Composition, Structure and Dynamics of the Lithosphere-Asthenosphere System

K. Fuchs
C. Froidevaux
Editors

Geodynamics Series Volume 16
International Lithosphere Program Contribution

Composition, Structure and Dynamics of the Lithosphere-Asthenosphere System

Edited by K. Fuchs
C. Froidevaux

Geodynamics Series
Volume 16

American Geophysical Union
Washington, D.C.

Geological Society of America
Boulder, Colorado
1987

Publication No. 0135 of the International Lithosphere Program

Published under the aegis of AGU Geophysical Monograph Board.

Library of Congress Cataloging-in-Publication Data

Composition, structure, and dynamics of the
lithosphere-asthenosphere system.

(Geodynamics series ; v. 16) (Publication no.
0135 of the International Lithosphere Program)
"Based on a symposium held in Moscow on the
occasion of the 26th International Geological Congress"—
Foreword.
1. Earth—Crust—Congresses. 2. Earth—Mantle—
Congresses. 3. Petrology—Congresses. 4. Geodynamics—
Congresses. I. Fuchs, K. II. Froidevaux, C. (Claude)
III. Series. IV. Series: Publication . . . of the
International Lithosphere Program ; no. 0135.
QE511.C65 1987 551.1'3 86-28822
ISBN 0-87590-518-8
ISSN 0277-6669

Printed in the United States of America.

Geodynamics Series

Geodynamics Series

1 Dynamics of Plate Interiors
A. W. Bally, P. L. Bender, T. R. McGetchin, and R. I. Walcott (Editors)

2 Paleoreconstruction of the Continents
M. W. McElhinny and D. A. Valencio (Editors)

3 Zagros, Hindu Kush, Himalaya, Geodynamic Evolution
H. K. Gupta and F. M. Delany (Editors)

4 Anelasticity in the Earth
F. D. Stacey, M. S. Patterson, and A. Nicholas (Editors)

5 Evolution of the Earth
R. J. O'Connell and W. S. Fyfe (Editors)

6 Dynamics of Passive Margins
R. A. Scrutton (Editor)

7 Alpine-Mediterranean Geodynamics
H. Berckhemer and K. Hsü (Editors)

8 Continental and Oceanic Rifts
G. Pálmason, P. Mohr, K. Burke, R. W. Girdler, R. J. Bridwell, and G. E. Sigvaldason (Editors)

9 Geodynamics of the Eastern Pacific Region, Caribbean and Scotia Arcs
Ramón Cabré, S. J. (Editor)

10 Profiles of Oragenic Belts
N. Rast and F. M. Delany (Editors)

11 Geodynamics of the Western Pacific-Indonesian Region
Thomas W. C. Hilde and Seiya Uyeda (Editors)

12 Plate Reconstruction From Paleozoic Paleomagnetism
R. Van der Voo, C. R. Scotese, and N. Bonhommet (Editors)

13 Reflection Seismology: A Global Perspective
Muawia Barazangi and Larry Brown (Editors)

14 Reflection Seismology: The Continental Crust
Muawia Barazangi and Larry Brown (Editors)

15 Mesozoic and Cenozoic Oceans
Kenneth J. Hsü (Editor)

FOREWORD

Raymond A. Price

Past-President, International Lithosphere Program
and
Director General, Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario, K1A OE8

The International Lithosphere Program was launched in 1981 as a ten-year project of inter-disciplinary research in the solid earth sciences. It is a natural outgrowth of the Geodynamics Program of the 1970's, and of its predecessor, the Upper Mantle Project. The Program — "Dynamics and Evolution of the Lithosphere: The Framework of Earth Resources and the Reduction of Hazards" — is concerned primarily with the current state, origin and development of the lithosphere, with special attention to the continents and their margins. One special goal of the program is the strengthening of interactions between basic research and the applications of geology, geophysics, geochemistry and geodesy to mineral and energy resource exploration and development, to the mitigation of geological hazards, and to protection of the environment; another special goal is the strengthening of the earth sciences and their effective application in developing countries.

An Inter-Union Commission on the Lithosphere (ICL) established in September 1980, by the International Council of Scientific Unions (ICSU), at the request of the International Union of Geodesy and Geophysics (IUGG) and the International Union of Geological Sciences (IUGS), is responsible for the overall planning, organization and management of the program. The ICL consists of a seven-member Bureau (appointed by the two unions), the leaders of the scientific Working Groups and Coordinating Committees, which implement the international program, the Secretaries-General of ICSU, IUGG and IUGS, and liaison representatives of other interested unions or ICSU scientific committees. National and regional programs are a fundamental part of the International Lithosphere Program and the Chairman of the Coordinating Committee of National Representatives is a member of the ICL.

The Secretariat of the Commission was established in Washington with support from the U.S., the National Academy of Sciences, NASA, and the U.S. Geodynamics Committee.

The International Scientific Program initially was based on nine International Working Groups.

- WG-1 Recent Plate Movements and Deformation
- WG-2 Phanerozoic Plate Motions and Orogenesis
- WG-3 Proterozoic Lithospheric Evolution
- WG-4 The Archean Lithosphere
- WG-5 Intraplate Phenomena
- WG-6 Evolution and Nature of the Oceanic Lithosphere
- WG-7 Paleoenvironmental Evolution of the Oceans and Atmosphere
- WG-8 Subduction, Collision, and Accretion
- WG-9 Process and Properties in the Earth that Govern Lithospheric Evolution

Eight Committees shared responsibility for coordination among the Working Groups and between them and the special goals and regional groups that are of fundamental concern to the project.

- CC-1 Environmental Geology and Geophysics
- CC-2 Mineral and Energy Resources
- CC-3 Geosciences Within Developing Countries
- CC-4 Evolution of Magmatic and Metamorphic Processes
- CC-5 Structure and Composition of the Lithosphere and Asthenosphere
- CC-6 Continental Drilling
- CC-7 Data Centers and Data Exchange
- CC-8 National Representatives

Both the Bureau and the Commission meet annually, generally in association with one of the sponsoring unions or one of their constituent associations. Financial support for scientific symposia and Commission meetings has been provided by ICSU, IUGG, IUGS, and UNESCO. The constitution of the ICL requires that membership of the Bureau, Commission, Working Groups, and Coordinating Committees change progressively during the life of the project, and that the International Lithosphere Program undergo a mid-term review in 1985. As a result of this review there has been some consolidation and reorganization of the program. The reorganized program is based on six International Working Groups:

- WG-1 Recent Plate Movements and Deformation
- WG-2 The Nature and Evolution of the Continental Lithosphere
- WG-3 Intraplate Phenomena
- WG-4 Nature and Evolution of the Oceanic Lithosphere
- WG-5 Paleoenvironmental Evolution of the Oceans and the Atmosphere
- WG-6 Structure, Physical Properties, Composition and Dynamics of the Lithosphere-Asthenosphere System

and six Coordinating Committees:

CC-1 Environmental Geology and Geophysics
CC-2 Mineral and Energy Resources
CC-3 Geosciences Within Developing Countries
CC-4 Continental Drilling
CC-5 Data Centers and Data Exchanges
CC-6 National Representatives
Sub-Committee 1 - Himalayan Region
Sub-Committee 2 - Arctic Region

This volume is one of a series of progress reports published to mark the completion of the first five years of the International Geodynamics Project. It is based on a symposium held in Moscow on the occasion of the 26th International Geological Congress.

Further information on the International Lithosphere Program and activities of the Commission, Working Groups and Coordinating Committees is available in a series of reports through the Secretariat and available from the President — Prof. K. Fuchs, Geophysical Institute, University of Karlsruhe, Hertzstrasse 16, D–7500 Karlsruhe, Federal Republic of Germany; or the Secretary-General — Prof. Dr. H.J. Zwart, State University Utrecht, Institute of Earth Sciences, P.O. Box 80.021, 3508 TA Utrecht, The Netherlands.

R.A. Price, President
Inter-Union Commission on the Lithosphere, 1981-85

PREFACE

This volume is devoted to recent advances in investigating the Earth's crustal and mantle structure, its composition and dynamics. Many of the papers reflect the debate organized by the International Lithosphere Program (ILP) during the Moscow International Geological Congress (1984). Others stem from discussions within one working group (WG-9) and one coordinating committee (CC-5) of ILP.

A glance at the table of contents shows that seismology has been the main tool for unravelling the deep structures resulting from ongoing or past geodynamical processes. The scope of seismology has been considerably broadened: first by the achievement of higher resolution over a depth range equal or just greater than that of the continental crust (reflection profiling); and second by the provision of a global or regional three-dimensional view of the structure of the upper or even the whole mantle, but with a resolving power limited to large wavelength because of the limited number of observing stations.

Reflection profiling opened the age of three-dimensional geology of the crystalline crust. Among the many specific structural characteristics of the deep continental crust that have been revealed were thrust faults that extend deep into the crust, and lamellar reflectivity in the lower crust in extensional regimes, which is evidence of pervasive tectonic mobility in this part of the lithosphere. The rheological properties of the lower crust govern a number of continental intraplate processes which cannot be directly explained within the classical plate-tectonic framework; these include: seismicity in the middle of continents, plateau uplift, basin formation and rifting.

Deep seismic probing with controlled sources on long-range profiles with several thousand kilometers of aperture have begun to penetrate, with high resolution, deep into the mantle transition zone on a regional scale. Almost simultaneously seismic tomography using natural sources has produced a global image of 3D-heterogeneities of the earth's mantle. Furthermore, directional analysis of P- and S-wave velocities have revealed a striking pattern of spatial distribution of anisotropy produced by preferred orientation of olivine that presumably is parallel with mantle flow lines.

The European Geotraverse (EGT) is an attempt to understand the structure and evolution of western Europe along a corridor from the ancient Precambrian shield to the young Alpine fold belts. It involves the compilation of existing data and also new field experiments. In a way, EGT is a very good example for the new ILP project of Global Geoscience Transects which was launched during the 1985 ILP-Commission meeting at Tokyo, and is modelled on the North American Ocean-Continent Transects Project. All available geophysical and geological data relating to the crust and upper mantle within a selected corridor are compiled and interpreted at a uniform scale and in the same format in order to permit worldwide comparison of cross-sections through crucial geological structures.

Other data sets from electromagnetic or gravity surveys are also analysed in this volume, and help provide a better structural view of the lithosphere and the underlying mantle. The mechanical behaviour of the lithosphere is analysed in various tectonic situations: island areas, mountain belts, passive margins, and these interpretations help to define the problems to be solved in a near future. Some new techniques of data acquisition are also discussed. The large list of recent references should also help the reader to catch up with subjects of special interest.

A new door is opened in the earth's sciences to a better understanding of the structure, composition and processes of the deep interior. Tomographic features on the mantle will soon be related to geochemical anomalies of magmatic outcrops at the earth's surface, which, in turn, by dating will provide estimates for the lifetime of the mantle reservoirs. This, together with the information on the direction of the flow, will provide important constraints for convection calculations which will link the correlation of geochemical anomalies and instantaneous tomographic heterogeneities. We are now seeing the beginning of this new development.

Claude Froidevaux
Karl Fuchs
Editors

CONTENTS

Foreword *Raymond A. Price* ix

Preface *Claude Froidevaux and Karl Fuchs* xi

A New Era in Understanding the Continental Basement; the Impact of Seismic Reflection Profiling *Ernest C. Hauser and Jack E. Oliver* 1

The Lower Crust of the Continents *J. A. Percival and M. J. Berry* 33

Rheology of the Oceanic and Continental Lithosphere *D. L. Turcotte* 61

Estimation of Crustal Viscosities and Shear Stresses From an Extrapolation of Experimental Steady State Flow Data *Jurgen Strehlau and Rolf Meissner* 69

Global Mapping of the Uppermantle by Surface Wave Tomography *Don L. Anderson* 89

Global Digital Seismographic Network: Research Opportunities and Recent Initiatives *Barbara A. Romanowicz and Adam M. Dziewonski* 99

Formation of Anisotropy in Upper Mantle Peridotites—A Review *Adolphe Nicolas and Nikolas I. Christensen* 111

Surface Plate Kinematics and Mantle Convection *A. M. Forte and W. R. Peltier* 125

Exploring Heterogeneities of the Continental Mantle by High Resolution Seismic Experiments *K. Fuchs, L. P. Vinnik, and C. Prodehl* 137

Upper Mantle Metasomatism: Chemical and Physical Consequences *J. B. Dawson* 155

Mantle Xenoliths and Continental Lithosphere Composition *N. V. Sobolev* 161

The Geochemistry of Magmatic Rocks and Paleodynamic Reconstructions *Mikhail Kuzmin, Alexandr Al'mukhamedov, and Gennady Anoshin* 165

The Forces Driving Plate Motions and Compression of the Crust in Fold Belts *E. V. Artyushkov* 175

Dynamical Extension of the Lithosphere During Rifting: Some Numerical Model Results *C. E. Keen* 189

Spherical Shell Tectonics and the Evolution of Subduction Zones *Koshun Yamaoka, Yoshio Fuako, and Mineo Kumazawa* 205

Interim Report on Electromagnetic Lithosphere-Asthenosphere Soundings (ELAS) to Coordinating Committee No. 5 of the International Lithosphere Programme *D. Ian Gough (Editor)* 219

Structural Model of the Subcrustal Lithosphere in Central Europe *V. Babuška, J. Plomerová, and J. Šílený* 239

The European Geotraverse (EGT) Project: A Progress Report *Daniel A. Galson and Stephan Mueller* 253

Deep Seismic Sounding on Long Range Profiles in the Atlantic Ocean *S. M. Zverev and G. A. Yaroshevskay* 273

The Geology of Ocean Floor *Kenneth J. Hsü* 291

Isostasy in the USSR I: Admittance Data *M. G. Kogan and M. K. McNutt* 301

Isostasy in the USSR II: Interpretation of Admittance Data *M. K. McNutt and M. G. Kogan* 309

A NEW ERA IN UNDERSTANDING THE CONTINENTAL BASEMENT; THE IMPACT OF SEISMIC REFLECTION PROFILING

Ernest C. Hauser[1] and Jack E. Oliver[1,2]

[1]INSTOC (Institute for the Study of the Continents), Snee Hall, Cornell University, Ithaca, NY 14853

[2]Department of Geological Sciences, Snee Hall Cornell University, Ithaca, NY 14853

Abstract. Seismic reflection profiling is a tool that is rapidly expanding our knowledge of the continental basement. The basic technique was developed in the 1920's and has since become the principal geophysical exploration tool of the petroleum industry. Although some successful attempts were made to observe reflections from within the continental basement in the 1950's and 1960's in Australia, Canada, Germany, the U.S., and elsewhere, a sustained program to record long crustal-scale deep reflection profiles began in 1974 with the inception of COCORP (Consortium for Continental Reflection Profiling) operated from Cornell University. Since that time several similar national programs have developed in Australia, Canada, France, Germany, and the U.K. and many other countries have begun, have plans for, or have expressed interest in deep reflection profiling of the continental basement. Although still in its infancy, deep reflection profiling has already explored a variety of major crustal features such as convergent orogenic belts and overthrusts, regions of important crustal extension, and other obscure or hidden basement features. The future of deep reflection profiling will include more regional traverses by a growing number of programs worldwide and will eventually involve still more elegant and specialized field and processing techniques both to address specific local problems after initial profiling and to gain additional general information about the subsurface. Perhaps the greatest impact of deep reflection profiling is that these data will provide constraints on the distribution and geometry of features of the continental basement and will further encourage the various fields of geoscience in a multidisciplinary approach to our understanding of the composition, structure, history, and evolution of the continental basement.

Introduction

Reflection seismic profiling on a crustal scale is in its infancy, but earth scientists have already demonstrated its unique ability to explore features of the deep crust with a detail unprecedented in the geosciences. Geoscientists have long been limited by the dominantly two-dimensional aspect of surface exposure; even though, in places, important insights into the third-dimension of the continental crust have been provided by exposures in mountainous regions, shallow drilling and mines, igneous activity, xenoliths in kimberlites, and various geophysical techniques. Locally exhumed features and traditional geophysical measurements allow the earth scientist to construct a generalized but commonly highly inferential picture of the continental crust at depth and its evolution. The variety of geophysical methods available for studying crustal structure such as gravity, magnetics, electrical conductivity, heat flow, and seismic refraction have generally lower resolution than reflection profiling and measure a crustal property averaged over a larger volume of the crust. Over the last few years the application of seismic reflection profiling with its greater resolution to the study of the continental basement has made a major impact upon the geosciences and ushered in a new era in understanding the continental crust and its evolution.

Concentrated efforts to expand the understanding of the continental basement are important in more than an academic sense. The future of modern societies will depend upon the continued ability to find the necessary resources for the well-being of their people. For example, many rare and valuable mineral deposits are found in the exposed Precambrian shields of the continents yet wide regions (and probably similar deposits) are covered by a blanket of younger sedimentary strata or other crystalline rocks. Even in the exposed shields the subsurface is poorly known. Many important resources are also found in Phanerozoic orogenic belts where the evolution of crustal deformation and its relation to the development of various resources are imperfectly understood. Through a more complete knowledge of the continental basement, both old and young, one

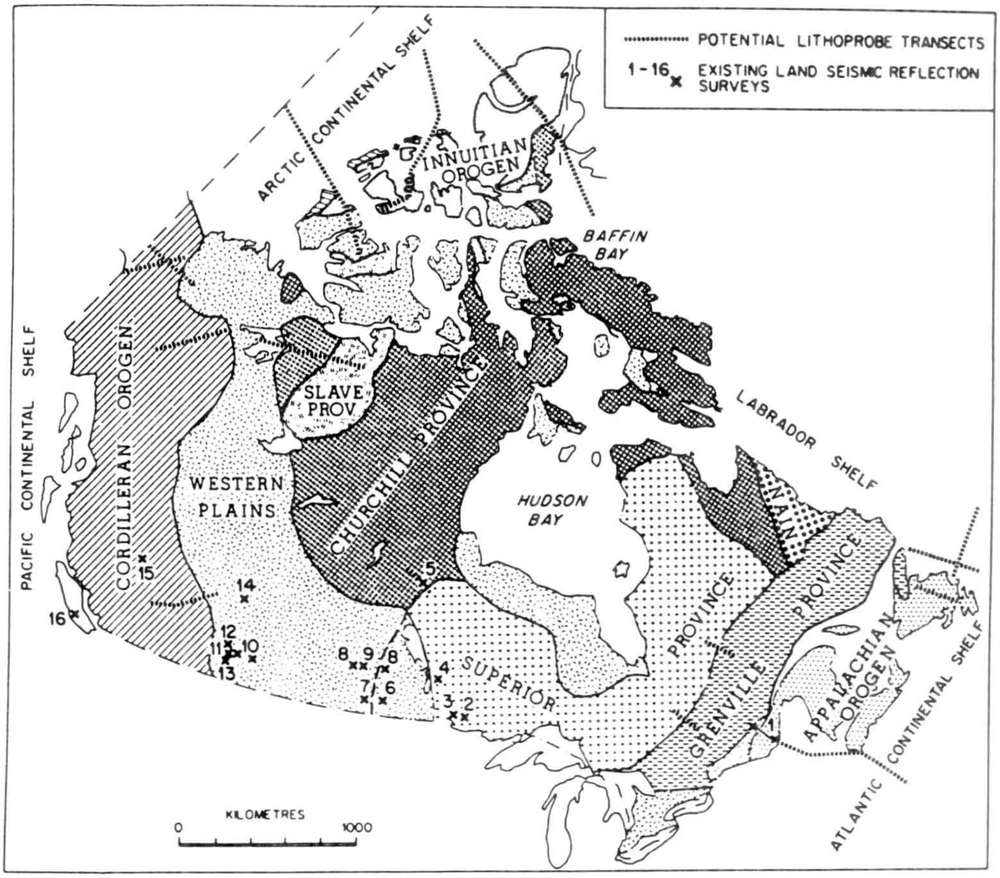

Fig. 1. Locations of existing and planned deep seismic reflection surveys in Canada (from Green and Clowes, 1983). Crosses with numbers refer to existing sites of seismic reflection data as referenced by Green and Clowes (1983). Segmented lines refer to the location of potential surveys by Lithoprobe (CANDEL, 1981). Note the continuation of the existing Canadian Appalachian survey (location 1) into Maine and eventually offshore by the U.S. Geological Survey.

may learn not only where important resources may occur but also how they form. Also the seismic and volcanic hazards related to tectonic processes will inevitably become more important as population densities increase in tectonically active areas. Through a more complete understanding of the continental basement, especially the details of crustal structure in earthquake-prone regions, geoscientists may develop the capability to predict future seismic events. In these and other ways the thorough understanding of the structure and evolution of the continental basement becomes essential.

The seismic reflection technique, first developed in the 1920's, today is the principle geophysical exploration tool of the petroleum industry (see Sheriff and Geldart, 1982). Seismic reflection profiling is a procedure whereby an energy source and set of receivers progress along a traverse by incremental steps to record the reflections from subsurface features. The modern technique allows significant redundancy of reflection data to improve the ratio of seismic signal to noise, especially important for weak deep reflections. The resulting acoustic image in some ways resembles a geologic cross-section, but it is a time section on which the orientation and position of dipping reflections on the seismic section are removed from the position of the reflector in the earth, requiring migration and care in interpretation. The basic technique of today is in principle the same as in the early years, but extensive improvements in equipment and data analysis have been achieved. Especially important is the development of digital recording and processing techniques, as well as, the development of the Vibroseis (TM of CONOCO, Inc.) technique as an alternative to conventional explosion sources. The development of these techniques has involved extensive

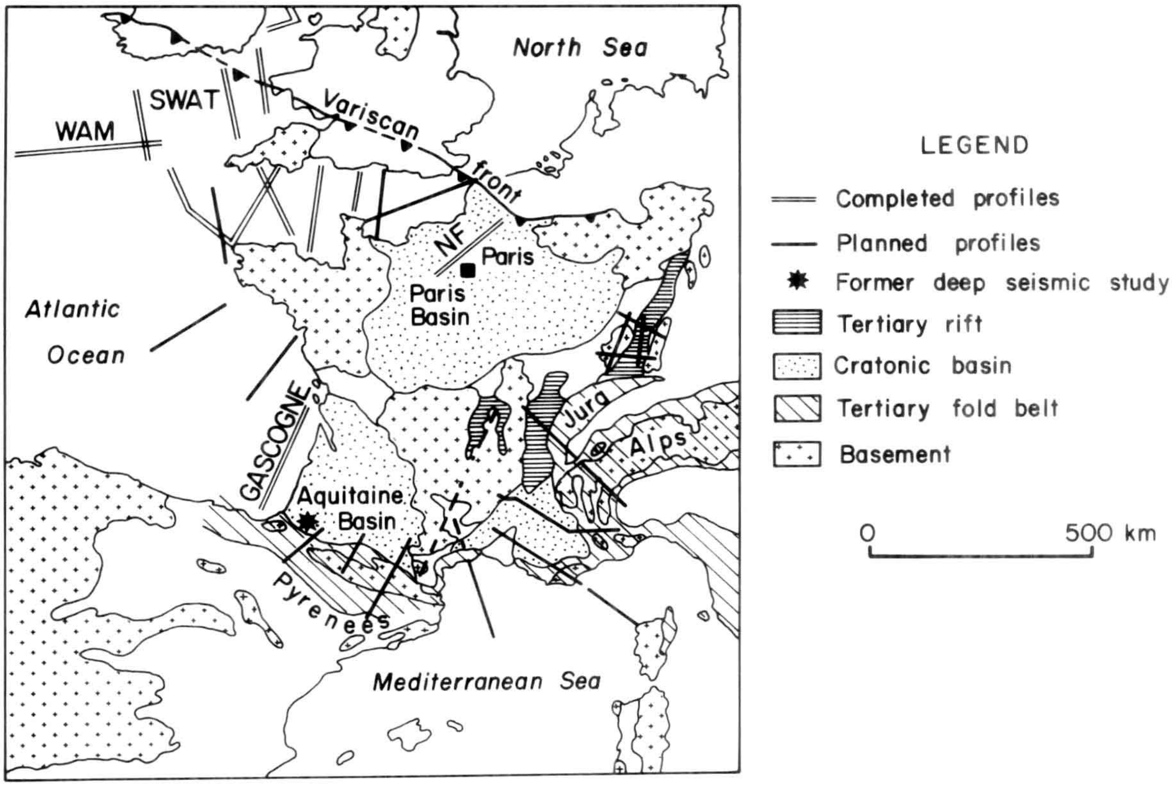

Fig. 2. Locations in France of existing and planned land and marine seismic reflection traverses by ECORS (from Bois and Allégre, 1983; and pers. comm. from C. Bois).

research, skill, and capital investment by the petroleum industry, an expense and task that scientific programs for deep reflection profiling have fortunately not had to bear.

Seismic reflections from crystalline basement were first reported from data collected during industrial surveys (Junger 1951; Reich, 1953; Widess and Taylor, 1959; Robertson, 1963; Dix, 1965; Dohr and Fuchs, 1967). Petroleum exploration, concerned with the shallow crustal sedimentary strata, rarely recorded data for two-way travel times greater than 4 to 5 s, corresponding to depths of approximately 8 to 12 km. Deeper features apparently in the basement were generally considered uneconomical or multiples originating within shallow layers.

Reflection profiling to explore the continental basement has come far since the early hints of reflections from basement features. This review first gives a synopsis of programs involved in deep seismic reflection profiling of the continental basement worldwide. This is followed by a summary of some of the major findings to this time. Lastly follows a discussion of the impact upon the breadth of the geosciences and some prospects for the future of this technique in improving the understanding of the continental basement.

Summary of Deep Seismic Reflection Profiling Worldwide

In 1985 there are at least six established national programs active, ACORP (Australia), Lithoprobe and COCRUST (Canada), ECORS (France), DEKORP (Germany), BIRPS (United Kingdom), and COCORP (United States). In addition there are deep reflection profiles collected intermittently or in the planning stage by other groups. The following is a brief and probably only partially complete synopsis of these programs.

In Australia, limited but successful deep seismic reflection experiments were carried out by the Australian Bureau of Mineral Resources (BMR) as early as 1957. Although some of these experiments in the late 1960's were specifically designed to record vertical reflections from the crust and upper mantle (Branson et al., 1976; Mathur et al., 1977), most of the early deep data were collected by extending recording times on a few analog recorders during standard BMR seismic surveys of the large sedimentary basins of Australia. After 1976, with the introduction of digital recording and precessing, several short reflection surveys to 16 s were recorded (Mathur, 1983a). More recently a more ambitious program of longer surveys with data to 20 s has been

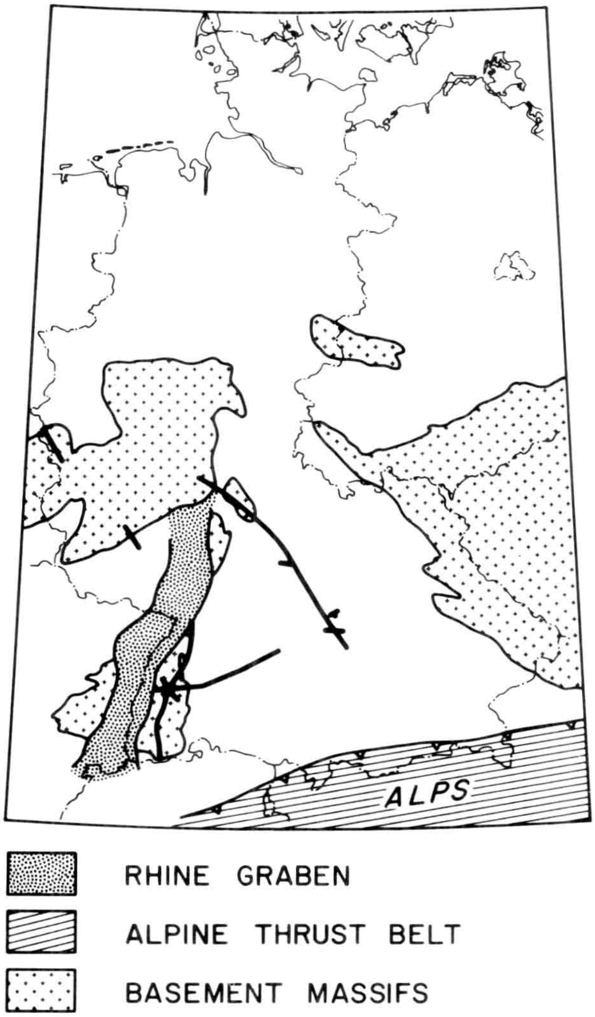

Fig. 3. Locations of existing German deep seismic surveys as of May 1985 (from Meissner and Lueschen, 1983; and pers. comm. from H.-J. Dürbaum.

undertaken and has traversed the central Eromanga Basin of Eastern Australia with plans eventually to extend the traverse to the Australian east coast (Mathur, 1983b; Moss and Mathur, 1986). The BMR, and other organizations, will be involved in the Australian Continental Reflection Profiling Program (ACORP) which has recently been established. ACORP is an ongoing co-operative government, academic, and industrial effort with a goal to collect nearly 1000 km of deep reflection profiles each year.

Seismic reflection studies of the continental basement have also been carried out intermittently in Canada for many years (Kanasewich and Cumming, 1965; Clowes et al., 1968; Kanasewich et al., 1968; Clowes and Kanasewich, 1972; Cumming and Chandra, 1975; Mair and Lyons, 1976; Berry and Mair, 1977; Green and Clowes, 1983; Cook, 1985) (see Fig. 1). The early reflection studies were short but good reflections were recorded from Moho and mid-crustal discontinuities which locally exhibited significant relief (Kanasewich et al., 1968; Clowes and Kanasewich, 1972). In 1975, COCRUST (the Consortium for Crustal Reconnaissance Using Seismic Techniques) was formed in an effort to organize a co-operative program for crustal seismic surveys in Canada. COCRUST surveys have included a study of the Superior-Churchill Boundary in southern Saskatchewan (Green et al., 1980) and VISP (Vancouver Island Seismic Project). VISP included refraction and on-land deep reflection profiles to explore the deep structure of the convergent margin and its subducting lithosphere (Green and Clowes, 1983). In 1981, the Canadian Committee on the Dynamics and Evolution of the Lithosphere (CANDEL, 1981) outlined plans for the Lithoprobe project, an integrated multidisciplinary effort to include several deep seismic reflection traverses to explore the Canadian continental basement (Fig. 1). The first of the Lithoprobe deep reflection profiles was a traverse of the Appalachians in Quebec which extended to the southeast an intermediate depth (4 to 6 s two-way travel time) seismic reflection profile originally recorded for the Quebec government for

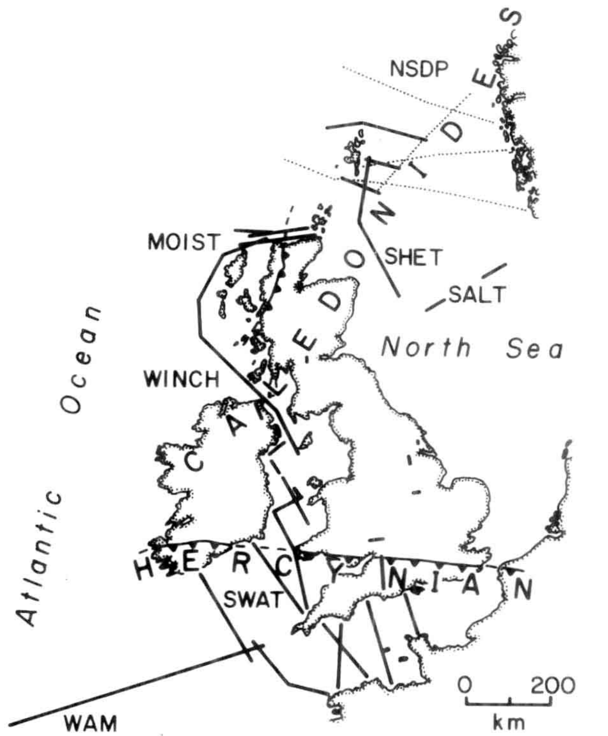

Fig. 4. BIRPS profile site map (after Matthews and Cheadle, 1986). Solid lines represent profiles completed before June 1984, and dotted lines represent profiles begun in 1984.

Fig. 5. Locations of existing deep seismic reflection data sets on land in the United Kingdom between 1979 and 1982 (after Whittaker and Chadwick, 1983). Profiles range in length from 1.5 to 30 km with two-way travel times of 6 s or greater.

petroleum exploration (Ministére des Richesses Naturelles du Québec, 1979a, 1979b; St. Julien et al., 1983; Green and Clowes, 1983). Good reflection data along these profiles reveal a geometry of thin-skinned thrusting similar to that discovered in the southern Appalachians by COCORP seismic reflection profiling (Green and Clowes, 1983; Cook et al., 1980; Ando et al., 1983). This traverse continues across Maine (see Fig. 1) as a series of recently collected deep reflection profiles by the U.S. Geological Survey (Hamilton, 1984). Future deep reflection profiling of the continental crust by Lithoprobe includes more surveys on the active margin on and near Vancouver Island, in the Canadian Cordillera, across the Precambrian basement in the Kapuskasing region and Abitibi greenstone belt of Ontario, across the Grenville Front in Ontario and Quebec, and across the Appalachian orogen around Newfoundland (Green and Berry, 1986).

In France in 1982, the ECORS (Etude Continentale et Océanique par Réflexion et Réfraction Sismiques) program was established by the Institut Francais du Pétrole and the Institut National d'Astronomie et de Géophysique, representatives of the petroleum industry and academic institutions respectively, as a long-term joint effort with the goal to study the continental crust of France using seismic reflection and refraction techniques (Bois and Allégre, 1983). Later these institutions were joined by the Société Nationale Elf-Aquitaine. This young consortium has recently published results from deep reflection profiling in northern France across part of the Paris basin and the buried Hercynian suture (Bois et al., 1986) and has developed ambitious plans for studying the continental basement of France both on land and offshore (Fig. 2) (Bois and Allégre, 1983). On land, there are planned deep reflection surveys across the Massif Central, the Aquitaine basin and the Pyrenees of southwestern France, and the Juras and Alps of southeastern France. Of the marine surveys planned, several in the Channel are to explore Hercynian crustal structure and

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
75		Hardeman Cnty.								Abo Pass		
76										Wind River		
77	Socorro			Parkfield / Coalinga							Wind River	
78				Charleston		Brevard Zone*			Michigan Basin		Southern	
79	Appalachians I*			Wichita-Anadarko		Minnesota		Laramie Range		Kansas MGA*		
80	Southern Appalachians II*			Adirondacks - New England Appalachians I						Anadarko Basin		
81	Ouachitas			Kansas Ext*.		Adirondacks - New England App. II				Kansas Ext*.		
82	Mojave Desert			Utah Basin & Range*			Northern Sierra*			Wasatch Front		
83	Death Valley			Nevada Basin & Range*								Florida-
84	South Georgia, Pine Mtn. Belt*				Oregon Active Cont. Marg.			NW Cordillera I		NW Nevada		
85	N. Am. - Africa Suture, S. App. Ext*.					NW.Cordillera II				NW Colorado Plateau*		

COCORP (* portions of first transcontinental traverse)

Fig. 6. Schedule of COCORP surveys during first decade of COCORP. The asterisk (*) denotes surveys which will probably comprise the first trans-continental deep reflection transect of North America.

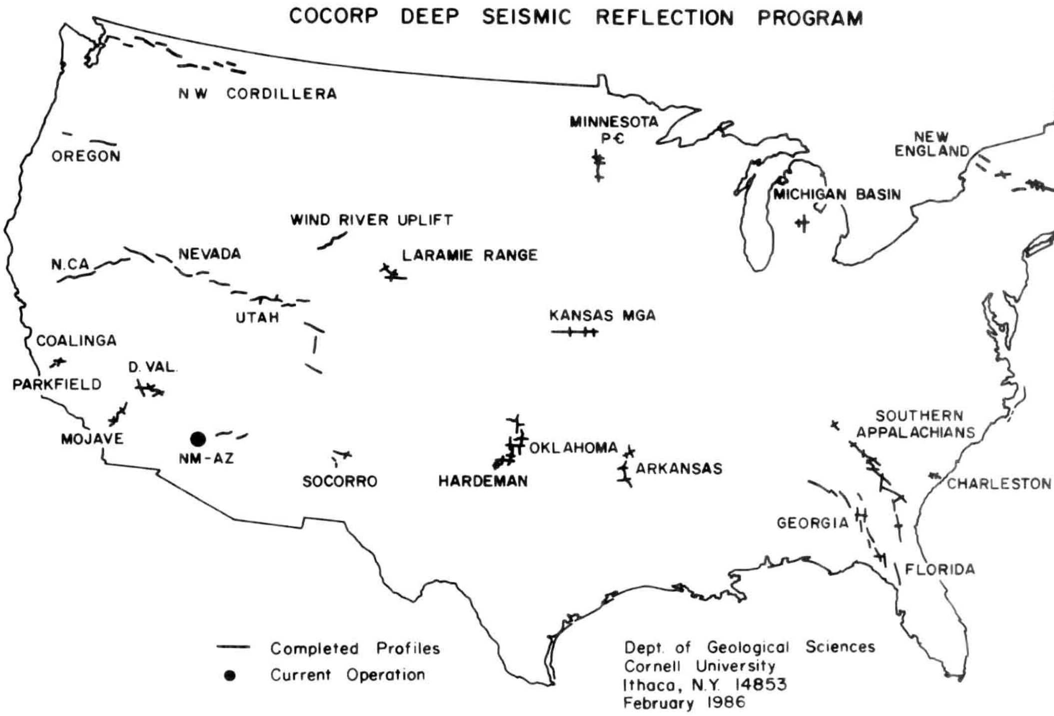

Fig. 7. COCORP deep reflection sites surveyed during 1975 through 1985.

overlying basins. Surveys in the Bay of Biscay are to study the South Variscan suture, the deep structure of the offshore extension of the Pyrenees, and crustal structures related to crustal thinning during the opening of the Bay of Biscay. The remaining two marine lines lie in the Mediterranean and are located to study features related to crustal thinning and the deep structure of the southeastern continuation of the Pyrenees. The planned ECORS program includes nearly 3500 km of land and marine deep reflection profiling with a goal of 500-800 km of combined land and marine data per year. Clearly there is a variety of crustal-scale tectonic features to be addressed by this new program.

Seismic reflection data from Germany were some of the first to demonstrate reflections from within the continental basement (Reich, 1953; Dohr, 1957). This was followed in the 1960's and later by intermittent experiments to record nearly vertically incident reflections from the basement and comparisons with wide angle reflection and refraction data (Fig. 3) (Meissner and Lueschen, 1983). Previous work has explored the nature of reflecting horizons in the deep crust, the nature of the Moho, and the variation of crustal structure (Meissner, 1967; Dohr and Fuchs, 1967; Glocke and Meissner, 1976; Fuchs, 1969; Meissner, 1973, Dohr and Meissner, 1975; Mueller, 1977). Data collected across the northern Variscan front in Germany have revealed an overthrust similar to that seen by COCORP in the southern Appalachians (Meissner et al., 1981; Meissner et al., 1983; Meissner and Lueschen, 1983; Bortfeld et al., 1985; Meisner and Wever, 1986; Cook et al., 1979). In the early 1980's a group called DEKORP was established in the Federal Republic of Germany with plans to collect a network of continuous deep seismic reflection profiles of the continental basement.

In the United Kingdom since 1981 BIRPS (British Institutes Reflection Profiling Syndicate) has operated a very successful program out of Cambridge University and has collected a large body of marine deep reflection data around Britain (Fig. 4). MOIST (the Moine and Outer Isles Seismic Traverse), organized by the Institute of Geological Sciences, was designed to cross the main faults and structural trend of the Scottish Caledonides and in 1981 the data were collected off the northern coast of Scotland (Smythe, 1982). Subsequent deep reflection marine profiles have been collected for BIRPS along western Britain, (WINCH, Western Isles-North Channel traverse), and southwestern Britain (SWAT, South West Approaches Traverse) (Brewer, 1983; Matthews, 1983; Matthews, 1984). WINCH was designed to cross the Caledonides and to establish in three dimensions the geometry of dipping mantle reflections observed on MOIST. SWAT was designed to cross and address Variscan features off southwestern Britain and the Channel. Other marine traverses (Fig. 4) have been recently collected or are planned in the

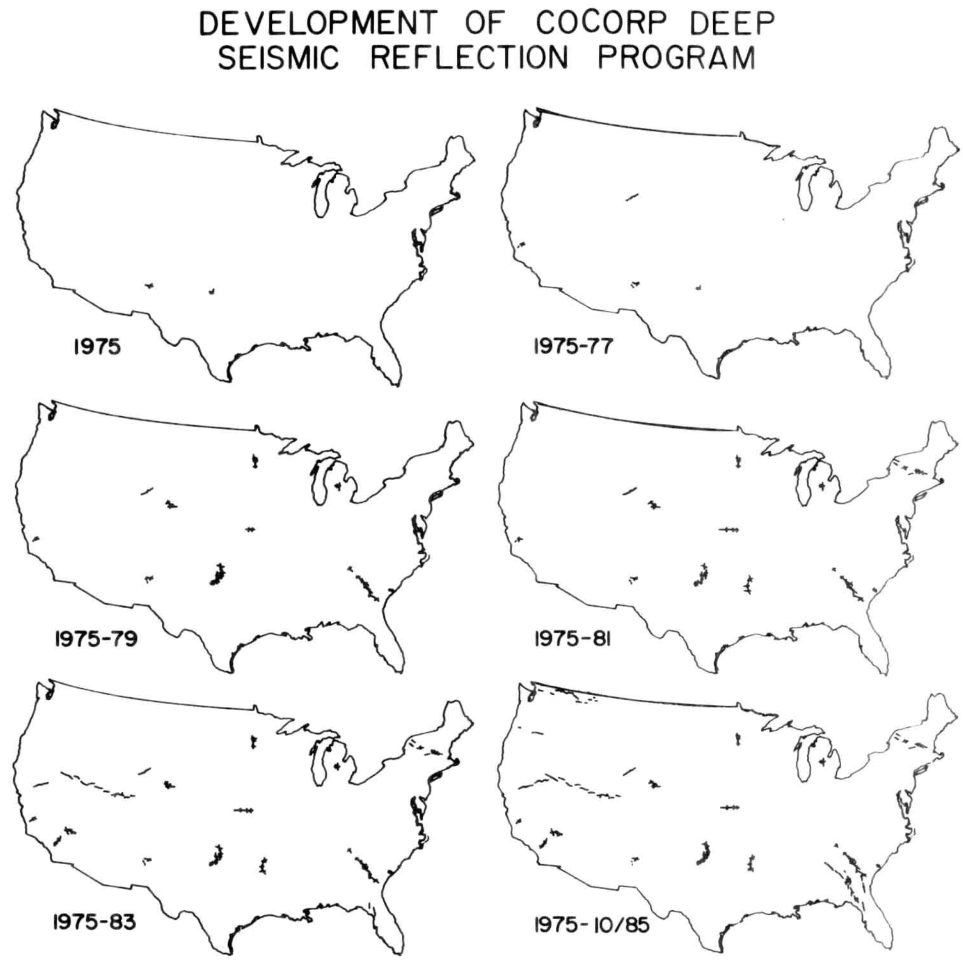

Fig. 8a. Maps showing the sequence and evolution of COCORP deep seismic reflection profiles in cumulative increments of two years.

North Sea. Some short deep reflection profiles have locally been collected on land (Fig. 5) (Whittaker and Chadwick, 1983), but the marine surveys of BIRPS have been a very cost-effective way to collect very good deep reflection data from the continental basement of Britain.

In the U.S., COCORP (the Consortium for Continental Reflection Profiling), operated from Cornell University, has been collecting deep seismic reflection data for over 10 years (Fig. 6; Brown et al., 1986). During that time over 6000 km of deep reflection data have been collected on land. Since the first profile in 1975 in Hardeman Co., Texas, COCORP profiles have explored a great number of features in the continental basement throughout the U.S. (Fig. 7). Four transects of the Appalachian-Ouachita orogen have been profiled, these include the now classical example of major crystalline overthrusting in the southern Appalachians (Cook et al., 1979, 1981), the Appalachians in New England (Brown et al., 1983; Ando et al., 1984), the Ouachita mountains in Arkansas (Nelson et al., 1982; Lillie et al., 1983), and a recent profile which traverses from the proto-African basement of Florida and southern Georgia across a suture into the southernmost exposed Appalachians in northern Georgia (Nelson et al., 1985; Nelson et al., 1985). One transect of the North American Cordillera from Utah to California is mostly complete (Allmendinger et al., 1983; Farmer et al., in review; Hauge et al., in review; Hauser et al., in review; Potter et al., in review) as are major parts of two other transects of the Cordillera in southern California and Nevada (Cheadle et al., 1986; Serpa et al., in prep.) and in the Pacific Northwest (Potter et al., in review). The Utah-Nevada transect along with the profiles in Death Valley (Serpa et al., in prep.) and Socorro (Rio Grande Rift) (Brown et al., 1979 and 1980) also traverse regions of important Cenozoic crustal extension of the Basin and Range