PB82-137118

Geodetic Monitoring of Tectonic Deformation
Toward a Strategy

(U.S.) National Research Council
Washington, DC

Prepared for

Defense Mapping Agency
Washington, DC

Nov 81

U.S. Department of Commerce
National Technical Information Service
NTIS

50272-101

REPORT DOCUMENTATION PAGE

1. REPORT NO.

2.

3. Recipient's Accession No. PB82 137118

4. Title and Subtitle
Geodetic Monitoring of Tectonic Deformation--Toward a Strategy

5. Report Date November 1981

6. 350046

7. Author(s)
Panel on Crustal Movement Measurements/Committee on Geodesy

8. Performing Organization Rept. No.

9. Performing Organization Name and Address
National Research Council
Committee on Geodesy
2101 Constitution Avenue, NW
Washington, D.C. 20418

10. Project/Task/Work Unit No.

11. Contract(C) or Grant(G) No.
(C)
(G)

12. Sponsoring Organization Name and Address
Defense Mapping Agency, National Aeronautics and Space Admin.,
National Oceanic and Atmospheric Admin., U.S. Geological Survey

13. Type of Report & Period Covered Final

14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

The report presents issues of interest and importance to society and science. The problems considered are of national concern; their solutions may contribute to a better understanding of tectonic deformation and earthquake hazards. The need for additional field data, the role of geodetic measurements, the importance of both ground and space techniques, and the need for advanced instrumentation development are discussed.

17. Document Analysis a. Descriptors

Geodesy, geodetic space techniques, geodetic ground techniques, tectonic deformation, earthquake hazards.

b. Identifiers/Open-Ended Terms

c. COSATI Field/Group

18. Availability Statement
This report has been approved for public sale; its distribution is unlimited.

19. Security Class (This Report) Unclassified

20. Security Class (This Page) Unclassified

21. No. of Pages 121

22. Price

(See ANSI-Z39.18) See Instructions on Reverse OPTIONAL FORM 272 (4-77)
(Formerly NTIS-35)
Department of Commerce

PB82-137118

Geodetic Monitoring of Tectonic Deformation —Toward a Strategy

Panel on Crustal Movement Measurements
Committee on Geodesy/Committee on Seismology
Assembly of Mathematical and Physical Sciences

Geodetic Monitoring of Tectonic Deformation —Toward a Strategy

Panel on Crustal Movement Measurements
Committee on Geodesy/Committee on Seismology
Assembly of Mathematical and Physical Sciences
National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C. 1981

i·a

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the Councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the Committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

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

The National Research Council was established by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and of advising the federal government. The Council operates in accordance with general policies determined by the Academy under the authority of its congressional charter of 1863, which establishes the Academy as a private, nonprofit, self-governing membership corporation. The Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in the conduct of their services to the government, the public, and the scientific and engineering communities. It is administered jointly by both Academies and the Institute of Medicine. The National Academy of Engineering and the Institute of Medicine were established in 1964 and 1970, respectively, under the charter of the National Academy of Sciences.

Available from
Committee on Geodesy
2101 Constitution Avenue
Washington, D.C. 20418

Committee on Geodesy

Ivan I. Mueller, The Ohio State University, *Chairman*
Duane C. Brown, Geodetic Services, Inc., Indialantic, Florida
Daniel B. DeBra, Stanford University
Adam M. Dziewonski, Harvard University
Edward M. Gaposchkin, Smithsonian Astrophysical Observatory
John C. Harrison, University of Colorado
George E. Jones, Chevron U.S.A., Inc., New Orleans
William M. Kaula, University of California, Los Angeles
Byron D. Tapley, University of Texas, Austin
Charles A. Whitten (National Oceanic and Atmospheric Administration (retired)

Liaison Members
William J. Best, U.S. Air Force Office of Scientific Research
John D. Bossler, National Oceanic and Atmospheric Administration
Frederick J. Doyle, U.S. Geological Survey
John R. Filson, U.S. Geological Survey
Leonard E. Johnson, National Science Foundation
Armando Mancini, Defense Mapping Agency
Thomas E. Pyle, Office of Naval Research (now National Oceanic and Atmospheric Administration)
Carl F. Romney, Advanced Research Projects Agency
Pitt G. Thome, National Aeronautics and Space Administration

Staff
Hyman Orlin, *Executive Secretary*
Penelope Gibbs, *Project Secretary*

Committee on Seismology

Keiiti Aki, Massachusetts Institute of Technology, *Chairman*
John C. Crowell, University of California, Santa Barbara
Gerald H. F. Gardner, University of Houston
Bryan L. Isacks, Cornell University
Paul C. Jennings, California Institute of Technology
Thomas V. McEvilly, University of California, Berkeley
Karen C. McNally, California Institute of Technology
Peter H. Molnar, Massachusetts Institute of Technology
Paul G. Richards, Lamont-Doherty Geological Observatory
Robert B. Smith, University of Utah

Liaison Members
William J. Best, U.S. Air Force Office of Scientific Research
John R. Filson, U.S. Geological Survey
Edward A. Flinn, National Aeronautics and Space Administration
William W. Hakala, National Science Foundation
Jerry Harbour, U.S. Nuclear Regulatory Commission
John G. Heacock, Office of Naval Research
Leonard E. Johnson, National Science Foundation
George A. Kolstad, U.S. Department of Energy
James F. Lander, National Oceanic and Atmospheric Administration
Mark E. Odegard, Office of Naval Research
Carl F. Romney, Advanced Research Projects Agency
Joseph W. Siry, National Aeronautics and Space Administration
Robert E. Wallace, U.S. Geological Survey

Staff
Joseph W. Berg, Jr., *Executive Secretary*

Panel on Crustal Movement Measurements

Adam M. Dziewonski, Harvard University, *Chairman*
Peter L. Bender, National Bureau of Standards and University of Colorado
Jonathan Berger, Scripps Institution of Oceanography
John C. Harrison, University of Colorado
David D. Jackson, University of California, Los Angeles
Hiroo Kanamori, California Institute of Technology
William M. Kaula, University of California, Los Angeles
Arthur G. Sylvester, University of California, Santa Barbara

Ex-officio Members
Keiiti Aki, Massachusetts Institute of Technology
Ivan I. Mueller, The Ohio State University

Liaison Members
Kenneth I. Daugherty, Defense Mapping Agency
Edward A. Flinn, National Aeronautics and Space Administration
John R. Filson, U.S. Geological Survey
Leonard E. Johnson, National Science Foundation
James C. Savage, U.S. Geological Survey
William E. Strange, National Oceanic and Atmospheric Administration

Staff
Hyman Orlin, *Executive Secretary*
Penelope Gibbs, *Project Secretary*

Preface

The improvement in geodetic instrumentation and measurement techniques during the past decade makes feasible the detection of crustal movements over reasonably short time intervals. This has generated strong interest in monitoring tectonic motions in seismic zones in order to understand the processes that cause earthquakes, detect possible earthquake precursors, and assess their usefulness for earthquake prediction. Monitoring worldwide plate-tectonic motions and crustal movements caused by human activity is also of major importance. The Executive Summary approaches the problem from its societal and economic aspects. The body of the report, including the Introduction, addresses the scientific aspects of the problem. From both points of view the conclusions and recommendations are the same.

As a result of a recommendation in the report *Geodesy: Trends and Prospects* (Committee on Geodesy, 1978), a Panel on Crustal Movement Measurements was formed under the Committee on Geodesy and the Committee on Seismology of the National Research Council. This report is the result of the efforts of that Panel.

The charge to the Panel, as formulated in February 1979 was: "The Panel on Crustal Movement Measurements shall investigate and make recommendations concerning strategies for determining present-time crustal movements with particular consideration of seismically active zones."

The Panel expected to address the following issues:

1. The deformation patterns precursory to major earthquakes, as currently indicated by observational programs and theoretical considerations;

their spatial and temporal distribution and the range of uncertainty; the significant alternative hypotheses to be tested; and the importance of measurements of transient postseismic displacements.

2. The leading types of strain accumulation and release patterns; the priority among them, considering economic and scientific aspects and instrument capabilities, both current and potential; a recommended program of geodetic observations, including horizontal, vertical, and gravity; the required precision of measurements and their spatial and temporal distribution; required geophysical and geological observations complementary to geodetic measurements; and theoretical developments.

3. Geodetic and geophysical instrumentation needed for monitoring crustal movements at various distance ranges from the fault zone; types of fixed geodetic instrumentation to be constructed and environmentally tested in order to monitor possible precursory displacements and gravity changes under different hypotheses concerning the expected characteristics of precursors; portable instrumentation needed for studies of transient deformations and gravity changes after large earthquakes; and priorities in the development and implementation of observational programs.

4. Possible improvements in organization arrangements, both within the United States and internationally.

This report addresses mainly issues 2 and 3 and partially responds to issues 1 and 4. Our current knowledge of precursory phenomena (issue 1) is poor and largely speculative; we believe that a properly designed and executed observational program may remedy this situation. The organizational arrangements were considered a policy matter that should be resolved by the federal agencies involved, in cooperation with the Office of Science and Technology Policy and the Office of Management and Budget.

The Panel was not able to deal with many of the problems in detail. Particularly, the quantification of ground deformation caused by human activity, an issue not included in the original charge to the Panel, is important and should be the subject of an extensive study; in this report only some of the problems in this area are identified.

The Panel did not consider a wide range of nongeodetic observations, such as fluctuation in groundwater level, geoelectric and geomagnetic effects associated with tectonic stress, animal behavior, and high-frequency seismic observations.

The objective of this report is to present the issues of interest and importance to society and science. The problems discussed are of broad interest and may contribute to a better understanding of the opportunities for rapid progress during the next decade.

Contents

Executive Summary

There is a critical need to develop a strategy for investigation of deformation of the earth's crust. The scale of effects that are of interest range over several orders of magnitude, from wavelengths of thousands of kilometers, related to worldwide plate-tectonic motions, to wavelengths of a few kilometers, related to crustal movements in seismic zones. While a wide range of magnitudes of crustal movements, as well as their causes, are addressed, the tectonic motions in seismically active zones are of particular importance for social and economic reasons.

The primary objectives of this report are to identify issues and to outline the directions that promise the most rapid progress toward quantifying crustal deformation during the next decade. The examples cited merely illustrate that practical solutions are feasible. It is expected that the appropriate federal agencies will select and support the development of the tools necessary to address a specific problem.

This report is written at a time when an entirely new approach to the measurement of distances between points on the earth's surface is about to advance from experimentation and testing into a stage of field deployment with the specific mission of resolving some of the fundamental problems of geodynamics. The very-long-baseline interferometry (VLBI) and satellite laser-ranging techniques are considered to be capable of determining the components of a vector connecting two points with an accuracy of a few centi-

This Summary emphasizes the societal and economic aspects of the problem, whereas the report approaches the subject as a scientific problem. The conclusions and recommendations, however, are the same.

meters over great distances. These measurements would address, for the first time, the question of whether surface motions on a large spatial scale are in accord with the steady velocities of the plate-tectonic hypothesis on a short time scale. It is expected also that in the near future signals from the satellites of the Global Positioning System (GPS) will be used to measure baseline vectors up to a few hundred kilometers in length to an accuracy of a few centimeters using inexpensive and highly mobile receivers.

It can be anticipated that, for distances less than 10 km, ground-based geodetic techniques will remain the principal tool for monitoring crustal motions. For distances of up to at least 30 km, and perhaps as much as 100 km, ground techniques (see Section 5.1) may be more accurate than space techniques, but the cost per measurement may be higher. For much longer distances, space techniques (see Section 5.2) are the most accurate methods available. One of the most important problems in the next few years will be to improve the ground techniques and develop the space methods so that the results over a significant time period can be compared critically. However, it would be highly regrettable if full use of present ground techniques were not made because of overreliance on the new space technology.

Proper and accurate geodetic measurements can provide data for quantifying crustal deformation. The principal findings of the Panel are the following:

- The time and length scales of crustal movements in seismically active zones are such that geodetic measurements by present-day techniques can make a major contribution to the understanding of such movements and thus to earthquake-prediction research.
- Increased knowledge of tectonic motions in several major seismic zones would greatly improve understanding of earthquake mechanisms.
- The current program of geodetic measurements of strain accumulation by ground techniques in seismically active zones is inadequate.
- Ground deformation caused by human activity and siting of "critical facilities" are problems that require further study.
- Significant improvements can be made in bridging the gap between seismic and geodetic methods for measurement of strain and tectonic deformation.
- An international program of worldwide tectonic plate motion measurements would be highly valuable for understanding the tectonic processes that have shaped the earth's surface.

The major recommendations growing out of these findings are grouped herewith under three headings. More specific recommendations may be found in the sections cited.

APPLICATIONS TO SEISMICALLY ACTIVE ZONES (See Sections 2.2 and 3.1-3.6)

Most earthquakes occur along the boundaries of the tectonic plates. However, not all motions at these boundaries occur as major earthquakes; appreciable deformation may occur also as creep or be associated with minor earthquakes that are preseismic, postseismic, or not obviously associated with a major earthquake at all. Hence, a solution to the practical problem of predicting the magnitudes, times, and locations of earthquakes is dependent on an understanding of crustal movements and the larger scientific problem of crustal deformation in seismically active zones.

Earthquakes tend to happen in a seismicity gap—a zone along a seismically active fault where no major earthquake has occurred for many years. However, the time of occurrence of the next earthquake in a gap is quite uncertain as at any one location the intervals between major earthquakes are irregular: in one important example, they vary from 50 to 300 years over the last 1400 years. Hence the hope of earthquake prediction with useful temporal definition depends on measurements of physical parameters within seismic gaps.

The spatial extent of substantial strain patterns associated with major damaging earthquakes is at least of the order of tens of kilometers. The rates of long-term strain accumulation are on the order of the relative plate velocities divided by the width of the strain zone. For California, this yields a strain rate of almost one part in 10^7 per year. This rate, although highly variable in both time and space, lies within the capability of currently available electronic distance-measuring devices deployed in well-designed networks with measurements performed at intervals of 6 months or a year. Where the zone of deformation is wider and strain rates correspondingly smaller, longer intervals between measurements are necessary to reveal long-term strain rates with conventional instrumentation.

However, the temporal variation in strain accumulation is uncertain. In the best recorded example there was steady tilting over decades, followed by some irregular variations in the last few months before the earthquake. There also are indications that strain changes, which may occur hours or days before large earthquakes, may be one of the best hopes for predicting the probable time of the earthquake. The extent of the seismic gaps, the uncertainties in the temporal variation of strain accumulation, and the spatial irregularities in tectonic structure all indicate that a reasonable chance of identifying a premonitory trend in strain requires an extensive network, entailing many more observations than is characteristic of the current program in seismically active areas of the United States. Hence:

We recommend a substantial expansion in the current program of trilateration and other geodetic measurements for crustal movement studies in the *western United States: more frequent measurements, more closely spaced sites, extension of networks to greater distances away from the main faults, and more complete coverage of the major fault systems.*

This recommended expansion of the program in the direction of higher frequency, closer spacing, and greater distances from the fault tends to push against the accuracy limits of the current techniques and available instrumentation. Furthermore, some techniques are slow and expensive and may involve systematic error due to environmental effects. In optimizing an expanded observing program, there is a need for theoretical modeling to interpret existing data and plan effective future programs. Thus, a balanced program must seek to improve methods as well as make more observations. Hence:

We recommend that an appreciable portion of the program of geodetic measurements of crustal movements be allocated to supporting research and development, particularly for improved ground instrumentation, more economical and accurate space techniques, the study of environmental limitations on accuracy, and theoretical modeling and data analyses.

For reasons of scientific readiness, as well as the population concentration, the primary emphasis in obtaining the most accurate crustal movement measurements and in the use of frequent resurvey measurements and fixed instruments at many points must be in California for the next decade or two. However, measurements in other active regions, although less frequent and made at a smaller number of points, can play an important role in increasing the chances of obtaining, during the next decade, valuable information about crustal movements before and after a large earthquake. Examples of suitable western hemisphere regions are the southern belt of Alaska, western South America, and the area of the Caribbean sea. These regions are of particular importance because of the significant differences in the characteristic strain patterns of these regions, which will lead to new insights, and because of the hazard to their inhabitants. The development of a method for measuring strain accumulation and release across subduction zones is an additional goal of importance for understanding large earthquakes. Hence:

We recommend that the main geodetic measurement goals during the next decade for major seismic zones should be as follows:

(a) Improvement of the accuracy and coverage of deformation measurements in the western United States and Alaska to include:

1. Semiannual or annual measurements with the highest possible accuracy over extended geodetic networks;

2. Frequent measurements (roughly 2-week intervals) between points every 10 or 20 km along the major faults; and

3. Nearly continuous measurements by stationary monitoring instruments at a similar spacing to detect any short-term precursory motions before large earthquakes;

(b) Extension of deformation monitoring to a number of the major non-U.S. seismic zones of the western hemisphere and western Pacific using space techniques, in cooperation with the countries involved;

(c) Subject to the development of the necessary instrumentation that can achieve 10-cm accuracy, roughly biannual measurements of 10 to 20 points on the ocean floor with respect to reference points on land (measurements across the Aleutian Trench should receive prime consideration); and

(d) Improved methods of installing monuments and evaluating the stability of same.

APPLICATIONS TO OTHER TECTONIC PROBLEMS (See Sections 2.1, 2.2, and 4.1-4.4)

Global tectonics represents an important direction of application of the methods of modern geodesy. By comparing present rates of plate motion obtained by geodetic techniques with the long-term average rates determined from magnetic lineations and other information, we can establish whether tectonic plates move steadily or episodically. This information would be useful for studies of lithospheric and asthenospheric tectonics. Also, variations in the rotation rate and polar motion of the earth and their relationships to earthquakes, meteorological effects, and core-mantle interactions are poorly understood because of lack of sufficiently accurate observations.

The worldwide geodetic measurements can only be carried out by space techniques, which are now reaching the accuracies needed for tectonically interesting results. The methods that are being used are long-baseline radio interferometry (VLBI) and laser ranging to the Lageos satellite. The need to intercompare techniques with different error sources as well as the desirability of obtaining early results dictate that both techniques should be employed initially. Hence:

We endorse current plans for the United States to participate in a worldwide program to measure tectonic plate motions by space techniques, using both the VLBI and laser-ranging methods, and to monitor polar motion and the earth's rotation when the accuracy of these techniques has been adequately verified.

Geodetic measurement programs using instrumentation of improved accuracy are expected to be important for understanding crustal movements in areas of the United States outside the major seismic zones. East of the California fault zones there is a scattering of earthquake activity in the mountainous regions, decreasing as the Great Plains are approached. Some regions, such as the area of Yellowstone National Park and the Rio Grande rift, evidence appreciable current or recent tectonic activity. Even in the apparently stable part of the continent there have been sizable earthquakes in historic time. Hence, when anticipated developments in the accuracy and responsiveness of geodetic techniques have been achieved, there are many scientifically interesting problems to which they could be applied.

SUPPORTING RESEARCH AND DEVELOPMENT (See Sections 3.4, 5.1, and 5.2)

As mentioned earlier, an efficient program for monitoring crustal movements requires increased emphasis on the development of more accurate and more rapidly responsive instrumentation. This is particularly true if an expanded program of measurements at closer temporal and spatial intervals is to be useful.

We emphasize the urgency of completing the development of instrumentation to attain the following goals of accuracy for mobile land systems:

- *5 parts in* 10^6 *(relative horizontal position difference) for ranging over distances up to 50 km,*
- *1 cm for elevation differences of 1 km,*
- *3 ×* 10^{-8} m/sec^2 *for the acceleration due to gravity, and*
- *2 cm for baseline vector measurements by means of Global Positioning System receivers, long-baseline radio interferometry, and satellite laser ranging.*

These accuracies require increased attention to environmental effects, such as control monument stability, atmospheric refraction, and the influence of groundwater. If space techniques are to predominate over distances of more than about 100 km, and are to contribute over shorter distances, then they must attain centimeter accuracy. Finally, since much of the tectonic activity of the earth is suboceanic, efforts should be made to improve acoustic ranging and ocean-bottom positioning techniques.

We also urge development of a capability to measure, to an accuracy of 10 cm, motions of points on the ocean floor up to several hundred kilometers offshore with respect to reference points on land.

1

Introduction

Earthquakes represent failure of geological materials to resist tectonic stress. The stress is accumulated over a period of time, usually many years, and must be accompanied by deformation and straining of rock. Laboratory experiments and theoretical considerations predict that a change in the strain rate should precede the failure. The temporal and spatial extent as well as the magnitude of the changes in the strain rates preceding earthquakes are not known.

This report is prepared jointly by representatives of the geodetic and seismological communities because there is a gap in the time scale over which crustal movements are traditionally monitored by these disciplines. The frequency with which geodetic networks are re-observed is often of the order of years or tens of years, while most of the seismographs are designed to register ground motion excited by an earthquake and their response is most favorable in a range of periods from, say, one tenth of a second to a few minutes.

Efforts are being made to bridge this gap through increasing the frequency of geodetic measurements in the regions of particular interest, establishment of a global network of long- and ultra-long-period seismometers, and development of geophysical and geodetic instrumentation that, in theory, should be capable of measuring rates of crustal deformation over arbitrary time scales.

This Panel has been charged by the Committee on Geodesy and the Committee on Seismology of the National Research Council with preparing an outline of a strategy for the next decade that would offer a promise of significant progress in monitoring crustal deformation. From the first meeting of the Panel it was clear that such a strategy would involve a broad, well-supported observational program, which, in its early stage, would require a major effort in the development of field instrumentation.

An important element in any consideration of a strategy for monitoring tectonic deformation is the forthcoming availability of space methods. Very-long-baseline interferometry (VLBI) and satellite laser-ranging techniques appear to be capable of determining differences of position between any two points on the earth's surface with an accuracy of a few centimeters. For baselines up to several hundred kilometers in length, signals from the satellites of the Global Positioning System (GPS) could be used in the next few years to measure the baseline vector components with an accuracy of a few centimeters using inexpensive and highly mobile receivers. This entirely new class of instrumentation should allow monitoring of the regional strain changes over a range of distances and on a time scale not yet achieved by the traditional geodetic methods. However, for local studies (baseline lengths of less than 30 or perhaps 100 km), ground techniques are likely to have higher accuracies than are space systems.

The primary attention of the Panel is focused on measurements in seismically active zones, and on the San Andreas Fault system in particular. The foremost reasons for this emphasis are the impact on society of a major earthquake in this densely populated area and the accessibility of this extensive land fault region. However, the San Andreas Fault is only a small part of the worldwide system of plate boundaries. In Alaska or the Caribbean sea area, where, for example, approximately half of the seismic rupture zone is submarine, measurements of needed accuracy can be made only on the land side of a subduction zone.

As there are no known answers, the search for crustal motions preceding major earthquakes should be considered a basic scientific experiment. The Panel believes that global-scale studies represent an important part of a balanced program. Development of VLBI and laser-ranging instrumentation offers an opportunity to determine current rates of relative plate motions by conducting interplate measurements. Furthermore, accumulation and release of the strain in the earth leads to a planetary-scale effect: change in the earth's moment of inertia as reflected in changes in rotation rate and polar motion.

As it is clear that the phenomena studied as well as the elements of the observational system are interrelated, this report begins with discussion in Section 2.1 of measurements of polar motion and the earth's rotation. The Polaris network (Carter *et al.*, 1979) should be capable of giving daily determinations of the pole position with an accuracy of 5 cm. This order-of-magnitude improvement over the precision of classical astronomic measurements might lead to a better understanding of the important problem of the contribution of aseismic slip to the release of the global strain built up during the process of plate motions.

Section 2.2 considers the prospects of application of space techniques in studying many problems associated with the large-scale (interplate) aspects of plate tectonics.

Plate tectonics, an outgrowth of the earlier hypotheses of continental drift and polar wandering, is a unifying theory that explains the principal features of the kinematic behavior of the earth's surface by the interaction of about a dozen major and several minor plates, which are in relative motion as almost rigid bodies. The currently available data on the plate motions are obtained from (a) the pattern of remanent magnetism of the seafloor, which allows one to infer the average rate of spreading at midoceanic ridges; (b) orientation of fracture zones; and (c) earthquake source mechanisms. The first two elements use the record of the past several million years; only the data on earthquake mechanisms are current. Applications of space techniques, with the projected accuracy of a distance measurement of 2 or 3 cm, will allow establishment of the current direction and rate of motion between most of the plates within 3 to 5 years; only in a few cases of exceptionally slow motion (e.g., Africa-Eurasia) would the required interval be of the order of a decade. In addition to the scientific significance of such a measurement program, there are also important practical implications as most major, devastating earthquakes occur near plate boundaries. Analyses of the seismic energy release show that the displacement at plate boundaries is nonuniform in time. This may indicate that the overall rates of plate motion vary on a time scale less than the resolution of the seafloor magnetic lineations, about 10,000 years at best.

While Chapter 2 deals with the basic scientific problems and discusses the effects and measurements on a planetary and intercontinental scale, Chapters 3 and 4 describe a program of regional studies and discuss the problems of monitoring crustal movements in the seismically active regions of the United States.

The United States Geological Survey (USGS) and the National Geodetic Survey (NGS) have been carrying out, for some decades, programs of monitoring the strain along the tectonically active fault systems of the western United States. Monitoring during the 1970's of trilateration networks has been particularly important. The interpretation of crustal motions from triangulation data has also been valuable. In recent years much effort has been devoted to repeated leveling surveys performed to monitor possible large and horizontally extensive vertical motions in southern California. In Chapter 3 we discuss these measurements and express our strong support for continuation and expansion of the trilateration network measurements and of some other parts of these programs. We discuss the need for, and suggest improvements in, the application of classical geodetic techniques and discuss additional means of monitoring crustal motions. We also encourage more extensive scrutiny, utilization, and interpretation of the existing data base.

The principal goal is to improve our knowledge of spatial and temporal patterns of strain accumulation and release. We believe that it is important to cover a relatively large range of distances in which a change in the pattern of deformation might occur. For this reason, the baseline length of suggested measurements ranges from 1 to 100 km and the sampling rate from one measurement per 10 years to one sample per second. Introduction of space techniques may reduce the cost of monitoring the strain over baseline distances of 30 to 100 km; however, the forthcoming availability of these tools should not divert our attention away from the need for the development and deployment of a new generation of ground-based instruments that could provide more accurate data than space techniques could over these distances.

Chapter 4 covers a wide range of topics, from a discussion of the need to study the geodetic evidence of seismic activity in the central and eastern United States, through the basic scientific problems of neotectonics associated with the deformation of crustal blocks, to the man-caused effects of subsidence due to mining and water withdrawal. We believe that ground deformation caused by human activity is an important problem, but in this report we only identify the issue. Chapter 4 also includes a discussion of the neotectonic nature of major physiographic province boundaries, the stability of the Colorado Plateau with respect to the surrounding tectonic provinces, and the patterns of deformation in the area between the San Andreas Fault and the Wasatch Front in Utah.

Reliable data on the geological stability of specific areas are important in making decisions about the location of "critical facilities." In particular, in choosing the sites for nuclear waste disposal it might be desirable to base decisions not only on the evidence of stability on the geological time scale but also on estimates of the present-day stability based on high-quality geodetic data.

Ninety percent of existing nuclear power plants are concentrated in the eastern United States. Few are located on the West Coast. A map of earthquake hazard based on historical cumulative seismic intensity shows two major areas of high intensity on the East Coast that outweigh the relatively low-level, but persistent, seismicity on the West Coast. Neither geologic data nor our knowledge of present-day tectonics provide insight as to where major earthquakes will re-occur in the east. Crustal deformation studies may provide evidence for the accumulation of crustal stress.

Some of the suggested applications of space techniques are of fundamental scientific significance, such as the measurements of the rates of the postglacial rebound. These are the principal data providing information on the viscosity distribution within the earth.

The success of these programs will depend to a great extent on the availability of proper instrumentation. Chapter 5 consists of two principal parts, the first dealing with ground instrumentation and the second with space techniques. This chapter serves a dual purpose: to familiarize the reader with the principles of operation of the instruments required for the execution of the proposed program and to present our opinion on the directions for improvement of the existing instrumentation and development of new equipment. It is our conclusion that a significant increase in financial support for research on insturmentation related to monitoring of crustal movements is necessary.

The aim of this report is to present the issues of interest and importance to society and to science. We believe that the problems discussed here are of broad interest, and it is our intention that this document contribute to a better understanding of the opportunities for rapid progress during the next decade.

2

Measurements on a Global Scale

2.1 EARTH ROTATION AND POLAR MOTION

Temporal variations in the distribution of the mass within the earth and in its atmosphere lead to changes in its moment-of-inertia tensor and, consequently, to variations in the length of day and in the instantaneous position of the pole of rotation. In addition, torques exerted on the crust and mantle by atmospheric winds or by fluid motions at the core-mantle boundary can change the angular momentum of the solid parts of the earth. While correlations exist between changes in the length of day and zonal winds or seasonal effects in the atmosphere (Lambeck and Cazenave, 1976), the source of excitation of the Eulerian free nutation of the earth, commonly called the Chandler wobble, still remains elusive.

The long-period variations in the earth's rotation rate can easily be observed by classical astronomical instruments, because the resulting offsets in angular position are large. For example, an annual variation in rotation rate with an amplitude of 1 part in 10^9 will give a periodic offset in the earth's position of about 2 m. However, our present knowledge of irregular variations in rotation rate with time scales of roughly a month or less is poor. Improved measurements by space techniques can give new information on the integrated shear stress that is transmitted to the earth's surface by winds. They also will give an independent constraint on determinations of global zonal winds by meteorological methods. Significant improvement of meteorological data is expected to result from worldwide efforts such as the Global Weather Experiment and should make possible considerably better comparisons with observations of the earth's rotation.

The observed period of the Chandler wobble (434 ± 2 days) can be well explained by the known mechanical properties of the earth, with the effect of the influence of the oceans and the frequency variation of anelastic attenuation remaining the most poorly known factors. However, even relatively inaccurate measurements of the pole position for the last 70 years indicate that the amplitude of the wobble has varied appreciably during that time. The amplitude decreased from approximately 9 m in 1910 to about 3 m in 1940 and then increased to 11 m in 1953. Thus, there must be a source of energy to excite the motion as well as a damping mechanism to make the oscillation decay rapidly.

In recent years, particular attention has been directed toward (a) atmospheric excitation (redistribution of mass and torques due to wind patterns) (Wilson, 1975) and (b) seismic excitation (Mansinha and Smylie, 1967; O'Connell and Dziewonski, 1976; Mansinha *et al.*, 1979). Kanamori (1976) pointed out that the magnitudes of earthquakes before 1957 were seriously overestimated, and it appears that the seismic moments determined from radiation of seismic waves were insufficient, by a factor of 5 or so, to account for the observed behavior of the Chandler wobble. Atmospheric excitation remains a distinct possibility, and with the rapidly improving global atmospheric data base and the higher accuracy of the polar motion data it might be possible to resolve the question in the near future. Wilson (1975) stated, on the basis of statistical analysis of the power spectra, that between 25 and 50 percent of the polar motion could be explained by the atmospheric sources.

Currently there are two questions concerning the relationship between the Chandler wobble and earthquakes. The first is whether earthquakes alone are sufficient to excite the Chandler wobble. The answer, at this time, must be a qualified *no*. That is, the combined effect of earthquakes with moments determined from seismic data, interpreted under the assumption that the release of stress is essentially instantaneous, is insufficient to explain the magnitude of abrupt changes in the polar path observed for the last 70 years. The qualification pertains to the potential effect of "silent earthquakes": deformation at rates below the threshold of seismometers (about 0.003 Hz), which may or may not be associated with earthquakes.

The second question is whether major earthquakes should cause a discernible change in the polar path. The answer to this question is *yes*. Independent calculations show that the change in the position of the mean pole of rotation (the center of the circular arc fitted to the instantaneous poles of rotation) should be of the order of 30 cm for the 1964 Alaskan earthquake and 50 cm or more for the 1960 Chilean earthquake. If the precision of determination of the pole position when these earthquakes occurred were the 5 cm projected for laser-ranging and very-long-baseline interferometry (VLBI) networks, both of these unusually large earthquakes should have been clearly detected.

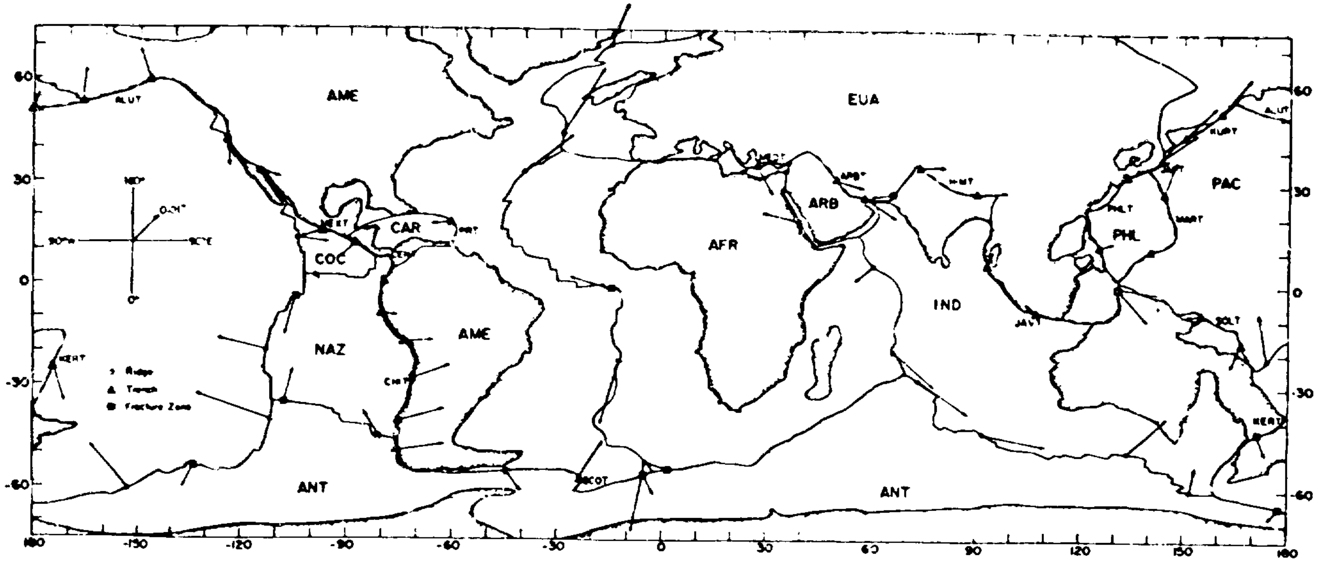

FIGURE 2.1 Magnitude (arrow's length) and direction (refer to inset for definition) of polar shifts in response to three types of hypothetical earthquakes with a standard moment of 10^{30} dyne-cm. The dots correspond to earthquakes on the midoceanic ridges; the expected mechanism is normal faulting (horizontal tension, vertical compression). The triangles designate shallow earthquakes in the subduction zones; a thrusting mechanism with a 20° dip of the fault plane has been assumed. Squares represent earthquakes associated with fracture zones (transform faults); the mechanism is strike-slip: horizontal displacement along the strike of the fault; this is the mechanism of earthquakes on the San Andreas Fault (Dziewonski and O'Connell, 1976).

Figure 2.1 (from Dziewonski and O'Connell, 1976) shows the magnitude and direction of the instantaneous change in the position of the mean pole of rotation caused by hypothetical earthquakes with a moment of 10^{30} dyne-cm located at various plate boundaries. Normal faulting has been assumed for events on midoceanic ridges, strike-slip mechanism for fracture zones, and thrust faulting with a 20° dip of the fault plane for subduction zones. Calculations were made for an earth model PEM-A (Dziewonski *et al.*, 1975) assuming a hypocentral depth of 30 km. Directions of the slip vector were obtained using the plate motions given by Solomon *et al.* (1975).

Thus, even though calculations of the excitation of the Chandler wobble due to earthquakes with moments determined from the amplitudes of the seismic waves with periods between 20 and 300 sec yield only a fraction of the observed effect, an association between crustal motions and the Chandler wobble should not be discounted. There is an increasing body of evidence that a large part of plate motion at the plate boundaries is aseismic (see Section 3.5). The earth is a superb ultra-long-period seismograph in that aseismic displacements that take place over a period of days and even weeks that escape detection by standard seismic equipment could be observed as instantaneous events in the path of the pole.

The Polaris network (Carter *et al.*, 1979), operated by the National Geodetic Survey, and a worldwide network of laser-ranging observatories, having projected accuracies in determination of the pole position of 5 cm for measurements every 2 days, should increase significantly the probability that correlation between earthquakes and changes in the pole path could be established within a relatively short time. This precision would be sufficient to detect an earthquake several times smaller than the Alaskan earthquake of 1964. For truly great events, such as the Chilean earthquake of 1960, estimates of the seismic moment at zero frequency from polar motion data would be superior to the values obtained by seismologists by the usual arbitrary extrapolation of the measurements made at periods of several hundred seconds.

RECOMMENDATION 2.1 *We recommend that the United States participate in the establishment of an international network of observatories to monitor polar motion and earth rotation using space techniques. The network should be capable of providing estimates of the pole position every two days and of variations in the earth's rotational position each day, both with an accuracy of 5 cm or better.*

Indication of an event in the polar motion data would stimulate re-examination of ultra-long-period recordings (for example, those collected by the International Deployment of Accelerometers networks; Agnew *et al.*, 1976) and could lead to a discovery of excitation of the gravest (i.e., longest-wavelength) normal modes and subsequently to the location and determination of the mechanism of a silent earthquake.

Precise polar motion data could become an important tool in the evaluation of the global balance of the stress accumulation and release in the earth. Improved information on short-period variations in the earth's rotation could give new results on the shear stress exerted on the crust by atmospheric winds.

RECOMMENDATION 2.2 *We recommend support for continuous-recording instrumentation necessary for establishment of the correlation between tectonic motions and the polar motion data: high-quality strainmeters, tiltmeters, and ultra-long-period seismographs (gravimeters).*

If permanent VLBI and laser-ranging stations are equipped with high-quality instruments for monitoring the tidal motion and local changes in level (gravity), we recommend digital recording of the data in the normal mode band (periods between 1 min and 1 h) with the proper sampling rate.

2.2 PRESENT-DAY PLATE MOTIONS

The theory of plate tectonics is now generally accepted by most earth scientists as a unifying theory that describes how the earth's lithosphere behaves in the global sense. In this theory, the earth's surface is covered by a relatively rigid layer called the lithosphere, which is underlain by a deformable layer called the asthenosphere (see Figure 2.2). The thickness of the lithosphere, determined from seismic data, averages about 100 km beneath oceans and is considerably thicker under most of the continents. The oceanic lithosphere is created by upwelling of hot material from the earth's mantle at oceanic ridges such as the mid-Atlantic ridges and the East Pacific Rise and spreads out hori-

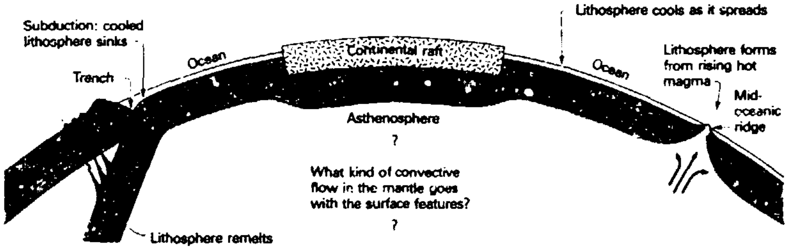

FIGURE 2.2 The motion of plates, spreading from midocean ridges and sinking in subduction zones, is the surface manifestation of convection currents in the interior. The nature of the flow in the interior is uncertain. From F. Press and R. Siever, *Earth*, 2nd ed., W. H. Freeman and Company, San Francisco, Copyright © 1978.

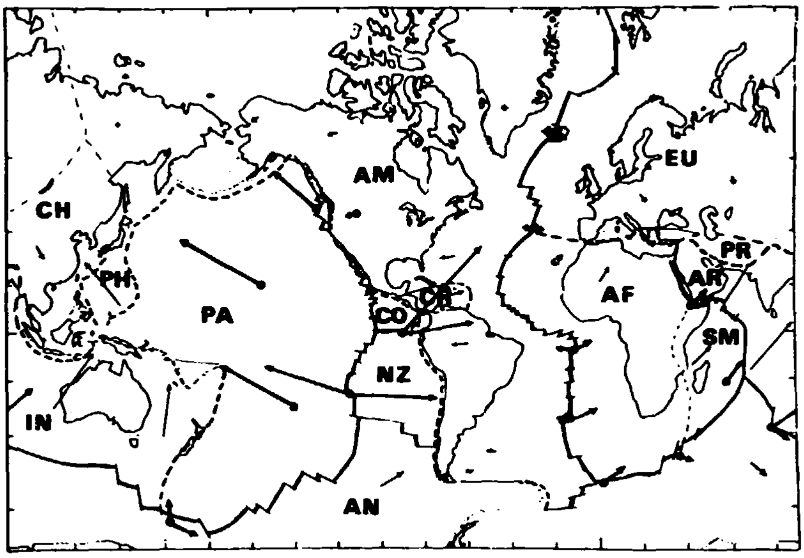

FIGURE 2.3 Present motions of plates over hot spots. The relative motions were determined from fault strikes and spreading rates on rise boundaries; with an appropriate constant rotation added, absolute motion of each plate over the mantle was determined. The lengths of arrows are proportional to the plate speed. The length of the arrow within the Nazca (NZ) plate corresponds to a plate velocity of approximately 10 cm/yr (Morgan, 1972).

zontally away from the ridge. As it spreads, it cools and becomes denser and, in the Pacific, eventually sinks back into the mantle at island arcs and (active) continental margins such as Alaska, Chile, and Japan. The lithosphere is subdivided into a number of large plates that are moving as distinct units relative to each other with speeds of up to 12 cm/yr. Figure 2.3 shows the distribution of these plates and their motion with respect to the earth's deep interior (in the "hot spot" reference frame, a concept proposed by Morgan, 1972). The boundaries of these plates can be classified into three types:

1. *Diverging boundary*. These are the boundaries where new lithosphere is formed as the plates move away from the worldwide rift system.
2. *Converging boundary*. Along these boundaries the cold and dense oceanic lithosphere is sinking back into the mantle and is represented by island arcs, active continental margins, and subduction zones.
3. *Transform boundary*. At these boundaries the plates slide past each other horizontally. The San Andreas Fault system in California is a well-known example.

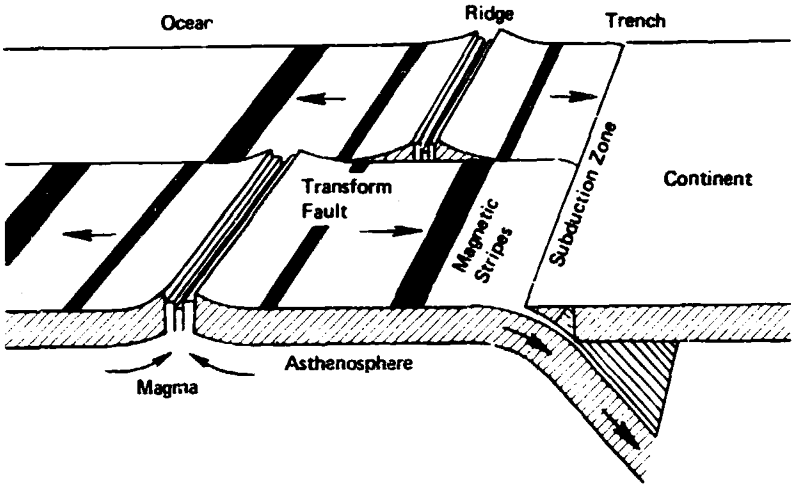

FIGURE 2.4 Three types of plate boundary: ridge (spreading center), subduction zone, and transform faults.

Figure 2.4 illustrates these three types of plate boundary.

The location and relative motion of the plates at these boundaries have been determined on the basis of various geophysical and geological data such as (a) distribution of earthquakes, (b) magnetic stripe patterns on the ocean floor, (c) geometry of the oceanic fracture zones, and (d) earthquake mechanisms. Many of these data show plate position in the past, and plate motion shown by Figure 2.3 therefore represents an average motion over the past several million years or longer. Current plate motion is consistent with the picture shown in Figure 2.3, if the vectors are considered as averages for some tens of thousands of years. However, it is possible that the actual plate motion is irregular on shorter time scales. Furthermore, the distribution of plates and of plate motion is far more complicated in detail than is shown in Figure 2.3. For instance, in Figure 2.3 the plates are assumed to be rigid (i.e., they do not deform or break) except at plate boundaries. However, it is known that the deformation at some plate boundaries is spread out over a considerable distance (several hundred kilometers) into the interior of the plate. Also, substantial deformation is taking place in the interior of the plates in the form of crustal deformations and earthquakes. The energy release associated with intraplate earthquakes is on the order of 1 percent of that associated with earthquakes at plate margins.

Unfortunately, the high-frequency part of lithospheric motion with its spatio-temporal irregularity has not yet been measured directly, except by estimates of slip vectors inferred from earthquakes. Precise measurements of such variation of the instantaneous lithospheric motion would provide key data for resolving many important problems in geodynamics, such as the rheology of the lithosphere and mantle, global interaction between plates, and the way the plates deform in response to the driving forces. More detailed discussions on plate tectonics can be found in various texts, e.g., Press and Siever (1978), Cox (1973), Le Pichon *et al.* (1973), and Wilson (1976). None of these texts discusses the underlying causes, however.

2.2.1 Plate-Driving Mechanism

Researchers in mantle convection agree that the plate motions are the response of the lithosphere to a flow driven by radioactive and primordial energy sources. The question of the distribution of the flow and energy sources with respect to depth and the nature of the lithospheric boundary layer are subjects of intensive current investigations. Because the lithosphere acts as a strong region in comparison with the less viscous asthenosphere, much of the discussion about the "driving forces" is in terms of the effects of the substrata on the lithosphere or vice versa.

Although the physical mechanism of the plate motion is not well understood, some authors believe that density variation within the lithosphere plays an important role; for a recent review see Uyeda (1978). At the spreading centers (ridges), the thermally maintained topographic high provides a gravitational force that pushes the plate away from the ridge. This force is called the "ridge push" (Figure 2.5). At subduction zones, the cold, dense

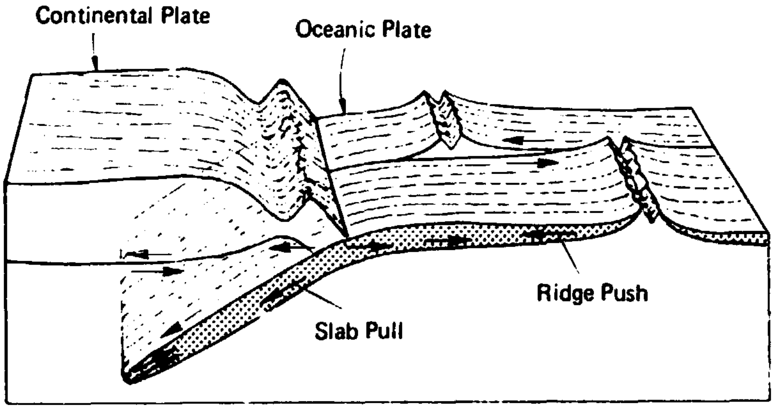

FIGURE 2.5 Possible plate-driving forces. Ridge push and slab pull are indicated. Other forces (asthenospheric drag and plate-resisting forces are indicated by arrows. (After Forsyth and Uyeda, 1975; Uyeda, 1978).

downgoing slab, colder and denser than the surrounding asthenosphere, sinks downward and pulls the plate along behind it. This force can be called "slab pull" (Figure 2.5). Some recent studies indicate that the ridge push resulting from the thickening of the cooling lithosphere may be more important in driving oceanic plates than the slab pull (e.g., Hager, 1978). Whether or not convection is a major component of the driving forces, shear stress at the base of the lithosphere must affect plate motion and deformation, as must the resisting forces at plate boundaries. The present plate motion is most likely to be affected by the distribution of oceanic ridges, subduction zones, and various other features in the plate interior and at plate boundaries. The direct determination of present plate motion at various boundaries is crucial for evaluating the relative importance of the possible driving forces.

2.2.2 Rheological Property of Asthenosphere

At most transform and subduction boundaries, the two opposing plates are usually locked to each other, with little or no relative motion taking place. As the stress on these plate boundaries increases due to the driving forces, the contact zone between them eventually ruptures in a large earthquake, and sudden displacement takes place. The displacement at the plate boundary can be estimated from the amount of energy release in large earthquakes at plate boundaries. A recent study (Kanamori, 1977a) showed that such displacement at plate boundaries is very nonuniform in historic time. As shown in Figure 2.6, most displacement during the time period from 1952 to 1965 took place in a rather impulsive manner. How this impulsive plate motion at plate boundaries propagates into the interior of the plate depends critically on the rheology, usually parametrized as viscosity of the asthenosphere

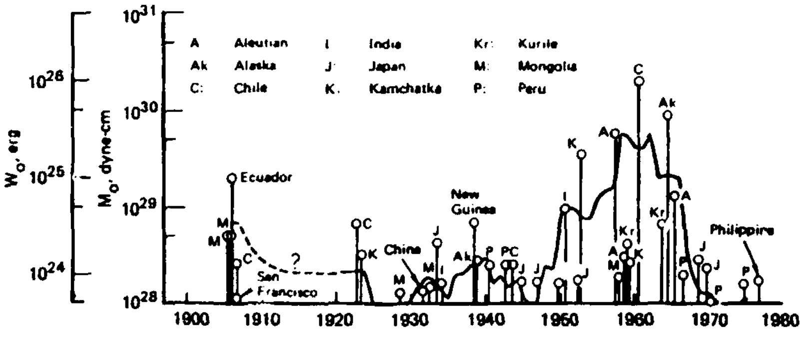

FIGURE 2.6 The energy release, W_0, in great earthquakes as a function of year (Kanamori, 1977a).

(Anderson, 1975; Melosh, 1976; Savage and Prescott, 1978). In general, the more viscous the asthenosphere is, the more slowly the lithosphere moves. Figure 2.7 illustrates this situation for points A and C, which are quite far from the plate boundary. By measuring the deformation of the lithosphere as a function of time, we can estimate the effective viscosity and other mechanical properties of the asthenosphere. The viscosity of the mantle has been estimated from the response of the earth's crust to the removal of glacial load (see Chapter 4). The results to be obtained from present-day plate-motion measurements will complement those obtained from glacial rebound and provide more complete information on the mechanical properties of the asthenosphere, which are of fundamental importance.

2.2.3 Mode of Subduction

Recent seismological studies suggest that the degree of mechanical coupling between the two opposing plates at subduction zones varies substantially from region to region. At some subduction zones, e.g., Alaska and Chile, the two plates are strongly coupled and are usually locked completely. Slip on the interface takes place only at the time of large earthquakes. In other words, the plate motion at the boundary is taken up mainly by seismic slip. On the other hand, at subduction zones such as the Marianas no large earthquake has occurred for at least several hundred years (e.g., Kanamori, 1977b). One possibility is that the mechanical coupling there is so weak that the plate can move continuously without causing intermittent large earthquakes (aseismic slip). Another possibility is that subduction in such areas has ceased in recent geologic time because of changes in the distribution of the forces acting on the plate (Kelleher and McCann, 1976). Direct measurements of plate motion at subduction zones would help to solve this problem.

2.2.4 Seismic Gaps

A segment of plate boundary that broke in a large earthquake at least once in the past but has not broken during the past several tens of years is called a seismic gap. In terms of the plate model described above, a locked plate boundary that has not broken for a long time (e.g., a large fraction of the mean reoccurrence time for large earthquakes in the area) is more likely to rupture in the near future. The concept of seismic gaps has been used successfully for long-term prediction of major earthquakes (for a recent review see McCann *et al.*, 1979). The examples are the 1972 Sitka, Alaska, earthquake; the 1973 Nemuro-Oki, Japan, earthquake; and the 1978 Oaxaca, Mexico, earthquake. In order to make effective use of this concept for earthquake prediction and hazard-reduction purposes, it is essential to evaluate the seismic

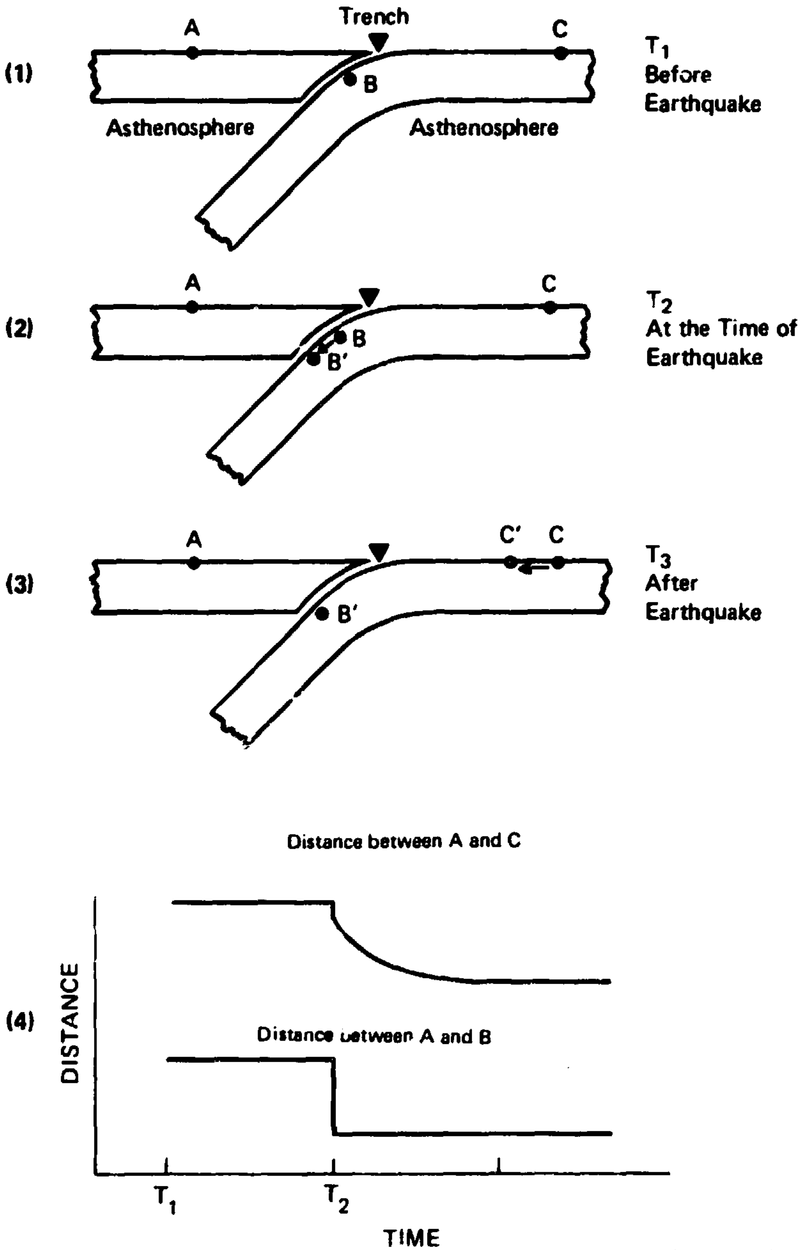

FIGURE 2.7 Transient plate motion at plate boundary (1) before earthquake. (2) at the time of earthquake B moves to B', (3) after earthquake C moves to C' with time delay, (4) distance between A and B and A and C as a function of time.

potential of existing seismic gaps, one example of which is a gap near Shumagin Island off the Alaska peninsula. The key parameters are the rate of present plate motion and the nature of the boundary (seismic or aseismic), both of which can be determined by direct measurements of the present-day plate motion in the regions of identified seismic gaps.

The present-day plate motion can be determined by directly measuring the change in interplate distances (distance between interior points on different plates) as a function of time. This type of measurement requires the capability of measuring very accurately (to a few centimeters or less) the length of very long (several thousand kilometers) baselines straddling different plates and continents. Such capability can only be provided by geodetic space techniques such as VLBI or satellite laser ranging or the Global Positioning System (see Chapter 5).

Since for a given time interval, a pair of fast-moving plates yields a larger measured displacement than a pair of slow-moving plates, it is desirable in the initial stage of the experiment to choose pairs of fast-moving plates for the measurements. This will provide more definitive results within a relatively short time period. Also, extensive use of islands located at key places within the interiors of mainly oceanic plates should be made, but the stability of the islands should be carefully examined.

Although it is generally agreed that the concept of rigid (undeformable) plates is a good first approximation, the lithospheric plates are not rigid and deform under large-scale tectonic stresses. This deformation takes place in the form of either seismic faulting (intraplate earthquakes), seismic creep, or slow tectonic crustal deformation, both vertical and horizontal (e.g., Melosh, 1976; Sykes, 1978). There is a possibility that the details of intraplate deformation have escaped observation because of various technical difficulties inherent in traditional geodetic methods (see Chapter 5). If the interplate measurements were made only between four points, two points on each plate, then the results could be contaminated by the possible intraplate deformation. In order to estimate the amount of intraplate deformation, it is necessary to have several reference points on each plate. Without these reference points (sites), the estimates of the inferred interplate motion would be subject to systematic error.

RECOMMENDATION 2.3 *We recommend that geodetic space techniques (very-long-baseline radio interferometry, satellite laser ranging, and the Global Positioning System) be used for the following:*

(a) Measurements of temporal variations in distances between interior points on different plates for the purpose of comparing contemporary velocities with those inferred from data for the last few million years;

(b) Global studies of the mode of the strain release at plate boundaries; and

(c) Measurements of intraplate deformation; and

that priority in selection of plates for which measurements are to be made should include the following considerations:

(a) Rates and precision of current estimates of plate velocities;

(b) Existence of seismic gaps;

(c) Current level of seismic activity;

(d) Expected mode of stress release as established by seismological evidence; and

(e) Evidence of intraplate deformation from seismological and neotectonic data.

3

Measurements of Deformation near Active Plate Boundaries

Relative motion between tectonic plates results in earthquakes and rock deformation concentrated in relatively thin zones known as active plate boundaries. Tectonic evidence indicates that these zones vary in width from less than 100 km (for example, at the Mid-Atlantic Ridge) to several hundreds of kilometers (for example, in western North America). Ground displacements in these zones may include sudden displacements, such as earthquakes; secular deformation, considered to be steady during our lifetimes; and displacements at intermediate rates (e.g., creep events). The relative contribution of these types of motion to earthquakes and rock deformation is unknown.

There are both practical and fundamental scientific reasons for application of advanced geodetic techniques to the study of these deformations. *Practical reasons* include the hope of detecting earthquake precursors and the assessment of geological hazards. The anticipated cumulative losses from earthquakes in California have been estimated to be in excess of $2 billion by the year 2000 (Alfors *et al.*, 1973). *Scientific reasons* include the need to understand better earthquake source mechanisms; the relationship between observed displacements and plate motions; and the mechanisms of mountain building, rifting, and other geologic processes. These topics are, of course, strongly coupled: a better knowledge of earthquake source mechanisms would help us to recognize earthquake precursors; mountain building is intimately related to plate-tectonic deformations; and earthquakes play an important role in plate movements.

We note specific contributions that geodesy could make toward further progress. Qualitatively, our recommendations can be summarized in four general conclusions:

1. Traditional geodetic methods, especially trilateration and leveling, are providing valuable data, and they should be strongly supported.

2. Substantial improvements in accuracy of traditional geodetic methods are feasible and should be given high priority.

3. Information obtained as a result of important new developments in geodetic and geophysical instrumentation, including long-baseline strain and tilt measurements, borehole tilt measurements, and data from space techniques such as the Global Positioning System, could dramatically improve our knowledge of the dynamic behavior of the lithosphere at active plate boundaries. These techniques should be aggressively developed over the next three years, so that the most suitable ones can be used in meeting the measurement goals for the remainder of the decade.

4. The main geodetic measurement goals during the next decade for major seismic zones should be as follows:

    (a) Improvement of the accuracy and coverage of long-term deformation measurements in the western United States and Alaska;

    (b) Establishment and operation for 5 years of a rapid resurvey (roughly 2-week intervals) measurement program between points every 10 or 20 km along the major active faults in the United States.

    (c) Establishment of fixed instruments with similar spacing to detect whether precursory motions occur over periods of minutes to a couple of weeks before large earthquakes;

    (d) Extension of long-term deformation monitoring to a number of the major non-U.S. seismic zones of the western hemisphere and western Pacific using space techniques. Such measurements would be made cooperatively with scientists in the countries involved; and

    (e) Establishment of the capability to measure motions of points on the ocean floor up to several hundred kilometers offshore with respect to reference points on land, with an accuracy of 10 cm.

We also discuss some specific experimental capabilities that are needed in the study of active plate margins. A summary of these recommended capabilities is given in Table 3.1.

3.1 OBJECTIVES FOR GEODETIC MONITORING IN SEISMIC ZONES

It is important to distinguish between different objectives for monitoring crustal movements in seismic zones, since different geodetic techniques may be appropriate. Approximately in order of increasing difficulty, the main objectives are as follows:

1. Monitoring of long-term strain accumulation patterns and rates in and around seismic zones,

TABLE 3.1 Recommended Experimental Capabilities

Recommendation Number	Baseline or Spacing (km)	Sampling Interval	Accuracy[a]	Component[b]	No. of Sites	Potential Types of Instruments and Methods
a. Long-Term Strain Accumulation						
3.3	1-100	1 yr	10^{-6}	v		Leveling
3.3	10-30	1 yr	10^{-7}	h		Trilateration
3.8	100	1 yr	3×10^{-7}	v, h	50	GPS, trilateration
3.4	50	10 yr	10^{-6}	v, h	100[c]	Leveling, trilateration
3.7	100	1 yr	10 cm	v, h		Ocean-bottom instrumentation
b. Rapid Resurvey Mode						
3.6a	1-10	1-4 wk	10^{-7}	h		Trilateration
3.5	10	1-4 wk	10^{-6}	v, h		GPS gravity, trilateration
c. Nearly Continuous Recording						
3.6c	1-10	1 day 1 h 1 sec	5×10^{-8} 10^{-8} 5×10^{-9}	v, h	3	C.M.O.[d]
3.6d	10	1 mo 1 day 1 h	10^{-6} 10^{-6} 10^{-6}	v, h	10	GPS, laser-EDM, tilt
3.6b	10	1 yr 1 mo 1 day	10^{-5} 10^{-6} 10^{-7}	v, h	100	Tilt, strain

[a] Accuracy in strain units unless otherwise stated, in which case displacement accuracy is given.
[b] v, strain from vertical displacement; h, strain from horizontal displacement.
[c] Alaska and Aleutian Islands.
[d] C.M.O., Crustal Movement Observatory (continuous-recording, high-accuracy strain, tilt, and gravity meters).

2. Detection of possible medium-term episodic strain changes, and
3. Detection of possible short-term precursors that may occur before large earthquakes.

These objectives are discussed in the following subsections. The various measurement techniques are described in Chapter 5.

In addition to the above objectives for regular geodetic monitoring, a rapid resurvey capability for measuring transient postseismic motions and strain release by aftershocks should be maintained. In order to detect postseismic motions after a large earthquake, a detailed plan of action needs to be available in advance. The type of rapid resurvey capability discussed in Section 3.4 is desirable, but much simpler instruments are likely to be equally important for measurements over shorter distances. A major requirement in either case is that suitable control points must have been established beforehand and their positions must be redetermined at regular intervals.

We believe that postseismic motion measurements for understanding earthquake processes must be important (see Section 2.2). Thus, substantial allocations of resources to the preparation of suitable control points and to the establishment of a detailed plan of action are well justified. The plan would have to be quite redundant, of course, because of obstacles arising from the major damage to facilities and breakdown in normal services that would follow a large earthquake.

3.1.1 Monitoring Long-Term Strain Accumulation

One of the most useful crustal movement monitoring efforts during the last decade has been the nearly annual remeasurement of the trilateration networks in California, Nevada, and Alaska. These networks cover a number of major seismic zones and consist of about 1200 lines. The accuracy is typically about 3 parts in 10^7, as discussed in Chapter 5. In order to achieve this accuracy, aircraft are flown along the lines to measure the atmospheric density and composition.

Another major monitoring effort involves vertical motions. A releveling of a large area in southern California was carried out by a number of agencies in 1978. The purpose was to provide a basic reference data base to which any later leveling results could be referred. Releveling of a few lines in critical areas is being carried out annually. A network of over 300 gravity measurement sites has been established in southern California in order to detect changes in gravity. Most of the sites are located on crystalline rock outcrops in order to minimize the effects of changes in the water content of deep aquifers or changes in the near-surface water-table level. Measurements are made roughly every 2 years at present.

Monitoring of the positions of approximately a dozen sites in California by space techniques has been started recently. The techniques being used are very-long-baseline radio interferometry (VLBI) and satellite laser ranging (SLR). The schedule of measurements is variable, and the accuracy does not appear to be well known at present. Measurements using signals from the Global Positioning System (GPS) satellites may complement the VLBI and SLR methods for most sites in seismic zones in the future.

Substantial extensions of the trilateration networks to cover wider areas around the fault systems are highly desirable. However, the most urgent needs are for improved measurement accuracy for each of the monitoring techniques now being used. For trilateration, an accuracy of 1 part in 10^7 would permit conclusions about changes in strain accumulation patterns to be made more reliably and over shorter time intervals. For gravity, an accuracy of 3×10^{-8} m/sec^2 would permit vertical motions of as little as 1 cm to be detected, depending on the accompanying mass redistribution that may take place.

In the case of leveling, the main need is for procedures to avoid systematic errors that are correlated with the topography. A maximum systematic error contribution of 1 cm/km of elevation difference is desirable if it can be achieved. For the space techniques, an accuracy of 2 cm in each coordinate is desirable; this accuracy would be independent of the distance between points for the most part.

If each of the techniques achieved the accuracy mentioned above, the efficient use of the various methods would depend on the costs and on the differences in accuracy. For sites where hydrological conditions did not cause gravity measurement problems, the combination of trilateration and gravity monitoring probably would be attractive from both the accuracy and cost standpoints. Thus it is important to determine the feasibility and cost of achieving the stated accuracies for routine measurements in the next few years. For long-term strain accumulation, space techniques may be most useful for determining the motion of points along the faults with respect to reference points some distance away. Both leveling and space techniques will be needed for checking on apparent changes detected by the other methods.

3.1.2 Medium-Term Episodic Strain Changes

In this section, we take medium-term motions to be those with time scales of roughly 2 weeks to 6 months. The reason for treating such motions differently from long-term strain accumulation is that the cost per measurement is likely to be a considerably more important factor. Also, since the phenomena of interest are episodic, there is no clear reason why the strain and tilt amplitudes should be limited to the 1 or 2 parts in 10^7 of the annual amplitudes observed for long-term strain accumulation. Thus, while high accuracy is still desirable, it may be necessary to sacrifice it to some degree in favor of more economical measurements that can be made more frequently.

One purpose of monitoring medium-term episodic motions is to learn more about the preparatory phases of large earthquakes. Increased information on what is happening may help in forecasting whether an increased level of hazard exists in a particular region. However, an additional benefit of medium-term monitoring is that any motions detected would help to identify regions of special study where dense networks of fixed instruments should be installed. Information from such dense networks, along with seismic measurements, may be the most likely data bases from which actual earthquake predictions could be made (also see Section 3.1.3).

As an example, we consider a possible rapid resurvey program consisting of measurements twice per month at sites located every 10 km along 2000 km of major fault systems in California and Nevada. With a GPS receiver and a water-vapor radiometer mounted in a small van or recreation vehicle, as discussed in Chapter 5, and with measurement sites located along roads, the travel time could be minimized. The philosophy would be to automate the data recording and radiometer scanning so that the driver would only have to orient the vehicle roughly over a control point and determine the offset. The measurement time could be as short as 30 min or less per site, provided that the previous control point locations were known and that measurements to resolve the phase ambiguities for the GPS signals were not needed. The recorded data could be fed to a computer once a day, and longer-duration repeat measurements would be made the next day at any site where the results were not consistent with the previous coordinates.

A GPS rapid resurvey program is, of course, only one of the options that needs to be considered for monitoring possible medium-term motions. Based on our present understanding, the accuracy would be considerably worse than probably could be achieved for horizontal strains by using multiwavelength distance-measuring instruments mounted in suitable vehicles. However, if the GPS approach turns out to be less expensive, then the tradeoff between accuracy and cost will have to be considered. We believe that at least these two options need to be explored thoroughly enough in the next 2 years so that establishment of a rapid resurvey program in at least some areas can be considered soon.

3.1.3 Possible Short-Term Precursors

The development of networks of fixed instruments along major fault systems for detecting possible short-term precursors before large earthquakes is a major task. We have no assurance that such precursors will have a substantial probability of occurrence, and their possible spatial patterns and amplitudes can only be estimated. However, recent experience indicates that precursory motions that occur only a few minutes to a few days before a large earthquake may be one of the two most valuable inputs to predicting the time, location, and size of the event. The other main input would be changes in local seismicity. A number of other types of information also would be used, but it is uncertain whether a valid prediction is likely to be made without either geodetic or seismic observations of precursory information, or preferably both. It therefore would be unfortunate if the next large earthquake occurs in the western United States before suitable networks for monitoring short-term geodetic precursors have been installed.

There are a number of types of instruments that could be used for monitoring at fixed sites. Most of these are discussed in Chapter 5. They range from various types of tiltmeters, strainmeters, and dilatometers to laser electromagnetic distance-measuring (EDM) instruments and to dedicated GPS receivers. The acquisition and installation costs vary considerably, as do the measurement accuracies and the sensitivities to local nontectonic disturbances. It should be kept in mind that the time between observations of spurious signals of a certain amplitude is likely to be a critical factor in evaluating performance. Instrument stability over periods of longer than a couple of weeks would be a substantial benefit, but it is not an absolute requirement because of the possibility of resurvey measurements at such time intervals.

One difficulty in evaluating the effectiveness of various possible networks containing different types and numbers of instruments is the lack of a generally accepted standard for detecting possible precursory events. In comparing two networks, one possible approach is to estimate the smallest magnitude earthquake for which the coseismic displacements would have perhaps a 70 percent chance of being detected if the earthquake occurred at random anywhere along the fault segment of interest. To avoid the singularities in strain and tilt amplitudes for short instruments crossing the fault when the fault break reaches the surface, only fault breaks with minimum depths of about 5 km probably should be considered. It is recognized that the possible precursory displacements before a large earthquake are likely to be considerably smaller than the coseismic ones and may have a much different spatial distribution. However, the smallest magnitude earthquake for which the coseismic displacements, strains, or tilts could be detected still seems like a useful measure of the relative effectiveness of two different proposed networks.

As an example, we show in Figure 3.1 the coseismic displacements and strains for a typical magnitude-6.0 strike-slip event that has a minimum depth of 5 km for the fault break. The fault break dimensions of 22-km length by 6.3-km depth and the offset of 20 cm are taken from Chinnery (1970). This case admittedly contains several arbitrary assumptions, but it still gives some initial indication of the relative sensitivities needed for strain and displace-

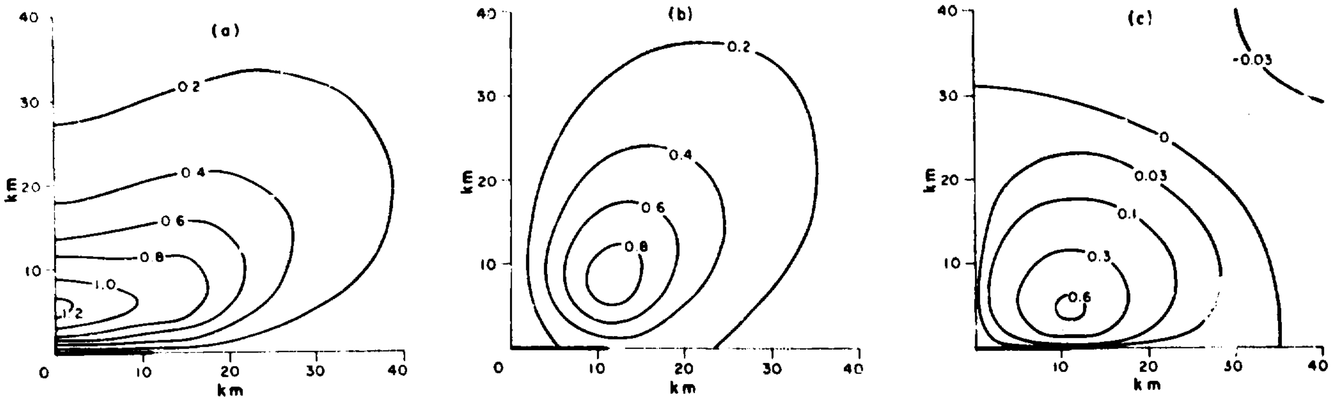

FIGURE 3.1 Ground displacements in centimeters for a magnitude-6 strike-slip earthquake with top of rupture at 5-km depth: (a) parallel to break, (b) perpendicular, (c) vertical.

ment measurements in order to detect precursory motions with maximum surface displacements of roughly 1 cm. Improved models for precursory motions under a range of assumptions about the strain release pattern are needed for evaluating proposed instrumental networks.

If the case is to be made for obtaining the additional resources required to install networks of fixed geodetic instruments, a considerable amount of preparatory work will be needed. The most promising types of instruments will have to be developed to see if they can meet their expected accuracy and cost figures. Small groups of instruments then will have to be deployed in field-type installations in order to determine the effects of local nontectonic noise sources, as discussed in Chapter 5. The magnitude of the required instrumentation development and testing is large, and a rapid start on this task is necessary if networks for monitoring possible short-term geodetic precursors are to be achieved by the mid-1980's.

3.2 PROBLEMS IN GEODETIC DATA ACQUISITION AND ANALYSIS

Geodetic data have contributed to the understanding of earthquakes and tectonic processes. However, many of the existing data have been examined only briefly, and some not at all. It is important to analyze these data thoroughly for several reasons. First, the data may contain important scientific findings. Sometimes these findings are not evident in a cursory inspection, and different types of analysis may suggest important generalizations. The discovery of seafloor spreading, the keystone of the theory of plate tectonics, was based in large part on marine magnetic data that were up to 17 years old (Heirtzler, 1968). Second, when new experiments are planned, the lessons from previous experiments should be learned well. Although we need to understand better the limiting factors in the accuracy of triangulation and leveling data, still, existing data may contain important clues. Information on the spectra of ground motion may be important in siting requirements for further geodetic study. Third, leveling data may be subject to serious systematic errors, as discussed below. The errors must be explained and their causes identified. Given the significance and the cost of acquiring geodetic data, the existing and newly acquired data certainly warrant more extensive analysis.

3.2.1 General Consideration

Theoretical modeling studies and data analysis need serious attention and should be closely integrated with the experimental studies recommended here. If experimental data are to be used to test hypotheses, these must be formulated in sufficient detail. Theoretical modeling is also important in relating geodetic data to geological and geophysical data. For example, the lack of a significant heat-flow anomaly along the San Andreas Fault poses a strong constraint on the plate displacement mechanism because the frictional heating implied by many simple models would produce such an anomaly (Lachenbruch and Sass, 1973). Theoretical modeling is needed to explore the consequences of such constraints for the possible modes of deformation in the active plate margin. Modeling may suggest specific geodetic experiments to test basic hypotheses.

RECOMMENDATION 3.1 *Theoretical studies and analysis of existing data should be given much higher priority than they currently enjoy:*

- *The efforts of the National Geodetic Survey and other federal agencies to make data available in computer-compatible form should be strongly supported;*
- *Implications of existing data should be thoroughly studied in the formulation stage of new experimental programs; and*
- *Plans for new experimental programs should contain adequate provisions for dissemination and analysis of data.*

3.2.2 Accuracy of Ground-Based Geodetic Techniques

3.2.2.1 Vertical Displacements

In the following discussion, the question of achievable accuracy of geodetic methods is important. The usually quoted estimate for the uncertainty in heights from a double-run first-order geodetic leveling survey are as follows:

The random part of the error (Bomford, 1971; Committee on Geodesy, 1978) is

$$\sigma = \alpha\sqrt{L},$$

where σ is the standard deviation in millimeters, L is the distance between benchmarks in kilometers, and α is about 0.7. In addition, there may be systematic errors of up to 0.06 mm times L resulting from such items as benchmark and turning-point instabilities and imperfect leveling instruments. Imperfect rod calibration and unequal refraction may contribute systematic errors generally claimed to be less than 10^{-5} times the elevation change observed, although relative errors of 2 parts in 10^4 have been reported (Bomford, 1971). For a 1-km survey with 100 m of elevation change, the random error and the elevation-dependent error should both be of the order of 1 mm. Thus, from repeat surveys, tilts of the order of 1 part in 10^6 should be resolvable. For a 100-km-long survey with 1 km of elevation change, all three types of error should be of the order of 10 mm; repeat surveying should resolve tilts of the order of 1 part in 10^7. Unfortunately, some recent results in the United States suggest that not all first-order leveling data are consistent with the above criteria.

The importance of measurement accuracy is highlighted by the ongoing debate about the reported aseismic uplift in southern California (the "Palmdale bulge"). As reported by Castle (1978), leveling data show that a large region of southern California was uplifted by as much as 450 mm between 1960 and 1974, then down-dropped to its previous elevation after 1974 (Castle *et al.*, 1977). The implied tilts were on the order of several microradians, well above the claimed accuracy of precise leveling. However, Jackson *et al.* (1980) and Strange (1981) have suggested that the apparent uplift may be the result of height-dependent systematic errors. Stein (1981) and Mark *et al.* (1981) have defended the tectonic interpretation. Regardless of the outcome of these discussions, it is clear that the effects of systematic errors in leveling data need to be studied thoroughly. Extra care must be taken in the development of new geodetic techniques. Because of the great importance of geodetic data in tectonic studies, we must be certain that we understand the limitations of the techniques before we interpret the data.

Gravity observations may be used to determine elevation changes, provided that lateral mass redistribution has not taken place. Gravity and either leveling or geometric height measurements should be used in conjunction in order to test this assumption. Moreover, gravity measurements are less expensive than leveling and could be used in reconnaissance to identify episodic changes. Special leveling surveys could then be used to aid in the interpretation of any episodic changes. The repeatability of gravity measurements is about 10^{-7} to 2×10^{-7} m/sec^2 under controlled conditions; this corresponds to an uncertainty in elevation change of 30-60 mm. This uncertainty is within the range of estimates of leveling uncertainty over 100-km lines with elevation changes of 1 km. But in view of the above-mentioned difficulties of precise leveling, gravity measurements may be a valuable supplement.

3.2.2.2 Horizontal Displacements

The most accurate ground technique for measuring horizontal distance over baselines of 10-30-km length is trilateration using the laser geodimeter. By flying an aircraft along the line of sight to determine the atmospheric index of refraction, a measurement uncertainty of

$$\sigma = \sqrt{a^2 + b^2 L^2}$$

has been achieved, where a = 3 mm, $b = 2 \times 10^{-7}$, and L is the distance in millimeters (Savage and Prescott, 1973). This measurement uncertainty includes contributions from both systematic and random errors. Thus, the uncertainty for some quantities of interest, such as dilation, may not be reduced substantially by averaging over many measurements within a network. Savage *et al.* (1981) have recently given a careful discussion of strain accumulation in southern California based on roughly annual trilateration measurements and have presented evidence that the systematic errors are probably within the range given by the above formula.

3.2.2.3 Conclusion

Both trilateration and leveling have provided valuable information about seismic displacements and about secular deformations. The trilateration results and many of the leveling results are not put in doubt by the estimated magnitude of systematic errors. These methods should continue to supply crucial information in the study of crustal deformation. However, systematic effects should be considered and resolved before apparent geodetic changes are interpreted as having tectonic causes.

RECOMMENDATION 3.2 *The techniques of acquisition and analysis of geodetic data used for monitoring tectonic motions should be thoroughly investigated for validity. Intercomparisons of space- and ground-based geodetic techniques should be given a high priority.*

Comparisons should be made over the range of baselines between 10 and 200 km and should include areas of steep topography. The VLBI and laser-ranging sites should be tied into the existing horizontal and vertical control networks to the greatest possible extent.

3.3 PROBLEMS IN EARTHQUAKE STUDIES

Important characteristics of earthquake mechanisms include the size and shape of the ruptured surface, its orientation and the faulting motion on this surface, and the time history of the process. Information on the dimensions of the faulting surface can be obtained from direct observation of ground breakage, geodetic data, the distribution of aftershock locations, and the characteristics of seismic radiation. Seismic data have in general provided most of the detailed information about seismic source mechanisms because seismic waves radiate away from the source region and can be detected at many distant sites. Observation of ground breakage and geodetic resurveying are in some sense more direct, but in many cases no ground breakage occurs in accessible areas, and geodetic resurveying requires accurate prior surveys in the source region of the earthquake. It is important, however, in the interpretation of these data to allow for the possibility that a considerable amount of this deformation may be due to either preseismic or postseismic slip.

Displacements directly observed on the earth's surface are consistent with three principal modes of faulting: i.e., strike-slip, thrust, and normal; these observations provided the first estimates of fault length and fault displacement.

Earthquake sources are generally described in terms of the "dislocation" model, in which the two sides of a fault surface undergo sudden relative displacement. The relative displacement of a point on one side of the fault surface with respect to its opposing point is a vector that depends on position within the fault plane and on time as well. It is usually assumed that the displacement vector must be tangent to the fault surface. It is also usually assumed that the fault surface is planar. However, many faults are known from direct observations to be curved, and commonly many separate fault surfaces are involved in a given earthquake. Except where the displaced fault surface (the rupture surface) intersects the ground surface, the fault displacement probably tends continuously to zero at the boundary of the rupture surface. In addition to the fault surface and the distribution of displacement on this surface, a completely specified fault model should include a time history of breakage on the fault and the variation of stress within the fault zone both before and after the rupture.

In practice, the general fault model described above is usually simplified greatly. The rupture surface is assumed to be rectangular, and only the average fault displacement, initial stress, and stress drop over the rupture surface are estimated from the data. For some long rupture zones, the direction and velocity of rupture may be estimated from seismic data; some earthquakes appear to have uniform rupture velocity, while others are characterized by jerky fault motion (multiple events). For magnitude-8 events, the fault length may be hundreds of kilometers, and the displacement may be several meters. For magnitude-5 earthquakes, the rupture length may be only a few kilometers and the displacement on the order of a few centimeters. The ratio of displacement to rupture length ranges from 1 part in 10^6 to 1 part in 10^4 for earthquakes in California and Japan, independent of magnitude (Kanamori, 1978).

The distinction between the more general fault models and the simple approximations may be important in better understanding earthquake source mechanisms and in predicting earthquakes. The postearthquake stress pattern, which largely determines the time and location of the next earthquake, depends on the distribution of fault displacement as well as on the mechanical properties of the fault zone. It is certainly not adequately described by the simplified models.

The task of obtaining information on the details of the faulting process from seismic data is extremely difficult. It is not clear that traditional seismic data can provide all the relevant information. Most of the energy in recorded seismic signals is limited to the range of periods from 0.1 to 10 sec, although a few long-period seismographs can detect ground motion at 1000 sec. Fault motion that takes place over longer times will be undetected seismically but may substantially alter the stress distribution. Nonelastic effects are almost surely involved in controlling the rate of occurrence of aftershocks, and thus there is a strong likelihood that slow nonelastic processes may change the stress distribution without releasing detectable seismic radiation. A major contribution can thus be made by geodetic methods capable of detecting the quasi-static displacements outside the seismic bandwidth. Classical geodetic techniques can be quite adequate for this purpose if they achieve the claimed accuracy.

A great contribution from geodesy to the conceptual understanding of earthquakes was the set of triangulation measurements before and after the 1906 San Francisco earthquake that led to the formulation by Reid (1910) of the elastic rebound theory. Leveling observations have been useful in estimating parameters of earthquake source models. Resurvey data for the 1923 Kwanto earthquake (Muto, 1932), the 1927 Tango earthquake (Tsuboi, 1932), and the 1946 Nankaido earthquake (e.g., Ando, 1975) have been exemplary in detailing both coseismic and postseismic displacements for these Japanese events. These data have been extensively used in constructing theoretical models of earthquake source mechanisms and postseismic adjustments (e.g., Fitch and Scholz, 1971; Nur and Mavko, 1974; Thatcher and Rundle, 1979).

3.4 MEASUREMENTS OF LOCAL STRAIN ACCUMULATION AND RELEASE NEAR THE FAULT ZONES

There are several ways in which geodetic data could provide important advances in knowledge of earthquake source mechanisms. Probably the greatest need is for improved area coverage. More information of the type already being collected by classical methods would be valuable in studies of the earthquake mechanism, plate-tectonic displacement accumulation, local tectonics, and earthquake prediction. Improvements in accuracy could make possible earthquake mechanism studies on smaller (and more frequent) earthquakes and may reveal earthquake precursors.

RECOMMENDATION 3.3 *Current efforts in trilateration, in repeat gravity measurements, and possibly in leveling and tide gauge measurements should be significantly expanded. Improvement of accuracy in horizontal distance measurements to 1 part in* 10^7 *or better and in gravity to* 3×10^{-8} m/sec^2 *are recommended.*

Much of what we now know about earthquake sources comes from a comparison of pre-earthquake and postearthquake geodetic surveys. The value of such comparisons depends on the accuracy of the pre-earthquake surveys, and the value is strongly enhanced when the pre-earthquake data are relatively recent. Most of California is covered reasonably well by the existing geodetic control networks. This is not true for other earthquake-prone parts of the United States, especially for Alaska, which contains the most remarkable convergent plate boundary on U.S. territory and several identified seismic gaps; a typical width of a seismic gap is 100 km.

RECOMMENDATION 3.4 *For investigation of near-field, postseismic effects of major earthquakes, a monumented network of geodetic and gravity stations should be established with a spacing of 50 km along the southern coastline of Alaska, including the Aleutians. This network should be monitored with an appropriate frequency after an earthquake of magnitude 7.5 or greater in the vicinity of the network, and at least once every 10 years.*

It is vitally important to obtain information between the short periods (up to 1 h or so) resulting from seismological observations to the longer periods (greater than several years) obtained from geodetic observations. For the 1964 Alaskan earthquake, Brown *et al.* (1977) found postseismic relaxation effects with a time scale on the order of 5 years. As shown in Figure 3.2, a large fraction of the vertical displacements occurred in the first year after the earthquake; it is not clear from the data how much of this early displacement is related to aftershocks, or whether there might be crustal relaxation processes on a time scale shorter than 5 years.

In the best-studied U.S. earthquake to date, the San Fernando earthquake of 1971, there is indication of a possibility of significant postseismic adjustment during a 2½-year period following the earthquake (Savage and Church, 1975; Figure 3.3). More frequent observations (at least monthly) are necessary to refine the time scale of these adjustments, and greater geographical coverage is necessary to determine the distribution of fault displacements.

There is increasing evidence that a substantial part of the faulting associated with earthquakes takes place too slowly to be detected by most seismometers. There is the further possibility that slow or "silent" earthquakes may result in significant displacements, and anelastic processes following earthquakes may strongly affect the stress environment. These phenomena would lead to episodic ground displacements that might not be much smaller than those produced by seismic events. Recent trilateration studies suggest changes in regional crustal strain on a time scale of months or less (Savage *et al.*, 1980).

RECOMMENDATION 3.5 *Measurements at intervals from 1 week to 1 month of horizontal distances (over 10-km baselines or less) with an accuracy*

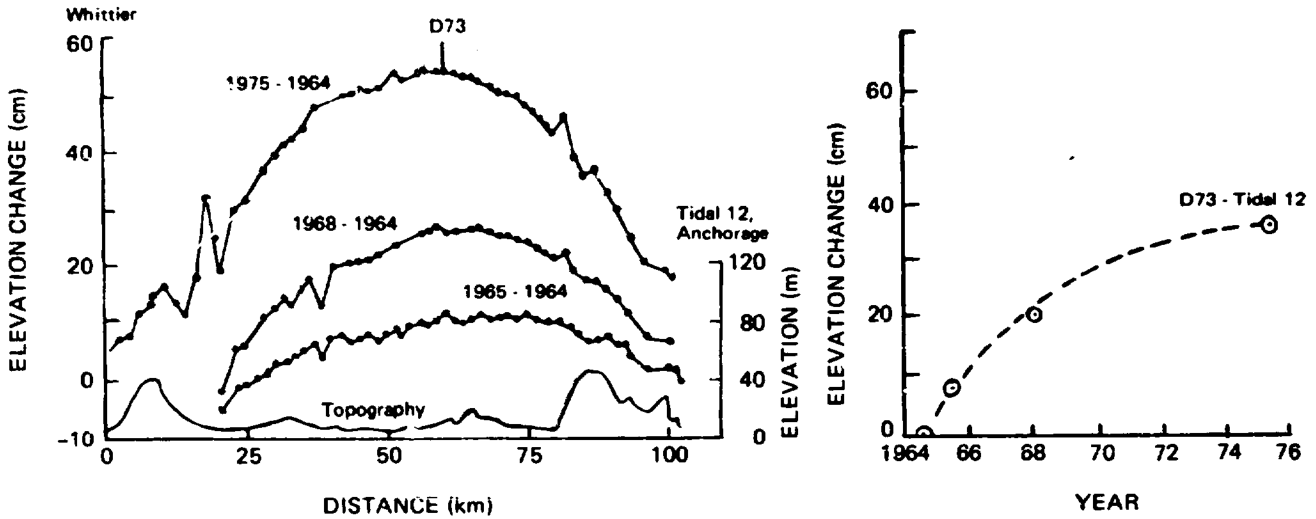

FIGURE 3.2 Vertical displacement after the 1964 Alaskan earthquake.

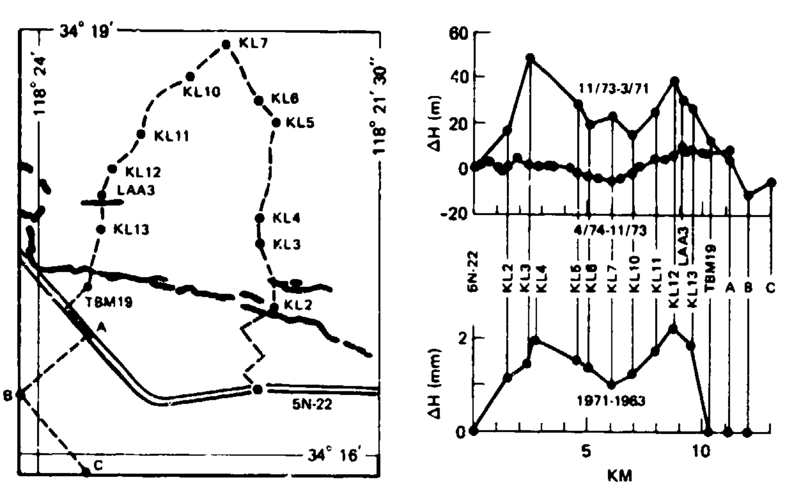

FIGURE 3.3 The Kagel-Lopez Canyons level route (left) and elevation changes along that route. The lower curve right shows elevation changes between 1963 and 1971, most of which presumably occurred in 1971 at the time of the earthquake. The upper curve shows the elevation changes in the periods April 1961 to November 1973 and November 1973 to April 1974. Note that the scale in the upper plot is in millimeters, and in the lower plot it is meters (Savage and Church, 1975).

of better than 1 part in 10^6 should be carried out along major faults at 20-km spacing to detect occurrence of episodic strain changes. Vertical displacements should be measured with an accuracy of 10-20 mm over the same baseline lengths and time intervals.

The recommended horizontal measurements could be made with existing multicolor laser distance-measuring systems or possibly by means of the new space techniques. The vertical observations could be made using a combination of frequent precise gravimetry and less frequent leveling or with space techniques.

In order to improve the chances of detecting precursory strain anomalies, and to monitor seismic and postseismic strains at reasonable distances from moderate earthquakes, greater accuracy is desired. Because the strain from a hypothetical precursory event will fall off rapidly with distance, the probability of detecting such an event depends on both the number and the accuracy of strain measurements to be made. Stated another way, the effective radius within which a strainmeter could detect a precursor depends strongly on its detection threshold. There is clearly a tradeoff to be made between the number of sites and their sensitivity. Because many populous areas are probably unsuitable for the deployment of strainmeters and tiltmeters, we should anticipate a minimum spacing of about 10 km. Thus we should develop instruments with the accuracy required to detect the strain and tilt signals from possible precursory fault motions at a distance of 20 km or more. If aseismic and seismic displacements are similar, the magnitude of expected strains is unlikely to exceed 1 part in 10^6 at a distance of 20 km from their source. In order to make a meaningful statement about the location or nature of any precursory strain or tilt episodes, an accuracy of at least 1 part in 10^7 would be required. Recommendation 3.6(a) addresses the minimum requirements for a program to detect strain or tilt precursors to earthquakes and to improve the spatial resolution of postseismic displacements.

Improved time resolution is important in order to understand better the history of stress release during earthquakes and other episodes of displacement. However, the expected strains may be above the noise level only in the near field of an earthquake, which prescribes a target zone of about 10-km radius for a magnitude-6 earthquake. But magnitude-6 events at a given site are rare: Richter (1958, p. 469) lists 37 earthquakes of magnitude 6 or greater for all sites in California and Nevada between 1903 and 1948. Three strategies can be employed to improve the probability of observing an event: (1) observe at moderate sensitivity in many places; (2) observe with the best achievable sensitivity at a few places; and (3) develop portable instrumentation to observe postseismic effects, including aftershocks. These strategies have strong scientific merit and provide the basis for Recommendation 3.6.

Several varieties of long-baseline and borehole tiltmeters are currently in the development stages and could possibly satisfy the requirements of Recommendation 3.6(b).

Earthquake mechanism studies require the observation of the history of episodic strain release during earthquakes. Detection of small-amplitude episodic displacements may also be useful in earthquake prediction. One strategy to observe these phenomena is to establish a few observatories having extremely high sensitivity for episodic displacements.

At present, the evacuated laser strainmeter, the borehole dilatometer, and several types of tiltmeter appear capable of providing this sensitivity. While these instruments are relatively expensive compared with those recommended in 3.6(b), the number of sites required is much smaller.

Adequate observations of coseismic displacements have been difficult to acquire because earthquakes seldom happen in the "right" place. However, the time, location, and magnitude of aftershocks can be predicted with useful accuracy, although a short response time would be allowed. Observations of postseismic deformation would also be important in earthquake mechanism studies.

RECOMMENDATION 3.6 *We recommend that*

(a) Instruments be developed and tested that would permit weekly to monthly observations of accumulated strain and tilt at an accuracy of 1 part in 10^7 over baselines of 10 km or less;

(b) Inexpensive instruments, for high-density coverage, be developed for monthly, daily, or more frequent monitoring of strain and tilt at accuracies of 1 part in 10^6 for monthly variations and 1 part in 10^7 for daily variations;

(c) Instruments capable of measuring strains and tilts with a short time relative sensitivity of 5 parts in 10^9 and at sampling frequency up to one sample per second be developed for recording episodic displacements with time scales from tens of minutes to days; and

(d) Portable, readily deployable instruments should be developed for monitoring postseismic strains and tilts on an hourly basis with a precision of 1 part in 10^6 and gravity changes to an accuracy of 3 μgal.

The required strain measurements could possibly be made with improved electronic distance-measuring (EDM) equipment. The tilt observations would be more difficult but could possibly be provided by medium-baseline (100-m) tiltmeters or hydrostatic levels.

One of the major problems in earthquake mechanism studies is to obtain reasonably accurate displacement measurements for large earthquakes at convergent plate boundaries. The main difficulty is that the plate boundary is usually covered by water. It thus will be necessary to establish small networks of reference points on the ocean floor and to measure the distances from the networks to points on land on the other side of the boundary. Periodic remeasurements can determine the rate of strain accumulation across the boundary, while additional measurements soon after an earthquake would be able to determine the coseismic displacements.

The postseismic crustal deformation associated with large earthquakes, especially at subduction boundaries, may be of relatively short duration (numerical models suggest days to months). However, substantial motions may continue for a period of years. The measurement of temporal variations of crustal deformation during such periods of time is extremely important to studies of the mechanical properties of the asthenosphere (see Section 2.2).

One promising approach is to use a ship as a transfer point in carrying out the measurements. The position of the ship with respect to reference points on land can be determined by using signals from the GPS satellites. After correction for roll, pitch, and yaw, the ship's position can be monitored continuously, with the expected accuracy over a 200-km distance being 2 or 3 cm. Acoustic distance measurements along slant paths from the ship to three or more transponders on the ocean floor would be made in order to determine the displacement of the ship from the center of the transponder network.

The main accuracy limitation for the acoustic measurements probably would be uncertainty in the water density along the slant paths and thus uncertainty in the acoustic propagation speed. However, studies of density gradients in data from the Mid-Ocean Dynamics Experiment indicate that a positioning accuracy of somewhat better than 10 cm can be achieved in the deep ocean, even without local measurements of temperature and salinity profiles. For a ship positioned over the center of a baseline between two transponders on the ocean floor, only the horizontal gradient of the propagation speed is important. The effects of the gradients are relatively small because the slant paths are quite close together above the thermocline, where the gradients are largest. If measurements are made of temperature and salinity profiles versus depth at different points in the network, then a position accuracy of 5 cm or better should be feasible.

RECOMMENDATION 3.7 *We recommend development of a capability to measure, to a 10-cm accuracy, motions of points on the ocean floor up to several hundred kilometers offshore with respect to reference points on land.*

3.5 MEASUREMENTS OF REGIONAL STRAIN ACCUMULATION AND RELEASE

Although tectonic plates behave as rigid blocks to the first order, they clearly undergo severe deformation at their boundaries, but details of this deformation are poorly understood. Important questions include the variability in the rate of strain accumulation at plate boundaries on time scales less than 10 years and the relative roles of earthquake displacement, aseismic fault displacement, and anelastic straining in accommodating plate motions. Studies of several plate boundaries have shown that the displacement from known earthquakes in the past few decades accounts for less than 50 percent of the relative plate motion estimated from global plate-tectonic studies. The latter studies represent averages of motion over about one million years. In some cases, known earthquakes account for only a few percent of the expected plate motion. These discrepancies suggest that either plate motion is unsteady, the rate of earthquake occurrence has recently been atypically low, or aseismic displacement and inelastic straining account for the difference. Over a long enough time, the plate motion should be accounted for by some combination of (a) seismic displacements, (b) aseismic displacements on major faults, (c) aseismic displacements on smaller faults, and (d) distributed strain accumulation.

If all the plate motion were expressed as earthquakes on major faults, one might expect elastic strain buildup in a wide zone to be transferred to slip across the fault at the time of the earthquake. This is essentially Reid's

(1910) elastic rebound theory. If elastic strain accumulates uniformly in a zone of width w, the strain rate is

$$\dot{e} = v/w,$$

where v is the relative plate velocity. Over the last decade in southern California, shear strain has been accumulating at the rate of about 3 parts in 10^7 per year (Savage *et al.*, 1978; Figure 3.4). The shear strain is superimposed on an areal contraction, resulting in a puzzling uniaxial (north-south) contraction in the region of the big bend in the San Andreas Fault system. If we take the plate velocity to be 55 mm/yr, as determined from global plate motion studies, then the approximate width of the shear zone is $v/\dot{e} = 2 \times 10^5$ m = 200 km. To estimate relative plate velocity to within ±5 mm/yr, one would want to measure the relative velocity of two points at least 200 km apart to this same accuracy, implying a strain-rate sensitivity of 2.5 parts in 10^8 per year. [The strain patterns in southern California have been modified since 1979. Slater (1981) informed the Panel that recent results reveal that strain rates normal to the San Andreas Fault are highly variable.]

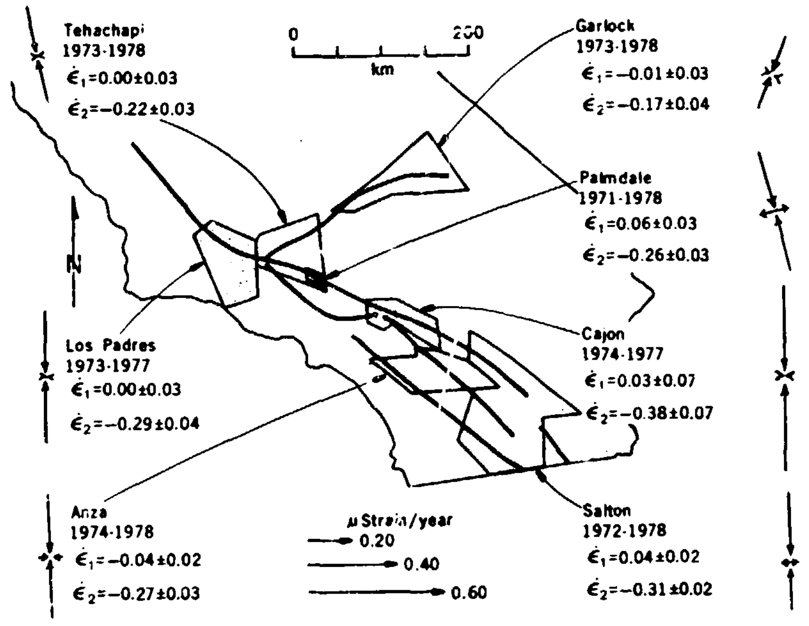

FIGURE 3.4 Map of southern California showing the location of the seven trilateration networks and the principal strains (in μstrain/year) measured at each. The heavy sinuous lines represent the major faults (Savage *et al.*, 1978).

If some plate motion is accomplished by aseismic slip on major faults, then the aseismic slip should be easily observed by geodetic surveys such as those currently being made across the San Andreas Fault system (Savage *et al.*, 1978). Thatcher (1975; 1979a; 1979b) has studied the displacement accumulating across the San Andreas Fault zone in northern, central, and southern California, using both triangulation and trilateration data. The trilateration data are more accurate; however, the triangulation data go back nearly a century, while trilateration data go back only two decades. Thus both data sets are comparable in importance. Almost all data were collected within 30 km of the major fault zones, with monument spacings of 10-30 km. In each region, net displacement across a zone of 60-70 km width has been estimated and compared with displacement localized at the San Andreas Fault.

Since 1950, the net displacement near Pt. Reyes, north of San Francisco, has been only 12 mm/yr, concentrated near the San Andreas Fault. Farther south near San Francisco Bay, the net displacement rate is approximately 25 mm/yr. This displacement is concentrated near the Hayward and Calaveras Faults east of the San Andreas Fault and appears to be parallel to the Calaveras rather than the San Andreas. Before 1950, the displacements near San Francisco were dominated by apparent aftereffects of the 1906 earthquake.

In central California, the net displacement rates have been steady at about 33 mm/yr since 1885, almost entirely concentrated at the San Andreas Fault itself (Figure 3.5). After fitting the data to a model of a buried dislocation

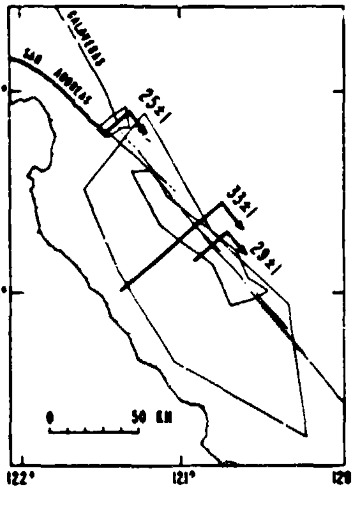

FIGURE 3.5 Relative right-lateral movement rates parallel to the San Andreas Fault determined using fault-crossing measurements from the Primary Arc, Hollister Arc, and Salinas Valley triangulation nets. Shown for reference is the area coverage of data used in each rate estimate (Thatcher, 1979a).

(that is, a dislocation embedded in the structure at a certain depth), the rate of total displacement at depth is estimated to be up to 45 mm/yr, comparable to the plate velocity.

In the "big-bend" region of southern California the picture is rather complicated; displacement rates vary with time and do not seem to be concentrated on major faults. Shear strain rates up to 2 parts in 10^7 per year persist out to distances of 100 km from the fault, but a meaningful net displacement rate is difficult to estimate because of the temporal and spatial variations of displacement.

Farther south in the Salton Trough, Savage *et al.* (1979) found that the total displacement rate is comparable to the plate velocity of 55 mm/yr. However, the displacement appears to be distributed across the valley, possibly on several faults, rather than localized on one fault as in central California.

Laser-ranging measurements to the Beacon Explorer-3 satellite (Smith *et al.*, 1979a) show an apparent shortening of the baseline between San Diego and Quincy, California, by 90 mm/yr during the interval 1972-1976. This rate is consistent with the results of measurements made in 1979 (NASA, 1980a). This baseline spans a much wider zone than that of the trilateration or triangulation studies and therefore presumably includes deformation on additional fault zones. The observed displacement rate apparently is larger than that estimated from plate tectonics, and if it is correct, it suggests that there are some dramatic surprises to be uncovered in attempting to reconstruct ongoing plate motion. (On the other hand, the possibility that the results might have been affected by errors in gravitational models used in analyzing the satellite data does not appear to have been ruled out.)

In summary, aseismic fault motion appears to play a major role in central California and possibly in the Salton Trough. In the latter case, it is difficult to distinguish aseismic fault motion from uniform straining because of the number of faults involved. In northern California the current displacement rate is much smaller than the plate velocity. In the big-bend region the situation is very complicated. Thus there are several distinct regimes of plate motion in California, none of them completely understood. Outstanding questions include:

(a) What is the net rate of plate displacement in southern California?

(b) What has happened to the expected displacement in northern California?

(c) How is the displacement in southern California distributed among elastic straining, inelastic straining, and slip on minor faults?

(d) Is the apparent displacement rate of 90 mm/yr across California real?

In California, at least, it is safe to assume that any motion on the major faults, seismic or otherwise, that is large enough to contribute more than 5 mm/yr to plate motion will be detected within two years by ongoing measurements. Assuming that the U.S. Geological Survey horizontal distance measurement program is vigorously supported and that Recommendations 3.3 to 3.6(a) are implemented, the question of aseismic motion on the major faults should be resolved in time, at least for California. We are still left with two important questions: (1) What are the relative contributions of aseismic slip on minor faults and uniform inelastic straining? (2) How wide is the active plate margin?

The first question can be answered with conventional geodetic data, but improvements in geographic coverage, spatial resolution, and accuracy are required. Recommendations 3.3 through 3.6(b) address these concerns.

The second question can best be answered directly by displacement measurements over baselines spanning the active plate boundary. The accuracy in strain rate required to resolve 10 percent of the estimated plate velocity for the North American-Pacific boundary over a 200-km baseline would be 2.5 parts in 10^8 per year. Even over 10 years, this would require a strain sensitivity of 2.5 parts in 10^7, a difficult task for conventional geodesy. We strongly urge the development of instrumentation (three-wavelength laser ranging, space techniques) capable of this accuracy.

RECOMMENDATION 3.8 *A capability should be developed for measurement on an annual basis of vector displacements of 100-km baselines with an accuracy of 3 cm or better.*

Special consideration must be given to convergent plate boundaries. Because of the great depth to which faulting takes place, it may be possible to distinguish between aseismic fault displacement and distributed inelastic straining. Furthermore, the fact that much of the active plate boundary is under water makes thorough study rather difficult. Certainly, the ocean bottom measurements suggested in Recommendation 3.7 would be valuable for documenting the displacements resulting from earthquakes. An additional consideration is that vertical displacements are expected to be significant in convergent plate boundaries. Vertical displacements deduced from tide gauge, leveling, gravity, and tiltmeter data could be important in revealing aseismic displacements [Recommendations 3.3, 3.5, 3.6(a), 3.6(b), and 3.8].

3.6 SUMMARY

Geodetic data have been extremely important in seismology and geology, and the needs are becoming stronger. To a large extent, seismologists and geologists have used geodetic data that have been collected for engineering or other purposes. There is now a need to design more geodetic experiments specifically for tectonic studies. Experimental capabilities required for seismic and tectonic studies in active plate margins are summarized in Table 3.1, which is divided into three parts according to the objective and mode of measurements. The columns "Baseline or Spacing," "Sampling Interval," and "No. of Sites" represents an order-of-magnitude estimate of the envisaged level of effort. Since most of the instrumentation involved needs yet to be developed, it is reasonable to expect that modifications will be necessary, depending on the performance and cost effectiveness of the specific type of equipment.

Theoretical studies and data analysis should be given high priority so that geodetic experiments can be designed to distinguish between major hypotheses and answer fundamental questions. Questions about systematic errors, environmental noise, and nontectonic ground motion, which affect both ground and space geodesy, must be given special attention in the next few years. Ongoing studies using conventional ground techniques, including leveling, trilateration, gravimetry, and tide gauge studies, should be given increased support so that greater geographic coverage, spatial resolution, and sampling rates may be achieved. Several recent developments in ground-based measurements, including multicolor laser interferometers, evacuated laser interferometers, tiltmeters, dilatometers, and absolute gravimeters could be important in studies of earthquake mechanisms and tectonic processes. Finally, space-based techniques such as the use of the Global Positioning System, very-long-baseline radio interferometry, and laser ranging offer the possibility of making major contributions to geodetic monitoring of crustal movements in seismic zones. At the very least these techniques offer an accuracy over baselines of several hundred kilometers, which is not feasible using ground techniques. By combining ground and space techniques, an important combination of accuracy and spatial coverage can be achieved. It is also possible that space techniques can provide frequent displacement measurements at intermediate distances at substantially lower costs, thus allowing the greater geographical coverage and sampling rate required for tectonic studies.

4

Measurement of Deformation within Plate Interiors and Other Neotectonic Motion

The preponderance of crustal movement occurs at plate margins, but earthquakes, broad uplift, and subsidence in plate interiors give increasing cause to regard at least some plates as nonrigid and others as mosaics of smaller platelets. Earthquakes such as the great New Madrid, Missouri, earthquakes of 1811-1812, the Charleston, South Carolina, earthquake of 1868, and the frequent moderate earthquakes in New England in the late eighteenth century clearly show that the interior of the North American plate is active indeed, although at a much lower level, and possibly for different reasons than the boundaries of the plate.

Earthquakes are manifestations of crustal deformation, and appreciable seismic activity takes place across the entire United States (Figure 4.1). However, outside the seismically active region of the far west (including Alaska), we have little documentation and virtually no understanding of the geodetic manifestations of that seismic activity. What is the areal extent and timing of the crustal movement, if any, related to the low and moderate levels of seismic activity in plate interiors? Are the earthquakes preceded by uplifts of areas of hundreds or thousands of square kilometers, as are believed to have preceded some major plate margin earthquakes? Where major earthquakes have occurred, such as in the Missouri Valley, South Carolina, and New England, are aseismic crustal movements taking place similar to those so well documented along active faults in California? And, if we can identify and characterize areas of plates that are truly active, where are and what is the nature of areas of plates that are inactive now and have been inactive over recent geological time? Thus, for practical considerations, just as we wish to

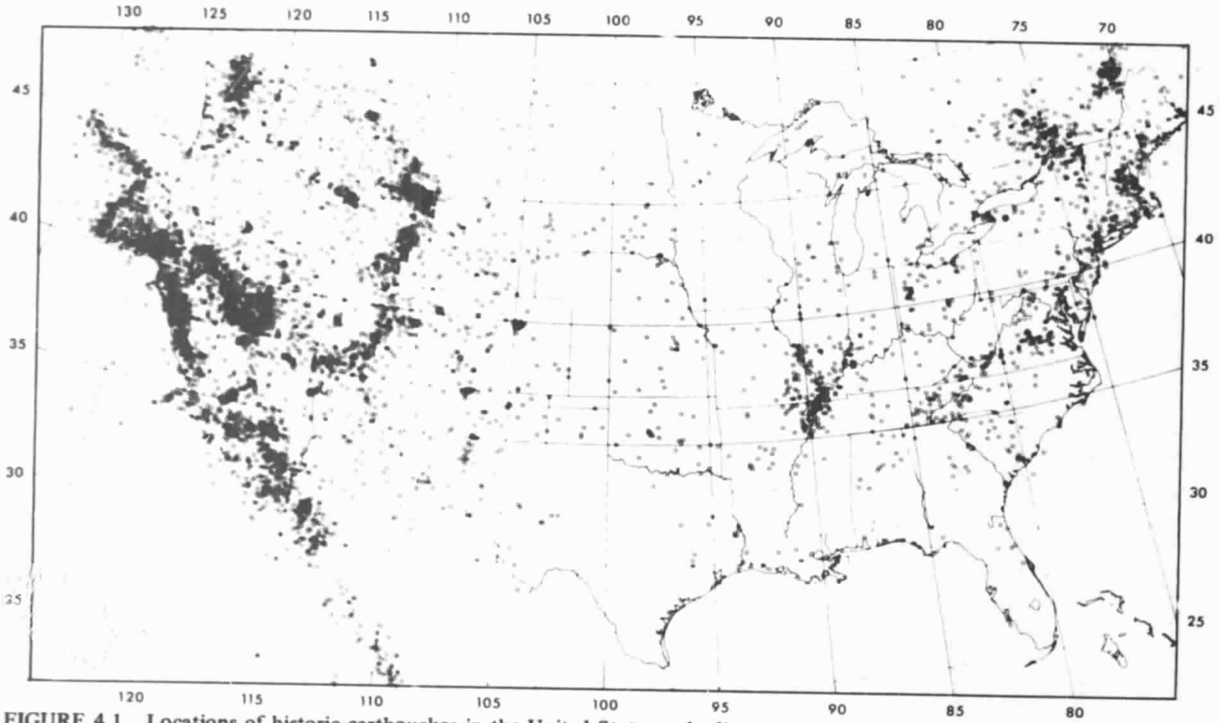

FIGURE 4.1 Locations of historic earthquakes in the United States and adjacent areas through 1974 (National Earthquake Information Service, USGS, Boulder, Colorado).

know the hazardous active areas to avoid risks to critical facilities such as nuclear-power-generating and waste-disposal facilities, so also we wish to know where these same kinds of critical facilities can be constructed with confidence.

Other concerns related to the deformation of plate interiors include a favorable supply of water to agricultural and population centers, flood prevention, and navigation in harbors and along inland waterways. In this context, not only the episodic seismic activity but also the continual deformation associated with mountain formation and the earth's response to postglacial melting are of economic and scientific interest. Significant deformation also results from such human activity as the extraction of underground resources and the creation of reservoirs.

In spite of decades of careful ground-based surveying together with recent superb work using the latest and most sophisticated technology (e.g., Prescott *et al.*, 1979), we have little real understanding of the character of crustal movements in the interior of the North American plate in general and the United States in particular. We do not really know whether the Appalachian Mountains, the Sierra Nevada Mountain Range, the Colorado Plateau, and the myriad of block-uplifted mountains of the Basin and Range continue to rise relative to their surroundings as the recent geological records so clearly indicate. What knowledge we have is derived mostly from the geologic record and from geodetic data observed primarily for establishing geodetic control networks. Hence, a new, well-designed measurement program should make effective use of recent technological advances in geodetic instrumentation. We encouarge the development of new models of deformation of plate interiors to be used in the interpretation of existing and future data sets.

4.1 REGIONAL CRUSTAL MOVEMENTS

Conventional geodetic measurements have been made in the United States since about 1812 in support of topographic mapping, cadastral and engineering surveys, and, just in the last 15-20 years, systematic investigations of crustal movements outside of California and Alaska. Today the United States is intricately crisscrossed by networks of lines for horizontal and vertical control surveys (Committee on Geodesy, 1978, pp. 35, 36). Whereas the older survey data have usually been adequate for the purposes for which they were originally intended, they are lacking in requisite accuracy and in regional and temporal extent to document crustal movements nationwide that take place at geological rates (less than 1 part in 10^7 per year), as well as the tectonic processes responsible for such motion (Brown and Reilinger, 1980).

In spite of the inadequacies of the data, analyses of repeated surveys suggest large elevation and distance changes on a time scale of from 10 to 20 years, which appear to exceed errors on the one hand but which on the other hand are much too great when extrapolated to, and compared with, geologically derived rates. Compilations of vertical data on a national scale (Brown and Oliver, 1976; Gable and Hatton, 1980) indicate that major crustal movements are taking place far from the recognized boundaries of the North American plate—movements that are seemingly unrelated to plate-tectonic processes, at least insofar as we understand them at present. Other movements can be attributed to plate tectonics, but the details are not understood.

Some examples of intriguing regional and local geotectonic problems that may be better understood using carefully designed geodetic networks established by modern techniques are presented below. Much of the supporting discussion is based on published interpretations of conventional geodetic data, and there is some doubt about the reliability of those data as well as the credibility of interpretations. Nonetheless, the problems are sufficiently interesting by themselves to warrant careful and intensive study.

(a) What is the neotectonic nature of major physiographic province boundaries, such as that at the front of the Rocky Mountains, around the Columbia and Colorado Plateaus, the edges of the Great Basin, the Sierra Nevada Mountain Range on the west and the Wasatch Mountains on the east, and across the Rocky Mountain trench in Canada? Do some of these provinces move independently of their neighbors and constitute miniplates? Present data are insufficient in scale to answer these questions.

(b) Zoback and others (1979) consider the recently identified 50-km-wide fault zone in the Missouri Valley, which was responsible for the great 1811-1812 earthquakes, as a fundamental intraplate rift in the North American continent across which differential crustal movement takes place. Their analysis of seismic reflection profiles suggests that current tectonic activity in the region is related to reactivated major faults now blanketed by several hundred meters of sedimentary rocks. Are there surficial manifestations of this deep faulting that can be measured geodetically, perhaps as strain accumulation or plastic deformation spread over a band several hundreds of kilometers wide?

(c) Are the Appalachian and Adirondack Mountains really rising and the intermontane valley subsiding as indicated by recent compilations of vertical control data (Gable and Hatton, 1980)? These observations need to be validated because they do not accord with geological evidence, although they do accord with the expected effect of atmospheric refraction when repeat leveling surveys are made over shorter sight lengths than was common in earlier times. Present rates of uplift relative to the Atlantic coastal plain, according to sparse geodetic data, are up to 6 mm/yr (Brown and Oliver, 1976), whereas erosion rates from Late Cenozoic time to present yield a geological uplift rate of only about 0.04 mm/yr (Hack, 1978). According to Isachsen (1976a; 1976b) and Isachsen *et al.* (1978), the Adirondack Mountains are doming upward at the rate of 3-4 mm/yr during Holocene time, whereas tide-gauge levels on Lake Champlain just east of the dome register no more than 1 mm/yr in historic time, contradicting the leveling estimates (Barnett and Isachsen, 1980). In the moutainous parts of New England from near Troy, New York, northeastward into Maine, the Appalachian axis appears to be rising at the rate of 1 mm/yr faster than glacio-isostatic uplift according to geodetic leveling data (Fairbridge, 1974). In addition, two tectonically active zones are believed present in New England (Hadley and Devine, 1974) that may be the seismogenic sources for earthquakes in that region in the late eighteenth century. One zone is a broad belt of seismicity that extends northward from just east of the lower Hudson River to Quebec, Canada. The second zone extends from New Haven, Connecticut, northeast through New England into New Brunswick (Block *et al.*, 1979). Barosh (1979) considers it unlikely that the earthquakes are due to regional postglacial unloading of ice and consequent rebound of the crust, nor is there a compelling relationship to known faults. On the other hand, Aggarwal and Sykes (1978) make a strong case for relating seismicity to the Ramapo Fault in New York/New Jersey. Analysis of existing geodetic data, and careful surveys in the future, augmented and enhanced by space techniques, may shed considerable light on crustal strain in the eastern and northeastern United States.

(d) The internal stability of the Colorado Plateau is widely recognized from geological evidence, but just how stable is it as a crustal block relative to the surrounding tectonic provinces such as the Great Basin, the Rio Grande rift, and southern California? Lucchitta (1979), on the basis of geological evidence, suggests that plateau uplift on the Wheeler Fault has been at least 800 m over the last 5.5 million years.

(e) The western edge of the North American plate is a broad zone of deformation nearly 1000 km wide stretching from the San Andreas Fault zone eastward across the Great Basin to the Wasatch Front in Utah. Whereas most of the deformation is horizontal and takes place episodically along the San Andreas Fault, abundant geological data show that significant horizontal and vertical separation is also distributed on active faults at the bases of numerous mountain ranges in Nevada, Utah, Arizona, eastern Oregon, and eastern California. That distributive deformation is currently occurring across the western United States is shown by the high level of earthquake activity throughout the Great Basin, but the nature and rate of this deformation is known only approximately from geologic studies (Stewart, 1971); it is less well known from seismologic studies and not at all from geodetic studies.

(f) What is the nature of recent crustal movements within major tectonic provinces? Recent geodetic, seismologic, and geologic studies have revealed a host of intriguing neotectonic problems of broad scientific and applied interest. A brief listing includes the following problems in the western United States.

Yellowstone National Park is seismically active, and it is a major geothermal anomaly as shown by high heat-flow measurements, abundant and widespread hot spring activity, great volcanic activity in recent geologic time, and by new fumaroles that have come into being in the last few years (Smith and Christiansen, 1980). What is the geodetic manifestation of this crustal unrest? Recent leveling (Pelton and Smith, 1979a) shows that the region is a broad area of uplift with a smaller area of very high uplift upon it; parts of the Yellowstone area show relative uplift of 750 mm from 1923 to 1977 (Figure 4.2). These are quite rapid rates in terms of a geological phenomenon and are thought to reflect recent influx of molten material into an upper crustal magma body (Pelton and Smith, 1979b). Indeed, Smith and Christiansen (1980) among others regard Yellowstone as a "hot spot" in the earth's crust, and they maintain that its strong volcanic and tectonic activity make it a unique natural laboratory to study in detail the processes of the deep earth, with particular emphasis on the fine structure of the crustal movements and their relation to heat, volcanic, and earthquake sources. Continued geodetic investigations there will make important basic contributions to our understanding of these processes.

Recent releveling in west Texas and southeastern New Mexico reveals that about a 20-cm uplift of the Diablo Plateau-Salt Basin region took place relative to the Great Plains from 1934 to 1977 (Reilinger *et al.*, 1980). The uplifted area is 120 km wide in an east-west direction. Reilinger *et al.* (1980) favor a tectonic explanation for the uplift, such as intracrustal magmatic activity or even preseismic deformation. Continued geodetic monitoring with added coverage in a north-south direction would yield valuable insight and detail to this local uplift in the middle of the continent.

California is one of the most seismically active regions in the United States, and, not surprisingly, some of the greatest rates of crustal movement have been documented there or are suspected. Not all are adequately documented, much less understood. Some of the problems include the following:

(i) The Ventura Basin and coastline: Geologic studies show that the Ventura Basin has subsided relative to sea level at rates up to 10 mm/yr over periods of a few thousand years and on the order of 1 mm/yr over periods of a few million years (Yeats, 1977; 1978). Dating of terraces along the Ventura

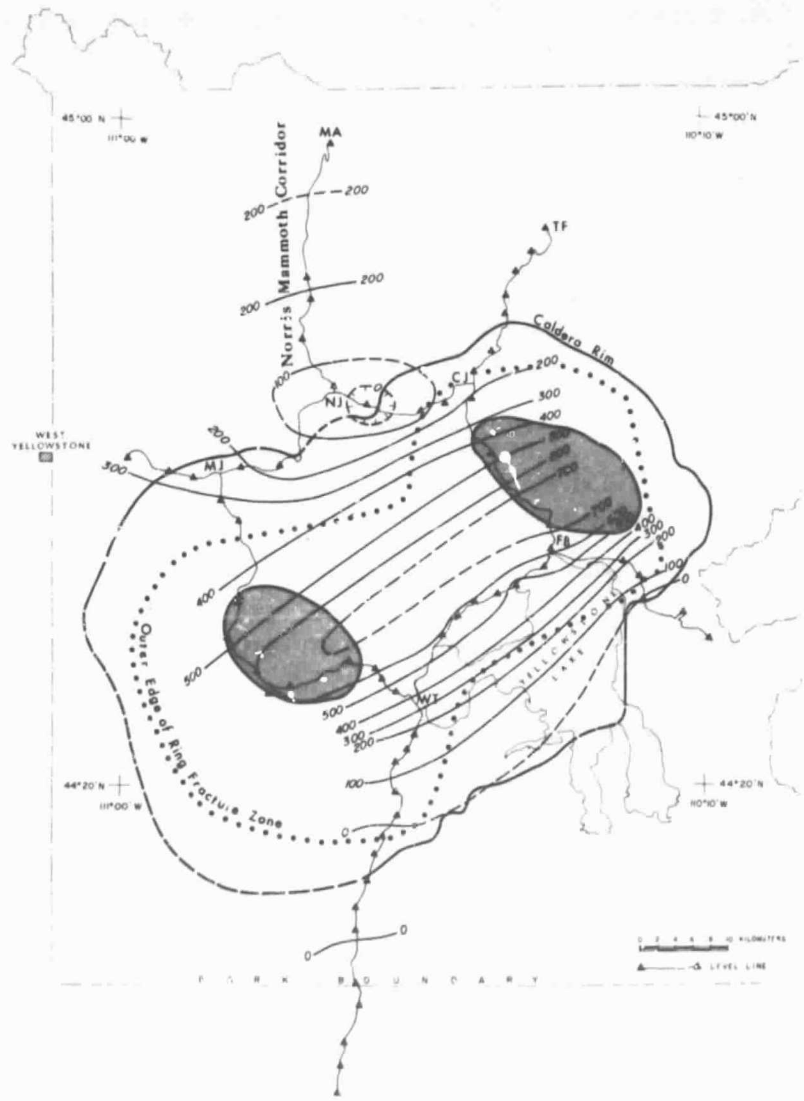

FIGURE 4.2 Orthometric elevation change data for the time interval from 1923 to 1975-1977, Yellowstone National Park. The contour interval is 100 mm. The benchmarks are shown as black triangles (Pelton and Smith, 1979b).

coast by amino acid, uranium-series, and carbon-14 techniques record intense crustal deformation and remarkably high uplift rates of 4-10 mm/yr over the past 200,000 years (Lajoie *et al.*, 1979; Sarna-Wojcicki *et al.*, 1979). Such rapid rates of uplift, if they occur fairly constantly in time, are easily detectable over reasonably short time periods by careful leveling.

(ii) The San Bernardino Mountains: On the basis of geomorphic studies, it has been suggested recently that the San Bernardino Mountains 40 km northeast of Los Angeles have risen at a rate of 18-36 mm/yr between 18,000 and 10,000 b.p. (Morton and Herd, 1980). This is an exceedingly high uplift rate and would be easily detectable by conventional leveling over reasonably short time periods if it is still continuing.

(iii) The Salton Trough: The opening of the Gulf of California over the last 4 m.y. has resulted in a sharp cleft within the continent. The physiographic expression of the cleft is the Salton Trough at the head of the Gulf, and it is functioning as an oblique-divergent plate boundary. The Salton Trough is a complex pull-apart, where the western wall is moving relatively northwestward away from the North American continent (Crowell and Sylvester, 1979). En echelon spreading centers arranged with transform fault characterize its floor (Lomnitz *et al.*, 1970; Elders *et al.*, 1972). Some of the transforms crack landward and extend into the San Andreas Fault system. To some extent, these local spreading centers control the location of subsurface geothermal prospects.

Tilted, warped, folded, and faulted Quaternary strata around the margins of the trough clearly attest to the intensity, duration, and recency of deformation. Geodetic measurements show that the rate of shear displacement across the trough is about 50 mm/yr (Savage *et al.*, 1979). Several hundreds of kilometers of first-order level lines crisscross the trough, and, although no comprehensive study has synthesized the data, studies localized in time and space reveal significant vertical movements. Closer studies of these vertical movements, together with the horizontal movements, may yield much information about the mechanics of divergent plate boundaries. Measurements in the future are necessary to monitor the continuing tectonic activity there.

(iv) The Sierra Nevada Mountain Range: Interpretation of recent releveling across the Sierra Nevada Mountain Range between Roseville, California, and Reno, Nevada, indicates that large vertical movements of crustal blocks take place along old faults unaccompanied by earthquakes (Bennett *et al.*, 1977). One explanation is that these movements are the rule, rather than the exception, and that it is only when block movement sticks or is otherwise inhibited along the old faults that earthquakes occur and the pent-up strain is ultimately released. On the other hand, Chi *et al.* (1980) attributed most of the movements along the Roseville-Reno line to systematic errors. These movements and their interpretations need to be validated, because the implication that such a mobile crust and mechanism can generate earthquakes may be more widely applicable than just to the Sierra Nevada Mountain Range.

RECOMMENDATION 4.1 *Modern geodetic methods, including space techniques, should be employed to determine the large-scale tectonic stability of the North American continent.*

4.2 EVALUATION OF CRUSTAL STABILITY

The U.S. Geodynamics Committee (1979) has called attention to three areas in which a lack of fundamental knowledge concerning earthquakes has seriously impeded programs of generally high national priority:

- The finding of suitable sites and techniques for isolating nuclear waste products,
- The siting and earthquake-resistant design of nuclear-power generating facilities,
- The siting and design of major dams.

Similar lack of knowledge concerning crustal movements and ground stability seriously impedes safe future development of energy.

1. Where raw materials are withdrawn, problems include:
    (a) Collapse of the ground above underground mines;
    (b) Subsidence above water, oil, and gas withdrawal areas;
    (c) Landsliding and subsidence around new surface water reservoirs.
2. Where energy conversion facilities are located, problems include:
    (a) Site stability and seismic hazards to nuclear power plants, major dams, refineries, and storage facilities for liquified natural gas;
    (b) Earthquakes induced by filling or draining major reservoirs.
3. The finding of suitable sites and techniques for disposal of energy waste by-products, especially:
    (a) Nuclear wastes;
    (b) Open-pit mine overburden and gangue;
    (c) Geothermal brines.

A major impediment to wider development of nuclear power is the disposal of nuclear wastes. Invariably the argument is raised that no one can ensure the stability of a disposal site over the thousands or tens of thousands of years of greatest radioactivity levels—no matter how the wastes are technically isolated.

At present, the future tectonic stability of a site is estimated from geological considerations. If the site has been stable over the past 10 million or 100 million years, then the probability is acceptably high that it will be stable over the next 10 million years. Critics of this approach may assert that some new geological process may have begun imperceptibly in historic time, either naturally or by the actions of man, and that these may have altered the short-term stability of the proposed site. Long-term, high-quality geodetic data could be helpful in substantiation or refutation of the assertion. These kinds of data are available for only limited parts of the United States, especially populated areas. Vast, unpopulated parts of the western United States, which seem to offer many of the site requirements for safe disposal of nuclear and other hazardous wastes, are unsurveyed or have been surveyed so infrequently or imprecisely that no meaningful conclusions concerning short-term crustal stability can be made. Virtually nothing is known about what parts of the United States are truly stable.

Confident recognition of instability requires knowledge of what constitutes stability. The "Palmdale Bulge" (Castle *et al.*, 1976) was presumed to be an anomaly because of its spatial relation to the San Andreas Fault and because similar crustal bulges were thought to have preceded some kinds of major earthquakes in other countries. Bennett *et al.* (1977) have postulated that the bulge may be a normal phenomenon, and truly anomalous activity in that part of southern California may be when the crust does not flex and bulge. Still other investigators (Jackson *et al.*, 1980; Strange, 1980) maintain that the bulge is an artifact of survey error. Unfortunately, sufficient experience in time or numbers of events are lacking on which to define the normal crustal behavior in order to recognize what is abnormal or anomalous. Even in California, the amount of geodetic data are inadequate. Hence, priority for further measurements should be for that area.

However, the problem of finding truly stable sites remains. Evidence for the absence of recent movement on local faults may be a sufficient indicator of stability in the near future. But greater assurance is desirable. Hence, repeated geodetic measurements should be made in a variety of physiographic environments believed to be stable by geologic criteria, to determine whether they are indeed free of significant strain change (i.e., not earth tides or very slow, steady regional vertical movements).

RECOMMENDATION 4.2 *While primary reliance should be placed on geological studies, investigations should be carried out to determine whether geodetic techniques giving the highest possible accuracy could be used in evaluaton of crustal stability in areas of interest for the siting of nuclear power plants, waste-disposal areas, and other critical facilities.*

4.3 CULTURALLY INDUCED CRUSTAL MOVEMENTS

Much of the surface of the United States is in motion on several scales owing to the activities of man. The movements range from nearly imperceptible expansion, contraction, and creep of soil beneath a single house, to slow- or fast-moving landslides beneath one or many houses, to gradual differential sinking of towns and cities over old undergound mines (as in Des Moines, Iowa, and Butte, Montana), and over areas where oil, gas, and water are extracted. The economic losses from damages caused by these activities are costly reminders that the earth's surface is not everywhere a stable place upon which to build, live, and work.

Geodetic and geologic studies reveal the locations and rates of these movements. Several areas of the Texas-Louisiana Gulf Coast are subsiding primarily because of withdrawal of groundwater (largely for industrial purposes) and of petroleum. One of the most active areas is Atchfalaya Bay, Louisiana, which is subsiding at the rate of 13 mm/yr (Schlemon, 1975). In the Houston-Galveston area, fissures due to groundwater withdrawal are causing severe problems in developed areas (Sheets, 1976; Kreitler, 1976; Gabrysch, 1976) (Figure 4.3). The problem here is extremely critical, not just because of the cracking but also because of the potential for large-scale flooding from the sea in parts of this low-lying area.

More localized, but still major, subsidence has been occurring for decades over oil fields and in agricultural valleys of California because of extraction of hydrocarbons and groundwater, respectively, especially in the San Joaquin Valley (Figure 4.4). By 1970, about 13,500 square kilometers of irrigable land, that is, one half of the entire valley, had been affected, and maximum subsidence exceeded 8.5 m (Poland *et al.*, 1975). Subsidence has created serious and costly problems not only for repair or replacement of deepwater wells because of ruptured casings but also in construction and maintenance of surface water-transport structures. Thus, the subsidence problem in the San Joaquin Valley is of critical importance to the California aqueduct, which has a gradient of only 64 mm/km through much of the valley (Figure 4.4), because subsidence rates as high as 23 cm/yr have been documented in the central part of the valley where rate differentials of 15 mm/km/yr were observed along the California aqueduct between 1967 and 1969 (Meade, 1973). Even though the problem has been alleviated in recent years by large imports of surface water from northern California, other cities in the southwestern United States are also experiencing insidious subsidence problems, such as ground fissuring and faulting, as they draw increasingly on their groundwater supplies. At present these cities include Las Vegas, Nevada (Holzer, 1978), and several in central Arizona (Holzer *et al.*, 1979). As other cities in the arid Southwest draw ever more heavily on their groundwater supplies, they may expect to encounter subsidence problems too.

FIGURE 4.3 Many houses built on or near faults in the Houston, Texas, area require service releveling every 2 to 10 years to maintain structural integrity. Without this costly and temporary repair, hundreds of houses would resemble this one. The camera was not tilted to take the photograph. Although cosmetic repairs have covered most visible signs of major damage, costly, but hidden, damage to water, sewer, and gas lines accompany this kind of damage (USGS, Denver, Colorado).

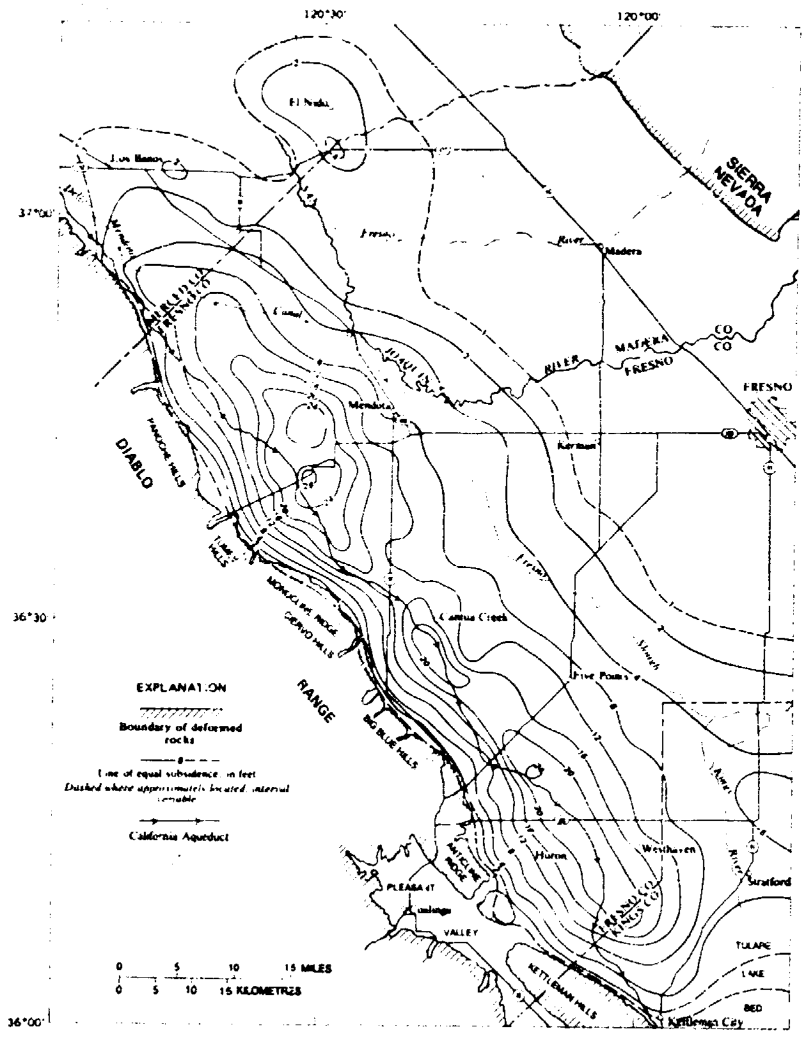

FIGURE 4.4 Land subsidence 1926–1972, central San Joaquin Valley, California. Contour lines show amount of subsidence in feet. The route of the California Aqueduct, which transports water from northern California to southern California, follows closely the axis of maximum subsidence. Base from U.S. Geological Survey Central Valley map, 1:250,000, 1958.

The importance of repeated geodetic measurements in areas of culturally induced crustal movements is evident from the cited examples. Although traditional geodetic ground techniques achieve higher accuracies than the space systems, it is likely that the Global Positioning System will play a more important role because the cost is likely to be lower. In addition, the ground techniques may, in certain situations, be too slow for water withdrawal and preseismic deformation studies.

4.4 RHEOLOGY OF THE EARTH

The interpretation of vertical crustal movements depends on a knowledge of the rheology of the lithosphere and asthenosphere. Rheological information concerning viscous behavior is derived chiefly from the isostatic response of the solid earth to melting of the great continental ice sheets and to the subsequent loading of the oceans and great lakes by the meltwaters. Thus, the postglacial response is one of the two or three main pieces of evidence that the mantle flows. The principal data are carbon-14 dates of ancient shorelines, now uplifted and tilted, which give points in the historical record over the last few thousand years.

Geodetic leveling measurements are an important supplemental source of information, particularly for the interior of North America, where identifiable long-term shorelines suitable for carbon-14 dating are scarce. The geodetic data help to define the periphery of the isostatic bulge, and this information is critical for inferring elastic and nonlinear rheological effects (Kaula, 1980). Unfortunately, leveling measurements are rare in those parts of North America expected to be isostatically rebounding from postglacial unloading, and as discussed by Brown and Reilinger (1980), the available measurements are contradictory in some instances. The present level of detail of the data warrants, at most, linear viscoelastic models (Clark *et al.*, 1978). To go beyond these models and infer nonlinear viscosity or transient rheological effects may require an amount of detail that only geodetic data can supply (Kaula, 1980).

RECOMMENDATION 4.3 *Modern surveying techniques of highest possible accuracy should be used to improve determination of the present-day rate of postglacial rebound.*

4.5 UTILIZATION OF EXISTING DATA

As presented in Section 4.1, most knowledge of intraplate deformation has been derived from the geologic records and the existing geodetic data. These informational sources should be exploited more fully, especially the geodetic data set, to design more effective networks for monitoring the deformation. Design considerations, such as the frequency of observation, the choice of instrumentation, station density, and network geometry, depend on the knowledge of the magnitude and nature of the deformation to be monitored. Hence, to extract more information from the existing geodetic data, we encourage (a) the development of more effective forms of data analysis and (b) the coordination of new observational programs so that they are compatible with the existing data.

Repeated measurements, properly spaced in time, of the same observables over a given network is the simplest and probably the most useful method of monitoring crustal deformation. Unfortunately, most of the existing data do not conform to this design, because these data were primarily observed for the establishment of geodetic reference networks. Other problems, including the destruction of stations and the changes in observational procedures over time, further contribute to the nonconformity of the data to this simple design. Consequently, data analysis must rely on modeling efforts. Models are needed to integrate different types of data from networks that may only partially overlap. This is accomplished by parameterization of both deformation and systematic errors of the different types of data. Thus, the appeal for the development of more effective forms of analysis translates into a search for better models of deformation as well as observational effects. In the realm of systematic effects, particular concerns include the development of better models to separate the effects of the gravitational field and the refraction of electromagnetic waves. These and other environmental effects contribute to the incompatibility of the various data types. For describing deformation, we encourage the introduction of more realistic models. Previous data-reduction schemes have concentrated on empirical models, e.g., polynomial or multiquadratic expressions (Vanicek *et al.*, 1979; Snay and Gergen, 1978; Holdahl and Hardy, 1979). Physical models have yet to find widespread application except perhaps for the dislocation models (Chinnery, 1961; Savage and Hastie, 1966). Those models have found application mostly because of their simplicity. More rigorous models should now be considered because of modern computational capabilities.

A second appeal concerns the compatibility of new observational programs with the existing data. The national control networks are nearly complete, and in many places the observations date back over 50 years. In California these early observations were used in combination with later measurements to derive much of what we know about crustal deformation in that region during most of this century and to serve as a basis for the design of observational programs in that state. The same methodology could be extended to other areas of the United States, where for the most part the observations have not been repeated. In the case of vertical data, a releveling of 110,000 km of the United States network is in progress (Whalen, 1980). In addition to the crustal motion information obtainable by comparing these new observations with the existing data, this releveling program will provide an opportunity to check the compatibility between the traditional leveling data and independent results obtained by the newly developed space-related techniques. In the horizontal case, the compatibility between space and ground techniques has already been demonstrated to some extent (Niell *et al.*, 1979; Carter *et al.*, 1980).

We suggest the following plan of an observational program whose data could be used in combination with existing data for determining long-term horizontal motion in a geographic area of interest like New Madrid, Missouri. A set of existing horizontal control stations would be selected at 50-km intervals to span the specified geographic area in a two-dimensional grid pattern. Observations of baseline length would be performed between adjacent grid stations (considering diagonals) possibly using the Global Positioning System or satellite laser ranging or some variation of the baseline interferometic technique (see Chapter 5 for a detailed description of these techniques). These data could then be combined with those of the United States Horizontal Control Network to estimate the average strain rate realized by the network since the time of the original observations. In most areas of the United States, the original data consist of triangulation observations performed, on an average, 50 years ago. Assuming an accuracy of 1 part in 10^5 for the triangulation data and a significantly improved accuracy of modern observations, the resulting accuracy for detecting the deformation of any given baseline is approximately 2 parts in 10^7 per year. Although this accuracy limit is large in comparison with the expected rate of interior plate deformation for most areas, the results still would be useful in detecting anomalously large strain rates, which might have occurred in regions such as New Madrid, Missouri.

5

Instrumentation for Measuring Tectonic Deformation

Data from repeated geodetic surveys, both horizontal and vertical, have been analyzed to determine tectonic deformation. The present body of geodetic data related to horizontal crustal deformation shows that the long-term deformation rates in seismic zones (such as the San Andreas Fault) are less than 3 parts in 10^7 per year (Savage, 1978), which might be considered a threshold level for studies of long-term horizontal crustal deformation rates. Much of the interesting and anomalous horizontal deformation will be smaller than this, and only in the near field of earthquakes will the rates occasionally exceed it.

Figure 5.1 illustrates the strain magnitudes to be expected as a function of earthquake moment (and hence magnitude) and hypocentral distance. This figure refers to coseismic deformations, and it is reasonable to assume that most preseismic or postseismic deformations that may occur will be smaller than this. From this figure we can clearly see that only in the near field (i.e., within a fault rupture dimension) will the strains be much larger than 1 part in 10^7.

Figure 5.2 illustrates the strain magnitudes as a function of displacement over a certain baseline. Superimposed on this figure are the current capabilities of geodetic and space techniques. Ground geodetic techniques are capable of resolving 1-cm to 1-mm displacements, whereas current space techniques are capable of resolving 5-cm to 1-cm displacements. Therefore, their application to the problem of measuring crustal deformations in seismic zones lies in relatively well-defined and nonoverlapping areas of this figure. Ground geodetic techniques are useful over distances of from 1 or 2 km to 100 km.

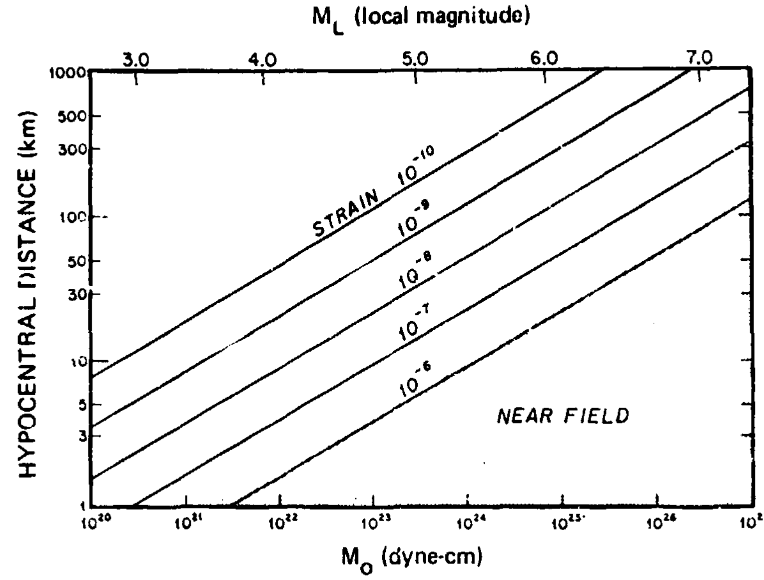

FIGURE 5.1 Dependence of strain on earthquake moment (M_0) or local magnitude (M_L) and hypocentral distance.

Space techniques should provide optimum results for distances above 100 km but may provide useful data for distances as short as 10 or 20 km.

5.1 GROUND TECHNIQUES

Ground instrumentation generally falls into two categories: geodetic instruments that operate in a survey mode and fixed instruments such as strainmeters and tiltmeters that are installed at one site permanently. The former techniques provide measurements of deformation at a number of places at discrete times, whereas the latter usually provide continuous data at one site. Tiltmeters and strainmeters often have very high sensitivities so that strains on the order of 1 part in 10^{10} may be resolved. However, the relevant measure of an instrument's capability is not the resolution or sensitivity but rather the instrument's noise level when installed in the field. The best results to date show secular noise levels on the order of 1 part in 10^7 per year. It is not known whether these noise levels represent intrinsic instabilities of the instrument-earth interface or whether they are results of true crustal deformations.

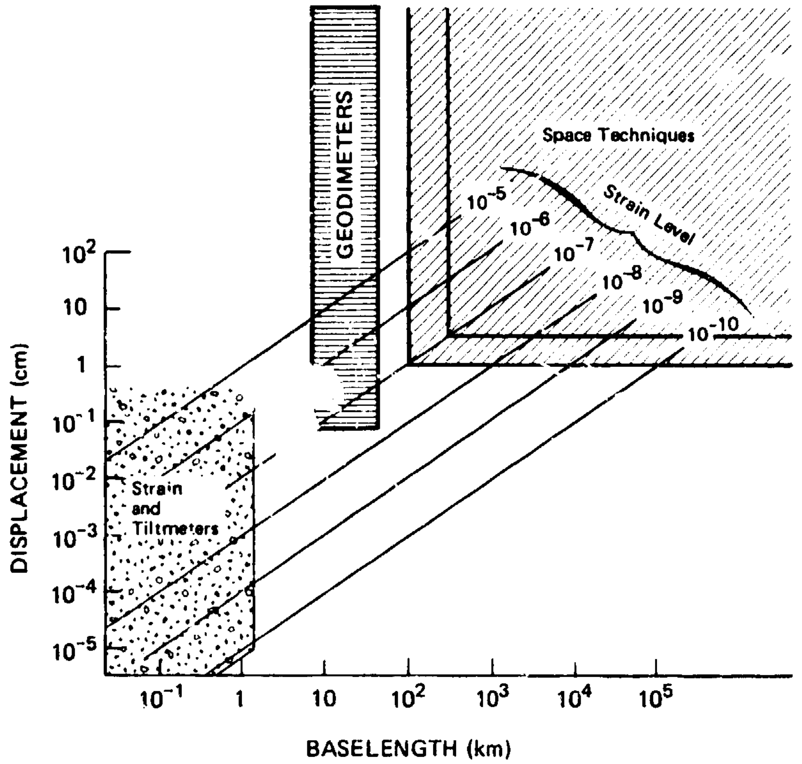

FIGURE 5.2 Range of applicability, as a function of baselength, of different instrument types used for measurement of strain.

RECOMMENDATION 5.1 *Careful tests of methods for minimizing the distorting effects of short-wavelength or near-surface crustal (nontectonic) noise on ground measurements should be conducted at different types of locations in seismic zones. This is important both for less-expensive instruments, which could be installed at many points in seismic zones, and for highly accurate instruments for use at a limited number of sites.*

Geodetic techniques can at best resolve motions of a few millimeters, so that, for crustal deformation studies, baselines of 5 km and greater are needed to achieve the desired strain resolution. Since geodetic instruments operate through the atmosphere more or less horizontally, refraction and attenuation limit the baseline distances to approximately 50 km for a single horizontal measurement. However, by using these instruments in a survey mode, the effective distances may be increased.

At the lower end of their effective range, geodetic techniques, employing two-color laser-ranging devices, have operated over several kilometer base lengths in a semifixed mode. A single instrument is used to range to several retroreflectors distributed azimuthally around the central site, making many observations per day. This type of multiwavelength instrumentation has been applied successfully in recent years to the measurement of crustal movements, and efforts to extend the range of such measurements have been started. We believe that this measurement method may have an important impact on our ability to determine both secular and episodic strain rates in seismic zones and on investigation of the stability of critical regions in plate interiors.

RECOMMENDATION 5.2 *Multiwavelength distance measurements should be evaluated for use in a rapid resurvey mode as well as at fixed locations, and development work on increasing the range of these instruments should be continued.*

The status of geodetic instrumentation has changed little since the summary given in Chapter 5 of *Geodesy: Trends and Prospects* (Committee on Geodesy, 1978). There has, however, been recognition of the critical role played by the benchmark stability, because no measure of tilt or horizontal strain is significant beyond the stability of the reference point. This problem of the instrument-earth interface is a fundamental one, common to both geodetic instruments and to continuous strain and tilt measuring devices, but it is perhaps more severe in the latter case, as the base lengths are shorter and the attempted precision greater.

RECOMMENDATION 5.3 *Standards for structures and methods for achieving stability of control points and benchmarks essential in crustal movement studies are not yet available and should be developed in conjunction with new observational programs.*

5.1.1 Strainmeters

Most strainmeters in use today for crustal deformation measurements are linear extensometers. They measure strain by monitoring changes in the distance L between two fiducial points compared with the length L_0 of some length standard. The linear strain ϵ is then calculated as

$$\epsilon = [\Delta(L - L_0)/L].$$

If it is assumed that there are no changes in the length standard L_0, then

$$\epsilon = \Delta L/L.$$

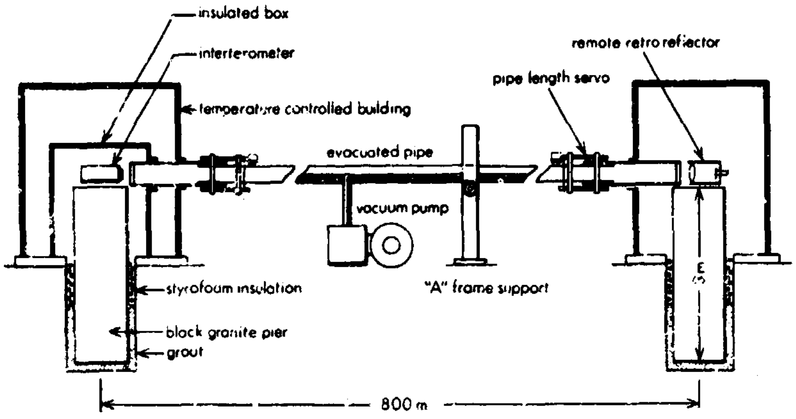

FIGURE 5.3 Mechanical design of an evacuated laser strainmeter. The device, in a simple form, consists of a Michelson interferometer (although other interferometers such as a Fabry-Perot are also used) with the source, beam splitter, and fixed arm on one pier and the long-arm mirror on another pier at a distance L away. The light returning from the far end is mixed with the light from the local mirror to produce the classic fringe pattern. The long arm path must be a constant-pressure path (usually in an evacuated chamber) to reduce the effects of wave front distortion so that a fringe pattern is visible and to reduce the effects of refraction corrections (Berger and Lovberg, 1970).

The linear strain ϵ is simply one component of the strain tensor e. This tensor has six components in a homogeneous elastic three-dimensional medium. On a free surface (a surface where the normal components of stress are zero), it reduces to a three-component tensor. Hence, the measurement of the linear strain in three different directions will serve to determine the strain tensor.

Linear strainmeters were built before the turn of the century, but it was not until 1935 that a modern, sensitive strainmeter was constructed by Benioff (1935). Many instruments of his basic design are in use today. They consist of two piers fixed to the ground with a quartz rod cemented into one pier and extending to within a small distance of the other pier. The length standard, the quartz rod, is made nearly as long as L, the distance to be monitored. Changes in the small distance $(L - L_0)$ are measured with a variety of electromechanical transducers. Various other materials such as Invar wire and carbon fiber wire have also been used for these purposes.

Because of the inhomogeneous nature of the earth's crust, in particular the cracks and joints characteristic of surface layers, it is imperative that the base length of the extensometer be made as long as possible. The use of a length standard as long as the base length poses certain practical restrictions, not only mechanical but also those caused by environmental effects such as temperature and humidity. In practice, these types of instruments have been limited in length to less than 100 m. Many such instruments have been operated with success in underground installations, but near-surface installations (such as in trenches) have not proven to be practical. Basically, the problem is isolating the length standard from the environment. Whereas in a mine or other sufficiently deep underground cavity the environment is usually stable, as one nears the surface the effects of temperature, atmospheric pressure, rainfall, and other environmental phenomena are increasingly felt. Yet the inhomogeneities of the crust undoubtedly increase as one nears the surface. Hence, a longer base length is needed to average these inhomogeneities; this, however, increases the difficulties of environmental isolation.

A fundamentally different approach was adopted by Berger and Lovberg (1970) in their design of the laser strainmeter (Figure 5.3). With the development of the laser as a coherent light source, it became possible to extend the techniques of optical interferometry to much greater distances. With conventional light sources, path lengths of only a few centimeters were possible. However, because of the laser's coherence, laser interferometers with paths up to 1 km have been operated successfully. The stability or noise level of

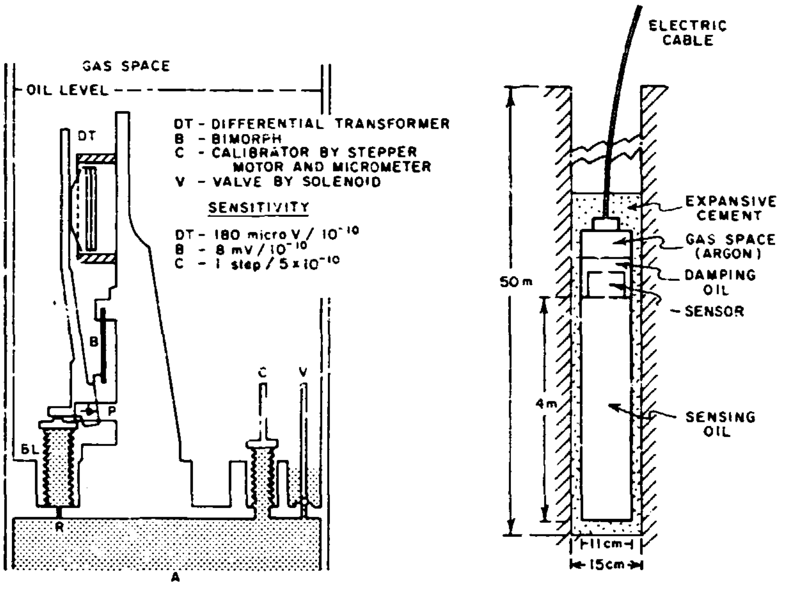

FIGURE 5.4 Borehole dilatometer. As the strain in the surrounding rock changes, the tube is deformed, and the liquid is forced from reference volume A through constriction R into thin-walled bellows BL. The bellows extends or contracts, displacing the liquid into or out of the gas space, the pressure of which remains substantially independent of the rock strain changes. The motion of this bellows is transmitted to the arm L, which rotates about flexural pivot P. The movement of the arm is then measured by a suitable transducer to produce an electrical analog of the strain (Sacks, 1978).

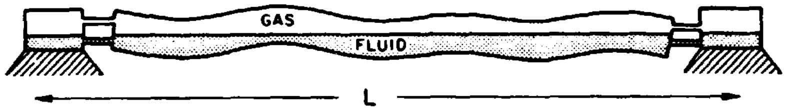

FIGURE 5.5 Schematic arrangement of the half-filled fluid tube tiltmeter; the baseline, L, can be many hundreds of meters. The liquid surface is continuous between the two end measurement reservoirs. Ground tilt, T, causes an equal and opposite change of water level, Δh, at each end, where $T = 2\Delta h/L$.

such a device is to first order dependent on the stability of the laser wavelength or frequency. Several schemes of laser frequency stabilization have been developed, including stabilization by atomic absorption (Levine and Hall, 1972) and stabilization by mechanical standards (Berger and Lovberg, 1970). In either case, the length standard is compact and can easily be contained in a controlled environment even in the field.

An alternative approach to extending the base length on surface instruments is to implant the instruments below the surface in competent rock. This is the method followed by several kinds of borehole instrumentation. Perhaps the most successful example of this type is the borehole dilatometer (Sacks, 1978). In essence, this instrument consists of a liquid-filled resilient tube, which is buried in a borehole and held in intimate contact with the rock wall (Figure 5.4). The thickness of the tube wall can be chosen so that the apparent rigidity of the tube and its contents is nearly equal to that of the surrounding rock. Therefore, when the tube is buried and bonded to the rock, the strainmeter measures genuine strain in the rock and not an amplified strain on the surface of an empty hole.

Typically, these instruments are installed in boreholes at a depth of 100 m or greater. A number have been operating in this country and Japan for some years.

5.1.2 Tiltmeters

Tiltmeters are instruments similar in many respects to strainmeters and share many of the same problems. Basically these devices attempt to measure changes in the difference in height Δh between two points a distance L apart. The tilt is simply $\Delta h/L$. For most phenomena associated with crustal deformations one expects the tilts and strains to be on the same order of magnitude, and hence the problems of stability or long-term noise are important.

Several different techniques have been employed to measure tilt over a base length of from 25 m to several hundred meters, but all are variants of the Michelson and Gale (1919) liquid-level tiltmeter. Figure 5.5 illustrates the

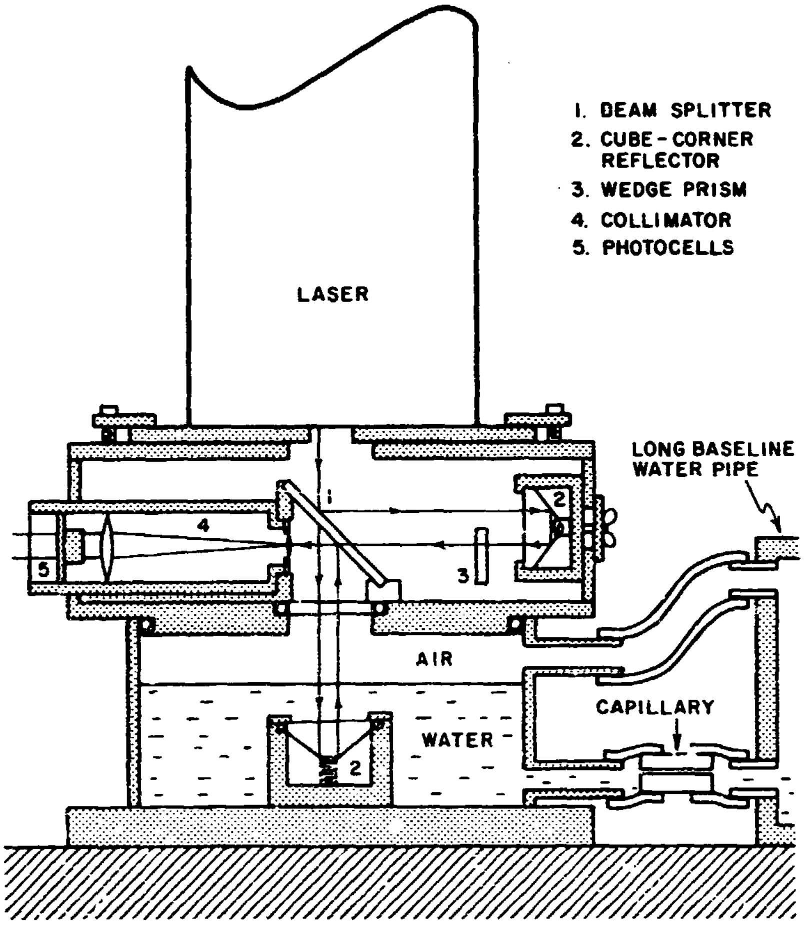

FIGURE 5.6 Cross section of one of the two equal-arm Michelson-interferometer water-depth transducers. The uncollimated light from a Be/Ne gas laser is split by semi-reflector (1) into a vertical and horizontal beam. The transmitted vertical beam passes through a window into the pressure-tight 10-cm-diameter reservoir and reflects from a submerged 2.5-cm cube corner. Variations in water level change the optical path length and result in fringe movements on recombination with the horizontal beam. The visible fringes are converted from circular to parallel using a wedge (3) and collimated (4) to produce a 1-cm fringe spacing that is observed by the twin photocell (5). The laser can be replaced without additional alignment and because of the small physical size of the system high-quality optics are not essential. The units are made of brass and lined internally with nylon (Plumb *et al.*, 1979).

principle. The surface of the liquid approximates an equipotential surface, and the differential heights of the two ends are measured by monitoring the level of the liquid at each end by a suitable transducer. Figure 5.6 shows one example (Plumb *et al.*, 1979).

A second promising approach is to use a pendulum-type tiltmeter installed in boreholes at depths of roughly 30 m or deeper (Herbst, 1979; Cabaniss, 1978; Sato, 1979; Edge *et al.*, 1981). The stability achievable with such instruments is quite good, but the cost of the instruments used in most previous work is high. However, recent experiments with less-expensive sensors appear to be encouraging.

A more economical approach uses shallow borehole tiltmeters, which are in essence miniature liquid-level devices with a base length of a few centimeters. Comparisons between these devices and longer base-length devices (Wyatt and Berger, 1980) have shown them to be unsuitable for most applications associated with crustal deformation. Some work on these devices still continues, experimenting with different methods of emplacement, and installation in somewhat deeper boreholes (see several discussions in the *Proceedings of Conference VII: Stress and Strain Measurements Related to Earthquake Prediction*, USGS Open-File Report 79-370). In particular, employment of new installation techniques seems to provide more encouraging results (Morrissey, 1979).

The validation of recommended experimental capabilities outlined in Table 3.1 requires a substantial program devoted to instrumental development as distinct from a program of monitoring crustal deformation. An apparatus might work as designed in the laboratory under controlled conditions but yet produce erroneous data in the field environment. In most cases, it is impossible to isolate the instrument from its environment and examine its output in the absence of a bona fide signal.

We must be satisfied with observing the signal plus the noise and somehow *post facto* eliminate or isolate the noise component. In many cases the only practical way to perform this test is to operate a group of instruments (at least two) side by side and take the coherent part of their outputs as the signal and the incoherent or unrelated part as the noise.

5.1.3 Gravity Meters

Precise repeat gravity measurements have a number of applications, including the following:

(a) The detection and interpretation of vertical ground motion in earthquake prediction (for example, the development of dilatancy should result in vertical motion with gravity change at the free-air gradient, and subsequent inflow of fluid will result in gravity change with little vertical motion);

(b) The monitoring and interpreting of postearthquake vertical motion;

(c) Postglacial rebound at, for example, 5 mm/yr should yield observable gravity changes on the decade time scale and confirm that such rebound is associated with the inflow of mantle material at depth;

(d) In volcanic areas, leveling and gravity changes give indications of movement of magma and have been so used in Hawaii and Iceland;

(e) Reservoir depletion studies of all kinds, including withdrawal of groundwater, oil, and geothermal steam and water; and

(f) Tectonic motions and crustal warpings (the technique may aid detection of such movements and should assist in their interpretation).

LaCoste-Romberg model G and D gravity meters are almost invariably used for gravity measurements. Repeatability of gravity difference measurements with both models depends on the individual instrument used, the diligence of the operator, the distance over which the meter is transported, and the bumping it receives during transportation. 10- to 15-μgal repeatability at a single station or 20 μgal for a single difference measurement are typical figures. In addition, there are periodic screw errors in the model G, but these screw errors should be substantially reduced in the model D. Several carefully intercalibrated meters are normally used, and resulting gravity differences are typically good to about 15 μgal.

Several improvements in these instruments appear feasible. The beam can be nulled using electrostatic feedback, and, provided the necessary linearity and readout precision can be obtained over the 70-mgal period of the screw errors, it will be possible to eliminate these errors entirely. Several modifications in internal construction and use of materials are also possible, and these could reduce hysteresis, sensitivity to magnetic field, and long-term stability.

Other instruments hold promise for this application. The absolute free-fall apparatus of Hammond and Faller and that of the Instituto di Metrologia "G Colanetti" of Turin, Italy, are functioning with an apparent accuracy of about 10 μgal and good agreement between different instruments at most sites. Occasional larger discrepancies have been found in a few cases, but presumably the cause will be identified and eliminated soon. An instrument with a comparable reported accuracy has been constructed in the Soviet Union. While these instruments are too expensive and difficult to transport, a smaller apparatus with a drag-free falling corner cube and a 20-cm drop is under development. This apparatus should be transportable and is designed for 3-μgal absolute accuracy.

Recent results from the cryogenic gravimeter developed by Goodkind (1978) indicate an apparent drift rate of roughly 5 μgal per year. If real changes in gravity of this magnitude are found to exist, even in good crystalline rock areas, where hydrological effects are absent, such variations are of intrinsic interest. In this case several cryogenic gravimeters, widely spaced and operating in a continuous mode, would be valuable both in understanding the long-term gravity variations and in determining the tidal corrections for other surveys.

The acceleration due to gravity at the earth's surface is affected by both the variations in the height of the surface and the redistribution in subsurface density. Gravity can thus vary without a change in surface height (e.g., a movement of subsurface groundwater); alternatively, gravity may remain constant during a change in surface height (e.g., if pure elastic compression of the crust occurs).

Repeated, highly accurate gravity measurements can make important contributions in detecting and understanding vertical crustal movements; such measurements require the employment of the most improved instrumentation.

RECOMMENDATION 5.4 *Support and encouragement are needed for (a) improving the accuracy of spring gravity meters; (b) producing a portable free-fall apparatus with an accuracy of about 3 μgal; and (c) building high-quality superconducting gravity meters for continuous operation at a few sites in the United States.*

In addition, we recommend that state-of-the-art gravity observations be made, at least at the intersections of the lines in conjunction with the new releveling of the United States. The intention is that these points be reoccupied periodically for investigation of possible crustal deformation.

5.1.4 Laser-Ranging Devices

The basic single-frequency laser-ranging device for geodetic applications is illustrated in Figure 5.7. Light from a laser (usually a helium-neon laser) passes through an electro-optical modulator, which modulates the beam at a radio or microwave frequency f_T and then into a beam-expanding telescope. At the other end of the line to be measured, a distance d away, a retroreflector sends the beam back upon itself. The returning light is collected by a telescope (which may or may not be the beam-expanding telescope) and directed onto a photodetector. The signal from the photodetector is mixed with a frequency f_R slightly below f_T, and the phase of the mixed return $(f_T - f_R)_R$ is compared with the phase of the transmitted signal $(f_T - f_R)_T$. The distance d is measured in terms of the distance traveled by the light in one modulation period. At a modulation frequency of 50 MHz, each 180° of phase difference between $(f_T - f_R)_T$ and $(f_T - f_R)_R$ corresponds to a one-way distance of

$$c/4f_T = 1.5 \text{ m},$$

where c is the velocity of light. If the phase difference is measured to ±7 min,

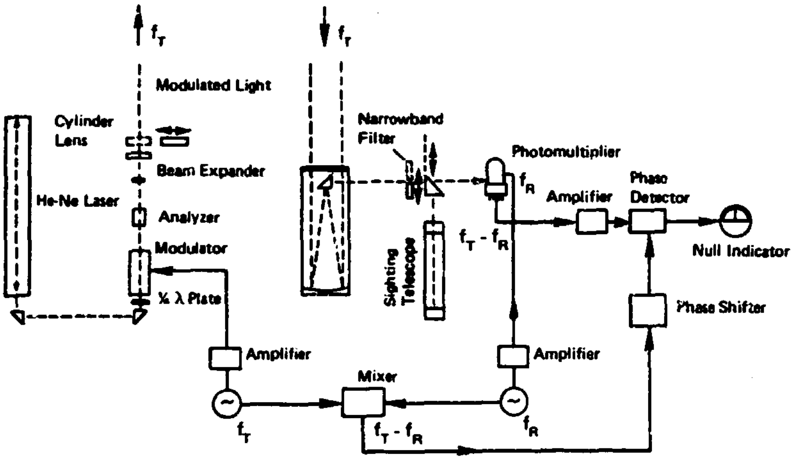

FIGURE 5.7 Single-frequency laser ranging device (after AGA Model 8 geodimeter).

the resolution will be ±1 mm. These values, after correction, may well be optimistic by a factor of 3, say. If the distance is not known beforehand to 1.5 m, then measurements at other modulation frequencies can be made to determine *d* uniquely.

The fundamental limitation on the accuracy obtainable with these ranging devices is a result of the uncertainties in the index of refraction of the air along the path. The instrument measures the optical distance, which is the sum of the geometric distance L and a small contribution S due to the intervening atmosphere. The quantity S depends on atmospheric pressure, temperature, and, to a lesser extent, water-vapor content. To achieve errors of less than 1 part in 10^6, it is necessary to know the average atmospheric pressure along the path to 3 mbar and the temperature to 1° C. This means that accurate temperature and atmospheric pressure measurements must be made along the entire path while the ranging is in progress. Normally this is done by flying an instrumented aircraft along the lines during the survey.

A technique discussed by Bender and Owens (1965) makes use of the dispersive properties of the index of refraction in the atmosphere to reduce these errors automatically and avoid measuring the atmospheric pressure and temperature along the entire line. Instruments based on this technique measure the optical length of the path at two (or more) different frequencies (different color lasers). Because of the atmospheric dispersion, the additional contributions S_1 and S_2 at two frequencies will be different. It has been shown that the quantity $(S_2 - S_1)/S_1$ is nearly independent of atmospheric density and only moderately dependent on water-vapor content. Thus from laboratory measurements of this quantity, and optical length measurements at two frequencies, the geometric length can be deduced. For a 15-km path, using red and blue lasers, S is approximately 400 cm and ΔS will be about 40 cm. The ultimate accuracy of this method depends on the measurements of the ratio of refractivities and the approximations involved. Water-vapor content also limits accuracy, although instruments are under development that will use a third "color"–a microwave frequency–to reduce this source of error. The current demonstrated state of the art for two-color devices appears to be somewhat better than the accuracy of the single-color devices with aircraft measurements along the path. However, improvements are still needed in both portability and range for the two-color ranging devices.

5.1.5 Spirit Leveling

A large amount of present information on vertical crustal movements is based on spirit-leveling measurements. Concern about the reliability of the usually quoted accuracy for leveling has become apparent recently, particularly for regions of steep terrain and for older data. It has been noted that systematic errors due to inadequate rod calibration and failure to correct the historic data for vertical refraction may have produced anomalous crustal deformation information (Strange, 1981).

Before 1965, the National Bureau of Standards (NBS) quoted rod calibrations to the nearest 0.1 mm, and only three or four points on the rod Invar strip were calibrated; there is strong suggestion of systematic error of the order of 50 parts in 10^6. Under these conditions rod calibration error as large as 50 to 100 parts in 10^6 is not unreasonable to expect. Today, NBS quotes calibrations to the nearest 0.002 mm and calibrates every measurement line on the Invar strip; under this procedure it is unlikely that the systematic error can exceed 5 parts in 10^6. Thus, currently achievable calibration accuracy is about an order of magnitude better than older calibrations and would cause errors of no more than 0.5 to 1.0 cm/km of elevation difference.

Another cause of error in historic leveling is the failure to apply a correction for refraction. In the past, long sight lengths (greater than 60 m) were often used and a refraction correction was not applied. This could lead to terrain-correlated systematic errors greater than 20 cm/km of topographic relief. For these historic data the effects of refraction can be partially modeled, thereby removing as much as 75 to 80 percent of the effect in some cases. Nevertheless, evaluation and further development of refraction corrections for historical data are still needed, and, in addition, in order to reduce leveling errors to less than 1 cm/km of topographic relief, short sight lengths should be used (20 m) and a correction for refraction should be applied based on the temperature gradient measured along the level line.

5.1.6 Conclusions

Considerations related to ground techniques presented in the subsections above as well as in Chapters 3 and 4 lead us to conclude that there is a need for a major change in the direction, structure, and level of support for the development, testing, and deployment of geodetic and geophysical ground instrumentation used in monitoring crustal movements. Our findings are summarized in the following recommendation.

RECOMMENDATION 5.5 *Concerted national efforts in development and validation of ground instrumentation must be expanded. These efforts should include*

(a) The designation of a single agency to lead and coordinate development of geodetic instrumentation related to measurement of crustal movements;

(b) Increased funding for development of surface-type instrumentation, at a level of $1 million per year over the next 3 years, to accomplish the program for the next decade outlined in this report; and

(c) Improved facilities where researchers can deploy prototype instrumentation for comparison with other instruments. Such intercomparison should precede field deployment.

5.2 SPACE TECHNIQUES

The future accuracy of space techniques (Bender, 1980; Flinn, 1981) for measuring baseline vectors with lengths of up to intercontinental distances is envisaged to be about 3 cm or better in each component, as discussed in the following sections. Thus, even if ground measurements of horizontal distances with 1 part in 10^7 accuracy were available, the space techniques would have higher accuracy for station separations of roughly 300 or more kilometers. The space methods therefore are expected to be used for measuring large-scale distortions within plates, as well as for determining the present rate of interplate motions. In addition, they can provide a framework surrounding seismic zones to which measurements by ground techniques can be tied. The use of satellite laser ranging and long-baseline radio interferometry for such purposes, and for measuring the earth's rotation and polar motion, will be discussed in Sections 5.2.1 and 5.2.2.

In addition to the above measurements, for which space techniques are the most accurate or are the only ones available, there are other cases for which cost considerations may favor the use of such methods. Since measurements on a monthly or more frequent basis at many points along major fault systems are needed in order to determine whether measurable precursory motions occur before most large earthquakes, the cost can be highly significant. On the other hand, ground techniques may be more sensitive. Thus, it is important that the space techniques considered be as accurate as possible.

A space method that appears to provide a favorable combination of cost and accuracy is the use of signals from the Global Positioning System (GPS) satellites for measuring baselines with lengths of up to 100 km or more. This method will be discussed in Section 5.2.3, and some other possible approaches will be mentioned in Section 5.2.4.

Before discussing the satellite laser-ranging and long-baseline interferometry techniques separately, it is worth noting that the development and utilization of both methods appears to be highly desirable. Adequate evaluation of the accuracy and effectiveness of both techniques will require a substantial interval of time. Moreover, the best source of information on the correctness of the geodynamic results obtained may be the comparison between the laser and radio results because the sources of error in these methods are quite different. Continuation of some support for each method beyond the period of validation and intercomparison is important to detect possible time-dependent systematic errors or bias.

5.2.1 Satellite Laser-Ranging Measurements

Most of the information from satellite laser ranging on large-scale tectonic motions and on the earth's rotation is likely to come from tracking of the Lageos satellite (Smith *et al.*, 1979a; 1979b; 1979c), the moon, or other satellites in high-altitude orbits for which both gravitational and nongravitational perturbations have been minimized. Lageos is in a nearly circular orbit at 5900-km altitude, so that only the low-degree spherical harmonic components in the earth's gravitational field give appreciable orbit perturbations. The satellite is spherically symmetric and of high density, so that direct solar radiation pressure, atmospheric drag perturbations, and other effects are minimal in amplitude and as constant in time as possible. The effect of radiation pressure from sunlight reflected from the earth, which is difficult to model, is also reduced.

Lageos is currently being tracked by a worldwide network of about 15 stations, some of which have roughly 10-cm range measurement accuracy for the resultant "normal" point fit at 2 or 3 minutes of data (NASA, 1980b). A few stations have 2- to 4-cm normal point measurement accuracy. Further improvement at most of the stations to 1-cm accuracy, not including the uncertainty of the atmospheric refraction correction, is highly desirable. A larger number of fixed stations is not needed, but the relocation of some of the existing stations would be useful. Several European countries, Australia, Peru, and Brazil currently are making important contributions to the worldwide Lageos ranging efforts, and other countries are planning to do so.

Range measurements to Lageos from the fixed stations are analyzed to obtain four main kinds of information. One is the variation of the earth's angular orientation in space, i.e., polar motion and earth rotation. A second is an accurate orbit for the satellite, in which the gradual accumulation of errors due to slight inaccuracies in the dynamical model is suppressed by having a sufficient frequency of observations. A third is an occasionally corrected model for the locations of the fixed stations with respect to each other and for their relative motions. The fourth is an occasionally improved set of other parameters needed in the orbit calculation, including, in particular, values for some coefficients in earth and ocean-tide models and low-degree spherical harmonic coefficients of the earth's gravity field.

The fixed stations will give some information on plate-tectonic motions, as well as on variations in the earth's rotation and polar motion. However, it appears desirable to obtain most of the information on tectonic motions by sending highly mobile lasers to specific sites of interest and ranging to Lageos until the station location is well determined from the data. We can think of the Lageos orbit as being determined with respect to the fixed stations and then the location of the high-mobility station being determined with respect to the time-varying satellite position as the earth rotates underneath the orbit. The length of time necessary for the observations at a site with average weather conditions appears to be about 1 week. However, somewhat longer measurement times probably will be used in cases where the costs of transportation to the site are high.

One such high-mobility station has been constructed and tested recently by the McDonald Observatory of the University of Texas (Silverberg, 1978). The essential measurement apparatus fits in one single-chassis vehicle, which is 2.4 m X 3.0 m X 6.5 m in dimensions and can be carried in a Boeing 747 commercial cargo plane. Auxiliary transportation for a power source, repair facilities, and desk working space is needed. An even more compact mobile facility is being completed at NASA's Goddard Space Flight Center. High-mobility stations also are being procured by the Institute for Applied Geodesy in Germany and the Delft University of Technology in The Netherlands. Two additional high-mobility stations are planned in the United States.

Estimates of the stability of the Lageos orbit plane against nonpredictable perturbations have been made and indicate that changes in the orbit plane can be modeled within a couple of centimeters over periods of the order of a month (Smith and Dunn, 1980; Bender and Goad, 1979). Early experimental results on the orbit stability also are encouraging (Smith and Dunn, 1980). Thus laser range measurements to Lageos are expected to give accurate measurements of polar motion at all periods and of variations in the earth's rotation rate with short to medium periods. Completely optical measurements of the earth's rotation rate over longer periods can be obtained by combining the Lageos results with those from laser ranging to retroreflectors on the moon (Silverberg, 1979). So far, most of the lunar ranging results have come from measurements made at the McDonald Observatory in Ft. Davis, Texas. However, regular results from additional stations are expected to be available soon. The accuracy capability of the McDonald station is being upgraded at present, and it is expected to be one of at least three stations capable of accurate ranging to both Lageos and the moon during most of the 1980's.

5.2.2 Very-Long-Baseline Radio Interferometry

Astronomers first developed the method of very-long-baseline radio interferometry (VLBI) for measuring accurately the positions and spatial structure of astronomical radio sources. However, this method also has been developed for geodynamics studies using signals from extragalactic sources (Shapiro and Knight, 1970; MacDoran, 1974; Counselman, 1976, 1979, 1980; Flinn, 1981). In general, the signal received at each of two or more ground stations is mixed with a reference signal from a high-quality local frequency standard and recorded. Then the difference between the respective instants of reception of a given wave front from the extragalactic source at the two stations is derived. This time difference is estimated by cross-correlation of the two recordings. It is equal to the difference in travel time of the signal to the two antennas, which is proportional to the projection of the baseline between the antennas onto the direction to the astronomical source, plus the clock synchronization difference. When signals from four or more sources whose directions, known *a priori*, are sufficiently different have been observed, the three components of the baseline vector and the clock difference can be derived.

The VLBI method has some similarities to the satellite laser-ranging approach and some substantial differences. In both methods a number of fixed stations are used in order to determine fluctuations in the earth's rotation and polar motion, to measure plate-tectonic motions on a number of baselines, and to contribute to maintaining a reference system with respect to which the motions of additional points can be determined by means of high-mobility stations. The VLBI method is more affected by uncertainties in the tropospheric propagation correction, because radio waves are more sensitive to the water-vapor content along the path. However, the problem of determining the satellite oribit is removed, and the earth's rotation is also determined directly with respect to an inertial frame without any intermediate steps.

One of the successes achieved with VLBI is the demonstration of better than 1-cm accuracy in all three components of a 1-km baseline (Rogers *et al.*, 1978; Carter *et al.*, 1980). This was done using the Haystack and Westford antennas in Massachusetts. Another impressive success was the demonstration of 4-cm repeatability over a 2-year period for the length of a baseline from Haystack, Massachusetts, to the Owens Valley Radio Observatory in California (Figure 5.8) (Ma, 1981). These latter results were achieved without the

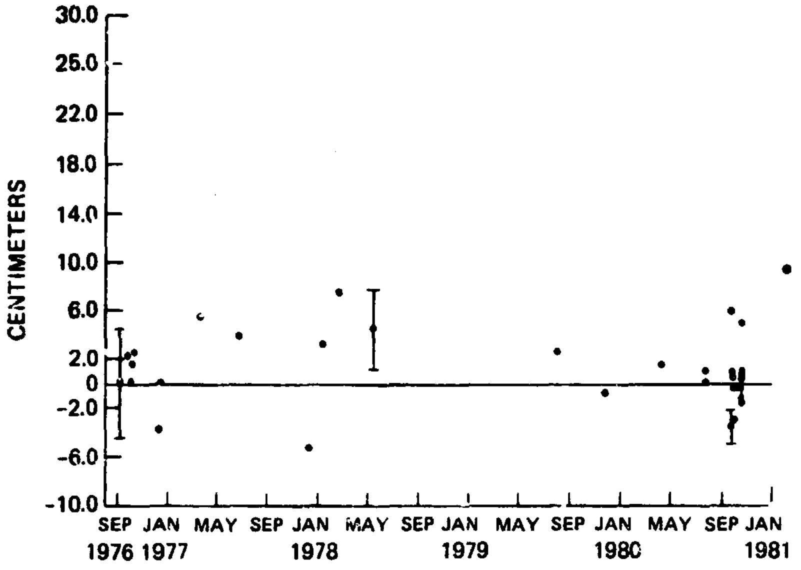

FIGURE 5.8 Determinations by very-long-baseline interferometry (VLBI) of the distance between the Haystack Observatory in Massachusetts and the Owens Valley Radio Observatory in California, spanning the period from early September 1976 to late September 1980. The weighted mean distance has been subtracted. Prior to 1979, the "Mark I" narrow-band VLBI recording system was used; typical distance determination uncertainty, as indicated by the error bars shown on two points, was then ±4 cm. Starting in 1979, the wider-band "Mark III" system was used; the uncertainty was somewhat reduced, to 2-3 cm. (All uncertainties given are estimated standard deviations.) Water-vapor radiometers were not available. (Ma, 1981.)

use of water-vapor radiometers at the observing sites to measure the water-vapor corrections to the atmospheric propagation and without the high-bandwidth recording systems and other improvements that have become available recently.

Intercontinental VLBI measurements with high accuracy now are being made between the following sites: Haystack, Massachusetts; Owens Valley, California; Greenbank, West Virginia; Fort Davis, Texas; Onsala, Sweden; and Bonn, Germany. An extended measurement program is planned in order to determine the relative motion of the North American and Eurasian plates (Herring *et al.*, 1981), as well as to measure the earth's rotation and polar motion (Robertson *et al.*, 1979). A U.S. program to determine the earth's rotation and polar motion accurately on a regular basis every 1 or 2 days is being started by the National Geodetic Survey, and it is hoped that this will become

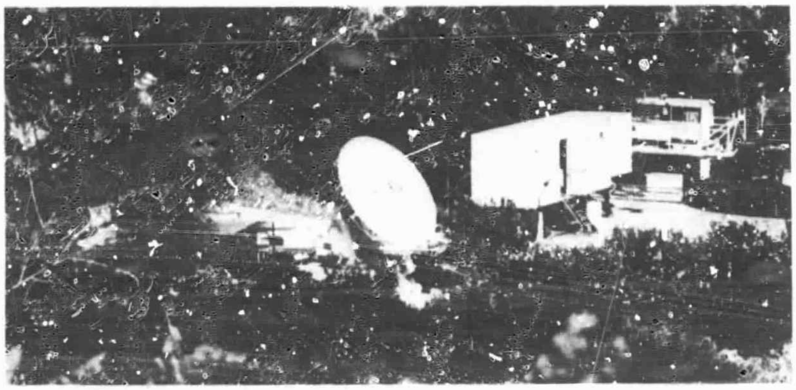

FIGURE 5.9 4-m mobile VLBI station.

part of a continuing international program (Carter *et al.*, 1979). In addition, measurements at weekly intervals are being made using the NASA Deep Space Network antennas in California, Spain, and Australia (Fanselow *et al.*, 1979).

Measurements with mobile VLBI stations (MacDoran, 1974) were started some time ago using a transportable 9-m antenna. One experiment (Niell *et al.*, 1979) was a direct comparison with a conventional geodetic measurement of the length of a 42-km path across Santa Monica Bay in California. A 6-cm accuracy was demonstrated by differencing two baseline vectors each of about 400 km length and measured at different times. Monitoring a number of sites in southern California was begun with the 9-m antenna in 1974, and a high-mobility station using a 4-m antenna (Figure 5.9) became operational in 1980. The required measurement time per site with either antenna system is 1 day or less. The 4-m antenna can be established at a new site within 1 day. Simultaneous operation of the 4-m and 9-m antenna stations is planned, and a second high-mobility station is planned for delivery in 1983.

5.2.3 Global Positioning System

In order to consolidate and improve present navigation systems, the Department of Defense is establishing the Global Positioning System (GPS). The system will include 18 satellites in 12-h circular orbits with an inclination of about 55° and an altitude of 20,000 km. Six developmental Navstar satellites with orbital inclination of 63° were in orbit by mid-1980. The entire system is intended to be in operation by 1987.

The signals transmitted to the earth (Spilker, 1978) consist of biphase modulated spread spectrum signals. The signals are generated with a chip frequency of 10.23 MHz and a different pseudo-random code for each satellite.

Observations at both frequencies permit accurate corrections to be made for the effects of the ionosphere. The accuracy goals for the system are 16 m in geocentric position and 3 cm/sec in velocity at the 90-percent confidence level for individual moving vehicles. However, much higher accuracy can be achieved for the relative positions of fixed stations separated by up to at least a few hundred kilometers.

Several concepts have been proposed for the use of the GPS signals to measure crustal movements. One method makes use of measurements of the phases of what are called the "reconstructed carrier" signals, with knowledge of the original modulation code being used in generating these signals. A second method makes use of knowledge of the general structure of the code but not the code itself. A third method is similar to astronomical radio interferometry but uses the GPS signals as the "noise" sources. No knowledge of the signal structure or the code is needed with this method. These methods are discussed below.

The first method makes use of nearly simultaneous measurements to two or more satellites from each ground station; the effects of station frequency standard instabilities can be almost eliminated in any of the methods. In the most favorable cases, the main accuracy limitation appears likely to result from the uncertainties in the radio-wave propagation corrections due to limitations in determination of the water-vapor content of the atmosphere. Water-vapor radiometers probably will need to be used at both ends of the baselines to infer the integrated water-vapor content along the lines of sight to the satellites (Guiraud *et al.*, 1979; Moran and Rosen, 1980; Resch, 1980; Resch and Claflin, 1980) to achieve centimeter-level accuracy, unless the baseline lengths are short. This is because the atmospheric water-vapor content is likely to be quite variable in time and somewhat inhomogeneous spatially at many locations. The time scale for variability can be a few hours, which is comparable with the time scale of interest for measurements at a given site. The total water-vapor correction frequently will be 30 cm or more for observations at a 20° elevation angle. If only surface measurements are used to estimate the correction, the uncertainty typically will be about 5 cm at a 20° elevation angle.

The basic principle of using the measured difference in phase for signals received at two sites to determine the component of the baseline in the direction of the source is well known from astronomical radio interferometry (Counselman, 1976). Such measurements would be simplified if the signals transmitted by the GPS satellite were sinusoidal. Unfortunately, instead of being nearly monochromatic, the GPS signals have strongly suppressed carriers. The code modulation produces a spectrum spread over about 20 MHz for each of the two frequency bands transmitted. However, signals equivalent to the carriers can be reconstructed in the ground receiver without much loss in the signal-to-noise ratios if the code used in the satellite is known. The basic idea is to generate a local oscillator signal that is phase modulated in the same way as the signal for the satellite of interest, so that the beat between the two signals is nearly free of the modulation effects. The beat is used to produce a clean phase-locked output signal that will change its phase by one cycle each time the radio path length to the satellite changes by one wavelength. This is called a reconstructed carrier signal.

The reconstructed carrier phase method (Bossler *et al.*, 1980; Counselman, 1980) makes use of nearly simultaneous phase measurements from a particular Navstar satellite by receivers at both ends of a baseline. Only the phase difference between the signals received at the two ends is needed in the analysis, so that satellite clock instabilities cancel out. In order to determine all three components of the baseline and the difference of the receiver oscillators or clocks, satellites in at least four different directions in the sky must be observed. The receivers could be used in a sequencing mode where both receivers are switched simultaneously, cycling through the desired four satellites. In this case, short switching time is needed to reduce the stability requirements on the receiver clocks.

Two techniques are available for resolving the ambiguities of integral multiples of the wavelength that are inherent in phase measurements. One technique, usable with receivers that reconstruct the carrier with knowledge of the pseudo-random noise (PRN) modulation code, relies on measurement of the PRN code epoch and the determination of the pseudo-range (biased range) to the satellite. This measurement, having an uncertainty of about 2 m, gives less accurate but unambiguous information that can be used to determine the components of the baseline (Anderle, 1978; Fell, 1980a, 1980b). After several minutes of averaging, the uncertainty can be reduced enough to remove the ambiguity in the phase measurement.

The other technique is to solve for biases in the phase differences for all but one of the observed satellites. If observations are made for a long enough period, any errors in the baseline components due to ambiguity mistakes will project differently onto the satellite directions and be recognized as range biases. Some simulations of this approach indicate that for measurements on long baselines, where atmosphere fluctuations are significant, about 2 h of observations will be needed in order to resolve the ambiguities (Bossler *et al.*, 1980; Fell, 1980a, 1980b).

Three coordinated test programs are being carried out. The first is at the Naval Surface Weapons Center, Dahlgren, Virginia, and has as its primary objective the development of a worldwide GPS geodetic measurement capability as a replacement for geodetic measurements with the Navy Navigational Satellite System. The second is being carried out jointly by the Massachusetts Institute of Technology (MIT) and the Draper Laboratories (Counselman, 1980). It is aimed at demonstrating the highest possible accuracy for differential measurements over shorter distances.

The second method is similar to the one just discussed in that signals equivalent to the reconstructed carrier signals are generated in the receivers. However, this is done without exact knowledge of the code being required (MacDoran, 1981).

Two versions of this method are being pursued currently. At the Jet Propulsion Laboratory, the systems that are being built and tested use directional antennas about 1.5 m in diameter to track individual GPS satellites. Knowledge of the approximate switching rate for the code is employed to resolve ambiguities without the requirement for a long observing time at each site, but no other information on the code is needed. Another version of this method (Counselman, 1981) uses small, nearly omnidirectional antennas and a different data-processing technique. Results so far indicate that reflection of the satellite signals from the ground or nearby structures is not a serious problem, even with the nearly omnidirectional antennas (Counselman *et al.*, 1981).

The third method is analogous to the one used with radio-astronomical signals. The use of long-baseline radio interferometry with noise power transmitted from a satellite was actually demonstrated some time ago at MIT (Preston *et al.*, 1972). An adaptation of this method for accurate baseline determinations with the spread-spectrum GPS signals as the radio noise sources was proposed by MacDoran (1978; 1979). Since the received flux density is about 10^5 times larger than for extragalactic radio sources, the apparatus can be much less expensive and more compact than that needed for astronomical long-baseline interferometry.

The second method discussed above appears to be superior to the third one because it requires less data recording and processing to achieve a given signal-to-noise ratio. However, a comparison of the advantages of the first and second methods is difficult because of uncertainty concerning the future availability of the code to non-Department of Defense users. The Department of Defense is reported to be considering adopting a policy under which incomplete knowledge of the characteristics of the GPS signals by nonapproved users would limit the accuracy of absolute position determinations but not of relative position determinations for which real-time results are unnecessary. However, how this policy would be implemented is not known at present. It would be highly valuable if information on the future availability of the code and other related questions could be provided soon.

Under the circumstances, the development of high-accuracy GPS receivers using both methods through to the stage of extensive field tests seems necessary. The methods under consideration all appear capable of making sufficient measurements in less than an hour per site at any time of day when the complete constellation of satellites is in orbit. By 1980 six satellites were in orbit, and simulations have shown that, at sites in most areas of the world, measurements at least once per day are possible.

An additional interferometric approach that has been investigated jointly by MIT and Draper Laboratories involves placing some small supplemental transmitters on future GPS satellites (Counselman and Shapiro, 1979). This would permit considerable simplification in GPS receivers for geodetic uses, which is highly desirable, and would avoid ambiguity problems. However, it is not known what the chances are of adding the necessary equipment to the satellites. As an interim step, demonstrations of both the reconstructed carrier interferometry method and the spread-spectrum interferometry method are being carried out to assess the accuracy likely to be achieved with the proposed future system.

Although there are still many uncertainties, the prospects seem good that all the GPS methods being developed will achieve 3-cm accuracy for the three baseline components at a high confidence level. For very short baselines, about 100 m in length, Counselman *et al.* (1981) have demonstrated 1-cm accuracy in each of the three components. However, a much better knowledge of the range of errors associated with tropospheric water vapor in different regions is needed in order to clarify the prospects further. It seems clear that at least two of the GPS methods will be preferred over the use of astronomical long-baseline interferometry for baselines that are short enough so that the error contributions due to the GPS orbit uncertainties do not become substantial. This contribution will be about 1 cm for a baseline length of 100 km, if the expected 2-m horizontal position uncertainty discussed by Anderle (1979) is assumed. However, much lower GPS satellite orbit uncertainties are likely when accurate interferometric tracking data are available from a well-distributed set of fixed ground stations (MacDoran, 1979; Counselman and Shapiro, 1979).

5.2.4 Other Space Techniques for Measuring Positions

The techniques discussed above appear to be the most promising ones for use in crustal movement measurements during the next decade. However, two other techniques also deserve mention. One is the proposed Spaceborne Ranging System, which has been discussed in the report *Geodesy: Trends and Prospects* (Committee on Geodesy, 1978) and elsewhere (Institute for Advanced Study in Orbital Mechanics, 1979). The basic idea is to put the active part of a laser-ranging system in a satellite and the less-expensive retroreflector packages at many points on the ground. This system was suggested to provide a cost-effective way of obtaining frequent remeasurements of relative position at many points of interest throughout the world. However, the apparent high initial cost of designing and launching the system makes it difficult to see how it can compete economically with the GPS approach for investigating crustal movements or for providing a warning system for detecting possible earthquake precursors. An alternative approach with the laser-ranging system mounted in an aircraft is now being considered but is not discussed further in this report.

The other technique that should be mentioned is the possible use of laser range measurements from simple ground stations to a number of medium-altitude satellites with a high mass-to-area ratio like Starlette (Wilson *et al.*, 1978). After the earth's gravity field has been mapped quite well with a dedicated gravity satellite mission (Committee on Geodesy, 1979), it is expected that the orbit-determination problem for dense satellites with altitudes of roughly 1000 km will be substantially reduced. A number of suitable satellites could be launched cheaply to reduce the measurement time per site. The much larger signal level compared with Lageos means that the ground stations could be simple and rugged enough to be carried in simple four-wheel-drive vehicles, as proposed for GPS receivers.

Whether the above approach should be developed appears to depend mainly on the relative accuracy that can be achieved with such a system and with GPS receivers. It seems unlikely that the cost per site can be made as low as for measurements with GPS receivers. However, if the water-vapor correction problem for GPS signals turns out to be serious at an accuracy level achievable by laser ranging, the merits of the suggested system will need to be considered carefully.

5.2.5 Recommendations Concerning Space Techniques

The various opportunities for the utilization of space techniques in determining crustal movements, variations in the earth's rotation, and polar motion during the 1980's have been discussed in the previous sections. Considerably more attention was given to GPS methods than to other approaches for measuring crustal movements, because a great deal of progress in understanding these possibilities has been made since the publication of *Geodesy: Trends and Prospects* in 1978.

RECOMMENDATION 5.6 *Global Positioning System receivers for use in the mobile mode and at fixed locations should be developed. The instrumental accuracy should be sufficient so that the main baseline errors are limited to those due to the unavoidable uncertainties in the atmospheric refraction corrections. The accuracy achievable for these corrections with water-vapor radiometers over both short and long baselines should be evaluated carefully.*

For the satellite laser range measurement technique, accurate determinations of short baselines and comparison with ground surveys have not yet been published. There is a serious limitation, for most stations, in the normal point accuracy (i.e., combined systematic and random errors for the average of about 100 returns). This will impair the long-term usefulness of data taken in the next 2 or 3 years.

RECOMMENDATION 5.7 *The normal point accuracy of satellite laser-ranging stations should be improved rapidly in order to contribute effectively to the program of measurements of crustal deformation.*

5.3 COMPARISON AND EVALUATION OF GROUND AND SPACE TECHNIQUES FOR MEASURING CRUSTAL MOVEMENT ALONG MAJOR FAULTS

Ground and space techniques for detecting crustal movements are discussed earlier in this chapter. For some applications, ground techniques clearly are preferable. These include, for example, cases for which the tightest possible limits need to be placed on the relative horizontal motions of points in the vicinity of active faults. On the other hand, space techniques are the only approach available for checking the large-scale stability of major tectonic plates and measuring their present rates of motion.

For monitoring the stability of reference points near major faults that are capable of producing large earthquakes, the choice of approach is not clear. The main purposes of such measurements are to detect precursory motions before large earthquakes if they are large enough to record and to set as tight bounds as possible on the amplitudes of such motions if they cannot be observed. However, our knowledge is very limited concerning the probable amplitude of such precursory motions, their expected spatial extent, and how long before the earthquake they may occur. We therefore need to consider the trade-offs between the frequency of measurements along the fault and the minimum size of the displacements, strains, or tilts that we try to detect.

In view of the extent of our ignorance concerning the nature of possible precursory ground motions before large earthquakes, it is difficult to compare the benefits of monitoring with different methods. Therefore, the first priority should be a continuation and improvement of the present monitoring programs along major faults, as discussed in Chapter 3. This includes particularly the continuation and improvement in accuracy of roughly annual resurveys of the USGS Trilateration Networks, the Southern California Gravity Network, and special leveling lines in the Palmdale area, as well as roughly monthly resurveys of special gravity profiles near Palmdale and some other special networks. In addition, we assume that some observatory-type installations will be operated in order to provide very sensitive and essentially continuous monitoring at a limited number of sites and that at least annual resurveys by space techniques at intervals of roughly 100 km along the major fault systems will be carried out with increased accuracy.

To go beyond the measurement programs mentioned above will require additional funding beyond currently available resources. However, we believe that a strong case can be made for a much expanded monitoring program for investigating possible medium- and short-term precursors. What is needed most at present is improved information on the accuracies that can be achieved by the different ground techniques and by using GPS signals and other space techniques. Such information is required within the next 3 years so that rational decisions can be made concerning the relative merits of different monitoring systems for use in the 1980's. Final evaluation should follow completion of the development of the most promising systems. This requirement, in addition to the need for improved accuracy for present crustal movement monitoring programs, forms the main basis for Recommendations 5.5 and 5.6.

Present understanding of the factors governing the accuracies of modern geodetic techniques, and even some classical techniques, is inadequate. We often do not know what level of confidence to attach to a particular measurement result given, for example, the type of instrument used, the distance between points of measurement, and the environment at each point or along the path between the points.

Special efforts are required to obtain the requisite knowledge and understanding of measurement errors. Measurements must be made for this purpose outside of regions where crustal motions are likely to be large or erratic. Controlled experiments must be performed.

The achievement of an adequate characterization of measurement error may require an effort that is not trivial in comparison with the effort devoted to measurements in geophysically interesting, i.e., tectonically active, regions. We endorse the special attention that experimenters and sponsoring organizations have already devoted to validation but believe that these efforts should be strengthened.

RECOMMENDATION 5.8 *Special studies should be undertaken to improve the understanding and characterization of the types of errors that are likely to affect geodetic measurements and their interpretation in terms of crustal motion. These studies should include the formulation of recommended experimental designs and analytical procedures for evaluating and intercomparing the different techniques.*

In view of the magnitude of the task to be accomplished, the instrumentation development and assessment capabilities of agencies such as the National

Aeronautics and Space Administration, the Defense Mapping Agency, the National Geodetic Survey, and the National Bureau of Standards are required if adequate progress is to be made. Therefore, we suggest that the agencies responsible for earthquake-prediction research and earthquake-hazard reduction seek the assistance of these other agencies in developing and evaluating ground techniques, the GPS methods, and other space techniques for monitoring crustal movements along major faults.

6

Conclusions

6.1 A GEODETIC STRATEGY FOR MONITORING TECTONIC DEFORMATION

The subject of this report is the direct measurement of motions in the solid earth over time scales greater than those characteristic of seismic-wave propagations but within those of accurate geodetic techniques, i.e., roughly one hour to one century. The specification of direct measurement confines attention to the solid surface, and hence to problems of tectonic deformation.

Tectonic deformation is the consequence of much deeper processes commonly lumped under the heading of mantle convection. These processes are, in general, the upwelling of hot material and the sinking of cold material in flows ultimately driven by radioactive and primordial heat. The most obvious manifestation is plate tectonics: the division of most of the earth's surface into relatively rigid plates of hundreds or thousands of kilometers extent, moving with respect to each other at average rates of a few centimeters per year. Most recent geological activity occurs at the boundaries between these plates, which may be zones of (a) plate spreading, such as the mid-Atlantic rise, or (b) plate convergence, where one plate dips under the other, such as the Aleutian trench off Alaska, or (c) lateral plate motion, such as along the San Andreas Fault in California.

However, the plate-tectonic system as described in the foregoing paragraph is an idealization, and the actual earth is considerably more complex because of appreciable compositional and thermal inhomogeneities, strong temperature and strain-rate dependence of rheology, and other factors. Hence the relative motion of plates is often spread irregularly over a wide region. For example, only half of the relative motion between the Pacific and North American plates appears to occur on the San Andreas Fault in California; the balance (as evidenced by seismicity and geologically inferred faulting) is taken up in a chain of relative motions extending 1200 km to the northeast, as far as western Montana. In the Caribbean, which has long been a hinge zone between North America and South America, earthquake motion studies indicate a considerable complex of strike-slip faults, thrust zones, and even a spreading rise. Finally, although strain rates probably vary across North America by more than a factor of 100, no region is completely quiescent, as evidenced by sizable earthquakes in historic times in Quebec, Massachusetts, South Carolina, and Missouri.

In addition to spatial variations, there may be significant temporal variations in the plate motions, as discussed in Section 2.2. The steady rates inferred from seafloor remanent magnetism have, at best, a resolution of 10^5 years; within this time scale there could be appreciable variations in rates. Associated with these variations is the redistribution of stress from one region to another. Hence, any program to study crustal movements in fault belts should take into account recent seismic history, because earthquake stress relief has probably shifted stress to the seismic gaps in these zones.

In recent years, there have been significant improvements—range and economy, as well as accuracy—in several measurements such as vertical acceleration, horizontal distance, and strain change. There is a better understanding of problems related to crustal movements to which geodetic measurements apply. In particular, it has been perceived that the spatial scale of measurable strain patterns associated with moderate-size earthquakes is of the order of the fault length (kilometers to tens of kilometers), while the temporal scale covers a wide range from hours to years. Whether possible precursory strain changes before a large earthquake are likely to occur over a similar area or over a considerably larger region is not yet known. Meanwhile, the time since California last had a major earthquake of great economic and human impact now stretches to 75 years.

These developments strongly indicate the need for an expanded geodetic field program along the San Andreas and associated fault zones in the western United States. However, some of the new techniques are still in the developmental phase and have not been proven in the field; the understanding of some environmental effects, such as atmospheric refraction or effects due to changes in level of groundwater, is imperfect; and some essential measurements—most notably leveling—are still slow and tedious. Hence a prudent program should be a balanced one, allocating an appropriate proportion of resources to research and development as well as to field observations and their analysis.

6.1.1 Observing Programs

In general, the panel endorses the present strategy for crustal movement measurements under the USGS National Earthquake Hazards Reduction Program as an optimization of limited resources. At the current modest level of support, it is appropriate to concentrate effort on work within 50 km of the major faults in southern California and to give the bulk of support to the annually measured trilateration networks and also to carry out annual relevelings and repeat gravity measurements and to maintain some fixed tiltmeter and strainmeter stations. It is particularly important to build a continually improved record of horizontal and vertical motions to use in future, more-refined analyses, analogous to the present cruder use of decade interval surveys by the U.S. Coast and Geodetic Survey (now the National Ocean Survey). However, the program is definitely minimal in extent and, in some aspects, marginal in capability. Hence, concurrent with the measurement improvements emphasized in Chapters 3 and 5 and discussed in Section 6.2.2 below, there should be an extension and intensification (temporally and spatially) of the surveys in California (Recommendations 3.3 and 3.5), as well as an initiation of programs in other active areas, such as the Aleutians and the Gulf of Alaska (Recommendation 3.4).

The eventual systems developed for the active fault zones—southern California, southern Alaska, and, to some extent, Owens Valley, Yellowstone, and other regions in the west showing recent geologic and seismic activity, should cover many different types of measurements, as indicated in Recommendations 3.6 and 3.8 and Table 3.1. Aside from the inverse correlation of frequency with range for a basic framework extending from space measurements over hundreds of kilometers at annual intervals down to continuously recording observatories, there should be capabilities of saturation with seismic "listening posts" (Recommendation 3.6b) as well as of rapid response after an earthquake occurs (Recommendation 3.6d).

The recommendations for expansion of the USGS program of geodetic measurements involve three main parts. One is the improvement in accuracy and extension in coverage of measurements of long-term strain accumulation. The second is the early establishment of a roughly biweekly resurvey program for points every 10 to 20 km along the major faults to detect possible medium-term precursory motion. Application of space techniques may be needed to achieve this goal. The third is the installation of continuously operating instruments at similar intervals to determine if short-term precursors occur before large earthquakes. All three parts of the recommendations are of major importance to a successful program of earthquake prediction research.

After the demonstration of 2- to 3-cm accuracy in determining changes in baseline lengths, the use of the VLBI and laser-ranging techniques under the NASA Geodynamics Program should have as its first priority the strengthening of our understanding of worldwide plate-tectonic motions through direct measurements (Recommendation 2.3). This task can be regarded both as a major contribution to our understanding of the forces shaping the earth's surface and as a valuable source of information related to the occurrence of earthquakes. The same fixed observing stations that provide a reference frame for measuring plate motions also should be used to monitor the earth's rotation and polar motion (Recommendation 2.1). Another major task of the space techniques should be to determine the preseismic strain-accumulation pattern in several major seismic zones, outside the United States as well as in California and Alaska, over larger distances than those covered by ground techniques. The resulting information is likely to extend our knowledge of events preceding great earthquakes to different tectonic settings at a considerably earlier date than would be possible otherwise. Observations of motions of the ocean floor also are needed in order to understand strain accumulation and release in subduction zones (Recommendation 3.7).

Application of geodetic measurements to intraplate tectonic problems must await development of higher accuracy in most cases, if the present rates are comparable with geologically recent rates. However, a few intraplate features in the western United States, such as the Yellowstone region, are manifestly active enough to have measurable rates. Furthermore, some other regions, such as Diablo Plateau-Salt Basin region discussed in Section 4.1, yield inferred uplift rates of several millimeters per year, which at this writing appear to be real and not explicable by the instrumental and environmental distortions discussed in Section 6.2.2.

Selecting nuclear generation and waste-disposal sites, as discussed in Section 4.2, represents a practical need for a better understanding of the nature of tectonic motions. For such purposes tectonic stability on a time scale of at least centuries is needed. Each geodetic technique gives information, at most, only over the duration of its application and, therefore, must be, at best, auxiliary to primarily geologic evidence of recent tectonic motion. Similarly, the somewhat cruder surveys needed to monitor culturally induced crustal subsidence (See Section 4.3) should be auxiliary to hydrology, mining, and engineering geology applicable to these problems. In most cases, the extents of affected areas are small enough and their land values high enough to establish relevelings as a local responsibility.

6.1.2 Research and Development

In discussing the problem related to research and development we use the same categories as those in the report of the U.S. Geodynamics Committee

(1980): theoretical and laboratory studies, instrumentation, and data management. In addition, the limitations on the ultimate accuracy due to the natural environment are great enough to warrant discussion as a separate topic.

6.1.2.1 Theoretical and Laboratory Studies

The present-day motions of the solid earth surface, which we hope to delineate by geodetic techniques, are part of the more general problem of the mechanical behavior of the lithosphere. These include (1) the recent evolution, as inferred from geological evidence; (2) the state of stress, measured by techniques such as hydrofracture; (3) the properties at depth, as inferred from drill holes and seismic studies; (4) seismicity, its spatial and temporal pattern with consideration of magnitudes; (5) earthquake source mechanism studies; and (6) laboratory studies of the rheological properties of rocks.

Models are needed to connect these data. A "model" exists as soon as data are interpreted or as soon as a decision is made about what to measure next. As in any scientific problem, it is better that models be explicit, rather than implicit. In the case of lithospheric mechanics, models relating the data must obey at least the conservation laws for continua, plausible rheological equations of state, and various boundary conditions. Simple models (e.g., a uniform elastic half-space with an earthquake fault represented by a plane) can be solved analytically. However, tectonophysicists concur that the real world requires numerical models using techniques such as finite-element or difference analysis. If crustal-movement data are to be used effectively, then they must be provided in computer-compatible format; the implications should be studied thoroughly, in the context of the assumed theoretical models, and the results of these studies might be used to plan future measurements (Recommendation 3.1). Another need for numerical modeling arises from the differences in scale between the geological processes monitored by geodetic measurements and the data on rock rheology as measured in a laboratory.

6.1.2.2 Instrumentation

Chapters 2 to 4 discuss problems that demand improvement and development of geodetic instruments; Chapter 5 of this report and Chapter 5 of the report of the Committee on Geodesy (1978) discuss several prospects for attaining significant progress. However, these prospects depend on adequate and continuous funding (Recommendation 5.5), and the full realization of their application to crustal movement measurements depends on a carefully coordinated program of development, calibration, and validation (Recommendation 5.1). Accuracies and ranges that appear achievable in mobile instruments include (a) three-wavelength distance measurements with accuracy of 5 parts in 10^8 over a distance of 50 km, (b) gravity measurements to 3×10^{-8}

m/sec^2, and (c) relative point positioning to 2-cm accuracy by means of long-baseline radio interferometry or satellite techniques. Achievement of accurate multiwavelength angle measurements, important for rapid determination of elevation differences, and seafloor ranging with accuracies on the order of 10 cm over 100-km ranges are still in the stage of conceptual development.

Improvements in the efficiency with which measurements can be made and reduction in the cost per site are also of great importance. Such improvements are necessary if monitoring of medium- and short-period strain changes is to be carried out at many points along major faults.

6.1.2.3 *Data Management*

A signficant program to study crustal movements will generate a large amount of data. For maximum effectiveness, these data should be coded, combined, stored, and transmitted in such a way as to be useful for analysis, modeling, and further planning by researchers at several locations (Recommendation 3.1). The National Geodetic Survey is developing the appropriate procedures for handling the data related to the North American Datum adjustment. Similar tasks should be undertaken by the National Earthquake Research Center to handle the data generated by its seismometer network and by the NASA Centers for their spacecraft tracking data. However, geodetic data obtained with the program of crustal movement studies will have some significant differences in character as well as differences in the nature of their use. Hence, the responsible agencies should consider the management of the data as far in the future as possible and should establish working groups to develop procedures and standards.

6.1.2.4 *Environmental Effects*

An important difference in emphasis of this report from that of the Committee on Geodesy (1978) is recognition of the fact that the limitation on the accuracy of most measurements is the natural environment. The factors limiting accuracy include atmospheric refraction; local ground motions arising from groundwater and temperature variations; temperature, humidity, and pressure variations acting directly on instruments; and motions of control points. Overcoming some of these effects will require research programs into properties of the natural environment (e.g., variations in atmospheric temperature gradient near the surface); others will require the development of better procedures (e.g., stability criteria for site selection) or supplementary instrumentation (e.g., water-vapor radiometers for refraction effects on radio interferometry). The Panel recommends that the following efforts be undertaken: (1) detailed tests of local crustal distortions at several types of locations in order to obtain optimum siting for high-accuracy observatories and reference stations (Recommendation 5.1) and (2) development of standards for achieving stability of control points and benchmarks (Recommendation 5.3).

The study of environmental effects should be pursued not only to achieve better accuracies and procedures in future measurements but also to use existing data effectively. Such a study is particularly important for meaningful inferences from leveling performed under varying standards and specifications with regard to such items as lengths of sights, heights of sights above the ground, times of day, thermal corrections, misclosure treatment, and calibration procedure.

6.2 THE GEODYNAMICAL CONTEXT

The general topic of crustal dynamics has been selected by the U.S. Geodynamics Committee (1980) as the principal focus for U.S. activities in the 1980's. There is, therefore, substantial affinity between the interests of the earth-science community at large and the questions considered by this Panel.

The Geodynamics Committee recommends exploration of the continents as the major priority for the coming decade. To implement the program of geodynamics in the 1980's, it proposes several activities. One of these activities is closely related to the concerns of this Panel:

> Crustal strain and crustal movements, especially within North America and adjacent oceanic areas by diverse techniques including space laser ranging and very-long-baseline interferometry.

However, other activities proposed should obviously affect where and how crustal movements are measured:

> Studies of . . . plate boundaries, with emphasis on boundaries between oceanic and continental crust, associated earthquakes, ...
>
> Studies of plate interiors, especially . . . the North American continent; . . . isolation of toxic wastes.
>
> Geological and geophysical mapping . . . .
>
> Geodynamics in the Caribbean area . . . .
>
> Geodynamic modeling, ...
>
> Geodynamic syntheses, ...
>
> Geodynamic data collection, storage, retrieval, ...
>
> Instrumentation . . . capable of meeting the requirements for a wide range of analytical and experimental investigations.

Relevant to the practical needs for a better understanding of crustal dynamics, the Geodynamics Committee emphasizes natural hazards and waste disposal. In the problem of earthquake prediction, hypotheses have been developed regarding the mechanisms causing earthquakes associated with plate margins, and increased accuracy of prediction in some such areas is foreseeable. However, for improved understanding of intraplate earthquakes, we need an increased emphasis on regional and local studies of crustal strain variation. In the problem of radioactive wastes, there is required better knowledge of state of stress and evidence for long-term stability of potential sites.

6.3 FUTURE DIRECTIONS

We have identified leading hypotheses and problems with regard to measurements of crustal deformation and established a priority of effort and described in a general way the required instruments and procedures. Some vagueness in response to part of the charge to the Panel reflects the difficulty of the problem, both because essentials had to be inferred indirectly from a complex of details that are sketchily known at present and also because the nature of the problem is highly interdisciplinary. There has not yet developed a scientific community with a comprehension of all aspects of the problem and a consensus with respect to future directions, unlike the situation that exists in such areas as seismic-wave propagation and physical geodesy.

However, much progress has been made in developing experimental and theoretical tools that are needed for the solution of problems in crustal dynamics. Also, there is a major earthquake threat to California, the state of greatest population and capital investment. Because of this threat, crustal movement studies must be established as a national priority and be vigorously pursued by the scientific community. It is clear that this pursuit should involve geodetic measurements, since their spatial and temporal ranges, 1-100 km and 1 h-100 years, are commensurate with the scale of the phenomena. To achieve an optimum balanced program of field observations and supporting research will require contributions from a great variety of scientists and engineers. Interaction will also be required between the responsible federal agencies and the scientific and engineering communities. Working groups must be formed, somewhat in the manner used by NASA for space exploration. These groups, in turn, should plan methods to attack problems identified in this report and to establish priorities and strategies in greater detail than was expected of this Panel.

References

Aggarwal, Y. P., and L. R. Sykes, Earthquakes, faults and nuclear power plants in southern New York-northern New Jersey, *Science 200*, 425-429 (1978).

Agnew, D., J. Berger, R. Buland, W. Farell, and F. Gilbert, International deployment of accelerometers: a network of very-long-period seismology, *EOS 57*, 180-188 (1976).

Alfors, J. T., J. L. Burnett, and T. E. Gay, Jr., *Urban Geology-Master Plan for California*, Calif. Div. Mines and Geology, 112 pp. (1973).

Anderle, R. J., Application of Global Positioning System to Determinations of Tectonic Plate Movements and Crustal Deformations, Dept. of Geodetic Sci., Ohio State U. Rep. 280, pp. 53-57 (1978).

Anderle, R. J., Accuracy of geodetic solutions based on Doppler measurements, *Bull. Geodesique 53*, 109-116 (1979).

Anderson, D. L., Accelerated plate tectonics, *Science 187*, 1077-1079 (1975).

Ando, M., Source mechanisms and tectonic significance of historical earthquakes along the Nankai trough, Japan, *Tectonophysics 27*, 119-140 (1975).

Barnett, S. G., and Y. W. Isachsen, The application of Lake Champlain water level studies to the investigation of Adirondack and Lake Champlain crustal movements, *EOS 61*, 210 (1980).

Barosh, P. J., *New England Seismotectonic Study Activities During Fiscal Year 1978*, U.S. Nuclear Regulatory Comm. Doc. CR-0939, Washington, D.C. (1979).

Bender, P. L., Improved methods for measuring preset crustal movements, *Dynamics of Plate Interiors*, Geodynamics Series, Vol. I, A. W. Bally, P. L. Bender, T. R. McGetchin, and R. I. Walcott, eds., Am. Geophys. Union, Washington, D.C., and Geol. Soc. Am., Boulder, Colorado, pp. 155-162 (1980).

Bender, P. L., and C. C. Goad, Probable LAGEOS contributions to a worldwide geodynamics control network, *The Use of Artificial Satellites for Geodesy and Geodynamics*, Vol. II, G. Veis and E. Livieratos, eds., National Technical U., Athens, pp. 145-161 (1979).

Bender, P. L., and J. C. Owens, Correction of optical distance measurements for the fluctuating atmospheric index of refraction, *J. Geophys. Res. 10*, 2461-2462 (1965).

Benioff, H., A linear strain seismograph, *Bull. Seismol. Soc. Am. 25*(4) (1935).

Bennett, J. H., G. C. Taylor, and T. R. Toppozada, Crustal movement in the northern Sierra Nevada, *Calif Geol. 30(3)*, 51-57 (1977).

Berger, J., and R. H. Lovberg, Earth strain measurements with a laser interferometer, *Science 170*, 296-303 (1970).

Block, J. W., R. C. Clement, L. R. Lew, and J. de Boer, Recent thrust faulting in southeastern Connecticut, *Geology* 7, 79-82 (1979).

Bomford, G., *Geodesy*, 3rd ed., Oxford U. Press, London (1971).

Bossler, J. D., C. C. Goad, and P. L. Bender, Using GPS for geodetic positioning, *Bull. Geodesique 54*, 553-563 (1980).

Brown, L. D., and J. E. Oliver, Vertical crustal movements from leveling data and their relation to geological structure in the eastern United States, *Rev. Geophys. Space Phys. 14*, 13-35 (1976).

Brown, L. D., and R.E. Reilinger, Releveling data in North America: implications for vertical motions of plate interiors, *Dynamics of Plate Interiors*, Geodynamics Series, Vol. I, A. W. Bally, P. L. Bender, T. R. McGetchin, and R. I. Walcott, eds., Am. Geophys. Union, Washington, D.C., and Geol. Soc. Am., Boulder, Colorado, pp. 131-144 (1980).

Brown, L. D., R. E. Reilinger, S. R. Holdahl, and E. I. Balazs, Postseismic crustal uplift near Anchorage, Alaska, *J. Geophys. Res. 82*, 3369-3378 (1977).

Cabaniss, G. H., The measurement of long period and secular deformation with deep borehole tiltmeters, *Applications of Geodesy to Geodynamics*, I. I. Mueller, ed., Dept. of Geodetic Sci., Ohio State U. Rep. 280, pp. 165-169 (1978).

Carter, W. E., D. S. Robertson, and M. D. Abell, An improved polar motion and earth rotation monitoring service using radio interferometry, *IAU Symposium No. 82, Time and The Earth's Rotation*, D. D. McCarthy and J. D. H. Pilkington, eds., D. Reidel, Dordrecht, Holland, pp. 191-197 (1979).

Carter, W. E., A. E. E. Rogers, C. C. Counselman, and I. I. Shapiro, Comparison of geodetic and radio interferometric measurements of the Haystack-Westford baseline vector, *J. Geophys. Res. 85*, 2685-2687 (1980).

Castle, R. O., Leveling surveys and the southern California uplift, *USGS Earthquake Information Bull. 10*, 88-92 (1978).

Castle, R. O., J. P. Church, and M. R. Elliott, Aseismic uplift in southern California, *Science 192*, 251-253 (1976).

Castle, R. O., J. P. Church, M. R. Elliott, and J. C. Savage, Pre-seismic and co-seismic elevation changes in the epicentral region of the Point Mugu earthquake of February 21, 1973, *Bull. Seismol. Soc. Am. 67*, 219-231 (1977).

Chi, S. C., R. E. Reilinger, L. D. Brown, and J. E. Oliver, Leveling circuits and crustal movements, *J. Geophys. Res. 85*, 1469-1474 (1980).

Chinnery, M. A., Deformation of the ground around surface faults, *Bull. Seismol. Soc. Am. 51*, 355-372 (1961).

Chinnery, M. A., Earthquake displacement fields, *Earthquake Displacement Fields and the Rotation of the Earth*, L. Mansinha *et al.*, eds., D. Reidel, Dordrecht, Holland, pp. 17-38 (1970).

Clark, J. A., W. E. Farrell, and W. R. Peltier, Global changes in post-glacial sea level: a numerical calculation, *Quarternary Res. 9*, 265-287 (1978).

Committee on Geodesy, National Research Council, *Geodesy: Trends and Prospects*, National Academy of Sciences, Washington, D.C., 86 pp. (1978).

Committee on Geodesy, National Research Council, *Applications of a Dedicated Gravitational Satellite Mission*, National Academy of Sciences, Washington, D.C., 53 pp. (1979).

Counselman, C. C., Radio astronomy, *Ann. Rev. Astron. Astrophys. 14*, 197-214 (1976).

Counselman, C. C., Meeting on radio interferometric techniques for geodesy, *EOS 60*, 673-674 (1979). See also papers in *Radio Interferometry Techniques for Geodesy*, NASA Conf. Publ. 2115, Washington, D.C. (1980).

Counselman, C. C., Miniature interferometer terminals for earth surveying (MITES): geodetic results and multipath effects, *IEEE International Geoscience and Remote Sensing Symposium Digest 1*, 219-224 (1981).

Counselman, C. C., and I. I. Shapiro, Miniature interferometric terminals for Earth surveying, *Bull. Geodesique 53*, 139-163 (1979).

Counselman, C. C., S. A. Gourevitch, R. W. King, T. A. Herring, I. I. Shapiro, R. L. Greenspan, A. E. E. Rogers, A. R. Whitney, and R. J. Cappallo, Accuracy of baseline determinations by MITES assessed by comparison with tape, theodolite and Geodimeter measurements, *EOS 62*, 260 (1981).

Cox, A., ed., *Plate Tectonics and Geomagnetic Reversals* W. H. Freeman and Co., San Francisco, 702 pp. (1973).

Crowell, J. C., and A. G. Sylvester, *Tectonics of the Juncture Between the San Andreas Fault System and the Salton Trough, Southeastern California–A Guidebook*, Dept. Geological Sci., U. of California, Santa Barbara, 193 pp. (1979).

Dziewonski, A. M., and R. J. O'Connell, Application of normal mode theory to calculations of changes in the Earth's moment of inertia due to earthquakes, Semiannual Technical Summary (31 December 1975), Seismic Dissemination, Lincoln Laboratory, MIT, pp. 61-64 (1976).

Dziewonski, A. M., A. L. Hales, and E. R. Lapwood, Parametrically simple earth models consistent with geophysical data, *Phys. Earth Planet. Interiors 10*, 12-48 (1975).

Edge, R. J., T. F. Baker, and G. Jeffries, Borehole tilt measurements: a periodic crustal tilt in an aseismic area, *Tectonophysics 71*, 97-109 (1981).

Eld[illegible] W. A., R. W. Rex, T. Meidav, P. T. Robinson, and S. Biehler, Crustal spreading in southern California, *Science 178*, 15-24 (1972).

Fairbridge, R. W., Neotectonic activity in the eastern United States and the late Holocene eustatic record of Florida, *Geol. Soc. Am. Abstracts with Programs* 6(7), 729 (1974).

Fanselow, J. L., *et al.*, Determination of UT1 and polar motion by the Deep Space Network using very-long-baseline interferometry, *IAU Symposium No. 82, Time and The Earth's Rotation*, D. D. McCarthy and J. D. H. Pilkington, eds., D. Reidel, Dordrecht, Holland, pp. 199-209 (1979).

Fell, P. J., Geodetic positioning using a global positioning system of satellites, Dept. of Geodetic Sci., Ohio State U., Rep. 299 (1980a).

Fell, P. J., A comparative analysis of GPS range, Doppler and interferometric observations for geodetic positioning, *Bull. Geodesique 54*, 564-574 (1980b).

Fitch, T. J., and C. H. Scholz, Mechanism of underthrusting in southwest Japan: a model of convergent plate interactions, *J. Geophys. Res. 76*, 7260-7291 (1971).

Flinn, E. A., Application of space technology to geodynamics, *Science 213*, 89-96 (1981).

Forsyth, D., and S. Uyeda, On the relative importance of the driving forces of plate motion, *Geophys. J. R. Astron. Soc. 43*, 163-200 (1975).

Gable, D., and T. Hatton, Vertical crustal movements in the conterminous United States over the last 10 million years, U.S. Geological Survey Open-File Report, pp. 80-180 (1980).

Gabrysch, R. K., Land-surface subsidence in the Houston-Galveston region, Texas, *Land Subsidence-Symposium Terrestre: IAHS-AISH*, Publication 121, pp. 16-24 (1976).

Goodkind, J. M., High-precision tide spectroscopy, Dept. of Geodetic Sci., Ohio State U. Rep. 280, pp. 309-311 (1978).

Guiraud, F. O., J. Howard, and D. C. Hogg, A dual-channel microwave radiometer for measurement of precipitable water vapor and liquid, *IEEE Trans. Geosci. Elec. GE-17*, 129-136 (1979).

Hack, J. T., Rock control and tectonism–their importance in shaping the Appalachian Highlands, U.S. Geological Survey Open-File Report 78-403, 39 pp. (1978).

Hadley, J. B., and J. F. Devine, Seismotectonic map of the eastern United States, U.S. Geological Survey Misc. Field Studies Map MF-620 (1974).

Hager, B. H., Oceanic plate motions driven by lithospheric thickening and subducted slabs, *Nature 276*, 156-159 (1978).

Heirtzler, J. R., Sea floor spreading, *Sci. Am. 227*, 60-70 (1968).

Herbst, K., Interpretation of tilt measurements in the period range above that of the tides, Rep. AFGL-TR-79-0093, Air Force Geophysics Lab., Bedford, Mass. (1979).

Herring, T. A., *et al.*, Geodesy by radio interferometry: intercontinental distance determination with subdecimeter precision, *J. Geophys. Res. 86*, 1647-1651 (1981).

Holdahl, S. R., and R. L. Hardy, Solvability of multiquadric analysis as applied to investigations of vertical crustal movements, *Recent Crustal Movements*, C. A. Whitten, R. Green, and B. K. Meade, eds. (1977), reprinted in *Tectonophysics 52*, 139-156 (1979).

Holzer, T. L., Documentation of potential for surface faulting related to ground-water withdrawal in Las Vegas Valley, Nevada, U.S. Geological Survey Open-File Report, pp. 78-79 (1978).

Holzer, T. L., S. N. Davis, and B. E. Lofgren, Faulting caused by ground-water extraction in south-central Arizona, *J. Geophys. Res. 84*, 603-612 (1979).

Institute for Advanced Study in Orbital Mechanics (IASOM), The report from the workshop on the spaceborne geodynamics ranging system, U. of Texas, Austin (1979).

Isachsen, Y. W., Possible evidence for contemporary doming of the Adirondack Mountains, New York, and suggested implications for regional tectonics and seismicity, *Tectonophysics 29*, 169-181 (1976a).

Isachsen, Y. W., Contemporary doming of the Adirondack Mountains, New York, *EOS 57*, 325 (1976b).

Isachsen, Y. W., E. P. Geraghty, and S. F. Wright, Investigation of Holocene deformation in the Adirondack Mountains dome, *Geol. Soc. Am. Abstracts with Programs 10*(2), 49 (1978).

Jackson, D. D., W. B. Lee, and C. C. Liu, Aseismic uplift in southern California: an alternative interpretation, *Science 210*, 534-536 (1980).

Kanamori, H., Are the earthquakes a major cause of the Chandler wobble, *Nature 262*, 254-255 (1976).

Kanamori, H., The energy release in great earthquakes, *J. Geophys. Res. 82*, 2981-2987 (1977a).

Kanamori, H., Seismic and aseismic slip along subduction zones and their tectonic implications, *Island Arcs, Deep Sea Trenches and Back-Arc Basins*, M. Talwani and W. C. Pitman, IV, eds., American Geophys. Union, Washington, D.C., pp. 162-174 (1977b).

Kanamori, H., Use of seismic radiation to infer source parameters, U.S. Geological Survey Open-File Report 78-380, pp. 283-318 (1978).

Kaula, W. M., Problems in understanding vertical movements and earth rheology, *Earth Rheology, Isostasy and Eustacy*, N. A. Morner, ed., John Wiley and Sons, Chichester, pp. 577-588 (1980).

Kelleher, J., and W. McCann, Buoyant zones, great earthquakes, and unstable boundaries of subduction, *J. Geophys. Res. 81*, 4885-4896 (1976).

Kreitler, C. W., Faulting and land subsidence from ground water and hydrocarbon production, Houston-Galveston, Texas, *Land Subsidence Symposium–Subsidence Terrestre: IAHS-AISH*, Publication 121, pp. 435–446 (1976).

Lachenbruch, A. H., and J. H. Sass, Thermo-mechanical aspects of the San Andreas Fault system, *Proceedings of the Conference on Tectonic Problems of the San Andreas Fault System*, R. L. Kovach and A. Nur, eds., *Geol. Sci. 13* Stanford U. Publ. (1973).

Lajoie, K. R., J. P. Kern, J. F. Wehmiller, G. L. Kennedy, S. A. Mathieson, A. M. Sarna-Wojcicki, R. F. Yerkes, and P. F. McCrory, Quaternary marine shorelines and crustal deformation, San Diego to Santa Barbara, California, *Geological Excursions in the Southern California Area*, P. L. Abbott, ed., Dept. of Geological Sci., San Diego State U., pp. 3–15 (1979).

Lambeck, K., and A. Cazenave, Long-term variations in the length of day and climatic change, *Geophys. J. R. Astron. Soc 46*, 555–573 (1976).

Le Pichon, X., J. Francheteau, and J. Bonnin, *Plate Tectonics*, Elsevier, Amsterdam, 300 pp. (1973).

Levine, J., and J. L. Hall, Design and operation of a methane absorption stabilized laser strainmeter, *J. Geophys. Res. 77*, 2595–2609 (1972).

Lomnitz, C., F. Mooser, C. R. Allen, and W. Thatcher, Seismicity and tectonics of the northern Gulf of California region, *Geofis. Intern. 10*, 37–48 (1970).

Lucchitta, I., Late Cenozoic uplift of the southwestern Colorado Plateau and adjacent Colorado River region, *Plateau Uplift: Mode and Mechanism*, T. R. McGetchin and R. B. Merrill, eds., *Tectonophysics 61*, 63–95 (1979).

Ma, C., Geodesy by radio interferometry: Polar motion and UT1 from Project Merit, *EOS 62*, 260 (1981).

MacDoran, P. F., Radio interferometry for international study of the earthquake mechanism, *Acta Astron. 1*, 1427–1444 (1974).

MacDoran, P. F., SERIES GPS Geodetic System (abs.), *EOS 59*, 1052 (1978).

MacDoran, P. F., Satellite emission radio interferometric Earth surveying SERIES-GPS Geodetic System, *Bull. Geodesique 53*, 117–138 (1979).

MacDoran, P. F., SERIES–Satellite emission radio interferometric earth surveying, Third Annual NASA Geodynamics Program Review, Crustal Dynamics Project Geodynamics Research, NASA, Washington, D.C., pp. 76 (1981).

Mansinha, L., and D. E. Smylie, Effect of earthquakes on the Chandler wobble and the secular polar shift, *J. Geophys. Res. 72*, 4731–4743 (1967).

Mansinha, L., D. E. Smylie, and C. H. Chapman, Seismic excitation of the Chandler wobble revisited, *Geophys. J. R. Astron. Soc. 59*, 1–17 (1979).

Mark, R. K., J. C. Tinsley III, E. B. Newman, T. D. Gilmore, and R. O. Castle, An assessment of the accuracy of the geodetic measurements that define the southern California uplift, *J. Geophys. Res. 86*, 2783–2808 (1981).

McCann, W., S. Nishenko, L. Sykes, and J. Krause, Seismic gaps and plate tectonics: seismic potential for major plate boundaries, *Pure Appl. Geophys. 117*, 1082–1147 (1979).

Meade, B. K., Report of the sub-commission on recent crustal movements in North America. XV General Assembly IUGG, International Association of Geodesy, 1971, *Reports on Geodetic Measurements of Crustal Movement*, U.S. Govt. Printing Office, Washington, D.C. (1973).

Melosh, H. J., Nonlinear stress propagation in the earth's upper mantle, *J. Geophys. Res. 81*, 5621–5632 (1976).

Michelson, A. A., and H. G. Gale, The rigidity of the earth, *Astrophys. J. 50*, 330–345 (1919).

Moran, J. M., and B. R. Rosen, The estimation of the propagation delay through the troposphere from microwave radiometer data, *Radio Sci. 16*, 235-244 (1981).

Morgan, W. J., Deep mantle convection plumes and plate motions, *Am. Assoc. Petrol. Geol. Bull. 56*, 203-213 (1972).

Morrissey, S. T., Tiltmeter array in New Madrid, USGS Semi-Annual Tech. Rep. 6 (1979).

Morton, D. M., and D. G. Herd, Earthquake hazard studies, Upper Santa Ana Valley and adjacent areas, southern California, Summaries of Technical Reports IX, N.E.H.R.P., U.S. Geological Survey Open-File Report 80-6, pp. 32-33 (1980).

Muto, K., A study of displacements of triangulation points, *Bull. Earthquake Research Inst. 10*, 384-392 (1932).

NASA, NASA Geodynamics Program: Annual Report for 1979, NASA Tech. Memo. 81978, Washington, D.C. (1980a).

NASA, Laser ranging system development for crustal dynamics applications, Geodynamics Branch, NASA Headquarters, Washington, D.C. (1980b).

Niell, A. E., K. M. Ong, P. F. MacDoran, G. M. Resch, D. D. Morabito, E. S. Claflin, and J. F. Dracup, Comparison of a radio interferometric differential baseline measurement with conventional geodesy, *Recent Crustal Movements*, C. A. Whitten, R. Green, and B. K. Meade, eds. (1977), reprinted in *Tectonophysics 52*, 49-58 (1979).

Nur, A., and G. Mavko, Postseismic viscoelastic rebound, *Science 183* 204-206 (1974).

O'Connell, R. J., and A. M. Dziewonski, Excitation of the Chandler wobble by large earthquakes, *Nature 262*, 259-262 (1976).

Pelton, J. R., and R. B. Smith, Recent crustal uplift in Yellowstone National Park, *Science 206*, 1179-1182 (1979a).

Pelton, J. R., and R. B. Smith, Releveling and microgal gravity reobservations: an evaluation of these techniques for delineating buried thermal bodies, Part II, The analysis of deformation-induced variations in orthometric height and gravity with an application to recent crustal movements in Yellowstone National Park, Final Tech. Rep., Geothermal Program, U.S. Geological Survey, Washington, D.C., 200 pp. (1979b).

Plumb, R., R. Bilham, and J. Beavan, A stable long-baseline fluid tiltmeter for tectonic studies, U.S. Geological Survey, Open-File Report 79-370, pp. 43-83 (1979).

Poland, J. F., B. E. Lofgren, R. L. Ireland, and R. G. Pugh, Land subsidence in the San Joaquin Valley, California, as of 1972, U.S. Geological Survey Prof. Paper 437-H (1975).

Prescott, W. H., J. C. Savage, and W. T. Kinoshita, Strain accumulation rates in the western United States between 1970 and 1978, *J. Geophys. Res. 84*, 5423-5435 (1979).

Press, F., and R. Siever, *Earth*, W. H. Freeman Co., San Francisco, 945 pp. (1978).

Preston, R. A., R. Ergas, H. F. Hinteregger, C. A. Knight, D. S. Robertson, I. I. Shapiro, A. R. Whitney, A. E. E. Rogers, and T. A. Clark, Interferometric observations of an artificial satellite, *Science 178*, 407-409 (1972).

Reid, H. F., The mechanism of the earthquake, *The California Earthquake of April 18, 1906*, Report of the State Earthquake Investigation Commission, Vol. 2, Carnegie Institution of Washington, D.C., 192 pp. (1910).

Reilinger, R. E., L. Brown, and D. Powers, New evidence for tectonic uplift in the Diablo Plateau region, west Texas, *Geophys. Res. Lett. 7*, 181-184 (1980).

Resch, G. M., Water vapor–the wet blanket of microwave interferometry, *Atmospheric Water Vapor*, A. Deepak, T. D. Wilkerson, and L. H. Ruhnke, eds., Academic Press, New York, pp. 265-282 (1980).

Resch, G. M., and E. S. Claflin, Microwave radiometry as a tool to calibrate tropospheric water vapor delay, *Radio Interferometry Techniques for Geodesy*, NASA Conf. Publ. 2115, Washington, D.C., pp. 377-384 (1980).

Richter, C. F., *Elementary Seismology*, W. H. Freeman Co., San Francisco, 768 pp. (1958).

Robertson, D. S., W. E. Carter, B. E. Corey, W. D. Cotton, C. C. Counselman, I. I. Shapiro, J. J. Wittels, H. F. Hinteregger, C. A. Knight, A. E. E. Rogers, A. R. Whitney, J. W. Ryan, T. A. Clark, R. J. Coates, C. Ma, and J. M. Moran, Recent results of radio interferometric determination of a transcontinental baseline, polar motion, and earth rotation, *IAU Symposium No. 82, Time and the Earth's Rotation*, D. D. McCarthy and J. D. H. Pilkington, eds., D. Reidel, Dordrecht, Holland, pp. 217-224 (1979).

Rogers, A. E. E., C. A. Knight, H. F. Hinteregger, A. R. Whitney, C. C. Counselman, I. I. Shapiro, S. A. Gourevitch, and T. A. Clark, Geodesy by radio interferometry: determination of a 1.24-km baseline vector with 5 mm repeatability, *J. Geophys. Res. 83*, 325-334 (1978).

Sacks, I. S., Borehole strainmeters, Proceedings of Conference VII, Stress and strain measurements related to earthquake predictions, U.S. Geological Survey Open-File Report 79-370, pp. 425–484 (1979).

Sarna-Wojcicki, A. M., K. R. Lajoie, S. W. Robinson, and R. F. Yerkes, Recurrent holocene displacement on the Javon Canyon fault, rates of faulting, and regional uplift, western Transverse Ranges, California, *Geol. [illegible] Am. Abstracts with Programs 11*(3). 125 (1979).

Sato, H., A short note on borehole-type tiltmeters and earthquake prediction, *Res. Note National Research Center for Disaster Prevention 34*, 32 pp. (1979).

Savage, J. C., Strain patterns and strain accumulation along plate margins, Dept. of Geodetic Sci., Ohio State U. Rep. 280, pp. 93–98 (1978).

Savage, J. C., and J. P. Church, Evidence for afterslip on the San Fernando Fault, *Bull. Seismol. Soc. Am. 65*, 829–834 (1975).

Savage, J. C., and L. M. Hastie, Surface deformation associated with dip-slip faulting, *J. Geophys. Res. 71*, 4897–4904 (1966).

Savage, J. C., and W. H. Prescott, Precision of geodolite distance measurements for determining fault movements, *J. Geophys. Res. 78*, 6001-6008 (1973).

Savage, J. C., and W. H. Prescott, Asthenospheric readjustment and the earthquake cycle, *J. Geophys. Res. 83*, 3369-3376 (1978).

Savage, J. C., W. H. Prescott, M. Lisowski, and N. E. King, Strain in southern California: measured uniaxial north-south regional contraction, *Science 202*, 883–885 (1978).

Savage, J. C., W. H. Prescott, M. Lisowski, and N. E. King, Deformation across the Salton trough, California, 1973–1977, *J. Geophys Res. 84*, 3069-3079 (1979).

Savage, J. C., W. H. Prescott, M. Lisowski, and N. E. King, Strain accumulation in southern California, *EOS 61*, 1127 (1980).

Savage, J. C., W. H. Prescott, M. Lisowski, and N. E. King, Strain accumulation in southern California 1973-1980, *J. Geophys. Res. 86*, 6991-7001 (1981).

Schlemon, R. J., Subaqueous delta formation–Atchafalaya Bay, Louisiana, *Deltas, Models for Exploration*, Houston Geol. Soc., pp. 209-221 (1975).

Shapiro, I. I., and C. A. Knight, *Geophysical Applications of Long-Baseline Interferometry in Earthquake Displacement Fields and the Rotation of the Earth*, L. Mansinha, D. E. Smilie, and A. E. Beck, eds., Springer, New York, 284 pp. (1970).

Sheets, M. M., Subsidence and active surface faulting in the Houston vicinity, *Guidebook*, Houston Geol. Soc., South-Central Section, Geol. Soc. Am., 9 pp. (1976).

Silverberg, E. C., Mobile satellite ranging, Dept. of Geodetic Sci., Ohio State U. Rep. 280, pp. 41–46 (1978).

Silverberg, E. C., On the effective use of lunar ranging for the determination on the Earth's orientation, *IAU Symposium No. 82, Time and Earth's Rotation*, D. D. McCarthy and J. D. H. Pilkington, eds., D. Reidel, Dordrecht, Holland, pp. 247-255 (1979).

Slater, L. E., Cooperative Institute for Research in Environmental Sciences, Univ. of Colorado, Boulder, private communication (1981).

Smith, R. B., and R. L. Christiansen, Yellowstone Park as a window on the Earth's interior, *Sci. Am. 242*(2), 104-117 (1980).

Smith, D. E., and P. J. Dunn, Long-term evolution of the LAGEOS orbit, *Geophys. Res. Lett. 7*, 437-440 (1980).

Smith, D. E., R. Kolenkiewicz, P. J. Dunn, and M. H. Torrence, The measurement of fault motion by satellite laser ranging, *Tectonophysics 52*, 59-67 (1979a).

Smith, D. E., R. Kolenkiewicz, P. J. Dunn, and M. H. Torrence, Determination of polar motion and Earth rotation from laser tracking of satellites, *IAU Symposium No. 82, Time and the Earth's Rotation*, D. D. McCarthy and J. D. H. Pilkington, eds., D. Reidel, Dordrecht, Holland, pp. 247-255 (1979b).

Smith, D. E., R. Kolenkiewicz, P. J. Dunn, and M. H. Torrence, Determination of stations coordinates from LAGEOS, *The Use of Artificial Satellites for Geodesy and Geodynamics*, Vol. II, G. Veis and E. Livieratos, eds., National Technical U., Athens (1979c).

Snay, R. A., and J. G. Gergen, Monitoring regional crustal deformation with horizontal geodetic data, applications of geodesy to geodynamics, I. I. Mueller, ed., *Proceedings of the Ninth Geodesy/Solid Earth and Ocean Physics (GEOP) Research Conference*, Dept. of Geodetic Sci., Ohio State U. Rep. 280, pp. 87-92 (1978).

Solomon, S. C., N. H. Sleep, and R. M. Richardson, On the forces driving plate tectonics: inferences from absolute plate velocities and intraplate stress, *Geophys. J. R. Astron. Soc. 42*, 769-801 (1975).

Spilker, J. J., Jr., GPS signal structure and performance characteristics, *Navigation 25*, 121-146 (1978).

Stein, R. S., Role of elevation dependent errors on the accuracy of geodetic leveling in the southern California uplift, *The Earthquake Prediction: An International Review*, Maurice Ewing Series 4, D. W. Simpson and P. G. Richards, eds., Am. Geophys. Union, Washington, D.C., pp. 441-456 (1981).

Stewart, J. H., Basin and range structure: a system of horsts and grabens produced by deep-seated extension, *Bull. Geol. Soc. Am. 82*, 1019-1044 (1971).

Strange, W., The effect of systematic errors on geodynamic analysis, in *Proceedings, Second International Symposium on Problems Related to the Redefinition of North American Vertical Geodetic Networks*, Canadian Institute of Surveying, Ottawa, Canada, pp. 705-727 (1980).

Strange, W., The impact of refraction correction on leveling interpretations in southern California, *J. Geophys. Res. 86*, 2809-2824 (1981).

Sykes, L. R., Intraplate seismicity, reactivation of pre-existing zones of weakness, alkaline magnetism, and other tectonism postdating continental fragmentation, *Rev. Geophys. Space Phys. 16*, 621-688 (1978).

Thatcher, W., Strain accumulation on the northern San Andreas fault zone since 1906, *J. Geophys. Res. 80*, 4873-4880 (1975).

Thatcher, W., Systematic inversion of geodetic data in central California, *J. Geophys. Res. 84*, 2283-2295 (1979a).

Thatcher, W., Horizontal crustal deformation from historic geodetic measurements in southern California, *J. Geophys. Res. 84*, 2351-2370 (1979b).

Thatcher, W., and J. B. Rundle, A model for the earthquake cycle in underthrust zones, *J. Geophys. Res. 84*, 5540-5556 (1979).

Tsuboi, C., Investigation on the deformation of the Earth's crust in the Tango district connected with the Tango earthquake of 1927, *Bull. Earthquake Res. Inst. 10*, 411-434 (1932).

U.S. Geodynamics Committee, National Research Council, *Continental Scientific Drilling Program*, National Academy of Sciences, Washington, D.C., 192 pp. (1979)

U.S. Geodynamics Committee, National Research Council, *Geodynamics in the 1980's*, National Academy of Sciences, Washington, D.C., 55 pp. (1980).

Uyeda, S., *The New View of Earth*, W. H. Freeman Co., San Francisco, 217 pp. (1978).

Vanicek, P., M. R. Elliott, and R. O. Castle, Four-dimensional modeling of recent vertical movements in the area of the southern California uplift, *Recent Crustal Movements*, C. A. Whitten, R. Green, and B. K. Meade, eds. (1977), reprinted in *Tectonophysics 52*, 287-300 (1979).

Whalen, C. T., Status of the national geodetic vertical control network in the United States, *Proceedings of the Second International Symposium on Problems Related to the Redefinition of North American Vertical Geodetic Networks*, Canadian Institute of Surveying, Ottawa, Canada, pp. 11-24 (1980).

Wilson, C. R., Meteorological Excitation of the Earth's Wobble, Ph.D. Thesis, U. of California, San Diego (1975)

Wilson, J. T., ed., *Readings from Scientific American: Continents Adrift and Continents Aground*, W. H. Freeman Co., San Francisco, 230 pp. (1976).

Wilson, P., E. Silverberg, R. Schutz, I. Mal[illegible]ch, and S. Ramsden, A proposal for the design and application of a high-mobility, low-cost satellite laser ranging system, *Proceedings of the European Workshop on Space Oceanography, Navigation and Geodynamics*, S. Hieber and T. D. Guyenne, eds., European Space Agency, SP-137, pp. 111-117 (1978).

Wyatt, F., and J. Berger, Investigations of tilt measurements using shallow borehole tiltmeters, *J. Geophys Res. 85*, 4351-4362 (1980).

Yeats, R. S., High rates of vertical crustal movements near Ventura, California, *Science 196*, 295-298 (1977).

Yeats, R. S., Neogene acceleration of subsidence rates in southern California, *Geology 6*, 456-460 (1978).

Zoback, M. D., R. M. Hamilton, A. Crone, D. P. Russ, and S. R. Brockman, Preliminary interpretation of faulting in the New Madrid fault zone, *EOS 60*, 310 (1979).