanding the processes of the growth of this forearc. Teleseismic earthquakes are essentially absent between the trench axis and the edge of the shelf. Landward of the shelf edge, teleseismic earthquakes are concentrated in a zone that dips only 4° continentward beneath Kodiak Island at the inner side of the forearc. Northwest of the island, the zone dives at 35° - 40° to the roots of the volcanic arc. Thus, in the zone of most active tectonism at the edge of the North American plate, the rocks have insufficient strength and the coupling between plates is not enough to produce frequent large earthquakes.

In seismic reflection sections that cross the Aleutian Trench axis and landward slope of the trench slope, a 2-km-thick and 20-km-long, little-disrupted sequence of stratiform sediment is subducted beneath a major decollement at the deformation front. The absence of significant stratal disruption (quarter wavelength or "resolution" in the seismic record equals about 50 m) at depths greater than 4 km requires low friction. Such low friction is possible if pore fluids cannot readily drain from the subducted sequences and instead become pressured to near lithostatic levels. Given weak rocks in walls of major thrust faults in the forearc, the lack of teleseismicity is not surprising, and the low friction along the plate boundary thrust faults may even extend to the depths indicated by the zone of infrequent teleseismic earthquakes.

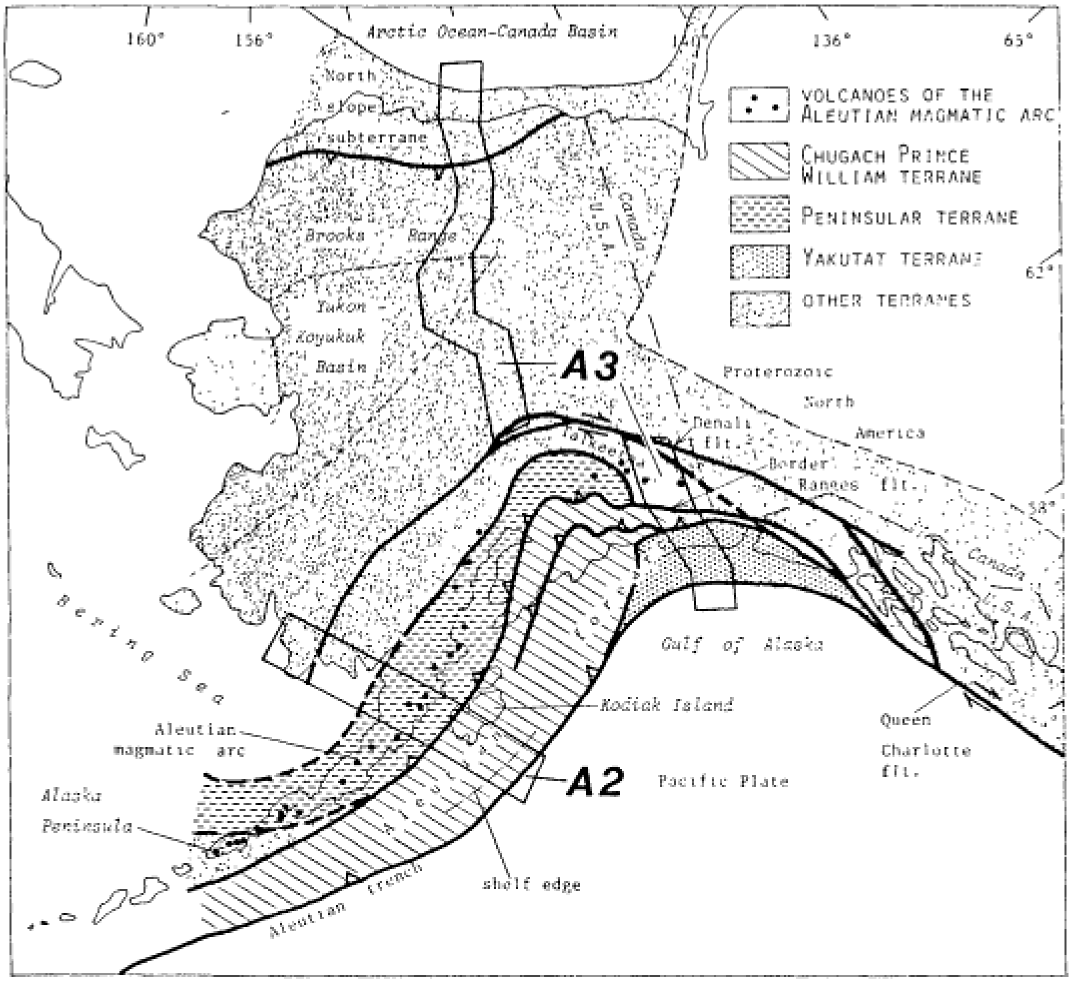


Figure 4
Map of Alaska showing positions of corridors A2 and A3.

At the deformation front of the forearc, a decollement divides the subducted and accreted ocean basin sediment. The accreted sediment is tectonically thickened by tilting, folding, and imbricate thrusting to about twice its original thickness. Along the seismic section that A2 follows, the original 1.5 km- to 3-km-thick offscraped section is thickened to perhaps 4 to 6 km. Further thickening of the forearc requires another process because maximum landward rotation and active faulting are not observed in the mid- and upper-slope areas. Since the seismic refraction data indicate 10- to 12-km-thick sedimentary and metasedimentary rock beneath the forearc basins (between Kodiak island and the magmatic arc, Figure 2), we appeal to underplating to form about 5 km of the forearc thickness above the subduction zone.

This contention is supported by onland studies that indicate an underplated origin for the Cretaceous accretionary complex that crops out across most of Kodiak Island; early Tertiary rocks have been interpreted similarly. We propose that the Cretaceous and early Tertiary underplated rocks were once about 10 km deep and were uplifted by younger underplating of Oligocene to Quaternary rocks.

Underplated sedimentary rock is the most abundant protolith in the Aleutian forearc in A2. Sediment attached to the toe of the forearc by frontal accretion and sediment of forearc basins do not appear to be as readily preserved. The absence of frontal accretionary materials suggests their removal by tectonic erosion of the front of the forearc. An ancient example is the tectonic erosion along the Border Ranges fault, which is the contact between older terranes and the Aleutian forearc (Figure 4) where the front of the Permian to Early Cretaceous margin in the Peninsular Range has disappeared. Similarly, it is proposed that the middle Eocene to middle Miocene margin front has disappeared within the Aleutian forearc, causing juxtaposition of Early Eocene and Pliocene accreted sediment along the midslope of the present forearc.

The foundation for the landward part of the Aleutian arc and parts of A2 north of the Aleutian volcanic chain (the backarc zone) is made up of five major terranes (Figure 4). These include Precambrian, Paleozoic, Mesozoic, and in the seawardmost, Paleogene rocks, representing continental, oceanic, subduction zone, and magmatic arc origins. The three northernmost terranes, all north of the modern volcanic chain, assembled to one another at their present latitude by Early Cretaceous time. Their boundaries, however, took up further displacement, mainly strike-slip, later in the Cretaceous, and they attached as a composite to terranes north of A2 in Late Cretaceous time (Figure 4). In contrast, the Peninsular terrane, which lies south of these in the Alaska Peninsula (Figure 4), was apparently far to the south in the Cretaceous and must have arrived at present latitudes in post-Cretaceous time. Moreover, the most seaward terrane (Chugach-Prince William), which is the Aleutian forearc, was apparently also well south (30° latitude) of its current position as late as Oligocene time. It contains Cretaceous rocks at its inner reaches; the rocks are generally younger seaward.

The history of the northward movement and attachment of the southern two terranes is poorly known, as are the latitudinal positions of the earlier, mid-Cenozoic parts of today's Aleutian forearc. Moreover, the pre-mid-Cretaceous evolutions of all rocks within A2 probably represent histories at other, probably distant, sites elsewhere in the Pacific realm.

TRANSECT A3 GULF OF ALASKA TO THE ARCTIC OCEAN

Synopsis and Findings

Transect A3 (Figure 1) traverses mainland Alaska between bordering oceanic lithospheres—the Pacific plate at an active margin on the south, and the Amerasia plate of the Arctic Ocean at a passive margin on the north. Between the margins, Alaska in A3 is composed entirely of displaced terranes and at least two collapsed basins floored by oceanic lithosphere. The edge of Proterozoic North America lies well east of A3 (Figure 4).

The active margin in the Gulf of Alaska is fronted by a complex zone of right-oblique subduction. The toe of the continent is an accretionary wedge, the Aleutian forearc, comprised of thick Cenozoic clastic sediments derived from Late Mesozoic accretionary wedges and accreted terranes in the Coast Ranges of northwestern North America. In the eastern Gulf of Alaska the accretionary wedge buttresses against the

Yakutat terrane (Figure 4). In the western part of the Gulf, it buttresses against the Pacific plate. The transition between these structural domains is a zone of southeast-verging thrust folds. The Yakutat block, consisting of slightly deformed southward-prograding Cenozoic clastic rocks overlying a continentalized Late Mesozoic accretionary prism on the east and Paleogene oceanic crust on the west, is an example of a terrane now undergoing accretion to the continent's leading edge. Pacific-North American displacements southeast of A3 are mainly strike-slip and confined to the Queen Charlotte fault in Transect B1 (Figure 1). Between B1 and A3, faults splay into the continent to the northwest and take up oblique convergence as the plate boundary curves from NW to SW around the Gulf of Alaska (Figure 4).

The forearc in the active margin in A3 is about 200-km wide, and comprises the Chugach, Prince William, and Yakutat terranes. In the western part of the Gulf of Alaska the forearc widens to 400 km, and there is a gap in the associated volcanic arc. The continental side of the forearc is apparently a north-dipping accretionary surface, the Border Ranges fault zone (Figure 4), against the south side of the amalgamated Peninsular and Alexander-Wrangellia terranes (the Talkeetna superterrane). This mainly early- and mid-Tertiary fault is a major splay of the plate boundary zone. Other major splays, which in general are younger southward and down section, lie within the forearc prism (accretionary wedge).

North of the forearc and Border Ranges fault zone, there is a 1,500-kin-wide region in A3 comprising displaced terranes with locally intervening wedges of deformed Cretaceous flysch. The flysch probably represents wedges of ocean-floor sediment accreted from now-consumed oceanic lithospheres that separated terranes before their collisions. Attachment ages are mainly Cretaceous, and attachment structures are, in general, mid- and late-Cretaceous paleoobduction and paleosubduction zones and latest Cretaceous and Tertiary right-slip faults. The terranes include protoliths of highly varied tectonic kindred, including arcs, oceanic plateaus, and deep seated metamorphic rocks of continental affinity. A number of them have had large northward transport in or since the Cretaceous. Some terranes, such as the Talkeetna superterrane, apparently arrived in Alaska as a complete amalgam, but others may have accreted individually. The post-attachment disruption of terranes by right-slip faulting of the diffuse plate boundary zone as far north as the southern foothills of the Brooks Range (Figure 4) creates difficulties in deciphering the earlier tectonic evolution.

The northern region of the transect contains the deep Yukon-Koyukuk basin, of Cretaceous age, which was probably founded on oceanic basement and which is bordered by obducted ophiolite at both margins. North of the basin is the Brooks Range, which is underlain by a continental fragment, the North Slope subterrane of the Arctic Alaska terrane. This subterrane consists of little-deformed shelf and shelf basin deposits of Late Devonian to Neocomian age resting on deformed early Paleozoic sedimentary rocks. It is overthrust from the south by coeval outer shelf and slope deposits, Precambrian to Devonian metasedimentary rocks, and by Jurassic(?) ophiolite. North of the range is a north-vergent foreland thrust belt and foredeep of Cretaceous and Tertiary age which was deposited on the North Slope subterrane. Late Early Cretaceous strata of the foredeep succession prograded northward across the passive margin that forms the boundary between the North Slope subterrane and the oceanic Amerasia plate of the Arctic Ocean. The progradational succession across this boundary, which is the present northern margin of Northern America, locally exceeds 13 km in thickness (Figure 4).

The Arctic Alaska terranes may have been derived from Arctic Canada and have undergone about 70° counterclockwise rotation during the opening of the Canada Basin by seafloor spreading. The rifted northern margin of this terrane may represent predrift extension within northwestern North America. The thrusting at the southern margin of this terrane appears to be a consequence of convergence between the northward-drifting plates of the paleo-Pacific, with its entrained lithotectonic terranes, and North America.

TRANSECT B1 INTERMONTANE BELT (SKEENA MOUNTAINS) TO INSULAR BELT (QUEEN CHARLOTTE ISLANDS)

Synopsis and Findings

Transect B1 (Figure 1) displays the structure of the active margin of the North American continent at and near the Queen Charlotte Islands of British Columbia and near the triple junction among the Pacific, Juan de Fuca (or Explorer), and North American plates (Figure 5). The transect extends northeast of the active margin through the Insular and Coast Plutonic Belts to the Intermontane Belt (Figure 5) within the region of ancient displaced terranes.

The Queen Charlotte fault is a major transpressive boundary between northwest-translating, underthrusting oceanic lithosphere of the Pacific plate and the transitional lithosphere of North America that is comprised of terranes of Mesozoic attachment ages (Figure 5). The obliquity of displacement is about 20• from strike-slip. Transpression apparently evolved from a transtensional mode in this area at about 6 mybp. The Queen Charlotte fault forms a backstop to an active accretionary wedge on the Pacific plate. Several active NW-striking strike-slip faults occur inboard and parallel to the Queen Charlotte, implying that displacements are currently distributed at this active margin. The kinematic change at 6 mybp was associated with large uplift of the continental edge in the Queen Charlotte Islands and subsidence to the rear in the Hecate Strait (Figure 5).

South of the Queen Charlotte Islands are the triple junction and the Neogene Juan de Fuca plate, which underthrusts the margin with near normality (Figure 5).

The earlier tectonic evolution of the B1 region is registered in three principal stages: terrane accretion in the Mesozoic, transpression and magmatism in Cretaceous to Eocene times, and transtension from the Eocene to 6 mybp. The first stage represents tectonic progradation of the continental margin relative to nuclear Precambrian North America (farther east from B1, Figure 1), whereas the second, third, and modern stages record diverse effects of active margin tectonism on the earlier accreted terranes.

Transect B1 includes four major terranes (Figure 5); from the present continental edge eastward, they are the Wrangellia, Alexander, Stikine, and Cache Creek terranes. The first three apparently arrived at the edge of North America in sequence, from inboard out. The Stikine, composed of Late Paleozoic arcs, was attached to the Cache Creek, a subduction complex, in Late Triassic time, before the terrane pair collided with North America in mid-Jurassic time. The Alexander terrane, which consists of Late Paleozoic and Early Mesozoic arc or rift-related rocks, collided with the Stikine, then at the western edge of North America, later in Jurassic time. The Wrangellia terrane, composed of Late Paleozoic arc and Triassic oceanic plateau rocks, then underthrust and stuck to the Alexander in the Late Jurassic. The Coast Plutonic

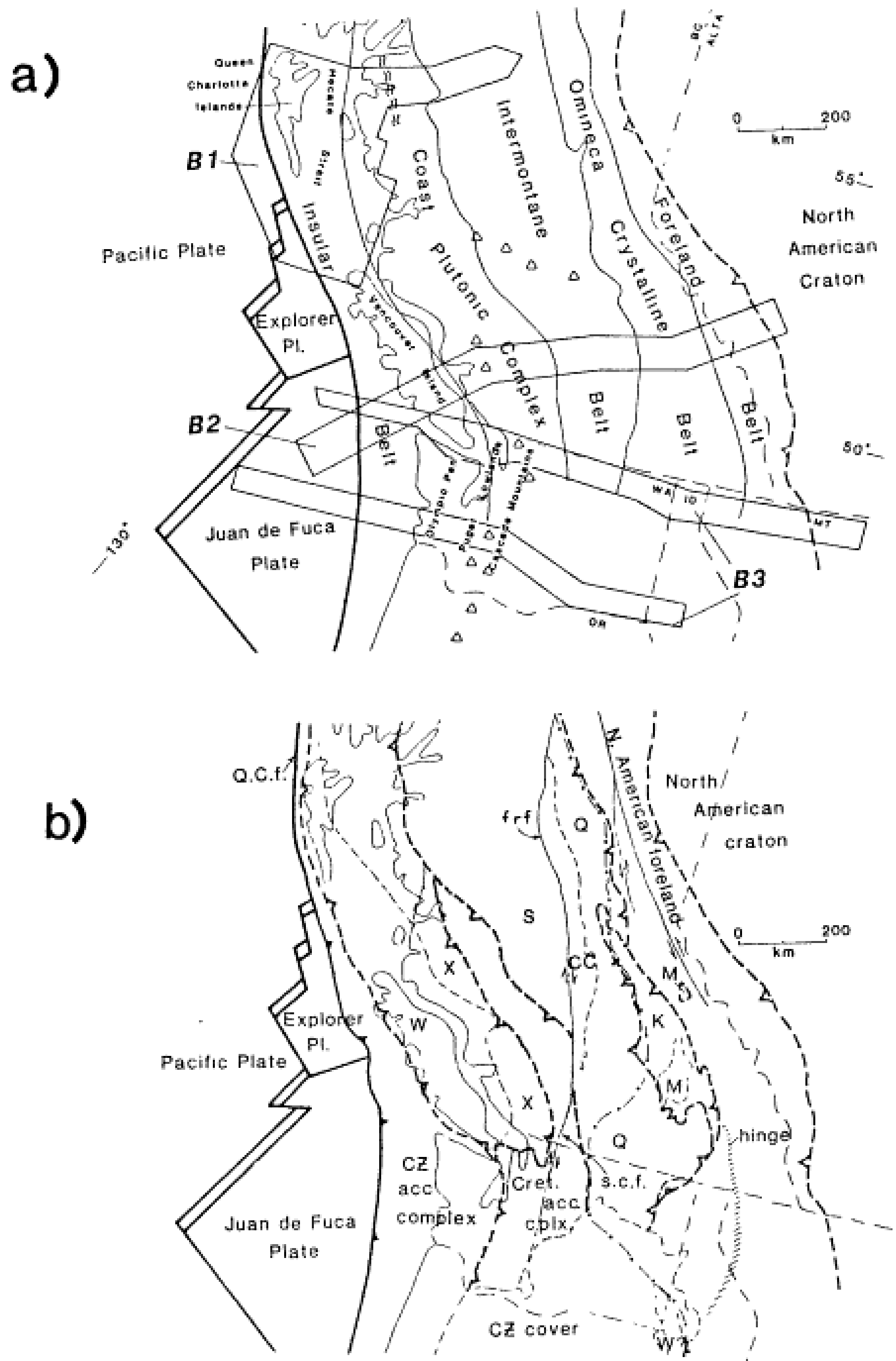


Figure 5
Map of western Canada and northwestern United States showing positions of corridors B1, B2, and B3.

belt (Figure 5) probably formed along the suture zone of the Alexander and Stikine terranes and may contain collision-related magmatic and metamorphic rocks.

Post-accretionary active margin displacements appear to be concentrated in the Coast Plutonic Belt. These include probably eastward thrusting of the Coast Plutonic Belt onto rocks of the Intermontane Belt and the development of a major belt-parallel ductile dextral shear zone, the Work Channel Lineament of Cretaceous through Eocene ages of activity (Figure 5). The vertical motions unroofed rocks of the western Coast Plutonic Belt as much as 25 km at rates up to 2 mm/yr. Magmatism, perhaps anatectic, and crustal thickening occurred to the east in the Intermontane Belt during this stage.

During the third stage of Oligocene and Miocene duration, block faulting and magmatism were widespread in the Intermontane Belt. These are interpreted to have resulted from dextral transtensional motions at the plate boundary.

TRANSECT B2 JUAN DE FUCA PLATE TO ALBERTA PLAINS

Synopsis and Findings

Transect B2 (Figure 1) spans the southern Canadian cordillera that lie between the oceanic Juan de Fuca plate on the west and cratonic North America in Alberta on the east. The cordillera are the transitional zone of western North America, and their structure includes the cumulative effects of 2 by of earth history.

Modern tectonic features of the cordillera include the Cascade magmatic arc (Figure 5) and an accretionary wedge at the continent's leading edge offshore of Vancouver Island. Both features are related to the subduction below North America of the Late Neogene oceanic lithosphere of the Juan de Fuca plate, which is a remnant of the former, once extensive Farallon plate.

The Neogene tectonic features are superposed on older structures of the cordillera that permit division of the cordillera into five strike-parallel belts (Figure 5); from east to west, they are called Rocky Mountain, Omineca Crystalline, Intermontane, Coast Plutonic, and Insular belts. The Rocky Mountain Belt contains mid-Proterozoic to Tertiary mainly sedimentary strata on continental crust, the earliest being rift deposits that were followed by continental shelf and slope deposits of Cambrian to Jurassic age, and last, foreland basin deposits of Late Jurassic to Early Tertiary age. The Intermontane and Insular belts are mainly low-grade metamorphic and unmetamorphosed sedimentary and volcanic strata and comagmatic granitic rock of mainly Late Paleozoic to Tertiary ages. The older parts of these are derived largely from intraoceanic magmatic arcs and ocean basin deposits, and the younger, from continental margin arcs and orogenic clastic basin deposits. Permian to Jurassic strata and Cretaceous intrusions in these two belts yield paleomagnetic and/or paleontological data which imply that the rocks did not form in the positions they now occupy in the continental margin. The Intermontane and Insular belts contain most of the displaced terranes of the Canadian Cordillera. The Omineca and Coast belts are welts of high-grade metamorphic and granitic rocks of mid-Mesozoic to Tertiary ages that developed in regions of tectonic overlap and/or crustal thickening and incorporated the little metamorphosed strata in the flanking belts.

The Canadian Cordillera in a general way is a two-sided orogen. East-directed Late Cretaceous-Paleocene thrusts occur in its eastern part; west-directed Tertiary to Recent thrusts occur in its westernmost part associated with subduction of Pacific Ocean crust. The two belts of metamorphic and granitic rocks form the cores of smaller asymmetric but typically two-sided orogens and show complex polyphase deformation, mainly Jurassic in the east and Cretaceous in the west. Late Cretaceous and Early Tertiary dextral wrench faults, the latter related to widespread extension faults, occur in the central cordillera.

Deep seismic reflection studies are restricted to the structurally simple eastern and western margins. Gravity and seismic reflection studies along the line of the transect show a thickening of the crust from about 40 to 45 km under the Alberta Plains to a maximum of 50 to 55 km near the Rocky Mountain Trench, which separates Rocky Mountain and Omineca belts. West from here, the crust thins progressively to about 35 km under the Intermontane Belt and about 20 km under the Insular Belt.

The region crossed by Transect B2 evolved in the following four main stages:

(1) Rifting of the ancestral North American supercontinent in mid-Proterozoic (Belt-Purcell) and/or late-Proterozoic (Windermere) time.
(2) Development and continuation of a long-lived, Cambrian to Jurassic passive margin, part of which is preserved in the eastern Cordillera, and arc magmatism at sites an unknown distance west of the margin.
(3) Onset of convergence at or near the western edge of the sialic continent that began in Jurassic time with accretion of the Kootenay terrane (Figure 5) to North America. Subsequently, an assemblage of noncontinental terranes of the Intermontane and Omineca belts accreted to the Kootenay. Convergence continued into Cretaceous and Paleocene time, causing collision of the displaced terranes of the Insular Belt and development of the Rocky Mountain foreland thrust belt and related foreland basins.
(4) Development of today's tectonic features by oblique convergence. These include Eocene dextral wrench fault systems and normal faults with east-west extension. Part of the dextral slip may have occurred as early as Late Cretaceous time and indicates earlier phases of oblique convergence.

The terrane assemblages of the Intermontane and Insular belts record tectonic histories that differ substantially from that of Precambrian North America. They indicate convergence in Late Paleozoic and early Mesozoic times within the Panthallasic/ancestral Pacific Ocean basin and in the Jurassic, near the margin of North America before attachment to the sialic continent. Upper Paleozoic and Lower Mesozoic volcanic and sedimentary strata that are in terranes of the Intermontane Belt formed in offshore(?) arcs, related subduction complexes and backarc basins. The three terranes of the Intermontane Belt (Quesnel, Slide Mountain, Cache Creek) were together by earliest Jurassic time, and subsequently were accreted to Kootenay terrane in late Early Jurassic time at a suture in the Omineca Crystalline Belt. To the west, in the Insular belt, Paleozoic arc rocks, Triassic rift rocks and Lower Jurassic arc rocks form the extensive Wrangellia Terrane (Figure 5) which arrived with attached small oceanic and arc terranes. These were accreted to the new continental margin in Early to mid-Cretaceous time. The suture lies within the Coast Plutonic Belt, where voluminous bodies of granitic rock and local calcalkaline volcanics presumably record crustal convergence until the present day.

Speculatively, the southern Canadian Cordillera can be interpreted to show several stages in the formation of continental crust, from the thick (40 to 55) km) old continental crust in the east, through intermediate (30 to 35 km) crust beneath terranes in the Intermontane Belt accreted to North America in the Jurassic, to thin (20 km) crust beneath terranes accreted in the Cretaceous in the west.

Problems

1. *Precambrian Rifting and Drifting*: It is not clear whether supercontinent drifting followed rifting in mid-Proterozoic (Belt-Purcell, ca. 1500 Ma) and/or in Late Proterozoic (Windermere, ca. 800 Ma) times. The configuration of the Windermere succession suggests that drifting occurred in the Late Proterozoic, but the significance of the earlier basin development is uncertain.
2. *Kootenay Terrane*: The degree of allochthoneity of the Kootenay Terrane and the nature and significance of its lower and mid-Paleozoic tectonic events are not understood. Comparable deformational, metamorphic, and magmatic events do not occur in North American continental margin strata in B2, implying the Kootenay is allochthonous. However, similar rocks occur along much of the Cordillera, and it is difficult to argue that the Kootenay is greatly exotic.
3. *Early Permian Accretion*: The Kootenay and Slide Mountain terranes were joined in Early Permian time by thrusting. Is this a phase of the Sonoma orogeny that occurred in Early Triassic and perhaps earlier times to the south in Nevada (transects C1 and C2)?
4. *Pertoo-Mesozoic Plate Tectonics*: What is the cause of the change between convergence recorded by intraoceanic magmatic arcs in the Late Paleozoic and Early Mesozoic, and convergence recorded by apparent collisions and arcs on the continental margin starting in late Early Jurassic time? Is this due to major changes of absolute plate motions, recorded elsewhere by the North Atlantic opening, or a change from old, heavy subducting oceanic crust to young, light crust?
5. *Interpretation of Superposed Deformation*: It is difficult to distinguish the effects of collisions of accreted terranes and subsequent, continuing deformation on the same site because of tectonic burial and crustal softening, from behind-the-arc shortening.
6. *Question of Anatexis*: Are some granitic rocks and their extrusive equivalents generated by tectonic burial and anatexis of transitional and continental crust, aside from those generated in subduction zones?
7. *Dip of Old Subduction Zones*: Dip directions of possible subduction zones prior to Cretaceous collision in the Coast Plutonic Belt are not known.
8. *Strike-Slip Displacements*: What is the magnitude of possible postaccretionary or intraplate dextral strike-slip movements within the Canadian segment of the Cordillera? Recent paleomagnetic results suggest that mid-Cretaceous plutons within the southern Coast Plutonic Belt and northern Cascades were intruded and cooled at least 2400 km to the south of their present positions. What was the locus of this movement? There is structural evidence using offsets of markers for dextral displacements in the northern Canadian Cordillera in excess of 1000 km, but at the latitude of the transect the only clearly recognizable strike-slip fault is the Fraser River Fault System with offset of 80 to 110 km.
9. *Deep Structure*: It is impossible without further seismic reflection work to do other than speculate on the deeper crustal structure in Intermontane and Coast Plutonic belts. In the former, there is evidence for a least four deformations: local, probably Triassic-Jurassic deformation (in lower crust of the early Mesozoic arc?); west-directed, mid-Jurassic(?) deformation on the west side of the Omineca Crystalline

Belt (Louis Creek Fault and kindred structures); east-directed Late Jurassic structures on east side of Intermontane Belt (thrusts near Cache Creek); and Early Tertiary transtensional deformation. What is the nature of the deep fabric of the Intermontane Belt, and what proportion of it is contributed by each of these structures seen at the surface?

10. *Depth of Strike-Slip Faults*: What is the termination at depth of such major strike-slip faults as the Fraser River fault system?

TRANSECT B3 JUAN DE FUCA SPREADING RIDGE TO MONTANA THRUST BELT

Synopsis and Findings

Transect B3 (Figure 1) comprises two corridors. The northern (B3n) extends from the subduction zone between the Juan de Fuca and North American plates on the west, across the cordillera of northern Washington and Idaho to cratonal North America in Montana. The southern (B3s) runs east from the spreading ridge between the oceanic Pacific and Juan de Fuca plates across the Columbia Plateau of southern Washington to the foreland thrust belt in Idaho. The objective of the two corridors is to display differences in the structure of the continental edge and the cordillera along strike.

Active tectonic regimes (Figure 5) are the eastward subduction of the Juan de Fuca plate below and accretion of sediment to the western edge and base of the modern continent. The Cascade magmatic arc lies on the continent east of the subduction zone, and behind it is a broad zone of modern extensional faulting, uplift, and magmatism that may represent backarc rifting.

The modern tectonic regimes are superposed on mid-Cenozoic and earlier tectonic provinces that are on land and extend west of the present shoreline. These occur in a broad region of ancient displaced terranes from the Puget Lowlands east to eastern Washington and western Idaho and to the boundary with Precambrian North America and its suprajacent exotic(?) and thrusted foreland cover (Figure 5). Ages of attachment of the displaced terranes to North America and to one another and the ages of foreland thrusting are Late Mesozoic and Early Cenozoic. This reflects convergence of oceanic and other lithospheres below western North America for most of Mesozoic and Cenozoic time.

During this active margin phase, the leading edge of continental North America has grown westward and thickened greatly as a forearc by two repetitive processes: the collision of terranes and the underplating by ocean-plate sediments and underlying oceanic crust. Examples in the northern corridor are as follows. In the Late Cretaceous, a thick (up to 15 km) pile of nappes, derived from the edge of North America, was driven westward onto the Wrangellia terrane (B3n, Figure 5) as it collided with the continental margin. In the Eocene a thick (>15 km) terrane of seamount basalt was accreted to the expanded continent. Subsequent convergence has carried submarine-fan and ocean-plate sediments beneath these accreted terranes, and panels of sediments and oceanic crust have been sliced off the descending plate and plated as imbricate stacks and duplexes on the base of the tectonically prograding continental front. Active offscraping and frontal accretion continue at present. In B3s, the Puget Lowland (arc-trench gap) is underlain by an 8 km-thick slab of Paleogene seamount basalts that was accreted in the Eocene. This slab overlies a zone up to 25 km thick consisting of imbricated fault-bound panels of submarine fan turbidites and oceanic lithosphere. The sediments, originally deposited along the continental slope, were subducted and underplated beneath the accreted seamount terrane. As in B3n, 40-km-thick crust west of the magmatic arc comprises both accreted terranes and underplated materials.

These interpretations about the structure and constitution of the continental edge are prompted by geophysical data indicating that the Moho is 35 to 40 km deep where it intersects the descending Juan de Fuca plate beneath the forearc region about 200 km east of the deformation front just west of the subduction zone. Thus, young continental crust of full thickness has developed in the last 100 my near a consuming plate boundary.

The unexposed basement beneath the magmatic arc and the western and central Columbia Plateau basalt is interpreted to consist of the southeastern continuation of the thrust and nappe system that is exposed in the western Cascade Mountains (Figure 5). A major fault or fault zone separates this composite terrane from the separate and distinct Wallowa-Seven Devils terrane that underlies the eastern plateau. The Wallowa-Seven Devils terrane was juxtaposed with Precambrian sialic crust of North America along a steep, crustal-scale fault zone that was last active in mid-Cretaceous time.

The westernmost extent of sialic Precambrian North America lies buried west of the Kettle and Okanogan domes in eastern Washington (Figure 5). The domes are structural culminations that expose amphibolite-grade rocks that are interpreted to belong to the Precambrian continent. They are overlain by terranes of oceanic and arc-related rocks that were thrust eastward across the former continental edge, probably in mid-Jurassic time. The domes are unroofed by Tertiary low-angle extensional faults, some of which reactivated earlier thrusts.

The westward-tapering wedge of Precambrian North American crust beneath eastern Washington may include a cryptic west-dipping thrust that extends east as the sole fault of the Late Jurassic to Late Cretaceous Montana or Rocky Mountains-Foothills thrust belt (Figure 5). In eastern Washington, the hanging wall may include, together with Precambrian crystalline basement, all of the exposed Belt Supergroup of mid-Proterozoic age at this latitude. The footwall probably consists of basement in Washington and basement together with Belt and platformal Paleozoic cover in Montana due to ramping of the sole fault to horizons within the stratified rocks. In the frontal part of the thrust belt, in B3n, only Paleozoic cover is imbricated. This differs significantly from the thrust belt geometry in the southern Canadian cordillera (Transect B2) where Paleozoic and Proterozoic strata are widely imbricated together above a sole fault that is localized near the top of crystalline basement.

Problems

1. Locally in the frontal part of the accretionary wedge, thrusts and ramp folds verge landward rather than in a more typical seaward direction. The mechanical parameters or physical properties responsible for landward vergence are unknown.
2. The northern corridor crosses several major strike-slip faults (e.g., San Juan, Straight Creek) that dip vertically at the surface and that have estimated displacements of tens of kilometers. It is unknown whether the faults continue vertically downward

to end at the Moho, offset the Moho, or flatten into mid-crustal zones of dislocation or detachment.

3. In the northern corridor, the western edge of Precambrian sialic North America is not well located. Strontium-isotope data are inconclusive, and most of the crystalline rocks west of known Proterozoic North American sedimentary rocks are poorly dated.
4. The identity and structural configuration of rocks responsible for a positive gravity anomaly west of the Purcell anticlinorium are unknown. The Belt Supergroup is possibly underlain by either a parautochthonous wedge of Paleozoic carbonates, or a displaced slice of Precambrian crystalline basement.
5. The nature and orientation of the terrane boundary beneath the central Columbia Plateau are unknown, as are the amount and sense of displacement along what must be a major fault zone.

TRANSECT C1 MENDOCINO TRIPLE JUNCTION TO NORTH AMERICAN CRATON

Synopsis and Findings

Transect C1 (Figure 1) crosses the cordillera of the western United States from the Mendocino triple junction off the coast of northern California to the craton in Wyoming. The tectonic record of C1 (Figure 6) contains events throughout Phanerozoic time and comprises the following stages: (1) rifting and drifting at the end of the Proterozoic; (2) maintenance of a passive margin together with episodic deformation in Paleozoic and deformation plus accretion in Early Triassic times; and (3) onset of active margin tectonism that has existed to the present and includes accretion of terranes, continental arc magmatism, foreland thrusting, and distributed strike-slip deformation with senses of slip and obliquity that have varied with time and place.

East of the Cascade arc and its recently extinct southerly prolongation, active tectonism is manifested by a broad region of regionalized uplift as great as 1.5 km in the last 10 my or less. The region includes the Sierra Nevada, Basin-Range, Colorado Plateau, and Rocky Mountains (Figure 6). The uplift is apparently related to shallowing of the asthenosphere and advection of mantle-generated magma. Within the uplifted region, the Basin-Range province, which presents the most conspicuous deformation, is a broad region of rifting, volcanism, high heat flow, high seismicity, and low-velocity upper mantle. Extension in the Basin-Range, regionally east-west, is highly heterogeneous. It is probably at a maximum in eastern Nevada where mid-crustal rocks (core complexes) are exhumed by low angle normal faults. These may also be sites of maximum volume addition to the crust by mantle-derived magma. The Neogene uplift and extension of the cordillera may be related to backarc rifting and to diffuse plate boundary shear linked to the San Andreas transform. The backarc regime began as far back as 35 mybp whereas the transform-related regime is `10 my.

The older Phanerozoic tectonic evolution in C1 begins with rifting of the Precambrian supercontinent in two or more episodes in the Late Proterozoic, consummated by the onset of drifting and subsidence of an unusually broad shelf at about 500 mybp. The present edge of Proterozoic North America probably lies in west central Nevada (Figure 6) below thick sedimentary and tectonic cover; the edge in C1 may be closest in western North America to the original 600 my drift juncture, reflecting a minimum of tectonic erosion of the continental margin at this latitude.

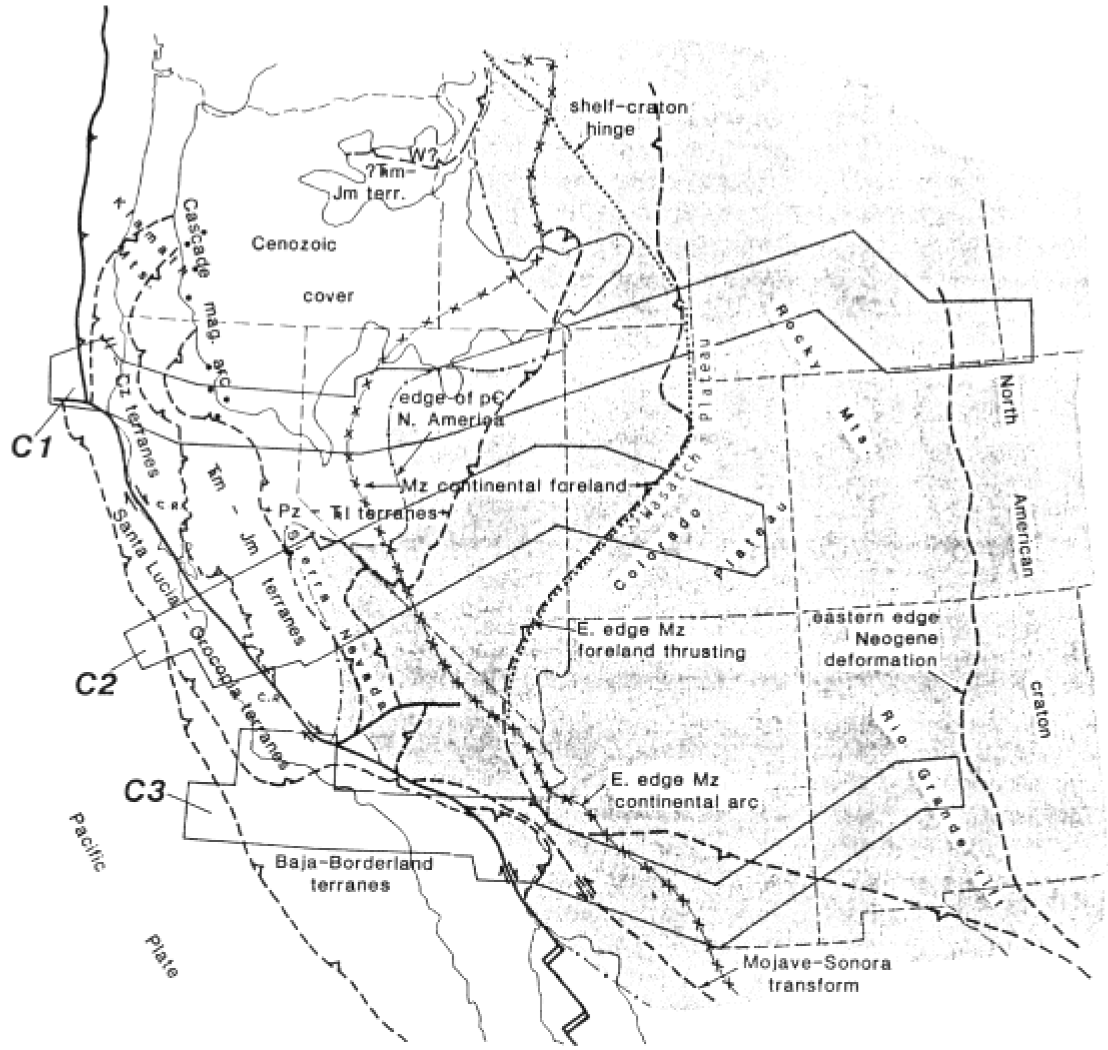


Figure 6
Map of western United States showing positions of corridors C1, C2, and C3.

A passive margin was maintained from Cambrian to mid-Triassic time, although repetitive collisional events occurred at the margin which emplaced major allochthons of oceanic and basinal rocks eastward at least 100 km across the continental slope and outer shelf. The older of the passive margin allochthons (Figure 6) was emplaced in Early Mississippian time, the later in the Early Triassic. Both passive margin orogenies probably represent arc-continent collisions, although the magnitude of arc translation before collision is disputed.

The active margin to western North America in C1 began in mid-Triassic time and continues today. In the early Mesozoic, a continental magmatic arc developed above the earlier terranes in C1 (and above Proterozoic North America to the south in Transect C2) and above a subduction zone that was probably in the present Great Valley (Figure 6). Active margin events west of the continental arc have been mainly the accretion of terranes and phases of strike-slip faulting and rifting among the terranes. East of the continental arc, events consisted of extensive foreland thrusting and moderate magmatism but only minor unroofing in the Mesozoic and major extension and rifting in later Cenozoic time.

In the Coast Ranges (Figure 6), the oldest recognized event is the Middle Jurassic (165 my) formation of the Coast Range ophiolite, probably in a backarc basin of an offshore arc. The arc and its cover were thrust above the edge of North America (then the western flank of the continental arc) in the Nevadan orogeny at about 150 mybp. Attachment of Franciscan-type terranes outboard of the Coast Range ophiolite may have followed the Nevadan orogeny. The discrete Early and mid-Cretaceous ages of blueschists in such terranes suggest sequential collision of preassembled terranes rather than continuous accretion at the continental edge. Attachment of early Franciscan terranes, mainly melange, was followed by right-slip faulting between 50 and 85 mybp within the terrane assembly, perhaps in response to passage of the Kula-Farallon triple junction. Such faulting further dismembered the Franciscan melanges. Underthrusting and attachment of younger Franciscan terranes resumed at 38 mybp.

The Sierra Nevada and Klamath Mountains (Figure 6) witnessed copious continental arc magmatism from Late Triassic through Cretaceous times and record collisional tectonism. Accretion of several terranes to early Mesozoic North America in the Klamaths occurred between 180 and 150 mybp. The accretionary surfaces for each were subplanar east-dipping thrusts. The final phase of such accretion occurred during the Nevadan orogeny. It is uncertain whether all the terranes assembled elsewhere and then collided with North America in the Nevadan orogeny, or each terrane attached in sequence from east to west with the Nevadan orogeny as the culminating event. In the Sierra Nevada, terranes were also accreted to the edge of early Mesozoic North America during or before the 150 mybp Nevadan orogeny, probably above a west-dipping thrust. Obduction of the Coast Range ophiolite onto earlier terranes of the Sierran foothills climaxed this sequence. Terranes of the Sierra and Klamaths are not easily correlated.

On the eastern side of the Sierran-Klamath continental arc in C1, active margin tectonism caused an unusually broad realm of thin-skinned foreland contraction in Early Jurassic to Eocene time. The realm extends from the backside of the arc east to the hinge between the craton and subsiding shelf of Paleozoic North America (Figure 6). Within the realm, thrust belts occur in several discrete strands with varied vergence; such belts are probably positioned by pre-existing declivities in and above the top of the basement. Between strands there is probably a through going detachment that connects displacements across the foreland. There is little recognized involvement of basement. Minor plutonism, perhaps anatectic, occurred in two short episodes (160 and 80 mybp) during foreland contraction. Displacements in the cordilleran foreland thrust belts in C1 have little evident contemporaneity with collisional events to the west at the continental edge, although timing of events is not well known in either realm. The cordilleran foreland realm differs from others in the world by minimal hinterward increase in unroofing and metamorphism.

The classic Laramide orogeny, which is restricted to central and eastern Wyoming in C1, differs from the foreland contraction just discussed. The Laramide is thick-skinned, brings basement over cover, and occurred in the Paleogene mainly after contractile events to the west. The Laramide may differ also in tectonic origin and relate to rotation of the Colorado Plateau.

TRANSECT C2 CENTRAL CALIFORNIA OFFSHORE TO COLORADO PLATEAU

Synopsis and Findings

Corridor C2 (Figure 1) starts 80 km offshore of Monterey Bay in central California at a fossil Franciscan trench and extends eastward to a region of the Colorado Plateau in Utah (Figure 6). The main tectonomorphic features crossed are the California Coast Ranges and Great Valley, Sierra Nevada, Basin and Range, the Wasatch Plateau, and the western edge of the Colorado plateau. Important tectonic regimes represented are the Late Precambrian rifted sialic edge and the superjacent Eocambrian to Late Paleozoic subsiding shelf sediments, a mosaic of allochthonous terranes accreted to Late Precambrian passive margin between Mississippian and Late Jurassic time, the Cretaceous Franciscan subduction regime and related Sierra Nevada composite batholith evolution, Late Mesozoic foreland shortening and related basin development, Cenozoic detachment faulting, and the Late Cenozoic establishment of the San Andreas transform plate juncture and the Basin and Range extensional province.

The region of Transect C2 offers one of the most complete and intact records of the Late Precambrian rift generation of the Cordilleran margin. Major accretionary events which resulted in the addition of ensimatic materials directly to the rifted margin include the early Mississippian Antler orogeny and the Early Triassic Sonoma orogeny. In both, oceanic sediments and basalt were thrust eastward across the slope and outer shelf. Subsequent accretionary events occurred along the locus of the western Sierra Nevada foothills suture. In this regime the autochthonous buttress appears to have been an oblique section through the ancient rifted edge of the sialic continent and the suprajacent Antler and Sonoma allochthons, modified by transcurrent faulting in the Sierra Nevada foothills that occurred before or during accretion. Accretion in the foothills began with emplacement of young, warm primitive island arc and interarc basin assemblages. The California Great Valley basement and Coast Range ophiolite were accreted at the end of this episode in what is called the Nevadan orogeny.

Subsequent accretions of Franciscan rocks in the Coast Ranges modified the outer edge of Jurassic and Cretaceous North America, and the related continental magmatic arc in the Sierra Nevada (Figure 6) annealed the foothills suture belt into new sialic crust. Trench turbidites and Pacific basin pelagic deposits form the main mass of Franciscan accretionary materials. Seamount fragments and related pelagic limestones appear to represent remnants of the mirror image of the Hess Rise/Mid-Pacific Mountains oceanic plateau province which drifted eastward and was subducted beneath North America. Blueschist facies metamorphism in the Franciscan appears to be more closely related to major accretion events than steady state subduction. High *P/T* conditions may have existed in a steady state within the subduction regime, but it is the accretion of thickened crustal fragments (oceanic plateaus, seamount chains, island arcs) which led to uplift and hence the dated blueschist events.

Voluminous batholithic activity of the continental arc in the Sierra Nevada that was related to Franciscan subduction began between the axial Great Valley and western Sierra metamorphic belt at about 130 Ma with the emplacement of mainly gabbroic to tonalitic plutons. Subsequent magmatism swept eastward and became more granitic with an ˜85 Ma termination along the eastern Sierra. Remnants of Triassic and Jurassic batholithic rocks are split obliquely by the major Cretaceous batholithic belt.

The Late Cretaceous forearc basin was built in part across the Early Cretaceous magmatic arc.

Remnants of foreland basins related to the Antler and Sonoma orogenies are present in central and western Nevada, and major Jurassic to earliest Tertiary foreland deposits are present in Utah. Mesozoic foreland deformation was distributed along three well-defined belts in Nevada and Utah, and each may root into a common decollement. There does not appear to be a direct relation between foreland deformation and marginal accretion in the Mesozoic.

Modern transform motion of the San Andreas plate juncture is distributed over a zone of ~100 km width with a possible minor component also hidden within Basin and Range extensional motion. The Salinia sialic crystalline terrane and Late Cretaceous and Early Tertiary accretionary prism complexes are amalgamated onto the western edge of the Pacific plate and are thus sliding northward along the transform juncture. Such phenomena in the tectonic attrition of sialic fragments and earlier ensimatic accretionary complexes are believed to have been a first order process interspersed with accretionary events along the Mesozoic California margin as well.

Mid-Cenozoic extensional tectonism displayed in C2 by the Snake Range and related "metamorphic core complexes" offers an opportunity to view mid-crustal processes in extensional regimes. Fundamental questions raised by such exposures are whether similar structural patterns are currently developing beneath the widespread graben-horst structures of the Basin and Range; do major decollements develop by large-scale pure shear or simple shear; might Cenozoic decollements be reactivated Mesozoic foreland thrusts; and what is the role of magmatism during extension?

TRANSECT C3 PACIFIC ABYSSAL PLAIN TO RIO GRANDE RIFT

Synopsis and Findings

Transect C3 (Figure 1) contains the following modern tectonic provinces, in eastward succession (Figure 6): a region of the Pacific plate that comprises a seamount province on abyssal oceanic crust and displacing terranes of the continental borderland, including a batholithic belt in the Peninsular Ranges; a transform rift floored by nascent oceanic crust that is the Pacific-North American plate boundary; the greatly extended Basin and Range province, here in its widest zone in North America and developed mainly in former cratonal lithosphere; and the stable craton.

Older terranes exist both east and west of the plate boundary. Their histories of attachment to one another and to Proterozoic North America have been complex, beginning in the Cretaceous. The superposition of the modern and Neogene tectonic provinces on these has yielded extreme structural heterogeneity along C3.

The Phanerozoic tectonic evolution of C3 is contested from two main perspectives regarding the degree of allochthoneity of terranes outboard of Proterozoic North America. The concept of parautochthoneity derives from geochemical and petrologic relations that seemingly link aspects of terranes across the full length of the transect and implies only small displacements. Conversely, the concept of great allochthoneity stems from stratigraphic relationships and paleomagnetic data from some terranes that imply several thousand kilometers of transport. The C3 transect group includes spokesmen from both viewpoints, but the perspective of great allochthoneity prevailed.

The principal findings in Corridor C3 are as follows:

Precambrian Rocks: Five distinct suites of Precambrian rocks are inferred to exist in C3: (1) stable cratonal rocks east of the Rio Grande Rift; (2) block-faulted and attenuated "cratonal" rocks between the Rio Grande Rift and the left-slip fault of the Mojave-Sonora discontinuity, (3) and (4) exotic Precambrian rocks of a terrane that occurs both between the Mojave-Sonora megashear and the San Andreas fault and west of the San Andreas (Figure 6), and (5) cryptic Precambrian rocks from a terrane in coastal southwestern California (Figure 6) inferred from the geochemistry of suprajacent rocks.

Rifting and Truncation: Gradients in thickness and facies among Lower Paleozoic and latest Precambrian North American continental shelf sediments in Nevada, north of C3, imply Late Proterozoic rifting and the onset of drifting at about 600 mybp. Only a thin sequence of Paleozoic platformal cover strata occurs in Proterozoic North America in C3, however, and the thick subsiding shelf sections present in Nevada are missing. This suggests that a major tectonic truncation of the craton occurred in C3 after the Paleozoic, possibly associated with Jurassic left slip on the Sonora-Mojave discontinuity. A third phase of rifting and right slip translation exists in the Salton Trough (Figure 4) at the North America-Pacific plate boundary. Detachment faulting and associated basin-range faulting indicate widespread rifting of the craton in C3 and the possibility of drifting or truncation at some future time.

Terrane Amalgamation, Accretion, and Dispersion: The stratigraphy of sedimentary overlap sequences and the distribution of stitching plutons chronicles a history of amalgamation, accretion, and dispersion of displaced terranes. The history is a continuous series of tectonic events surrounding the coastwise translation of terranes that has been ongoing for the past 100 Ma. Detritus derived from the continent lies within all the terranes, a circumstance that requires contiguity with the craton. Paleomagnetic data indicate that terranes amalgamated in southern latitudes, generally in present Central America. Two accretion events occurred in the Tertiary: (1) the 55 Ma arrival of the composite Santa Lucia-Orocopia allochthon, and (2) the Miocene accretion of the Baja-Borderland composite terrane. The modern San Andreas fault system is the youngest displacement zone causing terrane dispersion.

Problems

1. To what extent did the rifting and drifting in the Caribbean and Gulf of Mexico influence the history of the Bisbee Basin and Chihuahua trough of southern Arizona and northern Mexico?
2. What is the driving force that affects intraplate thrusting, e.g., terrane accretion, subduction polarity, Benioff angle?
3. What is the geological framework of northwest Mexico and how does it correlate with rocks of the basin and range?
4. What is the geometry and kinematic history of the Mojave-Sonora megashear in the Mojave Desert area?
5. What is the tectonic significance of the Pelona-Orocopia schist: direction of vergence, age, depositional setting of protolith, and conditions of metamorphism?
6. What is the paleogeography of the Late Mesozoic batholithic rocks of western North America—one exceptionally long continuous magmatic arc, a variety of double volcanic arcs, or many unrelated arcs that are now juxtaposed?

7. What are the age and tectonic significance of the McCoy Mountain Formation? Was it deposited within an intracratonic rift or did open-ocean conditions exist to the southwest?
8. Tertiary volcanic events: what controls their chemistry and spatial distribution?
9. How deeply rooted is each of the terranes?
10. What kinematic and dynamic models best explain the large-scale rotations recorded for parts of southern California?
11. Are the large-scale northward translations real as required by paleomagnetic data from all the terranes of southern California?
12. What tectonic model best explains the mid-Tertiary extension in the Basin and Range province and the local regions of marked stretching manifest by detachment faults and core complexes?

TRANSECTS D1 TO D4EASTERN CANADA AND NORTH ATLANTIC OCEAN

Synopses and findings of each D Transect are discussed separately; the problems occurring in them are treated together.

Transect D1: Northern Appalachians: (West Sheet) Grenville Province, Quebec, to Newfoundland; (East Sheet) Rifted Margin Offshore Northeast Newfoundland

Synopsis and Findings

Transect D1 displays the full width of transitional lithosphere in eastern Canada between the craton composed of unmodified Grenvillian basement and an arm of Atlantic oceanic lithosphere in the southern Labrador Sea (Figures 1 and 7). The Phanerozoic evolution of the continent-ocean transition in eastern Canada occurred in three phases. The first included rifting, drifting, and the development of a passive continental margin with the Iapetus Ocean in Late Precambrian and earliest Paleozoic time. The second phase saw the closing of Iapetus and the emergence of the Appalachian orogen through collisional tectonics in Ordovician and later Paleozoic times. The third phase began with rifting in the Appalachian orogen late in Triassic time, followed by opening of the Atlantic basin from the Jurassic to the present.

The opening of Iapetus is recorded in western Newfoundland (Figure 7) by rifting of the one-billion-year-old Grenvillian basement, accumulation of thick clastic sequence, and basaltic magmatism in Late Precambrian time. Following the rift-related events, drifting and the thermal subsidence of the continental shelf is indicated by facies changes in the sedimentary cover of Early Cambrian to latest Early Ordovician age. These thicken eastward across the shelf and grade upward from immature to mature siliciclastic rocks to platformal carbonate rocks. Contemporaneous sediments of the slope and rise—turbidites, hemipelagites, and sedimentary breccias—are now in allochthons above the carbonate shelf strata.

Collisional tectonics at and above the passive margin of North America in Newfoundland caused the effacement of the Iapetus basin and the protracted development of the Appalachian orogen. They began near the end of Early Ordovician time, probably by arc-continent collision. The subduction zone apparently dipped away from

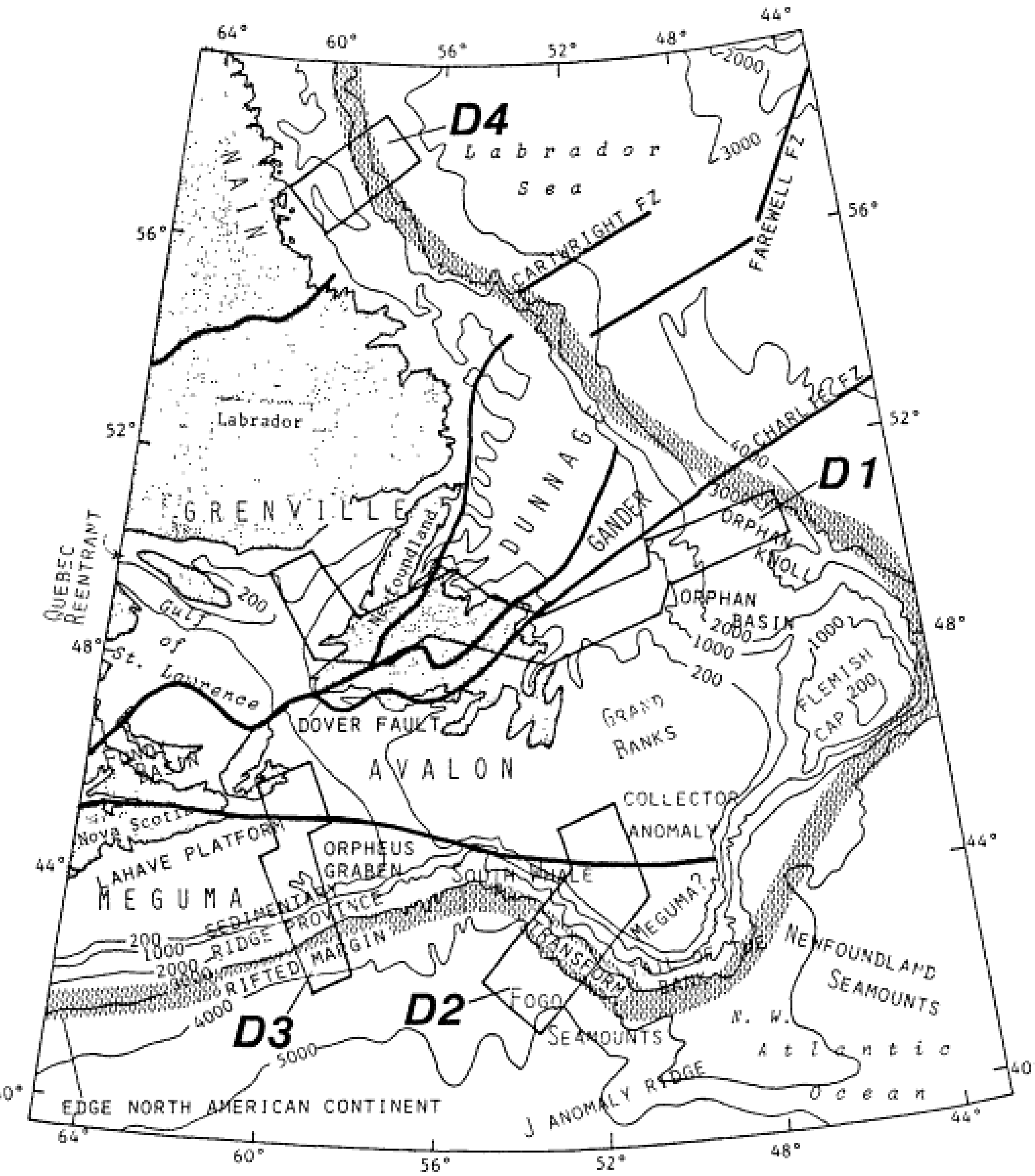


Figure 7
Map of eastern Canada showing positions of corridors D1 to D4.

North America, which was overridden by exotic terranes by at least 75 km. Subsequent collisions occurred in Paleozoic time, causing further growth of the Appalachian orogen by deformation of the continental margin and growth of the continent by accretion of terranes. The first indication of instability is indicated by an ancient karst topography developed across an upwarped carbonate shelf. Later subsidence is recorded first by the deposition of deeper water carbonates across the disturbed bank, then by a flood of clastic rocks from the east. These were structurally overridden by a sequence of contrasting rock assemblages in separate slices. The structurally lowest slices consist of sedimentary rocks from the nearby continental margin, and the highest ophiolitic slices represent farther travelled oceanic crust and mantle. The structural pile propagated from east to west, possibly through accretion successively of landward sections from the subsiding continental margin. The present contacts between the structural slices are marked by thin zones of shale melange.

In Newfoundland, Precambrian North America is circumscribed progressively outward by three large terranes, all of unknown paleogeography with respect to North America. From west to east, these are the Dunnage, Gander, and Avalon terranes (Figure 7), An additional, more easterly terrane, the Meguma, occurs in mainland Nova Scotia. Island arc rocks of the Dunnage terrane overlie an ophiolitic substrate. The Dunnage is an example of a Lower Paleozoic island arc built upon the crust of Iapetus. The Gander terrane contains a thick clastic sequence that may be a miogeoclinal apron along the west flank of the continental Avalon terrane. The Gander terrane may have once bordered a continental craton but it is nowhere linked to a craton now. The Avalon terrane contains probable Grenvillian basement, Late Precambrian thick sedimentary and volcanic cover, and overlying Cambrian shales with Atlantic or European faunal affinities. Its cover probably records rifting and subsidence in the growth of Iapetus, but it is uncertain whether Avalon existed as a fragment within Iapetus or at its eastern margin and whether Avalon emerged from the same or a very different paleolatitude than its current position.

Important findings on the relation of surficial and deep crustal structures have emerged from analysis of seismic reflection sections that extend from the craton across Newfoundland. Crustal blocks defined by distinctive deep reflection sets do not coincide with major terranes defined at the surface, except for the Gander-Avalon boundary, which is the Dover fault. The vertical Dover fault penetrates the crust, and the Avalon terrane has deep lithospheric underpinnings.

Subsurface data confirm that Grenvillian basement extends eastward about 70 km beneath the ophiolitic Dunnage terrane but also indicate the sialic crust of the Gander terrane extends westward to the subsurface edge of Precambrian North America. Thus, a collisional suture exists in the lower crust beneath the Dunnage terrane. The opposing vergences of structures on opposite sides of the Dunnage terrane coupled with its thin-skinned geometry suggest that the collision of Gander and North America was normal to their mutual boundary. In contrast the nature of the Dover fault suggests oblique transport of the Avalon terrane with respect to the Gander.

The appearance of cosmopolitan faunas in Middle Ordovician rocks of the Appalachians, and in Middle Ordovician rocks of the Caledonides of Scandinavia on the opposite side of Iapetus, requires a breakdown of faunal barriers. This implies proximity of terranes across the Iapetus tract, and it agrees with the Ordovician destruction of some of its continental margins. Widespread occurrences of Late Silurian and Devonian terrestrial rocks throughout most of the Appalachian-Caledonides orogen, coupled with the wide extent of middle Paleozoic orogenesis, indicate the almost complete destruction of Iapetus at this time. Restricted Late Paleozoic marine deposits and limited extent of Late Paleozoic deformation in the Appalachian-Caledonides orogen signify the closure of remaining narrow seaways and structural tightening of weak crustal areas.

Stratigraphic and sedimentologic analyses of the Appalachian orogen in Newfoundland indicated that it built up from the miogeocline outward by three accretionary events. These are dated stratigraphically as Early to Middle Ordovician, Silurian-Devonian, and Carboniferous-Permian; and these times of accretion coincide with the main orogenic episodes affecting the system, namely Taconian, Acadian, and Alleghanian, respectively. The boundaries between the first accreted western terranes are subhorizontal to moderately dipping zones marked by ophiolites and melanges, implying head-on subduction and obduction. Later boundaries between eastern terranes are steep ductile shears and brittle faults, implying transcurrent movements. Late Paleozoic transcurrent motions may have modified the early Paleozoic boundaries.

Accretionary analysis of the Appalachian orogen in Newfoundland indicates Early to Middle Ordovician linkages between the North American miogeocline and Dunnage terrane, and between the Dunnage and Gander terranes. The Avalon terrane was added later. It lacks Ordovician linkages and effects of Ordovician Taconian orogeny, and its latest time of accretion is defined by stitching to the Gander terrane by Devonian plutons. The boundaries between the first accreted western terranes are subhorizontal to moderately dipping zones marked by ophiolites and melanges, implying head-on subduction and obduction. The Gander-Avalon terrane boundary is a steep mylonite zone, suggesting transcurrent movement.

The third and modern phase of development of the continent-ocean transition in the Grand Banks region (Figure 7) of Canada began with rifting that started in Triassic time with incipient breakup between Africa and North America. A second rifting phase in the Early Cretaceous or the Late Jurassic created the rifted margin east of the Grand Banks in response to plate motions between Iberia and North America. Drifting between northwest Europe and North America created the margins northeast of Newfoundland in Late Cretaceous time. The Mesozoic history of this area is complex because of the variety, proximity, and geometry of plates in continental breakup during the Cretaceous, and because rifting appears to have taken place over a long time interval, about 50 Ma.

South of Newfoundland, early Mesozoic opening parallels the axis of the latest compressional event related to Iapetus closure. North of the Grand Banks, the axis of opening developed two branches at an Early Tertiary triple point in the southern Labrador Sea. The northwestern arm of this triple junction cuts obliquely across older structures.

Where Mesozoic-Cenozoic rifting cuts across the Appalachian orogen in northeast Newfoundland and the Grenville structural province of Labrador, some Paleozoic terrane boundaries and Precambrian structural features propagated eastward, and their prolongations coincide with offsets in the present margin and major oceanic fracture zones. Most obvious is the prolongation of the Dover fault into the Charlie Fracture Zone (Figure 7). The importance of the former as a Paleozoic terrane boundary is apparent from the contrasting surface geology of the Avalon and Gander terranes as well as their deep crustal contrasts. Similarly, the prolongation of the Precambrian Grenville structural front is expressed in the Cartwright Fracture Zone (Figure 7). Surprising, the fundamental Avalon-Meguma terrane boundary is not expressed in a rift or transform margin, although it localized the Fundy rift basin and the Orpheus depression.

The Tail of the Bank at the Grand Banks transform margin is a modern promontory that parallels the Paleozoic St. Lawrence Promontory of the Appalachian orogen. Furthermore, the "transform" linking the St. Lawrence Promontory to the Quebec Reentrant lies along the prolongation of the older Labrador Trough, which may represent a much older (Aphebian) continental margin. Although inheritance and ancestral controls are implied among these features, there are no actual structural breaks that can be traced from one to another. The Orphan Basin, crossed by D1, is a broad depression, partly filled with sediments, which is bounded to the east by Orphan Knoll (a continental fragment) and to the north by the Charlie Fault Zone, created along the seaward continuation of the Dover fault. To the south lies the Flemish Cap, another continental fragment similar to that of Orphan Knoll. Thus, the fragmented nature of this margin is quite different from the relatively sharply rifted margin south of the Grand Banks. The subsidence history of this margin is difficult to interpret according to a simple cooling model. Very rapid subsidence occurred in the Eocene, with little or no tectonically controlled subsidence thereafter. This rapid subsidence may be related to decoupling between Rockall Plateau and Orphan Basin, between which the northern transform boundary of the latter developed.

The deep structure of Orphan Basin (Figure 7) is characterized by crustal thinning, and by a high velocity lower crustal layer. The thin crust is consistent with extension of the lithosphere during rifting. The lower crustal layer may be a product of magma generation during rifting that has intruded or underplated the thinned continental crust. Orphan Knoll separates the Orphan Basin from the deep ocean. It appears to be a large horst, stranded at a distal point with respect to the basin. A fairly sharp transition from continent to ocean occurs to the east of Orphan Knoll.

A large positive gravity anomaly lies over the outer shelf, landward of the Orphan Basin. It is important to recognize that this anomaly does not mark the ocean-continent transition which lies several hundred kilometers farther east. Such observations at modern margins suggest caution when using gravity to define ancient ocean-continent transitions.

Transect D2: Transform margin south of Grand Banks: Offshore eastern Canada

Synopsis and Findings

Transect D2 is designed to illustrate the nature of the transitional region formed at a transform fault in a passive margin system. The edge of North America south of the Grand Banks (Figure 7) is of transform origin and formed by shearing in a NW-SE striking plate between the African and North American plates during opening of the Atlantic. The Grand Banks margin traces the northern limit of these plate motions. Its age is Early-Middle Jurassic in the northwest where it joins the rifted Nova Scotian margin (Figure 7) and Early-Middle Cretaceous at its southeastern terminus.

The northwestern segment of this margin has similarities to the adjacent rifted margin off Nova Scotia. The stratigraphy and depositional environments in the northwestern part are similar to those of sediments at the Nova Scotia rifted margin. Thus, the junction between the Nova Scotian rifted margin and the Grand Banks transform margin is complex and diffuse. It is only southeast of the South Whale Basin that the geological style of margin typifies transform tectonics.

Continental basement beneath the southern Grand Banks comprises the Meguma and Avalon terranes of the Appalachian orogen. The boundary between the Avalon and Meguma terranes is defined by the Collector magnetic and gravity anomalies and is interpreted as a steep transcurrent fault (Figure 7). The Meguma terrane consists primarily of Cambro-Ordovician deep water sediments. Basement to the Meguma is thought to be of Grenvillian age.

Elongate rift basins which are half graben occur on the Grand Banks. Most reflect reactivation of faults in Avalon crust. They are filled with Triassic nonmarine and paralic clastic sediments, Triassic and Lower Jurassic salt and carbonates. These basins remained active sites of rifting until Early-Middle Cretaceous time, as long as the African and North American continents were in contact along the transform. In Late Cretaceous time, the Grand Banks were uplifted, perhaps in response to the onset of rifting between Iberia and the eastern Grand Banks. This produced a major unconformity, above which latest Cretaceous and younger marine clastic sediments blanket the rift basins and basement. Except for the rift grabens and the northwestern segment of this margin, sediments are thin over much of the Grand Banks and a deep wide sedimentary basin, such as those along the rifted margins, did not develop along the transform margin, although a narrow basin occupies the continental slope.

The contact between the Avalon and Meguma terranes appears to have been reactivated either by rifting or by plate reordering on a more global scale. Early-Middle Cretaceous volcanism occurred near this boundary on the Grand Banks and also on oceanic crust producing the Fogo Seamounts and the J-Anomaly Ridge along the southeastern part of the transform margin. Farther north and east, the Newfoundland Seamounts of mid-Cretaceous age were created after the separation of Iberia from North America. The relationship between volcanic activity in these different regions is unclear. The Newfoundland Seamounts may be the seaward prolongation of the Avalon-Meguma boundary.

The ocean-continent boundary appears to be much sharper across the transform margin than across the rifted margins. Unlike the rifted margins, there is no broad zone over which the crystalline continental crust has been thinned, and there are no deep marginal sedimentary basins on the transform margin. The ocean-continent transition is only 30 km wide in the region of transform motion. At present there is no evidence for basaltic intrusion in the transition region. Landward of this transition there may be a zone of thinned crust, but thinning is not as intense as on the rifted margins. Some of this thinning is due to erosion during the mid-Cretaceous uplift of the Grand Banks region and not to necking of the crust.

The oceanic crust adjacent to the transform margin is anomalous: it consists of a very thick layer 2 while layer 3 is either thin or absent. This may be related to the excess volcanism of the region. The narrow ocean-continent transition at the transform margin supports the hypothesis that extensional forces cause crustal thinning at the rifted margins, whereas transform margins exhibit little or no thinning. The absence of a large sedimentary basin along the transform margin may be due to the absence of extension and thinning during rifting.

The oceanic crust south of the Grand Banks and east of Nova Scotia contains the Jurassic Quiet Magnetic Zone. Exceptions occur where seamounts are present. There is no equivalent of the East Coast Magnetic Anomaly along the transform. The free air gravity anomalies across this transform margin are weak by comparison with those across the rifted margin. In general, large positive gravity anomalies, 60 to 100 mGal, are associated with the deep sedimentary basins on rifted margins, while smaller anomalies correspond to platform regions. Such a pattern is consistent with a significant contribution to these anomalies from sediment loading and isostatic adjustment. The small size of the positive gravity anomalies across the transform margin, 40 mGal or less, may therefore reflect the absence of a major basin above the transition zone.

Transect D3: Rifted continental margin off Nova Scotia: Offshore eastern Canada

Synopsis and Findings

The objective of Transect D3 (Figure 1) is to depict the structure of the continent-ocean transition at a typical rifted margin. The contemporary margin off Nova Scotia was formed over the Meguma and Avalon terranes in response to rifting and drifting between Africa and North America (Figure 7). Rifting began in the Late Triassic and produced basins beneath the present continental shelf. Of these, the Orpheus sub-basin which lies on the Avalon-Meguma boundary is a prominent example (Figure 7). Regionally, the rift basins are not uniformly distributed throughout the Nova Scotian and southern Grand Banks regions. Most are in the Avalon terrane, rather than the Meguma terrane. Triassic mafic volcanism appears to lie well inland of the present ocean-continent transition. Triassic rifting was accompanied by the deposition of nonmarine clastics within the rift basins. During the Early Jurassic, thick salt beds developed beneath much of the present shelf and slope. In Early-Middle Jurassic time, a deepening, less restricted marine environment led to the construction of carbonate platforms. During this time, seafloor spreading began east of the rifted North American continent. The rift-drift transition does not appear to be marked by a period of uplift, erosion, or by the development of a clear breakup unconformity.

After the onset of seafloor spreading, the margin subsided and over 10 km of Jurassic and younger sediments were deposited on the outer shelf and slope. Variations in morphology, sediment type, and deposition rate throughout the post-rift history of the margin were largely controlled by the paleoenvironment, and by the balance between rates of subsidence, sediment influx, and eustatic sea level changes. These factors caused a major change in sedimentation, from carbonate deposition to clastic influx in Late Jurassic-Early Cretaceous time. They also produced several regional unconformities within this section and controlled the position of the edge of the shelf. Salt diapirism further altered the stratigraphy of the marginal sedimentary basin and produced the Sedimentary Ridge province beneath the continental slope (Figure 7). Diapiric growth was most active in Cretaceous time.

The Sedimentary Ridge province contains over 10 km of sediment (Figure 7). Its landward edge is marked by the hinge line, an extensional fault. At this point, the sediments thicken rapidly towards the shelf edge. Landward of the hinge line, there has been progressive onlap of sediments, forming a coastal plain sequence. The Upper Triassic-Lower Cretaceous carbonate banks terminate beneath the shelf as defined seismically, and presumably mark the position of the paleoshelf edge. The seaward extent of the Scotian Basin is not clearly delineated; it gradually merges with the North Atlantic basin across the continental rise. Beneath the continental slope, the Sedimentary Ridge province consists of salt diapirs. Salt diapirs also occur beneath the shelf.

Basement to this section includes rocks of the Meguma and Avalon Appalachian terranes whose boundary is probably a steep transcurrent fault (Figure 7). The Meguma terrane consists principally of deep water sediments of Cambro-Ordovician age. This terrane is believed to extend seaward to the outer shelf region, on the basis of seismic velocities and because Megurea rocks are found in the bottom of deep exploratory wells on the outer shelf of the LaHave platform (Figure 7). Carboniferous sediments may also occur below Mesozoic strata in the Scotian Basin.

The deep structure of the margin is characterized by extensive thinning of the crystalline continental crust by factors of 2 to 3. The thinning intensifies towards the ocean-continent transition. The thinned crust may be a measure of the amount of lithospheric extension that occurred during rifting. The cooling of the lithosphere after the rifting episode can explain the shape of the subsidence history curves determined from deep borehole data.

The region of truly transitional crust has probably been both thinned and intruded and has properties that are different from either oceanic or continental material. This transitional region has high seismic velocities of 7.4 km-s-1 in a zone about 100-km-wide off Nova Scotia. This velocity, typical of basaltic rocks, is evidence for the intrusion of basaltic magma, which underplated or intruded the thinned continental crust during rifting. The transition zone is also associated with the East Coast Magnetic Anomaly, a prominent marker that can be traced southwards as far as the Blake Plateau. Its cause is unknown, but it is generally accepted that it marks the ocean-continent transition.

A large positive gravity anomaly lies over the outer continental shelf and a corresponding negative anomaly lies over the continental slope and rise. These anomalies do not coincide with the East Coast Magnetic Anomaly but rather, they follow the morphology of the present margin. The gravity anomalies have two causes: (1) changes in crustal thickness, sediment thickness, and water depth near the shelf edge; and (2) the lateral extent over which the load of sediment and water is isostatically compensated by flexure in the underlying lithosphere.

In general the heat flow over oceanic and over continental parts of the rifted margin are similar. There is a large scatter in heat flow values over the Sedimentary Ridge province, which is attributed to the high conductivity salt diapirs surrounded by lower conductivity sediments.

The oceanic region seaward of the transition zone represents the oldest oceanic crust, generated in Jurassic time. This region lies within the Quiet Magnetic Zone, so no seafloor spreading anomalies are apparent. There is no evidence for anomalous oceanic crustal thicknesses, or oceanic basement highs near the ocean-continent transition in this region.

Transect D4: Rifted continental margin off Labrador

Synopsis and Findings

The continent-ocean transition in Labrador (Figure 1) is the result of continental breakup between Greenland and North America in Late Cretaceous time. This margin formed by rifting of the Precambrian craton. The Nain cratonal province probably extends offshore beneath the region of Transect D4 (Figure 7) It consists primarily of Archean rocks and is older than the Grenville province to the south. Paleozoic rocks are virtually absent from the mainland. Thin Paleozoic sediments have been sampled locally in the bottom of deep boreholes in the continental shelf.

The present continental margin formed by rifting beginning in Early Cretaceous time. Precambrian basement rocks were disrupted by normal faults, and subaerial volcanic rocks and nonmarine clastic sediments filled the rift basins. During mid-Late Cretaceous time a regional unconformity developed (the breakup unconformity?), probably in response to uplift just before the onset of seafloor spreading. Subsequently, continental separation was completed and postrift sediments, mainly fine-grained clastics, were deposited on the margin. The postrift subsidence of the Labrador margin can be described by models in which the lithosphere is stretched, then thinned during rifting. However, postrift sedimentation on the Labrador continental shelf was delayed for about 10 Ma after the beginning of seafloor spreading because of uplift late in the rift phase.

Thinned and intruded continental crust occurs beneath the outer shelf. Deep boreholes have bottomed variously in Precambrian rocks, Paleozoic sediments, and Early Cretaceous volcanics. The lower crust is characterized by a velocity of 7.3 km-s-1; because this velocity is similar to that of oceanic layer 3b, it is difficult to use the velocity structure of the margin to define the ocean-continent transition. The best estimate for the position of the oldest oceanic crust is where the top of oceanic basement can be seen as a clear reflector. However, there remains a broad region beneath the edge of the continental shelf and the continental slope where crustal affinities are unclear. The similarity of the 7.3 km-s-1 velocity under the shelf to those of basic intrusive rocks suggests magma migration during rifting and the underplating of the lower crust by basaltic magma intrusion. Alternatively, this high velocity crustal layer may be typical of the adjacent continental crust. There are no measurements of continental crustal thickness or velocity in eastern Labrador, within the Nain province of the Canadian Shield.

A prominent free air gravity anomaly exists across this rifted margin. A large positive anomaly lies over the outer continental shelf, and a much smaller negative anomaly lies over the continental slope or rise.

There are no equivalents of the East Coast Magnetic Anomaly on the Labrador margin. The oldest oceanic magnetic anomaly that can be identified in this region is anomaly 33 (80 Ma). However, the anomalies are weak and confusing near the margin, leading some to speculate that transitional or continental crust underlies a large part of the Labrador Sea. Near the continental margin, flat-lying oceanic basement horizons exhibit internal reflections that probably represent oceanic basaltic flows interbedded with sediment. This is perhaps the best evidence for the position of the continent-ocean boundary.

Transects D1 to D4: Problems

1. What was the fate of the lower subcrustal lithosphere during Taconian and Acadian overthrusting and collision of the ancient passive margin with an island arc?
2. Why is there little extension observed in the Appalachian orogen by comparison with the Cordillera? What is the role of transcurrent faults in creating an extensional environment? Are they particularly important in the later stages of orogenic development?
3. How many outboard terranes, each with a distinct geological history, are present off eastern Canada? Can they be directly related to those to the south?
4. What is the nature of terrane boundaries at depth? How deep do they extend? Does the Meguma terrane have its own lithosphere?
5. Are there differences in the prerift lithospheres off Nova Scotia and Labrador, whose last deformational events are Paleozoic and Precambrian (Archean), respectively? Can these differences be detected in differences in vertical motions, for example, rates and amounts of rift and postrift uplift and subsidence, thermal time constants?
6. Under what thermomechanical conditions does lithospheric rupture occur? What causes the lithosphere to break where it does?

7. The mode of isostatic balance across some of the rifted margins is unclear, as large positive gravity anomalies are not balanced by comparable negative anomalies. How can this be explained?
8. What is the role of volcanism in the rifting process? Is it of primary or secondary importance? How can we devise experiments to determine this? Why does volcanism sometimes occur well inland of the continent-ocean boundary.
9. What causes uplift late in the rift stage and the development of regional breakup unconformities?
10. How sharp is the break from continental to oceanic crustal thickness across a transform margin? If there is minor thinning at this margin, what causes it?
11. Why does the oceanic crust adjacent to the transform appear to be anomalous? Are there analogs with oceanic transform faults?
12. What causes the East Coast Magnetic Anomaly?
13. What conditions trigger subduction along a passive margin?

TRANSECT E1 ADIRONDACKS TO GEORGES BANK

Synopsis and Findings

Transect E1 (Figure 1) extends east from the Grenvillian basement of the North American craton in the Adirondack Mountains across the Appalachian orogen of New England to Atlantic lithosphere off Georges Bank (Figure 8).

The two phases of passive margin development—first in Late Proterozoic and Early Cambrian times and second in the Mesozoic—were similar in E1 to regions north and south (Transects D1 and E2-5). The intervening evolution of the Appalachian orogen from mid-Ordovician to Permian times, however, had some marked differences in E1 from that of other transects, although features such as the Blue Ridge-Green Mountain axis and certain gravity and magnetic anomalies extend throughout the orogen (Figure 8).

Evidence for an Acadian event is strong in New York, northern New England and maritime Canada (El and D1), but sparse, if not absent, farther south (E2-5) (Figure 1). The Alleghanian deformation of the Valley and Ridge province (E2 and south) dies out northward, and the last traces of it are believed to occur east of the Catskills in E1 (Figure 8). In Canada, by contrast, a flat-lying veneer of Late Devonian and Carboniferous strata overlies earlier Paleozoic deformed rocks of the New Brunswick platform. The Blue Ridge-Green Mountain axis first became active in the Taconian and coincides with a prominent gravity high extending from Newfoundland to Vermont. Farther south this gravity high lies progressively farther southeast of the Blue Ridge-Green Mountain axis; the separation of the two features is some 60 km in the central and southern Appalachians. This separation may be the result of Late Paleozoic, low-angle thrusting. The above phenomena are consistent with the consolidation of Laurasia as a single landmass during the Devonian. Northern Iapetus had then closed, but its southern part did not close until the end of the Paleozoic.

Problems

1. Does the Meguma terrane of Nova Scotia extend southwestward as far as the continental shelf off New England in Transect E1?

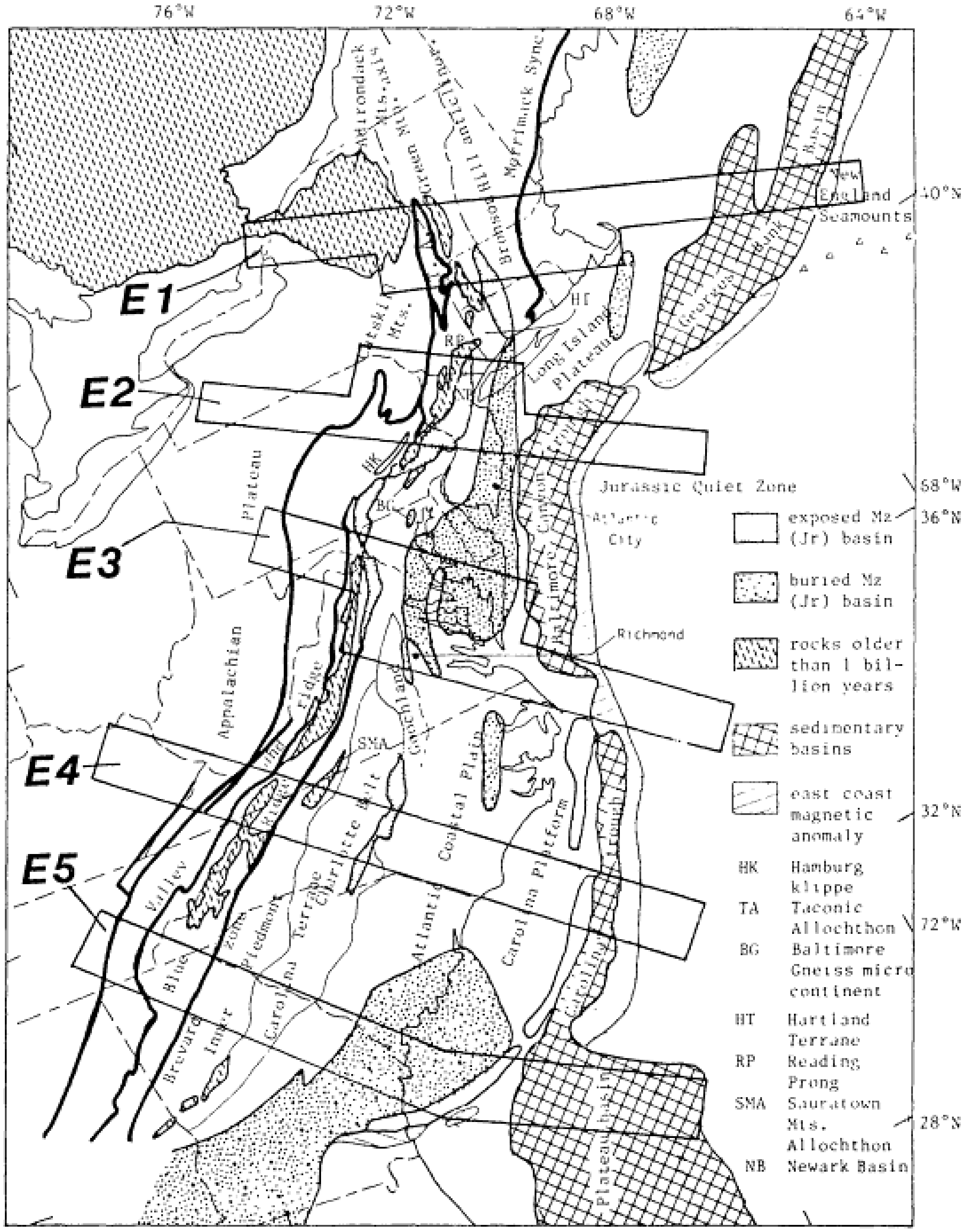


Figure 8
Map of eastern United States showing positions of corridors E1 to E5.

2. The geographic limits within E1 of the overlapping Paleozoic orogenic phases of Appalachian system are poorly established and necessary for confident assessment of the tectonic origin of each phase. Although the northwesterly limit of the Taconian orogeny is adequately known, the southeastern margin is uncertain, and the Acadian and Alleghanian limits are poorly located.
3. The extents and histories of subsidence, sedimentation, deformation, and metamorphism of sedimentary basins associated with the Taconian and Acadian intervals (Ordovician through Devonian) need clarification.
4. Did Iapetus exist after the Taconian orogeny, either as a large basin or as a series of small basins of vastly reduced area, or did it close completely in the Taconian?
5. A major obstacle to interpretation of Paleozoic tectonic evolution of the Appalachian system is the paucity of dating of metamorphic events, particularly their *P-T* histories.
6. The source of the positive gravity anomaly along the Green Mountain axis whose basement exposures consist of lower density rocks is an important unknown.

TRANSECT E2 NEW YORK APPALACHIAN BASIN TO BALTIMORE CANYON TROUGH

Synopsis and Findings

Transect E2 (Figure 1) extends from the Allegheny Plateau of New York across the Valley and Ridge, Great Valley, Hamburg klippe, Reading Prong, Newark Mesozoic basin, Piedmont, and Atlantic Coastal Plain to the Baltimore Canyon Trough. It has a northward extension to the Manhattan Prong. Its Phanerozoic tectonic history includes three phases: (1) development of Late Proterozoic and Early Cambrian passive margins on the eastern edge of the North American craton and all margins of the Baltimore Gneiss microcontinent (Figure 8) subsequent to continental rifting; (2) collisional events (a) of the microcontinent with North America, (b) of island arcs with both the microcontinent and North America during the early Paleozoic and (c) of Africa with the earlier formed composite terrane during the Late Paleozoic; and (3) Mesozoic rifting and drifting. Phases (2) and (3) are emphasized.

The first collision (Taconian orogeny) in Transect E2 began in late Middle Ordovician time although an earlier Late Cambrian (Penobscottian) deformational event is recognized a short distance south of E2. The Taconian event resulted from subduction with southeastward underriding of North America and the closing of a small ocean basin between North America and microcontinent, possibly the Baltimore Gneiss microcontinent. The closure led to the development of a foreland basin and the replacement of thrust sheets, including Middle Proterozoic basement, and recumbent folds. In the northern part of the transect a southeast-dipping subduction zone developed in the Ordovician between the North American craton and an island arc, probably the continuation of the Hartland terrane of the northern Appalachians (Transect El, Figure 6). Oceanic rocks, including ophiolite fragments, occur in thrust sheets formed during this event. No Ordovician volcanic rocks are known in the main part of the transect, but volcanic rocks of Cambrian age crop out a short distance to the south. Oceanic rocks have been obducted onto and over the Baltimore Gneiss microcontinent and onto North America in the Philadelphia area. The oceanic rocks are characterized by strong positive Bouguer gravity anomalies, which permit the tracing of the Taconian suture zone beneath deposits of the Atlantic Coastal Plain.

The effect of the Middle Paleozoic Acadian orogeny is detected in E2 by the thick wedge of synorogenic and particularly postorogenic (Catskill delta) sediment that underlies the transect from eastern Pennsylvania to its western boundary, and by plutonism and metamorphism in the Manhattan Prong (Figure 8). During the Late Paleozoic Alleghanian orogeny, resulting from the collision of Africa with the previously formed composite terrane, the region underwent a ramp-and-flat type of deformation that resulted in the classic Appalachian folds. Thrust faults are largely blind and are shown mainly by drilling and seismic reflection. It appears that many of these Alleghanian thrust faults experienced later right dextral slip, probably late in the orogenic period. North American basement, although thrust faulted, extends at least as far east as the obducted eugeoclinal rocks.

Triassic and Jurassic rifting, in part along older faults, resulted in most marked thinning in the 100 km seaward of Atlantic City, forming the Baltimore Canyon Trough. Seafloor spreading began in the Middle Jurassic; the western edge of the oceanic crust is marked by the East Coast Magnetic Anomaly. As much as 5 km of synrift deposits occur within the onshore Newark basin and beneath the Baltimore Canyon Trough. That thickness decreased landward to less than 2 km at Atlantic City where a thin wedge of Coastal Plain deposits continues another 80 km to the northwest. During the Middle and Late Jurassic, a carbonate shelf-edge platform prograded 40-km-oceanward across the oceanic crust. During the Late Cenozoic, the shelf edge retreated 20 km in response to numerous sea level fluctuations.

Tectonic heredity was of major importance in this region. Extensional faults formed during the Late Proterozoic rifting event appear to have become thrust faults during the closing of the early Paleozoic ocean. Such thrust faults can clearly be shown to have been further reactivated by extension during the opening of the Atlantic.

Problems

1. Was there a Late Cambrian collisional event in the northern part of the transect as there was farther south?
2. Did Acadian metamorphism, plutonism, and deformation occur in the crystalline terrane of this transect south of the Manhattan Prong, or, on the other hand, did the Acadian clastic wedge derive entirely from the "Acadian mountains" of the northern Appalachians and the post-Taconian metamorphism and deformation date from the Alleghanian?
3. Differentiation of terranes requires further study of Middle Proterozoic basement rocks. Those of the Baltimore Gneiss microcontinent clearly differ from those of the Trenton Prong, and both differ from those of the Reading Prong, which are quite similar to those of the Adirondacks and, thereby, are clearly North American. To some, the Fordham Gneiss of the Manhattan Prong appears similar to the rocks of the Reading Prong; to others, not similar at all. All these rocks are apparently of about the same age. If this is true, do the outboard terranes represent rifted blocks that have come back home, or are they slices of 1-Ga basement juxtaposed on lateral faults? Is the Manhattan Prong a northern extension of the Baltimore Gneiss microcontinent on the other side of the Newark Basin?
4. Where are the syn- and post-orogenic sediments related to Alleghanian mountain building? Abundant sediment related to the earlier tectonic episodes is preserved. Is the Alleghanian sediment all eroded away or is the Triassic-Lower Jurassic basin fill the Alleghanian molasse?

5. Did the development of the Appalachian orogeny really occur in three discrete phases from Ordovician (or Cambrian?) to Permian times, or was it in fact a heterogeneous continuum representing the protracted closing of Africa and North America?
6. Why are the terranes west of the Taconian suture and east of the Avalonian terranes in New England and eastern Canada largely absent in E27

TRANSECT E3 PITTSBURGH TO BALTIMORE CANYON TROUGH

Synopsis and Findings

Transect E3 (Figure 1) begins in the Appalachian Plateau and crosses the Valley and Ridge, Great Valley, Blue Ridge, Piedmont, Atlantic Coastal Plain, Baltimore Canyon Trough, and East Coast Magnetic Anomaly. Seismic reflection subsurface control was available for all but the basement under the Atlantic Coastal Plain (Figure 8). Autochthonous North American Grenvillian basement extends in the subsurface under the Atlantic Coastal Plain to the east edge of Richmond, Virginia. At Richmond, Grenvillian rocks were overridden along the trace of an east-dipping Taconian suture by the volcanic Carolina terrane. Thick-skinned tectonics involved nappes of Grenvillian basement and Carolina terrane cover which were thrust westward in dextral transpressional movements during the Alleghanian. Subsequent erosion has exhumed the Grenvillian Goochland and Richmond nappes along and under the west edge of the Atlantic Coastal Plain of Virginia and adjacent states.

Along the central Piedmont of Virginia, the west edge of the Goochland nappe was thrust westward over the Cambrian Chopawamsic volcanics of the Carolina terrane. The west edge of the Chopawamsics bounds the Taconian suture zone consisting of east dipping melange and turbidites. Thus, between the Chopawamsics and the subcrop of the Carolina terrane under the Coastal Plain, the Taconian suture has been breached by erosion over the Goochland and Richmond Grenvillian basement uplift. At the west edge of the melange-turbidite sequence, deep water North American rift (Late Proterozoic Lynchburg) and rift/drift (Late Proterozoic to Cambrian Evington Group) sequences are in depositional contact with the allochthonous Grenvillian rocks of the Blue Ridge anticlinorium. Taconian metamorphism and ductile deformation affected the entire Virginia Piedmont.

The melange sequence contains several Cambrian to Early Ordovician plutons that may have been generated over oceanic crust during subduction of a spreading ridge.

The Taconian clastic wedge in Virginia was largely derived from cannibalized platform drift and deep water rift/drift sequences of the North American continental margin.

"Acadian" metamorphism, at about 350 Ma, may have locally affected the central Virginia Piedmont. This deformation produced the Catskill delta clastic sequence in the Valley and Ridge. The "Acadian" of Virginia is younger than the deformation of the type region in the northeastern United States and may reflect the initial stages of the Late Paleozoic Alleghanian orogen in the central Appalachians.

The Alleghanian orogeny is characterized by amphibolite facies and penetrative fabrics in the eastern Piedmont. In the central and western Piedmont, it is characterized by local discrete zones of ductile deformation and mylonite zones. Regionally the central and western Piedmont behaved as a semi-brittle block during Alleghanian deformation. Dextral transpressional movements were the main theme during the Alleghanian from the maritime Canadian crystalline Appalachians to the Piedmont of Georgia and Alabama. Translation parallel to the orogenic axis is distributed over the crystalline terrain in discrete zones and conservatively amounts to 200 km of right lateral movement. Therefore, the movement parallel to the orogenic axis is of the order of magnitude of the movement orthogonal to the axis and could be much larger. The Alleghanian suture originally lay to the east of the present middle Atlantic Coast and may now be on the African continent. A major clastic sequence was deposited during the Alleghanian in the Valley and Ridge Province, and most structure of the Valley and Ridge was produced at this time.

Middle Ordovician to Pennsylvanian plutons were generated during times of tectonic thickening of the orogenic belt. Several mechanisms may have been involved: (1) frictional heat of deformation, (2) depression of the crust to higher temperature zones, (3) decompressional melting in uplifted nappes, (4) introduction of mantle-derived mafic melts into the crust, and (5) melting in the pelitic sequences overridden by hot nappes.

The Mesozoic to Holocene rift and drift history related to the opening of the Atlantic Ocean is well documented by: (1) Mesozoic rift basins on both sides of the hinge zone, the Norfolk Fracture Zone, and Norfolk Basin; and (2) drift facies that are post-middle Jurassic prograding shelf and slope sequences.

Problems

1. The tectonic history and crustal architecture in Transect E3 show major differences from interpretations in other E Corridor transects. To what extent will these new interpretations from E3 be found to apply more widely?
2. E3 Corridor shows the easternmost known North American Grenvillian crust. With additional seismic reflection data, how far east can the eastern margin of Proterozoic North America be traced?
3. Recent reprocessing of USGS 1-64 seismic data (just north of the E3 crustal section) shows abundant east-dipping layers indicating deformation of the deep crust as far east as the Blue Ridge; two intervals of near horizontal layering also occur, one near the middle of the crust, and another several kilometers thick at the base of the crust. Most reflectors end abruptly along a near vertical zone near Richmond, and few reflections are seen in the line from Richmond to the coast. What is the origin of the lower crustal laminations, and how far east toward the suture will they persist? Is the termination of reflectors under the Coastal Plain real or a problem of data acquisition? Additional reflection work is needed to resolve the enigma. This should include wide angle seismic surveying to determine the deep velocity (density/lithology) structure and the geometry of the suture at depth. Structure in the Carolina plate east of the suture at Richmond should also be sought by reflection work. Deep velocity information will also allow better evaluation of the rise of the Moho under the Piedmont and its relation to the Piedmont Appalachian gravity anomaly. Present analysis of the crustal structure under the Piedmont suggests that the crust was thinned by more than 10 km during the early Mesozoic rifting that preceded the opening of the Atlantic. If this is the origin of the upwarping of the Moho under the Appalachian gravity anomaly, then the anomaly cannot be used to directly infer buried sutures as has been done in the past. Certainly the anomaly does not coincide with the Taconian suture in the

autochthonous crust in Virginia. If Mesozoic thinning of crust was so extensive, then the present thicknesses cannot be taken to have their origin in Iapetus-related rifting or in compressional orogenic deformation as has been assumed in gravity modelling along the COCORP line in Georgia and elsewhere.

4. What is the extent and cause of the Alleghanian dextral transpressional deformation?
5. Did early Mesozoic rift basins offshore inherit their structural control from Paleozoic deformation zones as did those onshore?

TRANSECT E4 CENTRAL KENTUCKY TO THE CAROLINA TROUGH

Synopsis and Findings

Transect E4 (Figure 1) extends from cratonal North America at the Grenville front in central Kentucky, east across the southern Appalachian orogen through Cape Fear to oceanic lithosphere east of the Carolina Trough (Figure 8). As in other Appalachian transects, the Phanerozoic history comprises three phases: (1) Late Proterozoic-Early Cambrian passive margin development, (2) Ordovician to Permian evolution of the Appalachian orogen, and (3) Mesozoic development of the Atlantic passive margin.

Distinctive onshore geological features from northwest to southeast include: Paleozoic sedimentary cover as thin as 0.7 km over the Jessamine Dome and as thick as 3.7 km under the Appalachian Plateau in the Early Cambrian Rome trough; the Alleghanian foreland thrust belt (thrust faults root deep in the crystalline Appalachians); two large windows (Mountain City and Grandfather Mountain) exposing duplex structures; Middle Proterozoic basement exposed in allochthonous external (Blue Ridge) and internal (Sauratown Mountains) massifs; Late Proterozoic rift-facies sedimentary and volcanic cover sequences; a zone of abundant ultramafic rocks (Blue Ridge); and a Late Proterozoic to early Paleozoic magmatic arc (Kings Mountain, Charlotte, and Carolina slate belts of the Carolina terrane) intruded by Devonian and Alleghanian plutons. In the Piedmont, E4 crosses the Appalachian gravity gradient at the latitude of its greatest amplitude (-100 mGal on the west +20 mGal on the east). Crustal thickness is poorly constrained by seismic refraction data but gravity modeling suggests that it is 40 to 50 km under the gravity low and 30 to 40 km east of the gravity gradient. On the modern margin, depth to pre-Mesozoic basement increases 2 km at 100 km offshore, where a narrow graben of inferred Triassic age and basement hinge zone, marked by a magnetic anomaly (Brunswick), form the seaward edge of the Carolina platform. Continental crust (35 to 40 km thick) occurs west of the magnetic anomaly; transitional crust (20 to 25 km) occurs beneath the Carolina trough (which contains slightly more than 12 km of postrift sediments) between the Brunswick anomaly and East Coast Magnetic Anomaly (ECMA); and oceanic crust (6 km thick) extends landward to the ECMA.

Transect E4 contains well-preserved evidence for the tectonics and timing of the first or Laurentian phase of passive margin development, perhaps better understood here than elsewhere in eastern North America. Late Proterozoic continental rifting is indicated by rift-facies sedimentary and igneous rocks and continental crust containing dike swarms. The Taconian orogeny (closing of Iapetus) is indicated by the Middle to Late Ordovician (Llanvernian to Caradocian) flysch clastic wedges, obduction and fragmentation of ophiolites and metamorphism. A thick sequence of nonfossiliferous gneiss, schist, and amphibolite (Ashe Formation) lies southeast of the Blue Ridge external massif. Parts of the base of the formation are tied stratigraphically to North America through a basal conglomerate. Elsewhere the lowest parts of the Ashe and most of the upper Ashe contain numerous bodies of ultramafic rock thought to be fragmented ophiolites. The leading edge of the Taconian Iapetus suture is probably the northwestern limit of ultramafic-bearing Ashe. The effects of the Acadian orogeny in E4 are uncertain. The Alleghanian orogeny (collision with Africa?) produced the foreland thrust belt, a Late Paleozoic clastic wedge, and large crystalline thrust sheets. Possibly the Carolina terrane was accreted at this time.

Palinspastic reconstruction suggests that autochthonous North American crust must extend in the subsurface well east of the Appalachian gravity gradient. The accreted magmatic arc of the Carolina terrane has no apparent prearc basement and may have originated elsewhere than on the eastern rifted margin of Iapetus.

The westernmost Mesozoic continental graben (Dan River-Davie County basin) probably formed along reactivated Paleozoic thrusts, which in turn may have been reactivated Iapetan structures. The present width of the Iapetan extensional zone (area of Rome trough to Iapetus suture) is about 400 km; the width of the Mesozoic extensional zone (Dan River-Davie County basin to the ECMA) is about 570 km. The original width of the Iapetan extensional zone is not known, but 200 km of Paleozoic shortening, which includes westward thrusting of Laurentian crust, is reasonable. Sedimentation in the Carolina Trough (CT) was most rapid during the Jurassic; the paleoshelf edge lay just landward of the ECMA. A string of salt diapirs, presumed to originate from an evaporite unit near the base of the CT, was emplaced along the axis of the ECMA. Salt flow contributed to the configuration of the trough by causing growth faults to form along the CT.

Problems

1. Amount of crustal extension during Iapetan rifting.
2. Better knowledge of the absolute timing and sequencing of events such as Iapetan rifting, metamorphism across E4, thrusting, and accretion of the Carolina terrane.
3. Provenance and age of the ultramafic bearing parts of the Ashe Formation. Does it represent an accretionary wedge from the eastern side of Iapetus or are the sediments derived from the Laurentian Margin and somehow mixed with ophiolitic material during underplating of an obducting oceanic slab?
4. Provenance of the Inner Piedmont terrane and how it related to the terranes around it.
5. Tectonic history of the internal massif of the Sauratown Mountains anticlinorium.
6. Significance of the Acadian orogeny.
7. Origin of the Appalachian gravity gradient and the location of the subsurface Iapetus suture.
8. Geological history of the crystalline rocks beneath the emerged and submerged Atlantic Coastal Plain.

TRANSECT E5 CUMBERLAND PLATEAU TO BLAKE PLATEAU

Synopsis and Findings

Transect E5 (Figure 1) extends from the North American craton in the Cumberland Plateau of Tennessee across the southern Appalachian orogen to transitional crust of the Blake Plateau, ending in Atlantic oceanic lithosphere. The region includes a complete cycle of the opening and closing of an ocean (Iapetus) and the opening of a second ocean (Atlantic). It is therefore possible to compare the parallel evolution of two passive margins, one whose development began in the Late Proterozoic (Hadrynian) and the other which began in the Triassic-Jurassic. The accretionary and collisional history related to the destruction of the Late Precambrian-Early Paleozoic margin of North America and the formation of the Appalachian orogen throughout much of the Paleozoic may be observed in Transect E5.

The Late Precambrian continental margin of eastern North America is clearly indicated by the rifted Grenvillian crust (1.0 to 1.2 Ga) overlain by suprajacent platform succession. The eastern edge of the Grenville crust is tectonically buried but has been located by restoration of surface structures, potential field, and seismic reflection data.

Some of the Late Precambrian-Cambrian rifted margin sequence is visible in the frontal thrust zone of the Blue Ridge. The Cambro-Ordovician platform succession is clearly visible as a thin veneer on the basement.

The accretionary/collisional phase of the history of the southeastern North American margin began in Middle Ordovician (Llanvirn/Llandeilo) time, as indicated by the development of a flysch succession derived from the east that filled an earlier (latest Arenig or early Llanvirn) foredeep. This was also a time of metamorphism, deformation, and plutonism in rocks oceanward of the foredeep, and several pre- to synmetamorphic thrusts (for example, Greenbrier, Hayesville) occur in this region. The Hayesville thrust is considered an Early Paleozoic thrust that is rooted in the Ordovician continent-ocean transition zone, because it juxtaposes sedimentary and volcanic rocks deposited on oceanic or a rifted continental basement onto a contemporaneous rifted margin sequence that was deposited on North American continental crust. Plutons emerged in this early phase and are confined to the Hayesville thrust sheet.

The middle Paleozoic Acadian event is not reflected by deposition in E5 but is possibly indicated by unconformities in the foreland succession, indicating erosion, nondeposition, or both, and metamorphism in the hinterland. In the continental hinterland, however, plutons, several major faults, fabric relationships, and radiometric ages suggest that the Acadian was a major event. This may have been the time of accretion of the Avalon (Carolina) terrane along the central Piedmont suture.

The Late Paleozoic Alleghanian deformation of the foreland, produced as a huge crystalline thrust sheet (Blue Ridge-Piedmont thrust sheet), was driven westward by the collision of Africa with the North American margin, and the Iapetus and related Theic-Rheic oceans were finally closed. Structures produced at this time include both thrust and dextral strike-slip faults. Thrusts attain displacements >250 km; Alleghanian strike-slip faults have much less movement. Alleghanian plutonic activity was largely granitic; both S- and I-types are present. Alleghanian metamorphism is restricted to the southern and eastern exposed parts of the Appalachian orogen.

The development of the most recent trailing margin/platform began in the latest

Triassic (Norian?) to early Jurassic (Sinemurian to Pliensbachian?) time with the formation of the rift basins in the eroding Appalachians which filled with terrestrial locally derived sediments. Mafic dikes were intruded as late as the Middle Jurassic (Bathonian), indicating the continental crust was still being extended. However, by Late Jurassic time a carbonate platform had developed on the Paleozoic/Precambrian crust and the Atlantic was open.

The Cretaceous and Tertiary sediments deposited in the platform record progressive inundation of the eroded Appalachians to a maximum transgression during the latest Cretaceous to earliest Tertiary followed by general regression until the present.

Problems

1. Timing of metamorphism is uncertain in the central part of the southern Appalachians, due to the lack of younger sedimentary rocks and detailed geochronological studies.
2. Eastern extent of the Blue Ridge-Piedmont detachment.
3. Origin of the Piedmont gravity gradient.
4. Distribution of North American and non-North American terranes beneath the Coastal Plain.
5. Nature of the Brunswick terrane-East Coast Magnetic Anomaly boundary in the offshore.
6. Crustal controls of Cretaceous-Tertiary depositional platform in the continental shelf-Blake Plateau area.

TRANSECTS F1 AND F2 GULF OF MEXICO BASIN

The F1 and F2 transects (Figure 1) are unique because they cross the southern edge of the North American craton and also cross entirely a small ocean basin, the Gulf of Mexico. A problems section is given for F1 and F2 together.

Transect F1: Ouachita Orogen to Yucatan

Synopsis and Findings

Transect F1 (Figure 9) illustrates four major phases in the tectonic evolution of this area: (1) the Late Proterozoic through Middle Paleozoic evolution of a south-facing passive margin, (2) the Middle to Late Paleozoic closing of an ocean basin and collision of South America and associated Sabine/Yucatan terranes with North America, (3) the Mesozoic (Late Triassic through mid-Cretaceous) development of the modern Gulf of Mexico basin, and (4) the post-mid-Cretaceous partial filling of the basin mainly by huge prograding siliciclastic wedges, first from the west and then from the north. Emphasis here will be only on the second and third phases.

During Middle Paleozoic time, the Early Paleozoic ocean basin that flanked the south-facing passive margin of North America began closing along a south dipping subduction zone, as South America and associated terranes moved relatively north. An associated volcanic arc system, either isolated or within a continental block, provided flysch and volcanics to adjacent forearc and trench areas. By Pennsylvanian time, a combined Sabine/Yucatan/South America terrane had collided with and overrode the

North American passive margin. Flysch continued to fill a deepwater basin between the two colliding continents, but as collision continued, the basin shallowed and was finally filled with nonmarine molasse. Enormous tectonic thickening of the sedimentary section took place through northward-verging folding and thrusting that formed the Ouachita orogen (Figure 9). Late stage detachment and northward displacement of a large block of North American crust formed the Benton Uplift and other basement cored uplifts (Figure 9). The tectonic activity associated with this collision was accompanied by widespread metamorphism. Most tectonic activity had ceased by mid-Pennsylvanian (Desmoinesian) time and Sabine/Yucatan/South America was sutured to North America to form one welded continent. During Late Pennsylvanian through mid-Permian time, widespread postorogenic episutural or successor basins formed across the entire northern Gulf region, characterized by deposition of shallow marine carbonates and clastics.

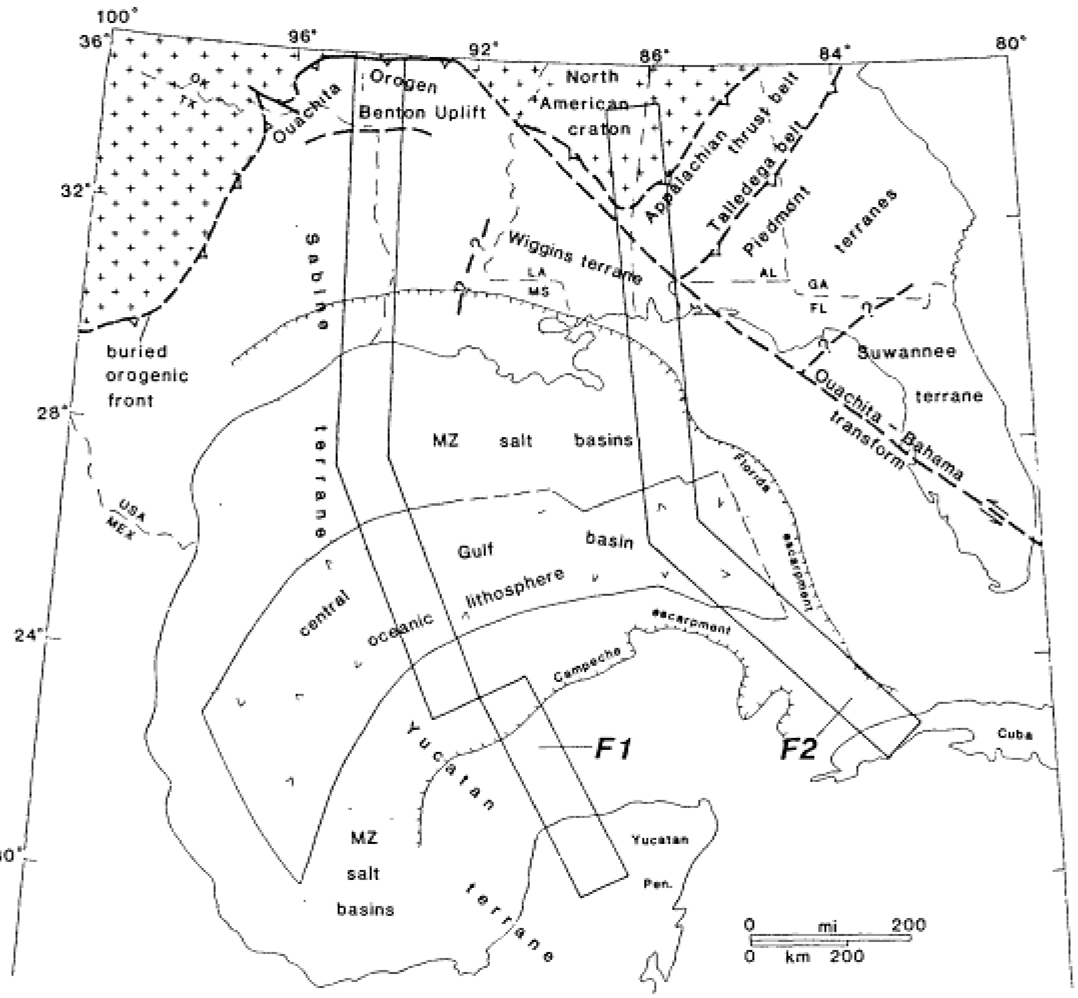


Figure 9
Map of southeastern United States, northeastern Mexico, and Gulf of Mexico, showing positions of corridors F1 and F2.

Late Permian through Middle Triassic was a time of widespread uplift and erosion throughout the region, but by Late Triassic, widespread continental rifting accompanied by volcanism and deposition of nonmarine sediments in broad rift basins had begun. The rifting, which continued through Early Jurassic, was due to stresses created by the initial relative movements between Africa/South America and North America and concentrated along Paleozoic crustal weaknesses on sutures (collisional and extensional). The Sabine/Yucatan terranes were still in the northern Gulf region.

During Middle Jurassic time, the entire Gulf area became the site of broad mantle upwelling and extreme attenuation of the continental crust, resulting in a large region of stretched or transitional crust. The crust along the outer rim of the region remained relatively thick (20 to 35 km), forming broad basement highs and lows with wavelengths of 100 to 500 km. In the central Gulf area, however, stretching was more concentrated and the crust thinned considerably (8 to 20 km). Thick salt was deposited in large basins throughout the entire area of transitional crust, as marine waters entered the Gulf controlled by sills in central Mexico. This Middle Jurassic period of rifting and stretching of the crust created much of the basic architecture of the Gulf basin as we see it today (primary basement highs and lows). This influenced subsequent deposition of the overlying Upper Jurassic through Lower Cretaceous sediments. Overall crustal stretching was as much as 400 to 500 km.

During the Late Jurassic, rifting and mantle upwelling became even more concentrated in the central Gulf, creating an elongate east-west basin floored by oceanic crust. The central Gulf basin is over 300 km wide in the west but considerably narrower to the east. Its distribution suggests that the Yucatan terrane moved out of the northern Gulf away from the Sabine terrane with counterclockwise rotation, separating the salt basins on either side of the ocean crust, similar to the Red Sea today. This was a time of general marine transgression or relative rise in sea level across the basin due mainly to basin subsidence as the crust cooled. Broad carbonate ramps and deep shelves extended across areas of transitional crust, while deep-marine sediments were deposited in the newly formed oceanic trough.

By Early Cretaceous time, subsidence continued but the central Gulf area was locked in its present configuration, and spreading had jumped to the Caribbean region south of Yucatan. Broad carbonate platforms rimmed the entire deep basin with prominent margins (including Campeche and Florida escarpments, Figure 9) developed along regional tectonic hinge zones that marked the boundary between thick and thin transitional crust. Cyclic deep-marine carbonates were deposited in the adjacent deep basin seaward of the margins.

Finally, by mid-Cretaceous time (Middle Cenomanian) the outer platform margins were terminally drowned, possibly by a rapid drop followed by a rapid rise in sea level, and the margins retreated to more landward positions. At this time a prominent, Gulf-wide sequence boundary was formed, characterized by both subaerial erosion on the banks and submarine erosion along the submerged parts of the margins. This mid-Cretaceous sequence boundary marks a major turning point in the history of the Gulf, which set the scene for the later Cenozoic filling of the basin.

Transect F2: Mississippi to Cuba

Synopsis and Findings

Transect F2 (Figures 1, 9) extends from northeastern Mississippi across the deep eastern Gulf of Mexico to western Cuba. The southern edge of continental North

America, which includes the stable interior, Appalachian thrust belt and Piedmont terranes, is in southwestern Alabama along a Late Paleozoic suture coincident with the western end of the Brunswick-Altamaha Magnetic Anomaly. North of the suture with the Piedmont terrane, North American Precambrian basement is overlain by Lower Paleozoic platform carbonates and Upper Paleozoic foreland basin clastic rocks in the stable interior and Appalachian thrust belt. The Talladega belt contains marbles and slates; the Piedmont terrane, gneisses. Beneath the present coastal Alabama and Mississippi, accreted continental crust of the Wiggins terrane (Figure 9) lies south of the Alleghanian suture. Subsurface data along the proposed trace of the suture define a magmatic arc complex of serpentinites, basalts, and late-stage granites. The southern part of the Wiggins terrane was thinned during the Triassic-Jurassic opening of the Gulf.

Oceanic crust underlies the abyssal regions of the eastern Gulf at depths of 8.5 to 10.5 km; thickness ranges from 6.0 to 9.0 km. Strata of earliest Cretaceous age overlie the oceanic basement. Rifted and injected transitional crust of South American or African affinity flanks the oceanic terrane in the southeastern Gulf, and thickens to continental dimensions beneath western Cuba. Basinal clastic rocks of Jurassic age and Cretaceous platform carbonates overlie rifted basement in western Cuba and are, in turn, tectonically shingled with oceanic crust and sedimentary rocks obducted from the Caribbean during Late Cretaceous-Early Tertiary transpressional episodes related to Cuba-Bahama collision. North American crust adjoins the pre-Mesozoic Wiggins terrane along a zone generally coincident with the westernmost trace of the Brunswick-Altamaha Magnetic Anomaly (BAMA) in southwestern Alabama. The relationship between the Wiggins terrane and the Suwannee terrane (Figure 9) to the east and of the Wiggins and the Sabine to the west are not known, but commonality is possible. North of the BAMA, wells that penetrate pre-Mesozoic rocks define subsurface belts of metamorphic rocks laterally correlative to exposed suites in the Appalachian Piedmont. Major thrust faults juxtapose belts of northwestward decreasing metamorphic grade against one another and against unmetamorphosed sedimentary rocks continuous with the Appalachian thrust belt. The few wells penetrating pre-Mesozoic rocks south of the BAMA find basalt rubble (extrusive arc?), chlorite schist (back-arc basin?), and granites (magmatic-arc core and late-stage plutons?); one well on the south flank of the anomaly penetrated serpentinite. Gravity modelling defines a relatively smooth mantle surface at depths of approximately 32 km beneath the BAMA, and about 36 km to the north and south.

A southward-dipping suture zone is proposed because marbles, slates, and schists of the buried Piedmont terrane represent platform carbonates and slope and rise sediments of a southward-facing early Paleozoic continental margin that were later thrust northwestward during the Alleghanian continental collision. Our interpretation of a suture zone and accreted terrane in southwestern Alabama is consistent with recent interpretations of COCORP data in southern Georgia and Florida.

Transects F1 and F2: Problems

1. Better geophysical definition of the Early Paleozoic south-facing passive margin, its boundary with a Paleozoic oceanic crust, and the remnants of the inferred south-dipping subduction zone is needed.
2. The nature, timing, and distribution of Late Paleozoic collision events are poorly constrained, as is the associated regional metamorphism.

3. What are the depositional settings for the various thick flysch deposits—forearc, trench, or collisional trough?
4. Is the core of the Benton Uplift a displaced piece of the North American craton? When was it displaced?
5. What are the nature and age of the Yucatan and Sabine terranes? Are they rifted parts of South America or independent microplates with different origins?
6. The origin and distribution of the post-orogenic, undeformed, successor basins are poorly known.
7. Several major linear potential field anomalies within the Sabine terrane need to be modeled (i.e., Houston magnetic anomaly). Are they major crustal boundaries or sutures?
8. More geophysical and geological evidence for a volcanic arc system within the Sabine terrane is needed.
9. Better definition of crustal types, crustal thickness, depth to basement, and sediment thickness are needed to better model total tectonic subsidence, amounts and mechanisms of extension, and accurate reconstructions of transitional crust.
10. Were the Late Triassic-Early Jurassic nonmarine sediments and volcanics in the northern Gulf really deposited in large rift basins, as along the East Coast? If so, what is the nature of the boundary faults? Are they low-angle listric faults? Was the Late Triassic-Early Jurassic rifting concentrated along older Paleozoic weaknesses and sutures?
11. Was there a later, separate phase of mid-Jurassic rifting that formed the wide area of attenuated or transitional crust in the Gulf and created the prominent basement highs and lows that make up the basic architecture of the basin? How do these basement features reflect older Paleozoic elements?
12. What is the origin and timing of deposition of the thick salt in the Gulf? Was it deposited quickly in already existing deep rift basins? Was deposition controlled by sills in Mexico? Is the salt younger on the flanks of the basin? What was its original distribution and how has it been later mobilized?
13. What is the nature, origin, and timing of the tectonic hinge zone that forms the boundary between thick and thin transitional crust? Why did the Lower Cretaceous carbonate margins become established along this hinge zone?
14. An accurate distribution of oceanic crust and its associated boundaries, ocean ridges, and fracture zones is needed to constrain opening directions and allow for accurate reconstructions. Was Yucatan originally in the northern Gulf?
15. The exact age of the oceanic crust is poorly constrained. Detailed magnetic surveys are needed to identify Jurassic magnetic anomalies. Did the crust in the eastern Gulf have a different origin, and form later, than the crust of the central Gulf?

TRANSECT G SOMERSET ISLAND TO CANADA BASIN (ARCTIC OCEAN REGION)

Synopsis and Findings

Transect G (Figure 1) focuses on the polar continent-ocean transition in Canada, its geophysical character and geological structure, the time and manner of its origin, and the history of tectonic events in the region during the Phanerozoic.

Thick Cenozoic sediment wedges appear to be the main source of gravity anomaly highs and magnetic anomaly lows along the polar continental margin. Low level seismicity along the margin may be produced by the release of stresses built up by this load of prograding sediments in combination with a tensional regime across much of the continental boundary. The clastic wedge began to form no later than latest Cretaceous time and it unconformably overlies the Early Carboniferous to Late Cretaceous Sverdrup Basin sequence which is superposed on the highly deformed Early Paleozoic Franklinian Basin sequence (Figure 10).

The present continent-ocean transition was produced by the formation of the oceanic Canada Basin beginning in Early Cretaceous time. Although the kinematics of ocean formation and the crustal masses involved are constrained poorly, the favored mechanism is the anticlockwise rotation of continental crust away from Arctic Canada about a pivot near the Mackenzie Delta (Figure 10). The rotated block(s) is (are) thought to have included all of Alaska north from the Brooks Range.

Two other major tectonic events affected what is now polar Canada during Phanerozoic time. The Late Devonian to Early Carboniferous Ellesmerian orogeny produced local intrusion and metamorphism plus regional folding and faulting throughout the Franklinian Basin (Figure 10). Associated uplift created a thick southward-tapering prism of clastic sediments that paleocurrent studies suggest were transported mainly from northeast to southwest across the Canadian arctic islands. Existing paleomagnetic constraints are few, but the data allow that the Ellesmerian event may have been caused by collision and left-lateral shearing between Siberia and North America.

The Maastrichtian to Miocene Eurekan orogeny terminated subsidence in the Sverdrup Basin and produced folding and uplift of broad northwest-trending arches and syntectonic deposition of clastics in intervening depositional basins within the central and eastern Arctic Islands. This was followed by regional compression that produced at least 60 km of northwest-directed crustal shortening. Clastic detritus from uplifts produced by Eurekan tectonism migrated mainly northwestward from Campanian time onward and formed the thick deposits of the Arctic Terrace Wedge that cover the present continent-ocean transition.

The lithospheric plate motions that produced the Eurekan event remain unclear but post-Ellesmerian geological continuity across the arctic archipelago precludes significant lateral displacement of rocks within the regions after mid-Paleozoic time.

Problems

1. Nature and degree of crustal thinning from Canadian Shield to Canada Basin. Franklinian Basin/Sverdrup Basin structural geometry in relation to crustal thickness.
2. Nature and age of the crust below northern Canada Basin and comparisons with southern Canada Basin. Correspondence between magnetic field variations and seafloor basement relief throughout the Canada Basin.
3. Nature and degree of changes in crustal properties along and across the polar continent-ocean transition in Canada. Multiparameter traverses of the margin at about 400-km intervals are envisaged along with deep drilling of the shelf where technically feasible.

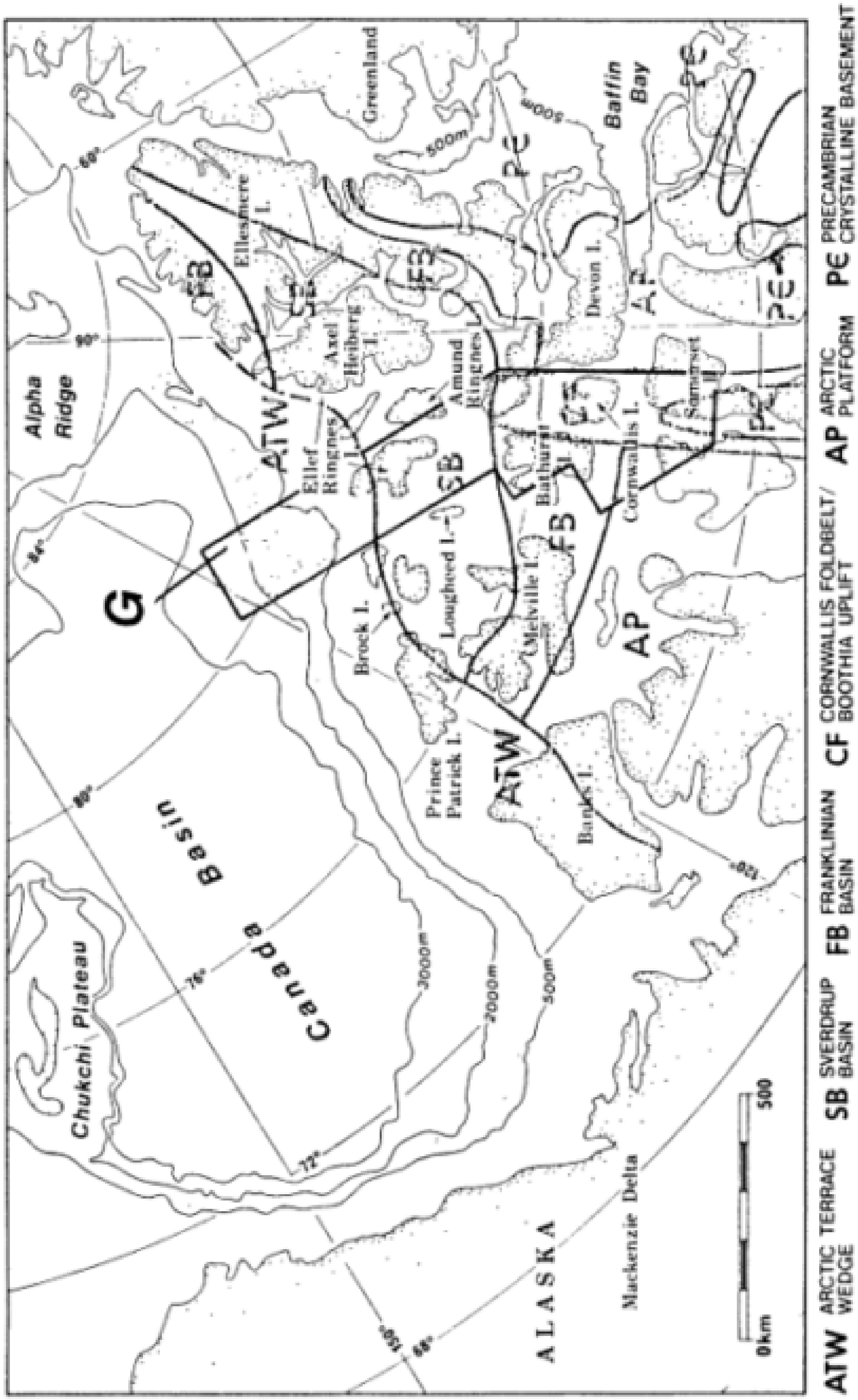


Figure 10
Map of arctic Canada showing position of corridor G.

TRANSECTS H1 TO H3PACIFIC BASIN LITHOSPHERES TO OR ACROSS MAINLAND MEXICO

Transect H1: La Paz to Saltillo, Northwestern and Northern Mexico

Transect H2: Acapulco to Tuxpan across the Central Mexican Plateau

Transect H3: Acapulco Trench to Gulf of Mexico across Southern Mexico

Synopsis and Findings

Transects H1-3 (Figure 1) cross eastward from oceanic lithospheres of the Pacific basin through the North American continent in central and southern Mexico. The modern ocean-continent transition in H1 is a passive margin generated by Late Neogene seafloor spreading in the Gulf of California and the northwestward motion of Baja California as an actively displacing terrane on the Pacific plate (Figure 11). Transects H2 and H3 cross active margins between modern North America and the oceanic Cocos Plate of the Pacific basin. H2 extends east of mainland Mexico across a passive continental margin to oceanic lithosphere of the Gulf of Mexico.

Cratonal North America extends into northern Mexico (zone 1, Figure 1), apparently only as far south as the Mojave-Sonora megashear, a left-slip fault of major, mid- or late-Jurassic displacement. South of the megashear and in the regions of Transects H1-3, Mexico comprises displaced terranes whose identification and characterization are partly new products of this study. The terranes of Mexico may be divided into two geographic groups: an interior and eastern group, and a Pacific margin group (Figure 11).

The first group contains most of the Precambrian and Paleozoic rocks of Mexico south of the craton. Some of the interior and eastern terranes contain Precambrian rocks with Grenvillian affinities (age of metamorphism, anorthosites) and may have been derived from North America. Other Precambrian rocks, however, are unlike Grenvillian or other known North American basements. The terranes in this group accreted to one another to form a collage in Early Mesozoic time. The younger movements of the collage, however, are less certain.

The terranes of the Pacific margin of Mexico, in contrast, include mainly Mesozoic rocks of arc and oceanic kindred. These accreted to the collage of terranes now in interior and eastern Mexico before the end of the Cretaceous. The terranes at the Pacific margin contain a record of convergent margin tectonics that dates as far back as Late Triassic. Several terranes include magmatic arc rocks, flysch, and oceanic crust, all of Jurassic age.

The original positions, extents, and displacement histories of any of these terranes, however, are little known.

A more coherent tectonic evolution can be deduced by Late Jurassic time for the group of interior and eastern terranes from their overlapping strata and superimposed tectonic features. The NW-SE opening of the Gulf of Mexico and associated left-lateral strike slip disruption of the southern North American craton on the Mojave-Sonora megashear (Figure 11) began in later Jurassic time. These regional motions created pull-apart basins in which red beds were deposited within the collage of accreted terranes. The later Jurassic block faults are apparently partly reactivated sutures of the terrane collage, and thus, patterns of sedimentation are somewhat related to configurations of subjacent terranes. The region of the collage of interior and eastern terranes underwent protracted subsidence after the pull-apart phase in the

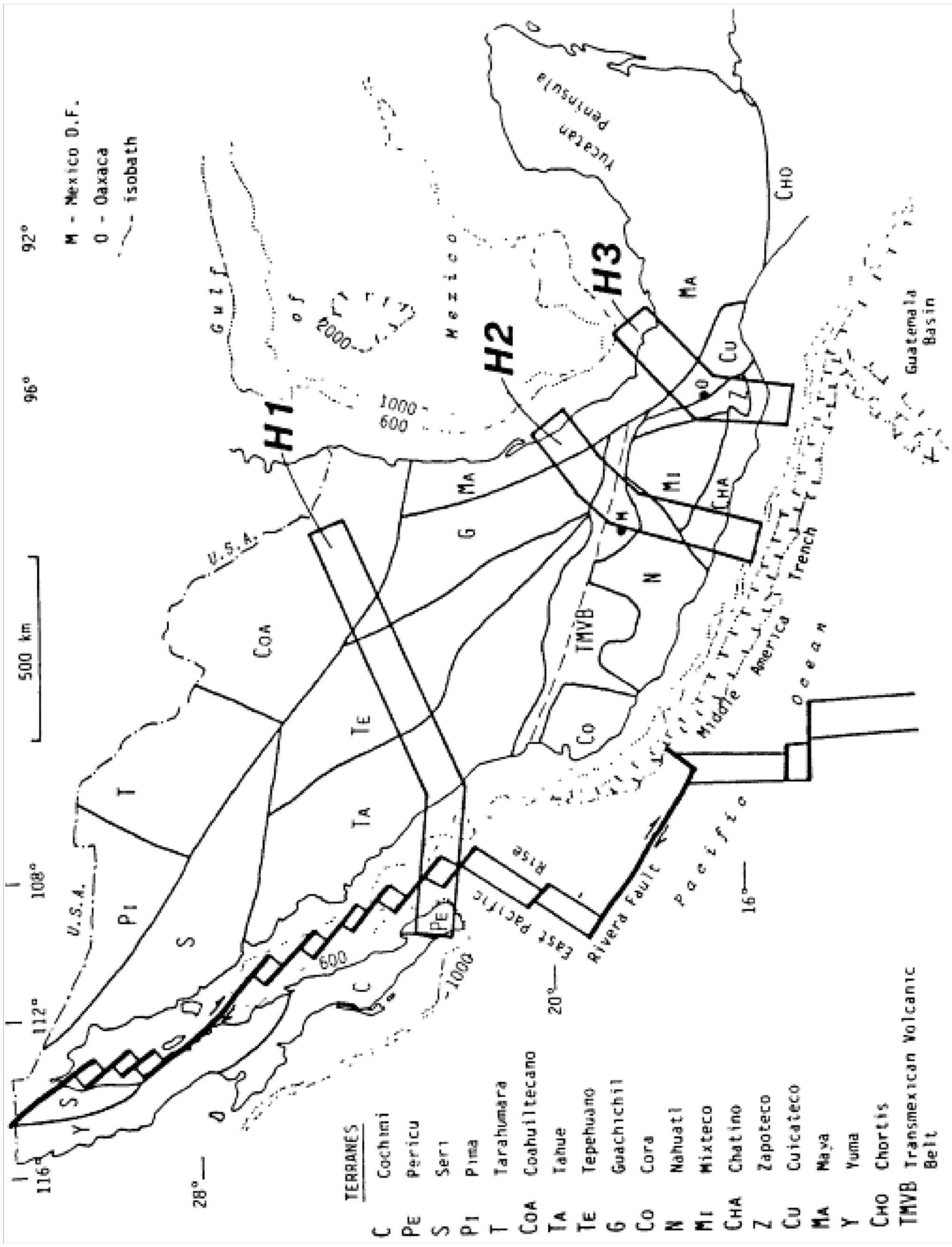


Figure 11
Map of tectonostratigraphic terranes of Mexico showing positions of corridors H1, H2, and H3.

Jurassic. This was probably accompanied by the closing of small ocean basins in the Pacific region and with collision of intervening are terranes against the active Pacific continental margin.

The Gulf of Mexico waters transgressed progressively to the west until, by the mid-Cretaceous, the passive continental margin created by the Gulf opening was depressed under the mixed Atlantic and Pacific waters. Continental rifts of mid-Jurassic age related to the expansion of the Gulf of Mexico, in one case, probably evolved into a small ocean basin that closed by Late Cretaceous time, creating the inboard intracontinental terrane (Cuicateco).

In the second half of the Cretaceous (Laramide tectonic regime) accretion of terranes into the mosaic of western Mexico was complete, but the long-lived Pacific subduction regime continued to exist at the edge of the tectonically prograding continental margin.

Superposition of magmatic arcs occurred during this outward building of the continental margin. The record of subduction-related magmatism was more continuous in southern Mexico, where an apparent migration of island arc volcanism advanced inland from the Cretaceous to its present position well within the continent. In contrast, the magmatic activity of NW Mexico swept the continental crust forth and back creating, during its Oligocene return, the Sierra Madre Occidental Ignimbritic Province. By Miocene time Pacific convergence came to a halt in this region but continued in southern Mexico.

South of the Trans-Mexican Volcanic Belt (TMVB), however, the Pacific margin of Mexico was truncated in Cenozoic time so that the history of older arcs there is mainly lost. The truncation was due either to subduction-erosion or strike-slip faulting.

The modern configuration of the Pacific continental margin of Mexico developed from the fragmentation of the East Pacific Rise as it approached and finally collided with the western margin of North America. The truncated margin of southern Mexico and the associated disappearance of a continental fragment by lateral sliding or frontal underthrust permitted the emplacement of oceanic crust closer to the present continental margin, and current arc magmatism jumped northward to the present site of the TMVB. At the same time, the opening of the Gulf of California marked the Neogene tectonic history of the NW Pacific margin of Mexico, and in the last part of geological history of the region, a new attempt by the East Pacific Rise to take another piece of continental crust off Mexico is revealed in the western part of the TMVB where coexistent calcalkalic and alkalic magmas are extruding through a tensionally fractured crust.

Problems

1. The origin of terranes with Precambrian and Paleozoic basements in Mexico and their alliance to North America or another continent, and their history of accretion.
2. The tectonic kindred of Paleozoic blocks.
3. The pre-Jurassic extent of cratonal North America and the Appalachian orogen into Mexico.
4. Timing of accretion and provenance of the terranes of mainly Mesozoic basement that constitute the western margin of Mexico.
5. Thickness and structures of crusts and depths of sutures of the various terranes.

6. Origin of the obliquity of the TMVB with respect to the trench and of some other anomalous characteristics in this intracontinental calcalkalic arc, such as (a) the low linear density of stratovolcanoes, (b) low Sr isotopic ratios of volcanic products with common petrographic evidence of crustal contamination, and (c) the aseismic nature of the underlying (is it one?) Wadati-Benioff zone.
7. The tectonic history of the Gulf of California region and the lithospheric structure of the rift and margins.
8. The timing, nature, kinematics, and crustal evolution resulting upon truncation of the southern Pacific margin of Mexico.

APPENDIX A

23 NORTH AMERICAN CONTINENT-OCEAN TRANSECTS: TITLES, AUTHORS, AND PUBLICATION PLAN

Transect	*Titles and Authors*
A2	Kodiak to Kuskokwim, Alaskan—Roland von Huene, Stephen Box, Bob Detterman, Michael Fisher, Casey Moore, and Hans Pulpan
A3	Gulf of Alaska to the Arctic Ocean—A. Grantz, T.E. Moore, and S.M. Roeske
B1	Intermontane Belt (Skeena Mountains) to Insular Belt (Queen Charlotte Islands)—C.J. Yorath, G.J. Woodsworth, R.P. Riddihough, R.G. Currie, R.D. Hyndman, C.G. Rogers, D.A. Seemann, and A.D. Collins
B2	Juan de Fuca Plate to Alberta Plains—J.W.H. Monger, R.M. Clowes, R.A. Price, P.S. Simony, R.P. Riddihough, and G.J. Woodsworth
B3	Juan de Fuca Spreading Ridge to Montana Thrust Belt—Darrell S. Cowan and Christopher J. Potter, with contributions by M.T. Brandon, D.M. Fountain, D.W. Hyndman, S.Y. Johnson, B.T.R. Lewis, K.J. McClain, and D.A. Swanson
C1	Mendocino Triple Junction to North American Craton—M.C. Blake, Jr., R.L. Bruhn, E.L. Miller, E.M. Moores, S.B. Smithson, and R.C. Speed, with contributions by Andrew Griscom, D.P. Hill, C.A. Hurich, D.L. Jones, A.H. Lachenbruch, D.S. McCulloch, K.D. Nelson, J.B. Saleeby, R.B. Smith, D.A. Stauber, C.M. Wentworth, and M.L. Zoback
C2	Central California Offshore to Colorado Plateau—J.B. Saleeby, with contributions by R.C. Speed, M.C. Blake, R.W. Allmendinger, P.B. Gans, R.W. Kistler, D.C. Ross, D.A. Stauber, M.L. Zoback, A. Griscom, D.S. McCulloch, A.H. Lachenbruch, R.B. Smith, and D.P. Hill
C3	Pacific abyssal plain to Rio Grande rift—D.G. Howell, J.D. Gibson, G.S. Fuis, J.H. Knapp, G.B. Haxel, B.R. Keller, L.T. Silver, and J.G. Vedder

D1 Northern Appalachians: (West sheet) Grenville Province, Quebec, to Newfoundland—R.T. Haworth, H. Williams, and C.E. Keen Northern Appalachians: (East sheet) Rifted margin offshore northeast Newfoundland—C.E. Keen and R.T. Haworth, with contributions by H. Slade and W. Kay

D2 Transform margin south of Grand Banks: Offshore eastern Canada—C.E. Keen and R.T. Haworth

D3 Rifted continental margin off Nova Scotia: Offshore eastern Canada—C.E. Keen and R.T. Haworth

D4 Rifted continental margin off Labrador—C.E. Keen and R.T. Haworth

E1 Adirondacks to Georges Bank—James B. Thompson, Jr., W.A. Bothner, Peter Robinson, K.D. Klitgord, J.S. Schlee, and Y.W. Isachsen

E2 New York Appalachian Basin to Baltimore Canyon Trough—A.A. Drake, Jr., J.A. Grow, N. Ratcliffe, R.T. Faill, and W. Manspeizer

E3 Pittsburgh to Baltimore Canyon Trough—Lynn Glover III, K. Klitgord, and J.K. Costain

E4 Central Kentucky to the Carolina Trough—D.W. Rankin, W.P. Dillon, D.F.B. Black, S.E. Boyer, D.L. Daniels, R. Goldsmith, J.A. Grow, J.W. Horton, Jr., D.R. Hutchinson, K.D. Klitgord, R.C. McDowell, D.J. Milton, J.P. Owens, and J.D. Phillips

E5 Cumberland Plateau to Blake Plateau—R.D. Hatcher, Jr., W.D. Dillon, F. Cook, D. Colquhoun, C. Merschat, R.C. Milici, A.E. Nelson, D.T. Secor, R. Sheridan, A.W. Snoke, and W.S. Wiener

F1 Ouachita Orogen to Yucatan—R.T. Buffler, C.D. Winker, D.B. Rosenthal, G.W. Viele, S. Suter, R.J. Lillie, A.E. Miles, R.H. Pilger, R.L. Nicholas, J.S. Watkins, R.G. Martin, and D.S. Sawyer

F2 Mississippi to Cuba—W.A. Thomas, R.G. Martin, and R.T. Buffler

G Somerset Island to Canada Basin—J.F. Sweeney, with contributions by H.R. Balkwill, R. Franklin, Ulrich Mayr, P. McGrath, E. Snow, L.W. Sobczak, R.J. Wetmiller, and Panarctic Oils, Ltd., Calgary, Alberta

H1 La Paz to Saltillo, Northwestern and Northern Mexico—Luis-Miguel Mitre-Salazar, and Jaime Roldan-Quintana, with contributions by F. Ortega-G., G. Sanchez-R., M. de la Fuente, B. Colleta, F. McDowell, C.D. Henry, and E.R. Swanson

H2 Acapulco to Tuxpan across the Central Mexican Plateau—G. Sanchez, F. Ortega, and L.-M. Mitre

H3 Acapulco Trench to Gulf of Mexico across Southern Mexico—Fernando Ortega-Gutierrez, with contributions by Luis-Miguel Mitre-Salazar, Jaime Roldan-Quintana, Gerardo Sanchez-Rubio, and M. de la Fuente

PUBLICATION PLAN BY THE GEOLOGICAL SOCIETY OF AMERICA (GSA)

Products of the North American Continent-Ocean Transect Program are being published by the Geological Society of America (GSA) as part of the publication series of the Decade of North American Geology, in three parts:

1. The 23 transects—maps, sections, and text.
2. Compiled tectonic section display—a separate display of the tectonic sections for all 23 transects.
3. Phanerozoic Evolution of North American Continent-Ocean Transitions—a 12-chapter book interpreting structure and tectonics of continent-ocean transitions around North America over the last 700 million years.

The transects and the compiled tectonic display are published in a series with titles "Centennial Continent-Ocean Transect #1" et seq. The GSA transect number reflects sequence of publication; it appears on the envelope of the transect and is used in GSA catalogues.

The transect number of the North American Continent-Ocean Transects Program is included as part of the title of each transect (see above in this appendix, and in the text of this report).

The relations between the basic transect numbers and the GSA numbers, through mid 1989, are shown below. (In parentheses: anticipated numbers of transects in press.)

North American Continent-Ocean Transect Number		GSA Transect Number
A2	....	6
A3		
B1	....	8
B2	....	7
B3	....	9
C1	....	12
C2	....	10
C3	....	5
D1	....	1
D2	....	2
D3	....	3
D4	....	4
E1		
E2		
E3		
E4		
E5		
F1		
G	....	11
H1	....	(13)
H2		
H3	....	(14)

APPENDIX B

U.S. GEODYNAMICS COMMITTEE: REPORTORIAL TOPICS AND REPORTERS

The U.S. Geodynamics Committee (USGC) was established in 1969 to foster and encourage studies of the dynamic history of the earth, with appropriate attention to both basic science and applications. The USGC also serves as the U.S. national committee for the International Lithosphere Program (ILP).

In the 1970s, the U.S. Geodynamics Committee served as the U.S. counterpart to the International Geodynamics Project. The USGC developed recommendations for U.S. participation in the Geodynamics Project, published as *U.S. Program for the Geodynamics Project: Scope and Objectives* (1973). Three additional major reports were prepared by the USGC more recently: *Continental Scientific Drilling Program* (1979), *Geodynamics in the 1980s* (1980) and *The Lithosphere: Report of a Workshop* (1983).

To implement its recommendations, the USGC established a system of special priority topics and corresponding reporters.

The term "reporter" can be misleading. The USGC adopted this word from the usage in international geophysical programs in which it has a connotation of activity and responsibility. The duty of each reporter is to provide recommendations to the USGC regarding steps that could be taken to implement the topic or priority in question.

Much of the work of the USGC is based on the activities and recommendations of the reporters and the groups that they have convened. Meetings have ranged from small groups to two major workshops on continental scientific drilling. These activities have led to well-defined results including the following: deep reflection profiling programs; preparation and publication of the plate margins cross sections; the Continental Scientific Drilling Program; and the North American Continent-Ocean Transects Program.

The reportorial topics adopted by the USGC are subject to continual review, with additions and phasing out as appropriate. In addition, the USGC has designated USGC-ILP reporters.

USGC Reportorial Topics and Reporters

Seismic Reflection Profiling	Larry Brown
Continent-Ocean Transects	Robert C. Speed
Geodynamic Data	William J. Hinze
Sedimentary Systems	Peter R. Vail
Chemical Geodynamics	Donald J. DePaolo
Internal Processes and Properties	Raymond Jeanloz
Mantle Dynamics	Bradford H. Hager
Crustal Dynamics	Leigh H. Royden
Fluids in the Crust	Mark D. Barton
Global Seismology	Stewart W. Smith
Continental Drilling	Mark D. Zoback
Marine Geology and Geophysics; and Planetology	Sean C. Solomon
Volcanic Hazards	Grant H. Heiken

USGC-ILP REPORTERS

In recognition of the importance of linkage and interaction between the USGC and the ILP, those U.S. scientists who have major responsibilities on the Inter-Union Commission on the Lithosphere (ICL) are designated as USGC-ILP reporters.

LITHOSPHERE PROGRAM TOPICS—WORKING GROUP (WG) OR COORDINATING COMMITTEE (CC)

WG-1	Recent Plate Movements and Deformation	Robert S. Yeats (ch)	
WG-2	Nature and Evolution of the Continental Lithosphere		
	Task Group A.	Variations in the Nature and Evolution of Mobile Belts	
	Task Group B.	Plate Motions and Orogeny through Time	Christopher R. Scotese (ch TG-B)
	Task Group C.	Thermal, Mechanical, and Chemical Evolution of the Continental Lithosphere	Gerald Schubert (vc TG-C)
WG-3	Intraplate Phenomena	Mary Lou Zoback (mb)	
WG-4	Nature and Evolution of the Oceanic Lithosphere	John C. Mutter (ch)	
WG-5	Paleoenvironmental Evolution of the Oceans and Atmosphere		
WG-6	Structure, Physical Properties, Composition, and Dynamics of the Lithosphere-Asthenosphere System		
	Task Group A.	Structure	
	Task Group B.	Physical Properties	
	Task Group C.	Dynamics	
	Task Group D.	Composition	
CC-1	Environmental Geology and Geophysics	George Kiersch (ch)	
CC-2	Mineral and Energy Resources		
CC-3	Geosciences Within Developing Countries		
CC-4	Continental Drilling	Mark D. Zoback (ch)	
CC-5	Data Centers and Data Exchange	Michael A. Chinnery (mb)	
			William J. Hinze (mb)
CC-6	National Representatives	Frank M. Richter (US rep)	
	Subcommittee on the Arctic	G. Leonard Johnson (ch)	
CC-7	Global Geoscience Transects	Randall Van Schmus (mb) (and leader, N.Am. section)	
			John W. Harbaugh (mb)

Role on the ICL WG or CC: ch = chairman; vc = vice chairman; mb = member.