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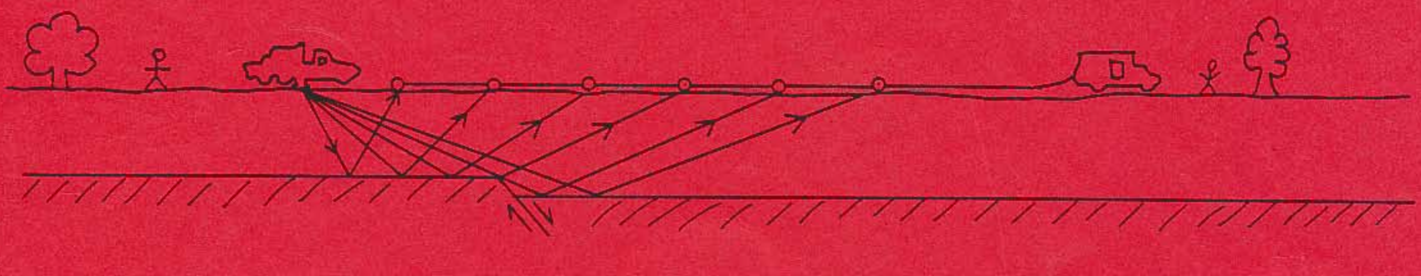
INTERNATIONAL SYMPOSIUM ON DEEP STRUCTURE OF THE CONTINENTAL CRUST:

RESULTS FROM *REFLECTION SEISMOLOGY*

JUNE 26-28, 1984



INSTITUTE FOR THE STUDY OF THE CONTINENTS

CORNELL UNIVERSITY

ITHACA, NEW YORK 14853

SPONSORSHIP OF THE CONFERENCE

The conference is organized by the Institute for the Study of the Continents (INSTOC) and is sponsored and financially supported by the Cornell Program for Study of the Continents (COPSTOC). Partial financial support is also provided by IASPEI. Other co-sponsors include:

- American Geophysical Union
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    - Coordinating Committee 5: Structure and Composition of the Lithosphere and Asthenosphere
    - Working Group 3: Proterozoic Lithospheric Evolution
- Society of Exploration Geophysicists

The views, opinions, and findings reported in this symposium are those of the participants and not necessarily those of any of the above sponsors.

STEERING COMMITTEE OF THE CONFERENCE

-- Muawia Barazangi, Coordinator

Department of Geological Sciences
Cornell University
Ithaca, New York 14853, U.S.A.
Telephone: (607) 256-6411 or (607) 256-2377
Telex No. 937478

-- Albert Bally (Rice University)

-- Robert Hamilton (U.S. Geological Survey)

-- Leonard Johnson (U.S. National Science Foundation)

-- Robert Phinney (Princeton University)

-- Donald Turcotte (Cornell University)

INTERNATIONAL SYMPOSIUM ON DEEP STRUCTURE OF THE CONTINENTAL CRUST: RESULTS FROM REFLECTION SEISMOLOGY

General Announcements

1. PLACE AND DATE OF THE CONFERENCE:

The conference will be held June 26, 27, and 28, 1984, in Statler Hall on the Cornell University campus in Ithaca, New York.

No concurrent sessions are planned. The official language will be English. There will not be any facilities for translation.

2. PURPOSE OF THE CONFERENCE:

The main purpose of the conference is to bring together a group of geologists and geophysicists who are actively working on research related to the deep structure and evolution of the continental crust. The recent application of reflection profiling to decipher the deep structure of the continental crust will be particularly emphasized. It is planned that state-of-the-art knowledge of the deep structure of the continental crust will be discussed during the conference by researchers from all countries where such research is being performed. The conference will provide the opportunity to identify future research needs, emphasize the importance of such research on a global basis, and stress the relevance of such research to present and future needs of human society.

3. REGISTRATION:

The regular registration fee is $75.00 (USA) for all who attend the symposium, except that for students a reduced registration fee of $25.00 will apply. No registration fee is required for accompanying spouses and children. The registration fee will cover the administrative costs of the conference, coffee breaks, a wine-and-cheese reception on Monday, June 25, 1984, from 8:00 P.M to 10:00 P.M., at the registration area of the Purcell Union, and, finally, the abstracts of papers and other materials (e.g., a name tag to use at Cornell academic and sports facilities.) The registration fee does not cover the costs of housing, cafeteria meals, and the planned barbeque on the shore of Cayuga Lake.

Conference materials will be available at the registration desk in the main lobby of the Robert Purcell Union on Cornell's North Campus beginning on Monday, June 25, 1984 from 5:00 P.M. to 10:00 P.M. During the following three days of the conference, registration and an information desk will be available from 7:30 A.M. to 6:00 P.M. in the lobby of the Statler Hall auditorium. The meetings will take place in the auditorium of Statler Hall on Cornell's main campus and will conclude about 6:00 P.M. on June 28, 1984. Coffee breaks and poster sessions and exhibits will be held in the ballroom of Statler Hall.

4. INFORMATION FOR INVITED AND CONTRIBUTED SPEAKERS:

A. General Information:

Speakers are allocated 20 minutes for invited papers and 15 minutes for contributed papers for both presentation and discussion. Please plan to allow three minutes for a discussion of your presentation. It is essential that your talk not exceed the allocated time. A flashing green light on a timer will warn the speaker that there are only three minutes left. At the end of the allocated time an alarm will sound. You _must_ stop talking when you hear this sound. Two standard 35 mm slide projectors and one overhead projector will be available. Please make sure to give your slides and/or overhead transparencies to the projector operator on the balcony of the Statler Auditorium at least 15 minutes before the beginning of your session. Speakers must load their own slides into the carousels (available at the slide booth before all sessions) before giving them to the projectionists. If your slides need remounting please arrange this at the slide booth well before your talk.

B. Proceedings of the Conference:

All scientists who present invited or contributed papers are requested to prepare their contributions for publication in the proceedings of the conference. Please remember that you have already agreed to do so! The American Geophysical Union (AGU) has agreed to publish the proceedings as a volume, or possibly two volumes, in the AGU's Geodynamics Series. As most of you know, the publications of the AGU adhere to the highest standards in the process of reviewing the submitted manuscripts. All authors of individual papers within this volume are required to assign and transfer copyright for their articles to the AGU by separate correspondence. This is the policy of the Union and applied to all papers submitted to AGU.

Because of a limitation on the size of the volume and because of the large number of speakers, there will be a strict limitation on the length of acceptable manuscripts. A manuscript should not exceed 12 pages for the text material, appendices, references, and legends, plus 8 pages of figures and tables. Moreover, all manuscripts will be on _author-produced_, _camera-ready copy_. Enclosed in your plastic portfolio is a brochure on "AGU Style: A Guide for Contributors". After the acceptance of your paper for publication you will be provided with instructions on how to prepare author-produced, camera-ready copy.

There will be no charge to authors for publishing their papers in the volume, if accepted by the editorial committee. However, there will be a charge to authors if they desire to have fold-out pages and/or sheets in the volume. This page charge will be $140.00 each for fold-outs comprising a single fold. Fold-outs requiring more than a single fold may have a higher page charge, which will be quoted separately by AGU.

The senior author of each paper will receive a complimentary copy of the volume. Moreover, all authors may purchase personal copies (not for resale) at 50% off the list price of the volume for a six-month period following publication.

The editors of the volume will be Muawia Barazangi and Larry Brown. The deadline for submission of the manuscripts will be 1 October 1984. Please send four (4) copies of your manuscript to:

Muawia Barazangi
Department of Geological Sciences
Cornell University
Ithaca, New York 14853

5. POSTER EXHIBITS:

Some scientists have elected to show their results as a poster exhibit. Moreover, the COCORP group at Cornell will display some of its seismic sections and results of previous and recent surveys. We plan to have some extra poster space available to other scientists who want to display a particularly interesting section and/or result. Most of the exhibits will be held in the ballroom of Statler Hall.

6. PARKING:

Parking on campus is by permit only. Conference parking permits will be available at registration for 50 cents per car per day. Your name tag can be used to ride campus buses free of charge. Campus buses make a circuit of the campus every fifteen minutes. Maps of the bus routes and stops will be available.

7. A TOUR OF A DYKE OF ITHACA KIMBERLITES:

Dr. Suzanne Mahlburg Kay of the Department of Geological Sciences at Cornell will lead a brief trip to one of the Ithaca kimberlites localities in scenic Cascadilla Gorge close to the Geology Department's building. The trip will take about 40 minutes and will be during the lunch break on Wednesday 27 June after people eat their lunch. Please sign up for the tour at the registration desk and note the exact time of the trip and meeting place.

8. SOCIAL ACTIVITIES:

An informal reception featuring New York State wines and cheese as well as soft drinks is planned for Monday, 25 June 1984 from 8:00-10:00 P.M. in the lobby of the Robert Purcell Union. Admission is free to all conference participants including spouses and children.

On Wednesday evening, June 27th, a special chicken barbeque is planned at Taughannock Falls State Park. The park is located on the shores of Cayuga Lake and is considered one of the loveliest New York State parks. On the way there your bus will stop at one of the outstanding natural attractions of the northeastern U.S., Taughannock Falls. The barbeque features entertainment by Peggy Haine and the Lowdown Alligator Jass Band playing their rousing revival of 1920's jazz. Conferees and guests are encouraged to attend. Please sign up for the event during registration time, and ask for more information on the buses' schedule and routes.

9. SPOUSE/GUEST PROGRAM:

If enough interest is shown during the registration time on Monday 25 June at the Robert Purcell Union, a variety of tours will be arranged for spouses/guests. The world-renowned Corning Glass Center features a spectacular new museum which takes the observer through 3500 years of glass making. You will see a special exhibit of Tiffany glass, visit the Hall of Science and Industry and the Steuben Exhibit and watch hot glass being fashioned into Steuben crystal right before your eyes.

-or-

A visit to Watkins Glen State Park. The craggy formations and racing waters of Watkins Glen form one of the most spectacular natural pageants in America. Grottoes, rock caverns, waterfalls, and gorges testify to the power of the great glacial forces that shaped them. A trail leads through the heart of the glen - into caves, beneath imposing rock formations, and past the waterfalls - while jagged cliffs tower hundreds of feet above the path. At the base of the glen, water tumbles through a twisting rock labyrinth, cascading through nineteen waterfalls.

Cornell University Conference Services
Box 3, Robert Purcell Union
Ithaca, New York 14853

International Symposium on Deep Structure of the Continental Crust: Results from Reflection Seismology

CORNELL UNIVERSITY
June 26 - 28, 1984

Welcome to the International Symposium on Deep Structure of the Continental Crust: Results from Reflection Seismology being held at Cornell University. We sincerely hope that your stay is very pleasant and that the information presented here contributes to your comfort and convenience while attending your conference. We kindly ask that you take a moment to fill out the questionnaire about conference services at Cornell so that we may serve you better in the future. Thank you.

Campus Information

Information About Your Room:

Your room is equipped with a telephone capable of local service only. For safety reasons, electrical outlets in your room are not suitable for small appliances such as hair dryers. The electrical outlets in your bathroom should be used for hair dryers, curling irons, etc.

Your key ring should contain two keys. One key is imprinted with a 4-digit number —this is your room key and suite key.Each number gives you the following information:

7(bldg #) 2(unit/floor #) 3(suite #) 4(room #)

Follow the signs to your suite, once inside the suite, your room is easily located. Buildings are usually locked at 11:00 p.m. Your second key on the ring is the outside door key so that you can gain admittance if you are out past 11:00 p.m.

Information about the dorm phone:
To make local off-campus calls, dial 9 and then the number you are calling. There is no charge for local calls.
Long distance calls can only be made if they are charged to another number. To make a long distance call, dial 9-0-area code - and the phone number. The operator will assist you.
To make campus calls, dial 6 and the last four digits of the phone number.

Room Check-Out Procedures:

Check-out time is 10:00 a.m. You are encouraged to check out prior to attending program sessions on your departure day, to facilitate room servicing for guests who may be arriving that day. Secure luggage storage areas are available for your use until your actual departure from campus. Please remove all personal items from the room (check the bathroom and laundry areas also), close and lock all windows, turn off the lights, lock your door, and return your keys to the reception desk. Please do not leave the keys in your room or take them with you.

If you leave before the end of your program, to ensure an adjustment in your billing you must notify the staff at the reception desk of your departure.

Dining Facilities On Campus:

Robert Purcell Union:	Monday - Saturday	Breakfast; 7:00 - 9:30 a.m.
		Lunch; 11:30 - 1:30 p.m.
		Dinner; 5:00 - 7:00 p.m.
	Sunday	Brunch; 10:30 - 1:30 p.m.
		Dinner; 5:00 - 7:00 p.m.

Willard Straight Hall:

Ivy Room:	Monday - Saturday	7:15 a.m. - 7:00 p.m.
	Sunday	9:00 a.m. - 7:00 p.m.
Okenshields:	Monday - Friday	Lunch; 11:00 a.m. - 1:30 p.m.
		Dinner; 5:00 - 7:00 p.m.

Medical Help:

Campus Security	256-1111
Tompkins Community Hospital	274-4411
Gannett Clinic, 10 Central Ave. (on campus)	256-5155
Hours: Monday- Friday	8:00 a.m. - 4:30 p.m.

Should an emergency illness occur when the clinic is not open, program participants should call Public Safety (256-1111) for instructions or they may go directly to Tompkins Community Hospital, Trumansburg Rd. (274-4411). Expenses incurred at Tompkins Community Hospital are the responsibility of the participant.

University Recreation:

Athletic Public Affairs— Schoellkopf House 256-3752

Athletic Facilities:Teagle Hall--Facilities available for use include the gymnasium, weight room, steam room, pool, and locker room. All participants should show their registration certificates at the equipment cage, where they will be issued a towel and use of lockers and baskets. Participants must provide their own locks and are responsible for their personal belongings.

Teagle Pool Hours: M-F 11:00 a.m. - 2:00 p.m.
Helen Newman Pool Hours: M-F 11:00 a.m.- 2:00 p.m.
Hours may vary: call (256-4261) to confirm the hours of operation.

Grumman Squash Courts--Facilities for squash and handball are available daily from 9:30 a.m. - 6:00 p.m. Participants must furnish their own equipment. Presentation of your official registration certificate is required for admittance.

Outdoor Facilities— These include numerous tennis courts near Teagle Hall, Helen Newman Hall, Baker Dorms, and the North Campus Dorms. The University Golf Course is open where a participant may purchase a summer membership or pay regular greens fees. Canoe rental is available on Beebe Lake.

Check Cashing:

A check cashing service is available at the First Bank Store Bank in the Cornell Campus Store. Checks up to $50.00 may be cashed with proof of identification. There is a fee of 25¢.

University Unions:

Two of the three Union buildings will be open this summer: Willard Straight Hall and the Robert Purcell Union. Both offer a variety of social, cultural and recreational activities.

Willard Straight facilities include a theater, haircutters--hours M-F: 9:00a.m.-5:30p.m. Art exhibition areas, numerous lounges and meeting rooms are also available. The main desk offers newspapers, magazines and sundries for sale. Hours are: Monday- Saturday, 9:00 a.m. - 5:00 p.m. Sundays: 10:00 a.m.- 5:00 p.m.

Robert Purcell Union contains such diverse facilities as a small store that sells drug-store items, a laundry and dry cleaning service, a game room, a tavern and various lounges and meeting rooms.

Some Places to Visit & Things to See at Cornell

Andrew Dickson White House- Now the home of Cornell's Society for the Humanities, the mansion was built in 1874 at the personal expense of Andrew Dickson White, the University's first president. White lived in it until his death in 1912 and then bestowed the mansion upon the University as the official presidential residence. In 1951 the mansion became the University's art museum, a function it served until the completion of the Herbert F. Johnson Museum of Art in 1973. Contact: Ann Marie Garcia, (256-4086).

Beebe Lake-Trail around the lake begins north of Noyes Lodge. At rock bridge hikers may continue around the lake or take a brief detour north to see "The Cascades", a small waterfall.

Cascadilla Gorge and Fall Creek Gorge & Suspension Bridge- Hikers may follow the Cascadilla Trail along the creek all the way down into Ithaca. The suspension bridge over Fall Creek offers a good view of the gorge.

Conservatory of the Bailey Hortorium- Tropical and exotic plants from all over the world, including palms, orchids, bromeliads(pineapple family) and gesneriads (African Violet family). Open Monday - Friday, 8:00 a.m.- noon & 1:00 - 5:00 p.m. Call: 256-2131

Cornell Plantations-Dedicated to the preservation of natural areas close to campus, the Cornell Plantations maintains some 1500 acres to the east of campus. Highlights include the Bowers Rhododendron Collection at Comstock Knoll, the Nut Tree Collection, Ornamental Test Gardens and Newman Meadow and hiking trails.

Mundy Wildflower Garden- An "outdoor laboratory" of native regional flora emphasizing the plants of the Cayuga Basin.

Robinson York State Herb Garden- A "touch and smell" garden of culinary, fragrant, medicinal and historical herbs. The enclosed garden with peripheral plantings of shrub roses and of fragrant or medicinal woody plants contains more than 250 species of herbs. For information about any of the above three areas, contact: Cornell Plantations, 256-3020.

Fuertes Observatory- The observatory has a twelve inch refractor telescope and a dozen six inch telescopes through which visitors may examine the heavens, weather permitting. Contact: James Houck, (256-4805)

Herbert F. Johnson Museum of Art- The museum's permanent holdings include an outstanding collection of Asian art. Open daily except Mondays from 10:00 a.m.-5:00 p.m.; Wednesdays from 10:00 a.m. - 9:00 p.m.; Sundays from 11:00 a.m. - 5:00p.m.Call: (256-5056).

Laboratory of Ornithology- (159 Sapsucker Road, northeast of campus). Open 8:00a.m.5:00 p.m. Monday -Thursday, 8:00 a.m.-4:00 p.m. on Friday and 10:00 a.m - 5:00p.m. on Saturday and Sunday.

McGraw Bell Tower- Visitors who climb the tower's 161 steps are rewarded with an excellent view of Cayuga Lake, Ithaca, and portions of campus. The tower is open to visitors only when the chimes are being played. (7:45a.m.,1:10 p.m., 6:00 p.m.)

Mineral Collection- A large collection of minerals from throughout the world is housed in Kimball Hall. Access to the collection can be obtained through the office of the Department of Geological Sciences,210 Kimball Hall, 8:00 - 5:00 p.m. Monday-Friday. Call: (256-5267).

Sage Chapel-The apse of the 101-year-old non-sectarian chapel bears and elaborate allegorical mosaic symbolizing the relationship between education, truth, and worship. The Memorial Antechapel houses the remains of Ezra Cornell, Andrew Dickson White, members of their families and other prominent persons in the University's history. Call: (256-4214).

Bradfield Tour- The eleventh floor of Bradfield, the tallest building on campus, gives you a spectacular view of the surrounding area with a special exhibit to help you identify the sights. Follow the yellow arrows for a self-guided tour of the Agronomy Department research facilities.

Souvenirs/Snacks/Supplies

TheRobert Purcell Union Store is located on the first floor of the Robert Purcell Union. Items in this store include toiletries, school supplies, souvenirs, and snacks. Store hours will be 8:00 a.m.-11:00 a.m. and 4:00p.m.-10:00 p.m.

The Campus Store is located directly across from Willard Straight Union and is open Monday - Friday, 8:30 - 5:00 p.m. and Saturday from 10:00 a.m. - 2:00 p.m.

THE SCIENTIFIC PROGRAM FOR THE INTERNATIONAL SYMPOSIUM ON DEEP STRUCTURE OF THE CONTINENTAL CRUST: RESULTS FROM REFLECTION SEISMOLOGY

Tuesday, 26 June, 1984

SESSION #1

General Opening - Chairman: S. Kaufman

8:30 - 8:40	S. Kaufman Cornell University	Welcome and introduction
8:40 - 9:00	*J. E. Oliver Cornell University	A global perspective on seismic reflection profiling of the continental crust
9:00 - 9:15	S. B. Smithson et al. U. of Wyoming	Crustal reflections and crustal structure
9:15 - 9:30	R. D. Hatcher U. of S. Carolina	Interpretation of seismic reflection data in complexly deformed rocks: A geologist's perspective
9:30 - 9:45	K. Fuchs Geophys. Inst., Karlsruhe	Reflections from the subcrustal lithosphere?
9:45 - 10:00	R. A. Phinney Princeton University	Wide angle reflection profiling in the Mojave desert
10:00 - 10:45	BREAK	

SESSION #2

International Deep Reflection Activities: Part I - Chairman: J. E. Oliver

10:45 - 11:05	*D. Matthews Bullard Lab, Cambridge U.	Deep reflection from the Caledonides and Variscides west of Britain and comparison with the Himalayas
11:05 - 11:25	*R. Meissner Institut für Geophys. Kiel	The continental crust in central Europe as based on data from reflection seismology
11:25 - 11:45	*F.J. Moss and S. Mathur Dept. Geol. & Geophys., BMR Australia	Continental reflection profiling in Australia
11:45 - 12:05	*R. Hamilton USGS, Reston VA	Seismic reflection studies by the U.S. Geological Survey

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* Asterisks indicate invited speakers.

12:05 - 12:25	*A. Green and M. Berry Earth Phys. Branch Div. EMR, Ottawa	The third dimension of geology from seismic reflection studies in Canada
12:25 - 2:00	LUNCH	

SESSION #3

Deep Reflections and the Western USA - Chairman : R. Hamilton

2:00 - 2:20	*G. Thompson Stanford University	The deep crust in convergent and divergent terranes: Laramide uplifts and Basin - Range rifts
2:20 - 2:35	R. Allmendinger et al. Cornell University	Tectonics of the eastern Basin and Range and Colorado Plateau, Utah, from COCORP seismic reflection data and geologic data
2:35 - 2:50	J. McCarthy Stanford University	Seismic constraints on the continuation and the nature of the Snake Range decollement beneath Spring Valley, Nevada
2:50 - 3:05	D. A. Okaya Stanford University	Reflection profiling of the lower crust in the Basin and Range: Dixie Valley, Nevada
3:05 - 3:20	B. Wernicke Harvard University	Extensionally sheared lithosphere in and adjacent to the Basin and Range province: Some critical tests
3:20 - 3:35	F. A. Cook Univ. of Calgary	Crustal reflections from a land air gun source along a profile in the Purcell anticlinorium of southeastern British Columbia
3:35 - 4:20	BREAK	

SESSION #4

Precambrian and Lower Crustal Structure - Chairman: W. Fyfe

4:20 - 4:35	R. J. Durrheim Inst. Geophys. Res. South Africa	Recent reflection seismic development in the Witwatersrand basin
4:35 - 4:55	*A. Kroner Inst. für Geowissenschaften Johannes Gutenberg Univ.	Structure and evolution of the Archean continental crust
4:55 - 5:10	A. Gibbs Cornell University	COCORP profiles of Precambrian crust: A qualitative assessment
5:10 - 5:25	D. M. Fountain and M. Salisbury Univ. of Wyoming	Geophysical nature of the lower continental crust based on crustal cross-sections

Wednesday, 27 June 1984

SESSION #5

International Deep Reflection Activities: Part II - Chairman: R. Allmendinger

8:30 - 8:50	C. Bois et al. I. F. P., France	Deep seismic profiling of the crust in France: The ECORS project
8:50 - 9:10	*C. Tomek Geophys. Dept., Brno Czechoslovakia	Thin-skinned tectonics of the Carpathian arc and the Bohemian massif revealed by seismic reflection profiling
9:10 - 9:30	*K. Posgay et al. Eotvos Lorand Geophys.Inst. Hungary	Characteristics of the reflection layers in the earth's crust and upper mantle in Hungary
9:30 - 9:50	*X. Yuan et al. Ministry of Geology Beijing	A review of research on deep structure in China
9:50 - 10:05	P. Finckh Inst. of Geophys., ETH Zürich	Crustal reflections on northern Switzerland
10:05 - 10:50	BREAK	

SESSION #6

General Geology - Chairman: G. Thompson

10:50 - 11:10	*W. S. Fyfe U. of Western Ontario	Fluid generation in deep continental crust
11:10 - 11:30	*R. A. Price Geological Survey of Canada	The foreland thrust and fold belt of the Canadian Rockies and its geotectonic significance
11:30 - 11:45	M. N. Qureshy Dept. of Science & Tech. New Delhi, India	Deep crustal signatures in India from satellite and ground geophysical data
11:45 - 12:00	K. Burke and C. Sengor LPI, Houston	Tectonic escape in the evolution of the continental crust
12:00 - 12:15	T. Stern DSIR, New Zealand	Crustal structure studies in New Zealand
12:15 - 12:30	C. Morelli Univ. of Trieste	Deep crustal knowledge in Italy
12:30 - 2:00	LUNCH	

SESSION #7

Wide-angle Reflection, Refraction, and Other Geophysical Methods
Chairman: R. Meissner

2:00 - 2:20	*S. Mueller Inst. of Geophys., ETH Zürich	Long-range seismic refraction profiles in Europe
2:20 - 2:35	R. F. Mereu, D. Wang and O. Kuhn U. of Western Ontario	The results of a wide angle reflection survey across the Ottawa-Bonnechere graben: Evidence for an inactive rift in the Precambrian
2:35 - 2:50	K. H. Olsen and C.-E. Lund Los Alamos Nat. Lab	Precambrian crustal structure of the northern Baltic Shield from the FENNOLORA profile: Evidence for upper crustal anisotropic laminations
2:50 - 3:05	R. M. Clowes U. of British Columbia	Structure of the crust in a young subduction zone: Results from reflection and refraction studies
3:05 - 3:20	Z. Hajnal U. of Saskatchewan	Crustal reflection and refraction velocities: A comparison
3:20 - 3:35	P. Barton Bullard Lab, Cambridge U.	Comparison of deep reflection and refraction structures in the North Sea
3:35 - 4:20	BREAK	

SESSION #8

General Geology and Geophysics - Chairman: L. Brown

4:20 - 4:35	D. J. Blundell Chelsea College, London	Modelling the lower crust
4:35 - 4:50	C. M. Wentworth, M. Zoback and J. Barton USGS, Menlo Park	Relations between the Franciscan assemblage, Great Valley sequence, and crystalline basement, central California
4:50 - 5:05	K. L. Kaila Nat. Geophys. Res. Inst. India	Tectonic framework of Narmada-Son lineament - a continental rift system in central India from deep seismic soundings
5:05 - 5:25	*C.J. Allegre and A. Hirn Inst. Phys. Earth, Paris	The crustal overthrusting, major feature in mountain belt. The horizontal and vertical mosaic model

NOTE: 6:00 - 10:00 PM - Barbeque on the shore of Cayuga Lake

Thursday, 28 June 1984

SESSION #9

Deep Reflections and the Appalachian System - Chairman: D. Matthews

8:30 - 8:45	D. B. Stewart USGS, Reston VA	The Quebec - western Maine profile: First year results
8:45 - 9:00	D. R. Hutchinson, J. Grow and K. Klitgord USGS, Woods Hole MA	Crustal reflections from the Long Island Platform of the U.S. Atlantic continental margin
9:00 - 9:15	J. Costain, L. Glover and C. Coruh Virginia Polytechnic Inst.	Seismic reflection and geology of the central Virginia Blue Ridge and Piedmont
9:15 - 9:30	J. C. Behrendt USGS, Denver	Multichannel seismic reflection profiles crossing the southeast U.S. and the adjacent continental margin: Where is the master decollement?
9:30 - 9:45	L. T. Long and J.-S. Liow Georgia Inst. of Tech.	Crustal thickness and velocity structure in the southern Appalachians
9:45 - 10:00	R. A. Young, J. Wright and G. F. West Phillips Research Center	Seismic crustal structure northwest of Thunder Bay, Ontario (Canada)
10:00 - 10:15	D. K. Smythe Inst. Geological Sci. Edinburgh	BIRPS crustal reflection on the Caledonian foreland and the development of the passive margins of NW Europe
10:15 - 11:00	BREAK	

SESSION # 10

Data Acquisition, Processing, and Techniques - Chairwoman: D. Jurdy

11:00 - 11:15	*L. Brown Cornell University	Deep seismic reconnaissance: COCORP technique and results
11:15 - 11:30	M. Warner Bullard Lab., Cambridge U.	Profiling the continental crust at sea: Optimum acquisition and processing parameters
11:30 - 11:45	M. D. Zoback et al. USGS, Menlo Park	Application of an 800-channel seismic reflection system for crustal studies in California and Maine
11:45 - 12:00	R. A. Johnson et al. U. of Wyoming	Processing of crustal seismic reflection data

12:00 - 12:15	J. Dorman et al. Exxon Prod. Res. Co.	Deep crustal exploration by a long-offset seismic technique
12:15 - 12:30	L. W. Braile and C. Chiang Purdue University	Comparison of near-vertical and wide-angle seismic reflection studies of the continental Mohorovicic discontinuity
12:30 - 1:45	LUNCH	

SESSION #11

Central USA and Others - Chairman: L. W. Braile

1:45 - 2:00	C.-S. Liu et al. Cornell University	An expanding spread experiment during COCORP field operation in Utah
2:00 - 2:15	M. C. Gilbert Texas A&M University	Interpretation of the Wichita Mountains structural axis
2:15 - 2:30	W. Rogers and D. Jurdy Northwestern University	Deep reflections on COCORP Michigan Basin data
2:30 - 2:45	R. Knapp, C. Somanas and H. Yarger Kansas Geological Survey	Integrated geophysical study of the Midcontinent Geophysical Anomaly along the Kansas COCORP profile
2:45 - 3:00	R. Lillie Oregon State Univ.	Rift-related seismic reflection sequences through the Wilson cycle: Implications for the recognition of continental and oceanic basement beneath passive margins and collisional mountain belts
3:00 - 3:15	J. A. Percival Geological Survey of Canada, Ottawa	Archean crustal structure as revealed in the Kapuskasing uplift, Superior Province, Ontario
3:15 - 4:00	BREAK	

SESSION # 12

General Session - Chairman: J. Dorman

4:00 - 4:15	G. A. Day British Geological Survey	The Hercynian evolution of the convergent continental margin of Southwest Britain
4:15 - 4:30	J. Hall Univ. of Glasgow	Nature of the lower continental crust -- Evidence from BIRPS work on the Caledonides

4:30 - 4:45	M. Cheadle et al. Cambridge University	The deep crustal structure of the Mojave Desert, California, from COCORP seismic reflection data
4:45 - 5:00	John Sharry et al. Gulf Res. & Devel. Co. Houston	Enhanced imaging of the COCORP Wind River line
5:00 - 5:15	D. Wagner and R. Byington Amoco Prod. Co., Tulsa	Deep seismic profile in southwestern Wyoming
5:15 - 5:30	L. D. McGinnis and R. Bowen Louisiana State Univ.	Deep reflection seismic study on the east-west Antarctic boundary

NOTE: 10 Minutes Concluding Remarks and Reminders

END OF SYMPOSIUM

SUMMARY OF PROGRAM FOR THE INTERNATIONAL SYMPOSIUM ON DEEP STRUCTURE OF THE CONTINENTAL CRUST: RESULTS FROM REFLECTION SEISMOLOGY

Tuesday A.M.

1. Oliver
2. Smithson
3. Hatcher
4. Fuchs
5. Phinney

6. Matthews
7. Meissner
8. Moss
9. Hamilton
10. Green

Tuesday P.M.

11. Thompson
12. Allmendinger
13. McCarthy
14. Okaya
15. Wernicke
16. Cook

17. Durrheim
18. Kroner
19. Gibbs
20. Fountain

Wednesday A.M.

21. Bois
22. Tomek
23. Posgay
24. Yuan
25. Finckh

26. Fyfe
27. Price
28. Qureshy
29. Burke
30. Stern
31. Morelli

Wednesday P.M.

32. Mueller
33. Mereu
34. Olsen
35. Clowes
36. Hajnal
37. Barton

38. Blundell
39. Wentworth
40. Kaila
41. Allegre

Thursday A.M.

42. Stewart
43. Hutchinson
44. Costain
45. Behrendt
46. Long
47. Young
48. Smythe

49. Brown
50. Warner
51. Zoback
52. Johnson
53. Dorman
54. Braile

Thursday P.M.

55. Liu
56. Gilbert
57. Jurdy
58. Knapp
59. Lillie
60. Percival

61. Day
62. Hall
63. Cheadle
64. Sharry
65. Wagner
66. McGinnis

THE CRUSTAL OVERTHRUSTING, MAJOR FEATURE IN MOUNTAIN BELT. THE HORIZONTAL AND VERTICAL MOSAIC MODEL.

Claude J. ALLEGRE and Alfred HIRN

Institut de Physique du Globe, 4, Place Jussieu, 75230 PARIS - FRANCE

In recent years adaptation of explosion seismology methods has resulted in the resolution of features of the crust-mantle boundary and of its strong variation across mountain belts including Pyrenees, Alps, Hercynian chain under the Paris Basin, Himalayas, Tibet.

A feature encountered where a large thickening of the continental crust occurred is the local existence of superposed segments of the Moho interface within a complex crust-mantle transition. Several such instances are documented on a section across the Himalayas and Tibet. They may be associated with major surface discontinuities some of which are clearly sutures, others intracontinental thrusts like the MCT. In the Paris Basin Hercynian domain a preliminary to the main ECORS vertical reflection profiling also establishes that it is not a single interface that separates crust and mantle materials. Similarly complex zones of layering and crust mantle interaction at depth are present on BIRPS sections of the Caledonides and may be inferred from DSS studies through the Ural.

These data document the existence of strong dips of interfaces and faulting at great depths with local emplacement of mantle material within the crust.

Such a structure reveals a complex interfingering during mountain building by collision of small or big continental segments.

The continental growth processes consist of continental accretion by addition of successive blocks but also of a crustal doubling process with interpenetration of mantle material.

Such processes resulted in a double mosaic of the continental crust: an horizontal mosaic and a vertical one as well.

TECTONICS OF THE EASTERN BASIN AND RANGE AND COLORADO PLATEAU, UTAH, FROM COCORP SEISMIC REFLECTION DATA AND GEOLOGIC DATA

R. Allmendinger, H. Farmer, J. Sharp, and D. Von Tish[1]

Department of Geological Sciences
Cornell University
Ithaca, New York 14853 0125

COCORP seismic reflection lines in central Utah cross a narrow (~100 km wide) transition zone that has been of fundamental tectonic importance for virtually the entire Phanerozoic history of the central part of the western North American Cordillera. Within this zone are located: 1) the late Precambrian and Paleozoic hingeline of the Cordilleran miogeocline; 2) the eastern edge of Mesozoic-early Cenozoic thin-skinned thrusting and the western edge of slightly younger, thick-skinned Laramide structures; and 3) the middle-late Cenozoic transition between the extensional Basin and Range Province and the more stable, uplifted Colorado Plateau block. Six COCORP lines totaling more than 380 km have been integrated with surface geological information and subsurface data from more than 15 wells to produce an extension-subsidence chronology of a major Cenozoic basin and balanced, palinspastically restored cross-sections illustrating the crustal geometries of Cenozoic, Mesozoic, and Paleozoic-Precambrian structures and basins.

The autochthonous position of the hingeline as defined by the rapid thickening of upper Precambrian clastic strata is located directly west of the Canyon Range in west-central Utah. Although both Mesozoic compressional structures and Cenozoic Extensional structures occur as much as 100 km or more farther east, the hingeline does spatially coincide with: 1) the position at which Mesozoic thrusts are inferred to cut deeply into the crust, and 2) the easternmost of the major Cenozoic low-angle normal faults (the Sevier Desert detachment).

Mesozoic thrusting in the region produced a minimum of ~120 km of shortening on three major faults. Thrust faults were clearly imaged as far east of the west side of the Wasatch Plateau, and may occur farther east as blind thrusts in the Jurassic section. Continuity of individual thrusts is obscured by thick, highly deformed Jurassic salt in the Sevier Valley west of the Wasatch Plateau. Farther east, the San Rafael Swell of the Colorado Plateau apparently has a structure different than other Laramide uplifts profiled by COCORP. No significant reverse fault can be seen in the basement

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[1] Present addresses: Farmer-Pecten International, Houston, TX; Sharp-Union Oil Company of California, Ventura, CA; Von Tish- Sohio Petroleum, Houston, TX

beneath the Swell. Instead, the Swell appears as a broad, nearly symmetric arch or flexure. However, a prominent mid-crustal horizon at ~28 km beneath the Swell is essentially flat, suggesting the possibility of some type of decoupling at or above that depth in the crust. The horizon at 28 km coincides with a sharp velocity gradient or discontinuity previously interpreted on a refraction profile with a midpoint about 200 km south of the COCORP line.

The small Cenozoic normal faults of the Wasatch Plateau do not appear to penetrate below the Jurassic section, and thus may reactivate an older thrust. However, a major step in the basement (1.4 km down-to-the-west) at the western margin of the Plateau may be interpreted as either the "rooting" of those normal faults into basement, or as an older Jurassic structure. Farther west, the Sevier Desert detachment has between 28 and 40 km of down-to-the-west displacement with a regional dip of 12°. Several structurally higher low-angle normal faults have also been recognized. The rate of extension on the Sevier Desert detachment varied between 0.7 and 1.9 mm/yr; this rate is similar in magnitude to shortening rates in foreland thrust belts.

The question of reactivation of thrust faults as low-angle normal faults has not been resolved by these studies. However, the recognition of the spatial relations of Cenozoic and Mesozoic structures to the much older hingeline indicates that general controls on crustal structural geometry may be very old.

Comparison of deep reflection and refraction studies in the North Sea

P J Barton, Bullard Labs, Madingley Road, Cambridge CB3 0EZ, England

We report a comparison between the Moho determined by a long range seismic refraction experiment and the results of a short normal incidence reflection profile shot along the same line, across the western edge of the Central Graben of the North Sea. The refraction experiment was completed in 1981. Seismograms were interpreted by amptitude modelling, allowing for a detailed velocity structure that varies both vertically and horizontally. These velocities were used to convert the model depth to Moho into the equivalent normal incidence two way travel time section. The seismic reflection profile was acquired for BIRPS by Western Geophysical in February 1983. The section shows layering in the lower part of the crust, apparently similar to that seen on deep reflection profiles shot elsewhere.

The Moho reflection times calculated from the refraction model were superimposed on a line drawing of the deep reflection data. The refraction Moho was found to lie along the base of the correlatable reflections from the lower crust. These observations are compatible with predictions of a lower crust that includes laminae of ultramafic rock just above the Moho. We believe that this is the first time that such a direct comparison has been made.

Multichannel Seismic Reflection Profiles Crossing the Southeast United States and the Adjacent Continental Margin: Where is the Master Decollement?

John C. Behrendt
U.S. Geological Survey
P.O. Box 25046
Denver, CO 80225

Multichannel seismic reflection profiles were collected in 1981 and 1982 on three lines perpendicular to the Atlantic coast that cross the states of South Carolina and Georgia. The positions of the ends of these lines are: S4, 32°40′ N, 80°03′ W to 34°30′ N, 82°10′ W; S6, 32°15′ N, 81°12′ W to 35°00′ N, 83°23′ W; and S8, 31°25′ N, 81°29′ W to 34°18′ N, 84°18′ W. These 96-channel, 24-fold data recorded to 6 and 8 sec, combined with data from the COCORP line in Georgia and the USGS offshore multichannel seismic reflection profiles, provide three transects from the Appalachian mountains across continental, transitional, and oceanic crust. Many arrivals are recorded in the seismic record section associated with structures beneath the Piedmont and below the pre-Cretaceous unconformity underlying the Coastal Plain sediments (i.e., several Triassic basins are defined). Although the previously reported decollement is apparent in places, an obvious continuous feature is not present from the Appalachians to the continental shelf. Reflections from the Moho offshore beneath transitional crust have a banded character over a range from 9 to 11 sec, similar to a pattern seen in the published COCORP line on land. Published aeromagnetic and gravity data can be integrated with the seismic data into an interpretation of the structure of the upper part of the crust. This interpretation is relevant in determining the cause of earthquakes in the southeastern United States in general and of the 1886 Charleston, South Carolina, earthquake in particular.

MODELLING THE LOWER CRUST

D. J. Blundell

Geology Department, Chelsea College, 552 King's Road,
London SW10 0UA, England.

Recently acquired BIRPS lines show typically an upper crust largely devoid of reflections below the sedimentary cover whilst the lower crust has prolific bands of reflections, in accordance with observations elsewhere. These bands are mostly sub-horizontal reflections that individually extend laterally from 1 to 10 km. Since these features have not been found in the upper crust and are not accessible to direct observations, it is left to modelling as a means of constraining hypotheses to explain their nature and cause. The questions to raise include:

i To what extent can topography on a single reflecting interface produce a number of reflection segments on a record section from reflections away from the vertical plane of section?

ii To what extent are reflection segments limited by interference effects from the boundaries of narrow zones of relatively high or low acoustic impedence?

iii How narrow could such zones be?

iv To what extent are the observed reflection segments indicating the true structure of reflecting interfaces?

v To what extent is the continuity of the reflections obscured by noise or processing effects?

Models for the lower crust need to show how acoustic discontinuities produce bands of reflections that stop abruptly at the Moho and to explain why there should not be equivalent discontinuities that give rise to similar reflections in the upper crust.

COMPARISON OF NEAR-VERTICAL AND WIDE-ANGLE SEISMIC REFLECTION STUDIES OF THE CONTINENTAL MOHOROVICIC DISCONTINUITY

L.W. Braile and C.S. Chiang
Department of Geosciences
Purdue University
West Lafayette, IN 47907

The continental crust-mantle transition or Mohorovicic discontinuity (Moho) was discovered over seventy years ago from observations of refracted wave travel times. The continental Moho has been recognized worldwide from refracted (Pn) and wide-angle reflected (PmP) phases from earthquake and explosive sources. Studies utilizing Pn and PmP arrivals have generally interpreted the Moho to be a simple discontinuity in velocity between lower crustal and upper mantle rocks which is laterally continuous and which exists virtually everywhere at the base of the continental crust. Recently, near-vertical, deep seismic reflection studies have been interpreted to indicate that the Moho consists of a transition zone of several km thickness and that it is laterally variable and even discontinuous or non-existent in places.

We have examined near-vertical and wide-angle seismic reflection record sections and performed extensive model studies in an attempt to understand this disparity in interpretation and to try to resolve the actual seismic structure of the Moho. Part of the discrepancy in interpretation is due to distinct differences in characteristics and information content of near-vertical and wide-angle reflection data. Differences in frequency content, angle of incidence, station spacing and processing methods can lead to disparate interpretation from the two data sets even for the identical Moho model. We have utilized near-vertical and wide-angle reflection/refraction synthetic seismogram studies for one- and two-dimensional velocity models to investigate the seismic signature of a variety of Moho transition zone models. For all Moho velocity structures, the wide-angle reflection (PmP) and the refraction (Pn) arrivals have simple and short-duration waveforms. The travel times are insensitive to details of the velocity structure of the Moho for these phases. However the Pn and PmP arrivals are excellent indicators of the existence and depth of the Moho and its general lateral continuity. Furthermore, the amplitude-distance characteristics of the Pn and PmP phases can be used to estimate the thickness of the Moho transition zone and the spectral content of the reflection may be used to infer fine structure of the Moho.

Near-vertical reflections from Moho transition zones are primarily sensitive to fine structure of the transition. "Smooth" velocity transitions have low reflectivity for near-vertical data. Constructive and destructive interference of reflections from laminated Moho structures produces a Moho signature consisting of bands of strong reflections which vary laterally. Where observed, these laminated reflectors indicate the nature of the transition zone and its approximate thickness.

Comparison of observed near-vertical and wide-angle reflection data with the results of synthetic seismogram model studies suggests that the continental Moho is normally a transition zone of about 1 to 4 km thickness in which the velocity generally increases with depth, but also consists of thin laminations of high and low velocity material. The gross structure of the Moho is laterally continuous and appears to exist virtually everywhere as the base of the continental crust. However, the fine structure of the transition zone, consisting of thin laminations, is laterally variable resulting in the discontinuous character of Moho reflections on near-vertical incidence record sections.

Deep Seismic Profiling of the Crust in France: the ECORS Project

Bois, C.(1), Cazes, M.(2), Damotte, B.(1), Galdeano, A.(3), Hirn, A.(3), Mascle, A.(1), Matte, Ph.(4), Raoult, J.F.(5), Torreilles, G.(2).

(1) Institut Français du Pétrole Boite Postale 311, 92506 RUEIL MALMAISON - CEDEX, FRANCE
(2) Société Nationale Elf-Aquitaine (Production, PARIS LA DEFENSE (FRANCE)
(3) Institut de Physique du Globe, PARIS (FRANCE)
(4) Université des Sciences et Techniques du Languedoc, MONTPELLIER (FRANCE)
(5) Université des Sciences et Techniques, LILLE (FRANCE)

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The earth's crust in France was mainly formed during the Variscan orogenesis (300-400 My). The resulting orogenic belt was deeply eroded and then overlain during the Mesozoic by three major sedimentary basins, i.e. the Paris Basin, the Aquitaine Basin and the Southeast Basin. Since the end of the Mesozoic, the southern and southeastern parts of France have undergone strong deformations resulting in the building of the Pyrenees and Alps ranges. Rifts were also formed in the eastern part of the country, such as the Rhine graben and the Rhone Valley in relation to the opening of the western Mediterranean Sea.

Continental France, only 500 000 km^2 in size, contains good examples of most of the major geological phenomena, such as old and young orogenic belts and subsidence of intracratonic basins, rifts and continental margins. The ECORS Project was designed to investigate these phenomena by deep seismic profiling of the crust. This project, which plans to study more than 12 regional profiles across the country, is being jointly carried out by the Institut Français du Pétrole, the Institut National d'Astronomie et de Géophysique (on the behalf of the Conseil National de la Recherche Scientifique and

French universities) and Société Elf-Aquitaine (Production). The Centre National d'Exploitation des Océans is also participing in the offshore aspects.

The first campaign carried out within the framework of the ECORS Project was the profile of northern France aimed at studying the Variscan belt lying underneath the sediments of the Paris basin. This profile, trending northeast over 230 km, cut across the North Variscan frontal thrust, the Bray faulted anticlinorium and the large Seine magnetic anomaly. These three features have prominent expressions on the surface, while their deep geometry and their relation with the Variscan belt remain unknown. All seismic methods were used at the same time on the profile, leading to an original field technique.

The first field work was performed at the end of June 1983 by Institut de Physique du Globe, Paris: two shot points 110 km apart with dynamite source in several holes drilled at 40 meters depth; self recorder three phone stations displayed every two kilometers between the two shot points.

The second field work was performed from November 2, 1983 to January 23, 1984 by Compagnie Générale de Géophysique:

(1) vertical reflexion: 192 traces (80 m interval) recorded by split spread with telemetric recorder Sercel SN 5 N 348; total reflection time recording 16 seconds after correlation.

(2) refraction: explosive source in drilled holes at 45 m depth; same spread as the previous one; refraction work performed as often as a progress of 192 traces was done in vertical reflection; recording distances from 0 to 45 km on each side of the spread; shot points drilled every 15 km along the line; recording length 20 seconds.

(3) wide angle reflection: only on one side of the normal refraction spread, two shots performed at 90 km and 105 km distance from the nearest trace close to critical distance for Moho signal; all explosive shots simultaneously recorded on some self recorder stations displayed along the same line or on a parallel line.

Some samples of processed records for each seismic technique are showed with comments on processing sequence. A detailed study of the data is in progress, and their geological interpretation will be published in a future paper.

DEEP SEISMIC PROFILING: COCORP TECHNIQUE AND RESULTS

Larry D.Brown
Department of Geological Sciences
Cornell University, Ithaca, N.Y. 14853

Seismic exploration of the continents on land using near-vertical reflection techniques represents a complex interplay of geological objectives and geophysical capability. In these early stages of crustal exploration, COCORP has leaned toward a reconnaissance strategy emphasizing long regional transects addressing the more fundamental problems of lithospheric geology. It has exploited the operational advantages of existing industry technology and the support structure of a professional contractor, and it has enjoyed the economic benefits of a continuing, large-scale effort. The reconnaissance strategy is reflected in most aspects of COCORP operations: the selection of survey routes, the choice of acquisition parameters, the degree of field experimentation, even the amount and type of data processing. Such technical issues often constitute important aspects of resulting geological interpretations.

COCORP's present recording system (5 Vibroseis sources, 96 channels, 10km spread, 100m VP spacing, 48 fold CDP redundancy, 8-32 hz signal) as fielded through a contractor, Geosource, Inc., has proven flexible and effective for a wide variety of surface conditions, noise environments, and geologic targets. Unlike field acquisition, processing appears best carried out in-house. COCORP's Megaseis Computing Center not only serves as an economical means to support production processing of the volume of data being generated, it facilitates experimentation and is critical for timely quality control. Most importantly, in-house processing insures effective interaction between data processor/analyst and interpreter. In crustal reflection profiling, perhaps more so than in the petroleum industry, geological and geophysical/signal processing issues are often closely intertwined. In COCORP, interpreters usually do their own processing.

Although similar to conventional oil exploration surveys, COCORP technique- both acquisition and processing - reflects the distinctly different geological nature of its targets (typically metamorphic and igneous vs sedimentary), the much greater depths to which it probes (e.g. 30 km vs. 3 km), and its own particular scientific objectives (mapping large-scale crustal structure vs., say, detailing a stratigraphic trap). Specific technical issues are numerous. Examples: How much energy is needed? What frequencies are most informative? How much stacking is optimum? How much noise/crooked line/skipping is tolerable? What arrays are appropriate? What kind of 3-D control is adequate? How much data editing is warranted? How often should velocity analyses be carried out? Is pre-stack velocity filtering worth the computational effort involved? Often these issues devolve into tradeoff decisions forced by hardware or economic constraints. Example: given a limited number of channels, should station spacing be large to maximize offset for better velocity resolution or small to maximize stacking redundancy and minimize non-hyperbolic travel time deviations? In practice such selections are often based not only on inferences as to the expected depth and nature of geologic targets, but on such considerations as the status of available resources (e.g. current computer load), the vagaries of logistics, and consistency with COCORP's overall strategy. To aid such deliberations, COCORP augments its mainstream profiling with special experiments designed to evaluate alternate or supplementary techniques: expanding spread and 3-D receiver geometries, sign-bit and mantissa recording, and numerous variations on the basic data processing stream have all been investigated to a certain degree.

While the technical particulars of a given survey are often site specific, experience seems to warrant a few operational generalizations, including:

--> Near-vertical reflection profiling is a robust approach to probing the crust: useful geologic information about the basement has been obtained in almost every area surveyed by COCORP.
--> Tracing known structures to depth is perhaps our most effective means, short of drilling, of mapping lower crustal structure.
--> Certain fundamental geologic problems cannot be recognized, much less investigated, without long, regional surveys.
--> Shallow structure can be as important as deep structure in unraveling a crustal geological problem. Reconnaissance surveys must recognize this target range.
--> Reconnaissance objectives usually result in relatively permissive acquisition parameters and require extended parameter searches when processing. Since it is generally unclear, a priori, which part of the wavefield will prove most informative, the tendency is to avoid filtering out as much as feasible in the field, and to search as broadly as possible in processing.
--> Special recording experiments, e.g. expanding spreads or 3-D recording, are best planned and executed after initial reconnaissance profiling has identified requirements and targets.
--> Dip bias, sidesipe and multiples are less a problem than initially feared by some, although both may contribute to background noise.
--> Logistics usually limit feasibility of full 3-D data acquisition.
--> Good data can be acquired in noisy areas, and "poor" data in ideal environments.
--> Reflections from Moho depth are common. On the other hand, unambiguous intra-mantle reflections have been extremely rare, even when penetration seems sufficient. Penetration has been limited in thick sedimentary basins.
--> Geologic considerations must heavily influence acquisition and processing.
--> Important discoveries in crustal reflection profiling sometimes owe as much to serendipity as careful planning.

The interplay of geophysical and geological issues is evident in many of COCORP's contributions: mapping variations in the nature of the Moho, discovering magma bright spots, documenting the role of reactivation in crustal tectonics, and establishing the importance of low-angle detachments in lithospheric evolution, for example. Yet COCORP's operation is also an evolving one, shaped by the availability of new hardware and software, matured by experience and experimentation in data acquisition and processing, and guided by the growing understanding of crustal geology. As a result, both technique and strategy in reflection seismology will undoubtedly continue to progress toward a comprehensive view of the continental lithosphere.

TECTONIC ESCAPE IN THE EVOLUTION OF THE CONTINENTAL CRUST

Kevin Burke and Celal Sengor. Lunar and Planetary Institute, 3303 NASA
Road One, Houston, Texas. Burke also at Geosciences, Univ. of Houston,
Houston, Texas and Sengor also at Istanbul Technical University.

Studies during the last decade have confirmed the basic idea that the continental crust originated by processes very similar to those operating today and that continents consist of material most of which originated long ago in arc-systems that have later been modified, especially at Andean margins and in continental collisions where crustal thickening is common. Seismic studies have confirmed the importance of major thrusting in mountain belts that was demonstrated by Bertrand, Heim, Lapworth and Suess about 100 years ago.

Molnar and Tapponnier emphasized the importance of major strike-slip motion in association with the Himalayan-Tibetan continental collision on the basis of LANDSAT and teleseismic evidence and Tapponnier and colleagues have illustrated this style of deformation in a simple mechanical model.

We here stress the importance of collision-related strike-slip motion as a general process in continental evolution. Because buoyant continental (or arc) material generally moves toward a nearby oceanic margin where less buoyant lithosphere outcrops during collision we call the process of major strike-slip dominated motion toward a 'free-face' "Tectonic Escape".

Tectonic escape is and has been an essential element in continental evolution throughout recorded earth-history. It promotes: (1) rifting and the formation of rift-basins -- in China with petroleum production; (2) thinning of thickened crust -- which enhances the possibility of local preservation of high-level rocks from collision zones; (3) pervasive strike-slip faulting late in orogenic history which breaks up mountain belts across strike and may juxtapose unrelated sectors in cross-section; (4) localized compressional mountains and related foreland-trough basins which have petroleum potential.

Illustrative examples are culled from several continents and much of earth history. In older examples the interpretation of tectonic-escape related structures provides the best evidence of where the oceanic free face lay.

The Pannonian rifts of Hungary record extension during an episode of eastward tectonic escape which is also marked by the Neogene convergent and igneous activity of the Carpathian arc. The late Cenozoic south-eastward escape of South-eastern Asia associated with the Himalayan collision was preceded in the earlier Cenozoic by an episode of southward escape interpretable as a response to a suturing event along the Ussuri (Wusuli) River. Pan-African escape is recorded by huge strike-slip faults in the Ahaggar and by the numerous arc-collisions and Nejd faulting of Arabia.

THE DEEP CRUSTAL STRUCTURE OF
THE MOJAVE DESERT, CALIFORNIA, FROM
COCORP SEISMIC REFLECTION DATA

by

Cheadle, M., Dept Earth Sciences, Cambridge University CB3 OEZ, UK;
Czuchra, B., Tenneco Oil Co, P O Box 51345, Lafayette, La 70505;
Byrne, T., Dept Geol Sci, Brown University, Providence, Rhode Is 02912;
Ando, C., Shell Dev Co, P O Box 481, Houston, Tx 77001;
Oliver, J., Brown, L., Kaufman, S., Dept Geol Sci, Cornell University, Ithaca, NY 14853; Malin P., Dept Geol Sci, USC, Santa Barbara, Goleta, Ca 93108; Phinney, R., Dept Geol & Geophysical Sci, Princetown University, Princeton, NJ 08544.

COCORP seismic reflection profiling in the western and northern Mojave Desert of southern California has revealed the presence of numerous major low-angle reflecting horizons within the crust. These complex, though laterally continuous, horizons are interpreted to represent major southwesterly dipping crustal detachments and as such they place important constraints on the tectonic evolution of the region. The uppermost horizon is interpreted to be the Rand Thrust. The other reflecting horizons are not traceable to the surface and so greater ambiguity remains in their interpretation. The most prominent of these horizons exhibits ramp and flat geometry and occurs at midcrustal depths (15 ± 6 km), extending over the northern area of the Mojave survey into the Basin and Range Province. The crust-mantle transition appears to be represented by a continuous series of reflections which occur at about 10 seconds (33 km), in the north of the survey and at about 8 - 9 seconds (26 - 29 km) in the south. These reflections are offset in the vicinity of the town of Mojave.

The intracrustal detachments inferred from the COCORP survey may represent:
1. The westward deep crustal continuation of the system of Mesozoic thrusts which cropout into southern Nevada and southeastern California;

2. Late Cretaceous to early Cenozoic, northeast vergent thrusts related to the emplacement of the Pelona-Orocopia-Rand Schist; or

3. low-angle normal faults related to Early Miocene northeast-southwest directed crustal extension.

The COCORP survey also traversed the major strike-slip faults that bound the Mojave block. The San Andreas fault zone appears to truncate reflectors at depths of 6,8 and 20 km within the Mojave basement, suggesting that it is a major vertical feature which extends to at least 20 km depth. Conversely, the Garlock fault does not appear to offset an underlying reflecting horizon which occurs at 9 km depth, and therefore may be a relatively shallow crustal feature.

Crustal Reflections From a Land Air Gun Source Along a Profile in the Purcell Anticlinorium Of Southeastern British Columbia

Frederick A. Cook

Department of Geology and Geophysics
The University of Calgary
Calgary, Alberta, Canada T2N 1N4

Seismic reflection profiling in the Purcell anticlinorium of southern British Columbia, Canada using a land air gun source has revealed reflections from depths of at least 15-20 kilometers. Interpretations of these data, in conjunction with related geological and geophysical information, confirm the allochthonous structure of the Purcell anticlinorium and suggest that autochthonous North American basement is at 15-20 kilometers depth beneath the anticlinorium. Comparisons of these data with other seismic reflection data indicate the North American basement surface, which has a uniform west dip of about 2° beneath the Rocky Mountains, has a much steeper west dip of 10°-20° beneath the anticlinorium. The thickness of the crust above the North American basement surface may be accomodated by structural repetition of Purcell strata, by thrust slices of North American basement rocks, or by both. The geometry observed on the reflection data implies the Purcell anticlinorium is cored by a crustal-scale thrust anticline (hanging wall anticline). Further, the data demonstrate that land air guns are effective sources for crustal reflection work.

ABSTRACT

Seismic reflection and geology of the central Virginia Blue Ridge and Piedmont

by
J. K. Costain, L. Glover, III, and C. Coruh
Virginia Polytechnic Institute
and State University
Blacksburg, Virginia 24061

A combined geophysical and geologic study of the tectonic framework of the Appalachians in central Virginia has been in progress at Virginia Tech since 1979. Approximately 190 km of VIBROSEIS multifold reflection data have been obtained by the Regional Geophysics Laboratory along the James River Blue Ridge and Piedmont corridor over igneous and metamorphic terranes. Reflection seismic profiles crossed thick units whose subsurface geometry and continuity, or lack of it, revealed the structure in the upper crust. Surface geologic mapping provided a boundary condition from which key structural elements and thick metavolcanic lithofacies are projected to depths of approximately 10 km. The successful definition of the regional geologic framework in the crystalline rocks of the Piedmont and Blue Ridge depends to a large extent on the placement of reflection seismic traverses where metamorphosed basalts/felsic volcanics, metamorphosed basalts/sandstones, or sandstones/carbonates are known or believed to occur in the subsurface. The excellent acoustic response of these lithofacies accounts for most of the energy return, and makes an interpretation possible. The entire upper crust is allochthonous, with a decollement dipping gently to the east. The northwestern end of the traverse begins on

the Blue Ridge where the seismic data show about 3 km of Grenville rocks thrust over unmetamorphosed lower Paleozoic rocks. The master decollement is at a depth of 9 km. To the southeast, the seismic signature of the Catoctin volcanics is well-defined and reflected events correlate well with surface contacts of the Catoctin. The Taconic suture dips moderately and then gently to the southeast from near the center of the Piedmont and continues beneath the allochthonous Columbia granite. One of the best seismic signatures along the traverse is from the Chopawamsic volcanics which have been intruded by the Columbia granite. Relatively well-constrained earthquake hypocenters plot on ramp and sole faults that are relict from Paleozoic deformation.

One of the results of the Virginia Tech program has been the higher quality of reflection data obtained from a single vibrator versus conventional multi-vibrator configurations. A comparison of results from a single vibrator and 4 vibrators is made possible at the western end of the James River traverse as a result of overlap with a commercial line.

The Hercynian evolution of the convergent continental margin of South-west Britain.

G A Day, British Geological Survey, West Mains Road, Edinburgh EH9 3LA, UK.

The Hercynian orogeny drastically deformed Carboniferous and older rocks in Southern Britain. Where these are exposed in SW Britain, recent geological mapping has demonstrated that they have been deformed by north-directed thrusting, active from some time in the Devonian until late Carboniferous times. Staff of the British Geological Survey have interpreted confidential and other seismic data from onshore and offshore in this area.

In the west English Channel several lines show distinct SSE dipping events in Devonian basement which are interpreted as thrust faults and at least one of these can be correlated with thrusts inferred from land observations. A study of seismic data has shown that these events are a dominant feature of the southern flank of the basement ridge that extends the SW Britain (Cornubian) Peninsula to the shelf edge.

South of the Cornubian Ridge the basement deepens and is overlain by considerable Permo-Triassic sediments which probably extend at least to the central English Channel, demonstrating a tensional environment in post-Hercynian times. Linear magnetic anomalies appear to be associated with intrusions at the base of the sediments. BIRPS seismic profiles in this area show similar SSE dipping events in the basement and on currently available brute stacks one of these events appears to extend to, or possibly through, the lower crust. These major extensional faults seem to form the northern margins of the sedimentary basins and it is postulated that the mechanism of extension has been to reactivate former thrust faults, creating the environment for the deposition of large sedimentary basins.

Although the main extensional event occurred after the period of Hercynian shortening, further stretching occurred using the same mechanism, in late Jurassic or Cretaceous times, before the final compressional event in the Tertiary.

DEEP CRUSTAL EXPLORATION BY A LONG-OFFSET SEISMIC TECHNIQUE

by H.J. Dorman, T.H. Crawford, J.W. Stelzig, and P.J. Tarantolo
Exxon Production Research Company
Box 2189
Houston, Texas 77001

Abstract

The well-known source-generated noise of the Edwards Plateau of West Texas defeats most ordinary attempts to record usable seismic reflection data. However, an attractive exploration alternative is suggested by the presence of a deep (about 20,000 ft), high-speed refractor, the Hunton-Ellenberger zone, which is also the zone of primary commercial interest in this region. A 15-mile reversed refraction profile (2 shot points, 698 traces from each shot) illustrates the point.

Signals were generated by shear vibrators shaking longitudinally and were received on vertical component 8-hz geophones. P waves and S-converted P waves were obtained from the fundamental and odd-order harmonics of the sweep. Addditional P wave data were obtained from the even-order sweep harmonics.

The convenience of a reflection profile display is secured by plotting the refraction data in a record section (single-fold) format similar to that of a reduced travel time plot. This makes

the refracted arrival appear as if it were a reflection event on traces recorded only at the critical distance. Dense coverage (station interval 110 feet) produces sections which are potentially useful for structural and stratigraphic interpretation. The quality of these single fold sections is surprisingly good because: 1) the reflection-refraction event is very strong near the critical distance, about 12,000 to 18,000 ft; 2) traces at longer offsets are beyond the reach of strong surface noise. These are significant advantages not enjoyed by conventional near-offset reflection data.

In this limited data set, the image of the marker appears intermittently but quite clearly, comparing favorably in some places with that obtained in a conventional multi-fold reflection profile on the same line. It appears that event continuity and quality exceeding that of reflection profiling results might have been obtained with more shot points. Deeper events, including Pn, could probably be profiled in comparable detail using vibrator or explosive sources at longer offsets.

RECENT REFLECTION SEISMIC DEVELOPMENT IN THE WITWATERSRAND BASIN

R. J. Durrheim

Bernard Price Institute for Geophysical Research, University of the
Witwatersrand, 1 Jan Smuts Avenue, Johannesburg 2001, South Africa

Deep reflection seismology has recently been applied to the exploration of the deeper regions of the Witwatersrand Basin; data from two areas will be presented in order to demonstrate the problems encountered and success achieved with the seismic method to date.

The Kaapvaal Craton, which is considered to be one of the ancient nuclei around which the South African subcontinent is built, has formed the basement for five Precambrian basins. The rocks of the Witwatersrand supergroup were deposited in an oval basin with a long axis of some 300 km during the second of these sedimentation episodes in the period 2300 - 2800 Ma. These rocks are of great economic importance due to gold and uranium bearing strata. The Witwatersrand supergroup rocks presently outcrop in an arc near Johannesberg, and on the rim of Vredefort Dome, which represents a violent penetration of a "diapir" of basement granite in the centre of the basin. It has been shown that the dome presents a 14 km section through the crust. Elsewhere the Witwatersrand rocks are covered by younger lavas and sediments. Subsequent to the deposition of the Witwatersrand rocks, folding and faulting has taken place, controlling the present day distribution of ore-bearing strata.

The earliest attempts at applying geophysical techniques to the exploration of the Witwatersrand Basin were made in the 1930's. Magnetometer traverses proved very successful in locating magnetic marker horizons stratigraphically near to the gold-bearing reefs. In this way the Evander, West Rand and Welkom gold-fields, which are concealed by younger rocks, were discovered.

Gravimetry proved successful in locating faults.

The latest phase in the exploration of the Witwatersrand Basin began less than 2 years ago with the introduction of reflection seismology. Preliminary tests and synthetic seismograms indicated prominent reflectors which would enable geological structure to be mapped. Initial results are generally satisfactory, although the faulted nature of certain areas in the basin is proving an obstacle. Several companies are recording occasional profiles to long times, allowing crustal structure to be studied. Attention is also being given to the mapping of possible thrust faults on the margin of the basin where it is postulated that Witwatersrand supergroup rocks may be preserved beneath basement granite.

Crustal Reflections on Northern Switzerland

by

Peter Finckh, Institute of Geophysics ETH, 8093 Zurich, Switzerland

In 1982 a vibroseis (R) survey of 180 km of high resolution reflection profiles was run in northern Switzerland to investigate the suitability of the crystalline basement for the deposition of radioactive waste. Data was recorded on a 144-channel system. This survey revealed a complicated fault and thrust system beneath the Swiss folded jura. Further, it revealed the considerable dimensions and the geometry of an unexpected basement trough filed with Permo-Carboniferous sediments (including coal seams) which is completely covered by Mesozoic sediments. Maximum thickness of the basin exceeds 3 km.

Reprocessing of the field tapes of a E-to-W line of 11.5 km length with half sweep correlation extended the listening time to 11 sec. The stack shows a strong sloping reflector between 3.0 and 3.5 sec which is interpreted as evidence for pronounced differentiation in the upper crust. A series of reflections is observed between 5.8 and 7.2 sec, the top of which can be correlated with the Conrad discontinuity. Between 9.0 and 9.5 sec a layered reflector is observed which is interpreted as Moho reflections.

Similar reprocessing down to 11 sec was applied to a N-to-S line from the outcropping basement in the Black Forest (FRG) to the thrust zone of the folded jura and which is crossing the above-mentioned E-W line at its western end. The stack does not confirm the reflector between 3.0 and 3.5 sec, probably because of poor velocity control in the Permo-Carboniferous trough. However the series of reflections between 6.0 and 7.2 sec as well as those at 9.0 sec are confirmed as reflections from the horizontal C- and M-discontinuities.

These main results are compatible with results from refraction surveys which were shot in the same region. Especially the wide angle interpretation permitted the definition of lower crustal reflections excluding multiple reflections, and it shed more light on the layered nature of these reflectors. The refraction velocity model of the lower crust shows an increase of about 0.5 km/sec at 15 to 20 km depth, followed by an inversion zone before reaching the Moho at depth of about 28 km. This model is suggested to be refined into a more laminated model which would encompass two major impedance contrasts at the C- and M-discontinuities, intercalated with minor positive and negative impedance contrasts. This model would be tectonically compatible with magmatic intrusions into the lower crust from the upper mantle during an incipient rifting phase in this region some 20 M.Y. ago associated with a change of the relative movements between Africa and Eurasia.

Geophysical nature of the lower continental crust based on crustal cross-sections

David M. Fountain (Dept. of Geology and Geophysics, Univ. of
Wyoming, Laramie, Wyoming 82071) and Matthew H. Salisbury
(Deep Sea Drilling Project, Geological Research Division,
Scripps Institution of Oceanography)

Based on various geological and geophysical criteria, Fountain and Salisbury (1981) proposed that complete or near-complete cross-sections of continental crust are exposed in orogenic belts along crustal-scale thrust faults. Examples of cross-sections are 1) Ivrea-Verbano (IV) and Strona-Ceneri zones in northern Italy; 2) Pikwitonei belt (PB) and Cross Lake subprovince along the Nelson Front in Manitoba; 3) Fraser Range (FR) in western Australia; 4) Musgrave Range in central Australia; 5) Wawa terrain and Kapuskasing zone (KZ) in central Ontario. These terrains afford excellent windows to deep levels of continental crust providing considerable insight into the structure, evolution and geophysical nature of lower crust.

In general, these cross-sections show that the crust exhibits vertical metamorphic zonation with granulite facies assemblages commonly comprising the deeper levels. This zonation is superimposed on a lithologically heterogeneous crust composed of both meta-igneous and meta-sedimentary rocks, ranging from silicic to ultramafic compositions. Some lower crustal sections are dominated by silicic gneisses (PB), others by mafic gneisses (FR) and some by both mafic and pelitic composition rocks (IV). Large bodies of anorthosite and mafic-ultramafic complexes are commonly found at deep crustal levels in many cross-sections (IV,PB,KZ).

An example of how the geophysical nature of the lower crust is determined by the complexities of crustal evolution is given by the Ivrea Zone. An interpretative geologic history of the zone can be summarized as follows: 1) pre-Caledonian deposition of sediments in a large basin; 2) pre-Caledonian greenschist and amphibolite facies metamorphism; 3) Caledonian intrusion of large mafic and ultramafic bodies into the base; 4) Caledonian granulite facies metamorphism in the lower sequence and partial melting of meta-pelitic gneisses; 5) isoclinal folding; 6) Hercynian formation of post-metamorphic granites and extrusives at shallow crustal levels; 7) early Mesozoic rifting along low-angle normal faults bringing shallow levels against deep levels.

The underplating event produced high velocity crust because mafic intrusions equilibrated in the granulite facies and the resulting meta-pelitic restites have high velocities. In detail, however, there is complex tectonic and magmatic interlayering of these rock types which would produce strong reflections and prominent diffractions in reflection records. The geophysical distinction between the upper and lower crust in this section is enhanced by low-angle faults, which may also be reflectors. Furthermore, Ivrea Zone deeper crust is less radiogenic than the upper crust because of the prevalence of mafic rocks and depleted restites and thus has low heat production. The mafic rocks also exhibit high magnetic susceptibilities and form a magnetic lower crustal layer.

These geophysical features are a consequence of 500 million years of crustal evolution. Other cross-sections are older examples of crust and show very different features, implying they will have quite different geophysical characteristics.

REFLECTIONS FROM THE SUBCRUSTAL LITHOSPHERE?

K. Fuchs

Geophysical Institute, University of Karlsruhe, Hertzstrasse 16,
Karlsruhe, West Germany

Fine structure of the subcrustal lithosphere has been revealed by deep seismic sounding on long range refraction profiles. The evidence for the fine structure includes strong heterogeneities in seismic P-wave velocities, unusually high velocities, and anisotropy. However, the refraction seismic data give only gross lateral averages of the structures. For a better understanding of the tectonic and compositional implications of these seismic anomalies in the lower lithosphere, seismic reflection data is required. Prospects for acquiring such data will be discussed.

Fluid Generation in Deep Continental Crust

W. S. Fyfe, Department of Geology,
University of Western Ontario,
London, Canada N6A 5B7

Abstract

Given an unperturbed 30 km continental crust with Moho temperatures in the 400-500°C temperature range, deep rocks will be in the high greenschist to amphibolite facies. The water content of such crust would be near 2% while carbonate rocks would be stable.

The widespread development of high grade and dry amphibolites and granulites demands an abnormal gradient with deep temperatures in the range 800-1000°C. Such temperatures are also required to produce crustal granites. Ultimately the thickness of continental crust must be limited by melting.

Extensive retrograde metamorphism of high grade rocks also requires deep sources of fluids, some of which appear to come from mantle sources.

Present knowledge of global tectonics shows that volatile phases are recycled into the deep mantle by subduction of sediments and ophiolites (for water $\approx 1.5\ \mathrm{km}^3\ \mathrm{a}^{-1}$). Water in subducted lithosphere must return during metamorphism to eclogite facies and eventually in mantle melts. Such rising fluids may cause hydration near the continental edge (even Moho serpentinization) and decoupling of crust

and mantle. As mantle magmas are commonly more dense than continental crust at Moho pressures, magma underplating may also cause decoupling. Such magmas must degass as they crystallize and flux crustal melting. Dense underplate magmas will tend to assimilate heavy crustal rocks (basaltic amphibolites, dolomites, etc.), a process which will also generate fluids rich in H_2O-CO_2 and even with sulfur species. The extensive development of graphite veins in granulites may result from such gases.

As recent continental seismic data show, low angle thrusts are common in deep continental structure. The formation of such thrusts requires fluids and the thickening processes associated with thrusting may lead to high grade metamorphism or even melting in the underplates while retrograde metamorphism may occur in the overthrust blocks. Retrograde metamorphism of high grade regimes may require a major thrust event. In thrusts of the Himalayan type, 4 km^3 of fluid per km^2 of thrust surfaces may be common. Such fluids while H_2O dominated may contain large amounts of CO_2. The total evolved fluid mass associated with the Himalayan event is similar to that of the ice caps.

As the mechanical properties of rocks are dramatically influenced by fluids, most regions of fluid production will be weak and ripe for deformation while retrograde, fluid-absorbing, zones will be strong. There is potential for mineralization whenever the flow of km^3 fluid volumes is focussed by major structure.

COCORP PROFILES OF PRECAMBRIAN CRUST: A QUALITATIVE ASSESSMENT

Allan K. Gibbs

Department of Geological Sciences, Cornell University, Ithaca, N.Y. 14853

ABSTRACT

COCORP profiles of several Precambrian terrane boundaries and cratonic basins show structural features throughout the crust that are probably of Precambrian age. Similarities between Archean, Proterozoic, and Phanerozoic structures imply that tectonic processes might have been qualitatively similar in all eras. Apparent persistence of Precambrian structures throughout the crust and into the uppermost mantle in some areas implies that some continental crust has remained coherent and refractory.

Most of the Precambrian crust that has been profiled can be classified by seismic characteristics into the following categories:

- Lacking coherent reflections or diffractions; seismically transparent. Found in areas of known granitoid rocks in Minnesota and Kansas, anorthosites in the Adirondacks and Laramie, Wyoming profiles, and some areas of gneiss.

- Well-stratified, relatively continuous reflections; typically in the upper crust. Typical of cratonic basins with sedimentary, volcanic, and shallow intrusive rocks (Texas, Oklahoma, Kansas, Michigan, and eastern New Mexico). Origin of well-stratified middle to lower crust is more obscure: those between about 18 and 26 km beneath the Adirondack anorthosite might be associated with underthrust sedimentary and volcanic strata, layered igneous rocks, or rocks with a strong planar deformation fabric.

- Relatively continuous, coherent, moderately-dipping reflection zones associated with known faults or terrane boundaries. Reflections might be from faults, associated cataclastic zones, strata folded into conformity with faults, or underthrust continental marginal sequences. Within Precambrian terrane boundary zones in Minnesota and Wyoming there are groups of events that extend from the upper to lower crust with migrated dips of 30 to 50 degrees.

- Complex reflection and diffraction patterns with highly variable dip, scale, and intensity. Numerous geological causes may account for these, involving complex deformation of rocks with contrasting seismic properties in zones of intrusion, diapirism, horizontal compression, etc. Complex patterns are associated with gneiss terranes in Minnesota and the Adirondacks, beneath granites in Minnesota and Kansas, and beneath cratonic basins in Texas and Kansas. In Minnesota the distribution of

reflection groups in the gneiss terrane correspond with gravity and magnetic anomalies: they might be due to mafic lower crustal rocks brought up to the middle to upper crust by faulting.

- Events at Moho depths. In most of the profiles some events appear to originate from Moho depths. They are typically weak or barely perceptible, discontinuous, and in many instances they have moderate dips. In several areas, such as Kansas, the base of the crust is expressed as a decrease in the abundance of reflections.

Part of a previously unknown, 7 - 10 km thick, cratonic basin, profiled in Texas and Oklahoma, was probably formed in an extensional environment, though extensional structures are not obvious. In Kansas and Michigan, the axes of rift basins were crossed. These are assymetric basins, with rotated sedimentary and volcanic fill. Similar profiles have been found in the Tertiary Rio Grande rift.

The COCORP evidence of imbricate, moderately-dipping and deeply-penetrating structures in the Precambrian terrane boundary zones in Minnesota and Wyoming adds an important depth dimension to the surface geological interpretations. The structures are interpreted as fault zones, analogous to those of Phanerozoic collision orogens. In both the Archean and Proterozoic examples, older continental crust appears to be underthrust beneath younger granite-greenstone terranes. Concentrations of very weak, moderately dipping events at Moho depths in Minnesota might be imbricated by the same fault zones. Comparable features can be seen in the DSS profiles of India. Younger deformation events that could have produced such structures are not known: thus the base of the crust and attached upper mantle must have retained structures that originated in the Precambrian.

In many areas, Precambrian structures are known to have been reactivated in several younger episodes; they exert a strong influence on continental deformation during the Phanerozoic. It is important to study Precambrian features in the cratonic regions, which might otherwise appear flat and uninteresting. It will be useful to extend reflection seismic profiling to fully cross the widths of Precambrian orogenic belts and extensional basins. Much more profiling will make it possible to determine which characteristics are typical of the various Precambrian crustal types, and eventually to seek evidence of temporal changes in crustal geometry. Two important Precambrian crustal types still await study by reflection seismology: classical granite-greenstone terranes and areas with prominent anorogenic granitoid cover.

INTERPRETATION OF THE WICHITA MOUNTAINS STRUCTURAL AXIS

M. Charles Gilbert
Department of Geology
Texas A&M University
College Station, Texas 77843

Background: The Criner Hills-Wichita Mountains-Amarillo Uplift of the southern U.S. Midcontinent is a Pennsylvanian structural axis. The related Hardeman/Hollis Basin, Anadarko Basin, Ardmore Basin, Marietta Basin, and Arbuckle Mountains, and this axis, approximately outline the Cambrian Southern Oklahoma Aulacogen. A COCORP line crossed this axis running from the Hardeman Basin (Texas) to the northern flank of the Anadarko Basin. The Cambrian igneous suite exposed in the Wichita Mountains is unique in time and offers an opportunity to develop a petrologic/structural model of the crust for this area which can be used as a guide in interpreting the seismic data.

Approach: Petrology of the silicic granites/rhyolites and regional geology together provide a minimum in the number of crustal levels which should be sought. This sort of analysis does not include the possibility of decollement zones. Generation of silicic partial melts works to destroy pre-existing stratigraphic horizons while also indicating the formation of new ones. The bulk composition of silicic melts is assumed to form on the boundary curve of the Qtz-Ab-Or system for the pressure of the site of generation.

Possible Crustal Levels: Ten potential levels below the surface are hypothesized. Some of these may coincide in reality. Levels are numbered down beginning nearest the surface.

Level	Geologic Relation	Possible Seismic Boundary
1	GMLC base - Tillman	Yes - density contrast
2	Tillman base - Central Okla. Granites	? - change in layering
3	Base Central Okla. Granites	? - change in layering
4	Generation of Wichita Granites/ Carlton Rhyolites	? - disrupted zone
5	Top of source gabbro for WG/CR	Yes - density contrast
6	Base of source gabbro for WG/CR	Yes - density contrast
7	Generation of Central Okla. Granites	? - disrupted zone
8	Top of source gabbro for COG	Yes - density contrast
9	Base of source gabbro for COG	Yes - density contrast
10	M-discontinuity	Yes - density contrast

Analysis: Level 1 should be 2 to 3 km deep. Level 2 is probably very close to 1 and may be unresolvable. Level 4 should be about 12 to 15 km (or deeper) and could be above or below 3. There is some seismic evidence for a change in character around 12 km which may be Level 4 or 5. Depths of Levels 3 and 6-9 are as now only speculative. Level 10 appears to be about 41 km to the south, 46 km to the north and could have an offset due to development of the Pennsylvanian Frontal Fault Zone.

THE THIRD DIMENSION OF GEOLOGY FROM SEISMIC REFLECTION STUDIES IN CANADA

A.G. Green and M.J. Berry, Division of Seismology and Geomagnetism,
Earth Physics Branch, Energy, Mines and Resources, Ottawa, Canada, K1A 0Y3

Seismic reflection studies of the continental crust have had a long but sporadic history in Canada. The early papers of Kanasewich, Cumming and Clowes are generally recognized as being among the first to provide convincing evidence that near-vertical reflections could be recorded from the deep crust and upper mantle. In the late-1960's their work resulted in the discovery of a Precambrian rift buried beneath the Phanerozoic sediments of the western Canada basin. Shortly afterwards, in 1973, Mair and Lyons demonstrated that Vibroseis was a viable source of probing the crust when they recorded a relatively continuous reflection at approximately 11 seconds two-way travel time along a 20 km profile in the Canadian Cordillera.

After a hiatus in deep seismic studies of all types during the mid-1970's, the Consortium for Crustal Reconnaissance Using Seismic Techniques (COCRUST) was formed in order to consolidate funding and pool the limited human resources and recording/processing capabilities in Canada. Most of the COCRUST seismic surveys have been of the refraction-wide angle reflection type recorded along profiles and fan lines, although short multi-coverage reflection profiles have been recorded at certain critical locations. For example, 100 km of 4- to 15-fold reflection data have been collected across the boundary zone between the Superior and Churchill Precambrian structural provinces. On these data shallow to moderately dipping reflections from a mid-crustal zone of low seismic velocity and high electrical conductivity have been interpreted as originating from a buried sequence of hydrated rocks that were once situated along the ancient continental margin of the Superior craton. Approximately 300 km to the west of the boundary zone, along the axis of the North American Central Plains electrical conductivity anomaly, a seismic survey with a novel triangular shot-receiver pattern has revealed the existence of elongated seismic low velocity zones and a coincident change in crustal thickness.

Perhaps the most successful COCRUST survey to date has been the Vancouver Island Seismic Project (VISP I). Seismic refraction-wide angle reflection data from both onshore and offshore profiles have been interpreted in terms of a dipping oceanic plate plunging beneath the continental North American plate. On a short 12-fold reflection profile, recorded onshore near the western coast of the island, coherent events were recorded from the top and from within the subducting oceanic plate.

In addition to the COCRUST work, intermediate and deep Vibroseis profiles have been recorded recently by industry and by a joint USGS-EMR group along a 400 km traverse that extends across the northern Appalachians from the St. Lawrence River in the province of Quebec to the margin of the Atlantic Ocean in the state of Maine. Clearly imaged on the industry data recorded near the St. Lawrence River is a series of southeasterly dipping normal faults that affect, for a distance in excess of 40 km, both the underlying Grenville Precambrian basement and the cover of platform sediments. The normal faulting and sedimentation occurred along an evolving Atlantic-type continental margin during the opening of the Late Precambrian-Early Paleozoic Iapetus Ocean. Ubiquitous shallow dipping reflections at intermediate depths originate from large scale faults generated during the closing of the Iapetus Ocean as large slices of continental rise and island arc material were thrust over the continental shelf. In the deepest data, recorded along a line that crosses the Canada-U.S. border, a series of very prominent shallow dipping events has been traced to two-way travel times of 8 seconds.

With the confirmation of funding for phase I of LITHOPROBE, a program of mutli-disciplinary studies across key geological targets, Canada has entered a new and exciting period of deep seismic studies. In May and June of this year, approximately 200 km of 30-fold Vibroseis data wll be collected across the subduction zone beneath Vancouver Island (VISP II) and in July an extensive seismic refraction-wide angle reflection survey and a short 24-fold, land-based, air gun reflection survey will be conducted across the exposed lower crustal section of the Kapuskasing Uplift zone (the KUSP I experiment).

NATURE OF THE LOWER CONTINENTAL CRUST:
EVIDENCE FROM BIRPS WORK ON THE CALEDONIDES

Jeremy Hall

Department of Geology, University of Glasgow, Glasgow G12 8QQ Scotland

The Western Isles and North Channel ('WINCH') seismic reflection profile traverses the metamorphic Caledonides of northern Britain. The lower crust appears to be more reflective than the crust above or the mantle below. The base of the reflective sequence, assumed to be the base of the crust, can be drawn with confidence over most of the profile. The top of the reflective sequence can also be picked, but with greater uncertainty.

Across the Caledonide Dalradian metasediments the profile indicates an antiformal Moho and a synformal top of the reflective sequence. There is little variation in the gravity field over this feature. In effect the Moho relief is compensated isostatically by necking of the lower crustal reflective layer. Modelling this using velocity-density systematics indicates that the lower crust here must have a density of around 3150 kg/m^3 and a mean P-wave velocity of near 7.5 km/s.

Along strike the same crust has a deep layer of high conductivity. It is suggested that the lower crust is of basic composition, of variable metamorphic grade, and containing free water trapped by contraction during cooling.

Seismic Reflection Studies by the U.S. Geological Survey

Robert M. Hamilton
U.S. Geological Survey
Reston, Virginia 22092

Abstract

The U.S. Geological Survey (USGS) has used seismic-reflection methods to study the continental crust in recent years. The areas and geologic features studied are listed below.

- Maine and southeastern Quebec - Geologic structure of the northern Appalachians.
- Northern New Jersey - Origin of seismicity in relation to the Ramapo fault zone and structure of the Newark basin.
- Central Virginia - Geologic structure of the central Appalachians and the Culpeper basin.
- Eastern Tennessee and western North Carolina - Geologic structure of the southern Appalachians.
- Eastern South Carolina - Regional structure of the Atlantic Coastal Plain and offshore area to investigate the origin of the Charleston earthquake of 1886.
- Central Mississippi Valley - Regional structure of the northern Mississippi Embayment to investigate the origin of New Madrid earthquakes of 1811-12 and continuing seismicity.
- Central Utah - Structure of the Wasatch fault zone.
- Central California - Regional structure of the Coast Ranges, Central Valley, and Sierra Foothills.

The seismic profiles in these areas were acquired in a variety of ways, including purchase of proprietary data, purchase of speculation lines, and contracting with private companies and universities. In addition, many profiles were acquired on the Atlantic, Pacific, and Alaskan continental margins through marine operations by both a USGS ship and contract ships. Data were processed both by contractors and by USGS staff using systems in Menlo Park, Calif., and Denver, Colo., and satellite facilities in Woods Hole, Mass., and Reston, Va. Seismic-refraction studies have been conducted in support of reflection work in some of the areas by using a set of 100 portable, tape-recording seismographs, which provides additional control on velocities, particularly at middle and lower crustal depths.

Seismic-reflection studies in the New Madrid seismic zone have been particularly successful in determining deep structure. The profiles reveal a linear, antiform structure, interpreted as a system of intrusive bodies along the rift axis, which coincides with the major zone of seismicity and lies within the sandblow area of the 1811-12 earthquakes.

During the next decade, efforts will be focussed on a comprehensive investigation of the lithosphere in Alaska along the pipeline corridor and in offshore areas near its ends. The project, dubbed Trans-Alaska Lithosphere Investigation (TALI), will involve scientists from academia, industry, and State and Federal governments in a multidisciplinary approach. Compilation of geologic data and further field work will result in a set of geologic maps of the corridor, and selected areas will be mapped in detail. Gravity and magnetic data will be compiled. Seismic-refraction studies will be conducted in 1984 in the southern part of the corridor. These studies are to prepare for seismic-reflection profiling along the 1400-km route in subsequent years.

Interpretation of Seismic Reflection Data in Complexly Deformed Rocks: A Geologist's Perspective

HATCHER, Robert D., Jr., Department of Geology, University of
South Carolina, Columbia, SC 29208

Horizontal seismic reflectors have recently been used to speculate on the existence and continuity of major tectonic features, such as thrust faults, in crystalline rocks or as boundaries between crystalline basement and cover sedimentary rocks. A large body of published seismic reflection profiles in areas where structure can be verified using drilling and/or down-plunge projection supports this interpretation. However, it has recently been shown with the Arizona A-1 hole and elsewhere that prominent, continuous horizontal reflectors in crystalline rocks do not necessarily indicate that a major tectonic break is present, or that there is a crystalline-sedimentary rock interface present.

Reflections occur where acoustic properties change and the acoustic energy may be reflected at a convenient angle to be detected on the surface. Steeply-dipping layers of contrasting acoustic properties are commonly not detected, although it may be theoretically possible to do so.

The interiors of mountain chains contain a complex assemblage of rocks of low to high metamorphic grade which have markedly different mechanical and probably acoustic properties. Opportunities for acoustic reflection occur at interfaces between rocks of different densities, anisotropies or compositions without any tectonic discontinuities being present. Subhorizontal tectonic discontinuities, e.g., thrust faults, may provide additional opportunities for reflection of seismic energy provided there is a difference in character of the rocks on either side of the discontinuity. Late thrusts in orogenic belts tend to be less deformed and, if they juxtapose rocks of contrasting properties, should provide excellent reflectors, as in the southern Appalachians. However, unless verifiable by independent evidence, continuous reflectors in orogenic terranes may not prove to be tectonic boundaries in every case.

CRUSTAL REFLECTIONS FROM THE LONG ISLAND PLATFORM OF THE U.S. ATLANTIC CONTINENTAL MARGIN

D.R. Hutchinson, U.S. Geological Survey, Woods Hole, MA 02543
J.A. Grow, U.S. Geological Survey, Denver, CO 80225
K.D. Klitgord, U.S. Geological Survey, Woods Hole, MA 02543

The Long Island platform of the U.S. Atlantic continental margin is an offshore segment of continental crust that underwent Late Paleozoic collision and early Mesozoic rifting between North America and Africa. The platform, which is adjacent to the Baltimore Canyon trough and the Georges Bank basin, extends south to the basement hinge zone, which represents a tectonic boundary associated with crustal thinning, subsidence, thickening of postrift sedimentary rocks, and the edge of continental crust. The platform is also east of the early Paleozoic Appalachian suture zone and south of Paleozoic eugeosynclinal rocks of Connecticut and Avalon rocks of Rhode Island and Massachusetts. A grid of thirty six-fold multichannel seismic reflection profiles contracted by the U.S. Geological Survey (six dip lines and two strike lines spaced 40 to 50 km apart on the Continental Shelf) provides an opportunity to map crustal reflections and observe the variability of crustal reflection events over relatively short lateral distances.

The clearest crustal reflections beneath the undeformed postrift sediments occur within buried synrift basins that formed during the early Mesozoic separation of North America and Africa. Two of the three most continuous examples of basins are half-grabens bounded by controlling faults that dip east (Long Island basin) and northwest (Nantucket basin).

Reflection events at midcrustal depths are numerous and consist of either isolated strong, continuous reflectors or packages of subparallel discontinuous events. The isolated strong reflectors cannot generally be traced between lines, and only one set of subparallel events can be correlated with any certainty on three lines. This latter set of events forms a wedge that dips west-northwest from 2 to 7 s two-way travel time south of Block Island, R.I., and may offset Moho. No obvious subhorizontal decollement can be traced beneath the platform.

The base of the crust is marked by either a single reflector or several strong reflectors between 9 and 11 s in depth. In two-way travel time, the map view of Moho shows an undulating surface that dips south towards the basement hinge zone. The regional southerly dip can be associated with the thickening of low-velocity post rift sediments. It is not clear whether the undulating relief is caused by true depth variations in the Moho or by velocity variations in the synrift and crustal rocks.

REPROCESSING of CRUSTAL SEISMIC REFLECTION DATA

Roy A. Johnson, William Pierson, Sharon L. Wilson, William P. Iverson and Scott B. Smithson, Program for Crustal Studies, Department of Geology and Geophysics, University of Wyoming, Laramie, Wyoming 82071

Because crustal reflection studies are new and targets are complex, special processing is necessary to improve data quality and to provide better understanding at the interpretive stage. First-pass processing provides seismic sections which are very useful in evaluation of data aquisition and processing procedures. From these data, initial interpretations can be made and areas that warrant closer investigation should be identified. Detailed analysis, modeling, and the use of advanced processing techniques can provide insights crucial to interpretations of complex seismic reflection data from the crust.

Since field records comprise the basic data, detailed analysis must begin with these records. Analysis of field records and common midpoint (CMP) gathers helps to determine static, velocity and mute problems and is useful in identification of multiples, sideswipe and reflected refractions. Advanced processing techniques, which include velocity filtering, median filtering, signal-to-noise ratio estimation and filtering, spectral whitening, true amplitude analysis, wavelet processing and migration, can be used to eliminate coherent noise and enhance data quality. These techniques also provide qualitative and quantitative information about geologic features that are imaged. Modeling, in the absence of deep crustal well control, provides final constraints on interpretation.

Advanced analysis of COCORP deep crustal reflection (DCR) data from the Laramie Mountains, Wyoming shows that processing artifacts confuse interpretation of the original data. Subsequent reprocessing enhanced data quality and enabled imaging a near-surface fault zone reflection. With model analysis and S/N ratio and median filtering, these data constrain the near-surface dip of Laramide faults at the mountain front to be 30°-45° W.

Identification of multiples in the Wind River, Laramie Range and other data sets requires caution in interpreting deep events. True amplitude analysis of Appalachian COCORP data emphasizes changes in seismic character and provides qualitative constraints on reflective geologic terrains. Wavelet processing of Oklahoma COCORP data gives estimates of reflection coefficients which argue for the presence of layered metasedimentary and igneous rocks within a Proterozoic basin. Reprocessing, migration and modeling of deep events from Minnesota COCORP data has possibly imaged a large recumbent fold. General model studies suggest that mylonite zones, which probably are common in the upper to middle crust, can be strong reflectors, and give valuable information on structural configurations that can be interpreted from deep crustal reflection data. Advanced analysis and new processing techniques clearly demonstrate that "final sections" should never be considered final.

TECTONIC FRAMEWORK OF NARMADA-SON LINEAMENT - A CONTINENTAL RIFT SYSTEM IN CENTRAL INDIA FROM DEEP SEISMIC SOUNDINGS

K. L. Kaila

National Geophysical Research Institute, Hyderabad 500007, India

Three Deep Seismic Sounding (DSS) profiles about 250 km long each have been shot by the National Geophysical Research Institute, Hyderabad, India, across the Narmada-Son lineament, which passes through Broach on the west coast of India in A NNE-SSW direction cutting across the whole of central India. These profiles running in the NNW-SSE direction are (1) Mehmadabad-Billimora, (2) Ujjain-Mahan and (3) Khajuriakalan-Pulgaon. Interpretation of both shallow refraction and the deeper reflection data along these profiles shows that the Narmada River, outside the Broach depression, flows over a basement ridge feature which on the eastern part is known as the Malwa Ridge. Narmada River alluvium (velocity of 3.3 km/sec) in the region of Hoshangabad is only about 300 metres thick forming a surficial half graben with faulting on the southern margin lying directly over the granitic gneisses (velocity 5.9 km/sec). South of the Narmada River, between Dorwa and Mahan, a large graben about 200 km in length extending in the WNW-ESE direction and about 100 km in width filled with Mesozoic sediments, maximum thickness about 1700 metres (velocity 3.2 km/sec) has been revealed under a thin Deccan Trap cover about 400 metres thick (velocity 5.0 km/sec). This graben called here "Tapti graben" may be extending under the Deccan Trap cover right up to the Anklesvar-Surat area on the west coast of India where about 1.2 km thick Mesozoic sediments have been revealed under about 1.1 km thick Deccan Traps. As the Deccan Trap thickness increases towards the west coast, the deepest part of the Mesozoic sea might have lain in the Anklesvar-Surat area south of Narmada joining further west with the Mesozoic basin in Saurashtra. Besides the above mentioned Tapti graben, quite separated from it lies a small Gondwana graben in the Multai-Pulgaon region with a maximum Gondwana sedimentary thickness of about 400 metres (velocity 3.2 km/sec) underlying about 100 metre thick Deccan Traps. This Gondwana graben most probably is the extension under Deccan Traps of the exposed Godavari graben in the NW-SW direction from the east coast of India. North of the Narmada River in the region of Ujjain-Indore-Khajuriakalan, the Vindhyan Basin has revealed A very thin combined Vindhyan and Bijawar section, varying in thickness from 200 to 400 metres (velocity 3.7 km/sec) underlying a thin Deccan Trap cover of about 100 metres thickness. Towards the west, the Broach syncline shows the absence of Deccan Traps even under the sedimentary cover, which is therefore presumed to be an uplifted block during the pre-Tertiary period. It is concluded that the Broach graben was formed during the Tertiary period only.

Between the Narmada and Tapti River, the Moho shows a big depression attaining a depth of about 42 km near Dorwa and 39 km near Chhipaner and Rahatgaon. The Moho is at a depth of 36 km near Sanwer and south of Sehore. There is an uplift of the Moho near Multai attaining a depth of 34 km. Near Bawanbir the Moho has a depth of 38 km increasing towards the northeast in the form of a nose. Near Mahan it has a depth of 38 km and near Pulgaon 36 km. The interval velocity function along the Ujjain-Mahan profile and the Mehmadabad-Billimora profile in the Cambay Basin reveals that the top of the crustal basaltic layer (velocity 6.9 km/sec) lies at a shallow depth of about 10 km. This implies thickening of the basaltic layer in the crust under a major portion of the Deccan Trap covered area. These DSS studies have revealed that the maximum thickness of Deccan Traps about 1.5 km lies near the west coast of India, and one may have to look for the source of Deccan lava flows also in that region. The crustal thickness along the Mehmadabad-Billimora profile becomes about 18 km under Billimora in the northern part of the large Bouguer gravity high extending in the north-south direction from Bombay. Therefore, it can be inferred that this gravity high is due to large scale upwarping of the Moho, with a basaltic layer top lying at about 6 km depth. The crustal structure in this region, almost approaching oceanic type, resulted in extensive lava flow through some rifting and spreading of lava in all directions.

INTEGRATED GEOPHYSICAL STUDY OF THE MIDCONTINENT GEOPHYSICAL ANOMALY ALONG THE KANSAS COCORP PROFILE

Ralph W. Knapp, Chaturong Somanas, and Harold L. Yarger
Kansas Geological Survey
The University of Kansas
1930 Constant Avenue, Campus West
Lawrence, Kansas 66044

Gravity and magnetic modeling was done on profiles coincident with the Kansas COCORP seismic reflection profile across the Midcontinent Geophysical Anomaly (MGA) in northeastern Kansas. The objective of this study was to integrate all known information from the area including Precambrian basement rock types from drill measurements, the COCORP reflection profile, gravity measurements, and aeromagnetic measurements.

The single most striking feature on the COCORP reflection profile is a thick layered wedge of west-dipping reflections between VP 1580 and VP 1960 and times 0.9 to 2.8 seconds. The distinct layering of the reflections and the results of the magnetic modeling clearly suggests that this wedge is composed of basalt or basalt interbedded with clastic sediments. At about 0.9 seconds the reflections are truncated unconformably by a quiet zone of reflection energy which is interpreted as being Precambrian clastic Rice Formation. This interpretation is also supported by gravity modeling.

To the east and west of the basalt wedge, apparently separated from the basalts by normal faulting, are thick bodies with quiet reflection characteristics. Gravity data require that these bodies be low-density Rice Formation clastics to account for flanking lows of the observed gravity anomaly. The positive gravity anomaly is accounted for with a massive mafic intrusive beneath the basalt wedge and a minor contribution by the basalt. The seismic evidence for this intrusive is an interruption of chaotic reflection energy within the lower crust at about 6 seconds.

To the east of the MGA maximum at about VP 1465 is a small positive magnetic anomaly. Reprocessing of the COCORP reflection data about this area has revealed a possible near vertical mafic dike. Paleopole studies suggest it to be younger in age than the flows of the central basaltic rift basis. That this dike crosscuts the Rice Formation further substantiates its relatively young age.

RIFT-RELATED SEISMIC REFLECTION SEQUENCES THROUGH THE WILSON CYCLE: IMPLICATIONS FOR THE RECOGNITION OF CONTINENTAL AND OCEANIC BASEMENT BENEATH PASSIVE MARGINS AND COLLISIONAL MOUNTAIN BELTS

by Robert J. Lillie
Department of Geology
Oregon State University
Corvallis, Oregon 97331

A growing body of deep seismic reflection profiles across the Appalachian/Ouachita orogenic belt reveals subthrust structures which have been previously interpreted as products of continental rifting, of later thrusting, or of some combination of rifting and thrusting. These interpretations are evaluated through a comparison of the reflection data from the orogenic belt to reflection profiles across modern extensional and compressional settings.

The comparisons suggest that dipping sequences observed beneath underthrusted shelf strata in the Appalachian foreland may represent strata deposited between tilted fault blocks, analogous to Mesozoic half-grabens observed beneath post-rift strata on the modern Atlantic margin of the United States. On the basis of the geometry of these dipping reflection sequences, it is possible to distinguish late Precambrian rifting normal faults from normal faults related to Paleozoic thrust emplacement.

Beneath more interior portions of the southern Appalachians and Ouachitas, seaward-dipping reflection sequences occur along a prominent (positive seaward) Bouguer gravity gradient. The gravity

gradient has in a general sense been related to the seaward extent of (late Precambrian) North American continental basement. Previous interpretations suggest that the seaward-dipping sequences are structural in origin, perhaps due to: a) stacking sedimentary strata and basement against the edge of continental crust as a series of imbricate thrusts; or b) a lithosphere penetrating "root zone" representing not the actual, but the truncated edge of continental crust. The comparisons in this study suggest an alternative interpretation, in that the seaward-dipping sequences are similar in seismic appearance to that of wedge-shaped sequences commonly observed in the narrow zone separating continental from oceanic basement on many modern passive margins. The implication of this new interpretation is that the actual continent/ocean boundary related to the earlier rifted margin of North America may be preserved on the lower thrust plate beneath interior portions of the Appalachians and Ouachitas.

AN EXPANDING SPREAD EXPERIMENT DURING COCORP FIELD OPERATION IN UTAH

Char-Shine Liu, Tian-Fei Zhu, Harlow Farmer, and Larry Brown
Department of Geological Sciences, Cornell University, Ithaca, NY 14853

COCORP expanding spread profile (ESP) data collected in the Sevier Desert, west-central Utah, provide a good opportunity to evaluate the logistic and scientific merits of improving velocity estimates through increasing shot-receiver offset. The ESP experiment was designed as a feasibility test of employing unmodified COCORP reflection profiling equipment to collect a longer than normal range of seismic reflection data. A maximum offset of 32 km was attained. Various processing techniques such as frequency filtering, pulse-deconvolution, velocity filtering, trace editing, etc. were applied to improve the signal-to-noise ratio. Assuming no horizontal velocity variation, two different approaches were used to extract vertical velocity changes from five distinct reflection events. The first approach is the classical T^2-X^2 method, i.e. the stacking velocity for each travel time curve was derived from linear least-squares fits to T^2-X^2 data. By increasing the offset to more than three times the maximum offset distance of the normal COCORP reflection survey, theoretically (Al-Chalabi, 1974) the standard deviation of the stacking velocity derived from ESP data should be 15 times smaller than that determined from normal reflection profile geometry for the deepest event (at 11.2 sec two-way vertical incidence time). However, as offset increases, traveltimes deviate further from the hyperbolic trajectory assumption and the difference between stacking and RMS velocity also increases. In order to obtain a more accurate interval velocity, we have used Al-Chalabi's method (1974) to remove the bias between the stacking velocity and the RMS velocity. Interval velocities were then calculated from the RMS velocities using Dix's equation. The second approach is a travel-time inversion technique. The velocity structure was determined from travel time data by constrained linear least-squares inversion using a 2-D finite element model. The velocity structures derived from these two independent approaches are very similar. Both results indicate that the Sevier Desert Detachment lies at about 5 km in depth, and the depth of Moho is about 30 km.

This expanding spread experiment indicates that medium-range ESP data can be collected by present COCORP equipment with modest effort and minor interruption of the normal production work. The wider range of offset available in an ESP can improve the accuracy of velocities estimated from reflections. However, it must be remembered that inversion of ESP data in the presence of horizontal structure in the crust can be complicated to the point of degrading the usefulness of resulting velocity estimates. Furthermore, the usefulness of an ESP depends strongly on its location and the nature of the geological problems involved. Therefore it should be designed after initial profiling. In reconnaissance work, ESP data are probably best collected along selected crosslines parallel to strike, insofar as it can be determined.

CRUSTAL THICKNESS AND VELOCITY STRUCTURE IN THE SOUTHERN APPALACHIANS

LONG, Leland Timothy and Jeih-San Liow, School of Geophysical
Sciences, Georgia Institute of Technology, Atlanta, GA 30332

The southern Appalachians, including the Great Smoky Mountains, are the largest mountain mass in the eastern United States. The extent of their topographic load and associated isostatic compensation is an essential ingredient in understanding the tectonics of their implacement, as well as their role in contemporary intraplate seismicity and tectonics. The COCORP Appalachian transverse in eastern Tennessee remarkably shows relatively little verticle distortion in the thrust plane. On the other hand, estimates of crustal thickness from gravity and seismic refraction studies imply significant topographic relief at the base of the crust. Refraction lines parallel to the Appalachians give a velocity of 6.13 Km/sec with no indication of a significant 6.7 km/sec deeper layer. This observation is in contrast to refraction data to the west of the Appalachian Mountains which show distinct areas of 6.7 km/sec crustal velocities. The total thickness of the crust varies from 30 km in west-central Alabama to greater than 55 km under the Smoky Mountains.

Deep Reflection from the Caledonides and Variscides west of Britain and comparison with the Himalayas

D H Matthews, Cambridge University, Dept Earth Sciences, Bullard Laboratories,
Madingley Rd, Cambridge CB3 0EZ

BIRPS - British Institutions Reflection Profiling Syndicate - works on the wide continental shelf around Britain, using seismic contracting and processing companies. We spend about half a million dollars per year and have support from Shell UK who have done all the migration so far. All our data is released within a year of acquisition. Since starting in 1981 we have acquired 3000 kms of data, almost all west of Britain, along lines which cross perpendicularly the Caledonian (c550-400MY) and Variscan (c360-300MY) continental collision structures. In 1984 we are working in the northern North Sea. On land in Britain, the Geological Survey have shot c160 km using vibrators.

Experience from MOIST, WINCH and SWAT lines, interpreted in the light of geological mapping, drilling and refraction data, enables us to sketch a typical record. This shows a sedimentary basin down to 2 or 3 seconds and containing mesozoic and tertiary rocks, and an apparently layered lower crust extending from about 6 seconds (about 20 km) down to the Moho at about 10 secs (about 30 km). We have traced major Caledonian thrusts down from the surface to their termination in the layered lower crust, and major sub-crustal dipping reflectors which extend from the lower crust down towards the base of our sections at 15 seconds two-way time. All the thrusts that we have seen cutting the crystalline basement have been reactivated as normal faults during the stretching events associated with the opening of the Atlantic and have sedimentary basins in their hanging walls. In the south, subsequent compression has folded these basins. Despite all these ancient fault movements, the reflection time to the Moho remains essentially constant, which has implications for velocity/density relations in crustal rocks. To look at the effects of present day continental collision one must go to the Himalayas, where French-Chinese work has recently suggested imbrication, by thrusting, of the two brittle layers in the lithosphere: one in the upper crust, the other in the uppermost mantle. This is just where BIRPS has imaged thrusts.

We plan to profile across continental collision zones elsewhere in the world. We are working on two major problems, how can we measure velocities at sea with resolution comparable to that with which we can obtain the structure, and by what quirk of physics do we obtain reflections from faults that cut high grade metamorphics? Both problems demand amplitude modelling techniques.

SEISMIC CONSTRAINTS ON THE CONTINUATION AND THE NATURE OF THE SNAKE RANGE DECOLLEMENT BENEATH SPRING VALLEY, NEVADA

MCCARTHY, J.; Geology Department, Stanford University, Stanford, CA. 94305

The Northern Snake Range Decollement (NSRD) in eastern Nevada represents an extremely sharp break between brittlely and ductilely deformed rocks in the Northern Snake Range. Within most of the Snake Range, the NSRD is subhorizontal and outcrops along the top of the Lower Cambrian Pioche Shale. In the westernmost exposures, however, the NSRD bends abruptly and dips 20-30° westward beneath Spring Valley. In this area, lower plate strain diminishes rapidly, the NSRD cuts down section to the west, and the decollement is offset by several small normal faults. 20 km to the west, in the Schell Creek Range, normal faulting has also resulted in significant extension, but no ductile deformation has been observed. Lower Cambrian and Precambrian units, which reside in the lower plate of the Snake Range, are brittlely faulted in the Schell Creek Range and there is no sign of the westward continuation of the NSRD.

A 128-fold sign bit seismic line, shot across Spring Valley between the Snake and Schell Creek Ranges, clarifies the structural relationship between these two adjacent mountain ranges. On the eastern portion of the seismic line a poorly imaged reflector, dipping ~25°, can be traced from the surface outcrop of the NSRD, westward. This reflector is offset by several 50-60° dipping normal faults before dying out beneath the deepest portion of the basin. Thus the seismic continuation of the NSRD cannot be traced beneath the eastern flank of the Schell Creek Range, implying that extension is being carried on at deeper structural levels. A deeper, and more steeply dipping (35°) band of reflectors also extends from shallow depths beneath the western flank of the Snake Range westward to depths of ~15 km. This highly reflective band may represent a stepping down of the decollement to deeper structural levels.

A highly reflective zone of mid-crustal reflectors is prominent beneath much of Spring Valley. This zone is subhorizontal and begins at ~15 km depth. The strong mid-crustal reflectivity presumably corresponds to the the location of the present day brittle-ductile transition beneath the basin.

Gravity modeling, rock velocity calculations, and migration and depth conversion of the seismic reflection profile are all presently underway and should provide addition constraints on this preliminary interpretation of the structure and the nature of the NSRD beneath Spring Valley.

DEEP REFLECTION SEISMIC STUDY ON THE EAST-WEST ANTARCTIC BOUNDARY

L. D. McGinnis and R. H. Bowen

One hundred kilometers of 24 channel seismic reflection profiling in McMurdo Sound indicates layered reflectors that dip steeply away from the coast. Layered reflectors are thought to be equivalents of Paleozoic metagraywackes and marbles outcropping in the dry valleys. Flat-lying, large amplitude reflectors at seven to eight seconds, two-way travel time, lie below the dipping reflectors and are thought to represent the Moho. Assuming a mean velocity of 5.9 km/s to reflectors at 7 seconds, as obtained from refraction data in the Sound, a depth of 20.7 km is determined for the shallowest flat-lying reflector. A depth of about 21 km to Moho suggests that the Sound is thinned relative to all other areas in Antarctica. A thinned crust, high heat flow, active volcanism, and listric faulting suggest that the east-facing Transantarctic Mountains are in the process of rifting. Whether or not this suggests the Ross Embayment segment of Antarctica is the next likely candidate of the original Gondwanaland to drift northward is a question open to speculation. Until further information is obtained on the rheology of the asthenosphere beneath the Ross Embayment, it cannot be ascertained whether the McMurdo Sound Rift will reach full maturity or if thermal excesses will be dissipated with the rifting phase becoming incipient.

THE CONTINENTAL CRUST IN CENTRAL EUROPE AS BASED ON DATA FROM REFLECTION SEISMOLOGY

R. Meissner

Institut für Geophysik der Universität Kiel
D-2300 Kiel

At present data sets from seven steep-angle reflection profiles in the Variscides of Central Europe are available while the first (preliminary) data from the French ICORS and the German DEKORP-project are still in the processing stage. Besides some CDP-investigations and the usual reflection profiling with a 6 tc 8 fold coverage also some especially long spreads of up to 23 km were tested during a velocity investigation of a geothermal area. So far, explosives were used for our studies in order to provide the additional collection of wide-angle data by means of portable refraction stations. Zones of positive velocity gradients in the uppermost 8 to 10 km, at the base of the crust, and in the uppermost mantle were reveiled by the wide-angle observations. Steep-angle reflection surveys, on the other hand, were concentrated on geologically outstanding structures. They provided a much better resolution of the structure of the crust and - by using appropriate spread lengths - could also map the parameter velocity better than the DSS-surveys could do (certainly no surprise to exploration geophysicits).

In addition to fine structure and velocity a special investigation of the reflectivity of the Variscan crust was carried out and compared with data from COCORP and BIRPS. Although different seismic sources were used for these investigations a systematic change of reflectivity from the old shield areas to the younger, thinner and more differentiated crusts of "Caledonia"and Variscan origin can be observed. Two mechanisms are suggested for the highly differentiated and thin Variscan crust: An interstacking of shallow continental platelets consisting mainly of material of the upper crust with a strong crustal shortening during the compressional phases, and a strong thermal event which produced melting of the lower part of the crust creating light, low-velocity, granitic-rhyolitic melt and a ultramafic residue. While the upper crust with its low velocity and with vertically dominated intrusions is thickened, the ultramafic residues become part of the uppermost mantle, hereby reducing the total crustal thickness. The final outcome of the Variscan (and Caledonian) orogeny is a thin and strongly differentiated crust with a strong reflectivity concentrated on the lower crust in a zone of strongest velocity gradients (or jumps). In contrast to the reflectophile horizontally stratified and low viscous lower crust the upper reflectophobe crust is dominated by vertically oriented intrusions in a hihgly-viscous surrounding.

The Results of a Wide Angle Reflection Survey Across the Ottawa-Bonnechere Graben: Evidence for an Inactive Rift in the Precambrian.

R.F. Mereu, Department of Geophysics, University of Western Ontario
London, Ontario, Canada, N6A 5B7.
Dapeng Wang, Department of Geophysics University of Western Ontario
London, Ontario, Canada, N6A 5B7.
O. Kuhn, Department of Geophysics ,University of Western Ontario,
London, Ontario, Canada, N6A 5B7.

During the summer of 1982 the Canadian Consortium for Crustal Reconnaissance using Seismic Techniques (COCRUST) conducted a major long range seismic refraction and wide angle reflection experiment across the Grenville Province of the Canadian Shield. Three seismic lines each approximately 300 km in length were located (i) along the Ottawa-Bonnechere Graben, (ii) perpendicular to the Graben and (iii) perpendicular to the Grenville Front. The latter two lines ran from Marmora ,Ontario to Val D'Or in Quebec. Geological evidence indicates that the Graben may have originated from a failed arm of the St. Laurence rift system, and the Grenville Front marks the boundary between the Grenville Province and the much older Superior Province. Other geological subdivisions of the Grenville province which were traversed by the profiles are the Central Metasedimentary Belt, the Ontario Gneiss zone and the Quebec Gneiss zone. The region between the Graben and Grenville Front is also marked as an area of high seismicity. The analysis of the data involved the use of conventional-travel time analysis coupled with the use of synthetic seismogram analysis using programs which were written to handle lateral heterogeneous structures with lateral gradients.

The results showed that the upper crust just north of the Graben is characterized by a wedge low velocity material (6.0 to 6.3 km/s) a few km in thickness. This is in sharp contrast to very high velocity material (6.4 to 6.5 km/s) across the Central Metasedimentary belt south of the Graben. Little evidence was found for any significant intermediate discontinuity such as the CONRAD. Wide angle reflection observations from the Moho indicate that the Moho is very disturbed and poorly defined along the length of the Graben. There is very strong evidence for a rise in high velocity material at the base of the Graben which gives added support to the theory that the Graben is a rift-like structure. The Moho is very well defined as a sharp discontinuity both to the north and south of the Graben. There is very strong evidence for a significant thickening of the crust of approximately 5 km directly beneath the Grenville Front. This gives added support to the geological theories that the Front is a major tectonic feature which may have had its origin in a continent-continent type collision. The wide angle reflection data also indicates that the boundary between the Central Metasedimentary Belt and Ontario Geiss zone has a deep-seated expression on the Moho.

C. Morelli

DEEP CRUSTAL KNOWLEDGE IN ITALY

From 1956 to 1982 extended DSS surveys have been performed in Italy under the auspices of the Consiglio Nazionale delle Ricerche and of the European Seismological Commission (IASPEI). They were on quite different tectonic domains, both on land and sea (orogens : Alps and Apennines; island arcs: Tuscany, Calabria; thick sedimentary basins : Po Plain, peri-Apenninic basins; rifting: Sicily Channel; paleo-rifting: Ligurian sea, Sardinia; oceanic crust: Tyrrhenian sea). In particular, the Apenninic domain is the area where geology discovered in the years'30 that overthrusts are the dominant feature (the terms "olistostrome" and "olistolith" have their origin here).

The main results are :

- different crustal typologies (both on the continental and in the oceanic domains);
- crustal doubling all around the Adriatic microplate;
- extended Moho faulting along the axis of the Apennines, from the Po Plain to Calabria;
- deep vertical Moho fault in the Larderello geothermal area (~ 10 kms throw).

A deep reflection program is in preparation.

CONTINENTAL REFLECTION PROFILING IN AUSTRALIA

F J MOSS AND S P MATHUR

Bureau of Mineral Resources, Geology & Geophysics, Canberra, ACT, Australia

The Bureau of Mineral Resources (BMR) has conducted experiments to record deep seismic reflections in Australia since 1957. Prior to 1976 the deep reflection data was obtained mainly by extending the recording time on a few analogue records from sedimentary basin surveys. In the late 1960s more comprehensive deep reflection investigations were made in the Precambrian Willyama Block and Palaeozoic Tasman Geosyncline in southeastern Australia, in the Amadeus Basin in central Australia and in the Archaean Shield in southwestern Australia.

After the introduction of digital recording and processing techniques in 1976 a number of single and 6 fold CDP profiles up to 15 km long were recorded at several sites in eastern and northern Australia. Since 1980 efforts to record deep reflections have increased significantly with over 1400 km of 6 fold CDP recordings to 20 s having been made along a number of long traverses crossing the main structural elements of the central Eromanga Basin in eastern Australia.

Fair-to-good quality reflections were recorded on the early analogue records, mainly between 8-13 s reflection time. Numerous events were generally recorded on each record; these have varying and conflicting dips making it difficult to determine which events should be correlated with the Moho and discontinuities within the crust. However, analysis of the reflection data together with large-scale refraction and regional gravity information, provided evidence of a major mid-crustal discontinuity over much of Australia; this horizon shows greater depth variations than the Moho. In addition the early recordings have provided a preview of the quality of the data which may be expected throughout Australia from more comprehensive surveys.

Reflection segments are seen to have variable strength, continuity, dip and spatial distribution on the short continuous profiles. Although these profiles are generally too short to provide detailed information on horizontal variations in deep crustal structure significant differences can be seen in the characteristics of deep reflections recorded in Phanerozoic and Precambrian domains; these are not readily seen on the early analogue records. The Phanerozoic crust is up to 43 km thick, equivalent to a reflection time of up to 13 s, with high amplitude, coherent, reflection segments up to 3 km long concentrated in distinct bands in a time range of 1 to 4.5 s in the lower crust. The Precambrian crust is about 50 km thick, corresponding to a reflection time of about 16 s, with low amplitude reflection segments up to 1 km long generally even ly dispersed throughout the deep crust.

Crustal reflection sections obtained from the long traverses in the central Eromanga Basin area can be divided into four main zones. The zone between 0 - 2.5 s shows fairly uniform, coherent and continuous events associated with the Mesozoic and late Palaeozoic sequences. The zone from 2.5 - 8 s, corresponding to depths from about 4 - 22 km, shows no primary reflections. This zone contains highly deformed rocks of the Early Palaeozoic Thomson Orogen. In contrast, a deep crustal zone of numerous prominent reflection segments between 8 - 12.5 s is interpreted to contain thin laminae of alternating low and high velocity, intermediate and basic, rocks correlating with the lower crust defined by refraction velocity discontinuities. The zone below 12.5 s is reflection-free and is interpreted to correspond to the seismically - homogeneous upper mantle.

An Australian Continental Reflection Profiling Program (ACORP) has now been initiated in which governments, academic institutions and industry will co-operate on surveys involving approximately 1000 km of deep reflection profiling each year. The ACORP work will be the focus of a major program of Lithosphere Transect Studies of the Australian Continent (LITSAC) over the boundaries of major tectonic provinces and structures within these provinces which are relevant to metallogensis or petroleum occurrences. Supporting studies will be made in stratigraphy, structure, petrology, geochemistry, seismic refraction, magnetotellurics, gravimetry, heat flow and palaeomagnetism.

The BMR will play a major role in the ACORP program. It will be mainly responsible for the seismic data acquisition and a new large-scale seismic data processing centre being set-up at the BMR will be available for processing the ACORP data and for associated research. The BMR will record a deep reflection profile in 1984, extending a central Eromanga Basin line to the coast in eastern Australia: the combined length of this profile will be 1200 km - the longest in Australia.

LONG-RANGE SEISMIC REFRACTION PROFILES IN EUROPE

Stephan Mueller
Institute of Geophysics, ETH-Hönggerberg
CH-8093 Zürich, Switzerland

Long-range seismic explosion observations have provided the means to elucidate fine details of the velocity-depth structure in the uppermost part of the mantle. There are now several profiles available in Europe, each about 1000 km in length with station spacings of 4 to 10 km. One long-range profile traversing the Baltic Shield was nearly 2000 km long. Good crustal control along all the profiles made it possible to resolve even minor changes in structures at depth.

A very consistent pattern of consecutive travel-time branches was found for all the profiles. It consists of 3 to 4 separate pairs of prograde and retrograde phases which can be correlated in addition to the P_n - P_MP system. An iterative inversion scheme was used to deduce a velocity-depth structure compatible with the observed travel times and amplitudes.

The lower lithosphere down to a depth of 140 km consists of four alternating high- and low-velocity layers with pronounced contrasts in velocity and strongly varying layer thicknesses. At depths below 140 km the velocity structure becomes much smoother. The top of the mantle transition zone under Scandinavia was found at a depth of 440 km, with an average P-velocity of 8.75 km/s in the depth range from 140 to 440 km. Only two less extended high-velocity zones (with a maximum velocity of 9.1 km/s) could be identified in that depth range. The presently available data do not allow to delineate structural features of less than about 5 km in thickness.

Reflection profiling of the lower crust in the Basin and Range: Dixie Valley, Nevada

David A. Okaya
Department of Geophysics
Stanford University
Stanford, California 94305

Seismic profiling of the lower crust has primarily been achieved by deep seismic programs such as COCORP. However, given certain source conditions, shallow industry data may be converted to image the lower crust. Recorrelation of unstacked field records to longer travel-times is possible provided 1) a Vibroseis* source was used; 2) the sweep was composed from low to high frequencies (upsweep); and 3) the original uncorrelated field records are available for reprocessing. Recorrelation may be performed using a sweep of fixed frequency bandwidth or a "self-truncating" sweep whose frequency content diminishes with time.

Twenty-two kilometers of seismic data in Dixie Valley, Nevada were collected using a linear 12-second, 12-65 Hz Vibroseis upsweep and a 16-second recording period, resulting in profiles of four seconds duration. Recorrelation to 12 seconds is accomplished using a "self-truncating" sweep. The upper bandwidth frequency ranges from 65 Hz at 4 seconds to 30 Hz at 12 seconds.

Conventional CDP stacking of the recorrelated data reveals many short, sub-horizontal reflections present in the intermediate to deep crust. Presence of reflected energy in the field records suggests the stacked reflections are real. The presence and orientation of the sub-horizontal reflections may be explained by lower crustal compositional layering, lamination plastering, igneous intrusion, in conjunction with lower crustal stretching.

Strong Moho reflections are not visible, but an abrupt termination of the sub-horizontal reflections occurs at approximately ten seconds, suggestive of the transition from the base

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of the crust to the upper mantle. Strong laterally continuous reflections indicative of low-angle detachment zones are not present in the intermediate crust. Structural models for Dixie Valley based on the seismic profiles and other geophysical information require detachment zones, if present, to be located below the seismogenic crust.

A Global Perspective on Seismic Reflection Profiling of the Continental Crust

by Jack Oliver
Department of Geological Sciences
Cornell University
Ithaca, NY 14853

Only during the last few hundred years have humans begun to explore and comprehend the earth in a global sense. Geographical, and then geological, exploration of the earth's surface was first carried out. Next, attention was focused on the interior. Of the subsurface, only the sedimentary basins and the ocean basins have been intensively explored to date. The next frontier is self-evident. Now it is the time in history for thorough exploration of the entire continental crust.

The seismic reflection profiling technique, developed by industry for petroleum exploration, will almost certainly be the principal tool for probing the deep continental basement. It has already been clearly demonstrated by studies in many countries that this method will be productive of basic information and important discoveries. One can safely anticipate an era in which the deep crustal features of all continents are discovered, mapped, named, studied, understood, and made familiar to all earth scientists, as has happened for features of the deep sea floor within the past few decades. As they have for earlier phases, major practical benefits are certain to accompany and follow this phase of earth exploration.

Earth scientists working in this field have both the opportunity to participate in exploration of this great frontier, and the responsibility to carry out this exploration effectively and expeditiously so as to provide prompt and optimum benefit for society.

Some possible goals for this branch of science include:

1. A comprehensive reconnaissance of major crustal features by surveying grids of seismic reflection profiles spanning all continents.
2. Detailed three-dimensional studies of selected features found during reconnaissance and deemed of critical importance.
3. Further development of seismic techniques to provide optimum and economical means for study of the features of the continental basement and the underlying mantle.
4. Development of effective means of communication through exchange of data, publication, and meetings involving scientists of the many disciplines bearing on deep crustal phenomena.
5. Development of modes of cooperation for sharing facilities and expenses among countries so that a truly global survey can be accomplished.

PRECAMBRIAN CRUSTAL STRUCTURE OF THE NORTHERN BALTIC SHIELD FROM THE FENNOLORA PROFILE: EVIDENCE FOR UPPER CRUSTAL ANISOTROPIC LAMINATIONS

KENNETH H. OLSEN, Earth and Space Sciences Division, MS C335,
Los Alamos National Laboratory, Los Alamos, NM 87545, USA
CARL-ERIK LUND, Institute of Solid Earth Physics,
University of Uppsala, S-75122, Uppsala, Sweden

Because Archean heat flow was 2 to 4 times its present value, the rates and style of crustal evolution and global tectonic mechanisms during the Archean and Proterozoic (3900-600 Ma) were probably quite different than those familiar from Phanerozoic plate tectonics. In particular, the lateral scales and depths of convection and lithospheric subduction elements may have been smaller than contemporary analogs. Structures preserved in the upper and midcrustal levels of the cratonic area of the northern Baltic shield may therefore be very useful in formulating more detailed models of Precambrian lithospheric tectonics.

The northern part of the NNE-SSW-trending FENNOLORA profile traverses Precambrian basement complexes ranging in age from 1800-2800 Ma, which are adjacent to the 3600 Ma Kola nucleus. We are using reflectivity method synthetic seismogram modeling to assist interpretation of a 700-km-long segment of the FENNOLORA line running from Northcape, across portions of Norway, Finland, and Sweden, to about the Arctic circle in the south. Our Finnish colleagues have also provided, for comparison, a record section approximately perpendicular to FENNOLORA running southeastward for ~300 km across Finnish Lappland (FINLAP). Relatively close and uniform spacing (~3.5 km) of FENNOLORA station records reveals an *en echelon* pattern of

P-wave first arrivals with apparent velocities between 6.0 and 6.8 km s. The *en echelon* pattern is observable in both north- and south-trending directions from shot point G. This suggests a fine structure of the upper crust to depths ~20 km consisting of several (3 to 6) alternating high- and low-velocity layers, each about 1 or 2 km thick. On the other hand, the *en echelon* pattern *cannot* be clearly seen on the perpendicular FINLAP profile from shotpoint G, which implies some of the laminations are anisotropic with the high speed axis trending approximately north-south. One speculative interpretation is that the anisotropic layers are basaltic fragments of Archean or Proterozoic oceanic crust that were "stranded" beneath thin sialic crust by very shallow angle subduction zones.

Accretional Architecture in the Continental Crust

Robert A. Phinney Kabir Roy-Chowdhury[1] James H. Leven[2]

Department of Geological and Geophysical Sciences Princeton University

Seismic reflection sections from the Long Island Platform, from the Eromanga Basin, Australia, from the western Mojave Desert, from two COCORP Appalachian lines, and from the Newark Basin provide a variety of good examples of continental crustal architecture assembled from large tectonic packages. The Long Island data, taken in a marine survey, establish a structure for the center of the southern New England sector of the Appalachian orogen, formed by successive accretional and relaxational episodes between 450 and 240mybp. We identify a consistently layered near-horizontal complex ('Layered Moho Complex'- LMC) which appears at 10.5sec (ca. 33km), with a thickness of 0.3 to 2.0 sec, corresponding in some way to the conventional Moho. The bulk of the superjacent continental crust is seen to be composed of large tectonic packages, identifiable by the continuity of their strong internal seismic layering. The boundaries between these elongate rhomboid packages are interpreted as detachment zones which may have undergone large displacement; the detachments dip generally at low angles, ranging from horizontal to as much as 50°. Tensional basins in the top of the basement are formed on faults which continue at depth into these tectonic boundaries.

We propose this section as a paradigm for the architecture of continental crust formed by lateral accretion in a plate tectonic setting. The interpretation is substantially assisted by correlation with the adjacent onshore geology of southern New England. We identify the internal packages as domains accreted to the crust during periods of compression. The LMC is, in our interpretation, a fossil detachment zone at the top of a subducting slab, and breaks in the LMC are discontinuities between different slabs. The effects of relaxational or tensional episodes are identified by the reactivation and flattening of package boundaries. Large upper crustal domains showing weak or no reflections at all are interpreted as steeply folded supracrustal packages of sedimentary and volcanic origin.

The other lines which we discuss are land lines, with somewhat lower signal/noise ratio than the Long Island marine data. Using the above paradigm, we suggest interpretations of major horizontal layering and clusters of dipping events which are commonly found in land-

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[1] Visiting from National Geophysical Research Institute, Hyderabad, India

[2] Visiting from Bureau of Mineral Resources, Canberra, Australia

based deep reflection profiles. The COCORP sections in New England and Georgia both cross the transition between North American Precambrian basement and the accreted core of the Appalachian orogen. In both cases, the accreted core shows the signatures of large dipping tectonic packages, which are truncated by the LMC. These lines show, with lower signal quality, the same features which characterize the Long Island transect of the Appalachian orogen. A USGS land line across the Newark Basin in central New Jersey shows clearly that the Precambrian basement throughout this area belongs to a single tectonic package characterized by eastward dipping (45°) dislocations. We claim that the structural history of the Paleozoic and Mesozoic supracrustal sequences in this area is largely the result of reactivation, both in compression and extension, of these basement dislocations. This basement package is nearly in place with respect to Phanerozoic movements, and its position along the axis of the major gravity gradient in the Appalachian orogen suggests that it represents the eastward distal limit of Cambrian North America, and the dislocations the effect of the initial Taconic collision.

The Eromanga Basin line shows a subhorizontal, strongly reflecting complex about 2 sec thick which appears from 8-10 sec; the superjacent crust is distinctly transparent. Beneath this LMC we see a west-dipping (40°) sequence of layered reflections, which persist faintly to the limits of the section at 20 seconds. Within this, one pronounced reflection complex is very similar in appearance to the LMC and, like the rest of the dipping sequence, is cut off above by it. In this example, and using our paradigm, the entire crust above the LMC is built by extreme shortening of supracrustal materials, while the LMC serves as a detachment zone, and the subcrustal complex is tectonically accreted from the subducting plate.

The COCORP crustal section in the Mojave Desert appears to be composed entirely of tectonically accreted packages. Unlike the Appalachian case, these packages are not of full crustal thickness, but are more like 10 km thick, and are stacked two or three deep to constitute the crust. The crust is penetrated by major thrust faults, with those of 45° dip and those of nearly zero dip defining a mosaic of tectonic packages. The often-discussed Rand Mountain thrust is seen to be one of the nearly horizontal faults in the structure.

We discuss these examples in terms of a collisional or accretional paradigm for the construction of continental crust, from smaller packages of supracrustal material. Tension or spreading plays a secondary role in modifying the accreted crust. Beyond the accretional paradigm, however, it is likely that tension may be associated with the accretion from below of large volumes of new crust, perhaps in the form of gabbroic intrusives not visible at the surface. These may be commonly associated with the large overlying andesitic or rhyolitic intrusions seen in Andean-style belts.

CHARACTERISTICS OF THE REFLECTING LAYERS IN THE EARTH'S CRUST AND UPPER MANTLE IN HUNGARY

Posgay K. - Albu I. - Ráner G. - Varga G.
Eötvös Loránd Geophysical Institute of Hungary, Budapest

The paper reviews the lithospheric studies by means of the seismic reflection method carried out by the Eötvös Loránd Geophysical Institute of Hungary. Since in some places the lithospheric complex is completely revealed by the seismic section, comparisons could be made with geothermal and magnetotelluric data, which have rendered possible to conclude on the structure and physico-chemical construction of the lithosphere and on its temporal changes.

THE FORELAND THRUST AND FOLD BELT OF THE CANADIAN ROCKIES AND ITS GEOTECTONIC SIGNIFICANCE

Raymond A. Price

Geological Survey of Canada
601 Booth Street
Ottawa, Ontario KIA OE8
CANADA

ABSTRACT

The foreland thrust and fold belt, a NE-tapering wedge, locally > 20 Km thick, comprises miogeoclinal, platformal and foreland basin rocks that have been scraped off the under-riding North American plate, and attached to an over-riding tectonic collage of foreign terranes that "collided" with and became attached to North America. It is an accretionary prism that was tectonically prograded northeastward across the western margin of the North American craton in two major episodes. The outboard part of the Cordilleran miogeocline (continental terrace wedge) was over-ridden by a tectonic collage of oceanic terranes, and descended to depths of > 25 Km during mid-Jurassic prograde synkinematic regional metamorphism, before heating restored its latent buoyancy. During the ensuing Late Jurassic-Early Cretaceous collisional compression tectonic wedges of the accreted terrane were driven between the outboard part of the miogeocline and its basement, leading to outward verging thrusting on either side of a central uplift and to tectonic loading and isostatic flexure of the lithosphere beneath the foreland basin where molasse accumulated. Mid-Cretaceous granitic plutons that rose through this tectonically thickened suture zone locked the outward verging structures on both sides of it. During the second episode, accretion of another collage of oceanic terranes, outboard from the first, involved oblique, right-lateral convergence. Much of the Late Cretaceous-Paleocene overthrusting in the southern Canadian Rockies was transformed northward into right-lateral strike-slip along the Tintina-Northern Rocky Mountain Trench (T-NRMT) transform fault zone. Laramide subsidence of the foreland basin, which resulted from isostatic flexure of the lithosphere in response to loading by thrust sheets, decreased northward as thrusting was transformed on the T-NRMT fault zone. During Early Eocene time, patterns of movement changed. The T-NRMT fault zone became linked to the en echelon Fraser River fault zone by ductile stretching of the intervening lithosphere. This stretching is expressed, over an area of about 150,000 km^2 in south-central British Columbia and adjacent parts of the United States, at a shallow level, by listric normal faults and Eocene dyke swarms and, at a deep level, by boudinage of the whole crust. Supracrustal rocks moved into the necked zones between the boudins as the metamorphic core complexes emerged in northeast-trending domal culminations with K-Ar mica cooling ages of about 50 Ma. This sequence of crustal thickening by tectonic overlap and tectonic wedging within and between different lithospheric plates followed by inhomogeneous crustal stretching linked to transform faulting provides a model against which to assess the internal structure of the continental crust in other areas.

DEEP CRUSTAL SIGNATURES IN INDIA FROM SATELLITE AND GROUND GEOPHYSICAL DATA

*M.N. QURESHY, ADVISER (ES)
DEPARTMENT OF SCIENCE & TECHNOLOGY
NEW MEHRAULI ROAD, NEW DELHI-110016, INDIA

The Indian sub-continent comprises several plateaus or parts of plateaus which have escaped denudation. More prominent of these are the Malawa in north-central and Deccan in South India; rejuvenated ancient mountains - the Aravallis in Western and Satpuras in Central India; block uplifted crustal segments - the Meghalaya Massif in East and Nilgiris in South India. The young folded mountains, the Himalaya, girdle it to the north, northwest and northeast. Thus, India is broadly divided into Peninsula in the south and Extra-Peninsula in the north with the Indo-Gangetic-Brahmaputra plains in between. The four usually recognised major trend lines or structural strikes in India are the NE trending Aravalli and Eastern Ghats; NNW trending Dharwar; ENE trending Satpura and the NW trending Mahanadi. Some other trends have also been recognised.

Extension of these peninsular shield elements beneath the tertiary Deccan Traps and sand-alluvial cover of Indo-Gangetic plains was first noted in the early part of this century from gravity studies based on pendulum observations. With the increased tempo of geophysical surveys for oil exploration, detailed pattern of the subsurface extensions of these elements into the Ganga basin and beyond have come to be known.

A combined analysis of ground and satellite based geophysical data has led to the recognition of an ENE trending feature that parallels Narmada-Son Lineament and cuts across

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*Views expressed are of author and do not in any way reflect those of the Department of Science & Technology.

Central India; and the other, northwest trending falls over the Gondawana (Mesozoic) Godavari Rift in east-central India and extends into the festooning ranges of Pakistan and beyond. There are indications on the Free Air Anomaly Map of India and Bay of Bengal that this zone may extend, though feebly, into the Bay of Bengal towards Borneo. A feature of significance is the behaviour of these two zones when the satellite derived gravity field is broken into 0 - 12 and 13 - 22 harmonics. The lower harmonics show the Narmada-Son zone more prominently as a region of transition, whereas the Godavari feature is more prominent on the upper harmonics map as a "low" extending from Borneo to the Atlantic Coast. That is, the source of the NE trending feature is relatively shallower than that of the NW trending one.

A strong northwest trending gravity "high" on one degree by one degree mean Airy-Heiskanen anomaly map over the middle Himalaya cuts across the diapir like Nanga Parbat massif, suggesting a deeper source for the gravity anomaly. The lineavity of gravity contours, corroborated with the Landsat-interpreted lineaments in Himalaya and Hindukush regions, is indicative of a block-like deeper structure.

A recently recognized megalineament is the northwest trending Gandak which extends from the Gangetic delta to the Karakoram region, cutting through the Ganga basin where its existence is supported by seismic, gravity, magnetic and satellite data.

When looked in totality, the geophysically and otherwise mapped lineaments in India exhibit a mosaic-like pattern most of which, probably originated in the Precambrian, have been getting reactivited now and then.

DEEP REFLECTIONS ON COCORP MICHIGAN BASIN DATA

William J. Rogers Jr.

Donna M. Jurdy (Department of Geological Sciences, Northwestern University, Evanston, Illinois 60201)

Reflections along COCORP Michigan Basin data are of varying quality. The maximum observed reflection depth on Line 2 varies widely along the section, from as little as one second of two-way travel time to a maximum of almost seven seconds. Many reflections are laterally discontinuous, strongly present over a short distance and then only weakly, or not at all, in adjacent areas. We question whether these reflections actually result from discontinuous structures or from data processing problems. A laterally-variable, inhomogeneous layer of glacial till covers the area, making static corrections especially important. Calculating the time-thicknesses of the surface layer from refracted wave arrivals with a modified version of the Generalized Reciprocal Method, we observe that where surface layer correction fluctuates most rapidly the maximum depth of observed reflections is less than elsewhere on the section. This relationship is not absolute, however; other factors are at work as well. For example, static corrections do not explain the small area near VP 330 where the deepest reflections at 6.5 sec are located. Here, we note that the fold of the coverage along this part of Line 2 is especially high, due to changes in recording geometry. Thus, it seems probable that much of the discontinuous nature of deep reflections observed along the Michigan Basin COCORP lines is due to the irregular surface layer, while the small area of unusually deep and clear reflections is due to a small area of unusually high coverage. The structures which produce the discontinuous reflections may be of greater continuity and lateral extent than is apparent.

Enhanced Imaging of the COCORP Wind River Line

J. Sharry, R. T. Langan, D. B. Jovanovich
G. M. Jones, N. R. Hill, T. M. Guidish

Gulf Research and Development Company
P.O. Box 37048
Houston, TX 77236

The COCORP seismic lines across the Wind River Mountains were reprocessed using state-of-the-art technology to improve imaging and analysis of the lines. Topics of interest to us were: 1) the proper imaging of the toe region of the Wind River Thrust, 2) the structure of the sub-thrust sediments and their termination at the thrust, and 3) the determination of proper processing techniques for deep structure. Interactive processing software for refraction static analysis and ray tracing were invaluable aids in testing the validity of a large spectrum of velocity models. Velocities of the first refractor derived from refraction statics were combined with surface and subsurface geologic data and special depth migration techniques to produce an improved model for the toe region of the Wind River Thrust. A sharp velocity boundary at shot point 275 (Line 1) indicates the presence of a second normal fault antithetic to and northeast of the Continental Fault. The toe region is underlain by imbricate slices of the sedimentary section and an imbricate fault within the Precambrian granite can be imaged. True amplitude processing and longer AGC windows (greater than 3000 ms) in the final processing step result in improved imaging of the deeper events. Deep reflectors (11 sec.) beneath the Green River Basin are correlated with other events beneath the Precambrian core of the Wind River Mountains suggesting that these events are not multiples. The strong amplitudes of these events and lack of multiple signatures on autocorrelation diagrams support this interpretation.

Extremely critical to the proper imaging and interpretation of the thrust is the projection of the data onto a proper dip line. The COCORP line runs approximately N54E. Gravity data (Hurich and Smithson, 1982) indicate that the dip direction of the Wind River Thrust in the vicinity of the seismic line is N22E. The shot records were projected onto the dip line with corrections for NMO and offset distance. This results in compression of events on the dip projected CDP section when compared to the regular CDP section. The resulting data were both depth and time migrated.

Crustal Reflections and Crustal Structure

Scott B. Smithson, Roy A. Johnson, Charles A. Hurich, and David M. Fountain,
Department of Geology and Geophysics, Program for Crustal Studies, University of
Wyoming, Laramie, Wyoming 82071

A new more detailed resolution of crustal features is expected and is being attained through application of reflection seismology to crustal structure. The source of crustal reflections, particularly ones that can not be tied to surface geology, still remains a major question. The general conclusion that deep reflections indicate crustal heterogeneity, while valid, needs to be carried much farther. Seismic modeling indicates that structures typical of the crystalline crust will have a complex reflection response, commonly a series of complex convex-upward hyperbolas. Such events are relatively rarely observed crustal reflection data, and when they are, may selectively originate from synformal structures.

Recent studies demonstrate that the best crustal reflections in deformed crystalline crust originate from ductile deformation zones (mylonites). The reasons for mylonite reflectivity are: 1) layering and thickness, 2) relatively planar geometry, 3) fabric, 4) chemical alteration. Simple considerations show that layering produces reflections several times stronger than a single interface of the same contrast in acoustic impedance. A composite reflection attributed to the Wind River thrust fault was the first suggestion that deep fault zones might be reflective; however, shallow faults are typically not reflective. Other areas such as the Outer Hebrides, Sevier Desert, and South Appalachians seem to produce seismic reflections from fault zones. This reflectivity may be caused by fabric that lowers velocity in a mylonite compared with its protolith and by layering in a mylonite. The final proof of mylonite reflectivity has been demonstrated by our recent seismic profiling over a 3-km thick mylonite dipping gently off the east flank of the Kettle dome, a core complex. Reflections that project to the surface outcrop of the mylonite are so abundant as to resemble reflections from a sedimentary succession. Mylonite zones may pass into zones of homogenous distributed strain in the lower crust where ductility increases. Good reflections from mylonite zones allow the seismic definition of such major structural features as crystalline nappes and recumbent folds, crustal doubling, sutures, crustal extension on listric faults, and exotic terrains in COCORP and other crustal-reflection data sets.

In low-to medium-grade metamorphic terrains dips are commonly steep. An interesting paradox is provided by reflection data which shows a number of reflectors with low dip commonly just a few kilometers beneath the surface. These reflections together with geologic observations in deep terrains suggest that steep dips at shallow levels of the crystalline crust pass into sub-horizontal dips in the deep crust although these sub-horizontal structures typically have open folds superposed on them. Archean terrains including greenstone belts show evidence of thrusting, recumbent folds, and other gently dipping structures. This suggests that plate motions were important in the late Archean and that greenstone belts are related to tectonic regimes that were at least compressive during part of their history. Granite batholiths may show reflections from beneath their floors but possibly not from their floors, themselves. This demonstrates that crustal heterogeneity is maintained at a seismic scale after intrusion. Crustal underplating by mafic magma may be associated with subsidence and basin formation.

Overall composition of continental crust is quartzo-feldspathic. This composition and structure described above is attached through interaction of exogenic and endogenic processes.

BIRPS CRUSTAL REFLECTION ON THE CALEDONIAN FORELAND AND THE DEVELOPMENT OF THE PASSIVE MARGINS OF NW EUROPE

David K. Smythe

British Geological Survey, 19 Grange Terrace, Edinburgh EH9 2LF

United Kingdom

The BIRPS MOIST and WINCH profiles show that the Caledonian foreland crust and upper mantle northwest of Scotland is cut by major eastward-dipping thrusts, some of which have been reactivated as normal faults.

Farther west, the Rockall Trough is a 250 km wide oceanic rift within the foreland. It represents the first of several abortive attempts at opening of the North Atlantic. Much of the deep structure of the trough is masked by thick Tertiary basalts, but at two localities on the conjugate margins, newly-reprocessed, old industry reflection data reveal that the continent-ocean transition on both sides is marked by westward-tilted continental blocks bounded by eastward-dipping low-angle normal faults. By analogy with the continental shelf of Scotland, these faults are probably reactivated intra-foreland Caledonian thrusts.

Such thrusts may also have controlled the development of the younger (Cretaceous and Tertiary) passive margins west of Rockall, and may explain why the very old continental lithosphere in the North Atlantic is apparently weaker and more easily rifted than very young oceanic lithosphere.

CRUSTAL STRUCTURE STUDIES IN NEW ZEALAND

Tim Stern

Geophysics Division, D.S.I.R.

P.O. Box 1320

Wellington

New Zealand

New Zealand is an area of continental crust through which the Indian-Pacific plate boundary passes. The character of the boundary within the North Island of New Zealand is one of convergence and subduction so that crustal structure here is controlled by a classical configuration of accretionary prism, fore-arc basin, volcanic arc and back-arc spreading basin. Crustal thickness and seismic velocities within the North Island show a wide range of variation. Seismic studies indicate a 15 km crust underlain by a 7.4 km/s upper mantle within the back-arc areas of the North Island and a crustal thickness of about 40 km, with associated upper mantle velocities of 8.0 - 8.5 km/s, within the fore-arc areas. Recent off-shore work has included a multichannel seismic reflection study across the accretionary prism to the east of the North Island.

In the South Island of New Zealand the boundary is largely transform and the crustal structure is dominated by the associated shear between the two plates. A seismic refraction survey at the Fiordland margin (southwestern coast of the South Island) shows continental rocks of 6.8 - 7.3 km/s at depths of 4-8 km. Also associated with the Fiordland margin is a 400 mgal peak to peak dipolar gravity anomaly. Both the gravity and seismic data can be reconciled with a model of upthrust continental crust juxtaposed against oceanic lithosphere.

THE QUEBEC-WESTERN MAINE PROFILE: FIRST YEAR RESULTS

DAVID B. STEWART

U.S. GEOLOGICAL SURVEY, NATIONAL CENTER 959

RESTON, VIRGINIA 22092 USA

The Quebec-western Maine seismic reflection profile is a cooperative project of the United States Geological Survey, Geological Survey of Canada, Canadian Earth Physics Branch, Maine Geological Survey, and several National Science Foundation-supported collaborators at universities. The goals are to perform research on methodology and produce state-of-the-art geologic interpretations of a nearly continuous reflection profile across the Appalachian orogen from the craton to the seacoast. A separate cooperative marine investigation will extend the profile from the seacoast to the continent-ocean margin.

During 1983, 219 km of 800-channel sign bit data were collected for 15 seconds 2-way travel time with VIBROSEIS sources and variable sweeps from 7 to 45 Hz, using a 12 km-0-12 km spread and 30-m group intervals. The resulting profiles have nominal 133 fold, and numerous reflectors can be seen. Extensive geologic, gravity and magnetic data are being gathered and utilized to assist interpretation of the reflection profiles.

The first 12 km of the northwesternmost profile (line 1) parallels profile 2001 of Ministère de l'Énergie et des Resources, Québec (MERQ) that was interpreted by P. St.Julien for SOQUIP, and lies 11 km southwest of it in Quebec so that correlation of shallow reflections is possible. The new profile trends southeast and south for 75 km nearly normal to regional strike, and crosses from Silurian and Devonian sedimentary rocks into Precambrian(?) Chain Lakes massif near the Canada-United States border, remaining on this massif for approximately 42 km. A prominent reflector dips gently southeast across the entire profile from a depth of about 3.5 seconds (2-way) in the northwest to about 7.8 seconds at the south end; this major regional feature, although has not yet definitively interpreted, may be a complex decollement. Numerous other reflectors at various depths up to 12 seconds are also observed. Another 30-km-long northwest-southeast profile (line 2) crossing the south end of the first profile has not yet been processed adequately for interpretation. This profile traverses from the Chain Lakes massif into Cambrian and Ordovician strata.

A third new profile (line 3A) begins about 19 km northeastward along regional strike and passes southeastward over several Devonian gabbro and granite batholiths for about 50 km and then goes 16 km normal to the regional strike of medium grade metasedimentary rocks on the northwest flank of the Siluro-Devonian Merrimack synclinorium. A fourth new profile (line 3B) is normal to the regional strike of the Coastal Volcanic Belt for 47 km and reaches the Maine seacoast east of Penobscot Bay. On both of these profiles the bottoms of plutons, several steep faults, and many as yet uninterpreted reflectors as deep as 11 seconds are observed.

During the period 1984-85 about 110 km of deep reflection profiles between profiles 3A and 3B will be collected across the Merrimack synclinorium and the major faulted antiforms along the southeast margin of the synclinorium. An extensive seismic refraction study in Maine and Quebec using dedicated explosions is planned for 1984 to aid in interpretation of the seismic reflection profiles.

THE DEEP CRUST IN CONVERGENT AND DIVERGENT TERRANES: LARAMIDE UPLIFTS AND BASIN-RANGE RIFTS

George A. Thompson
Department of Geophysics, Stanford University
Stanford, California 94305

Although deep seismic reflections resolved the problem of Laramide uplifts in favor of horizontal compression, the transition in mechanical processes from shallow folding to deep thrusting and to still deeper ductile deformation is still poorly understood. The Pacific Creek (PC) anticline in western Wyoming demonstrates the linkage between basement thrusting and a buckled, nine-kilometer-thick sedimentary section which is unfaulted except near its base (MacLeod, 1981). Parallel and east of the PC thrust is the great Wind River (WR) thrust zone. It is seen in migrated COCORP data to splay and flatten to a depth of about 32 km; it underlies both the WR Range and the western WR Basin (Lynn, 1979; Lynn et al, 1983). The curvature (listric flattening) of the fault, first seen in the depth-migrated reflection section, is independently required to explain the tilting of the range and adjacent basin, i.e. the curvature, in conjunction with the known displacement, quantitatively fits the amount of tilt. Of still broader significance, subhorizontal reflectors in continental crust may have originated in the nearly flat deepest parts of fault zones.

The Casper Arch, east of the WR basin, was studied in reflection data made available by the Gulf Oil Co. (Hill and Garing, unpublished). The arch is characterized by monoclines in the sedimentary section, which are underlain by thrust faults in the basement dipping both eastward and westward. Like the PC and WR thrusts, these thrusts tend to flatten with depth in the basement, but the reflection data allow them to be followed to only moderate depths. Presumably, below the seismogenic basement, at depths that are dependent on temperature, composition, and rate of deformation, the thrusts enter a more ductile regime and may become subhorizontal like the WR thrust.

The divergent terranes of the Basin and Range (BR) province and Rio Grande Rift (RGR) also show striking transitions in mechanical processes with depth. There the brittle behavior, expressed in tilted and sunken fault blocks, extends from the surface to depths that are much shallower than in convergent terranes (5-15 km vs about 30 km). At these depths high-angle normal faults give way abruptly to subhorizontal detachment faults, below which ductile deformation is prominent. The geometry of normal faults (e.g. Thompson, 1960, 1974), deep geologic exposures (e.g. Proffett, 1977; Miller and Gans, 1983), the depth range of earthquakes, and especially the new reflection data provide strong evidence for this conclusion. In the RGR, depth-migrated COCORP sections (Cape et al.,1983) demonstrate that the high angle, basin-bounding normal faults exposed at the surface extend no deeper than about 5 km, where they flatten and join subhorizontal reflections. The Utah COCORP data (Allmendinger et al., 1983) found similar relationships except that detachment faults are gently inclined and extend to depths of about 15 km.

In divergent terranes the abrupt transition from a brittle, highly faulted, upper plate to a ductile lower plate with laminated subhorizontal reflectors may be explained by a high geothermal gradient maintained by intrusions into the lower and middle crust and by hydrothermal quenching in the upper crust. Ductile and depositional self-sealing are probably important below the zone of easy hydrothermal convection. In both convergent and divergent terranes the stress field is perturbed where the heels of coherent upper crustal blocks rest upon the ductile transition, and this perturbation may help to explain the subhorizontal character of deformation zones which are prominent in reflection data. The thermal, hydrologic and inhomogeneous deformation processes, shifting through time, have imposed a laminated character on vast volumes of continental crust.

THIN-SKINNED TECTONICS OF THE CARPATHIAN ARC AND THE BOHEMIAN MASSIF REVEALED BY SEISMIC REFLECTION PROFILING

Č. Tomek, Geofyzika n.p. Brno, P.O.Box 62,
61246 Brno, Czechoslovakia

Interpretations of structural geology of the West Carpathian arc and the eastern part of the Bohemian massif may be now highly influenced by crustal reflection data.

Five seismic-reflection profiles (each 30-80 km long) have been recorded using dynamite technology and showing an allochtonous sheet of the Mesozoic and Cenozoic Carpathian flysch and Pieniny klippen belt rocks which has overthrust Precambrian crystalline basement of Brunnia (somewhere also with Hercynian allochton!) over a distance of larger than 70 km. Other fragmentary reflection data and supporting gravity and magnetotelluric evidence show that the Precambrian crystalline rocks of Brunnia can be traced at least 100-120 km from the Carpathian external boundary. The allochton is extremely thin (500-1000 m) and only slightly deformed in the first 20 km from the boundary. Southeastwards, the Precambrian autochton rapidly falls to a depth of 10-12 km 40-60 km from the boundary and becomes horizontally stable after that. It therefore appears that the concept of thin-skinned tectonics may be applicable to the flysch and Pieniny klippen deformed sedimentary rocks and to the northern part of the inner Carpathian crystalline and Mesozoic rocks. Parallel seismic refraction lines crossing the whole West

Carpathians show horizontally lying Moho at depth of about 35 km beneath both, the thin and thick allochtons. This implies that the Carpathian were thrust during upper Oligocene and lower Miocene over a passive continental margin of Krosno-Tarcau sea. The arcuate shape of this particular sea gave rise to the Carpathian arc strongly curved. It is noteworthy that similar idea of allochtonous flysch and crystalline rocks of the Carpathians was put forward in the first synthesis of the Carpathians by V.Uhlig in 1907.

The eastern part of the Hercynian Bohemian Massif is formed by highly deformed Lower Carboniferous (Culm) flysch rocks, Upper Devonian and Lower Carboniferous (Dinantian) platform carbonates, and Namurian paralic mollasse rocks. Two short (20 km long each) seismic lines confirmed their allochtonous nature over Precambrian Brunnia with its platform sedimentary cover. The style of thrusting is, however, strikingly different from the Carpathians. Twenty kilometres from the boundary the allochton is 8-9 km thick, the Culm flysch rocks are highly deformed and form typical duplexes on seismic records. In this part of the eastern Bohemian Massif, the thin-skinned thrusting is probable, but further westwards, the basement rocks were involved in thrusting and deformation.

During 1984 the deep Transcarpathian 150 km long reflection line will be measured and after that, during the 1985-1990, deep reflection profiling in length of 500 km is planned in Czechoslovakia.

ABSTRACT

DEEP SEISMIC PROFILE IN SOUTHWESTERN WYOMING

by Donald E. Wagner and Robert M. Byington

A 16 km, 24-fold seismic line was recorded by Amoco Research Party 45 on the western crestal portion of the Moxa Arch in the Dry Muddy Creek Area of Lincoln County, Wyoming. A dynamite source buried at depths of 25-30 meters was used to produce a deep-reflection section having a recording-time duration of 11 seconds.

Interpretation of the deep section indicates that 9.1 km of essentially undeformed Upper Precambrian sediments (equivalent to the Uinta Mountain Group of Southwest Wyoming and the Belt series of Montana) lie beneath 6 km of Paleozoic and Mesozoic sediments. At the base of the Precambrian sediments lies an angular unconformity dipping approximately 10 degrees to the east. This indicates a thickening of the granitic crust from 30 to 40 kilometers as one moves eastward from the Basin and Range province beneath the more stable Colorado Plateau. Geologists currently theorize that the transition zone of thin to thick crust correlates with the shelf-edge (site of Permo-Pennsylvanian carbonate deposition) of the Paleozoic Cordilleran geosyncline. The linear coherency of this basement unconformity should aid in resolving static alignment of the overlying sediments from the Intermountain Seismic Belt (ISB) to the Green River Basin.

Profiling the continental crust at sea: optimum acquisition and processing parameters

M R Warner, BIRPS, University of Cambridge, Bullard Laboratories, Madingley Rd,
Cambridge, CB3 OEZ, UK

BIRPS (British Institutions Reflection Profiling Syndicate) have collected some 3000 km of marine, multi-channel, deep seismic reflection data on the continental shelf around Britain. The processed data is of very high quality and we believe it to be some of the best deep data in the world. Reflections from the lower crust and Moho are clearly imaged over almost the entire data set and several significant events can be seen within the upper mantle. We believe that this high quality is at least partly a result of working at sea, where a repeatable, well coupled, high energy seismic source can be used. In the UK marine acquisition is about one tenth the cost of land acquisition and at sea it is possible to shoot very long straight lines with minimal statics problems.

The data are collected and processed for BIRPS by commercial contractors using conventional techniques modified to enhance deep reflections. Modifications to the acquisition system include the use of very large airgun arrays - 30-40 guns arranged in tuned sub arrays with a total volume of 5000-8000 cu ins giving a peak of peak signal of 120-170 bar meters. The data are recorded on a 3 km streamer with 60 x 50 m sections towed at 15 m depth. The increased depth of the streamer reduces ambient noise and enhances the low frequency (5-20Hz) response. Shots are fired only every 50 m to give a 30 fold stack with 25 m CDP spacing.

The processing sequence is fairly conventional but extensive testing is required to determine the often unconventional processing parameters. The (simplified) sequence consists of:- Edit; Spherical divergence correction; receiver and source array simulation and/or f-k filter; CDP sort; predictive deconvolution; velocity analysis; stack; predictive deconvolution; f-k filter; display. This sequence is designed to increase the signal to noise rather than enhance the resolution. Indeed, the inevitably high noise levels seen on deep seismic data mean that processing techniques which aim to increase resolution (eg signature deconvolution) are positively harmful.

The poor signal to noise inherent in deep data also has damaging consequences for most migration procedures. Both signal and noise are migrated to give a final section which is obscured by 'smiles'. Random noise becomes organised and looks like signal. To overcome this problem we have produced detailed line drawings from the unmigrated data and used simple inverse ray tracing to migrate these line segments. This has the advantage of migrating only 'real' events, using true depth migration which obeys Snell's law and, because it is very fast, allows many migrations with different velocity models.

RELATIONS BETWEEN THE FRANCISCAN ASSEMBLAGE, GREAT VALLEY SEQUENCE, AND CRYSTALLINE BASEMENT, CENTRAL CALIFORNIA

Carl M. Wentworth, Mark D. Zoback, and J. Alan Bartow
U.S. Geological Survey, Menlo Park, CA 94025

Seismic reflection profiles across the west margin of the Great Valley challenge accepted views about structural relations at this major tectonic boundary. Two profiles were obtained to explore the subsurface extent of the Coast Range thrust from its position at the boundary between Franciscan and Great-Valley-sequence rocks in the Diablo Range eastward to depth beneath the nearly flat-lying strata and basement of the San Joaquin Valley (SJV). A 6-s commercial VIBROSEIS line (SJ-6) that crosses the valley margin at Kettleman South Dome (lat. 35.75° N) was purchased and reprocessed to 12 s, and an original 15-s line (CC-1) that crosses the valley margin north of Los Banos (lat. 37.25° N) was obtained by contract (see abstract by Zoback). Associated refraction studies are underway by A. W. Walter and others of the U.S.G.S.

A regional unconformity on Sierran crystalline rock dips gently southwestward beneath similarly dipping Cretaceous and Cenozoic strata of the SJV. This unconformity is considered to be continuous with the base of the exposed Great Valley sequence (GVS) 75 km across the valley to the southwest in the Diablo Range. There the GVS dips steeply northeastward in a homocline that borders the Great Valley for 500 km. Together with its inferred ophiolitic basement, the GVS has been presumed to connect northeastward in the subsurface with the gently southwest-dipping strata and basement beneath the SJV to define a simple, extremely asymmetric syncline with its trough near the southwest side of the valley.

Instead, the reflection profiles indicate that basement beneath the SJV dips continuously southwestward across the full width of the valley to depths of 6-10 km and apparently extends even further beneath the northeast edge of the Diablo Range. The overlying strata, in contrast, are folded (SJ-6) or steeply upturned. At CC-1, the subhorizontal SJV strata extend slightly southwestward beneath the steeply dipping GVS exposed at the front of the range. Together with an abrupt 2-4 km thickening of the GVS between the subhorizontal and steeply dipping sections, this relation implies northeastward-directed thrusting. Similarly directed thrusting at SJ-6 produced Kettleman South Dome in Plio-Quaternary time and may be responsible for the M 6.7 earthquake that occurred beneath the range front near Coalinga in 1983.

Along both SJ-6 and CC-1 there is evidence near the valley margin for a fast (5.6 km/s), northeastward-thinning wedge of material several km thick between the GVS and faster underlying basement. We infer this to be Franciscan rock that was thrust northeastward onto the GVS-SJV basement while concurrently peeling up the GVS and a variable thickness of its ophiolite basement as well. Thus the Coast Range thrust, which is considered to juxtapose Franciscan and GVS/ophiolite along the length of the Coast Range, may be a backthrust above obducted Franciscan rather than a fundamental subduction-zone suture. The location of the oceanic-continental junction within the GVS-SJV basement is still uncertain.

Farther west where it crosses exposed Franciscan rocks, CC-1 shows a surprising amount of detail. An arched reflection occurs at about 1 s above a prominent reflection that dips eastward from 2 to 3 s across the 14-km width of exposed Franciscan and thence, perhaps, more steeply eastward to 5-6 s beneath the GVS at the east edge of the Diablo Range. At 8-10 s, distinct horizontal to east-dipping reflections occur at or near the base of the crust. Despite the typical scarcity of regular, well-defined bedding in the Franciscan, this western part of CC-1 exhibits a persistent subhorizontal grain that extends from about 1 to 7 s. The record shows no clear boundary near 5 s where interpretation of refraction data places a 15-km-deep base for 5.8 km/s rocks inferred to be Franciscan. The strong 2-3 s event may lie within a thick Franciscan terrane or could define the base of an unexpectedly thin Franciscan.

EXTENSIONALLY SHEARED LITHOSPHERE IN AND ADJACENT TO THE BASIN AND RANGE PROVINCE: SOME CRITICAL TESTS

Brian Wernicke, Department of Geological Sciences, Harvard University, Cambridge,
Massachusetts 02138

Geological and geophysical observations in the Basin and Range and elsewhere are consistent with (but not restrictive evidence for) the concept of uniform-sense normal simple shear of the entire lithosphere on a large scale along shallowly inclined planes. In Arizona and Utah, Tertiary extensional orogens comprised of east-directed extensional allochthons should be bordered by thinned lower (but not upper) crust and then thinned mantle lithosphere (with no crustal thinning) to the east, if this hypothesis is correct. Thin crust in the absence of significant upper crustal extension, and then a regional topographic welt are observed in sequence east of the extensional terrains, consistent with the hypothesis (in press, Can. J. Earth Sci.). However, the available refraction data in both areas, as well as precise quantitative estimates of upper crustal extension in Arizona are not as tightly constrained as they need to be to unequivocally demonstrate a discrepancy between upper crustal extension and total crustal thinning.

Between the Arizona and Utah extensional orogens, at about latitude 37 derees north, no east-directed low-angle normal faults of any age project beneath the Colorado Plateau. Values of surface heat flow, the electrical resistivity profile, and the crustal structure characteristic of the Plateau interior should persist at least as far west as the Virgin-Beaverdam Mountains (only 10-20 km east of the Nevada border), the area of the easternmost major upper-crustal extensional strain. If wide zones of anomalously thin crust and lithosphere at the margins of plateau regions are indeed expressions of shear down-dip from upper lithosphere extensional orogenic terrains, then at this latitude no such anomalies should be present outside the area of large-scale upper crustal extension.

SEISMIC CRUSTAL STRUCTURE NORTHWEST OF THUNDER BAY, ONTARIO (CANADA)

ROGER A. YOUNG *

JEFFREY WRIGHT **

GORDON F. WEST
GEOPHYSICS LABORATORY, UNIVERSITY OF TORONTO,
TORONTO, ONTARIO, CANADA M5S 1A7

* PRESENT ADDRESS: PHILLIPS RESEARCH CENTER,
169 GB, BARTLESVILLE, OK, USA 74004

** PRESENT ADDRESS: CHEVRON USA, INC.,
935 GRAVIER ST., NEW ORLEANS, LA, USA 70112

ABSTRACT

A series of crustal scale seismic refraction surveys 200 km northwest of Thunder Bay, Ontario, reveals distinctive features for this part of the Canadian Shield. Crustal thickness is everywhere about 40 km. Major faults fail to disrupt vertical marker horizons or to exhibit velocity contrasts: block structure is poorly developed. An upper crustal velocity of about 6.0 km/s is found throughout the area. Greenstone belts are thin vestiges of previously much thicker volcanic piles and provide a higher velocity cap resting on lower velocity granitoids. Metasedimentary-plutonic and metavolcanic-plutonic terrain types may have different velocity structures. The former may have a lower crust bounded above by a distinct mid-crustal boundary, display a steep velocity gradient throughout, and have a high average velocity. Metavolcanic-plutonic terrain, on the other hand, exhibits a lack of mid-crustal structure and maintains a constant velocity down to a very steep gradient in the lower crust.

Deep fine-structure must exist at the crust/mantle boundary. A widespread sub-M velocity increase to 8.3 km/s occurs at a depth of about 50 km.

A REVIEW OF RESEARCH ON DEEP STRUCTURE IN CHINA

Yuan Xuecheng, Bureau of Geophysical and
Geochemical Exploration, Ministry of
Geology and Mineral Resources (MGMR)

Wang Shi and Li Li, Institute of
Exploration Geophysics and Geochemistry,
MGMR

Wang Maoji and Yang Hua, Headquarters of
Airborne Exploration Geophysics, MGMR

ABSTRACT

The research on deep structure in China began in the year of 1958. Great progress has been made in recent years on the research of deep structure in China Mainland by using artificial seismology. According to incomplete statistics, about 11000 km of seismic profiles have been conducted , among which the one of largest scale and deeper study is the joint research project on the Formation and Evolution of the Crust and the Upper-mantle of the Himalayas carried out in the Qinghai-Tibet plateau by China Ministry of Geology and Mineral Resources, Academia Sinica and the National Center for Scientific Research of France during 1980 -1982.

The geophysicists and geologists of China and France have not reached full agreement on the interpretation of the data obtained. In the view of the Chinese geophysicists the crust of the Qinghai-Tibet plateau can be divided into three structural layers, of which the upper one is characterized by the superimposed thrust structure. The genesis of thrust faults may be related to the wide-spread sliding surfaces of low-velocity low-resistivity layers along the depth of some 10 to 30 km. The middle layer shows normal compression and the lower one is formed by anomalous mantle.

Before the collision of the India plate with the Tibet plate, the Tethys oceanic crust subducted northwards, forming the anomalous mantle of the Qinghai-Tibet plate, which caused the gradual uplifting of the crust. Since Eocene, owing to the collision of the two plates, the middle layer has thickened under compression and large-scale thrust superimposition occurred in the upper layer. As the crust thickened, the plateau took shape as it is today under isostatic gravity conditions.

In order to fully study the deep structure in China, a national research program is under formulation.

APPLICATION OF AN 800-CHANNEL SEISMIC REFLECTION SYSTEM FOR CRUSTAL STUDIES IN CALIFORNIA AND MAINE

Mark D. Zoback
Carl Wentworth
U.S. Geological Survey
Menlo Park, California

David Stewart
John Unger
U.S. Geological Survey
Reston, Virginia

This paper will present technical aspects of two programs recently undertaken by the U.S. Geological Survey utilizing seismic reflection profiling to understand structural relationships throughout the crust. One program is located in central California where reflection data have been collected along west-east profiles extending from the Gabilan Range to the foothills of the Sierra Nevada Mountains (see abstract by Wentworth, Zoback, and Bartow). The other program consists of a northwest-southeast trending profile extending from Quebec into western Maine (see abstract by Stewart and Unger). The interdisciplinary aspects of these investigations are discussed by R.M. Hamilton (see abstract).

Because an important goal of these studies was to get high-quality seismic reflection data from all depths in the crust, we decided to utilize a commercially-available, 800-channel, sign-bit seismic reflection system using 5 vibrators as a source. The principal advantage of this system was that very long spread-lengths could be achieved (to help determine stacking velocities at depth) while maintaining a relatively small receiver group spacing and split spread geometry (to maintain high-quality near-surface data). The receiver group spacing used was 30 m and the spread extended for 12 km in each direction from the vibrators. Compared with a conventional 96 channel recording system (with the vibrators off the end of a 12 km-long spread), the sign-bit system results in about a four-fold increase in spatial sampling and an eight-fold increase in CDP fold. Both of these factors have contributed greatly to improving the quality of the near-surface data. Other aspects of the data collection methods used will be discussed including two non-conventional methods used for velocity determinations in the California Central Valley. The long-spreads made it possible to analyse basement velocities using refracted waves in an area where there were few sub-basement reflectors, and the dense spatial sampling of the wave-field permitted the use of a τ-p inversion method for velocity determinations in the near-surface.

Overall, the performance of this system has been highly satisfactory. In the Diablo Range, composed of Franciscan melange, a well-resolved reflector is observed in the near-surface at about 0.8 seconds and an apparent Moho reflection is seen at about 10 seconds. In the eastern Central Valley, a well-resolved basement reflector is seen at very shallow depth as the sediments pinch out against Sierran granitic rocks, and strong continuous reflectors are seen in the lower crust with an apparent dip of about 30°. The most serious drawbacks of the method encountered to date are associated with the difficulty of processing such large quantities of data, and the inability to check cross-correlation which is done in real-time in the field.

INTERNATIONAL SYMPOSIUM ON DEEP STRUCTURE OF THE CONTINENTAL CRUST RESULTS FROM REFLECTION SEISMOLOGY

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Cornell University, Ithaca, New York 14853

LIST OF PARTICIPANTS

(* Asterisks indicate invited speakers.)
(† Daggers indicate contributing speakers.)

Aleman, Antenor
Gulf Oil Expl. & Prod.
PO Box 37048
Houston, Texas 77256
Phone: 713-754-0171

*Allegre, C.
Institut de Physique du Globe
4, Place Jussieu
75230 Paris, Cedex 05 France

†Allmendinger, Richard W.
Department of Geological Sciences
Cornell University
Ithaca, New York 14853
Phone: (607) 256-3376

Allong, A.F.
Union Texas Petroleum
P.O. Box 2120
One Riverway
Houston, Texas 77001
Phone: 713-960-7651

Alterman, Ina B.
Geosciences Branch - MS-P514
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555
Phone: 301-492-7856

Ando, Clifford J.
Shell Development Co.
PO Box 481
Houston, Texas 77001
Phone: 713-663-2627

Arden, Daniel D.
Louisiana Land & Exploration Co.
P.O. Box 60350
New Orleans, Louisiana 70160
Phone: 504-566-6827

Dept. of Geology
University of Toronto
Toronto, Ontario M5S 1A1, Canada
Phone: 416-978-4480 or 978-3022

Arnow, Jill A.
Dept. of Geological Sciences
Cornell University
Ithaca, New York 14853
Phone: (607) 256-3686

Asano, Shuzo
Earthquake Research Institute
University of Tokyo
1-1-1 Yayoi, Bunkyo-ku
Tokyo 113, Japan
Phone: 03-812-2111, Ex. 5708
Telex: 272-2148(ERI TOK)

Asudeh, Isa
Earth Physics Branch
Dept. of Energy, Mines, Res.
1 Observatory Cres.
Ottawa, Ontario K1A 0Y3 Canada
Phone: 613-996-5757
Telex: EMR 05 33 117

Barazangi, Muawia
Department of Geological Sciences
Cornell University
Ithaca, New York 14853
Phone: (607) 256-6411

Barstow, Noël
Rondout Associates, Incorporated
PO Box 224
Stone Ridge, New York 12484
Phone: 914-687-9150

†Barton, Penny
Bullard Labs
Madingley Rise
Cambridge CB3 0EZ England
Phone: 0223-60376
Telex: 817297 Astron G

†Behrendt, John C.
U.S. Geological Survey MS 903
Federal Center
Denver, Colorado 80225
Phone: 303-234-3472

Blot, Norbert
699 Hampshire Road #203
Westlake Village, California 91361
Phone: 805-496-4311

†Blundell, D.J.
Geology Department
Chelsea College
552 King's Road
London SW10 0UA England
Phone: 01-351 248

†Bois, Christian
Institut Français du Pétrole
1-4 Avenue du Bois-Préau
92506 Rueil-Malmaison, France
Phone: 749 02 14

Borcherding, Roger M.
Texaco Inc.
7755 S. Madison Circle
Littleton, Colorado 80122
Phone: Home: 303-740-7437
Office: 303-793-4377

†Braile, Larry
Dept. of Geosciences
Purdue University
West Lafayette, Indiana 47907
Phone: 317-494-5979

Brame, Jeffrey W.
Sohio Petroleum Co., Gulf Coast
8303 Southwest Freeway, Suite 600
Houston, Texas 77074
Phone: 713-981-1150

Brewer, Wayne
Allegheny College
Meadville, Pennsylvania 16335
Phone: 814-724-2350

Bridwell, R.J.
Arco Oil and Gas
Box 2819
Dallas, Texas 75221

Brooks, M.
Geology Dept.
University College
PO Box 78
Cardiff, Wales CF1 1XL United Kingdom
Phone: 0222-44211 ext. 2075
Telex: 498635 ULIBCFA

*Brown, Larry D.
Department of Geological Sciences
Cornell University
Ithaca, New York 14853
Phone: (607) 256-7357

Burgess, Steven P.
Department of Geological Sciences
Cornell University
Ithaca, New York 14853
Phone: (607) 256-3686

†Burke, Kevin
Lunar and Planetary Institute
3303 NASA Road 1
Houston, Texas 77058
Phone: 713-486-2180

Byrne, Tim
Dept. of Geological Sciences
Brown University
Providence, Rhode Island 02912
Phone: 401-863-3992

Cahill, Tom
Department of Geological Sciences
Cornell University
Ithaca, New York 14853
Phone: (607) 256-3521

Card, K.D.
588 Booth St.
Ottawa, Ontario K1A 0E4 Canada
Phone: 613-995-4935

Cargill, George
Utah Mines Ltd.
1406-4 King St. W.
Toronto, Ontario M5L 1B6 Canada
Phone: 416-783-9181

Carter, Jerry A.
Rondout Associates, Incorporated
PO Box 224
Stone Ridge, New York 12484
Phone: 914-687-9150

Cazes, Michel
Elf Acquitaine (Production)
Tour Générale - Bureau 2105
92088 Paris - La Défense
Cedex 22, France

†Cheadle, Michael
BIRPS, Bullard Labs
University of Cambridge
Madingley Road
Cambridge CB3 0EZ England
Phone: 0223-60376

Cheng, Arthur C.H.
E34-454, Dept. of Earth and Planetary
Sciences
Massachusetts Institute of Technology
Cambridge, Massachusetts 02159
Phone: 617-253-7206

Chiu, Jer-Ming
Memphis State Unviersity
Tennessee Earthquake Information Center
Memphis, Tennessee 38152
Phone: 901-454-2007

Chou, Xueqing
Central Laboratory of Petroleum Geology
Ministry of Geology and Mineral
Resources
Wuxi, China

Chroston, P. Neil
54-314, Dept. of Earth and Planetary
Sciences
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139
Phone: 617-253-6488/1918

Cisne, John L.
Department of Geological Sciences
Cornell University
Ithaca, New York 14853
Phone: Office: (607) 256-3698
Home: (607) 257-3875

†Clowes, Ron M.
Department of Geophysics & Astronomy
University of British Columbia
2219 Main Hall
Vancouver, British Columbia V6T 1W5
Canada
Phone: 604-228-2267

†Cook, Frederick A.
Dept. of Geology and Geophysics
University of Calgary
Calgary, Alberta T2N 1N4 Canada
Phone: 403-284-6594

Cordani, Umberto Giuseppe
Instituto de Geociências
Univ. Sao PauloCaixa Postal 20899
Sao Paulo, Brazil
Phone: 011-212-2011

Cordell, Lindrith
U.S. Geological Survey
Geophysics Branch, MS 964
Federal Center
Denver, Colorado 80225
Phone: 303-234-2623

Coruh, Cahit
Department of Geological Sciences
1046 Derring Hall
Virginia Polytechnic Institute and
State University
Blacksburg, Virginia 24061
Phone: 703-961-5096

†Costain, John K.
Department of Geological Sciences
1046 Derring Hall
Virginia Polytechnic Institute and
State University
Blacksburg, Virginia 24061
Phone: 703-961-5096

Coward, Robert I.
Gulf Oil Explor. & Prod.
PO Box 37048
Houston, Texas 77236
Phone: 713-754-0187

Crossley, David J.
Laboratory of Applied Geophysics
McGill University
3480 University St.
Montreal, Quebec, Canada H3A 2A7
Phone: 514-392-8022

Cunliffe, J.
Sun Oil Co.
CCII # 1560
PO Box 2880
Dallas, Texas 75221
Phone: 214-739-9736

Damotte, M.
Institut Français du Pétrole
BP 311
1-4 Av Bois Preau
92506 Rueil-Malmaison, France
Phone: 1 749 02 14
Telex: IFP A 203050 F

Davey, F. J.
Geophysics Division
D.S.I.R.
PO Box 1320
Wellington, New Zealand
Phone: Wellington 738208

†Day, Geoff
British Geological Survey
Murchison House
West Mains Road
Edinburgh EH9 3LA, United Kingdom
Phone: 031-667-1000
Telex: 727343 SEISED G

Decker, Edward R.
Dept. of Geological Sciences
University of Maine
Orono, Maine 04469
Phone: 207-581-2158

DeKeyser, Thomas
Marathon Oil Co.
PO Box 552
Midland, Texas 79702
Phone: 915-682-1626

Dennis, John G.
Department of Geological Sciences
California State University
Long Beach, California 90840
Phone: 213-498-4404

Detrick, Robert S., Jr.
Graduate School of Oceanography
University of Rhode Island
Kingston, Rhode Island 02881
Phone: 401-792-6926

De Voogd, Beatrice
Department of Geological Sciences
Cornell University
Ithaca, New York 14853
Phone: (607) 256-6249

DeYoreo, Jim
Dept. of Physics
Cornell University
Ithaca, New York 14853
Phone: (607) 256-3943

DiTullio, Lee
Dept. of Geological Sciences
Brown University
Providence, Rhode Island 02912
Phone: 401-863-5338

Domack, Eugene W.
Union Oil Co. of California
4635 SW Freeway, Ste. 265
Houston, Texas 77027
Phone: 713-621-1917

†Dorman, James
Exxon Production Research Company
PT 1855
Box 2189
Houston, Texas 77001
Phone: 713-940-4796

Dubois, Jacques
Laboratoire de Geophysique, ERA 804
BT 509
91405 Orsay Cedex France
Phone: 6-941 61 48

†Durrheim, Raymond John
B. Price Inst. for Geophysical Res.
University of the Witwatersrand
1 Jan Smuts Ave.
Johannesburg 2001, South Africa
Phone: 716-2519
Telex: 4-27125 SA

Eaton, Gordon P.
Office of the Provost
Texas A&M University
College Station, Texas 77843
Phone: 409-845-4016

Effimoff, Igor
Ashland Exploration, Inc.
PO Box 218330
Houston, Texas 77218
Phone: 713-531-2911

Ervin, C. Patrick
Dept. of Geology
Northern Illinois Univ.
De Kalb, Illinois 60115
Phone: 815-753-1943

Evans, Joyce M.
Texaco Inc.
PO Box 218330
Bellaire, Texas 77401
Phone: 713-432-3264

Farmer, Harlow G., III
Pecten International Comp.
PO Box 205
Houston, Texas 77001
Phone: 713-556-4594

Farr, John B.
Western Geophysical Company of America
PO Box 2469
Houston, Texas 77252
Phone: 713-789-9600 ext. 2539

Farrell, H.E.
Phillips Petroleum Company
266-E F.P.B.
Bartlesville, Oklahoma 74004
Phone: 918-661-6315

Fielding, Eric J.
Dept. of Geological Sciences
Cornell University
Ithaca, New York 14853
Phone: (607) 256-3521

†Finckh, Peter
Institute of Geophysics ETH
ETH-Hönggerberg
CH-8093 Zürich, Switzerland

Fletcher, Raymond C.
Center for Tectonophysics
Texas A&M
College Station, Texas 77843
Phone: 409-845-3281

Flinn, Edward A.
Center for Seismic Studies
1300 No. 17th St., Suite 1450
Arlington, Virginia 22209

Foster, Mark A.
Sohio Petroleum Co.
1801 California St., Suite 3500
Denver, Colorado 80202
Phone: Office: 303-295-4155
Home: 303-670-3117

†Fountain, David M.
Dept. of Geology and Geophysics
Univ. of Wyoming
Laramie, Wyoming 82071
Phone: 307-766-6299

†Fuchs, K.
Geophysical Institute
University of Karlsruhe
Hertzstrasse 16
D-7500 Karlsruhe, West Germany

*Fyfe, W.S.
Dept. of Geology
University of Western Ontario
London, Ontario, N6A 5B7 Canada
Phone: 519-679-3121

Gerhiser, Herman E.
10915 Bexley
Houston, Texas 77099
Phone: Home: 713-933-1887
Office: 713-774-7561 ext. 2799

†Gibbs, Allan K.
Department of Geological Sciences
Cornell University
Ithaca, New York 14853
Phone: (607) 256-5282

†Gilbert, M. Charles
Department of Geology
Texas A&M University
College Station, Texas 77843
Phone: 409-845-2464

Glover, Lynn, III
Department of Geological Sciences
4064 Derring Hall
VPI&SU
Blacksburg, Virginia 24061
Phone: 703-961-6213

*Green, Alan G.
Division of Seismology and Geomagnetism
Earth Physics Branch
Dept. of Energy, Mines, Res.
1 Observatory Cres.
Ottawa, Ontario K1A 0Y3 Canada
Phone: Home: 613-836-3535 Off:-995-5490

@ Greenhalgh, Stewart A.
School of Earth Sciences
Flinders University of South Australia
Bedford Park, 5042 Australia
Phone: 08-2778214
Telex: AA89624

Grimison, Nina L.
Department of Geology
University of Illinois
245 Natural History Building
1301 W. Green Street
Urbana, Illinois 61801
Phone: 217-367-5545 or 217-333-0836

Gussow, William C.
188 Dufferin Road
Ottawa, Ontario K1M 2A6 Canada
Phone: 613-749-9391

†Hajnal, Z.
Department of Geological Sciences
University of Saskatchewan
Saskatoon, Saskatchewan S7N 0W0 Canada
Phone: 306-343-2377

Hakkinen, Joseph W.
Denver Research Center
Marathon Oil Co.
PO Box 269
Littleton, Colorado 80160
Phone: 303-794-2601 ext. 430

@ Hales, Anton L.
Institute for the Study of Earth and Man
Southern Methodist University
Box 274
Dallas, Texas 75275
Phone: 214-692-3224

†Hall, Jeremy
Department of Geology
University of Glasgow
Glasgow G12 8QQ Scotland
Phone: 041-339-8855
Telex: 778421

Hamburger, Michael
Dept. of Geological Sciences
Cornell University
Ithaca, New York 14853
Phone: (607) 256-6249

*Hamilton, Robert M.
National Center MS 911
U.S. Geological Survey
Reston, Virginia 22090
Phone: 703-860-6531

†Hatcher, Robert D., Jr.
Dept. of Geology
University of South Carolina
Columbia, South Carolina 29208
Phone: 803-777-6684

Hauge, Thomas A.
Dept. of Geological Sciences
Cornell University
Ithaca, New York 14853
Phone: (607) 256-3376

Hauser, Ernest C.
Dept. of Geological Sciences
Cornell University
Ithaca, New York 14853
(607) 256-3376

Hawman, Robert B.
Dept. of Geol. & Geophysical Sciences
Princeton University
Princeton, New Jersey 08544
Phone: 609-452-4104

Hays, James Fred
Division of Earth Sciences
National Science Foundation
Washington, D.C. 20550
Phone: 202-357-7959

Heinrichs, Donald F.
Oceanography Section
National Science Foundation
Washington, D.C. 20550
Phone: 202-357-7312

Heirtzler, Jim
Woods Hole Oceanographic Inst.
Woods Hole, Massachusetts 02543
Phone: 617-548-1400 ext. 2576

Hickman, Robert G.
Union Oil Research Center
PO Box 76
Brea, California 92621
Phone: 714-528-7201 ext. 1693

Higgins, Ralph
Conoco Inc.
PO Box 2197
Houston, Texas 27252
Phone: 713-367-3305

Hirn, Alfred
Institut de Physique du Globe
4 Place Jussieu
75230 Paris Cedex 05 France
Telex: 202810 VOLSISM (FRANCE)

Huang, Jiazheng
Dept. of Geol. Sci., Cornell Univ.
Phone: (607) 256-5514
and
Wuhan College of Geology
Wuhan, Hubei, China

†Hutchinson, Deborah R.
U.S. Geological Survey
Woods Hole, Massachusetts 02543
Phone: 617-548-8700 ext. 163

Isacks, Bryan L.
Department of Geological Sciences
Cornell University
Ithaca, New York 14853
Phone: (607) 256-2307

†Johnson, Roy A.
Department of Geology and Geophysics
University of Wyoming
Laramie, Wyoming 82071
Phone: 307-766-5280

Johnson, Samuel R.
Sohio Petroleum Co.
1801 California St., Suite 3500
Denver, Colorado 80202
Phone: 303-295-4189

Jones, Rob
BIRPS, Bullard Labs
University of Cambridge
Madingley Road
Cambridge, CB3 0EZ United Kingdom
Phone: 0223-60376

Jones, Robert J.
Texaco, Inc.
19822 Sunbridge Ln.
Houston, Texas 77094
Phone: 713-578-2105

Jonsson, Geirfinnur
Department of Geological Sciences
Cornell University
Ithaca, New York 14853
Phone: (607) 256-3686

Jovanovich, D.B.
Gulf Research & Development Company
Room N1003
PO Box 37048
Houston, Texas 77236
Phone: 713-754-9079

†Jurdy, Donna M.
Department of Geological Sciences
Northwestern University
Evanston, Illinois 60201
Phone: 312-492-7163

Kadinsky-Cade, Katharine
59 Vinal Ave., Apt. #8
Somerville, Massachusetts 02145
Phone: Office: 617-861-5495
Home: 617-628-4301

†Kaila, K.L.
National Geophysical Research Institute
Hyderabad 500007 (A.P.) India
Phone: 851784, 851931
Telex: 155-478

Kallweit, Robert S.
Amoco Production Co.
11139 S. Hudson Ave.
Tulsa, Oklahoma 74102
Phone: 918-581-3859

Kaufman, Sidney
Dept. of Geological Sciences
Cornell University
Ithaca, New York 14853
Phone: (607) 256-7165

Kay, Robert W.
Department of Geological Sciences
Cornell University
Ithaca, New York 14853
Phone: (607) 256-3461

Kay, Suzanne M.
Department of Geological Sciences
Cornell University
Ithaca, New York 14853
Phone: (607) 256-7574

Kenyon, Patricia M.
Dept. of Geological Sciences
Cornell University
Ithaca, New York 14853
Phone: (607) 256-5199

Kerr, Richard A.
<u>Science</u>
1515 Massachusetts Ave., NW
Washington, D.C. 20005
Phone: 202-467-4324

Klein, James D.
Anaconda Minerals Co.
555 17th Street
Denver, Colorado 80202
Phone: 303-293-4339
Telex: 454545

Klemperer, Simon
Dept. of Geological Sciences
Cornell University
Ithaca, New York 14853
Phone: (607) 256-6249

†Knapp, Ralph W.
Kansas Geol. Survey
University of Kansas
Lawrence, Kansas 66044
Phone: Office: 913-864-4991
Home: 913-842-8101

Kong, Steve
Dept. of Geol. Sci.
Princeton University
Princeton, New Jersey 08544
Phone: 609-452-4104

*Kroner, A.
Institut für Geowissenschaften
Universität Mainz
Postfach 3980
D-6500, Mainz, West Germany

Kuckes, Arthur
212 Clark Hall
School of Applied and Engineering Physics
Cornell University
Ithaca New York 14853
Phone: (607) 256-3773

Langan, R.T.
Gulf Research & Development Company
Room N2109HTC
PO Box 37048
Houston, Texas 77236
Phone: 713-754-5532

Lavin, Peter M.
443 Deike Building
Penn State University
University Park, Pennsylvania 16802
Phone: 814-865-3951

Leven, Jim
Bureau of Mineral Resources
PO Box 378
Canberra 2601 Australia

†Lillie, Robert J.
Department of Geology
Oregon State University
Corvallis, Oregon 97331
Phone: 503-754-2484

†Liu, Char-Shine
Department of Geological Sciences
Cornell University
Ithaca, New York 14853
Phone: (607) 256-5514

†Long, Leland Timothy
School of Geophysical Sciences
Georgia Tech.
Atlanta, Georgia 30332
Phone: 404-894-2860

Maguire, Peter K.H.
Dept. of Geology
University of Leicester
Leicester LE1 7RH United Kingdom
Phone: LEICS. 554455
Telex: UNIVLIB LESTER 341198

Malin, Peter E.
Dept. of Geological Sciences
University of California at Santa Barbara
Santa Barbara, California 93106
Phone: 805-961-3520 or 805-969-7509

Martin, Kürsten
Federal Institute of Geosciences and
Natural Resources
Stilleweg 2
D-3000 Hannover, Fed. Rep. Germany
Phone: 0511-6432353
Telex: 923730 bfb (bgr) ha d

Mather, John David
Natural Environment Research Council
Polaris House
North Star Avenue
Swindon, Wilts, United Kingdom
Phone: 0793 40101
Telex: 444293

*Matthews, D.H.
Bullard Lab
Madingley Rise
Madingley Road
Cambridge CB3 0EZ United Kingdom
Phone: Cambridge (0223) 60376
Telex: 81240 CAMSPL G

Maxwell, John C.
Dept. of Geological Sciences
University of Texas
Austin, Texas 78713
Phone: 512-471-5355

Mayer, James
Dept. of Geological Sciences
Cornell University
Ithaca, New York 14853
Phone: (607) 256-3686

Mayne, W. Harry
10817 Sandpiper
Houston, Texas 77096
Phone: Home: 713-771-6817
Office: 713-774-7561 ext. 2225

McBride, John Henry
Dept. of Geological Sciences
Cornell University
Ithaca, New York 14853
Phone: (607) 256-3686

†McCarthy, Jill
Geophysics Department
Stanford University
Stanford, California 94305
Phone: 415-497-4469

McGeary, Susan
Geophysics Dept.
Stanford University
Stanford, California 94301
Phone: 415-497-1540 or 415-326-6442

†McGinnis, L.D.
Department of Geology
Louisiana State University
Baton Route, Louisiana 70803
Phone: 504-388-3353

Meeder, Charles A.
Marathon Oil Co.
PO Box 269
Littleton, Colorado 80160
Phone: 303-794-2601 ext. 412

Meisling, Kris
Arco Oil and Gas
Box 2819
Dallas, Texas 75221

*Meissner, Rolf
Inst. Geophysics
Neue Universität
Olshausenstr. 40-60
D-2300 Kiel, West Germany
Phone: Home: 0431-322128
Office: 0431-880-3914/18

†Mereu, R.F.
Dept. of Geophysics
University of Western Ontario
London, Ontario, N6A 5B7 Canada
Phone: 519-679-3143

Moran, Andrew I.
3350 Wilshire Blvd.
Los Angeles, California 90010
Phone: 213-739-7258

Morel-à-l'Huissier, Patrick
Earth Physics Branch
Dept. of Energy, Mines, Res.
1 Observatory Cr.
Ottawa, Ontario K1A 0Y3 Canada
Phone: 613-995-5467

†Morelli, Carlo
University of Trieste
4, Via R. Gessi
34123 - Trieste - Italy
Phone: 40-773-774
Telex: 460014

Morrison, Michael L.
Texaco Canada Resources Limited
605 Fifth Avenue SW
Calgary, Alberta T2P 3H5 Canada
Phone: 267-0703

*Moss, F.J.
Bureau of Mineral Resources
Geology and Geophysics Dept.
PO Box 378
Canberra City, A.C.T. 2601 Australia
Phone: Australia (062) 805704
Telex: AA62109

*Mueller, Stephan
Institute of Geophysics
ETH-Hönggerberg
CH-8093 Zürich, Switzerland
Phone: Zürich 377-2610
Telex: 823480 EHEB CH

Munsch, G. Bernard
European Science Foundation
1 Quai Lezay-Marnésia
F-67000 Strasbourg France
Phone: 33-88-353063
Telex: France 890440

Ni, James
Dept. of Geological Sciences
Cornell University
Ithaca, New York 14853
Phone: (607) 256-3521

Nolen-Hoeksema, Richard
Cities Service Research
PO Box 3908
Tulsa, Oklahoma 74102
Phone: 918-561-5335

O'Hara, Kieran
Geological Science
Brown University
Providence, Rhode Island 02912
Phone: 401-863-3338

†Okaya, David A.
Dept. Geophysics
Stanford University
Stanford, California 94305
Phone: 415-497-0253

*Oliver, Jack
Dept. of Geological Sciences
Cornell University
Ithaca, New York 14853
Phone: (607) 256-2377

†Olsen, Kenneth H.
Geophysics, MS-C335
Los Alamos National Laboratory
Los Alamos, New Mexico, 87545
Phone: 505-667-1007 or 505-667-8464

Opdyke, Scott N.
Dept. of Geological Sciences
Cornell University
Ithaca, New York 14853
Phone: (607) 256-6249

Pan, Gee-Shang
Dept. of Geological and Geophysical
Sciences
Princeton University
Princeton, New Jersey 08544
Phone: 609-452-4104

Pasta, Dave
Texaco Inc.
PO Box 2100
Denver, Colorado 80201
Phone: 303-793-4268

Pavlis, Terry
Department of Geological Sciences
Lehigh University
Bethlehem, Pennsylvania 18015
Phone: 215-861-3660

Payne, Barton
Department of Geological Sciences
Cornell University
Ithaca, New York 14853
Phone: (607) 256-4621

Peddy, Carolyn
Dept. of Geological Sciences
Cornell University
Ithaca, New York 14853
Phone: (607) 256-4621

†Percival, John A.
Geological Survey of Canada
588 Booth St.
Ottawa, Ontario K1A 0E4 Canada
Phone 613-995-4723

Pereira, Stanley J.
Amoco Production Company
1670 Broadway
Denver, Colorado 80202
Phone: 303-830-4875

Phillips, Jeffrey D.
U.S. Geological Survey, MS 927
Reston, Virginia 22092
Phone: 703-860-7233

Phillips, Joseph D.
University of Texas
Institute for Geophysics
4920 No. IH 35
Austin, Texas 78751
Phone: 512-458-5350

†Phinney, Robert A.
Department of Geology
Room 114 Guyot Hall
Princeton University
Princeton, New Jersey 08544
Phone: 609-452-4100

Phipps, Stephen Paul
Geology Department
University of Pennsylvania
Philadelphia, Pennsylvania 19104
Phone: 215-898-5725

Picha, Frank
9707 Burdine
Houston, Texas 77096
Phone: 713-728-1120

Piwinskii, A.J.
Lawrence Livermore Laboratory
University of California
Livermore, California 94550
Phone: 415-422-7083

Poprik, L.A.
Union Texas Petroleum
PO Box 2120
One Riverway
Houston, Texas 77001
Phone: 713-960-7651

*Posgay, Karoly
Eotvos Lorand Geophys. Institute
Columbus U. 17-23
PO Box 35
H-1440 Budapest XIV, Hungary
Phone: 635-010
Telex: 22-6194 ELGI H

Potter, Christopher
Dept. of Geological Sciences
Cornell University
Ithaca, New York 14853
Phone: (607) 256-5514

Pratka, James F.
Seiscom Delta United
PO Box 4610
Houston, Texas 77210
Phone: 713-556-1400
Telex: 4620441

Pratsch, J.C.
Sohio Petroleum Company
PO Box 4587
Houston, Texas 77210
Phone: 713-552-8845

*Price, Raymond A.
Geological Survey of Canada
601 Booth Street
Ottawa, Ontario K1A 0E8 Canada
Phone: 613-995-4208

†Qureshy, M.N.
Department of Science and Technology
New Mehrauli Road
New Delhi 110028 India
Phone: Office: 666076   Home: 38168
Telex: 31-2096 DST IN

Reinke-Wolter, John
Arco Oil and Gas
Box 2819
Dallas, Texas 75221

Roy-Chowdhury, Kabir
Dept. of Geol. and Geophys. Sciences
Princeton University
Princeton, New Jersey 08544
Phone: 609-452-4128

Ruth, Charles W.
Louisiana Land & Exploration Co.
PO Box 60350
New Orleans, Louisiana 70160
Phone: 504-566-6789

Ryder, Michal Ellen
403 Deike Bldg.
Geophysics Program
Pennsylvania State University
University Park, Pennsylvania 16802
Phone: 814-863-1667

Sales, John
Mobil Research
Box 819047
Dallas, Texas 75381
Phone: 214-851-8442

Salisbury, Gerald P.
Union Oil Co. of California
Box 7600 - Terminal Annex
Los Angeles, California 90051
Phone: 213-977-6209

Sanford, William E.
Dept. of Geological Sciences
Cornell University
Ithaca, New York 14853
Phone: (607) 256-3686

Sarewitz, Daniel
Dept. of Geological Sciences
Cornell University
Ithaca, New York 14853
Phone: (607) 256-5199

Schwartz, Robert
Allegheny College
Meadville, Pennsylvania 16335
Phone: 814-724-2350

Serpa, Laura
Dept. of Geological Sciences
Cornell University
Ithaca, New York 14853
Phone: (607) 256-6249

†Sharry, John
Gulf Research & Development Company
Room 2038HTC
PO Box 37048
Houston, Texas 77236
Phone: 713-754-5531

Smalley, Bob
Dept. of Geological Sciences
Cornell University
Ithaca, New York 14853
Phone: (607) 256-3521

Smith, Kenneth G.
189 Trenton Dr.
Slidell, Louisiana 70461
Phone: 504-641-5283

†Smithson, Scott B.
Dept. of Geology & Geophysics
University of Wyoming
Laramie, Wyoming 82071
Phone: 307-766-5280

†Smythe, David K.
British Geological Survey
19 Grange Terrace
Edinburgh EH9 1LF United Kingdom

Snyder, David B.
Dept. of Geological Sciences
Cornell University
Ithaca, New York 14853
Phone: (607) 256-3686

Spencer, Carl
Earth Physics Branch
Dept. of Energy, Mines, Res.
1 Observatory Cres.
Ottawa, Ontario, K1A 0Y3 Canada
Phone: 613-996-5757

Stanley, Rolfe
20 Overlake Park
Burlington, Vermont 05401
Phone: 801-863-4974

Stephenson, Randell
Geological Survey of Canada
3303 - 33rd Street NW
Calgary, Alberta T2L 2A7 Canada
403-284-0430

†Stern, Tim
Geophysics Division
D.S.I.R.
PO Box 1320
Wellington, New Zealand
Phone: 738-208

†Stewart, David B.
National Center 959
U.S. Geological Survey
Reston Virginia 22091
Phone: 703-860-6691

Stewart, Roger
U.S. Geological Survey
MS 922
Reston, Virginia 22092
Phone: 703-860-7481

Stockmal, Glen
Dept. of Oceanography
Dalhousie University
Halifax, Nova Scotia B3H 4J1 Canada
Phone: 902-424-2266

Strehlau, Jurgen
Institut für Geophysik
Neue Universität
2300 Kiel, Federal Republic of Germany
Phone: 0431-880-3915

Sutton, George H.
Rondout Associates, Incorporated
PO Box 224
Stone Ridge, New York 12484
Phone: 914-687-9150

Talley, Keith L.
Sohio Petroleum Co.
Two Lincoln Center, Suite 900
5420 LBJ Freeway
Dallas, Texas, 75240
Phone: 214-387-5168

Tamaki, Kensaku
Graduate School of Oceanography
University of Rhode Island
Narragansett, Rhode Island 02852
Phone: 401-792-6676
Telex: 927589 UNIVBSKI KTON

Thompson, Bruce
212 Clark Hall
School of Applied and Engineering
  Physics
Cornell University
Ithaca New York 14853
Phone: (607) 256-3773

*Thompson, George
Department of Geophysics
Stanford University
Stanford, California 94305
Phone: 415-497-3714

*Tomek, Cestmir
Geofyzika n.p. Brno
P.O. Box 62
61246 Brno, Czechoslovakia
Phone: 57464
Telex: 62512 ugfbo c

Trembly, Lynn D.
Sohio Petroleum Co.
100 Pine Street
San Francisco, California 94111
Phone: 415-979-3000

Turpening, Roger
Dept. of Earth & Planetary Sciences
MIT, E34, 446
42 Carleton Street
Cambridge, Massachusetts 02139
Phone: 617-253-7850
Telex: 92 1473

Ullrich, Laura
Conoco Inc.
PO Box 2197
Houston, Texas 77252
Phone: 713-367-3305

Unger, John D.
U.S. Geological Survey
922 National Center
Reston, Virginia 22092
Phone: 703-860-7481

Verrall, Peter
Chevron USA Inc.
PO Box 599
Denver, Colorado 80201
Phone: 303-691-7038

†Wagner, Don E.
Amoco Production Company
PO Box 59
Tulsa, Oklahoma 74102

Wagner, Jean-Jacques
Lab. de pétrophysique
Dpt. de Minéralogie de l'Université
13 rue des Maraîchers
CH1211 Geneva 4 Switzerland
Telex: 22-21.93.55

Walter, Allan
U.S. Geological Survey
MS 77
345 Middlefield Road
Menlo Park, California 94025
Phone: 415-323-8111 ext. 2010

Wang, Dapeng
Department of Geophysics
University of Western Ontario
London, Ontario, N6A 5B7 Canada
Phone: 519-679-3143

†Warner, Mike
BIRPS, Bullard Labs
University of Cambridge
Madingley Road
Cambridge, CB3 0EZ United Kingdom
Phone: 0223-60376

Wehr, Frederick
Exxon Production Research Co. MS 4130
PO Box 2189
Houston, Texas 77001
Phone: 713-966-6449
Telex: 9108815579 USEPRTX HOU

†Wentworth, Carl M.
U.S. Geological Survey MS 75
345 Middlefield Road
Menlo Park, California 94025
Phone: 415-323-8111 ext. 2474

†Wernicke, Brian P.
Dept. of Geological Sciences
Harvard University
Cambridge, Massachusetts 02138
Phone: 617-495-3598

White, David L.
c/o W.G.M. Ltd.
PO Box 5219
Jeddah, Saudi Arabia
Phone: 672-3244
Telex: 402417 WGM SJ

Whitsett, Robert
699 Hampshire Road #203
Westlake Village, California 91361
Phone: 805-496-4311

Willemin, James
Dept. of Geological Sciences
Cornell University
Ithaca, New York 14853
Phone: (607) 256-5514

Wirth, Karl R.
Department of Geological Sciences
Cornell University
Ithaca, New York 14853
Phone: (607) 256-3686

Withjack, Martha
Arco Oil and Gas
Box 2819
Dallas, Texas 75221

Wories, Henk
Union Oil Co. of California
International Oil Division
PO Box 7600
Los Angeles, California 90051
Phone: 213-977-6375

Wray, Tanner
Dept. of Geological Sciences
Cornell University
Ithaca, New York 14853
Phone: (607) 256-6249

Wright, Lauren A.
Dept. of Geosciences
303 Deike
Pennsylvania State University
University Park, Pennsylvania 16802
Phone: 814-865-6393

Wu, Gongjian
Institute of Geological Sciences
26 Baiwanzhuang Road
Beijing, China

Wu, Zhengwen
Beijing Graduate School
Wuhan College of Geology
Chengfu Road
Beijing 100083 China

Yoshii, Toshikatsu
Earthquake Research Institute
University of Tokyo
Tokyo 113, Japan
Phone: 03-812-2111 ext. 5710

†Young, Roger A.
169GB
Phillips Research Center
Bartlesville, Oklahoma 74004
Phone: 918-661-9550

*Yuan, Xuecheng
Bureau of Exploration Geophysics and Geochemistry
Ministry of Geology and Mineral Resources
Beijing, China

Zandt, George
Dept. of Geological Sciences
State University of New York at Binghamton
Binghamton, New York 13901
Phone: (607) 798-4378

Zheng, Li
Dept. of Geol. Sci., Cornell Univ.
Phone: (607) 256-5514
and
China Petroleum Corporation
Beijing, China

Zhu, Tianfei
Department of Geological Sciences
Cornell University
Ithaca, New York 14853
Phone: (607) 256-3686

†Zoback, Mark D.
U.S. Geological Survey
345 Middlefield Road
Menlo Park, California 94025
Phone: 415-323-8111

Zuber, Maria
Dept. of Geological Sciences
Brown University
Providence, Rhode Island 02912
Phone: 401-863-3338

MEMBERS OF THE CORNELL PROGRAM FOR STUDY OF THE CONTINENTS (COPSTOC)

Amoco Production Co.

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