A PROPOSAL TO CONDUCT A

# CARIBBEAN PLATE PROJECT

## INVOLVING THE APPLICATION OF SPACE TECHNOLOGY TO THE STUDY OF CARIBBEAN GEOLOGY

LPI Technical Report Number 81-02

LUNAR AND PLANETARY INSTITUTE 3303 NASA ROAD 1 HOUSTON, TEXAS 77058

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*Cover: LANDSAT image of southwestern Nicaragua and northwestern Costa Rica. The volcanoes extending into Lake Nicaragua lie above the subducting Cocos plate to the west. The Santa Elena peninsula in the south is part of a Late Cretaceous ophiolite accreted onto the Caribbean plate.*

# Contents

# Executive Summary

### Introduction

The Caribbean plate is a geological feature which is bounded to the north by the Greater Antilles islands (extending from Jamaica to Puerto Rico), to the east by the Lesser Antilles (extending from the Virgin Islands to Grenada), to the south by the northernmost portion of the South American continent, and to the west by the west coast of Central America. It is one of several semi-rigid bodies, referred to as tectonic plates, which form the outer portion of the solid earth. Motions of these plates in relation to one another are responsible for the majority of earthquakes that have occurred in historic time. On a geological time scale, the relative motions of tectonic plates are responsible for the formation of continental mountain chains and for the concentration of mineral deposits within certain portions of the earth's crust.

### Project Goals and Strategy

The Caribbean Plate Project envisioned in this proposal is an interdisciplinary, multi-institutional, scientific project designed to improve current understanding of geological resources and geological hazards within the Caribbean region. The twin goals of the Project are: 1) to develop improved models of mineral occurrence and genesis (including energy resources) on a regional scale, which can contribute to future nonrenewable resource investigations, and 2) to develop improved models of lithospheric stress and strain on a regional scale, which can eventually contribute to forecasting geological hazards such as earthquakes and major volcanic eruptions. These goals will be addressed through the synthesis of available geological information and through research using new tools provided by space technology for the study of the earth's crust. The Project has been organized in a thematic fashion, to focus on specific geological aspects of the Caribbean plate which are considered to be key factors in developing the types of models described above. A condensed description of these scientific themes is provided in Section II and a more thorough discussion is presented in Appendix A.

The Caribbean Plate Project is unique in two respects. First, the Project would adopt a synoptic perspective in seeking to characterize the three-dimensional structure, composition, state of stress, and evolution of the entire Caribbean plate. No previous geological study of this nature has attempted to model a tectonic plate of this size and complexity in such a comprehensive fashion. Secondly, the Project seeks to apply existing space technology to the study of the earth's crust and lithosphere in new and innovative ways. Electromagnetic remote sensing and potential field measurement techniques, which have been developed for use at orbital altitudes, are not viewed as replacements for conventional methods of geological research. Rather, geological information derived from analysis of space-acquired data can be combined with information provided by conventional methods to obtain new insight into the structure, composition, and evolution of the earth's crust. In addition, very long baseline interferometry (VLBI) and laser ranging techniques, which are also based upon the use of space technology, obtain unique information concerning crustal motion that, in turn, provides insight into the distribution and localization of crustal stress.

### Significance of Caribbean Geology

The Caribbean region is an important source of nonrenewable resources at the present time, and its importance as a producer of geological commodities is likely to increase in the future. The region now exports significant quantities of oil, bauxite and alumina, and copper. It also produces mineral resources of strategic importance such as manganese, tungsten, and chromium. There is a long history of exploration and mining of precious metals within the Caribbean. The oldest and largest open-pit gold mine in the Western Hemisphere is found here.

In addition to geological resources, the Caribbean also contains diverse geological hazards which threaten the lives and livelihood of its inhabitants. Major earthquakes occur relatively frequently, particularly in Central America. In the last ten years, major earthquakes in Guatemala and Nicaragua have killed tens of thousands of people, and have devastated national economies. Volcanic eruptions also occur frequently within the region, resulting in loss of life and livelihood. For example, inhabitants of two islands in the Lesser Antilles, Guadeloupe and St. Vincent, have had to be evacuated from threatening explosive eruptions of neighboring volcanoes.

Finally, the Caribbean possesses several distinctive geological characteristics which are of interest from a purely scientific point of view. The Caribbean plate is one of the smallest lithospheric plates with readily recognizable tectonic boundaries. The Cayman Rise, a miniature seafloor spreading center, forms part of the boundary. Elsewhere both convergent and transform boundaries are well developed, so the plate contains examples of all essential plate boundary features. Oceanic crust is being actively subducted beneath its eastern and western margins, and volcanic arcs are currently being constructed. In the Lesser Antilles, Atlantic oceanic crust is underthrusting Caribbean oceanic crust; whereas in Central America, oceanic crust forming the Pacific seafloor is being subducted beneath a block of continental crust. Contrasting styles of volcanism at these opposite margins provide insight into the manner in which crustal material is reprocessed by plate tectonic processes, and in how continents nucleate and grow.

## Project Organization and Management

The Caribbean Plate Project will encourage an interdisciplinary approach to crustal research and modeling. Scientific investigators will be organized into working groups which will meet regularly to exchange data and results and to coordinate future research activities. These working groups will address the major scientific themes of the Project described in this document.

A Steering Committee will be formed to provide overall scientific guidance for the Project. The Steering Committee will ensure that: 1) a synoptic overview of Caribbean plate geology is maintained, 2) working groups strive toward Project goals, and 3) existing space technology is fully employed and fairly evaluated. The Steering Committee will consist a of chairman, working group leaders, the Project management team, and representatives of funding organizations.

The Lunar and Planetary Institute (LPI), operated by the Universities Space Research Association, will be responsible for the technical management and administration of the Project. Over the years, the LPI has demonstrated the capability to assemble geoscientists with relatively narrow individual interests and to focus their combined talents on problems of a broader nature. On the basis of this past experience, the LPI is considered to be ideally qualified to manage the Caribbean Plate Project. The Director of the LPI will serve as Project Manager, and specific members of the LPI staff will fill the roles of Project Scientist and Project Administrator. These individuals will also serve on the Steering Committee. The LPI will provide a variety of logistical and administrative services to support the overall aims of the Project.

## Summary

The Caribbean Plate Project represents a unique opportunity to apply a new set of technological tools to the study of the earth's crust and lithosphere. The Project also represents a challenge to earth scientists to develop improved models of regional metallogenesis and crustal stress through the synthesis of conventional geological information and the analysis of data acquired from space. The Caribbean Plate Project will provide an interesting test of whether this approach can be applied profitably to synoptic scale studies of the geology of the Earth.

# I. Project Description

## A. Historical Background

That interest in the geology of the Caribbean region has grown significantly over the past two decades has been due in part to increased international demands for nonrenewable resources. A series of natural disasters, the 1972 Managua, and 1976 Guatemalan earthquakes and the 1976 eruption of La Soufrière, Guadeloupe, have also led to intensified study of tectonic and volcanic processes within the region. One indication of this growing interest has been the formulation of a scientific initiative in 1977, entitled "Geology, Geophysics, and Resources of the Caribbean," the intent of which was to combine land-based studies of Caribbean geology with marine geophysical studies of the Caribbean ocean floor. This initiative was submitted to the International Decade of Ocean Exploration (IDOE) sponsored by the United Nations Educational, Scientific, and Cultural Organization (UNESCO). The proposed initiative was not implemented due to organizational problems and to lack of research funds. A further indication of growing interest in Caribbean geology was the large and enthusiastic attendance at the Ninth Caribbean Geological Conference, which was held in the Dominican Republic in August, 1980. The economic geology portion of this meeting, in particular, surpassed all recent attendance records.

NASA's Office of Space and Terrestrial Applications received a preliminary proposal for a geological research project focused on the Caribbean in March, 1978. This proposal was based upon two workshops held at the Lunar and Planetary Institute (LPI) in January and February of 1978 on the theme "Caribbean Plate and Geodynamics." The proposed project concentrated primarily upon studies of tectonic processes, geothermal resources, and volcanic eruption phenomena in Central America. The proposed study was not implemented due to the untimely death of the project organizer, Dr. Thomas R. McGetchin, and to the lack of a geological applications staff at NASA Headquarters.

In February, 1980, the Director of the LPI convened a meeting of selected geoscientists with extensive experience in Caribbean research to reconsider the concept of a Caribbean project. This group, chaired by Dr. Kevin Burke (State University of New York, Albany), felt that a broad scale study of Caribbean geology employing existing space technology could make a significant contribution to understanding the geological resources and hazards within the region. The group concluded that such a study should treat the Caribbean plate in its entirety, rather than focus upon a particular plate boundary.

The participants in the February, 1980, LPI meeting formed an *ad hoc* steering group to develop a strategy for the envisioned Caribbean Plate Project. The group prepared a position paper entitled "Application of Space Technology to Caribbean Plate Science" which was formally submitted to NASA in August, 1980. The group also organized a Caribbean Plate Workshop, which was held at the LPI in September, 1980, in order to involve a broader spectrum of geoscientists in evaluating the need for, and the potential contributions of the proposed project. The Workshop was attended by leading researchers from government and academia, as well as by economic geologists from private industry. The consensus of the Workshop was that: 1) there exists a definite need to provide a focus for the diverse interests of various geological investigators working in the Caribbean, and 2) the Caribbean region represents a challenging test site for evaluating the geological utility of space methods and technology. Based in part upon the conclusions of this meeting, the LPI has developed this scientific plan for the proposed Caribbean Plate Project.

## B. Goals

The Caribbean Plate Project will be an interdisciplinary, multi-institutional, scientific project designed to improve current understanding of geological resources and hazards within the Caribbean region. The Project has two major goals.

The first goal is to develop improved regional models of mineral occurrence and genesis which can contribute to future nonrenewable resource investigations. The Caribbean contains diverse geological environments and represents a unique natural laboratory for the study of mineralization processes. For example, the eastern, northern, and western boundaries of the plate consist of volcanic arcs which have been constructed through tectonic plate subduction. Yet the types of mineral deposits found along each plate margin differ significantly. The Lesser Antilles Islands to the east have formed through the partial melting of Atlantic oceanic crust which is currently being subducted beneath the oceanic crust of the Caribbean. In contrast, much of the Central American volcanic arc to west is being constructed by the underthrusting and partial melting of the Pacific seafloor beneath a block of continental crust. The Greater Antilles to the north represent the eroded remnants of an earlier arc system. Detailed study of the types and modes of occurrence of mineral resources in these contrasting geological settings will provide insight into metallogenesis in island arc environments. Similarly, comparison of oil and gas occurrences at the southeast (Trinidad), southwest (Maracaibo Basin, Venezuela), and northern (Dominican Republic) boundaries of the Caribbean plate will provide insight into the formation of hydrocarbon deposits in different sedimentary environments commonly found along continental margins.

The second goal of the Project is to develop improved regional models of lithospheric stress and strain which will contribute to forecasting geological hazards such as earthquakes and major volcanic eruptions. Large compressive stresses caused by the collision of tectonic plates are currently concentrated at the eastern and western margins of the Caribbean. The northern and southern boundaries of the plate are zones of shear stress, similar to that which exists along the San Andreas Fault of North America. Earthquakes are common occurrences along the Caribbean plate boundaries, as evidenced by the Managua earthquake of 1972, and the Guatemalan earthquake of 1976. In addition, volcanic eruptions occur with greater frequency in Central America than anywhere else in the Western Hemisphere. The threat of a major explosive eruption at La Soufriére, Guadeloupe, as recently as 1976, led to an evacuation of 70,000 people for 3½ months. These geological hazards pose major threats to the lives and livelihoods of the region's inhabitants, and historically have disrupted the entire economies of individual nations. The frequency and intensity with which hazardous events occur make the Caribbean a unique natural laboratory in which to study such phenomena. As in the case of metallogenic studies, improvements in models of crustal stress and strain based upon research in the Caribbean will be applicable in other parts of the world as well.

## C. Research Themes

The Caribbean Plate Project will focus thematically on key research areas which are considered to be critically important in meeting the goals of the Project. These themes were identified by the Caribbean Plate Workshop held at the LPI in September, 1980. They are presented in outline form in Section II. A more detailed description of topical research problems related to these themes is provided in Appendix A of this document. The themes are:

GEOLOGICAL HISTORY OF THE CARIBBEAN PLATE
- (1) Evolution of island arcs
- (2) Temporal changes in tectonic regimes

CHARACTERIZATION OF THE PLATE INTERIOR

ACTIVE PROCESSES AT THE PLATE BOUNDARIES
- (1) Structural and tectonic variations
- (2) Volcanic variations

MINERAL RESOURCES: OCCURRENCE AND GENESIS

## D. Strategy

The goals of the Caribbean Plate Project will be addressed through: 1) interdisciplinary synthesis of existing geological information obtained by conventional techniques, and 2) interdisciplinary analysis of new types of geological data obtained through the use of space technology. Limitations in existing Caribbean plate models stem partly from the size and geological complexity of the plate itself, and partly from the linguistic and political isolation of small research communities. The meetings prior to the formulation of the Project pointed out the need for improved communication between investigators with different disciplinary backgrounds. The Project would provide an opportunity to make this improvement.

The importance of maintaining a synoptic perspective in examining the geology of the entire Caribbean plate leads directly to the second element of the Project strategy: namely, the utilization of space methods and technology. Space technology is inherently global in nature and can be used to obtain unique types of geological information at unique scales. It is ideally suited to the study of large-scale crustal features. Furthermore, space data acquired at synoptic scales can be used to perform comparative studies of key localities in a manner which could have a major impact upon our understanding of Caribbean plate geology.

The utility of existing space techniques for crustal research was a major discussion topic at the Caribbean Plate Workshop. The Workshop concluded that geological information obtained through the use of space methods could provide major insight into crustal structure, composition, stress, and strain; particularly if such information were analyzed in combination with geological information obtained by conventional techniques. Workshop participants were of the opinion that the Project would also provide an opportunity for meaningful evaluation of the actual utility of existing space technology for geological applications.

## E. Organization

Scientific investigators participating in the Project will be organized into interdisciplinary working groups which will address the research themes outlined above. Working groups will operate with a certain amount of autonomy. Each will meet regularly to exchange data, results, and problems, and to coordinate future research activities. Each group will be headed by an individual referred to as the working group leader.

An important feature of the Project will be the formation of a Steering Committee to provide overall scientific guidance. The Steering Committee will consist of working group leaders, the Project management team, and representatives of funding organizations. It will ensure that: 1) a synoptic overview of Caribbean plate geology is maintained, 2) working groups strive toward overall Project goals, and 3) the utility of existing space technology is tested and evaluated fairly. Communication among the working groups will take place through the representation of working group leaders on the Steering Group, and through plenary meetings of project participants which will be held on an annual basis.

The Lunar and Planetary Institute will be responsible for technical management and administration of the Project. The Director of the LPI will serve as Project Manager, and specific members of the LPI staff will serve as Project Scientist and Project Administrator. The LPI will provide a variety of administrative and logistical services to support the overall aims of the Project. These are discussed in greater detail in Section III.

## F. Schedule

The project is tentatively expected to take place over a period of five years. This schedule may be modified if necessary, depending upon preliminary results and the availability of funding in subsequent years.

## G. Products

The final products of the project will consist of the following:

1) A compilation of research papers produced by individual investigators during the course of the project.

2) A thematic atlas of the Caribbean plate. The atlas will consist mainly of overlay sheets at a scale of 1:5 M (34" × 18" sheets). The base-map for the overlays will be a condensed version of the 1:2.5 M scale map of Caribbean geology and tectonics by Case and Holcombe (1980). The themes illustrated in the atlas would include some data sets that have been compiled and published previously (e.g., gravity anomalies, Bowin, 1976), and others that are new. Some themes which would be included are:

i) Surface and satellite (GEOS-3) gravity
ii) Surface and satellite (POGO, OGO, MAGSAT) magnetics
iii) Satellite altimetry and geoid anomalies (SEASAT, GEOS-3)
iv) Heat flow
v) Crustal structure from seismicity
vi) Hypocenters and selected focal mechanisms of recent seismicity
vii) Small-scale lineaments and circular structures
viii) Mineral Deposits
ix) Quaternary tectonism
x) Quaternary volcanic centers and geothermal potential.

Some of these data sets, as well as others, will be needed by investigators during the course of the project. Interim products will include compilations of all relevant Landsat and spacecraft imagery, of all available radar imagery including Seasat SAR and Shuttle Imaging Radar, and of all the local specialized photography, such as IR surveys.

3) A final report, containing a summary evaluation of the contribution of space technology to the results of the project prepared by the Steering Group, and a set of overview papers prepared by the working groups. These papers would be based upon the themes outlined in the next section. They would attempt to provide some answers to questions such as the following:

i) What were the original positions of the American and African continents before rifting?
ii) How was the Caribbean plate thickened by igneous activity during the Late Cretaceous and what are the properties of the Caribbean lithosphere today?
iii) How were the components of the Cretaceous island arcs originally disposed?
iv) When were the important tectonic events and how were these events related to plate interactions?
v) Why do the plate boundaries display such a great lateral variety of tectonism and non-rigid behavior.
vi) How much magma and volatiles are currently being generated beneath, and how much reach the surface at the two Caribbean arcs?
vii) What are the roles of the transverse structural breaks at the Central American subduction zone in the genesis of mineral deposits?

These products will be completed within one year of the termination of the Project.

# II. Project Research

## A. Geological History of the Caribbean Plate

**Island arc evolution**

The relative motions of the North American, African and South American plates and of the plates of the eastern Pacific have produced convergent boundaries to the Caribbean since the Cretaceous. The active arcs of Central America and the Lesser Antilles on the west and east can be related to present-day plate motions. The older arcs of the Greater Antilles and northern South America are results of earlier periods of convergence which are less well-defined. In order to improve the definition of these earlier episodes of convergence, increases in our current level of understanding will be required in two areas: (a) the Mesozoic motions of the North and South American plates with respect to Africa and each other, (b) the pre-rifting configuration of the pre-Mesozoic continents. Satellite and marine geophysical studies of key areas such as the Chortis block (N. Central America) will be required, combined with ground-based structural analysis. The interdependence of these convergent zone phenomena with associated strike-slip movement and back-arc spreading also requires thorough evaluation, as for example in analysis of potential field data acquired over the Yucatan Basin.

**Temporal changes in tectonic regimes**

It is apparent that certain time periods in the geological development of the Caribbean saw fundamental changes in tectonic behavior, and that these changes can be correlated, to varying degrees, with plate motions. The end of the Cretaceous, Middle Miocene, Late Oligocene, Late Miocene and Late Pliocene are crucial periods of this nature in the more recent geologic record. These tectonic "nodes" are, however, far from well-defined in terms of intensity, style, extent or duration, particularly those of Cretaceous age. The potential is great for applying regional synthesis of local stratigraphic knowledge (which has increased dramatically in the last decade) to this problem. Structural mapping using LANDSAT and SAR in key areas may enable regional variations to be determined and calibrated in conjunction with ground-based stratigraphy. The application of multichannel, seismic stratigraphic techiques to the refinement of this tectonic record may prove of major value particularly in the ocean basins.

## B. Characterization of the Plate Interior

The age of the oceanic crust of the Caribbean, its provenance, and the reason for its great thickness remain, after many years of research, unsolved problems. There is no immediate prospect of their being resolved by Deep Sea Drilling. However, an integrated study of all available evidence on the composition and to the physical/elastic properties of the Caribbean lithosphere would contribute greatly to our understanding of how the plate evolved, its chemical and physical heterogeneity, and its response to stresses. The products of such an investigation might be a series of detailed columnar sections through the plate in critical locations. Data may come from a variety of sources. Combined analysis of SEASAT and GEOS-3 altimetry data with MAGSAT long-wavelength magnetometry would enable gravitational and magnetic constraints to be applied to such sectional models. Studies of seismic wave propagation can supply details of upper mantle structure and crustal anisotropy which may be related to an original seafloor spreading fabric. Information on the thermal state and chemical composition of the mantle could be supplied by studies of intraplate volcanism. The advent of VLBI and space laser ranging technology provides an opportunity to test the concept of a rigid Caribbean plate. The relatively small size of the plate means that a modest network of interconnected stations could monitor the behavior of the whole plate as it responds to the stresses due to motions of the four major plates which surround it.

## C. Active Processes at the Plate Boundaries

### Structural and tectonic variations

The position and behavior of many parts of the boundary of the Caribbean plate are poorly-defined. Diffuse zones of seismicity, seismic gaps, large free-air anomalies and geoid anomalies are common at these boundaries, particularly to the north and south. Magnitudes of the anomalies vary rapidly along the boundaries, as well. The present plate boundaries must be defined with greater precision, both at the surface and at depth. In addition, the irregularities in the deformation of the margins require explanation. Several tools are available for this work. Local seismic networks exist in many of the anomalous areas of the plate margin. The value of the data which they produce may be enhanced by satellite telemetry. Improved definition of mass anomalies obtained by utilizing both space radar altimetry and surface gravity measurements may enable a closer genetic relationship to be established between mass anomalies and tectonic behavior. SAR and multispectral data from selected regions will be employed to deduce neotectonic histories. The measurement of current crustal deformation using VLBI and laser ranging technologies will help to define boundary stress fields for specific sections of the plate margin. Such information will aid in understanding and forecasting potentially destructive Caribbean earthquakes.

### Volcanic variations

The contrasts between the Central American and Lesser Antillean volcanic arcs are striking, in terms of crustal setting, style and magnitude of volcanism. In particular, the rates of magma accumulation and eruption have been unequal over the past 100,000 years, which may be a function of rates of plate convergence at the two arcs: the Central American convergence rate is about three times that of the Lesser Antilles. Estimates of aerial and submarine deposits, made using a variety of sampling, dating and remote-sensing techniques, will be required to evaluate this. Complementary to this estimate of the solid-product budget, a plate-wide estimate of the current volatile emission budget can be supplied by satellite and ground-based remote-sensing and aircraft sampling of eruptive gases and particles. Such data will place constraints on the presence and characteristics of shallow-level magma bodies, on the probability of eruption and the potential hazards which they pose, and on models of sulfur partitioning in the formation of sub-volcanic porphyry coppers. An important component of Caribbean magmatism is the evolution of some volcanoes to form dacitic or large rhyolitic magma bodies which may be partially evacuated in explosive, caldera-forming eruptions. The frequency of occurrence and the processes responsible for the formation of such calderas, which are potentially prime sites for massive sulphide mineralization, are not fully understood. Northern Central America, in particular, contains many calderas of different ages and in various states of preservation. Multispectral and SEASAT-SAR imagery are excellent tools for identifying and correlating these features.

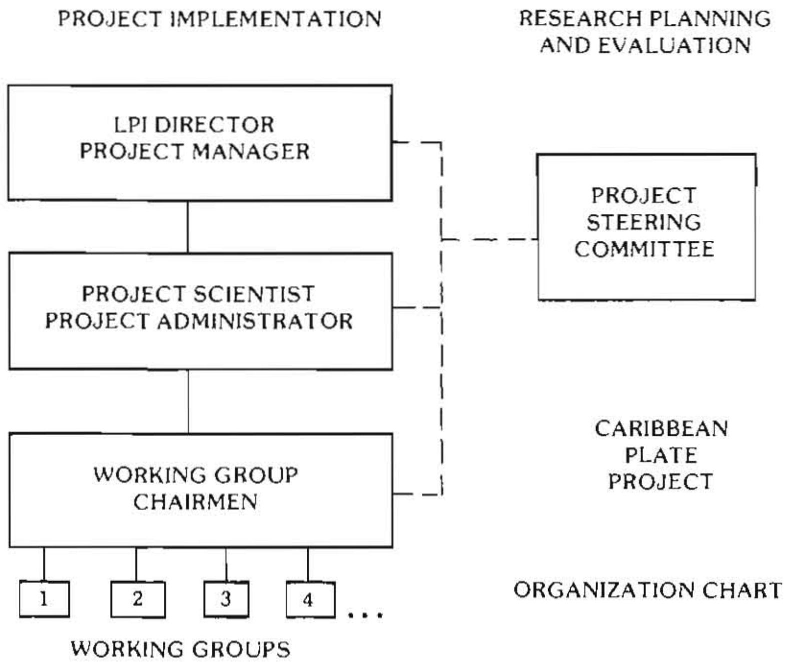
## D. Mineral Resources: Occurrence and Genesis

The Caribbean contains a large variety of mineral resources: some of global importance (bauxites, copper, gold, hydrocarbons) and others in large, poorly-explored areas which are covered by tropical vegetation. There are some outstanding problems of unexplained ore element distribution, structural controls on mineralization, and characterization of deposits and identification of exploration parameters that have significance beyond their regional settings. The localization of the W-Sb-Hg and Pb deposits in parts of northern Central America is such a problem. Its solution will require detailed investigation of trace-element and isotopic chemistries of both the ore and the parental igneous rocks, coupled with a detailed regional synthesis of their distributions and age relationships. Major transverse structural breaks in the plates at the subduction zone in Central America have been proposed. The extent of the landward continuity of these breaks is unknown, but they may be pathways for mineralizing solutions, particularly Au-Ag-bearing solutions. Systematic remote-sensing investigations along the strikes of these structures would utilize SAR data for structural mapping and multispectral imagery of promising sites including geobotanical interpretation of the densely-vegetated areas to the east. The origin of the Caribbean's major bauxite deposits in the western Greater Antilles is another unresolved problem which will require accurate dating of the deposits and an evaluation of the role of late Cenozoic uplift in the laterization process, for which satellite image characterization of erosion surfaces would be employed.

# III. Project Organization

## A. Overview

The Caribbean Plate Project is currently envisioned as a five-year activity. The final products, including a compilation of publications, final report, and thematic atlas, will be completed within one year of the termination of the project. The Lunar and Planetary Institute (LPI), which is operated by the Universities Space Research Association, will be responsible for technical management and administration. An organizational flow chart is presented below. The duties and responsibilities of individual elements of the Project are discussed in the following sections.




ORGANIZATION CHART

## B. Technical Management

The LPI will serve as a focal point for coordinating technical aspects of parallel research activities being performed by individual investigators. It will provide a variety of centralized services to assist individual investigators and to further the aims of the Project. The Director of the LPI will serve as the Manager of the Caribbean Plate Project, and will be responsible for all technical aspects of Project implementation. He will designate two members of the LPI staff to serve as Project Scientist and Project Administrator.

The Project Scientist will oversee day-to-day operations of the Project. He/she will supervise centralized service tasks performed at the LPI in support of the Project to ensure that such services meet the needs of the investigators. The Project Scientist will monitor the activities of the investigators and will strive to identify areas where increased communication and/or cooperation would be desirable. With the assistance of other LPI staff members, he/she will ensure that individual investigators complete specific technical tasks.

The Project Administrator will be responsible for budget administration and Project communications. He/she will organize workshops, seminars, and conferences, and will supervise the publication of Project reports.

The LPI staff will be augmented to conduct in-house research relevant to the Project. LPI in-house research efforts will be directed towards interdisciplinary aspects of the Project that are not being adequately addressed by outside (non-LPI) investigators. LPI staff scientists will assist the Project Scientist in the technical monitoring of Project related investigations at other institutions.

In view of the broad geological scope of the Project, no single individual is qualified technically to manage all scientific aspects. In recognition of this, an interdisciplinary Caribbean Plate Project Steering Committee will be created to provide overall scientific guidance. The Director of the LPI will appoint the Chairman of this Steering Committee. The LPI Director will organize Project investigators into working groups which focus individually on specific research themes, and will appoint working group leaders.

The Project Steering Committee will consist of the Chairman, the LPI management team (Project Manager, Scientist, and Administrator), the working group leaders, and representatives of various funding organizations. The Steering Committee will be responsible for ensuring that: 1) a synoptic overview of Caribbean plate geology is maintained throughout the Project, 2) working groups strive towards Project goals, and 3) remote sensing, orbital potential field, and crustal motion measurement techniques are fully employed and fairly evaluated within the Project. The Steering Committee will provide a formal mechanism for maintaining close communication among the thematically-oriented working groups.

The technical working groups within the Project will operate with a certain degree of autonomy. Under the guidance of an appointed leader, each working group will establish technical objectives related to the major research themes of the Project. Working groups will devise methods and timetables for obtaining necessary data, exchanging information and results, and discussing data interpretation and conclusions. It is expected that individual groups will meet at least semi-annually to evaluate progress and to coordinate plans for future research activities, while all Project investigators will be brought together to exchange interim results at an annual plenary conference.

## C. Support Services

The LPI will provide the following services to support the Project:

*Data center*

The LPI will establish, within the framework of its existing facilities, a data center for the Caribbean Plate Project. This will include an up-to-date library of articles and reports dealing with Caribbean plate geosciences. The information will be computer coded to facilitate rapid key-word searches, which will maximize the usefulness of the library as an efficient research tool. The Data Center will also include a comprehensive Caribbean map and imagery collection. Ties will be established with other data centers, such as the EROS Data Center and the National Space Science Data Center, so that scientists working on the Project can rapidly obtain additional products through the LPI.

*Cartographic services*

Although a great many maps of the Caribbean plate area exist, it is expected that there will be a requirement for additional cartographic products. For example, there will be needs to compile maps on a common scale, to create maps based upon space data, to prepare large-scale maps of specific test areas, etc. The LPI will furnish this cartographic support to investigators as required. A specific requirement, anticipated at the onset, is for LPI to generate and continually to update a 1:5,000,000 thematic atlas of the Caribbean plate. The atlas will contain a variety of geologic, geophysical, geochemical, and resource overlays for use as generalized geologic maps. Data will also be compiled as cross sections, fence diagrams, and tables. A complete atlas will be published at the conclusion of the Project.

*Publication services*

The LPI Publications Department will provide editorial and publications support to Project participants, as required, to produce camera-ready copy for various reports, journals, and volume publications.

## D. Reporting of Results and Expenditures

Progress will be monitored through the following series of reports prepared by the Project staff at the LPI:

*Monthly Financial Statement* - A written statement will report monthly expenditures of Project-related funds to the appropriate sponsoring organizations. This statement will compare actual expenditures to total levels of authorized funding and to previous estimates of expenditure rates.

*Semi-Annual Progress Report* - A written report will provide a summary of current technical accomplishments, a review and discussion of interim Project milestones, and an accounting of the overall Project budget.

*Annual Project Review* - An oral presentation, accompanied by appropriate written documentation providing a comprehensive review of recent progress and future plans, will be presented to Project sponsors by the LPI Project staff.

## E. Final Products

The LPI will produce the following products within one year of the termination of the Project:

a) A compilation of relevant scientific and technical publications produced by Project participants

b) A final report including
   - an overview of Project accomplishments within the major theme areas
   - a state-of-the-art summary of geological models describing Caribbean plate resources and hazards
   - an assessment of the contribution made by space technology to the Project and recommendations concerning future technology development

c) A thematic Atlas of the Caribbean plate based upon both space data and conventional geological information.

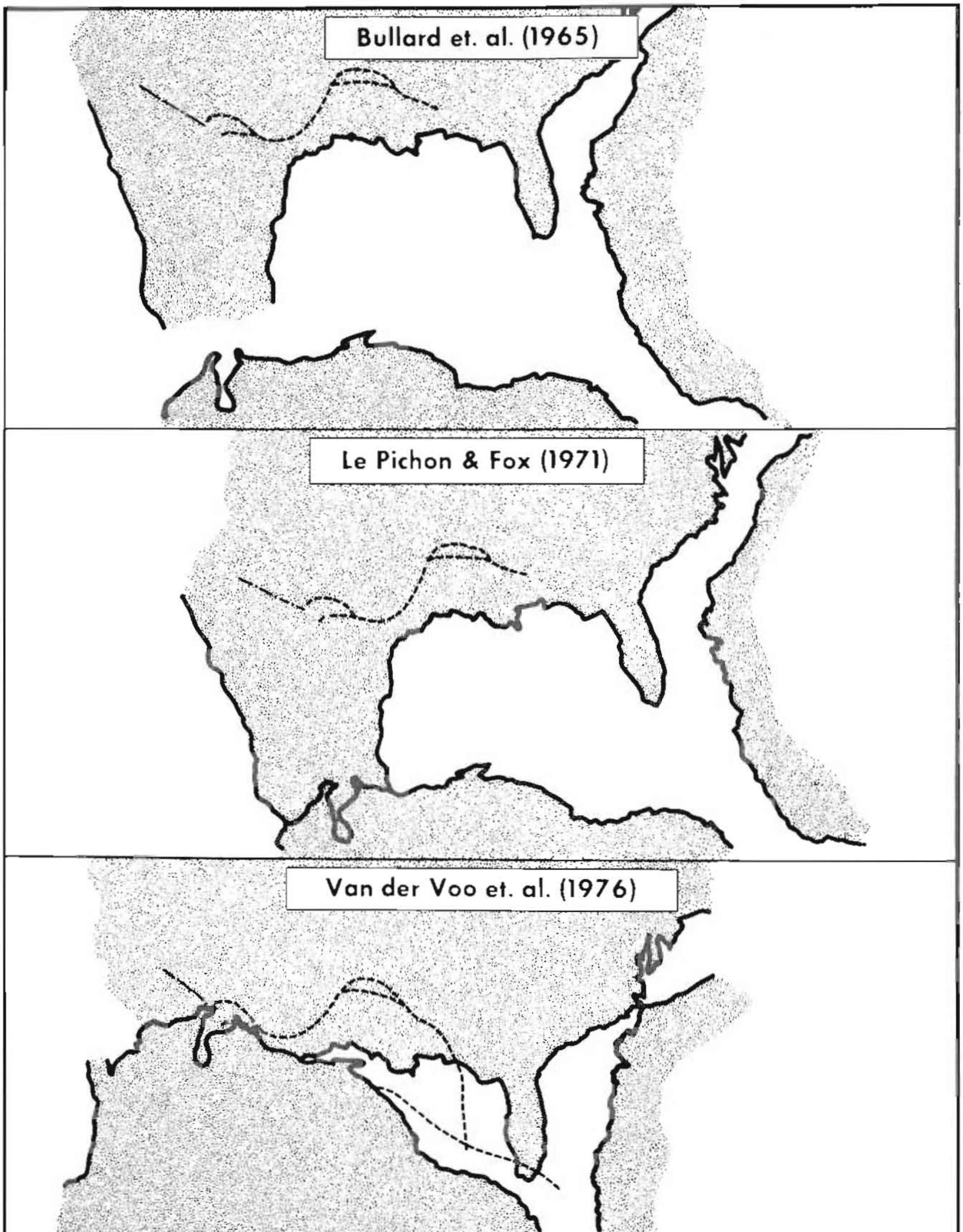



*Figure 1* *Three continental drift reconstructions to illustrate the starting conditions prior to formation of the Caribbean and Gulf of Mexico. A tight fit, such as Van der Voo's, leaves little room for objects such as Yucatan, but a loose fit can accommodate both Yucatan and Chortis on the site of the Gulf.*

# Appendix A: Research Plan

The four scientific themes outlined previously are discussed here in greater depth in order to emphasize the current levels of understanding, the outstanding problems and the approaches which the Project might adopt to solve them.

## A. Geological History of the Plate

### Island Arc Evolution

***Current Understanding*** The Caribbean plate is an exceptionally good area in which to study the evolution of the arc-systems that characterize convergent plate boundaries. Not only are there two contrasting active arcs in Central America and the Lesser Antilles, but the Greater Antilles provide a unique example of a complex arc system formed during the Cretaceous, only about 100 m.y. ago, and now, through later tectonics, exposed at levels ranging from those of the surface volcanoes and upperslope basin sediments to deep volcanic roots and metamorphic complexes. A similar tectonized Cretaceous arc complex, probably part of the same convergent system as represented in the eastern Greater Antilles is exposed in the offshore islands and coastal terrain of Northern Venezuela and was sutured to South America in Late Cretaceous time.

*Plate motions*

Understanding the historical development of the arc-systems of the Caribbean requires a clear idea of what the fit of the surrounding continents was before the floors of the Atlantic, Caribbean and Gulf of Mexico began to form. Of the three fits shown in Figure 1, the Bullard fit seems least likely to be accurate. The choice between the Le Pichon and Fox fit (several later published fits are close to this fit) and the Van der Voo fit depends on a number of as yet unresolved questions, such as whether the Chortis block of Central America came from within the Gulf of Mexico or from the Pacific. Van der Voo postulated a clockwise rotation of Africa and South America with respect to North America from his fit to that of Le Pichon and Fox in Triassic time. Whether there is any evidence for such a rotation is another unresolved question of Caribbean geology. Van der Voo's fit closes the Gulf of Mexico tightly and leaves no room for the Chortis block, which in that case must have originated in the Pacific. The Le Pichon and Fox fit leaves room for Chortis in the Gulf (White, 1980).

Evolution of the Caribbean since the time of its initial formation has been constrained by the motions of North and South America with respect to Africa. It is possible to display the continental motions by using, for example, the data of Sclater *et al.* (1977) to draw a line showing the track followed by South America with respect to North America through time (Figure 2).

As the figure shows, between about 165 and 125 m.y. ago (roughly throughout Jurassic time) South America moved away from North America and ocean floor formed at spreading centers on the site of the Caribbean. Between 125 and 65 m.y. ago (roughly throughout Cretaceous time) South America converged with North America and Cretaceous arc-systems formed (now exposed in the Greater Antilles and coastal Venezuela). During the older Cenozoic (65–36 m.y. ago), South America and North America diverged anew, South America has moved westward, over the last 36 m.y., neither converging with nor diverging substantially from North America.

*Arc structure*

The easterly movement of the Caribbean plate with respect to North and South America during the Neogene (displayed as strike-slip motion on both northern and southern margins of the Caribbean), has

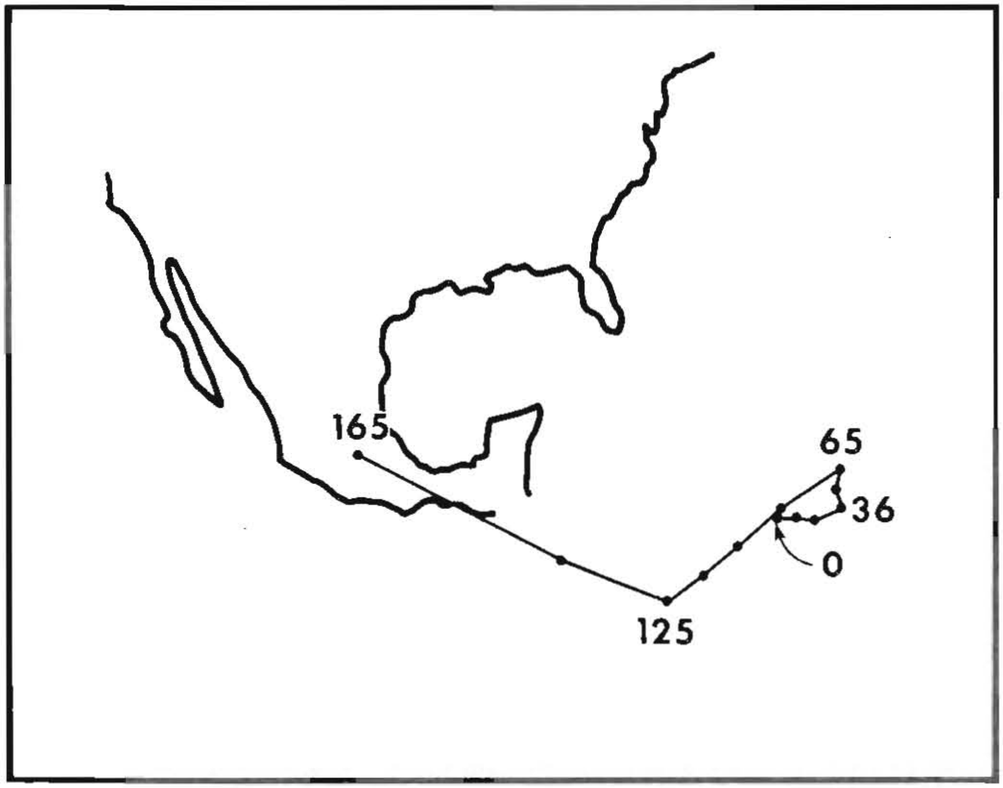



*Figure 2* *Motion of South America relative to North America since the Jurassic. Ages in m.y. compiled from Sclater et al. 1977. The place on the South American plate at the location today (0) has moved along the path indicated over the last 165 m.y.*

exposed the interior of the Cretaceous arcs due to secondary associated vertical movement. We have a unique opportunity in the Caribbean to study all levels of arcs formed as early crusts on a young ocean floor (100–50 m.y. old). During the project, geochemical, petrological and structural studies of arc anatomy will help to reveal how the processes of formation and evolution of arcs on an ocean floor operate. For example, Donnelly and Rogers (1980) have identified a suite of "primitive island arc" rocks in the northeastern Caribbean which they consider to be representative of the earliest stages of evolution. Comparative studies of the numerous ophiolitic fragments, particularly at the northern boundary, will constrain the local spreading histories and obduction events with which the Cretaceous arcs were intimately involved.

The later history of the Caribbean arcs that were formed in the Cretaceous involving strike-slip motions of hundreds of kilometers in complex plate boundary zones (Burke *et al.*, 1980) is of special interest. The structures formed in the later Cenozoic are exposed on-shore and are known offshore mainly from reflection seismic studies.

***Problems*** Two problems are of fundamental importance to our understanding of island arc evolution in the Caribbean. One is the pre-rifting configuration of the continents. This configuration is important because it defines the original crustal structure which the island arcs have subsequently modified. The second is that of the Mesozoic motions of the North American and South American plates with respect to Africa and with respect to each other. Although the approximate motions are known, details are not. It is difficult at present even to recognize the boundary between the North and South American plates in the North Atlantic.

Interpretation of the internal structure of the island arcs which formed during the Cretaceous requires that we be able to identify the effects of successive events which have since modified the arcs. The identification of such components: [i.e., the tectonic fabric of the arc basement, obducted ocean crust, high-pressure metamorphism, early (tholeiitic) and late (calc-alkaline) magmatism, uplift with block faulting, and strike-slip tectonism] has yet to be made in some areas. The integrated interpretation of these features over the full length of the arc is a challenging task.

For the Cenozoic arcs of Central America and the Lesser Antilles, the characteristics and ages of the underlying crustal structures are unresolved problems. The southward migration and uplift of the Central American arc which led to the closing of the Panama isthmus during the Pliocene is poorly understood, as is the possible involvement of Cretaceous island arc rocks beneath the northern Lesser Antilles.

***Approach*** It is of primary importance to review and reassess the relative motions of the North and South American plates with respect to Africa. In addition, field geological studies are needed to resolve the question of the pre-rifting split. Landsat, Seasat-SAR and, perhaps also, satellite-derived magnetic and gravity data may prove to be important tools in this respect.

The problem of the integration of onshore and offshore data in an area of strike-slip motion is difficult because different kinds of data are acquired in the two environments. Because the Caribbean islands expose so much well-dated Neogene sediment, onshore structures are correlated relatively easily with those offshore, where only reflection seismic and deep-sea drilling data exist. New techniques, such as SEASAT-SAR image interpretation onshore coupled with multi-channel seismic data offshore, may yield results that can be applied in other, more complex areas, such as coastal California and the Aegean.

Understanding the evolution of the Lesser Antillean arc requires integration of marine seismic studies of the Aves Ridge, Grenada Trough and the Atlantic margin of the Caribbean with on-island studies of stratigraphy, structure, petrology, volcanism and geochemistry. Opportunities for the use of satellite-derived data are less strong here than in the roughly contemporary Central American arc, where the arc overlies a much more extensive land area. Resolution of potential field data across the Lesser Antillean arc is more likely to prove feasible. Seasat-SAR data will be especially valuable because much of the terrain is normally cloud-covered.

## Temporal Changes in Tectonic Regimes

***Current Understanding*** The complexities of plate motions and associated phenomena have left a varied record in the structure and stratigraphy of the Caribbean. As Figure 2 shows, there have been obvious changes in the relative motions of the North American and South American plates. On a finer scale, the development of microplates has had a major impact on the tectonic history. Locating the pivotal points in tectonic development will help to focus attention on a) which are the important parts of the stratigraphic sections to study, b) the applicability of regional syntheses of tectonic interaction, c) the properties of the crust which behaved in this way.

The following are some of the more important tectonic events:

*Jurassic and Cretaceous*

The oldest, most deformed rocks are the most difficult to interpret and correlate. It is hard to distinguish significant tectonic events in the Jurassic and Early Cretaceous of the Caribbean. One possible exception is the Albian collision of the early Aruba-Blanquilla arc with South America (Maresch, 1974) which appears to be coincident with faulting and volcanism in both Guatemala and western Cuba, and with the Honduran folding and faulting reported by Mills and Hugh (1974). Similarly, the subduction-related magmatism and tectonism which occurred on almost all margins of the Caribbean during the Upper Cretaceous have not yet been correlated successfully.

*End of the Cretaceous*

This was a critical interval within the Caribbean. It is marked by the northward thrusting of ophiolitic rocks at the Motagua suture in Guatemala and in Pinar del Rio, Cuba (and later, in the Paleocene, in the rest of Cuba). This period was also crucial in the development of the Yucatan Basin, as by then it was bounded by Yucatan to the west and Cuba to the north. The magnetic history of the Yucatan Basin rocks should reflect this event. The final suturing of the southern Antillean arc onto the Venezuelan mainland took place at this time.

*Medial Eocene and the development of the Cayman Trough*

Within the western Caribbean, magmatism and tectonism continued during the Paleocene and Earlier Eocene in Oriente (Cuba), Jamaica, Cayman Ridge, E. Panama and Santa Marta, Colombia, although the style was different from that of earlier events and involved NW-SE graben tectonism in Jamaica. The Medial Eocene saw the last major magmatism on the northern and southern boundaries of the Colombian Basin. At this time on the northern and southern boundaries of the Venezuelan Basin, there existed obviously different tectonic regimes. To the south, strong N-S compression produced southward overthrusting on the Paria peninsula and folding of the deep-water clastic sediments of Barbados and Grenada. No such tectonism is seen in the north, although calc-alkine magmatism within NW-SE fault zones lasted into the Oligocene in Puerto Rico. This suggests different styles of behavior of the Northern and Southern American plate boundaries at this time.

The growth of the Cayman Trough is the most important geological development during the Cenozoic history of the Caribbean. The age of its initiation is not well constrained, but its determination is of primary importance. Inasmuch as the Trough developed by splitting the length of the Cayman Ridge-Nicaraguan Rise volcanic arc (Perfit and Heezen, 1978), its maximum age is defined by that of these arc rocks. Thus the initiation of the Trough is unlikely to have occurred before the medial Eocene (45 m.y. ago).

*Medial Cenozoic*

Towards the end of the Oligocene and the beginning of the Miocene, Panama and Costa Rica underwent tectonism which seems to have been shared by N.W. Colombia (Dugue-Caro, 1979). Farther east, in the Falcon Basin of Venezuela, extensional basin subsidence and alkaline magmatism were occurring (Muessig, 1978). Within the Greater Antilles, the fore-arc basin that had been developing to the north of the Cordillera Central in Hispaniola became uplifted (Lewis, 1980).

*Late Miocene*

At about 9–10 m.y. ago, there occurred a well-defined change of plate-spreading directions around the Caribbean, which was reflected by major tectonic events within the plate, although the dominant eastward motion of the Caribbean plate continued with respect to the American plates. The northern half of the Lesser Antilles arc jumped westward. The dramatic uplift of the block-faulted seafloor in the Southern Peninsula of Haiti occurred at this time (Mascle *et al.*, 1980; Maurasse *et al.*, 1980). At the southern margin of the plate with South America a series of microplates developed: the Santa Marta, Bonaire (Silver *et al.*, 1975) and Paria (Vierbuchen, 1979) blocks. The slow underthrusting and uplift of N.W. Colombia (Bonini *et al*, 1980) may have begun together with the equivalent underthrusting of the Venezuelan Basin beneath the Muertos and Curaçao Troughs.

*Late Pliocene*

The continental margin rocks of Colombia and Venezuela display the strongest expression of Late Pliocene tectonism although the effects in Hispaniola and Jamaica were nearly as great. The spreading rate in the Cayman Trough appears to have decreased by a factor of two at this time (2.5 m.y. B.P.)(MacDonald and Holcombe, 1978).

***Problems*** Deep-sea drilling within the Caribbean has shown that the Upper Cretaceous tholeiitic basalts below B″ within the Colombian and Venezuelan Basins apparently were being erupted at later periods in some places than others. Whether the initiation of this igneous activity was uniform over large areas is of great interest. In the last five years considerable multichannel seismic reflection data have been collected from these two basins. Computer processing to achieve optimum imaging, hence, optimum depth and reflector resolution, is expensive. Some early results from the Venezuelan Basin have been published (Talwani *et al.*, 1977; Biju-Duval *et al.*, 1978; Ladd and Watkins, 1980), but the definitive work in the early stratigraphy of the Colombian Basin (and possibly the Venezuelan Basin as well) is yet to be done. The timing of the initiation and cessation of episodes of subduction during the Late Cretaceous has been deduced locally. Attempts to synthesize local events into a coherent regional picture have had only limited success, partly because the detailed stratigraphy has not been available or cannot readily be correlated with neighboring areas. This is particularly true for the correlation of events in the Greater Antilles with those at the northern margin of South America.

The principal tectonic events during the Cenozoic are easier to recognize than those of the Cretaceous. In most of the known events cited above, however, correlation across the Caribbean as a whole is known only in the most general terms. The strength and direction of the changes in stresses associated with these events have received little study. For instance, the earliest history of the Cayman Trough is obscure, and the response of the adjacent landmasses, particularly of Cuba, at this time needs to be carefully evaluated.

***Approach*** Research efforts in progress at Lamont-Doherty Geological Observatory of Columbia University and at the University of Texas Marine Geophysical Laboratory are intended to provide better answers to the key questions of the age and nature of any pre-B″ volcanic events. Helping to solve this problem should be an objective as well as a result of the Caribbean Plate Project. Considerable attention, using the most advanced analytical techniques, should go into getting the best interpretations of rock types, time stratigraphy, and structural geometry from the sub-B″ interval.

In addition to the more obvious methods of stratigraphic and magmatic correlation of events during the Late Cretaceous, metamorphic rocks with their P/T mineral assemblages and tectonite fabrics offer one of the best means of identifying and correlating such events. Such rocks are common in the southeastern Caribbean (Tobago, Trinidad, Northern Venezuela and the Venezuela Antilles) and in the Greater Antilles (Jamaica, Cuba and the Dominican Republic).

The dating of sedimentary rocks by palaeontological methods has long been a mature science in the Caribbean, largely because of the efforts of scientists working in the petroleum industry in Venezuela, Trinidad and the Gulf of Mexico. This means that it is commonly possible to assign a geologic age to strata in the Caribbean with some degree of precision. Major efforts to further improve the resolution of geologic age determinations are now being made by members of the City Museum of Basle, Switzerland, and of the Institut Francais du Petrole in conjunction with the Smithsonian Institution and the National Science Foundation, and working in collaboration with scientists from several Caribbean nations.

As members of the project attempt to establish the geologic history of the Caribbean they will be able to make use of a full set of stratigraphic data. It is anticipated that work during the project will reveal areas and times for which more complete information may prove particularly useful in defining the timing of regional tectonic events. The alliance of the remote sensing approach with ground-based stratigraphy and tectonic analysis has already proven to be a valuable tool in Panama. Workers such as Wing (1971) and MacDonald (1969) were able to synthesize scanty, poorly-correlated ground data obtained in difficult terrain into a coherent regional picture using airborne radar. Such an approach can yield important results by focusing on areas where the timing of major changes in tectonic regime can be more precisely resolved by stratigraphic means.

The Cayman Trough is the key to understanding the Cainozoic history of the northern part of the Plate. Slight variations in relative plate motions are reflected in the structure of the Trough floor and boundaries (Sharman *et al.*, 1981) and integration of this record with the neighboring onshore tectonics will be of great value locally and possibly plate-wide.

## B. Characterization of the Plate Interior

In the following discussion the interior of the Caribbean plate is defined as the oceanic portion of the plate underlying the lower Nicaraguan Rise, the Colombian Basin, the Beata Ridge, and the Venezuelan Basin, away from the plate margins which coincide with the continental and island margins of South and Central America and the Greater Antilles. Not included are the Aves Ridge, which may have been a plate margin in pre-Eocene time; the Grenada Basin; and nuclear Central America/upper Nicaraguan Rise, which include areas of island arc and continental crust.

***Current Understanding*** Early seismic reflection lines revealed that sediments overlying most of the interior of the Caribbean plate contain two widespread and persistent reflecting horizons, termed horizons A″ and B″ (Ewing *et al.*, 1968). Drilling provided startigraphic control for these reflectors: where drilled, horizon A″ represents the upper surface of lithification of deep-sea oozes, within an interval containing chert horizons, dated as early as Eocene; horizon B″ represents the occurrence of oceanic basaltic rocks overlain by sedimentary rocks of middle late Cretaceous age (Turonian-Coniacian) (Edgar and Saunders, 1973). The drilling also established a minimum age of late Cretaceous for the crust of the Caribbean plate. Later studies of the extent of the post-horizon-B″ sediment section strongly indicated that the plate interior, although deformed locally, has maintained its integrity since at least the late Cretaceous—that is, large-scale destruction or creation of lithosphere has not occurred (Holcombe, 1977).

Refraction results reveal sub-B″ rocks, which yield a range of P-wave velocities typical of oceanic crust (4.0–7.5 km/sec) and which are thicker by a factor of two than "normal" ocean crust (Ludwig *et al.*, 1975; Edgar *et al.*, 1971). Basalts and dolerites, recovered by drilling, provide stratigraphic control for the top of this interval. The interior of the Caribbean plate yields free air gravity anomalies near zero, as is typical of ocean basins away from active plate margins (Bowin, 1976). Heat flow through the floor of the Caribbean interior is predominantly within the range of 1.0 to 1.7 HFU, or "normal" for oceanic regions away from spreading centers (Epp *et al.*, 1970).

A key factor in interpreting the post-formation history of the Caribbean plate interior is determining the orientation of the original Caribbean plate fabric as it relates to rifting of the seafloor, accretion, and the formation of fracture zones. The structural fabric developed in the interior of the Caribbean plate shows two preferred orientations, NW-SE and NE-SW (Case and Holcombe, 1980). Reasonably, one could assume that one of these directions represents the orientation of the rifted and faulted ridge-valley basement surface, and that the other direction represents the fracture zone direction. Subsequent changes in the stress regime applied to the plate might result in rejuvenation of structural displacements along the original trends. MacDonald (1980) has proposed that the NE-SW direction, which corresponds to the trend of the Beata Ridge and the Hess fracture zone, represents the fracture zone direction. Attempts to derive the direction of seafloor accretion through study of magnetic residual anomaly patterns have been hampered because of the low amplitude and poor definition of anomaly patterns and the lack of any reliable reference point in time for crustal age. Even so, a NE-SW-trending residual anomaly pattern has been recognized tentatively in the central Venezuelan Basin (Donnelly, 1973; Watkins and Cavanaugh, 1976), and an E-W pattern has been noted in the Colombian Basin (Christofferson, 1976).

Interpretation of later stresses acting on the Caribbean plate and resulting motions would need to agree with the relative North America/South America movement as reconstructed from North America-Africa and South America-Africa motions (Figure 2), and with the geology as recorded in the rocks of the circum-Caribbean region. The most recent episodes would need to take into account estimates of present-day plate motion (Jordan, 1975) and the evidence of large-scale eastward displacement of the Caribbean plate in post-Eocene time. Burke *et al.* (1978) have attempted a reconstruction of Caribbean plate history in which they noted that the fabric of the plate interior might reasonably represent structural effects of N-S compression across the plate, for which there is ample evidence. Intriguing questions arise as to whether a pre-existing plate with its own preferred fabric would be deformed structurally in a manner such that the new fabric would reliably reflect the more recent stresses.

A crucial problem is the age of the Caribbean plate. Evidence that the basalts encountered in drill holes are sills (Donnelly, 1975), that the "magnetic" basement beneath the Venezuelan Basin lies considerably beneath these basalts (Donnelly, 1973), and that the smooth sediment-like nature of horizon B", together with suggestions of sub-B" reflectors implies pre-B" sedimentation (Ewing *et al.*, 1968) have led to the general conclusion, that drilling has not established the time of formation of Caribbean crust precisely. Few meaningful constraints are placed on the age of the plate by what is known of the post-formation history of plate movement in the region.

The highest-resolution refraction results yet obtained in the Caribbean (Ludwig *et al.*, 1975; Stoffa *et al.*, 1981) are compatible with the interpretation that a substantial thickness of stratified material (e.g., flood basalts, high-velocity sedimentary rocks, or both) overlies the original oceanic crust, which is of "normal" thickness. Burke *et al.* (1978) and Fox and Heezen (1975) favor a massive flood basalt episode. On the other hand, Talwani *et al.* (1977) concluded tentatively from a study of multichannel seismic reflection data that horizon B" lies at or near the surface of original oceanic basement, and Christofferson's (1976) model of seafloor accretion, based on magnetic anomaly patterns, requires creation of Caribbean lithosphere in the Late Cretaceous.

Seismic evidence for the existence of lateral discontinuities separating areas of crust of different thickness and age (Biju-Duval *et al.*, 1978; Ladd and Watkins, 1980) is increasing, which suggests that the Caribbean has had a history of plate construction more complex than that indicated by DSDP drilling. Discussion of this question will continue until positive stratigraphic control is obtained by drilling. A recent decision was made not to attempt drilling the pre-horizon B" section of the Venezuelan Basin, on the upcoming IPOD leg, due to technical reasons and high risk factors. This decision postpones acquisition of the necessary stratigraphic control.

***Problems*** Within the context of an exhaustive study of the nature and evolution of the Caribbean plate, the plate interior is the logical place to study gross physical properties and bulk composition of the plate, away from complicating effects of the plate margins. As previously discussed, some constraints have been placed on the age and fabric of the plate and on the thickness of the crust. A major, integrated study of all available evidence and theory concerning composition and physical/elastic properties would be a major contribution to understanding the gross physical character of the Caribbean plate. This new knowledge could be applied to the solution of problems concerning the behavior of the plate at its margins.

Such a study would address the following questions:

(1) Is the Caribbean crust of anomalous thickness or is it of normal thickness, but overlain by flood basalts or a combination of sedimentary rocks and volcanic rocks? What is the best estimate of the age of the Caribbean crust?

(2) How thick is the lithosphere of the Caribbean plate? Is it underlain by a low-velocity seismic zone?

(3) What is the best guess for the gross composition of the Caribbean lithosphere? Is it anomalous in composition and physical properties with respect to other oceanic regions?

(4) What are the best estimates for variations of density, rigidity, temperature and other physical properties with depth?

(5) What do the best estimates of physical and chemical composition of the lithosphere suggest concerning the question of whether the Caribbean plate is stationary or moving with respect to the mantle beneath the lithosphere?

(6) What would be the predicted response of a plate with the above properties to external stress? To what degree would it behave as a brittle or as a plastic entity?

(7) What forms of magmatic differentiation would be expected to occur in a plate having this composition and these properties? Is there some particular aspect of property or composition which would make the Caribbean plate particularly susceptible to flood-basalt events?

The end result of such a study would be the development of a reasonable integrated model or models for the thickness, age, composition, and physical properties of Caribbean lithosphere. Development of such a model for the interior of the Caribbean plate is the focal problem toward which all studies specifically concerned with the interior of the Caribbean plate should be addressed.

***Approach*** Development of reasonable "columnar section" models necessitates the integration of state-of-the-art theory and best available data and data analysis in the fields of petrology, seismic wave propagation, source and budget of earth's heat, and mass distribution. An interdisciplinary group will need to be involved. Many of the properties which need to be predicted are unobservable or too expensive to observe. In other cases these properties can be studied only through the interactions associated with the plate boundaries. The rigidity of the plate under applied boundary stresses can be tested by VLBI and by satellite laser ranging techniques. A relatively small network of monitoring stations would be required, and could be tied to the measurement of local boundary deformation discussed in the next section (C).

The northwestern Caribbean contains many scattered centers of Late Cenozoic volcanism which cannot be related directly to conventional plate boundary magmatism. Much of this intraplate magmatism consists of alkali basaltic volcanism (Figure 4) whose parental magma source must be the sub-Caribbean-plate mantle. Study of these rocks may define the chemical character and thermal state of the mantle beneath at least one quadrant of the plate (Wadge and Wooden, 1982).

Investigative efforts in two subject areas which will require the acquisition and analysis of remotely-sensed data will be encouraged.

*Gravity field and magnetic field*

Satellite sensing of geoid height yields new and better information regarding the vertical and horizontal distribution of mass deep within the lithosphere. GEOS-3 radar altimetry data best display the medium and long wavelength anomalies of the deeper mantle. Residual geoid anomaly maps can be constructed and correlated with major geologic structures in the Caribbean (Bowin, 1980). SEASAT's higher resolution data should improve definition of the shallower, shorter-wavelength features of the geoid. "Synoptic" measurement of the longer-wavelength features of the earth's magnetic field from MAGSAT should also provide new and useful information about the depth, thickness, and susceptibility of magnetic source rocks, particularly when compared with marine and aircraft magnetic data. Efforts to obtain maximum resolution of these two parameters, using upward and downward continuation techniques, seem to have great potential for imposing constraints on columnar models of Caribbean lithosphere and for comparison of gross properties of Caribbean lithosphere to other oceanic regions, for example the Philippine Sea and Ontong-Java Plateau areas, which may have had similar histories of plate formation and/or evolution.

*Investigation of mantle properties through analysis of seismic wave propagation*

Investigation of seismic wave propagation through the interior of the Caribbean plate may detect the presence of a low-velocity zone at the base of the lithosphere, and should yield reasonable velocity-depth models from which various elastic property models can be derived.

Such an investigation would be particularly promising if, in the course of studies of seismic events along the plate margins, seismic stations around the perimeter of the Caribbean are tied together via real-time telemetry links.

*Body waves*

The analysis of travel times for direct and refracted arrivals of body waves yields direct information about compressional and shear wave velocities in the crust and very upper mantle. Officer *et al.* (1959) summarized much of the data collected for the eastern Caribbean; no fewer than 9 profiles provide average velocities of the crustal portion of the Venezuelan Basin. Similar data exist for other Caribbean basins. These results do not provide sufficient information, however, about the upper mantle, which comprises much of the lithosphere of the Caribbean plate.

A high frequency wave called $P_n(S_n)$ can provide constraints on the average velocity of the lithosphere. This wave, which propagates as a channel wave, samples much of the upper mantle and is channeled by the presence of a low-velocity zone at the base of the lithosphere (Menke and Richards, 1980). The observation of these travel times may reveal a velocity anisotropy in the mantle. Studies in oceanic crust formed at mid-oceanic spreading centers indicate that body wave velocities in the upper mantle are dependent upon azimuth. Phase velocities of these waves are fastest in the direction normal to the strike of the spreading axis at which the material was created (Shor *et al.*, 1980). As the present-day orientation of the original fabric of the Caribbean plate is unknown, the study of P and S waves may provide key information bearing on this problem.

To this end, sources of earthquakes in the Caribbean can be observed by any number of short-period stations distributed around the perimeter of the plate. The most complete coverage by seismic receivers now is found in the eastern Caribbean, surrounding the Venezuelan Basin. While cooperation now exists between the organizations operating these networks, a real-time telemetry link between the various recording sites would greatly facilitate analysis of data.

*Surface waves*

Rayleigh wave and Love wave dispersion studies provide constraints on the upper mantle structure, presence or absence of a low-velocity zone, and seismic wave anisotropy in the lithosphere, all of which reflect the origin and evolution of a region.

Both single-station and two-station techniques (Brune *et al.*, 1960) could be used to determine surface wave phase velocities for paths crossing the Caribbean plate. The two-station technique requires finding events located such that two stations lie along the same path from an earthquake. This method would use seismic events located outside the Caribbean plate. For example, Kafka (1979) has used this method to estimate Rayleigh wave phase velocities across the Caribbean using events located along the mid-Atlantic ridge. The single-station technique requires knowledge of the focal mechanisms and depths of the events used. If these source properties are known, then the initial phase at the source can be calculated, so the phase velocity can be determined along the path from the event to the station. This method uses events located along the edges of the Caribbean plate and stations on the opposite side of the plate from the events.

Forsyth (1975) determined Rayleigh wave and Love wave phase velocities in the eastern Pacific and found that both a systematic increase in velocity with increasing age of the seafloor and anisotropy in the elastic properties were required to satisfy the data; he interpreted these results in terms of the structural evolution of the oceanic lithosphere. A similar study could be performed in the Caribbean region.

Surface wave studies in the Caribbean region offer an additional feature which may further constrain the upper mantle structure. Specifically, both the eastern and western boundaries of the plate exhibit a wide depth distribution of hypocenters. As earthquake depth increases, the relative excitation of higher mode to fundamental mode Rayleigh wave increases. If these different modes can be properly identified and separated, then their respective phase velocities can be determined. Such information would enhance the resolution and accuracy of the deduced upper mantle properties.

## C. Active Processes at the Plate Boundaries

### Structural and Tectonic Variations

***Current Understanding*** Plate boundaries are the sites along which accommodation of relative motions between adjacent plates takes place. In applying plate tectonic theory, two simplifying assumptions are usually accepted. One is that the lithosphere is rigid except at specific boundaries at which the displacements occur. The second is that a boundary must be one of three types: accretionary, convergent, or transform. If these assumptions were correct, we would expect the deformation occurring at plate boundaries to have simple patterns and for the locations of the plate boundaries to be readily identifiable. In some parts of the earth, including the Caribbean, neither of these expectations is met, so it has proved difficult to define precisely the locations of some plate boundaries at the present time. The concept of "plate boundary zones" in areas of convergence and transform motion has proven useful in this respect, both at the northern boundary (Burke *et al.*, 1980) and the southern boundary (Kafka and Weidner, 1981).

Although the global interpretations of plate boundaries provide an important framework within which to analyze local geologic features, they may not be particularly helpful in explaining the geology observed at the earth's surface. Global seismicity studies, for example, locate plate boundaries to an accuracy of ± 250 to ± 100 km in regions of thick lithosphere, such as beneath continents and island arcs, where deformation commonly appears to be distributed more broadly than at spreading centers, where the lithosphere is only a few kilometers thick. A more accurate identification of structural features and tectonic behavior than ± 100 km is required for hazard prediction and for a more satisfactory understanding of the behavior of the earth.

Evidence of modern tectonic activity in the Caribbean is supplied by large variations in topography from deep-sea trenches to high mountains, by linear chains of volcanoes, by a high degree of seismicity, by large negative and positive free-air gravity anomalies, by geoid anomalies, by high heat flow in some localized areas, and deformed and uplifted young sedimentary layers. Usually, the patterns shown by these features display large variations in magnitude along the presumed plate boundaries. An estimate of seismic potential based on historical seismicity (Figure 3) illustrates the scale of this variability around the plate boundary.

There are locations where data suggest that there is significant tectonic activity, while in other locations there is very little. With the identification in recent years of the Mid-Cayman spreading center, the once puzzling decrease in intensity of seismicity in the Cayman Trough region and the shift in location of what seismic activity does occur from the north side of the east end of the Trough to the south side at the west end have become better understood. The Mid-Cayman spreading center trends nearly north-south across the center of the Trough. For the most part, however, the irregular patterns of activity indicated by the various types of data remain enigmas.

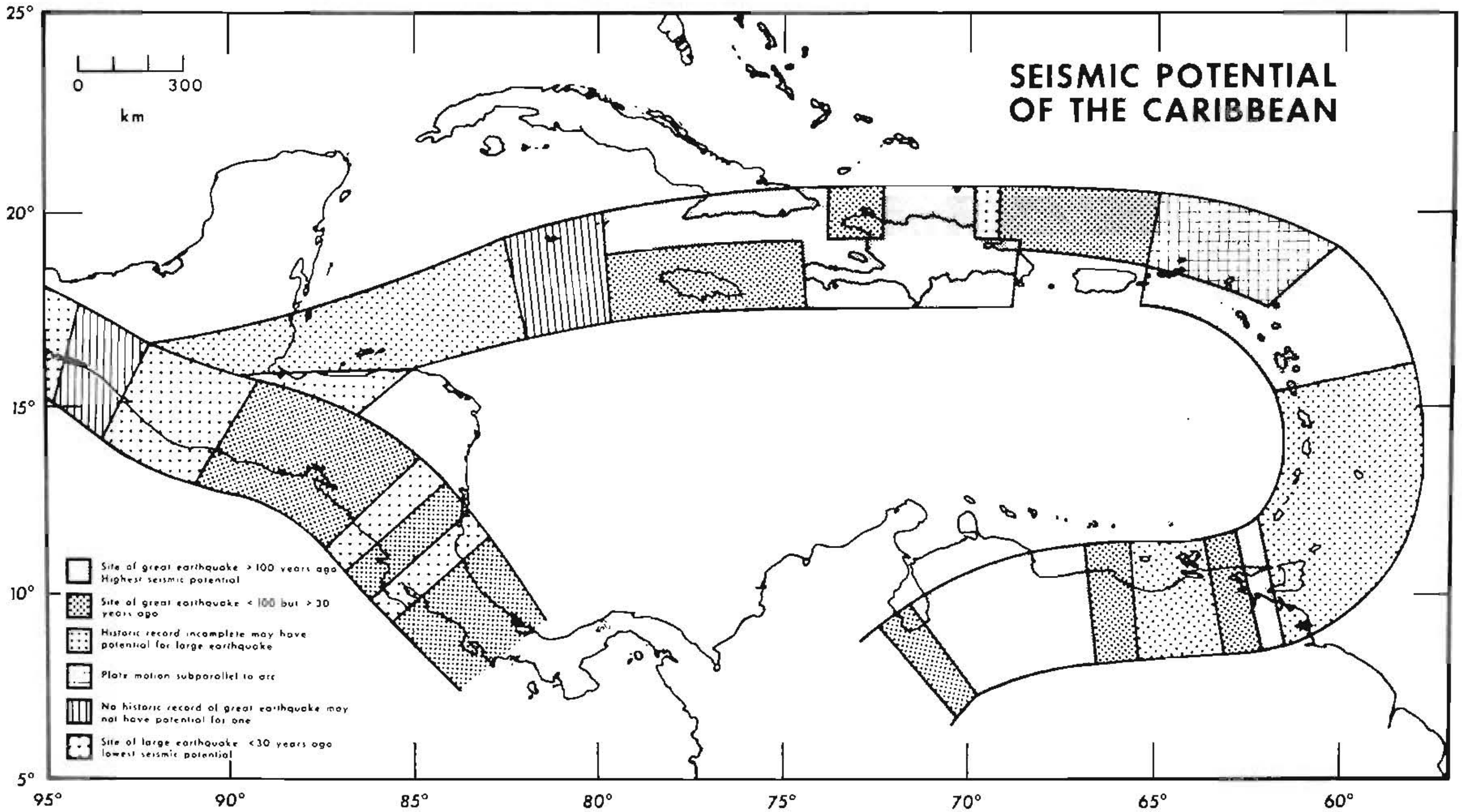



*Figure 3* *Seismic potential of the Caribbean plate boundaries based on historical seismicity after McCann et al. (1979). No estimates of potential are made for the Panama-Colombia section.*

***Problems*** The positions of plate boundaries in the Caribbean must be identified more precisely both at the surface and at depth. Particular attention must be directed towards boundaries which are poorly defined, or complex. Among the more pressing of these problem boundaries are the following:

(i) Northern Hispaniola where a short zone of convergence appears to correspond with a major change in the direction of strike of the Cretaceous island arc rocks.

(ii) Western Guatemala where the potentially unstable triple junction between the Caribbean, North American and Cocos plates is located.

(iii) Panama's northward curvature into the Caribbean. This is difficult to reconcile with the eastward motion of the Nazca plate to the south without invoking non-rigid deformation (Bowin, 1976).

(iv) The very poor definition of the Caribbean plate's boundary with the South American Andean system in Colombia (the Bucaramanga segment of Pennington, 1979).

In addition to improving the areal definition of these boundaries, we need to develop additional concepts that will be useful in understanding how local anomalies deform in response to stresses produced by plate motions. In particular, refined modeling of transpressional and transextensional tectonism, sedimentation and magmatism needs to be applied locally and integrated along the whole boundary.

***Approach*** The data from local seismic networks in crucial areas such as Hispaniola, Central Guatemala, Panama and N.W. Venezuela are of paramount importance in determining the geometry and magnitude of current plate boundary tectonism. Characterization of the fine-scale structure of the plate boundaries will require monitoring of local telemetered seismic networks. The Caribbean plate boundaries are rich in such networks (Table 1). The information likely to accrue from these networks during the project should be integrated as thoroughly as practicable. Satellite relay of this information to a single receiving station would be very beneficial to the rapid analysis of the seismicity.

The large variations in magnitude or intensity of seismicity, gravity and geoid anomalies, and in topography along the plate boundaries in the Caribbean region, together with the varied geology exposed at these boundaries, make these boundaries particularly significant. A large amount of information is already available for this region, and further field studies are underway at several of the anomalous portions of the Caribbean plate boundaries. Together with the new radar altimetry, satellite magnetic measurements (MAGSAT), SAR, and multispectral image data, this information can be integrated in a comprehensive examination of the problem of understanding the irregularities of deformation along active plate boundaries. For example, combinations of orbital radar altimetry (GEOS-3 and SEASAT) data with surface land and marine gravity measurements will allow better definition of mass anomalies both areally and with depth than previously possible. This in turn will improve our ability to determine the relationships between mass anomalies and tectonic variations. Coordinated investigations of the geology, petrology, and chemistry of critical regions, together with analysis of SAR and multispectral data by image processing techniques, should provide constraints on temperature and depth relations in the boundary zone during formation of magma and metamorphic rocks, as well as reveal the structural setting and mechanism by which such rocks were later uplifted to the surface.

Current crustal deformation can be measured by VLBI and laser ranging techniques using small instrument networks crossing areas of known or suspected "boundary zone" deformation. When coupled with plate-wide geodetic measurements, such information will contribute to models of the development of localized boundary stress fields in response to gross plate motions, which will be applied to earthquake hazard evaluations.

**Table 1** Seismic networks in the Caribbean Area.

| Country | Area Covered | No. of Stations | *System Descriptions | Date Installed | Current Status | Organization |
|---|---|---|---|---|---|---|
| Colombia | | | *BOG*† | | | |
| | | 9 | | | | Inst. Geofisica de Andes |
| Costa Rica | Northern C. R. | 10 | R, Hi | May, 1974 | Active | Inst. Costarricense de Electricidad, and Univ. of Texas |
| | Geothermal | 5 | R, Hi | June, 1977 | Active | Same as above |
| | Southern C. R. | 7 | R, Hi | June, 1980 | Planned | Same as above |
| Cuba | | 3 | Lo | | Active | Academy of Science, Havana |
| Dominican Republic | North central | 7 | R, Hi | Dec., 1979 | Active | Corporacion Dominicana de Electricidad and Univ. of Texas |
| | South-Southeast | 7 | R, Hi | July, 1980 | Planned | Same as above |
| El Salvador | | | *LPS*† | | | |
| | National | 12 | R, Hi | August, 1980 | Planned | Centro Investigaciones de Geotechnicas |
| | | 6 | R, Hi | | Planned | Comision Ejecutiva Hidroelectrica del Rio Lempa (CEL) and Univ. of Texas |
| Guatemala | Central to Southern Guat. | 15 | R, Hi | Circa 1974 | Active | INSIVUMEH |
| | Northern Central Guatemala | 7 | R, Hi | Jan., 1979 | Active | Inst. Nacional de Electrificacion and Univ. of Texas |
| Haiti | | 2 | | | | |
| Jamaica | | ~5 | | | Active | Seismic Research Unit, Univ. of West Indies |
| Nicaragua | National | 14 | R, Hi | Circa 1975 | Active | |
| Panama | | | *BHP*† | | | |
| | Western Panama | 11 | R, Hi | Nov., 1980 | Planned | Inst. de Recursos Hidraulicos y Electrification (IRHE) and Univ. of Texas |
| Puerto Rico | | | *SJG*† | | | |
| | National | 14 | R | 1974 | Active | USGS-Puerto Rico Electrical Authority and Univ. of Puerto Rico |
| Trinidad | | | *TRN*† | | | |
| | British Lesser Antilles | ~30 | Partial R | | Active | Seismic Research Unit, Univ. of West Indies |
| Venezuela | | 9 | | | Active | In addition, a multi-million dollar program for the national network is being planned. |
| Virgin Islands | Antigua to Eastern Puerto Rico | 17 | R, Hi | March, 1975 | Active | LDGO |
| French West Indies | Guadeloupe to Martinique | ~8 | | | Active | Institute de Physique de Globe Univ. of Paris |

* "R" Indicates the network is equipped with the radio telemetry system and central recording capability.

† Identifying station abbreviations of the World-Wide Standardized Seismic Network.

## Variations in volcanism

***Current Understanding*** Active subduction occurs both in Central America and the Lesser Antilles (and possibly beneath N. E. Hispaniola), but there are major differences between the two main zones. These differences include the following: 1) the Lesser Antilles is an arc, while Central America is nearly linear, 2) subduction is oblique to the spreading ridge in Central America, but nearly parallel in the central Lesser Antilles, 3) the distance from trench to volcanic front is much the greater in the Lesser Antilles, 4) old continental crust underlies northern Central America, but there is no such continental crust in the Lesser Antilles, 5) there is a more rapid rate of convergence in Central America.

A list of contrasting structural and volcanic features of the two active Caribbean volcanic arcs is presented in Table 2. Figure 4 is a map of the main volcanic centers.

Products of volcanism are typically calc-alkaline in nature in both regions. The geochemistry of the Lesser Antilles has been reviewed by Brown *et al.* (1977) and a similar recent general treatment of Central America is given by Carr *et al.* (1981). Divergences from the normal calc-alkaline character have received more attention in the literature of the Lesser Antilles, partly because of the superimposition of very different rock types on individual islands [e.g., Grenada, Arculus (1976)]. The spatial distinction between the volcanic front association (basalt-andesite-dacite), the rhyolite calderas, the bimodal areal volcanism, and the scattered alkalic volcanism is more obvious in Central America (Figure 4), although the origins of these magmas are largely undefined. However, a recent synthesis of the Lesser Antilles by Westercamp (1979) attempts to demonstrate that the occurrence of silica-saturated and undersaturated alkaline basalts is related to NE-SW transverse breaks in the arc which dominate the southernmost islands (Figure 4). Also, the assignment of a tholeiitic character to the rocks of the northern Lesser Antilles by Brown *et al.* (1977) has been disputed by both Smith *et al.* (1980) and Westercamp (1979).

Variations in the geochemistries of present-day magmas along the length of the volcanic front in Central America can be explained primarily by processes of shallow-level crystal fractionation. There are some exceptions to this explanation, such as the systematic decrease in $Na_2O$ content from Guatemala to

**Table 2** Comparison of Central American and Lesser Antillean Volcanism.

| | Central America | Lesser Antilles |
|---|---|---|
| *Structural* | | |
| | Subaerial arc | True island arc |
| | ~40-60° dip of Benioff zone | ~40° Benioff Zone |
| | 300-100 km spaced transverse breaks | ~50 km spaced transverse breaks |
| *Volcanic* | | |
| | ~80% products on land | ~20% products on land |
| | Volcanic front jumps transversely | 'Permanent' loci of volcanism |
| | High rate of magma output | Low rate of magma output |
| | Major rhyolitic caldera in N. | No true rhyolitic volcanism |
| | | No true calderas? |
| | Fields of bimodal volcanism in N. | |
| | Adventive eruptions | Characteristic development of lava domes at volcano summits |
| | Some volcanoes in state of persistent activity | Seismic swarms beneath volcanoes outnumber magmatic eruptions |

Nicaragua, which is presumed to be controlled by crustal structure. Cyclical evolution of shallow, fractionating magma systems with a tendency to increasingly evolved character with increasing maturity and size of the volcano have been recognized in Central America (Rose *et al.*, 1977; Mayfield *et al.*, 1981). Common cumulate nodules in Lesser Antilles magmas demonstrate the importance of crystal fractionation (Arculus and Wills, 1980). The eruption of mixed tephras (Carey and Sigurdsson, 1978) and the hypothesis of Westercamp (1979) which is that some Lesser Antilles calc-alkaline magmas are remelted from crystalline quartz diorite bodies at depths of 5–7 km, indicate growing awareness of the complexities of shallow magmatic processes.

***Problems*** Four topical problems in Caribbean volcanism have been identified:

*Rates of magma accumulation and eruption*

Historic records of volcanism in the two arcs are very different. Only three volcanoes in the Lesser Antilles have produced substantial quantities of juvenile magma, compared with about 15 volcanoes in Central America during the last 300 years. The total cumulative volumes of magma extruded are also very much greater in Central America, even after compensating for the greater length of arc. This could mean: (a) that very much more magma never reaches the surface in the Lesser Antilles, (b) this disparity is merely "noise" which would be removed over a longer period, or (c) that there is a higher rate of magma production beneath Central America which is reflected in the volume emitted.

There are several indications that (b) is incorrect and that the ratio of magma output at the two arcs throughout the last 100,000 years may have been similar to the historic ratio. If (c) is true, there is the interesting possibility that the difference may be wholly or partly due to the relative rates of plate convergence, which are greater between the Cocos and Caribbean plates than between the American and Caribbean plates.

*Eruptive gases and particles*

Studies of eruptive gases and particles are of obvious importance to theories concerning the earth's atmosphere, and also allow us to learn about the volcanoes and their eruptive mechanisms. Results of studies on the Mount St. Helens eruption have changed our ideas about which volcanoes may have the most profound impacts on the atmosphere. The effect on the atmosphere of silicate particles from the St. Helens eruption was much less significant than was anticipated, and the main long-term effects have been attributed to sulfate particles derived from magmatic $SO_2$. It seems especially important now to find out more about the volatile concentrations in various magmas. We also know far too little about the escape of volatiles during passive emissions. To advance our understanding of volcano-atmosphere interactions, we need: (1) estimates of rates of volatile release on a plate-wide and world-wide basis, (2) comparisons of passive emission rates of volatiles with rates of emission during eruptions, (3) much better data on the magmatic concentrations of species such as $H_2O$, $CO_2$, Cl, and S. These data can be integrated into a "gas budget" for a volcano which will allow us to gain a better understanding of volcanic mechanisms by constraining the volume, depth and geometry of shallow magma bodies (Rose *et al.*, 1981). The gas budget work may also be directly relevant to the formation of volcanogenic mineral deposits. Since older, eroded, but otherwise similar volcanic terrains exist to the north and east of the active volcanoes in Central America, such conclusions could be applied locally in the search for mineral resources.

*Magmatic evolution and volcanic structure*

The problem of why some volcanoes are essentially basaltic in character while a neighboring, nearly-contemporaneous volcano produces dominantly andesitic products, is a fundamental one. Smith *et al.*

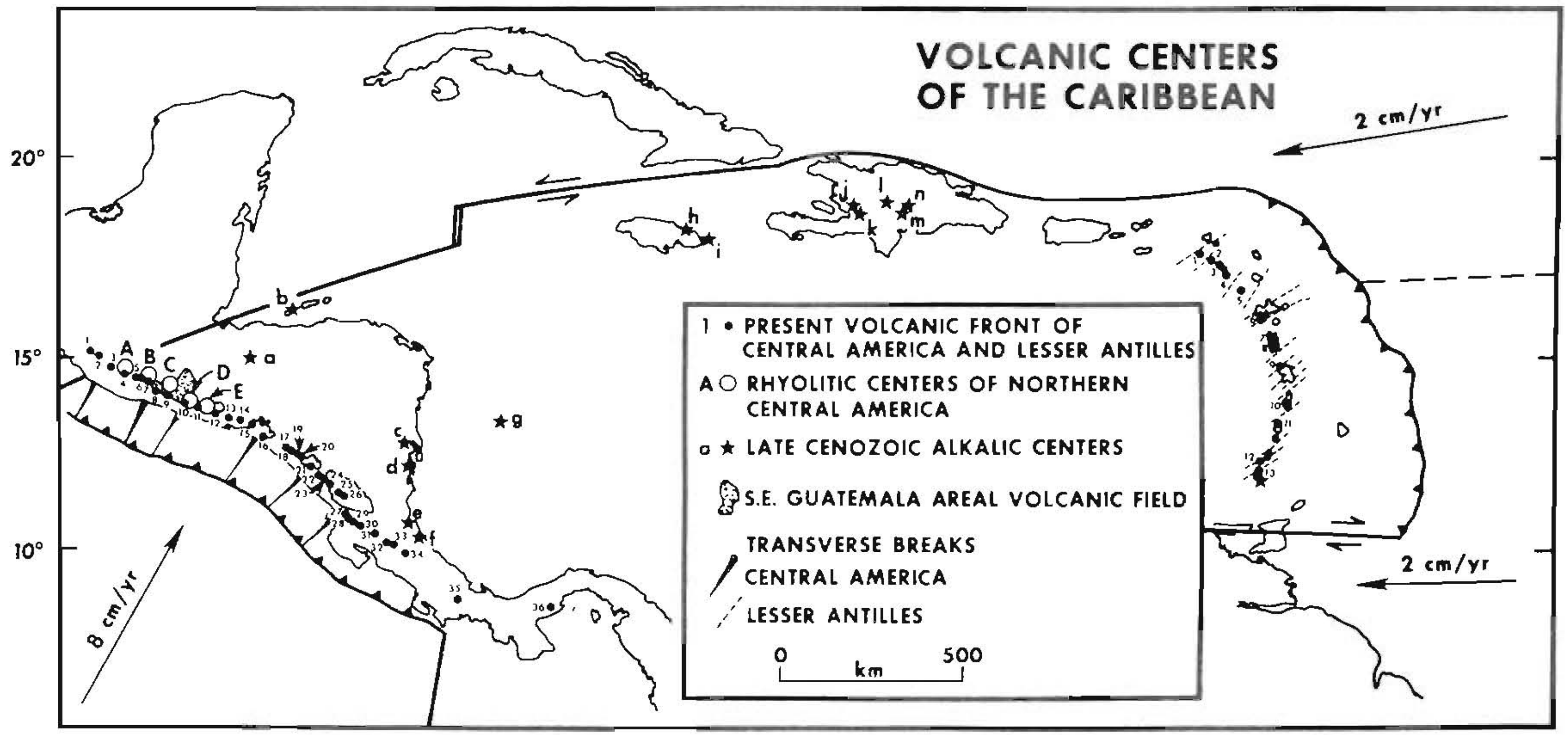



*Figure 4* *Map of modern volcanic centers within the Caribbean. Only the major centers are shown at the volcanic fronts. (See separate sheet.) Plate convergence vectors are mean values only.*

(1980) cited specific examples of this from Guadeloupe, but it is common to both arcs. It is reasonable to assume that, as a volcano's reservoir increases in size with maturity of the system, there is more chance for magmas to experience different degrees of fractionation. The residence times of individual batches of magma in volcanoes of great height (Rose *et al.*, 1977 ) and great volume (Mayfield *et al.*, 1981) will also tend to increase.

The evolution of dacitic magma bodies at the volcanic front may be a simple continuation of low pressure fractionation. This does not seem to be the case for the major rhyolite centers of Guatemala and El Salvador which are separated physically and chemically from the volcanic front (Figure 4). The continental crustal structure and distinctive tectonic setting of this part of the plate must have influenced the development of these very large magma bodies. The tentative identification of numerous overlapping circular structures has been made from Skylab imagery by Rose *et al.* (1975). This indicates the possible long history of this form of volcanism in this part of the plate.

The Lesser Antilles appear to have few calderas. It may be that resurgent activity or the close proximity of adjacent centers obliterates evidence of caldera structures, or that they did not form. Closer study of the centers responsible for the known major silicic eruptions of the past few 100,000 years may be able to resolve this.

*Segmentation of volcanic arcs*

The case for transverse segmentation of both the subducting Cocos plate and, particularly, the overriding Caribbean plate in Central America has been made by Stoiber and Carr (1973) and Carr *et al.* (1981). A similar claim for the Caribbean plate in the Lesser Antilles has been made by Westercamp (1979) (Figure 4). The Lesser Antillean segments are at a strong angular discordance (NE) relative to the plate convergence vector (E).

Large shallow-thrust earthquakes associated with the rupture of an individual segment apparently can trigger major eruptions and raise the general level of activity of nearby volcanoes for many years. Whether this strain release affects solely the sub-volcanic magma chambers, the magma generation processes within the mantle, or the whole supply system is unknown.

Volcanism at transverse breaks is different from intrasegment volcanism. Transverse volcanism is characteristically more diffuse (areal volcanism), typically bimodal (basalt-rhyolite) with a tendency to the

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[1] Supplemental Figure Caption for Fig. 4 Volcanic Front: Central America; *1. Tacona; 2. Tajumulco; 3. Santa Maria; 4. Atitlan-Toliman; 5. Fuego-Acatenango; 6. Agua; 7. Pacaya; 8. Tecuamburro; 9. Moyuta; 10. Santa Ana; 11. San Salvador; 12. San Vicente; 13. Tecapa; 14. San Miguel; 15. Conchagua; 16. Cosiguina; 17. San Cristobal; 18. Telica; 19. Los Pilas; 20. Momotombo; 21. Apoyeque; 22. Masaya; 23. Apoyo; 24. Mombacho; 25. Concepcion; 26. Madera; 27. Orosi; 28. Rincon de la Vieja; 29. Miravalles; 30. Tenorio; 31. Arenal; 32. Poas; 33. Barba; 34. Irazu-Turrialba; 35. Chiriqui; 36. El Vaule* Lesser Antilles; *1. Saba; 2. St. Eustatius; 3. St. Kitts; 4. Nevis; 5. Montserrat; 6. Soufrière, Guadeloupe; 7. Morn diablotin, Dominica; 8. Micotrin, Dominica; 9. Pelee, Martinique; 10. St. Lucia; 11. Soufrière, St. Vincent; 12. Kick 'Em-Jenny; 13. Grenada* Alkalic Centers; *a. Lago Yajoa, Honduras; b. Utila, Honduras; c. Pearl Lagaon, Nicaraugua; d. Cukra Hill, Nicaragua; e. Cerro Coronel, Costa Rica; f. Lomas de Sierpe, Costa Rica; g. La Providencia, Colombia; h. Low Layton, Jamaica; i. Jamaica Passage; j. Saut d'Eau, Haiti; k. Thomazeau, Haiti; l. San Juan, Dominican Repub.; m. Dos Hermanos, Dominican Repub.; n. Valle Nuevo, Dominican Repub.* Rhyolitic Centers of North Central America; *A. Atitlan; B. Amatitlan; C. Ayarza; D. Coatepeque; E. Ilopango*

production of alkali olivine basalt in the Lesser Antilles. The source regions of these magmas are probably different from those of the volcanic front magmas, as are their subsequent histories of crustal interaction. The proposed vertical tears in the lithosphere responsible for the segmentation must be characterized by a mantle thermal regime which is distinct from that of the unbroken segments, as manifested in the volcanic products.

The permanency of this form of segmentation is another key problem. If the transverse structures penetrate into the overriding plate for considerable distances, as seems to be true for some of the Central American structures, then they may be as old as the arc itself. There is also some evidence that the extensions of these structures contain abundant hydrothermal mineralization, which may reflect major crustal weaknesses susceptible to preferential mass transport.

***Approach*** Compilation of historic events, field estimates of lava and tephra volumes, radiocarbon dating, marine tephrachronology of discrete ash layers from piston cores and 3.5 kHz reflection surveys, dispersed ash, assessment of erosion and redeposition are the kinds of data required to evaluate the rates of magma eruption. Particular areas merit special attention. Dominica and St. Lucia are probably the most important and least-studied island centers in the Lesser Antilles. There virtually are no data on the major tephra deposits of Costa Rica. The S. E. Guatemalan field of areal volcanism needs to be dated to assess its contribution over the last 100,000 years. Remotely-sensed variations of vegetation cover, calibrated with some isotopic dates, may be a feasible technique for this problem.

The relationship among rates of magma production at depth, mode of transport to the surface and amount of magma left behind as intrusions is of fundamental importance to volcanism. Knowledge of long-term output rates of magma should help to interpret specific eruptive case histories of individual volcanoes in terms of whether magma is currently being supplied and stored. Utilizing magma output rates and the chemistry of the rocks, it should be possible to derive an approximate model for the role of shallow fractionation and storage. Highly-active volcanoes, capable of almost continuous magma effusion for many years (e.g., Santiaguito, Izalco and Arenal), are particularly valuable for studying the dynamics of magma transport. Patterns of activity with longer perodicities can be studied stratigraphically [e.g., the Holocene behavior of Mt. Pelee (Roobol and Smith, 1976)]. The rich history of major volcano-seismic swarms beneath the Lesser Antillean volcanoes is another source of information on magma flux rates.

Four fields of study of eruptive gases are particularly promising targets for the project:

1. *Gas emission rates at Caribbean plate boundaries.* A program of aircraft sampling of volcanic emissions along the Central American and Lesser Antilles volcanic fronts, using the RAVE project, can give a snapshot estimate of emissions along these plate boundaries. Low-level volcanic activity occurs constantly, especially in Central America. Low-level emission rates may make up an important fraction of the total volcanic emissions.

2. *Studies of major eruptions.* The probability of occurrence of a major eruption along the Caribbean plate boundaries during the term of the project is high. Although these probably would be the most relevant volcanic gases to sample from most points of view, the challenge in obtaining good data will be severe. Special effort to study such events should be made, using not only the high technology programs of NASA and others, such as HALO, SAGE, NOAA weather satellites, the RAVE project and U-2 and other high altitude aircraft, but also gound-based studies to examine the materials erupted and deposited near their source. These materials should be thoroughly studied mineralogically, chemically and petrographically to put the high-technology data in a strong geological context. Only with especially well-coordinated atmospheric and geological studies will we be able to construct a meaningful gas budget for these events. It is likely that major eruptions release the largest amounts of gases and small particles to the atmosphere.

3. *Pre-eruption volatile contents of magmas.* Although methods for determining pre-eruption volatile contents of magmas are known, these have been applied to too few examples for meaningful generalizations to be made concerning the compositional controls of magmatic volatiles. Such data are particularly important for S and Cl, which are pertinent to volcano/atmosphere interactions. Studies of the compositions of glass inclusions in phenocrysts from the rocks of selected volcanoes along the Caribbean plate boundaries will provide these crucial data. The results of these studies will be combined with data on the passive and active emissions to allow "gas budgets" to be formulated. We can use the budgets, along with seismological and other geophysical data, to constrain ideas of magma body depth, size and shape.

4. *Central volcanoes of intermediate composition as the tops of porphyry copper deposits.* The gas budget information which can be assembled from the data discussed above will establish sulfur partitioning between magma, vapor, ash and host rock. These data could be examined with a view toward developing models of Cu porphyry deposits. If porphyry coppers are produced by intrusive "events" near the end of a volcano's life (e.g., Whitney, 1975), then monitoring of volatile emissions probably can tell us little about their occurrence. If they are produced over a longer period of time (thousands of years?) then some volcanoes may be currently undergoing such a development, which could be detected by monitoring volatile emissions.

Massive sulphide mineralization associated with large caldera collapse structures is thought to be restricted to the resurgent stage of magmatism (Sillitoe, 1980), usually in a submarine environment. It is quite conceivable that some of the older, eroded, silicic centers have experienced these conditions and might be attractive mineral exploration targets.

The best way to address this problem initially is by remote sensing. Skylab, Landsat, Seasat SAR and other available imagery can be investigated systematically. The active arc in Guatemala could be the type area for primary study as it is the best known area. However, even there, major Quaternary discoveries of previously unrecognized calderas should be followed up by ground studies.

Any effort to understand fractionation processes at both arcs needs access to a comprehensive data base of geochemistry. This could best be compiled and manipulated by computer, and probably would contain about 3000 rock analyses.

Mayfield *et al.* (1981) have discovered a correlation between Salvadorean volcanoes whose rocks show low degrees of plagioclase fractionation and large negative Bouguer gravity anomalies. One implication of this may be that the density structure of the volcano itself, and that of its immediate basement, play important roles in the style and degree of low-pressure fractionation. Further evidence for such a relationship should be sought at other Caribbean volcanoes.

In Central America, the transverse breaks are major crustal features whose structures may be identifiable on the small scale of space imagery. Landsat and SAR imagery may be the best tools for defining the extents of these features. Extending studies inland along the traces of these breaks, taking particular interest in major structural intersections which may be sites of mineralization, could prove to be a worthwhile strategy. SAR may be the only method suitable for the cloud-covered interior of Central America, and aircraft SLAR data may be required to supplement SEASAT SAR coverage, particularly in eastern Nicaragua and Costa Rica. A combined effort involving studies of petrochemistry and magma dynamics together with a geophysical model of thermal and stress distributions will be a powerful approach to interpreting the role of transverse breaks in the generation of magmas at depth. The S. E. Guatemala–N. W. El Salvador break may be the best one to study.

## D. Mineral Resources: Occurrence and Genesis

### *Current Understanding*

*Distribution*

Mineral resources are widespread and abundant in the Caribbean region. In terms of present production, the most important mineral deposits in the region are laterites (Figure 5 ). Aluminum production from laterites in Jamaica, the Dominican Republic, and northern South America, accounts for at least 20% of world supplies. Nickel laterite operations are important in the Dominican Republic, Cuba and Guatemala. Among precious metal mines in the region, the Pueblo Viejo gold-silver deposit in the Dominican Republic is the largest open-pit gold mine in the western hemisphere. The silver-gold veins at El Limon and the silver-lead-zinc-gold veins at Neptune in Nicaragua are large producers. The Mochito silver-lead-zinc deposit in Honduras is one of the largest deposits of its type in the world. Several large mineral districts in the region are now dormant, but could be revived by new exploration. These include the massive sulfide deposits in the Matahambre area of Cuba, the Memé area of Haiti and the Rosita area of Nicaragua. Now abandoned precious metal producers extend from Guatemala to Panama in Central America and include such important districts as La Luz in Nicaragua and San Sebastian in El Salvador. At present metal prices, the gross value of ore in any one of these districts would be at least $500 million, while for some, such as Pueblo Viejo, the gross value approaches $5 billion. Operating profit (exclusive of tax) on these properties can range as high as 60%, making them important factors in local economies.

Hydrocarbon resources in the Caribbean area are distributed very unequally. Exploration drilling, both onshore and offshore, has been done on the most obvious targets in most basins in the region. By far the most important oil and gas reserves are in Venezuela and Trinidad, with much less important production coming from Guatemala and Colombia.

Although few, if any, important hydrocarbon discoveries have not been put into production, several important metal deposits have not been developed. Reasons for this range from uncertainty about future markets or lack of adequate financing to unresolved disputes between industry and government over revenue sharing, environmental safeguards or ownership. Among the most important such deposits are the huge Cerro Colorado and the large Petaquilla copper deposits in Panama and the large Tanama/Rio Vivi copper deposits in Puerto Rico.

*Processes of mineralization*

The three main types of ore-forming processes: (magmatic, hydrothermal, and weathering) can be further divided into sub-groups associated with specific geologic environments in the Caribbean region. Most magmatic deposits in the Caribbean, for instance, formed in the oceanic crust or mantle and contain pods and lenses of chromite. Mantle rocks containing these chromite deposits were obducted onto the north coast of Cuba during collision between the American and Caribbean plates. Most of these deposits are small and of questionable economic importance, but they could be keys to research on an as yet unrecognized form of Cr deposits—which would be important to the U.S., which essentially has no economic Cr deposits.

Hydrothermal processes can result in many types of ore deposits, ranging from warm brines expelled from sedimentary basins to extremely hot water exsolved from crystallizing magmas at depth. Classical vein deposits form from hydrothermal processes, as do hot spring deposits, which can be terrestrial or submarine. One of the curious aspects of Caribbean resource geology is the fact that, in spite of the widespread operation of many of these processes, there is a relatively systematic distribution of ore elements in the area. As can be seen in Figure 6, there are three main "stages" of hydrothermal deposits including: 1) Cu and Cu-Zn deposits of two types that are widespread throughout the area; 2) Pb-Zn-Ag and Au-Ag deposits of

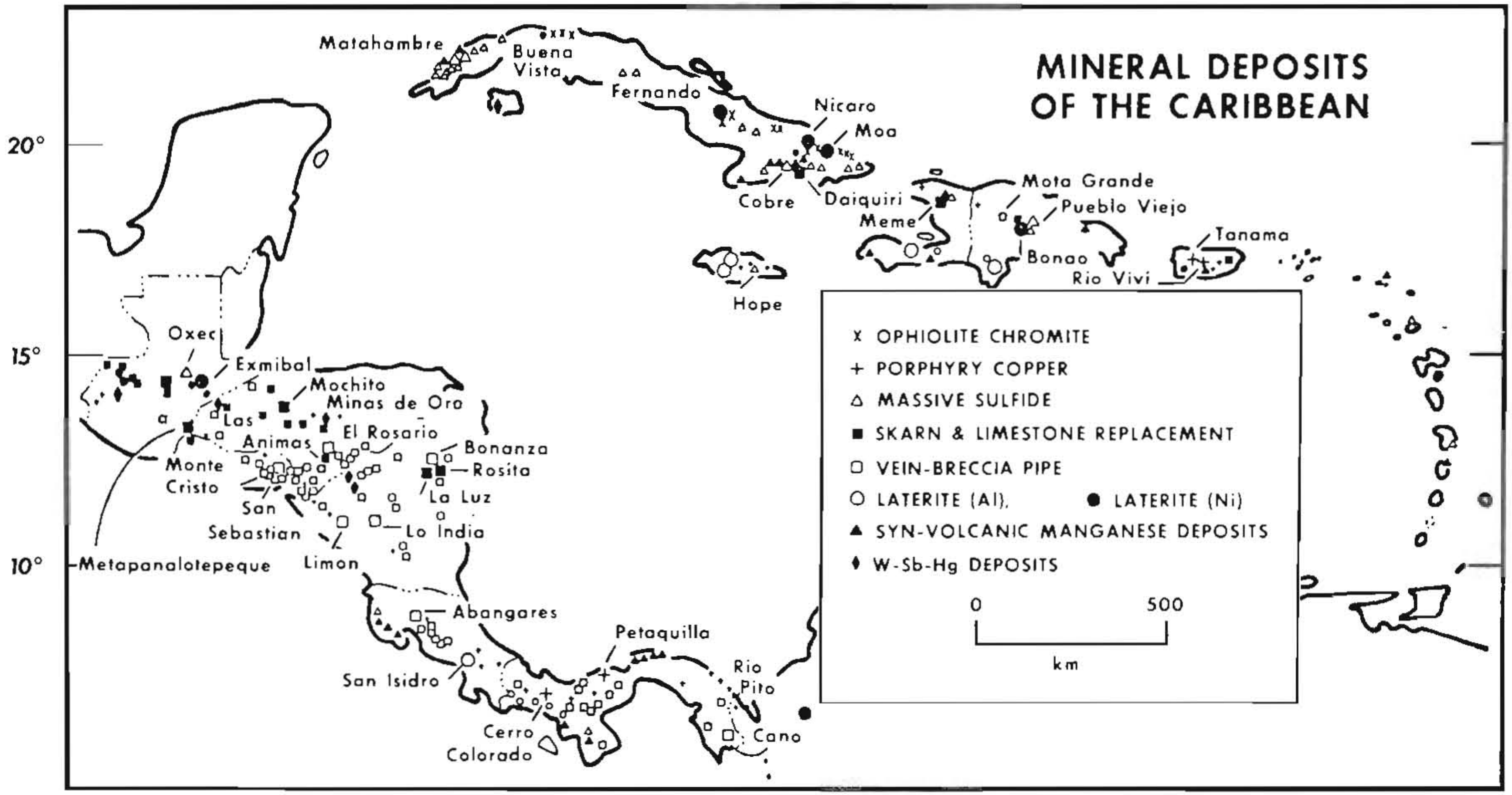



***Figure 5*** *Distribution of mineral deposits in the Caribbean region derived from Levy (1970) and other sources cited by Kesler (1978).*

two types that are found only in Central America, where the region is underlain by older cratonic basement rocks and where trace lead abundances are highest in igneous rocks (Cummings and Kesler, 1976); and 3) Hg-W-Sb deposits which are found only in a restricted area of northern Central America. Completely missing from the area are Sn deposits, which are found only in areas such as Bolivia, Malaysia and Mexico, which are underlain by a thick Precambrian craton.

The distribution of the final type of deposits, laterites, is shown in the last panel of Figure 6. These deposits require parent rock which has a composition which enhances the efficiency of the weathering process. Although appropriate parent rocks are widespread, these deposits are best-developed only locally. One of the reasons for this appears to be the amount of late Cenozoic uplift, as shown in the Greater Antilles.

***Problems*** The Caribbean region merits serious attention as a focus for concentrated resource-oriented research at this time because:

1) the variety of geologic environments and deposit types observed in the area is greater than in most other areas of similar size;
2) sufficient basic information is available in the area to permit recognition of problems of both regional and global importance;
3) the area contains many important mineral resources but still has large, poorly-explored areas.

As resource demand increases, it will become more and more desirable for governments to have reliable inventories of known and potential (undeveloped) resources. To attain this goal, we need more specific models for deposit-forming processes which operate on a regional and local scale. Work in the Caribbean region could make important contributions to this field both for local governments and in the form of basic principles which can be applied elsewhere.

The following summary of potential problems is oriented toward those for which some pay-back is relatively likely in the short term. Many other longer-range research efforts could be developed.

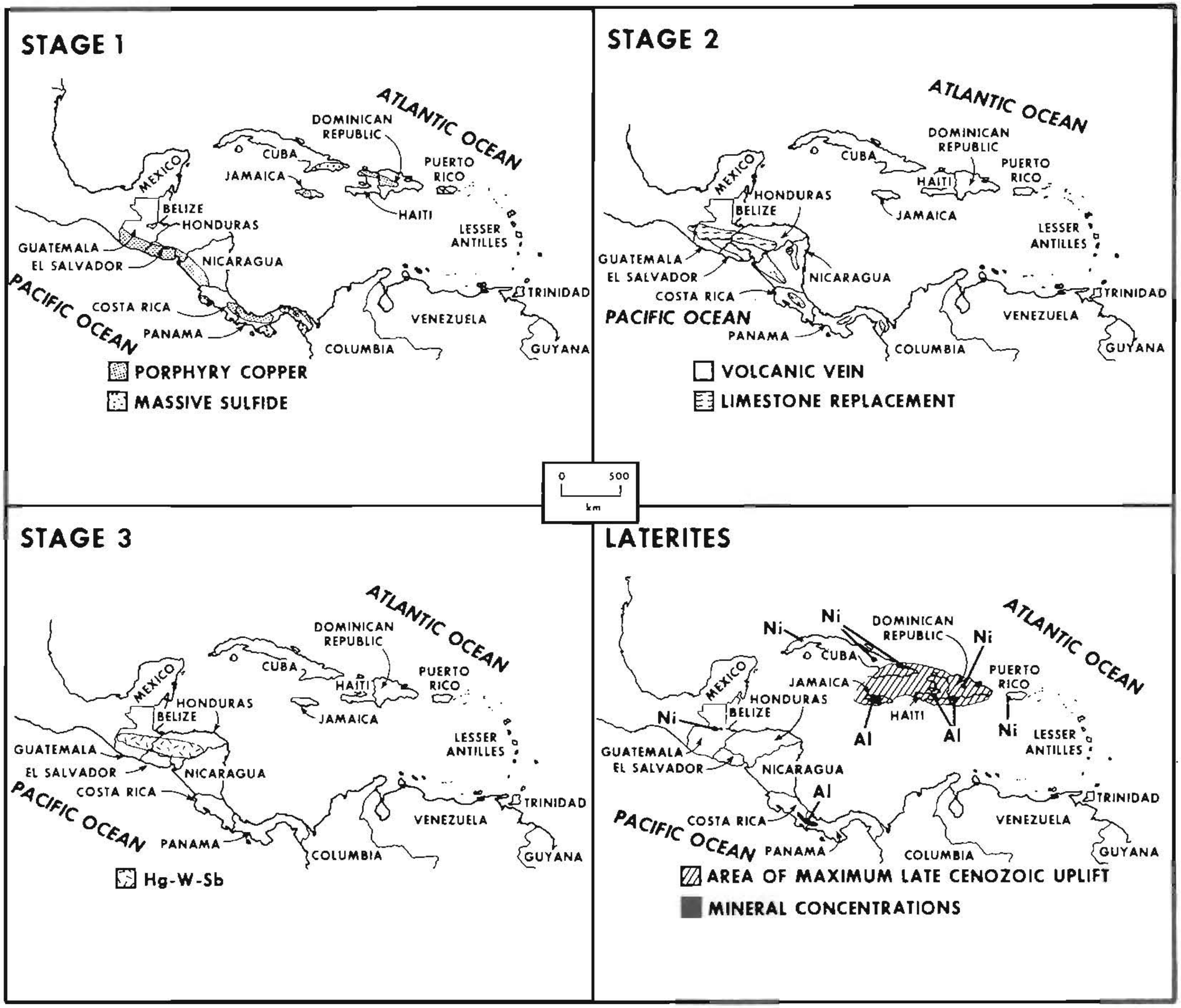
*Explanation of the W-Sb-Hg and Pb provinces in northern Central America*

This problem is perhaps the single most important mineral resource-related question in the region. Why are these metals found in local areas rather than distributed widely? To answer this question we need information on: a) the types of W-Sb-Hg and Pb deposits, their ages and relations to the local igneous rocks, and b) the trace element characteristics of the associated igneous rocks as well as the isotopic characteristics of both the ore and igneous rocks. This will involve studies comparing the lead-rich vein deposits in Honduras to those that are lead-poor in eastern Nicaragua and a detailed study of the W, Sb and Hg occurrences, and in particular, their relation to igneous rocks.

*Relation of Au-Ag deposits in western Central America to volcanic stratigraphy and regional fracture patterns*

These widespread deposits are formed by hot spring activity and could well have formed in specific favorable volcanic units or along favorable structures. To test this possibility, it will be necessary to establish the volcanic stratigraphy in local, mine-hosting areas, to extend it regionally between mineralized areas and to determine the location and distribution of major regional fractures. As an example of the ramifications of this problem, the greatest concentration of precious metal deposits is in the Gulf of Fonseca region, where

***Figure 6*** *Distribution of major mineral deposit types in the Caribbean. Three kinds of hydrothermal deposits are associated with successive stages in tectonic development and the distribution of lateritic deposits is related to the occurrence of appropriate source rocks and Late Cenozoic uplift.*


STAGE 1
ATLANTIC OCEAN
DOMINICAN REPUBLIC
CUBA
JAMAICA
PUERTO RICO
HAITI
LESSER ANTILLES
MEXICO
BELIZE
HONDURAS
GUATEMALA
EL SALVADOR
NICARAGUA
COSTA RICA
PANAMA
PACIFIC OCEAN
VENEZUELA
TRINIDAD
COLUMBIA
GUYANA
PORPHYRY COPPER
MASSIVE SULFIDE
STAGE 2
ATLANTIC OCEAN
DOMINICAN REPUBLIC
CUBA
HAITI
PUERTO RICO
JAMAICA
MEXICO
HONDURAS
BELIZE
LESSER ANTILLES
GUATEMALA
EL SALVADOR
NICARAGUA
COSTA RICA
PACIFIC OCEAN
PANAMA
TRINIDAD
VENEZUELA
COLUMBIA
GUYANA
VOLCANIC VEIN
LIMESTONE REPLACEMENT
0 500
km
STAGE 3
ATLANTIC OCEAN
DOMINICAN REPUBLIC
CUBA
HAITI
PUERTO RICO
JAMAICA
MEXICO
HONDURAS
BELIZE
LESSER ANTILLES
GUATEMALA
EL SALVADOR
NICARAGUA
COSTA RICA
PACIFIC OCEAN
PANAMA
TRINIDAD
VENEZUELA
COLUMBIA
GUYANA
Hg-W-Sb
LATERITES
Ni
Ni
DOMINICAN REPUBLIC
Ni
ATLANTIC OCEAN
CUBA
JAMAICA
PUERTO RICO
MEXICO
HONDURAS
Ni
BELIZE
HAITI
Al
Al
Ni
LESSER ANTILLES
GUATEMALA
EL SALVADOR
NICARAGUA
Al
TRINIDAD
PACIFIC OCEAN
COSTA RICA
VENEZUELA
PANAMA
COLUMBIA
GUYANA
AREA OF MAXIMUM LATE CENOZOIC UPLIFT
MINERAL CONCENTRATIONS

the strike of the west coast changes. Is this related to regional fracture patterns? Stoiber and Carr (1974) have suggested that the distribution of active volcanoes along western Central America is related to discontinuities (observed from seismic data) in the downthrust slab. How do these discontinuities relate to structures on land and in turn to the distribution of the precious metal deposits?

*Geochemistry of oceanic crust and mantle materials*

Much of the Caribbean area is underlain by remnants of oceanic crust and mantle that were obducted along the edges of the Caribbean plate (Case, 1980). Recent submarine surveys have disclosed that significant metal-depositing hot springs, as well as manganese nodule concentrations, are present on the nearby present-day Pacific and Atlantic ocean floors. Small manganese prospects and local base metal prospects of probable submarine hot spring origin are found in these ocean floor rocks (Petersen and Zantop, 1980; Kuypers and Denyer, 1979) but no effort has been made to determine their geochemical, structural and petrologic setting in order to see whether a terrestrial equivalent of the submarine resources can be found. The mantle rock in Cuba is known to contain pods of chromite, as noted earlier. However, little attention has been given to the possibility that disseminated chromite is present, and few geochemical and petrologic models are available to account for such deposits if they do exist. A study of this sort would involve field mapping to recognize and delineate units, followed by petrochemical study to relate units to seafloor analogs.

*Relation between laterite development and Cenozoic uplift*

Many direct geological and geophysical data are accumulating (or can be acquired) which will help to determine the nature of vertical movements in the Caribbean area. Satellite imagery could be used to delineate and characterize beach terraces (Horsfield, 1975), for instance. It is likely that the uplift which formed the terraces also will have facilitated the laterite-forming processes, so it should be possible to extend known areas of laterite development into less exposed areas. At the same time, an effort can be made to characterize the parent material of the laterites, particularly the bauxites. This is a major problem whose solution requires measuring their ages (Comer *et al.*, 1980) and relating them specifically to local tectonic uplift and to the source and transport mechanisms of their volcanic parent materials.

*Characterization of metamorphosed hot spring deposits of the Greater Antilles*

Recent work at Pueblo Viejo gold deposit in the Dominican Republic has shown that it is a metamorphosed hot spring deposit of a type which is not well-understood (Kesler *et al.*, 1981). Other prospects of a similar type are known in Haiti; it is possible that a belt of these deposits exists. If they can be better characterized and related to their tectonic environment, it is possible that a new class of large, low grade gold deposits can be established that would permit more effective global exploration for precious metals.

***Approach*** A basic requirement for the solution of the mineral resource problems in Central America is an analysis of regional lineaments. Lineament maps of Nicaragua based on SLAR imagery have been published (Schmoll *et al.*, 1975; Martin-Kaye and Williams, 1974), but there has been no comprehensive mapping of lineaments over the whole of Central America. The scale and resolution of LANDSAT, and of SEASAT-SAR where available, are well-suited to this task, which could also incorporate the mapping of circular features discussed earlier in this appendix. Particular attention should be paid to: (1) the traces of plate segmentation at the subduction zone, (2) the distribution of known mineral deposits on or adjacent to lineaments, (3) the lineaments which form the boundaries of known metallogenic provinces.

Examination of specific test sites at major mining areas or at evaluated prospects will be required for problems of a comparative nature outlined above. Digital remotely-sensed data should be obtained at these sites and searches made by computer processing techniques for diagnostic lithologic and structural features which may characterize similar deposits elsewhere. Ground-based investigations at both original sites and discovered "prospects" should follow, at which stage the data for stratigraphic and geochemical work can be collected.

Much of Eastern Nicaragua, Southern Costa Rica, and Panama is heavily vegetated with little surface rock exposure. The identification of hydrothermally-altered surface rocks associated with mineralization is impossible in this terrain. Satellite imagery could be used here as a potential exploration tool using geobotanical variables. Far too little has been done to test the possiblity that constant or time variable (Canney *et al.*, 1979) satellite images can be used to pinpoint targets in such regions. Several undeveloped deposits are present in this type of terrain that could be used as test areas. This effort could be very useful for the vein deposits of eastern Nicaragua, in particular.

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