APPENDIX 2A

The Program for Array Seismic Studies
of the
Continental Lithosphere

Incorporated Research Institutions for Seismology
(IRIS)

The Program for Array Seismic Studies of the Continental Lithosphere

(PASSCAL)

Program Plan

PASSCAL is a major new initiative to conduct high-resolution seismic studies of the continental lithosphere, using 1000 matched multichannel portable digital seismographs. This powerful new instrumentation will be used to form detailed geological images of the crust and upper mantle, to study the dynamical processes of earthquakes, and to serve as a state-of-the-art research tool for fundamental studies of wave propagation and the properties of the continental lithosphere. Seismologists from over 50 universities and other research institutions have joined together to formulate this ten year plan for the development of PASSCAL and for conducting a diverse, long-term program of seismological studies of the continental lithosphere.

December, 1984

Cover Picture: Three-dimensional seismic image based on actual seismic data, courtesy of Western Geophysical,Inc.

Foreword

The **Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL)** represents an unprecedented national grass-roots collaboration among seismologists from over 50 universities and research institutions to bring to bear modern digital instrumentation to the study of the continental lithosphere. It is an outgrowth of several key studies by the National Academy of Sciences recommending new initiatives in the study of the continental lithosphere and of a series of recent workshops devoted to defining instrumentation requirements for a new generation of seismic research. The past fifteen years have seen major advances in the technology of seismic wavefield recording and imaging, led by the hydrocarbon exploration industry; in contrast, the U. S. effort in basic seismological studies of the continents has lagged, save for the notable, and pioneering, success of COCORP in applying the techniques of seismic profiling to the continental crust.

PASSCAL proposes to make a major advance by mobilizing the power of 1000 portable digital multi-channel instruments for studies of structure, of physical properties, and of earthquake physics which have been quite beyond our capabilities. The unifying power of this large mobile array lies in its power to apply a diverse variety of seismological tools to the area being studied: reflection, refraction, earthquake hypocenter location, tomography, surface wave structure, and teleseismic body wave response functions being examples. It also makes possible a number of fundamental studies of the physics of wave propagation in the real earth, at significantly high frequencies.

This Plan for PASSCAL is the result of deliberations and contributions by scientists from over 50 institutions, government agencies, and companies. It represents substantially, the voice of the entire community of seismologists engaged in basic, nonproprietary research on the continents. The complementary Plan for a Global Seismic Network (GSN), is similarly the work of the entire community of U. S. seismologists engaged in global studies of the earth's interior. The following scientists have contributed to the development of the PASSCAL Plan:

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  Gilbert Bollinger, Virginia Polytechnic Institute
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PROGRAM FOR ARRAY SEISMIC STUDIES OF THE CONTINENTAL LITHOSPHERE

(PASSCAL)

December, 1984

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1. EXECUTIVE SUMMARY

1.1. What is PASSCAL and what are its goals?

The **Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL)** is a cooperative program among scientists from over 50 U.S. universities, research institutions, industry, and federal agencies to conduct detailed seismic studies of the continental lithosphere† and upper mantle. Most U.S. seismologists now actively studying the continental lithosphere have joined in this program, which offers a way of integrating all seismological research techniques and providing the most advanced technological support to participants from both large and small institutions. The organization was spurred by a 1984 National Academy of Science report, "Seismological Studies of the Continental Lithosphere" which recommends the establishment of a national facility for cooperative experiments to image the lithosphere and to advance seismological research. It is operated through IRIS (Incorporated Research Institutions for Seismology), a non-profit corporation whose members are universities and research institutions *(Chapter 3)*.

- Major goals of PASSCAL are the planning of a new generation of integrated seismological studies of key geological and geophysical targets, and the facilitating of broader communication among earth scientists from academic institutions, industry, and governmental and other national research programs.
- The main operational focus of PASSCAL will be in developing and implementing a flexible high-resolution seismic imaging system that can look deep into the earth's interior, in the way that a radio telescope looks at the sky or a medical imaging system scans the human body. This system will be based on a large complement of portable digital seismic instruments that can be combined in various ways as arrays.
- PASSCAL will employ diverse seismological techniques in basic research into the structure, properties, and processes that characterize the continental lithosphere.
- The subsurface geology of the continental lithosphere and its relation to the major-plate tectonic processes and to the underlying mantle can be studied in detail with this new capability, and a new level of understanding of earthquake processes developed. A number of fundamental experiments on the physics of elastic wave propagation in the lithosphere will become possible.
- The PASSCAL instrumentation will allow society to more fully understand and deal with the practical consequences of lithospheric structure and mechanics. New crustal models can be developed to help guide the exploration of hydrocarbon and mineral deposits, to examine the crustal properties in regions of proposed critical waste repositories, to assist in understanding lithospheric wave transmission related to nuclear blast detection, and to reach a fundamental understanding of the deep architecture of mineral deposits. PASSCAL is a cost-effective tool that will make it possible to mobilize for detailed studies of the focal regions of large earthquakes or to monitor regions where large earthquakes may be imminent.
- The 1000 instruments (up to 6000 sensors) of PASSCAL will be acquired, maintained, and deployed for the use of participating scientists through a facilities support program.
- Intensive studies of important geological targets will involve a substantial portion of the seismologial community and deployment of the full PASSCAL complement. These studies will provide a focus for continuing geological and geophysical investigations.

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† Readers are reminded that the continental lithosphere includes not only the crust but also that rigid part of the underlying upper mantle which has existed over geologic periods of time as an integral part of the continent.

- PASSCAL will provide and support facilities for handling the large data flow from the array of instruments (up to 200 Gbyte per experiment).
- PASSCAL assumes a parallel and supportive role with the Global Seismic Network (GSN)†, and will form a partnership to develop instrumentation, data management, and research plans.

1.2. PASSCAL makes possible wholly new kinds of studies of the continental lithosphere

The large number of matched digital array elements proposed by PASSCAL permits a combination of close sensor spacing and adequate array size that allows the array to function as an integrated system, much like a radio telescope *(Chapters 3—6)*.

- Use of the full 1000 stations as an array will permit nearly continuous spatial sampling of seismic wavefields. These can then be processed by coherent imaging methods to develop three-dimensional images of earth structure.
- Application of this kind of wavefield recording to earthquake source regions will provide a quantum jump in our ability to image the actual source volumes of microearthquakes, mainshocks and aftershocks in detail.
- The array is intended to go beyond current capabilities for crustal reflection and refraction profiling. It will enable scientists to look well below the crust into the deeper lithosphere and aesthenosphere, to image three-dimensional P- and S-velocity structures, and to determine models of attenuation.
- The potential of teleseismic earthquake data for detailed exploration of the lithosphere and underlying mantle will be realized for the first time. The PASSCAL array will complement the new Global Seismic Network (GSN) by providing localized, higher resolution information about deep earth structure, and by providing temporary arrays at GSN sites.

1.3. PASSCAL will require new modes of organizing and conducting seismological research

The large number of instruments, the demand for high, uniform performance, the large data volumes, and the cost of the array will require the seismological community and the funding agencies to adopt operational methods appropriate to large-scale projects *(Chapters 3-6)*.

- Collaboration and planning for cooperative experiments at a national and international level will be required if the scientific potential of the array is to be realized.
- Different types of field programs will evolve, each with its own style of planning and operation:

    Large cooperative studies (250—1000 instruments)
    Small, individual studies (about 100 instruments or less)
    Long-term deployments for studies of the lithosphere by earthquake monitoring.

- The facilities provided and diversity of approaches possible with PASSCAL will lead to involvement of a broad range of institutions and individuals. Smaller institutions with limited resources will be able to participate fully in small- or large-scale studies.
- A PASSCAL support organization will be required for deployment, data handling, maintenance, and system management, which go far beyond the capacity of traditional groups headed by a single Principal Investigator (PI).

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† The Global Seismic Network (GSN) is a major IRIS initiative aimed at placing 100 real-time telemetered state-of-the-art broad-band digital seismic stations around the world. The goals and plans of the GSN are described in the Science Plan for the GSN (1984), which is available from the IRIS office.

- Data quantities as great as 200 Gbyte† from a single experiment will present technical problems of data editing, sorting, and processing that lie close to those of the present state of the art. These issues will require substantial planning and central support for their solution.
- The technical and management issues raised are quite similar to those the exploration industry has faced in the past decade, and whose resolution has been achieved only after major effort. PASSCAL expects to base its operational strategy on the industry experience; moreover, it may depend on industry contracts from time to time to provide services that lie beyond the baseline capability of its own organization.
- During large-scale cooperative experiments with the full complement of instruments, the core of the scientific program, the needs for manpower and special services (e.g., permitting, blasting) will exceed the baseline capacity of any PASSCAL support organization. A special long-term budget line is provided for these field costs.

1.4. The Instrumentation Program

An intensive effort has been under way since spring of 1983 (including two national-international workshops) to define the technical specifications for the instrument packages and sensors that will make up the PASSCAL instrument complement *(Chapter 7)*:

- In recent years, the university community has generally had to rely on a few analog instruments, nearly all of which are outmoded. While digital instruments have been the standard in the oil industry for fourteen years, very few are available for lithospheric studies.
- No currently available or currently planned portable seismic instrumentation meets the requirements for flexible, large, mobile arrays.
- The PASSCAL Instrumentation effort is aimed at designing a new class of modular instruments that will be useable for at least the next decade. Prototypes will be available from industry in FY 1985 or 1986.
- The first instrument plans were developed at a Workshop on Guidelines for Instrumentation Design for Lithospheric Research, May 1983, Salt Lake City, Utah, held in conjunction with the annual meeting of the Seismological Society of America,
- In December, 1983, an international group of scientists and engineers met for the first time ever to discuss scientific goals and technological capabilities at a workshop on instrumentation design at Los Altos, California, that was sponsored by the Commission on Controlled Source Seismology (CCSS).††
- The instruments will be of versatile, microprocessor-based modular design, using a non-proprietary bus standard; they will have interchangeable standardized modules with distributed intelligence for A-D conversion, filtering, triggering, recording, etc., allowing both for flexibility of instrument configuration and easy implementation of modifications.
- Data storage will initially use state-of-the-art magnetic tape technology. Evolution towards satellite or other telemetry solutions is anticipatd within about 5 years.
- PASSCAL will also coordinate development work in sensors and in the evaluation of artificial seismic sources.

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† Throughout this Plan, we abbreviate: Mbyte = megabyte(s) = 10^6 bytes; Gbyte = gigabyte(s) = 10^9 bytes; Tbyte = terabyte(s) = 10^{12} bytes.

†† CCSS: The Commission on Controlled Source Seismology, of the International Association for Seismology and Physics of the Earth's Interior.

1.5. What support services are needed?

Maintenance, deployment, and quality control of the instruments and of the field data flow will be overseen by a central support organization. A major fraction of the support system will be mobile *(Chapter 8)*.

- The central facility will see to maintenance, repair, service, training, quality control, and routine engineering tasks for the array instrumentation. Vehicles will be needed for deployment, field tests, and maintenance.
- The initial data management will include cartridge retrieval, playback, editing, sorting, and integration into the IRIS data archive. PASSCAL will maintain field computers with software support for playback. The IRIS Data Management Center will provide large-scale edit and sort services to PI's.

1.6. How will large-scale field experiments be managed?

When the full complement of instruments is deployed for intensive studies of a region using multiple seismic techniques, a substantial number of participating research groups will be actively engaged in data acquisition and preprocessing. About one such 2—3 month experiment per year is anticipated. *(Chapter 8)*.

- Participating PI's will plan such studies under the coordination of PASSCAL, which will handle scheduling and the setting of priorities.
- Special costs of these scheduled major experiments, including extra personnel, travel, permitting, explosives, and related special services will be carried as a budget line of PASSCAL. Participating institutions will be reimbursed for their share of the cost of participation in the data acquisition by means of contract from PASSCAL.

1.7. How will the large quantities of data be handled?

The PASSCAL system, if it were operated full time at the maximum sampling rate, would be capable of producing over 60 Tbyte of data per year. By modeling a mix of possible experiments, we find that PI's will probably actually deliver a maximum of 0.4 Tbyte per year to the data archive. A detailed plan for the management of the data flow from the field must be a part of every experiment and a part of PASSCAL long-term planning *(Chapter 9)*.

- Data from most controlled source studies will be manageable with many presently-available computer systems. The workup of such data will mostly be handled by field computers.
- Data quantities from the recording of natural (earthquake) sources may run to 200 Gbyte per experiment, and require high-capacity computer services for the initial sort & edit.
- The data management plan provides for using contract services from the exploration industry to handle the preprocessing and processing associated with the largest (and relatively fewest) data sets, such as three-dimensional reflection-refraction data or large-volume microearthquake data.
- PASSCAL PI's will require facilities for preparation of event archive data.
- Archiving and database management services will be provided by the IRIS Data Management Center.
- Data retrieval from the IRIS archive will emphasize access within a reasonable time for all interested scientists.
- Participation of the scientific community will require adequate computers at the PI's institutions... currently high-capability, 32-bit hardware, with multi-user graphics workstations.

1.8. Organization and Terms of Reference for PASSCAL

Formal terms of reference are needed to spell out the processes of planning, administration, and giving and receiving advice, and PASSCAL's roles *vis-a-vis* universities and funding agencies. *(Chapter 10).*

- Participation in PASSCAL is open to all interested scientists regardless of institutional affiliation.
- The Standing Committee for PASSCAL, composed of active research scientists, will oversee all aspects of the program. The Standing Committee reports to the Board of Directors of IRIS. (Members normally will serve three-year terms.)
- An Annual Meeting will be held, at which PASSCAL participants will discuss and make recommendations about program operations as needed, including new appointments of Standing Committee members.
- The Standing Committee will have active subcommittees for
  - Science Planning and Coordination
  - Instrumentation
  - Data Management (includes data acquisition and field analysis)
  - Scheduling
- PASSCAL will have a Chief Scientist, an established seismologist who will oversee the operations of PASSCAL to the satisfaction and under the direction of the Standing Committee. The Chief Scientist will have administrative accountability to the President of IRIS.
- Normally, PASSCAL will receive funding only to discharge its functions of data acquisition and technical support. A portion of this will be subcontracted to participating groups to reimburse their incremental costs of participation in large-scale cooperative field experiments.
- Proposals for funding of projects that use the PASSCAL facilities will be submitted to normal review and funding agencies, and acted on by them in the usual fashion. Requests for use of the PASSCAL array and facilities, regardless of funding status, must be approved by the Standing Committee, in accordance with availability and with the need for a balanced, long-term program.
- PI's with specific research projects will submit their instrument and data management needs to PASSCAL, which will convene at least one workshop each year to schedule and coordinate future experiments.

1.9. PASSCAL and The Broader Science Community

The magnitude of the PASSCAL effort will obligate the program to maintain adequate communications with other new large-scale programs in the earth sciences, as well as with all sectors of government and industry. *(Chapter 11).*

- PASSCAL is but one of several related new national initiatives recommended in the 1983 COSEPUP report†

  Global Seismic Network (a co-program within IRIS)
  Continental Scientific Drilling Program (DOSECC)
  Global Positioning System (GPS) Consortium
  Instrumentation for Study of Geological Materials
- In addition, a Marine Multichannel Profiling consortium (NORPO) has been organized under JOI auspices, and cooperative, multidisciplinary efforts such as CALCRUST and the Trans-Alaska consortium (TALI) appear to be the model for regional geological/ geophysical programs.

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† National Academy of Sciences, Committee on Science, Engineering, and Public Policy (see chapter 3).

- PASSCAL expects that **seismic reflection profiling** will be a normal part of lithospheric seismology studies. It is hoped that COCORP and other groups doing reflection profiling will enter into the planning process and take part with PASSCAL in joint studies.
- PASSCAL seeks to open broad liaison among these initiatives, to promote optimum use of facilities, to strengthen long- range scientific planning, and to insure the participation of all interested parties in lithospheric studies.

The PASSCAL initiative is looking to the National Science Foundation for key agency support. Other government agencies with programs of research and extramural support which have much in common with PASSCAL are:

U. S. Geological Survey
Defense Advanced Research Projects Agency
Air Force Office of Scientific Research
Department of Energy
Nuclear Regulatory Commission
Office of Naval Research

- Regular communication with key people in these agencies is planned, and letters of understanding will be sought in instances where planned collaboration and sharing of resources may be mutually beneficial.

1.10. Industry Relationships

PASSCAL shares with the petroleum exploration industry many areas of interest in acquisition technology, data processing, and interpretation. Industry experience and knowledge in the techniques and technologies needed will be of greatest importance to PASSCAL. *(Chapter 11).*

- Close liaison with industry is planned to encourage communication of progress and experience in the different areas of modern seismic imaging, to explore parallel interests in instrument design, to use industry-designed data management schemes, and to share logistical and experimental experience.
- The seismological instrument companies are working closely with PASSCAL's instrumentation development committee. A **Society of Exploration Geophysicists (SEG)** liaison member now sits on the Standing Committee (K. Larner). It is hoped that joint activities with SEG will occur frequently in the form of research seminars, exhibits, technical papers, and visiting lecturers. It is planned to highlight PASSCAL results and progress at the annual SEG meeting with appropriate technical presentations.

1.11. International Cooperation

While many important studies can be done with the PASSCAL arrays within the U. S., the program will have significant international ties through scientific liaison, and international cooperative experiments, which will emphasize the need for technical compatibility between different national systems of instrumentation. *(Chapter 12).*

- PASSCAL plans a Council of Foreign Associates, the members of which will be invited to major PASSCAL meetings and receive minutes and proceedings of committee meetings and workshops.
- PASSCAL seeks support for international workshops, on subjects both scientific and technical, to further opportunities for joint international experiments and to share information on innovative instrumentation, data management, and new analytical techniques.
- PASSCAL plans liaison with the international community through a number of international organizations, including the Commission on Controlled Source Seismology (CCSS), the International Commission on the Lithosphere (ICL), the European Commission on Seismology, the European Geophysical Society (EGS), the European Association of Exploration Geophysicists (EAEG), COCRUST (Canada), CERESIS (Andean South

America) and others.

- Many important seismological experiments are outside the U. S., and will require extensive collaboration.

1.12. The Ten Year Plan and Budget

PASSCAL has developed a ten-year plan for building its program and resources. The Plan includes direct costs, such as design, purchase, and maintenance of equipment, facilities costs, and staff. It also provides for costs of data acquisition, particularly that associated with the large-scale cooperative studies that form the heart of the program. *(Chapter 13).*

- The plan involves a period (FY 85-87) devoted to design and testing, followed by a period (FY 87-91) in which staged buildup of resources to the full 1000 element array will occur.
- The budget is based on a mixed model for the way the instruments are utilized (§1.3); each year there is to be one large-scale cooperative experiment with essentially all the instruments (2-3 months), along with a combination of smaller projects by individual PI's and a longer-term deployment for earthquake recording.
- Projected annual steady-state costs, in constant 1985 dollars, which would apply in 1994 and onward are:

Instrumentation and equipment	$ 6.2 million
Maintenance and personnel	$ 4.6 million
Experiments and data acquisition	$ 3.0 million
Total	**$13.8 million**

- The expected budget totals for PASSCAL, exclusive of extramural support and IRIS Data Management Center support, but including funds to provide support services for experiments, are:

Year	**Budget**
FY 1985	$ 1.6 million
1986	4.7
1987	7.4
1988	10.2
1989	12.4
1990	13.5
1991	14.1
1992	13.1
1993	13.5
1994	13.9
Ten year total:	**$104.4 million**

1.13. Initial Program Period (FY85—87)

During the past year (FY 84), PASSCAL effort has been concentrated on:

Instrument definition
Organization
Development of this plan

The next three years are a critical period in which an operating organization must be put in place, technical development of the instruments and support facilities completed, and the scientific capabilities and limitations of large array deployments assessed in the field. *(Chapter 14).* The principal tasks will be:

- *Data logger definition and development.* Release of instrument specifications; competitive development and delivery of prototype instruments; procurement of the initial complement of instruments.
- *Sensor evaluation and selection.* Standard shaketable calibration of available sensors; initial development of portable broadband and long-period sensors, and a lightweight 1 Hz seismometer.
- *Field computer definition and selection.* System specification and emulation. Software development. Selection and procurement of initial systems.
- *Staffing and organization.* Hiring of Chief Scientist and Chief Engineer; studies to define detailed requirements for the support facilities; selection of prime contractor to operate support facilities and startup.
- *Pilot Field Studies.* Annual large-scale pilot experiments (1) to develop a base of experience with the operation of a large array, (2) to develop a base of experience in coordinating and utilizing many investigators and in simultaneously applying several seismic methodologies, and (3) to undertake studies of a technological nature to allow development and testing of new systems. These projects are essential to maintain continuity in the national effort in lithospheric seismology until the PASSCAL system becomes operational, and to build the broader base of participation that will be needed.

1.14. Support for University Research Participation

A primary purpose of PASSCAL is to enhance research opportunities for university scientists and their students, including in universities where state-of-the-art instrumentation is not otherwise available. The real potential of the PASSCAL instrumentation can be realized only if a substantial number of university research scientists can participate in instrumentation development, experiment planning, data acquisition, data analysis, and interpretation. While the special expenses of participation in the large-scale data acquisition activities are covered by the PASSCAL budget plan, funding for continuing research effort, including personnel, local computing capability, and the like, must come through the traditional route of individual project funding. *(Chapter 15).*

- Project funding for over 6 groups per year will be needed to support large-scale experiments.
- Project funding for a minimum of another 10 or more groups will be needed to support use of the PASSCAL instruments as smaller arrays (50-100 instruments) or for long-term deployment for earthquake monitoring.

Since PASSCAL will provide advanced general-purpose tools for seismic studies, we expect that a substantial proportion of U. S. seismologists will make regular use of the instruments, and that a commensurate proportion of project funding for seismology should be directed toward such programs.

2. PREFACE: THE PASSCAL PROGRAM PLAN

The PASSCAL initiative is probably the most complex cooperative venture yet undertaken in seismology; both the scope and complexity of its operations and the number of cooperating institutions are unprecedented in the experience of the scientific community studying the continental crust and lithosphere. It is necessary under these circumstances to formalize many of the understandings, plans, and procedures that are taken for granted in programs of less complexity. The PASSCAL Standing Committee, therefore, has undertaken to put together this Program Plan, which spells out the goals, rationale, constraints, plans, understandings, financial projections, and technical issues which define the status of the evolving Program.

The Program Plan is expected to serve as:

(1) A baseline document, to which PASSCAL Committees and participants may refer in the near future in their deliberations, which spells out the equivalent of "official policy".

(2) A Program summary that can be used more broadly by IRIS member institutions, by cooperating agencies and consortia, by international collaborators, and by funding agencies as a source of information about the Program.

(3) Supplemented as appropriate, a source of information to the interested public, including the Congress, science writers, students, and advisory bodies to the government.

(4) A reference document in support of the IRIS proposal to the National Science Foundation. The portion of the IRIS proposal concerning PASSCAL is drawn with little modification from Chapters 1, 3, 14, and 15 of this Plan.

This Program Plan was prepared by members of the PASSCAL Standing Committee and by additional invited participants (Appendix C), at a special meeting in Princeton, July 12-16, 1984. The drafting committee had available as input the conclusions and deliberations of the PASSCAL Standing Committee, the Instrumentation Committee, other committees, and from a series of meetings that began in fall, 1983, aimed at organizing the community for a coherent new initiative in lithospheric seismology (Appendix D). The Plan was adopted by the Standing Committee at a meeting in Golden, Colorado, on August 18, 1984. In addition, we are indebted to many other colleagues, participants in the PASSCAL organizing process, and others from university, government and industry who have kindly commented on the draft of this Plan. The PASSCAL Standing Committee is deeply appreciative of their helpful criticism in support of this Plan. The burden of responsibility for any omissions or errors in this Plan will, however, lie with the Standing Committee.

This Plan is written as a successor document to the National Academy of Sciences report, Seismological Studies of the Continental Lithosphere (1984) [SSCL], which contains a full rationale for the great importance of a modern lithospheric seismology effort, along with substantial discussion of the problems to be addressed, and the methods that could be used. Where a chapter or section of SSCL is singled out in this document, it should be regarded as an official element of the Plan itself.

As the program develops, it is anticipated that the Plan will be reissued annually in revised form, to reflect updated conditions and more fully developed detail. The Standing Committee may wish, subject to specific needs for consultation, to adopt interim changes to the Plan during the year, so that it may properly serve as a statement of the PASSCAL status. Particularly, the information gained from special technical or design studies and from recent scientific advances will be incorporated as appropriate quite regularly. In this key sense, then, the Plan is a working document. However, some of the material, such as Chapter 10, which deals with scientific management and coordination and directly guarantees the role of participating scientists and institutions, will be formally adopted as legislation by the PASSCAL Standing Committee, and submitted for adoption by the IRIS Board of Directors. Thus, the Plan contains formal legislation, which may be changed only through established modes of consultation, such as are spelled out in Chapter 10.

The Standing Committee of PASSCAL welcomes written comments on any aspect of the Plan, at any time. The process of consulting with so many constituencies and participants, and of keeping up with key events and technological advances is an imperfect one, and all constructive suggestions and criticisms are greatly appreciated.

3. SCIENTIFIC RATIONALE, SCOPE AND PURPOSES

The plate tectonics revolution in earth science, now 20 years old, was largely the fruit of more than two decades of exploration of the ocean basins. Spectacular breakthroughs were made in understanding of the earth using information from marine research methods, deep-sea drilling and geophysical measurements, to name just two. Ironically, among the most remarkable of the discoveries was that no oceanic crust is older than about 200 million years, less than 5% of the age of the earth. The key to understanding the whole of earth history, therefore, lies dominantly in the study of the continents, where the accessible geologic record extends nearly 4 billion years into the past.

Our present understanding of the continental lithosphere shows it to be immensely complex, a collage of superimposed collisional terranes, suture zones, subduction-related volcanic and orogenic belts, extensional features, hot-spot traces, and the like. The fundamental importance and rationale for understanding the origin and evolution of the continents in light of these complex processes is summed up briefly in the 1984 National Academy of Sciences, *Seismological Studies of the Continental Lithosphere* (SSCL):

" The continents are the part of the earth on which we live, and are the terranes from which we will continue to derive the bulk of our natural resources. We are subject to natural hazards that are both the direct result of modern plate motions, such as earthquakes and volcanic activity, and the indirect result of processes far from modern active boundaries, such as earthquake activity that is apparently unrelated to plate motion and for which we have no process on which to base prediction theory, or the sinking of continental margins long after they cease to be part of an active system." [†]

In recent years have emerged what are now recognized as unprecedented opportunities for major advances in the scientific understanding of the continental lithosphere, through the combined application of powerful new instrumentation and computer-based techniques for analysis of very large volumes of data. To capitalize on these opportunities, earth scientists are joining in large cooperative ventures, including PASSCAL, that are analogous to the deep-sea drilling program, where diverse scientific interests are organized around the advanced technological capabilities of expensive and highly sophisticated research vessels.

In response to the recognition of the importance and complexity of the continents, recent reports have recommended a strong new national effort for their study that takes particular advantage of new technologies. The 1983 National Academy of Sciences report, "Opportunities for Research in the Geological Sciences"[1] highlighted the importance of new initiatives in lithospheric seismology, deep drilling, global seismology, and laboratory instrumentation. This was followed by the 1983 Research Briefing to the White House Office of Science and Technology Policy[2] (the "COSEPUP Report") whose Panel on Solid Earth Sciences highlighted the study of the continental lithosphere as an area of highest priority for new initiatives. The five areas identified by this panel are:

...seismic studies of the continental crust and lithosphere
...global digital seismic network
...continental scientific drilling

[†] Seismological Studies of the Continental Lithosphere, 1984, Panel on Seismological Studies of the Continental Lithosphere, Committee on Seismology, Board on Earth Sciences, Commission on Physical Sciences, Mathematics, and Resources, National Academy Press, Washington, D.C.

[1] Opportunities for Research in the Geological Sciences, 1983, Committee on Opportunities for Research in the Geological Sciences, Board on Earth Sciences, Commission on Physical Sciences, Mathematics, and Resources; National Academy Press, Washington, D. C.

[2] Research Briefings, 1983, for the Office of Science and Technology Policy, the National Science Foundation, and Selected Federal Departments and Agencies; Committee on Science, Engineering, and Public Policy of the National Academy of Sciences, National Academy of Engineering, and Institute of Medicine; National Academy Press, Washington D. C.

...physics and chemistry of geological materials
...satellite geodesy

A detailed scientific justification for the importance of a new initiative in seismic studies of the continental crust and lithosphere was given by the National Academy of Sciences Report "Seismological Studies of the Continental Lithosphere"[3] [SSCL], which also made specific recommendations about the tasks of the new program. The discussions in SSCL cover the geological targets and the seismic methods that could be brought to bear using a large portable array. We regard this Plan as a follow-up to SSCL, and cite the discussions in SSCL as a part of our rationale.

PASSCAL has been organized by the scientific community as a vehicle for the realization of this recommended new initiative in seismological studies of the continental lithosphere. It is a program under the Incorporated Research Institutions for Seismology (IRIS), a corporation with nearly 40 member research institutions that was formed in May 1984 to serve as manager and operator for large cooperative initiatives of this sort. PASSCAL will enable earth scientists to investigate the structure and dynamical processes of the continental lithosphere in geologic detail to great depths, and at resolutions that are significantly superior to those previously attained. The program is based on a vigorous exploitation of newly-developed technology to bring forth a new system of portable seismic instrumentation of unprecedented power and versatility. The ten year Plan, 1985—1994, envisions the acquisition of at least 1000 of these new generation portable digital seismographs and their utilization to address a host of fundamental questions about the earth.

3.1. Justification for the PASSCAL Array Instrumentation

The justification for a new generation of portable seismic instruments deployed in arrays is very simple indeed; it will produce qualitative breakthroughs on a wide variety of fundamental problems in the study of the continental lithosphere. For the first time instruments can be sufficiently closely spaced to resolve subsurface details and give a faithful spatial representation of all the common types of seismic wavefields. The salient characteristics of this system are:

Its large number of digital instruments;
Its large bandwidth, wide dynamic range, resolution, etc.;
Its multicomponent, multipurpose sensors;
Its flexibility and portability; and
Its calibration and standardization.

While existing programs have embodied some of these features, the combination of them all in the PASSCAL array will permit a revolutionary improvement in capabilities that can be applied to a plethora of seismological and structural-tectonic problems. In particular, once the imaging of the lithosphere reaches a geologically significant resolution (ca 100m—1 km), the results begin to have a direct usefulness to society in many ways. Impacts will be felt in relation to mineral resources, energy reserves, mitigation of natural hazards, and waste disposal. PASSCAL is an ingenious and cost-effective scientific solution to the needs for society to understand the nature of the earth beneath its feet.

Two distinct abilities arise from the large number of instruments. The use of hundreds of sensors will lead to resolution of subsurface geologic features at scales mapped by geologists at the surface. For example, the difference between the 10 km resolution possible with the current number of instruments used for lithospheric tomography and the 1 km or better possible with PASSCAL is the difference between a fuzzy, averaged image of a lithospheric structure and a sharp one that can be correlated with the geology. In addition, the larger number of instruments will permit earthquake locations, focal mechanisms, and rupture mechanisms to be

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[3] Seismological Studies of the Continental Lithosphere, 1984, Panel on Seismological Studies of the Continental Lithosphere, Committee on Seismology, Board on Earth Sciences, Commission on Physical Sciences, Mathematics, and Resources; National Academy Press, Washington, D. C.

determined far more precisely than is now possible. A significant qualitative breakthrough will occur because enough sensors will be available to sample the wavefield without spatial aliasing at frequencies up to 30 Hz. This opens up the full range of powerful wavefield-processing methods that have been so important in reflection prospecting for hydrocarbons, in medical imaging, and in radio astronomy. Seismic imaging techniques (e.g., migration and waveform inversion) that were hithertofore used only for seismic exploration data can be applied to a wider frequency band and over a larger spatial scale. Extension of coherent wavefield processing methods to the study of earthquake sources and earthquake signal propagation will be a significant step forward.

The digital nature of the recordings is also essential, since it allows large data sets to be analyzed rapidly with modern, computer-based methods. The large bandwidth, wide dynamic range, and high resolution of the instruments permits a variety of sizes and types of sources to be observed in a single experiment, and will facilitate large multi-disciplinary experiments that actually consist of several simultaneous individual experiments.

Three components of ground motion will be recorded routinely, so that both P and S waves and their polarizations can be studied. While previous experiments have often treated the earth as an acoustic (fluid) body, recording both P and S waves in three components will permit more realistic elastic (solid) models of the earth. Additional special-purpose sensors such as accelerometers will allow experiments directed towards engineering and earthquake source studies.

The flexibility of the instruments, notably their capacity to be configured in many different ways, greatly facilitates interdisciplinary studies. The possibility of simultaneous recording of both artificial sources and teleseisms, for example, will encourage cooperation between students of structure and students of the earthquake process. Other, even more disparate disciplines, such as exploration seismology, and earthquake engineering, can benefit from the array deployments. An important use of the PASSCAL instruments may be to augment existing analogue, short-period telemetered networks (over 1500 instruments in the United States). The PASSCAL digital multi-component broad-band seismographs can be used to replace and supplement regional networks where special needs exist.

Finally, standardization will have substantial benefits. Quantitative intercomparison of results from different experiments will be possible. PASSCAL will be able to maintain calibration and quality control through its support organization, and, by establishing PASSCAL standards, will encourage the expansion of the standard technologies into other branches of seismology and earth science.

3.2. Scientific Capabilities of the PASSCAL System

We can address the usage of the PASSCAL arrays from three viewpoints: topical, methodological, and logistic depending upon whether we are focusing on the scientific object of the study, the seismological techniques being employed, or the type of planning that goes into the experiment, respectively.

3.2.1. Problems that can be addressed by PASSCAL

The most fundamental viewpoint is topical. Large portable arrays can be used to address a wide variety of lithospheric problems, as well as important seismological questions of broad interest. Possible topics of application include:

A. *Broad lithospheric structures*

- continental transects (Atlantic Coast to Appalachians, Midcontinent to Gulf Coast, Pacific Coast to Rocky Mountains)
- ocean-continent interactions, especially convergent margins (subduction zones), rifting and passive margins, and transform faults

- Moho and sub-Moho structures
- shields and their mantle roots (tectospheric studies)
- three-dimensional lithospheric, including upper mantle, heterogeneities

B. *Lithospheric processes*

- basin formation and extension
- continental terrane accretion
- detachment tectonics
- hot spots
- volcanism

C. *Continental lithospheric heterogeneites*

- Moho and intracrustal discontinuities; their origin and relationship to tectonics, heat flow, composition, pore pressure, etc.
- Lateral variations in structural layering and their relationship to age-tectonic provinces, active tectonics, geochemical compositions, elevation, heat flow, etc.

D. *Processes and properties*

- micro-profiling: detailed scale studies to determine the relation between outcrop geology and seismic response.
- studies of exposed cross-sections of continental crust: e.g., Kapuskasing, Bay of Islands, Ivrea, Wind River mountains.
- correlation with continental scientific drilling program (CSDP): seismic studies of velocities and attenuation around drill sites for comparison with in situ and laboratory results.
- special structures: calibration of the seismic characteristics of exposed faults and igneous bodies, as well as characteristic metamorphic-structural styles in gneisses.

E. *Small structures*

- listric and low-angle faulting
- crustal low-velocity zones
- batholiths, volcanoes, faults, domes, and other compact structures
- induced seismicity due to loading or hydrofracturing

F. *Sub-lithospheric structures*

- 400-and 670-km discontinuities
- mantle low-velocity zone
- core-mantle boundary

G. *Earthquake studies*

- seismicity, including foreshocks and aftershocks, hypocenter locations, and focal mechanisms
- rupture mechanics including observations of rupture initiation and propagation, asperities and barriers, stress-strain interactions
- engineering and strong-motion seismology

H. *Wave propagation studies*

- lithospheric phases such as P_n, S_n, P_g, L_g, and coda waves
- seismic attenuation
- anisotropy

- core phases, surface waves, and noise

I. *Volcanology*

- harmonic tremor
- volcanic earthquakes

J. *Laboratory studies*

- calibration for P- and S-wave velocities of different rocks at high pressures and temperatures
- determination of the effects of pore pressure or partial melts on velocity and attenuation
- development of relationship to solve for elastic properties from velocity and attenuation

3.2.2. Methods

A second viewpoint is the type of methodology that is employed to study any particular subject. The PASSCAL array is designed so its configuration is sufficiently flexible and its data are of sufficient quality that many different kinds of analysis techniques can be applied. These include:

- *Reflection methods*, in both linear and two-dimensional array deployments, and where migration processing techniques are employed.
- *Refraction methods*, in linear, two-dimensional, and fan configurations, where both travel time and waveforms are used to determine structure.
- *Tomographic imaging* with 1—5 km resolution (30 by 30 km to 150 by 150 km deployment area) using travel times and waveforms from densely-spaced instruments.
- *Full waveform inversions and holography.*
- *Wavefield decompositions* by transform methods (e.g., frequency-wavenumber analysis).
- Azimuth and ray parameter *beamforming.*
- *Polarization analysis.*

3.2.3. Logistics

The third viewpoint for the discussion of array experiments involves experimental logistics:

- *Number of instruments.* PASSCAL array deployments will range from very large experiments involving the complete set of 1000 instruments to small experiments involving 50 instruments or less. By their very nature, large experiments will differ in style from small ones. Large experiments will need to be cooperative multi-institutional efforts, if only because the workforce of several institutions will be needed to deploy the array and handle the data. This multi-institution nature will be exploited by using the array simultaneously in several different modes or for several different simultaneous experiments. For instance, a single deployment of the array could be used for a structural study using artificial sources and for determining seismicity patterns from microearthquakes. Some larger experiments will also involve some degree of cross-discipline or international cooperation. For instance, structural studies on the continental margin might be supplemented by ocean-bottom instruments, and ships equipped for multichannel seismic recording, and offshore sources. In contrast to these large-scale experiments, many smaller experiments will be run by single institutions and will be focused at a single problem or a set of closely-related problems.
- *Deployment time.* Experiments will last from as short as two weeks to as long as a year or more.

- *Controlled or natural sources (or both).* The main practical difference between these uses of the array is not only in the expense of explosives or vibrators used as controlled sources, but in the amount of data collected. Experiments involving only artificial sources will typically generate substantially fewer data than experiments utilizing aftershocks or other active earthquake sources. Data processing is a much more complex task when earthquake sources are involved, for each event must be correlated across every recording channel of the observing array. Moreover, the availability of S-waves from earthquake sources means larger quantities of useful data will be collected for each event.
- *Difficulty of access.* While many array deployments will be in areas accessible by trucks or four-wheel-drive vehicles, we anticipate that some will require the use of helicopters or ships.
- *Predictability of sources.* The timing of controlled sources can of course be pre-planned. In many instances, natural sources such as microearthquakes and teleseisms will occur with sufficient frequency that they can be counted upon even in short experiments lasting only a few days or weeks. On the other hand, events such as large earthquakes nearby will be very infrequent, so that long periods of waiting will be necessary to record even a single event. Nevertheless, these experiments could be attempted either as a secondary mode of an experiment with a different primary objective, or during a period when the instruments are not needed for other experiments. Finally, there will be occasional earthquakes of such magnitude or importance that full-scale unscheduled deployment of the instruments will be undertaken to record its aftershocks.

3.2.4. Examples

In the following, we present hypothetical experiments that illustrate how topical and methodological goals and logistic requirements or restrictions may be combined. This list is not meant to endorse any particular experiment (either in type or geographical location) but rather to emphasize the range of good science that can be pursued. More detailed descriptions of some of the experiments can be found in Chapter 6.

3.2.4.1. Major Lithospheric Experiments— Two- and Three-Dimensional studies

1. Refraction and reflection to distinguish thick-and thin-skinned thrust models of the southern Appalachians, Charlotte-Kings Mt. Belt.
2. Wide-angle reflection/refraction and earthquake tomographic study of the Columbia Plateau to determine the lithospheric structure of this largest continental volcanic complex in the United States and to evaluate its association with oceanic or continental crust.
3 Long Valley, California, multi-method controlled-and natural-source study of a shallow magma body and its related fault systems; in combination with existing fixed array and boreholes.
4. Reflection and tomographic study of the Wasatch fault zone (Utah), to trace surficial faults to depth and to examine the structural style of an active fault; areal deployment.
5. Seismic imaging (using both natural and artificial sources) of the Idaho or Sierra Nevada batholiths to determine their structure and geometry, to infer the source and volume of parental magma, and to examine the nature of the underlying igneous feeder systems of major batholiths; areal deployment, using both controlled and natural sources.
6. Test of model of continental accretion in Alaska; linear deployments, narrow-to wide-angle reflection and velocity determination, integrated with other geophysical and geological studies.
7. Study of the Colorado Plateau, to evaluate the lithospheric-aesthenospheric properties of this stable cratonic plateau; large-area deployment with maximum use of natural sources supplemented by explosions.

8. Passive continental margin refraction experiment (North Atlantic margin); combine with existing marine data.
9. Pan-cordillera tomographic experiment to study large scale (100 km) heterogeneities in the upper mantle from Alaska to California; sparse areal deployment, using natural sources.
10. Ouachita Mountains... to examine the structure of a major Paleozoic orogenic belt to depths >100 km; detailed linear arrays, narrow to wide angle, with explosive sources. Followup of a COCORP line.

3.2.4.2. Special-Purpose Large Experiments

1. Passive/active monitoring of the $M=7.3$ Borah Peak (October 28, 1983) earthquake area; areal arrays for detailed imaging of aftershock processes. Detailed linear reflection arrays for tracking of active fault.
2. Aftershock study of a magnitude 7+ earthquake; unscheduled deployment in response to an important natural event.
3. Resolution of the fine structure of the Moho discontinuity; overlapping Expanding Spread Profiles (ESP) over a portion of a well-recorded reflection profile showing clear Moho structure.
4. Observation of the rupture process of a moderate-sized fault; dense linear subarrays arranged radially about the fault to cover much of the focal sphere.
5. Seismic anisotropy in the continental crust and upper mantle; travel time and polarization analysis using arrays of three-component instruments.
6. Long-range DSS profile of lithosphere in the craton and in the cordillera; linear array of 1000 instruments, explosive sources, offsets out to 3000 km.

3.2.4.3. Smaller Experiments

1. The mode of wave propagation and source mechanism of volcanic tremor; waveform decomposition with a dense, linear array.
2. Observation of P-waves diffracted around the core-mantle boundary; dense, linear 100 km long array that is slowly leapfrogged across 1000 km.
3. Study of aftershocks of a medium-magnitude earthquake in eastern North America; areal deployment of 100 instruments.
4. Properties of regional lithospheric seismic phases and coda waves.
5. Microzonation experiment to evaluate amplification by surface geology; in cooperation with earthquake engineers.
6. Mapping the rupture of a hydrofracture; performed during a stress measurement in conjunction with a drilling program.

3.3. Planning for scientific utilization of the PASSCAL system.

Developing models for specific experiments that might be carried out has been an important aspect of defining the parameters for large mobile seismic array studies. These models help to define the actual scientific gains expected, and to provide numerical estimates of costs, personnel, time, equipment, and support services needed. They are also intended to stimulate interest in the geological and seismological communities in planning for the use of the array as it becomes available. A comprehensive discussion of the capabilities of a 1000-instrument multi-channel system in terms of type experiments and goals can be found in the National Academy report [SSCL, 1984].

In **Chapter 4**, we discuss the use of portable arrays for conducting controlled-source experiments. This includes a discussion of the current state of the art in reflection and wide-angle reflection/refraction studies and a comparison with tomographic and wavefield inversion methods. We highlight a comparison of the PASSCAL system with the seismic reflection profiling being conducted by the COCORP program, and show the essentially complementary nature of these approaches.

In studies using natural sources, PASSCAL instrumentation provides significant advantages over presently-available tools such as regional and global networks. **Chapter 5**, explores the impressive variety of problems that can be attacked with mobile array seismology, from earthquake source physics to lower mantle structure to three-dimensional velocity determinations in seismic regions. These capabilities make the PASSCAL mobile seismograph system a natural partner to the Global Seismic Network (GSN) now being organized under IRIS.

Finally, a set of concrete examples of possible PASSCAL experiments in **Chapter 6** illustrates these ideas in the context of studies of critical geological targets. We present examples of large cooperative experiments, small, single- institution experiments, and the uses of passive deployment in the form of a temporary network.

3.4. Insturmentation, support services, and data management.

The backbone of PASSCAL is the large digital array itself. For the past 8 months, following the special meetings on instrumentation in Salt Lake City (April 1983)† and Los Altos (November 1983), and the PASSCAL organizational meeting in Madison (January 1984), the Committee on Instrumentation (Appendix C) and its panels have been meeting to develop a plan that will lead to the new instrumentation being defined, designed, and produced for acquisition by PASSCAL. The Committee has found that existing designs, even those that use the most advanced technology, have been conceived to meet specific needs of a particular type of experiment, and lack both versatility and adequate provision for future modifications and additions. The needed instruments do not exist, and the available instruments are few, unmatched, and obsolete. The demand that the PASSCAL instrumentation actually have the flexibility to serve for the wide variety of studies that exploit the frequency band 0.01-50 Hz has led the Committee to propose the development of a class of compatible bus-oriented data loggers which go beyond those now available, but which make use of available technology. A detailed exposition of the conclusions of the Instrumentation Committee, to date, and its plan for developing, testing, and deploying the new instruments are given in **Chapter 7.**

The mechanics of maintaining a large complement of instruments in working condition, and of insuring that their deployment and retrieval are properly handled require that PASSCAL maintain facilities, vehicles, and support staff. The complex series of steps by which data are retrieved from the temporary memory or recording medium of the field instruments and converted into a fully documented, edited collection of event data sets in a data archive requires coordination between support operations and the PI's responsible for the data. In **Chapter 8** we present an analysis of the closely related questions of field support and data retrieval. A plan is presented for the establishment of PASSCAL support facilities, including a central support

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† The chronology of meetings is found in Appendix D

facility, vehicles, and field computers; preprocessing services will occur at the IRIS Data Management Center. We also highlight a management plan for large multi-institution cooperative field experiments, in which PASSCAL provides the support for participation by PI's in the data acquisition.

The IRIS Data Management Center (DMC) is the subject of a separate Plan and Proposal, somewhat parallel to this Plan in concept. Its purpose is to provide a digital data archive for IRIS and related geophysical data to which all investigators can have access. The large quantities of digital data expected from the PASSCAL array, including the special need for front-end data processing, define the very high performance specifications that must be planned into this program from the start. The particular needs of investigators for access to data sets of substantial size and for browsing or searching of the data bases further serve to define the performance required. In **Chapter 9** we specify a model for these demands on the DMC. This includes a model for the quantities and types of data to be expected from the PASSCAL system, and a model for the demands that seismologists will make on the DMC in the course of their analysis of PASSCAL experiment data. This model is presented for the use of the Standing Committee on Data Management in developing its own Plan.

3.5. PASSCAL organization, terms of reference, and outside liaison

We turn from scientific, technical, and logistical issues to those concerned with coordinating people and institutions into a successful program and with coordinating the PASSCAL program with other earth science initiatives.

The PASSCAL Standing Committee, with abundant help from many in the seismological community, has been involved over the past year in establishing mechanisms and guidelines for operation that meet the scientific, technical, and organizational needs of future scientific users, other major scientific programs, and the funding agencies. Specific concerns have focused on procedures for planning, scheduling, and coordinating large experiments, for providing granting agencies with objective expert advice in evaluating research proposals requiring use of PASSCAL facilities, and for coordinating PASSCAL activities with those of GSN and other scientific programs. These issues are not easily resolved, given the large number of cooperating institutions in PASSCAL and the strong tradition of local autonomy that characterizes the participating scientific community. In **Chapter 10** we set forth our current "terms of reference", which constitutes a management manual for the scientific coordination and planning side of PASSCAL. In addition, we discuss the management *sensu strictu* of PASSCAL facilities and services, and spell out the chain of consultation and responsibility that links these operational centers with the Standing Committee and with IRIS management.

In **Chapter 11** we review the evolving landscape of new initiatives and consortia in earth science, and set out the relationship between PASSCAL and other major institutional efforts, including the four other COSEPUP initiatives being coordinated by NSF, other programs in reflection seismology, regional consortia of geologists and geophysicists, the exploration industry, and U. S. government agency programs. The need for close liaison with all these groups is clear; PASSCAL will need to take a major role particularly in coordinating the advance planning for large-scale multidisciplinary field programs. Close industry liaison is a major priority, owing to the similarity of the field and data processing techniques and the common goal of obtaining high imaging performance. Support of PASSCAL experiments by U. S. government agencies other than NSF is expected to be an important component of the support profile of PASSCAL; early and continuing communication with relevant agencies is critical.

There will be no want of scientific rationale to keep a 1000-instrument array busy on many important problems within the United States. And since PASSCAL is such a major national effort, there may be a natural sentiment to regard international cooperation for the use of large arrays as a matter of somewhat limited priority. We reject this view. In **Chapter 12** we review the strong degree of international collaboration that has marked the field of lithospheric seismology over the past 20 years. Especially notable has been the spirit of cooperation shown by our foreign colleagues and institutions in helping U.S. investigators through recent periods of inadequate instrumentation and analysis resources. Therefore, we take particular notice of opportunities for continuing this collaboration, and of seeing that PASSCAL benefits international science in the broadest sense. The eventual goal of an international effort would be experiments involving important geologic targets not accessible in the U.S., such as a downgoing slab in a region of deep focus earthquakes.

3.6. The PASSCAL Program Plan

Chapter 13 summarizes the elements of the Program Plan, as drawn from the preceding chapters. We set forth a series of models that serve as a baseline statement of how we expect the Program to proceed. These models contain quantitative estimates of facilities and staff requirements, of levels of effort in field and data analysis, of the magnitude of university-sponsored projects, and of the budget levels demanded by these figures. The projections are first cast as a static, steady-state model, and then elaborated into a ten-year plan for growth to a hypothetical steady state.

Detail of the proposed Plan for the first two years is given in **Chapter 14**, which is in effect a specific funding proposal for the initial funding period of PASSCAL, from 1 February 1985 to 31 January 1987. This proposal also sets forth the intention of PASSCAL to sponsor major collaborative field programs during this initial period, using available hardware resources. The recommendation that PASSCAL be active from the start in carrying out key field studies is a central part of this entire Plan; delay of field operations until the new instrument designs become available would be a highly damaging strategy.

It is not possible to put in place a major initiative in field geophysical data acquisition, with its institutionalized support structure, without insuring that the financial support available to participating universities is adequate to permit their involvement in all key phases of the work. For most experiments, both large and small, personnel will be required above the level of PASSCAL staff support, and these personnel must be supplied by the sponsored research projects of the participating PI'S. Moreover, the existence of enough active PI groups to provide leadership, to manage the experiment data, and to analyze the results will be dependent on the provision of enough sponsored research funding. Finally, most participating PI groups will require local computing power in the form of high-capacity graphics workstations or micro-based systems, at the minimum. Support for these local facilities will be required. These issues are discussed in **Chapter 15**, and some cost estimates presented.

4. CONTROLLED-SOURCE STUDIES WITH A LARGE ARRAY OF PORTABLE INSTRUMENTS

This chapter highlights the opportunities that the novel PASSCAL instrumentation provides for various kinds of seismic studies using controlled (i.e. man-made) seismic sources. We emphasize, however, that the much increased capabilities of the new microprocessor-based seismographs over previous instruments greatly blur the once sharp distinctions between experiments utilizing controlled versus natural (earthquake) sources. Many PASSCAL experiments will be configured to record both controlled and natural events simultaneously. Thus, while convenient from an historic perspective to discuss controlled-source experiments separately from those which use natural sources, future PASSCAL experiments will almost certainly use the entire range of seismic sources. This unified seismic approach will yield the essential velocity, reflectivity, anisotropy, and Q structure necessary for geologic inferences about the composition, structure and processes of the deeper lithosphere. In addition, the detailed knowledge of structures represented by the distribution of velocities and densities throughout the crust and lithosphere directly yields societal benefits by allowing us to address such important problems as energy and mineral resources, earthquake risk, and waste disposal.

Traditional studies of continental lithospheric structures have used refractions and wide-angle reflections recorded from the wavefield generated by chemical and nuclear explosions. For decades this approach has formed the basis for controlled-source seismic experiments throughout the world. These experimental techniques rely upon the recording of explosions, fired near the earth's surface, whose origin time and location are precisely known. Data are typically recorded to distances of a few hundred kilometers and in some cases with large nuclear explosions to thousands of kilometers along linear profiles.

A variation on the controlled-source technique, developed and exploited principally by the oil industry is the use of large truck-mounted vibrators, known as Vibroseis†. With the Vibroseis technique, a vibrator repetitively produces vibrations of controlled modulated frequencies with relatively low amplitudes. The recorded wavefield data are processed to provide equivalent impulse (e.g. explosive source) seismograms. Industry developed the Vibroseis technique and employed it utilizing hundreds of field crews to provide the bulk of seismic reflection data on land.

Limitations of the controlled-source techniques include limited source energy compared to earthquakes, and minimal shear-wave energy. (Shear vibrators have been recently used for special surveys, however.) Nevertheless the controlled-source seismic methods have provided detailed reflectivity pictures of the layered lithosphere. For example, the M-discontinuity, a major seismic discontinuity, is world-encompassing. It occurs in continents at depths from 20 to 50 kilometers and is generally taken to represent the boundary between crust and mantle. The M-discontinuity has been mapped primarily on the basis of refraction and wide-angle reflection information. Intermediate crustal discontinuities, evidence of low-velocity zones, anisotropy, and velocity variations in the upper mantle have been seismically imaged using refraction and wide-angle reflection data from both earthquakes and controlled sources. Recently the COCORP program,‡ has been extremely successful in producing CMP (common mid-point) near-vertical incidence reflection sections in the U. S., by employing the Vibroseis techniques of the exploration industry, almost without modification. Of all geophysical techniques for exploration of the lithosphere — short of actual drilling — seismic techniques have offered the least ambiguity and the highest resolution. Taken together with information on physical properties of the earth from earthquake data, laboratory investigations and petrological studies, controlled seismic experiments provide the basis for understanding the structure, history, and origin of the continental lithosphere.

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† Registered service mark, Continental Oil Company

‡ Consortium for Continental Reflection Profiling

4.1. Historical Perspective

Wide-angle reflection and refraction studies of the continental lithosphere have been actively pursued since the late 1940's. At that time research institutions and (later) USGS groups had seismographs primarily with single-component sensors which were typically deployed along profiles at spacings of 10 km or more. During the 1970's FM-recording seismographs allowed the deployment of linear subarrays where station spacing could be reduced to a few kilometers. Still, only a few tens of instruments were available for recording profiles over hundreds of kilometers in length. Large-scale experiments involving numerous shot points were few. Often, repeated quarry blasts were the only energy sources available. Nuclear test explosions were occasionally utilized, but because of the limited source area in the western United States and the Aleutians, they provided detailed coverage in only restricted areas. Some examples of early refraction data are shown in Figure 4-1.

Despite these serious experimental limitations, results of early experiments showed that the crust and upper mantle were indeed heterogeneous at scales of hundreds to tens of kilometers and less. Detailed study of both crustal and mantle heterogeneities was seriously limited by a lack of resolution, a direct consequence of insufficient instrumentation, resulting in large distance intervals between recorders and a paucity of high-quality data. Additionally, analysis and interpretation techniques were largely limited to relatively simple models. Developments in theoretical and numerical methods of seismic analysis such as synthetic seismograms, wavefield imaging and tomography have now eliminated this difficulty. The Deep Seismic Sounding (DSS) technique employed by the Soviet seismologists for deep-crustal studies in the 1960's and 70's reemphasized the importance of the seismic method in providing higher-resolution information on the deep crust. DSS techniques are based on dense seismometer spacings (typically 100 m) along observing lines hundreds of kilometers long. Geophone spacing is such that dominant wavelets could be correlated from one station to the next with little or no aliasing. In the mid-1960's the European Seismological Commission established the first cooperative working group and developed a standard FM-recording three-component seismograph; eventually 125 units were distributed to a number of universities. This effort provided more than 100 lithospheric profiles throughout Europe, including some that approached the DSS standard in closeness of station spacing.

Support for deep crustal seismic sounding programs in the U.S. waned during the late 1960's and through the 70's, partly as a consequence of the demise of the DARPA-supported VELA UNIFORM program, but also because of a lack of innovations in methodology and especially of instrumentation to achieve improved resolution in imaging the subsurface. Over the course of the past several years, however, crustal sounding methodologies have witnessed an extraordinary revitalization, gained through a confluence of important technological advances in microprocessor-based instrumentation, in digital data processing, and in seismic wavefield analysis. The oil industry has moved aggressively to transform these advances into vastly improved seismic reflection techniques and now has the technical capability to image complex structures in three dimensions. Although the greatest technical advances to date have come in reflection techniques, special studies by the U.S. academic community and the U. S. Geological Survey employing the high-resolution refraction methods have continued to make important sophisticated seismic advances. Multichannel, multi-ship experiments on the oceans have been used widely for many years, but on land, sophisticated seismic experiments have progressed much more slowly. This is in part because of the previous lack of a PASSCAL-type organization that would bring together the instrumentational, scientific and technical skills of the many U.S. academic institutions. This pooling effect is required for such large projects.

The breakthrough achieved by the COCORP program in the late 1970's of putting modern reflection seismic methods to work on the imaging of the continental crust below the sediment cover has demonstrated the intrinsic power of modern seismic methods. COCORP's contribution has been to demonstrate the geological significance of the seismic reflection method (even at depths below the sediments) and to provide a series of geologically stunning reconnaissance profiles across targets of longstanding controversy.

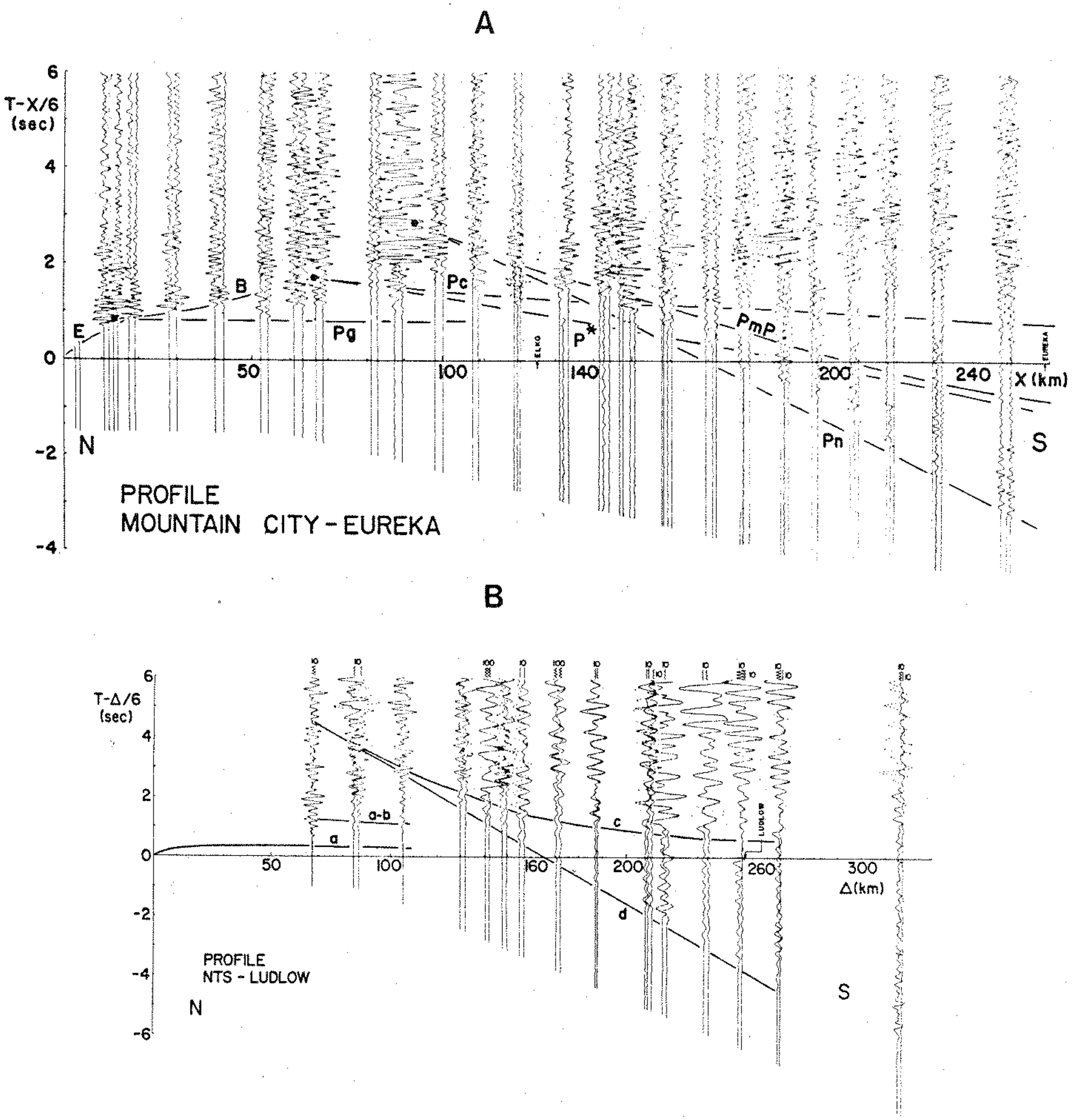


Figure 4-1. Examples of seismic refraction data recorded circa 1965, U. S. Geological Survey. (a) Mountain City, Nevada to Eureka, Nevada profile. (b) Nevada Test Site (NTS) to Ludlow, California profile. While these and similar profile data have yielded much information about the crust, the sparseness of the station and source array and the lack of adequate amplitude and waveform definition precludes other than simple regional modelling of the data. (From Prodehl, USGS Prof. Paper #1034, 1979)

One impetus for the PASSCAL initiative derives at least in part from the host of new questions raised by COCORP results; questions about the velocity structure and nature of the deeper crust, the Moho, and the underlying lithospheric mantle; questions about the nature of layering in crystalline rocks and the relation between this layering and the nature of seismic signals seen at narrow and wide angles. The other major impetus is to bring to fruition the technological advances of the microprocessor-based recording options in flexible array configurations, combining the advantages of the new data with those of the powerful new analysis techniques.

Several studies undertaken in the past few years have demonstrated the potential of new technologies and techniques. Two examples serve as illustrations.

Enhanced capability for detailed crustal studies came with the acquisition of 120 portable single-channel matched analog seismographs by the U.S. Geological Survey. Among the better examples of studies made possible by the new instrumentation is that of the Salton Trough, Imperial Valley, California (Figure 4-2). Seismic refraction data are shown in Figure 4-3 along with a ray tracing model and interpreted velocity cross-section. A complex velocity model of the Imperial Valley was made possible by the high density of recording stations and shotpoints. The seismic results reveal important new tectonic features of the Salton Trough rift zone. Fuis *et al*, Jour. Geophys. Res., 1984 interpret the Salton Trough as a region in which new crust is being generated. Mafic rocks (indicated by high velocities near 14 km depth in Figure 4-3) are the result of magmatic intrusion along the rift axis. Sedimentary deposits form in the graben structure above the rift. High heat flow produced by the rifting and related intrusion of magma produces metamorphism in the sedimentary basement to consolidate the new crust.

One of the most ambitious experiments in lithospheric seismology undertaken in recent years was the 1978 Yellowstone-Snake River Plan (YSRP) Experiment. The YSRP experiment was a major cooperative venture involving twelve institutions (including two European geophysics institutes and the U.S.G.S.). The experiment configuration (see Figure 4-4) included eleven shotpoints (plus an additional 23 in a follow-up experiment in 1980) and both profile and array recording by nearly 220 seismographs of varying vintage and design (including a large complement of European instruments).

Examples of the data collected are given in Figure 4-5. The two-dimensional structure of the eastern Snake River Plan (SRP) was determined by travel-time and true amplitude modelling of data recorded both along and across the axis of the eastern SRP (Figure 4-6). Figure 4-7 shows the interpreted crustal sections of the Yellowstone-eastern SRP and demonstrates a high degree of crustal complexity and heterogeneity. In concert with geological and geophysical data, however, the seismic results provide critical insight into the tectonic development and crustal evolution of the Yellowstone hot-spot during the last 20 m.y. (Figure 4-8).

The crustal structure of the zone through the eastern SRP to Yellowstone is in essence providing us with a "snapshot" in time of the geological development of a major volcano-tectonic system. As the North American plate slides southwest relative to the hot-spot, there is crustal uplift and intrusion of basaltic magma along the hot-spot trace. Apparently, the basaltic magma produces partial melting of crustal rocks, resulting in explosive silicic volcanism and caldera collapse. This phase of valcanism tyupically lasts about 2 m.y., controlled by the rate of northeast migration of the hot-spot. The hot-spot is, of course, now located beneath the Yellowstone area. Silicic volcanic rocks of the eastern Snake River Plain show progressive aging and association with subsidence to the southwest. The volcanic phase is followed by crustal cooling and subsidence as the hot-spot moves northeast relative to the continental lithosphere. The basins formed by subsidence are typically filled by silicic volcanics and later-accumulated sediments and basaltic volcanics. An anomalous intermediate velocity layer in the upper crust, representing the restite of the silicic volcanism, is the source of a large positive Bouguer gravity anomaly over the Snake River Plain.

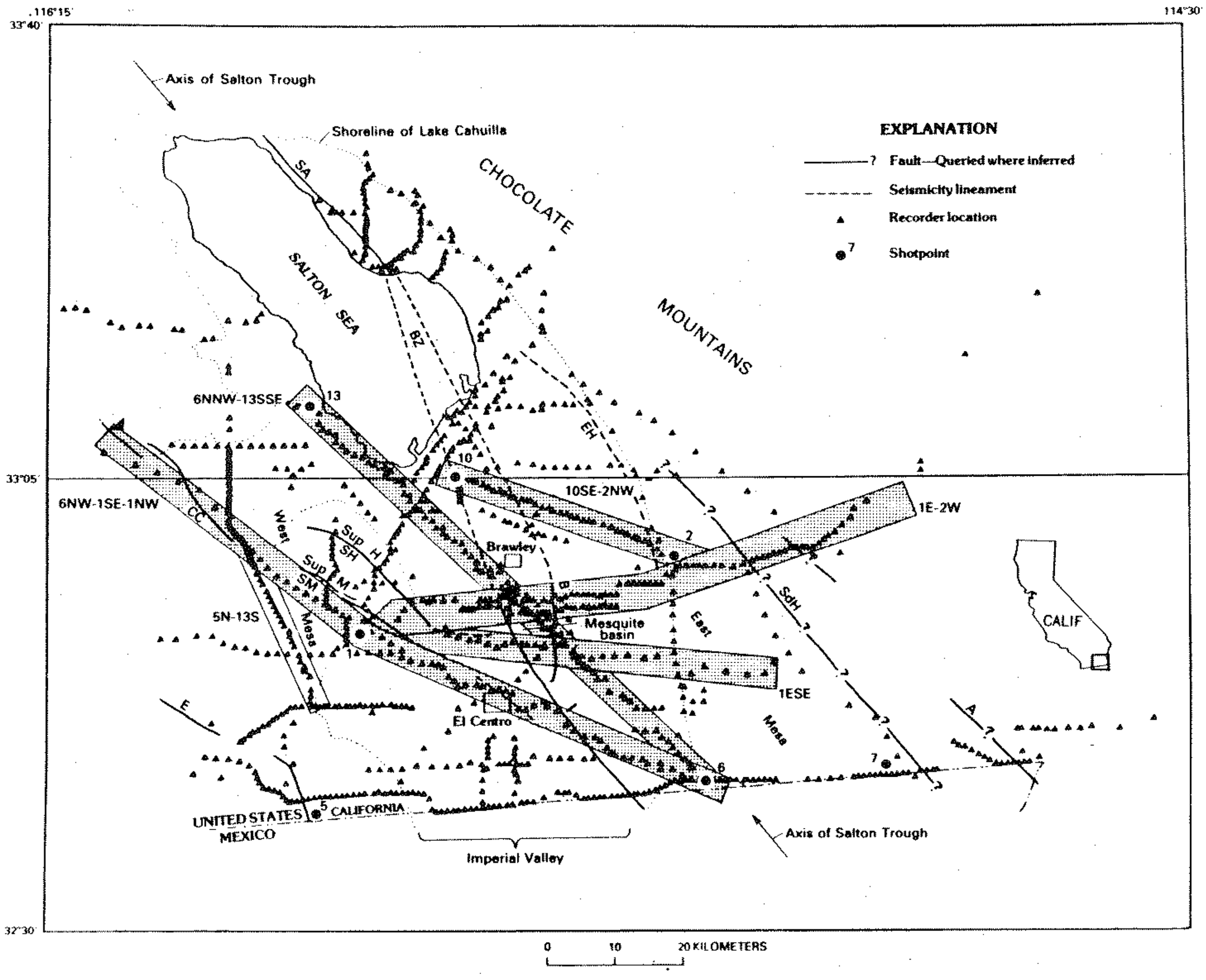


Figure 4-2. Index map of shotpoints and recording sites for the Imperial Valley/Salton Trough, California area. (From Fuis *et al*, Jour. Geophys. Res., 1984)

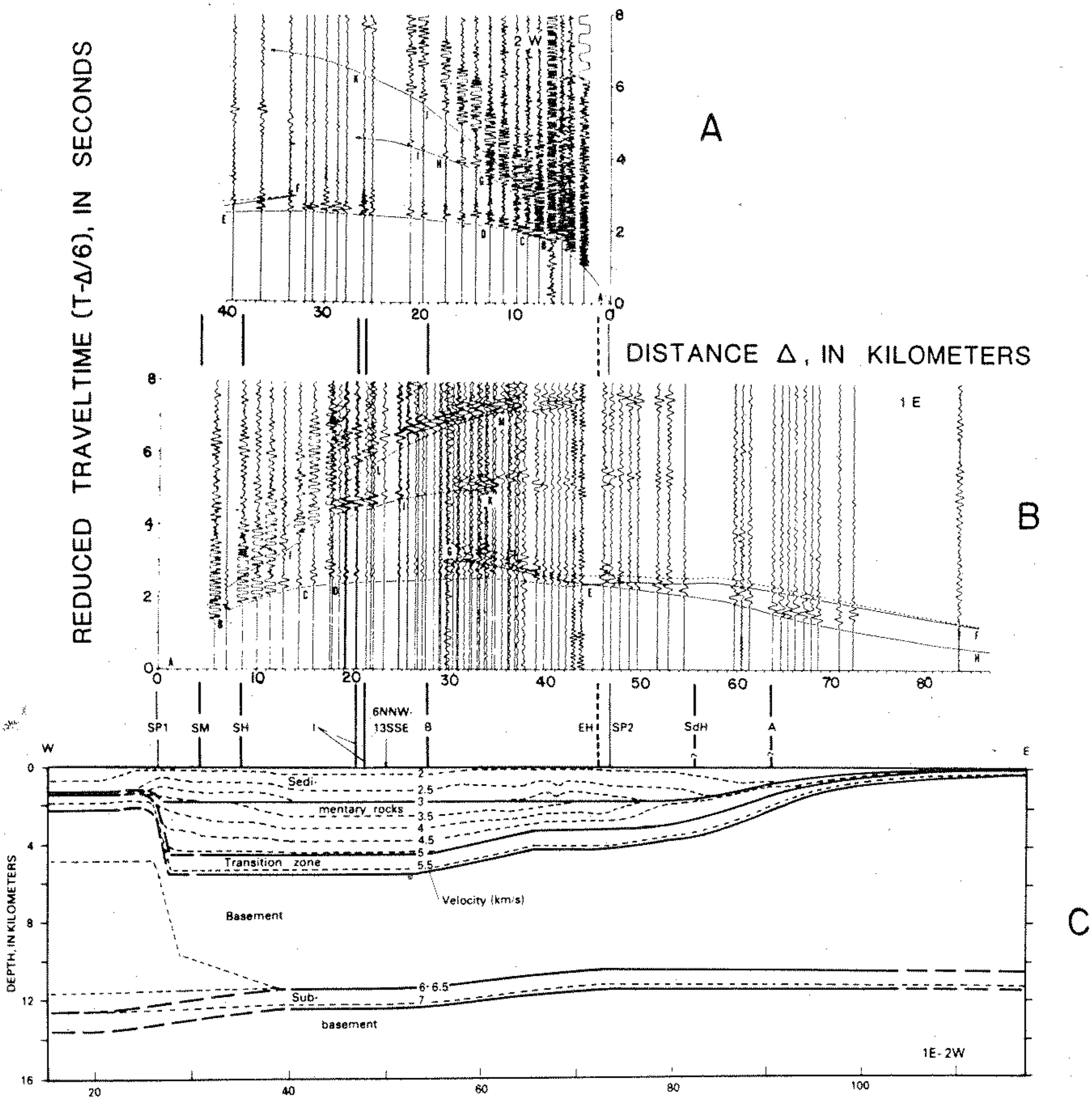


Figure 4-3. Seismic refraction data with calculated travel times from ray trace modelling and interpreted velocity model for the Salton Trough. Refractions and near-critical reflections with excellent phase correlation are visible on the record sections. (From Fuis *et al*, Jour. Geophys. Res., 1984)

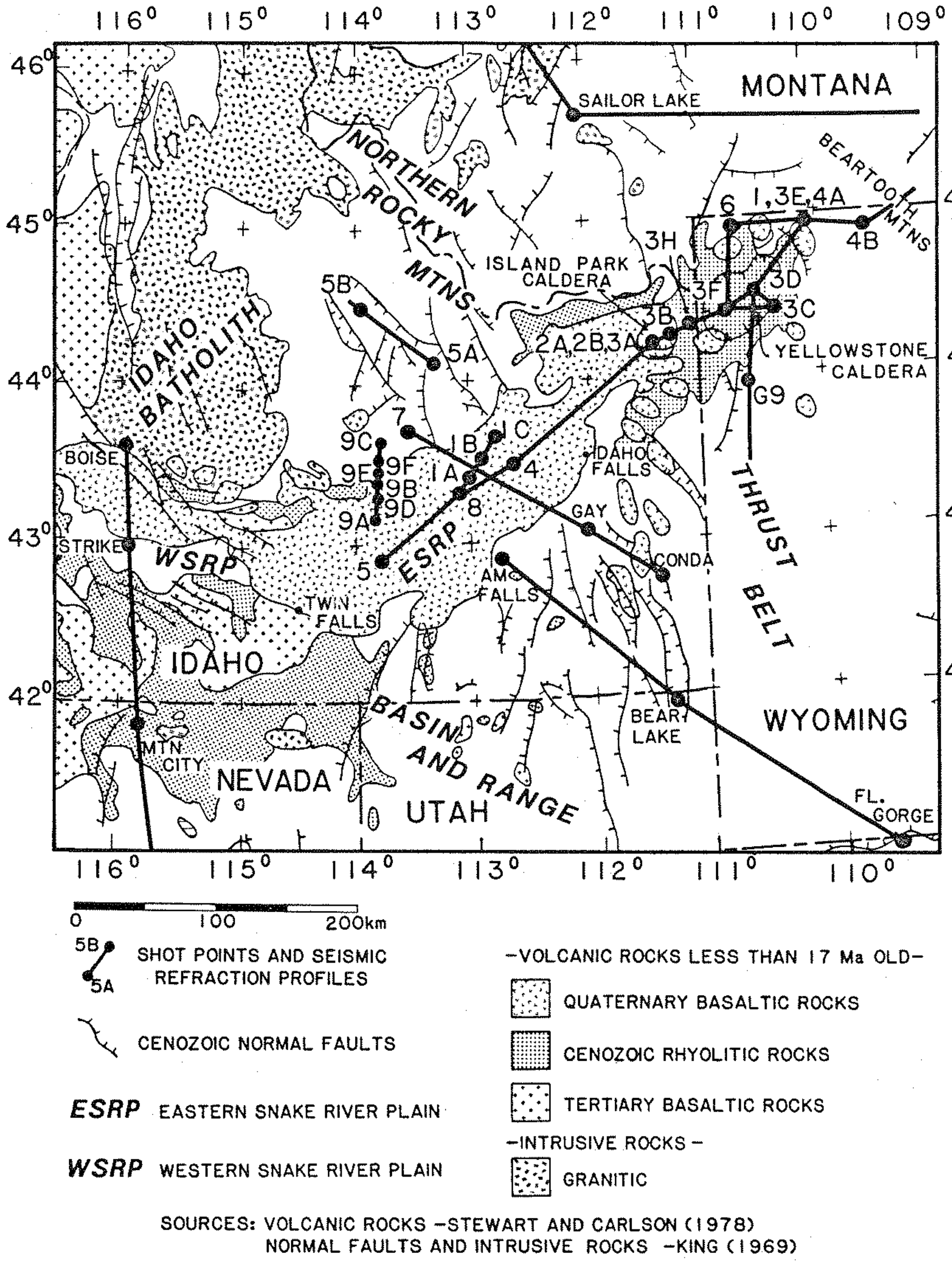


Figure 4-4. Index map of Yellowstone-Snake River Plain (YSRP) area showing shotpoints and seismic refraction profiles. The numbered shotpoints and the Gay and Conda shots were used as sources for the 1978 and 1980 YSRP experiments. Locations of other regional seismic profiles are also shown. (From Braile and Smith, with permission, 1984)

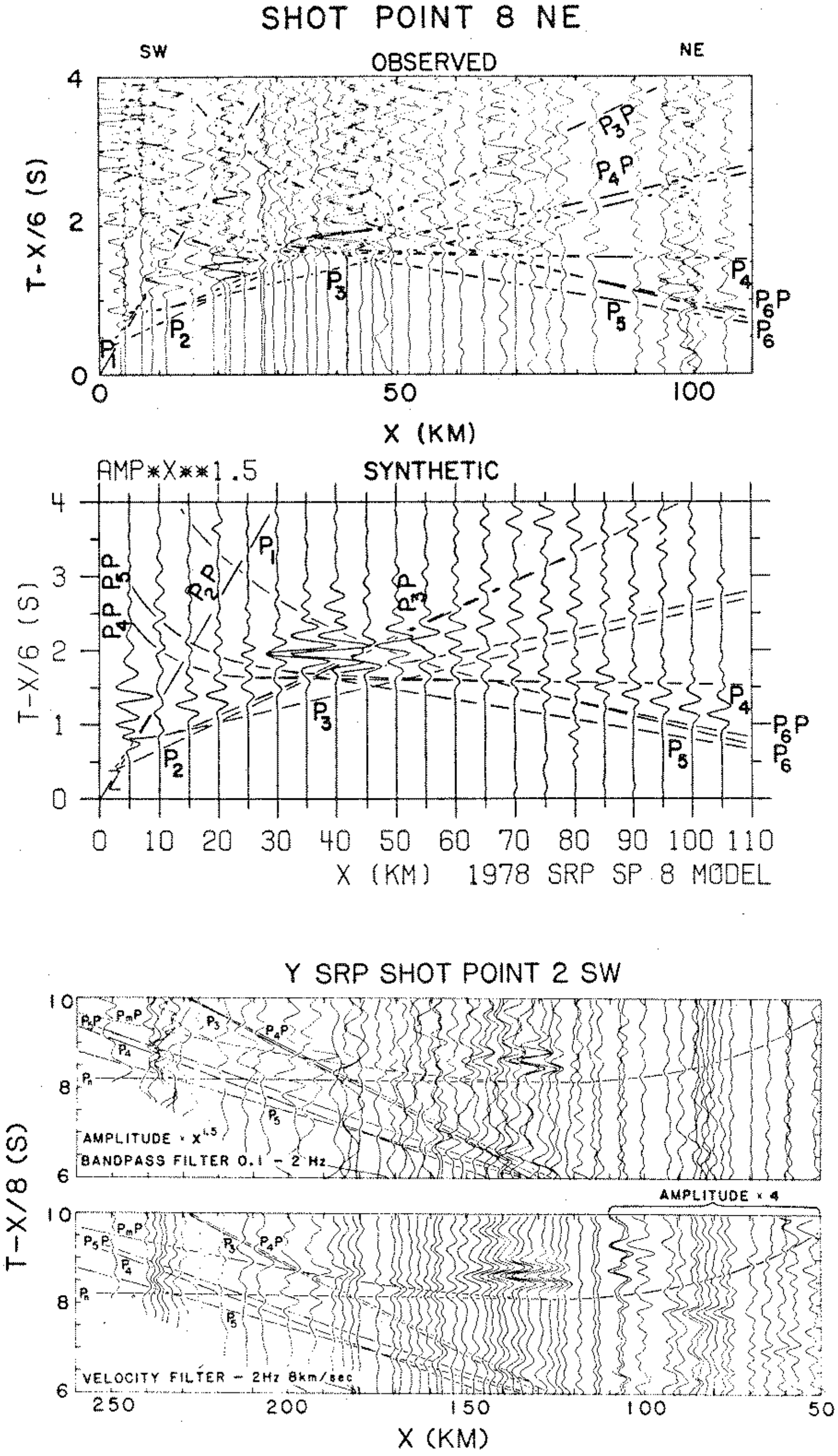


Figure 4-5. Examples of seismic data recorded in the 1978 YSRP experiment. Upper: Shotpoint 8 northeast profile and synthetic seismograms calculated from derived crustal model. Both record sections are plotted with true amplitude scaled by distance to the 1.5 power. The good travel-time, amplitude, and waveform comparison of the observed and synthetic data provide evidence for the validity of the crustal model. (Braile *et al*, Jour. Geophys. Res., 1984)
Lower: Observed record section for shotpoint 2 recorded southwest along the eastern Snake River Plain. Data are amplitude corrected and plotted with amplitude scaling factor of distance to the 1.5 power. The prominent near-critical reflections near 140 km are reflections from the M-discontinuity. Phase correlations evident on the observed record section are enhanced by velocity filtering shown in the lower record section. (Braile, with permission, 1984)

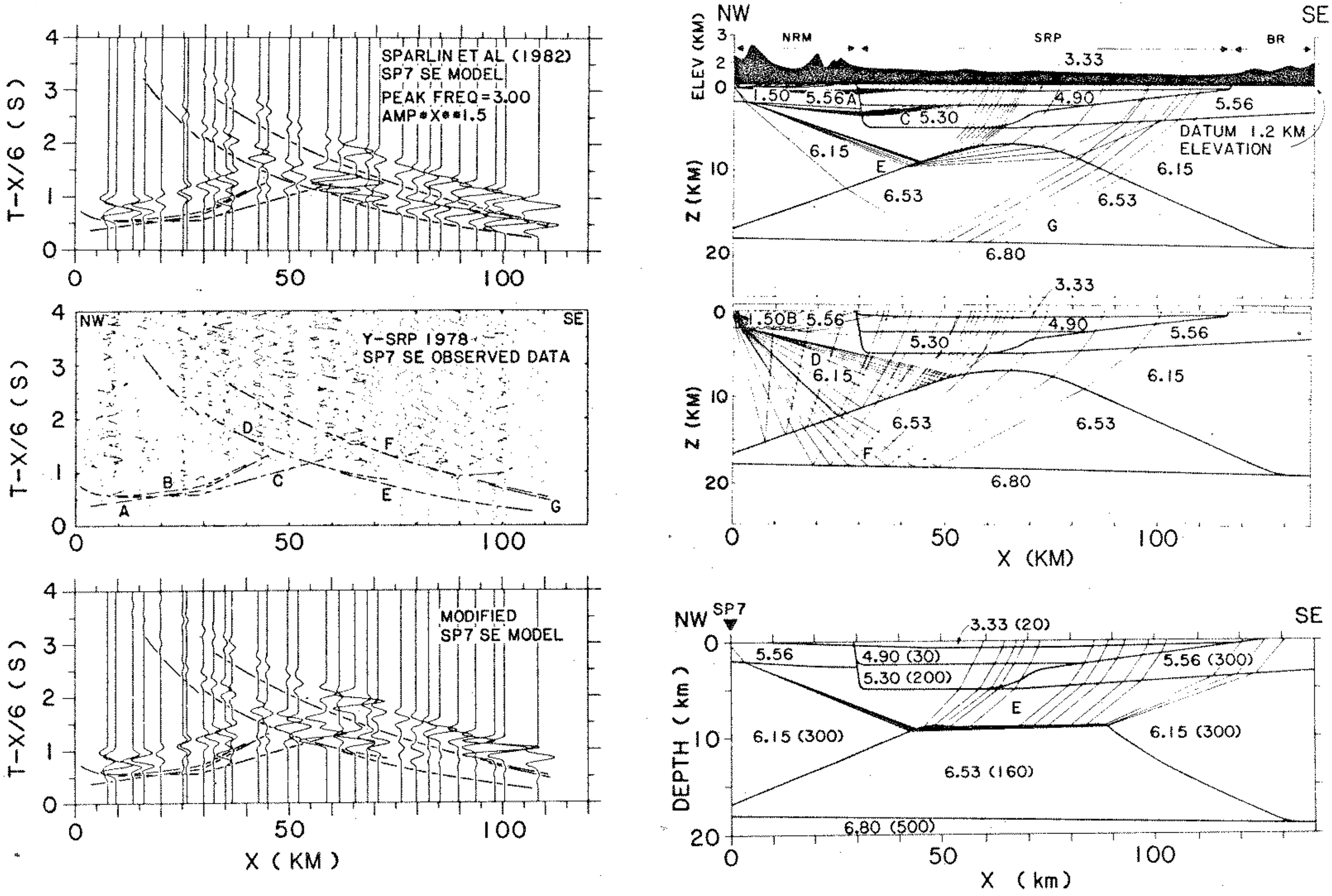


Figure 4-6. Two-dimensional interpretation using ray tracing and disk ray theory synthetic seismograms of profile across the eastern Snake River Plain (shot point 7, northwest end, to the Gay Mine shotpoint, southeast end). Initial ray tracing interpretation by Sparlin *et al*, Jour. Geophys. Res., 1982, gives a moderately good fit to the travel-time data of SP 7 shown here; however, a slightly modified velocity model (lower right) improves the amplitude and waveform comparison between the observed and synthetic data. (From Chiang and Braile, Bull. Seis. Soc. Am., 1982)

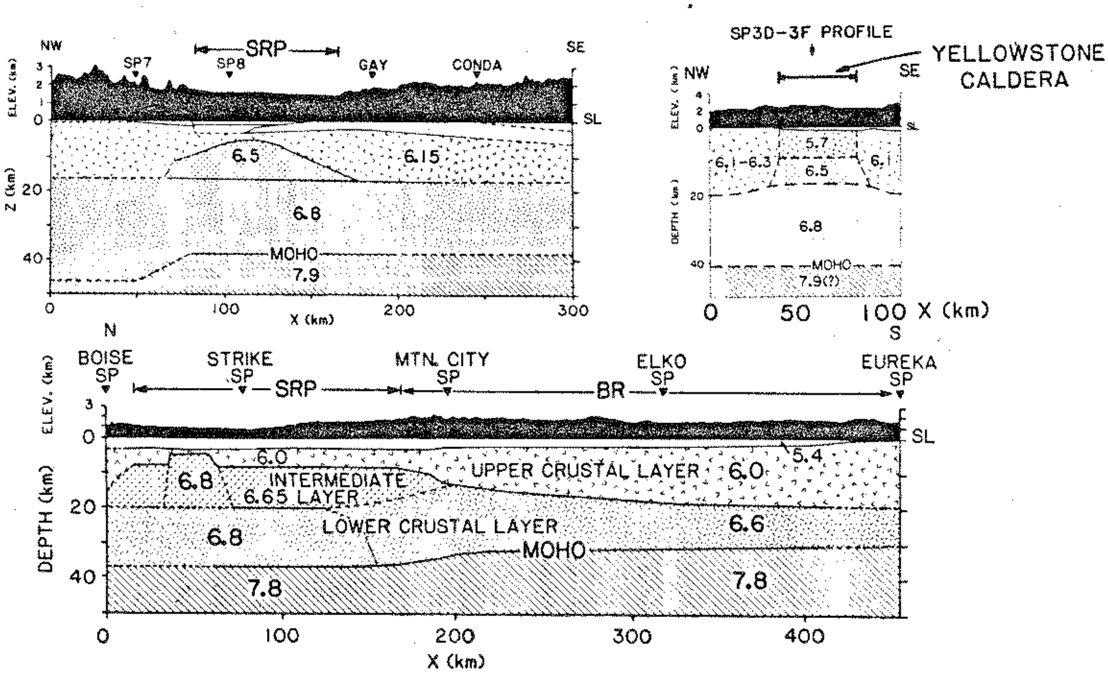


Figure 4-7. Interpreted cross sections through the Yellowstone, eastern SRP and western SRP crust, illustrating crustal heterogeneity, particularly evident in the intermediate velocity zone which now characterizes much of the upper crust beneath the Snake River Plain. (Braile and Smith, with permission, 1984)

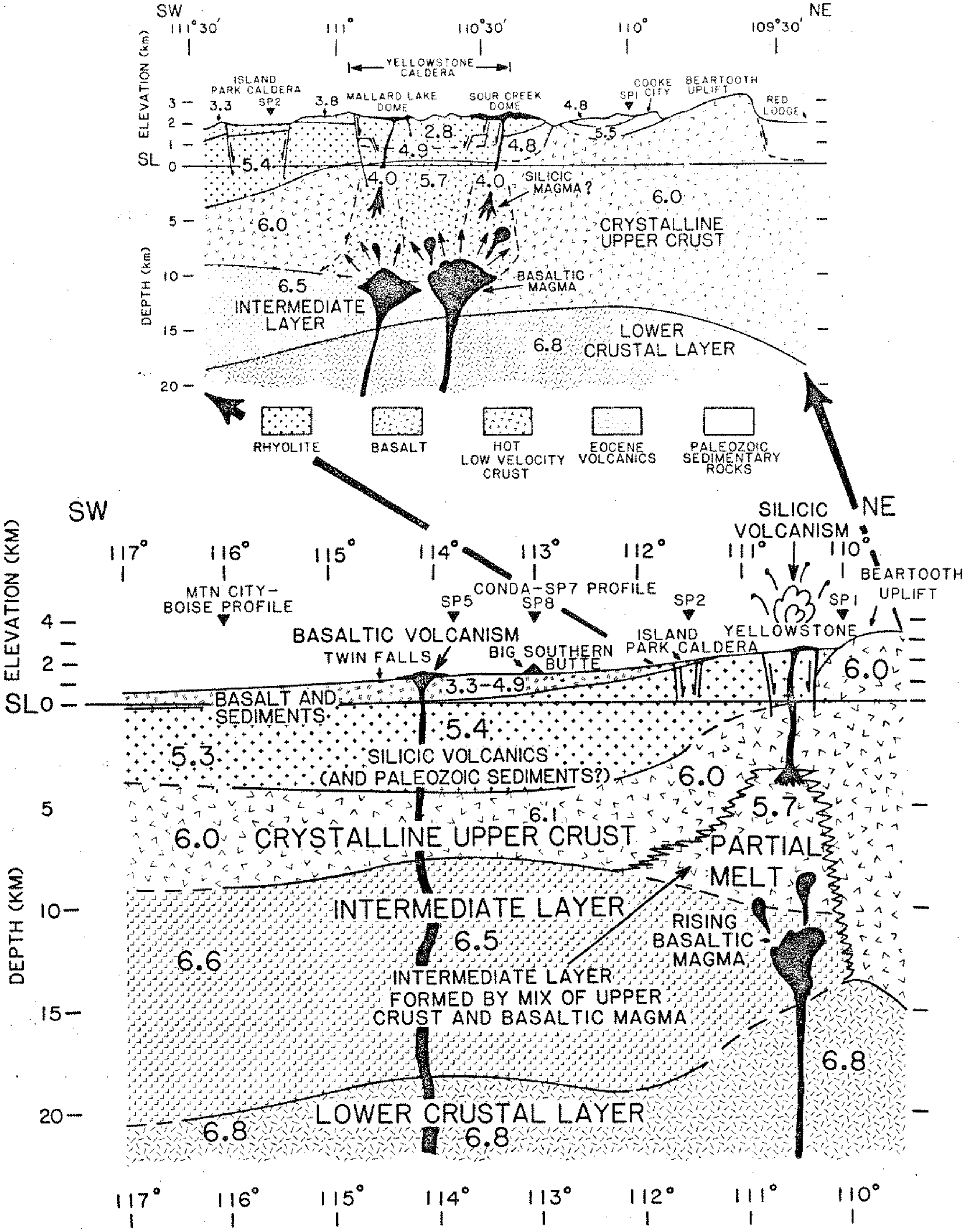


Figure 4-8. Schematic diagram portraying lithospheric structure and crustal evolution along the axis of the eastern SRP to Yellowstone. Seismic velocities (in km/sec) are interpreted in terms of geologic features. Shown here are the uplift and volcanism associated with the Yellowstone hotspot, including the collapse caldera. The seismic results also clearly show subsidence of the crust after passage of the hotspot, evidenced by filling of the trough with volcanic and sedimentary debris and a shallow zone of intermediate velocity, possibly representing the residue of the partial melting event that produced the silicic volcanism. (Smith and Braile, with permission, 1984)

4.2. Resolution and Precision of Active Seismic Experiments

The ability to record seismic wavefields with various novel array techniques (that are free of spatial aliasing), can be combined with the use of unified interpretation methods to provide excellent resolving power for geological details. These unified techniques can illuminate crustal structures at scales less than 1 km, i.e., at roughly the same scale at which geologists map major regional tectonic features at the surface. For example, vertical incidence (reflection) seismic waves in the frequency range of 5—250 Hz) can differentiate layered structures with a resolution of about 10 to 100m. The structure of Q can be resolved to as little as 1.5 km. Wide-angle reflections in the 1 to 10 Hz range can resolve structures of 100 to 1000 m. Horizontally propagating head waves have somewhat poorer resolution but yield excellent average velocities. The deployment of three-component digital recording systems would allow the routine imaging of the shear-wave structure, heretofore unattainable from only vertical-sensor arrays. Surface wave studies, while not capable of high-resolution seismic imaging, provide critical information on shear-wave velocities and attenuation and anisotropy. The simultaneous interpretation of vertical reflections, wide-angle reflections, and refracted rays can be used to map the continental lithosphere at scales of a few hundred meters from the near-surface well into the upper mantle. Thus, seismic imaging at these fine scales can provide for the first time detailed maps of the lithospheric subsurface structures at scales of geologic significance. The important goal of the PASSCAL arrays will be to seismically image, and thus define the impedence properties of the lithosphere in three dimensions - to provide P- and S-wave velocity structure, Q structure, and anisotropy to depths of several hundred km, but at scales comparable to tectonic features mapped at the surface. Thus, the PASSCAL arrays will "open up" the lithosphere as a volume to be explored in its three dimensions and with a resolution that is relevant in the context of geologic and tectonic studies that are commonly constrained to near-surface features.

4.3. Three-dimensional Surveys with PASSCAL Arrays

One of the main justifications for the PASSCAL program is to provide the scientific community with the option to deploy the full compliment of 1,000 instruments for three-dimensional deep crustal imaging. In a typical three-dimensional experiment, for example, the instruments may be deployed over an area or along grid lines, with the lines separated by one to several kilometers and the stations spaced at 200 meters along the lines. The cover figure represents a three-dimensional seismic image of an upper-crustal volume obtained by industry using modern techniques. These techniques are equally applicable to the study of the deeper lithosphere. For reflection purposes, Vibroseis stations or dynamite shot holes would provide sources at many station positions in the array, and recorded at all others. For tomographic imaging of the velocity structure, there may be special shotpoints outside the array that may require larger explosive yields. If natural seismic activity occurs in the area, the stations will be set to be triggered for recording these events. Teleseisms recorded by the array will yield P- and S-wave delays and surface wave phase shifts to further constrain the velocity model. Such a multi-purpose field effort may last two to three months and require at some times the labor of over 50 people for logistic support.

A typical three-dimensional study would produce an unaliased seismic image of a lithospheric volume with dimensions of 30 km x 30 km or more on the surface and up to hundreds of kilometers in depth. Such large-scale experiments are akin to those of astronomy where a large phased-array telescope is deployed on the surface of the earth, except in this case the array is looking downward rather than upward. Because of its versatility in recording controlled sources and earthquakes simultaneously, and because of its great dynamic range and recording of three-components of ground motion, the PASSCAL instrumentation will allow the "inverted" seismic telescope to obtain high-fidelity recording of all wave types. It is capable to record wavefields from earthquakes, teleseisms and regional earthquakes, as well as controlled sources, providing full P-wave and S-wave information for inversions of the laterally heterogeneous structure.

As a complement to data obtained from natural sources, explosions and Vibroseis sources provide a precise and high density of ray paths throughout the targeted crustal volume. Wide-angle reflection/refraction energy yields the average velocity measurements that are necessary not only for subsequent data processing to determine structures in the reflection mode, but are also essential for determining relationships between velocities and lithology (or composition). Near-vertical reflections provide the primary control for mapping impedance boundaries. At reflection angles greater than 15° from vertical, rms velocities provide good estimates of P- and S-wave velocities. High-resolution imaging of laterally heterogeneous layers is obtainable by mapping both the reflections from surface sources and the near-vertical-incidence teleseismic waves that move upward through the crust. Thus, three-dimensional, three-component PASSCAL experiments can sample the full range of vertical to horizontal traveling ray paths of P- and S-waves and at redundancies necessary to perform both the travel-time and seismic-wavefield inversions in laterally and vertically heterogeneous velocity structures, with the added option to map natural seismic sources and their properties.

The necessary mathematical techniques for inversion of three-dimensional velocity structures using both P- and S-wave arrival times are sufficiently advanced to guarantee full extraction of information from the new PASSCAL-type data. The ability to invert the entire seismic waveform is being investigated by simulations. Experiments suggest that practical techniques applicable to real data will be available within perhaps 1 to 2 years. The application to three-dimensional volumes and usage of full wave forms will be limited chiefly by computational speed, namely the ability to extend the number of ray path elements to hundreds of thousands or millions — a mathematical and computational problem that requires ready access to high-speed computers.

The three-dimensional seismic mapping of lateral and vertical heterogeneities in the lithosphere at scales of the tectonic structures that are observed at the surface, will provide the images that can reveal subsurface geology. In the past decade, the oil industry has developed the three-dimensional imaging technique to a high degree but has applied it mostly to shallow crustal levels. Industry, for example, has for the past 5 years employed field crews operating up to 2,000 instruments per array and recording volumes over areal regions that measure up to 15 km x 15 km. Their success is demonstrated by the fact that in the summer of 1984 over 20 crews will operate on three-dimensional surveys in the oil provinces of western Canada and in the Rocky Mountain region. Commercial marine three-dimensional surveys are now routine, and the general sense in industry is that because of the improved resolution of geologic structures numerous dry holes have been eliminated, thus making the three-dimensional seismic technique an industry standard.

4.4. Two-dimensional Recording with PASSCAL Arrays

Traditional crust-upper-mantle seismic profiling involves the deployment of stations at sparse spacing (10 km or greater) with shotpoints spaced along the line tens to hundreds of kilometers apart. This technique has been effective in providing information on the overall structure of the crust and upper mantle on a regional scale. At present these techniques still provide most of the velocity information from which composition and structure of the crust and upper mantle are inferred. In an important advance over these previous techniques, European and Soviet seismological groups have expanded and refined the use of two-dimensional profiling known as the Deep Seismic Sounding (DSS). DSS techniques involve station spacings of approximately 100 m and shot spacings of 10 to 20 km along profiles hundreds of kilometers long. These methods provide nearly continuous wavefield recording of vertical- to wide-angle-incidence ray paths. Through extensive use of the DSS methodology, the structure of crust and upper mantle of the European continent has been mapped at far higher resolution than that for most of North America. The U.S. Geological Survey used linear arrays of instruments in deployments usually more limited than those used in Europe and the USSR. Several profiles in the Western U.S., and recently in Alaska, have been recorded and their results provide examples of interpretation of lateral heterogeneities of the earth's crust and upper mantle. Interpretation of two-dimensional structure is principally by synthetic modeling of entire waveforms utilizing asymptotic, finite element-difference, on full-wave-theory techniques that are now available. Two-dimensional synthetic-seismogram techniques, when implemented with inversion algorithms can be used to develop detailed models of lateral heterogeneities in the lithosphere for both P and S velocity structures along profiles up to thousands of kilometers in length. Such experiments on a continental scale will be possible when large numbers of PASSCAL seismographs will be ready for deployment.

4.5. Progress on Seismic Interpretation Methods for Laterally Heterogeneous Media

Rapid progress in the past several years has been made on seismic interpretation of laterally heterogeneous media. A variety of approaches have been used involving travel time and waveform data to interpret velocity structure. These include detailed modeling of arrival times using modified ray tracing methods, forward modeling utilizing synthetic seismogram techniques, and inverse procedures such as tomography and imaging techniques. Although these methods require significant computational effort, their application is within the computational capabilities of modern research institutions engaged in seismological research. It is now possible to derive detailed two- and even three-dimensional models of the lithosphere resolving heterogeneity of characteristic dimensions as small as one kilometer or less. These new techniques have advanced beyond our present capabilities for collecting adequate seismic data along profiles or in arrays. A fundamental purpose of the PASSCAL initiative is to provide the essential instrumentation for collecting the quantity and quality of seismic data necessary for high-resolution imaging of lithospheric structures, that can be handled by modern analytical techniques.

Among the important recent developments of analytical techniques are included those based on forward modelling of waveform data to generate synthetic seismograms in laterally heterogeneous media by such methods as Gaussian-beam, asymptotic ray theory and disk ray theory. The use of travel-time, amplitude and waveform information in modeling of observed seismic record sections has significantly improved resolution obtainable in modern seismic experiments. More accurate, but more computationally taxing, synthetic seismogram methods employing finite-difference and finite-element calculations have also been developed in the past few years and are seeing important applications to model studies and comparison with approximate techniques (Figure 4-9). Such methods are particularly promising in the study of scattering, coda-waves, and Q-structure. With improvements in computer speed and increased storage, these techniques may also become routine modeling methods for the interpretation of laterally heterogeneous earth structure on a variety of scales. (Figure 4-10)

Inverse or imaging techniques which utilize the entire seismic wavefield have also been developed recently and applied to modeling of subsurface heterogeneities. These methods are based on downward continuation of the wavefield similar to the migration process that is commonly applied in reflection seismology. These new inverse methods are applicable to elastic wave propagation over a wide range of angles of incidence, in contrast to the near-vertical incidence restriction in reflection seismological applications. These inverse techniques map all features in the wavefield back to reflection and refraction bodies or 'image points' in the subsurface, thus providing high-resolution "pictures" of the subsurface (e.g. Figure 4-11).

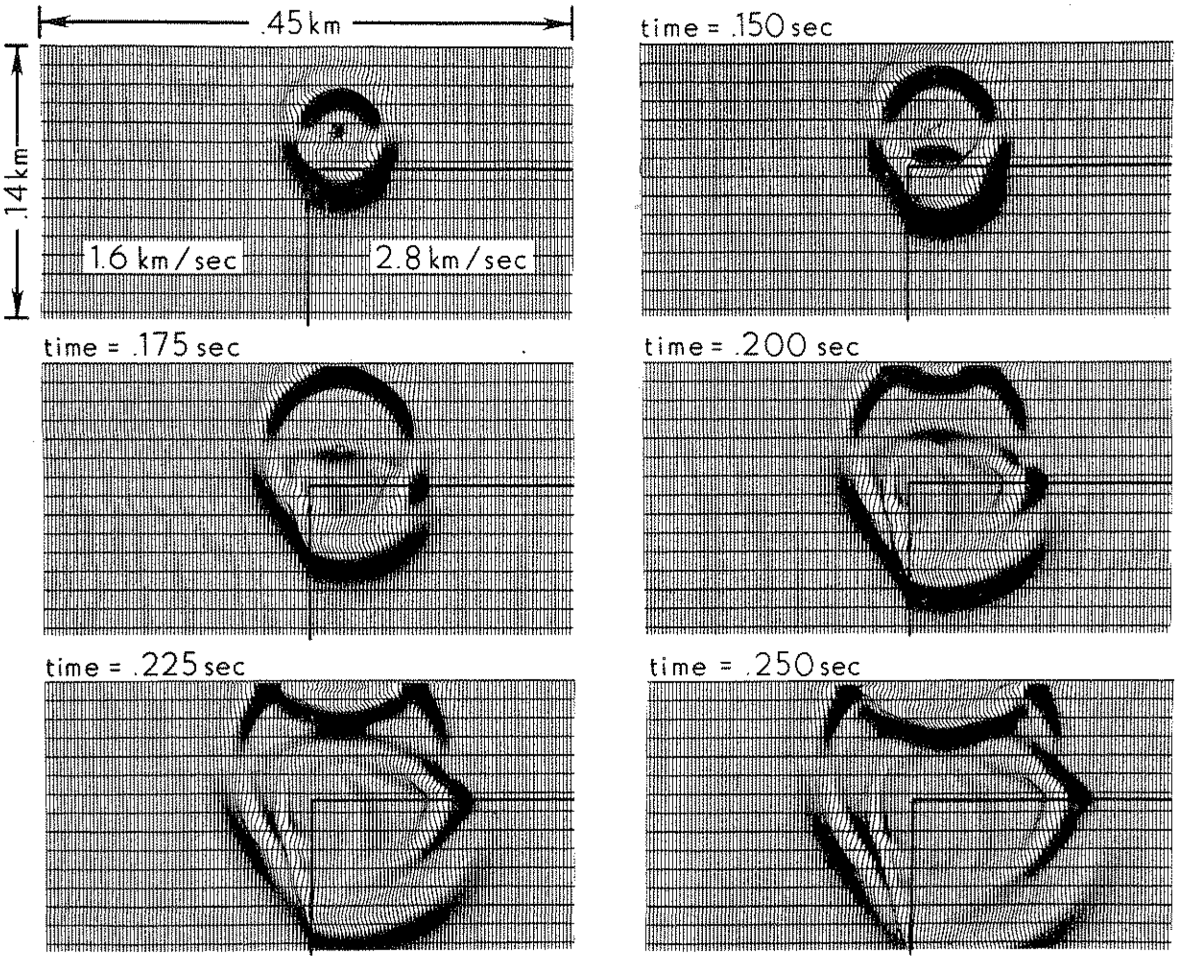


Figure 4-9. Elastic (P- and S-wave) propogation through a two-dimensional heterogeneous body calculated by the finite-difference technique. (Harley Benz, with permission, 1984)

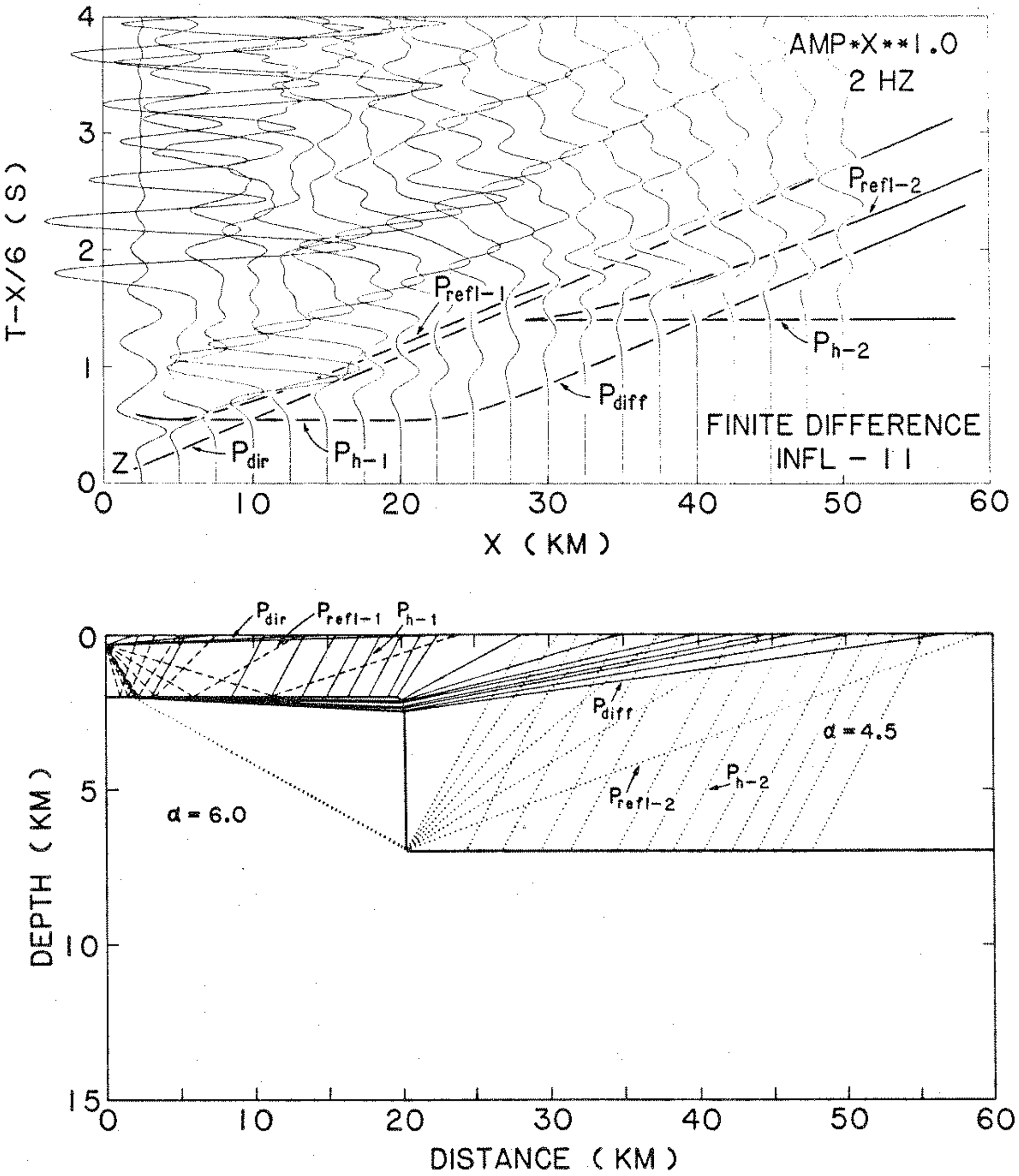


Figure 4-10. Examples of elastic finite difference synthetic seismograms calculated for a fault model. Head waves and reflected waves from the upper and lower horizontal interfaces, shown by raypaths in the lower figure and synthetic seismograms in the upper figure, illustrate the seismic response of a heterogeneous fault model. (Braile, with permission, 1984)

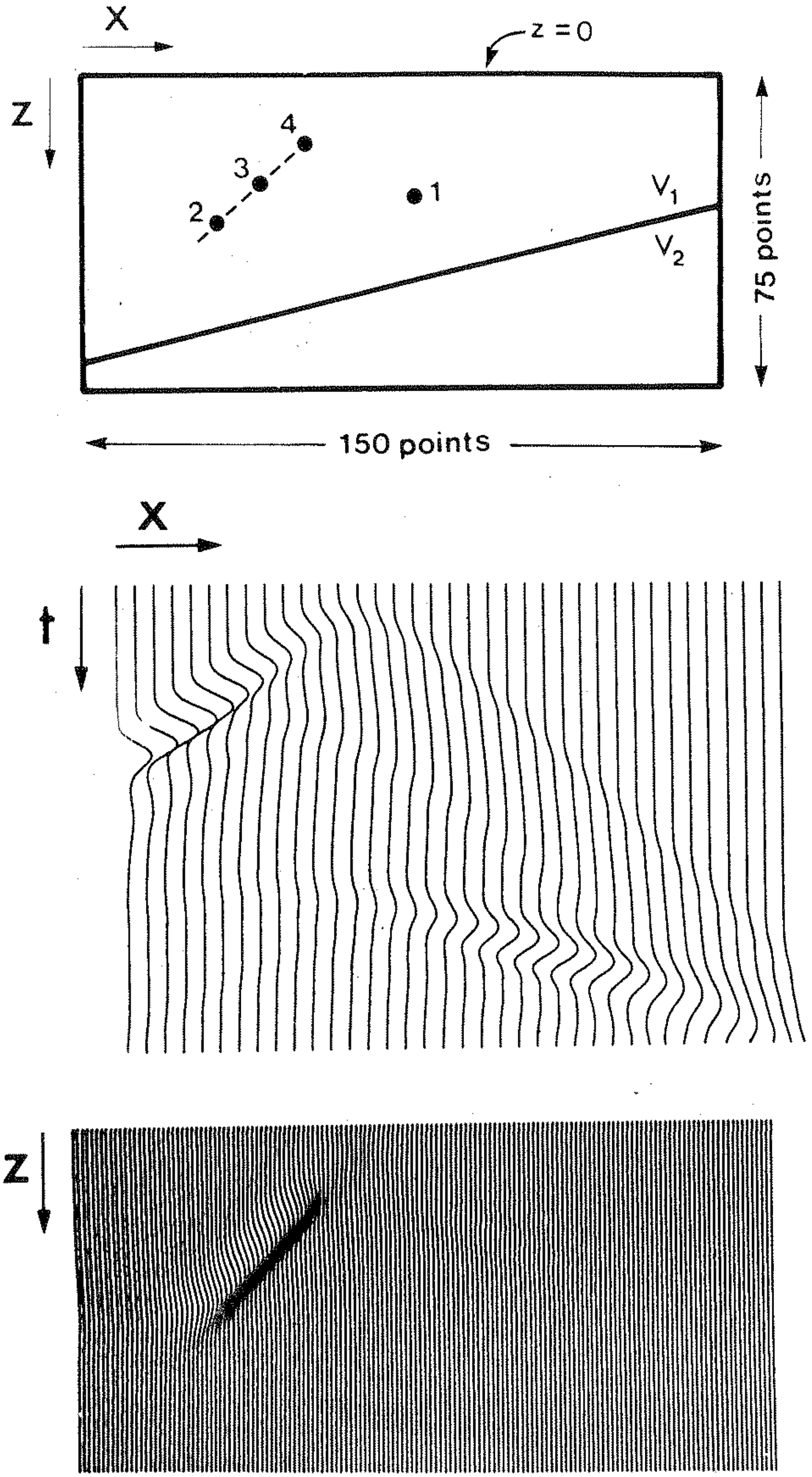


Figure 4-11. Imaging of fault model in a heterogeneous medium. Top: Velocity model with dipping interface between two velocity regions. The fault source is represented by solid circles along the dashed line. Middle: Synthetic seismograms calculated for the fault source model shown above. Bottom: Inversion of the seismograms to obtain a continued image of the fault. The wavefield uses the acoustic wave equation. (From McMechan, Geophys. Jour. R. Ast. Soc., 1982)

5. NATURAL-SOURCE STUDIES USING A LARGE ARRAY OF PORTABLE INSTRUMENTS

To study the earth, seismologists utilize waves excited by natural or artificial sources. Many crustal imaging experiments are using primarily natural earthquakes as the source of elastic wave excitation or the earthquakes themselves are the targets of study. Earthquakes and explosions are often complementary in the information they can provide on the structure of the crust and upper mantle. Earthquake origin times and locations are known less well than those of explosions. But earthquakes generate higher levels of energy over a broader frequency range. In addition, they are strong radiators of shear wave energy whereas explosions generate mostly P waves. In addition, earthquakes contain information on stress levels and stress orientation through interpretations of focal mechanisms and spectral characteristics. Earthquakes occur in many regions of the world beneath both continents and oceans and at depths that range from the earth's surface to 700 km. Thus, earthquakes occurring at variable depths illuminate deep structures in ways which are not possible using only surface explosions. In the future, determinations of moment tensors, origin times and locations of earthquakes may improve on a global scale with the installation of a new Global Seismic Network. Thus the suitability of natural sources for lithospheric studies will only improve with these seismological advancements.

5.1. Potential Results of Experiments Using Earthquake Sources

A PASSCAL array of three-component instruments deployed to record waves from earthquake sources can provide answers to many fundamental questions to modern earth science. Taking advantage of signals generated by earthquakes, one can design experiments to map the lateral heterogeneities of the earth, particularly of the lithosphere. Mapping can range in area from local to continental scale, and in depth from the earth's surface to the mantle or deeper. Three-component digital recording of shear waves allows for the first time to carefully study the nature of anisotropy of the earth's interior. The spatial distribution of heterogeneity and anisotropy may permit to directly map the location of, and the sense of movement in convection cells. The discovery of convection cells, their distribution, and configurations, would be a major scientific advancement with fundamental bearing on revealing dynamic processes in the earth. On a smaller scale, an array of densely distributed instruments over an area of high seismicity, such as an aftershock zone, will provide sufficient data to delineate the dynamic rupture process of earthquakes and the strains reliefed with a detail never before achievable. Tectonic forces, their principal stress directions and spatial variability can be inferred from such data.

5.2. Body-Waveform Inversion and Crustal Transfer Functions

As a body-wave signal (P or S) passes through the lithosphere, it is modified in a manner similar to that produced by a filter on the signal. The transfer function for a layered lithosphere has an analytic expression that is a function of the elastic properties of the lithospheric layers. An array of three-component sensors can be used to map the structure of the lithosphere at a scale on the order of the array dimensions and spacing of its elements. Teleseismic body-wave signals from deep earthquakes provide the most useful data for this type of study. By rotating the three-component signals and taking the ratio of horizontal to vertical spectra, the contribution of the source will drop out leaving a numerical function which contains information related only to the properties of the lithosphere beneath the array. An inversion either in the frequency domain or time domain will yield the structure of the lithosphere under a receiving station of the array. Over the dimensions of that array, one can combine contributions from each station and delineate the lateral heterogeneity of the underlying lithosphere. As one shifts the array location, a systematic mapping of the lithosphere over a regional or a continental scale can be achieved. The lithospheric transfer function is crucial to the construction of a deconvolution filter, which must be applied to teleseismic body-wave signals before they can effectively be used to study the spectral behavior of the source.

5.3. Three-Dimensional Modeling Using Teleseismic Body Waves

Until recently, most methods available to seismologists yielded models which described the earth in terms of a number of laterally homogeneous layers. Several methods have been developed since the mid-1970's, however, which allow to consider lateral as well as vertical variations of velocity. One method considers body waves from teleseismic events that travel upward through the lithosphere beneath a seismograph array. To apply the method, the lithosphere is divided vertically into a number of layers and each layer is further divided laterally into blocks, the dimensions of which depend upon the station spacing of the overlying network. The denser the station spacing, the more finely the layer can be divided provided that sufficient numbers of ray paths traverse each cell. Modern tomographic inversion theory is applied to residuals of travel times observed at individual stations of the array to yield perturbations of velocity in each block from the average velocity value in that layer. The method has been applied successfully utilizing data from several permanent and temporary arrays throughout the world (Figure 6-5).

The studies performed up to now have most often utilized data from fixed permanent arrays and have consequently been adversely affected by station spacing which is too large and by a lack of data in certain key areas. The instruments used have often been less than ideal, in that responses were geared primarily to the study of local earthquakes rather than also teleseisms, or responses were not suitable for teleseismic shear wave measurements. Further, because existing arrays consist predominantly of vertical-component instruments, all three-dimensional modeling using teleseisms has, up to now, been restricted to the study of compressional-wave structure. If horizontal-component instruments are available, it will be possible to obtain models of combined compressional and shear-wave perturbations, and other additional parameters of lithological importance such as the Poisson ratio can be mapped. Furthermore, S-wave velocity variations, particularly in regions of magma genesis, can be very large relative to P-wave variations.

5.4. Surface Wave Tomography

PASSCAL arrays of digital seismographs, together with broad-band sensors, provide an exciting opportunity for lithospheric mapping using a method of surface-wave tomography. The method makes use of a large number of sampling surface-wave paths in the region of study. The configuration of each path is well-known, and the seismic surface-wave dispersion information along each path is measurable and can be considered as the Radon transform of a certain "picture function." Here the line integral is taken along the known path and the integrand is the surface-wave slowness, instead of an attenuation integral associated with the conventional image reconstruction. The surface-wave slowness (phase or group) data are a function of wave period, this additional information introduces complexity into the inversion process, but, in return, it provides an additional dimension to the reconstructed "picture function," namely, the depth dependence of the structure. The region of reconstruction is completely defined by the distribution of earthquake sources and recording stations. As long as the number of surface-wave sampling paths is sufficiently large, we can invert the slowness information for the surface-wave dispersion information with adequate resolution for all "pixels" that constitute the picture region. The dimension of a pixel in a lithospherical study may be tens of km. A second inversion on the surface-wave dispersion data within each grid element gives the third (depth) dimension of the structural picture. Thus the conventional inverse Radon transform associated with the image reconstruction is replaced by two inversions in this problem: one being the pure-path decomposition, the other being the velocity-depth inversion of surface-wave dispersion data.

The pure-path decomposition is achieved by a stochastic inversion resulting with pure-path dispersion curves for all grid elements. A pure-path inversion applied to the surface-wave dispersion data for a layered-earth structure can be performed on each grid element resulting in a shear-wave velocity-depth function for that grid element. Combining these velocity-depth functions for all grid elements contained in R, it is impossible to obtain a three-dimensional shear wave velocity structure for the entire region R.

An example is given here for the case of the Pacific basin. Figure 5-1 gives the surface-wave ray paths that define the region R, which has been divided into many (128) grid elements of 10 × 10 degree dimensions. Sample results from a surface tomography analysis described above are shown in Figure 5-2 as one of the cross-sections of the crust and upper mantle through the Pacific basin is presented.

For studies of a reduced scale, we can capitalize on the usefulness of the PASSCAL array with broad-band sensors. Let us visualize the deployment of an array of these digital recorders over a region of 50 to 500 km in linear dimensions. The surface-wave period-range will be 0.1 to 50 sec, and has a resolution to depths of 15 to 100 km. Many deployment configurations can be designed. Figure 5-3 shows the surface-wave mapping of a region making use of aftershocks. Even a ten-instrument moving array recording a few dozen aftershocks will give several paths that practically span the entire region. If teleseismic surface waves are to be used, an array of the type shown in Figure 5-3 (bottom) will give detailed phase velocity measurements adequate for the inversion for upper crustal structures. Note that surface-wave mapping will provide shear wave velocity information that will complement the regional seismic refraction/reflection work which primarily provides the compressional wave velocity information.

Experiments making use of aftershocks (Figure 5-3 (top)) will need at least 10 to 20 instruments with field time lasting several weeks. Experiments making use of teleseismic sources may need 100 instruments operating in the field for up to six months to capture enough events of magnitude 6 or bigger.

5.5. Dynamic Imaging of Earthquake Sources

If a sufficient number of stations records an earthquake signal so that the wavefield is not aliased, if a reasonable fraction of the focal sphere is covered, and if the velocity structure is reasonably well known, then wavefield continuation methods can be used to reconstruct the spatial and temporal behavior of the source for the duration of rupture. This ideal experiment is performed if a large number of instruments is densely deployed in an areal pattern directly over the source. With the capability of the PASSCAL array to trigger on natural events, it is possible to capture the dynamical history of local earthquakes and aftershocks routinely in an appropriate monitoring program. Figure 5-4 shows an image of an event in the Long Valley, California area, captured quite fortuitously by an array of USGS refraction instruments.

5.6. Application of Earthquake Data to Tectonic Modeling

An example of the application of earthquake data to the study of tectonic features and processes is illustrated in Figure 5-5, for the Borah Peak aftershock study. The Borah Peak study was a cooperative effort involving the University of Utah, the U.S. Geological Survey, and several other universities. A large number of seismographs (only a few of which were digital) were deployed in the epicentral area of the 7.3 magnitude Borah Peak earthquake and many thousands of aftershocks were recorded. The much better than average spatial coverage of the epicentral region, the large number of events, and existence of an accurate, previously determined, velocity model provided the necessary input to produce a highly accurate definition of the fault plane and the earthquake mechanism. Of particular importance is that focal depths are confined to the range 0 to 16 km, the same range that mechanical models of the crust identify as the brittle zone for the central Idaho extensional regime.

With the availability of large numbers of digital triggered instruments, such studies are likely to become quite commonplace, confirming with hard data the many and varied tectonic processes at work throughout the continents. (e.g. Figure 5-6)

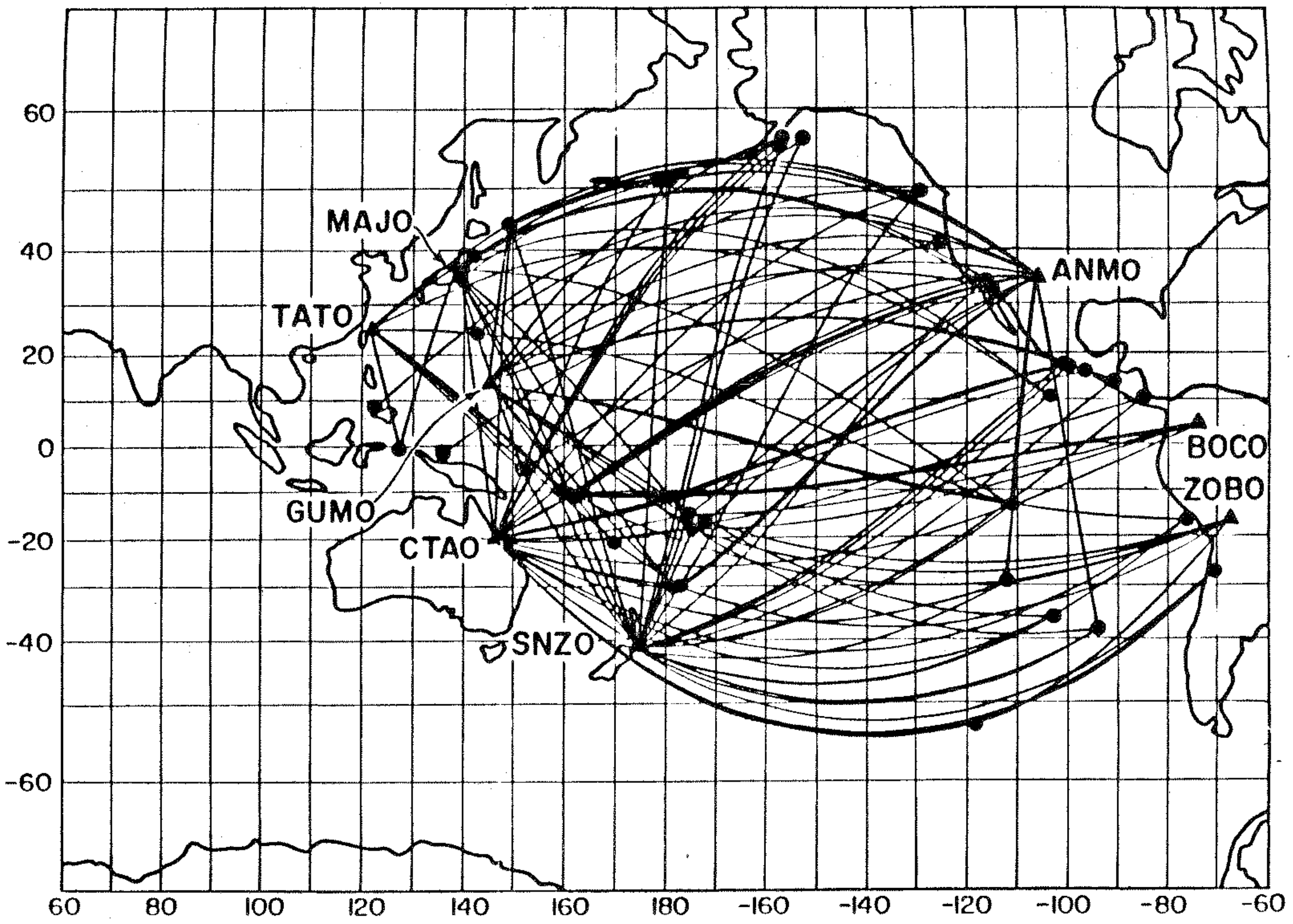


Figure 5-1. Surface-wave paths used to image the Pacific Ocean.

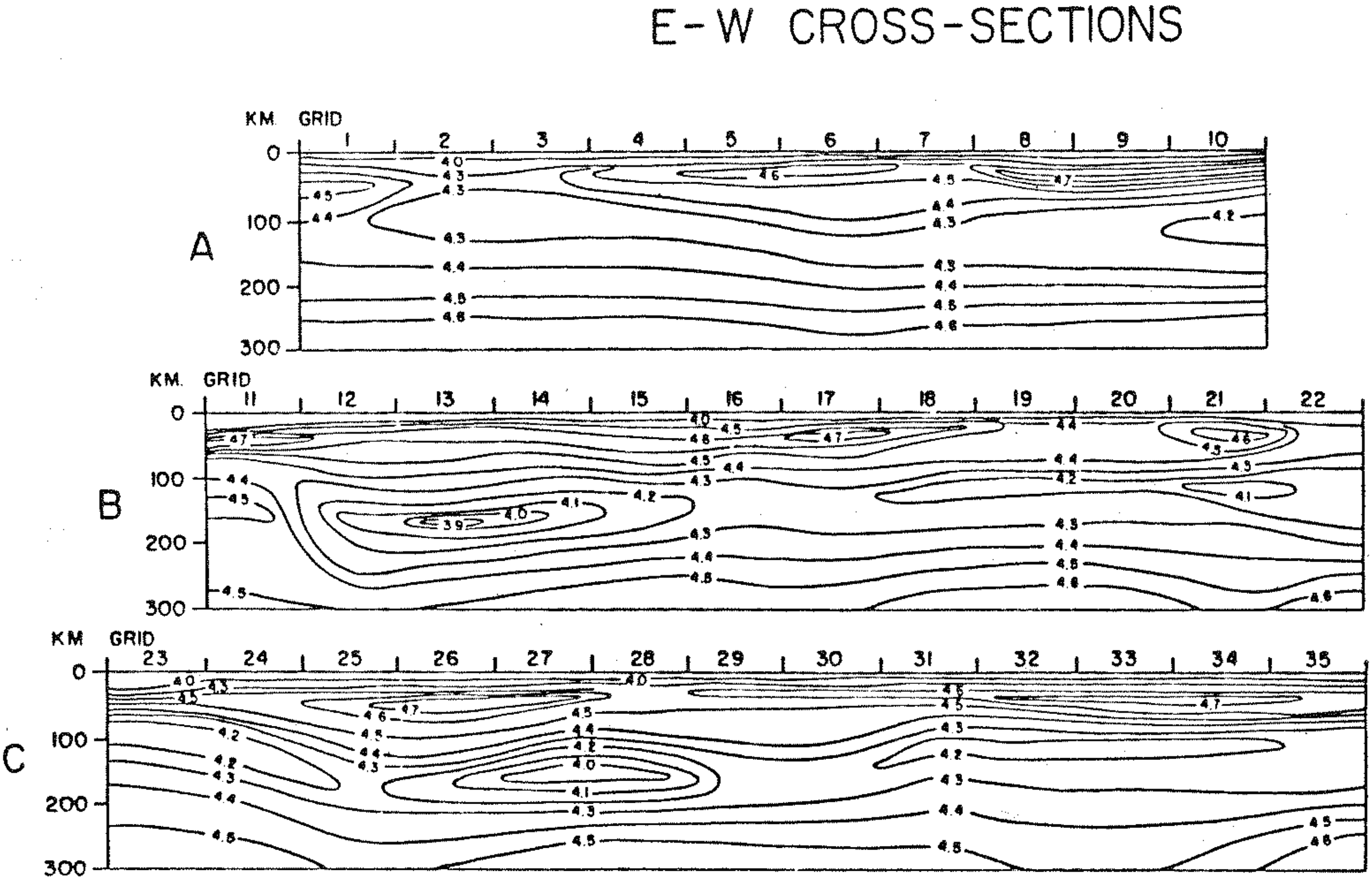


Figure 5-2. Shear velocity cross sections of the Pacific along lines (A) Hokkaido — Seattle, (B) Tokyo — Los Angeles, (C) Taiwan — Baja California.

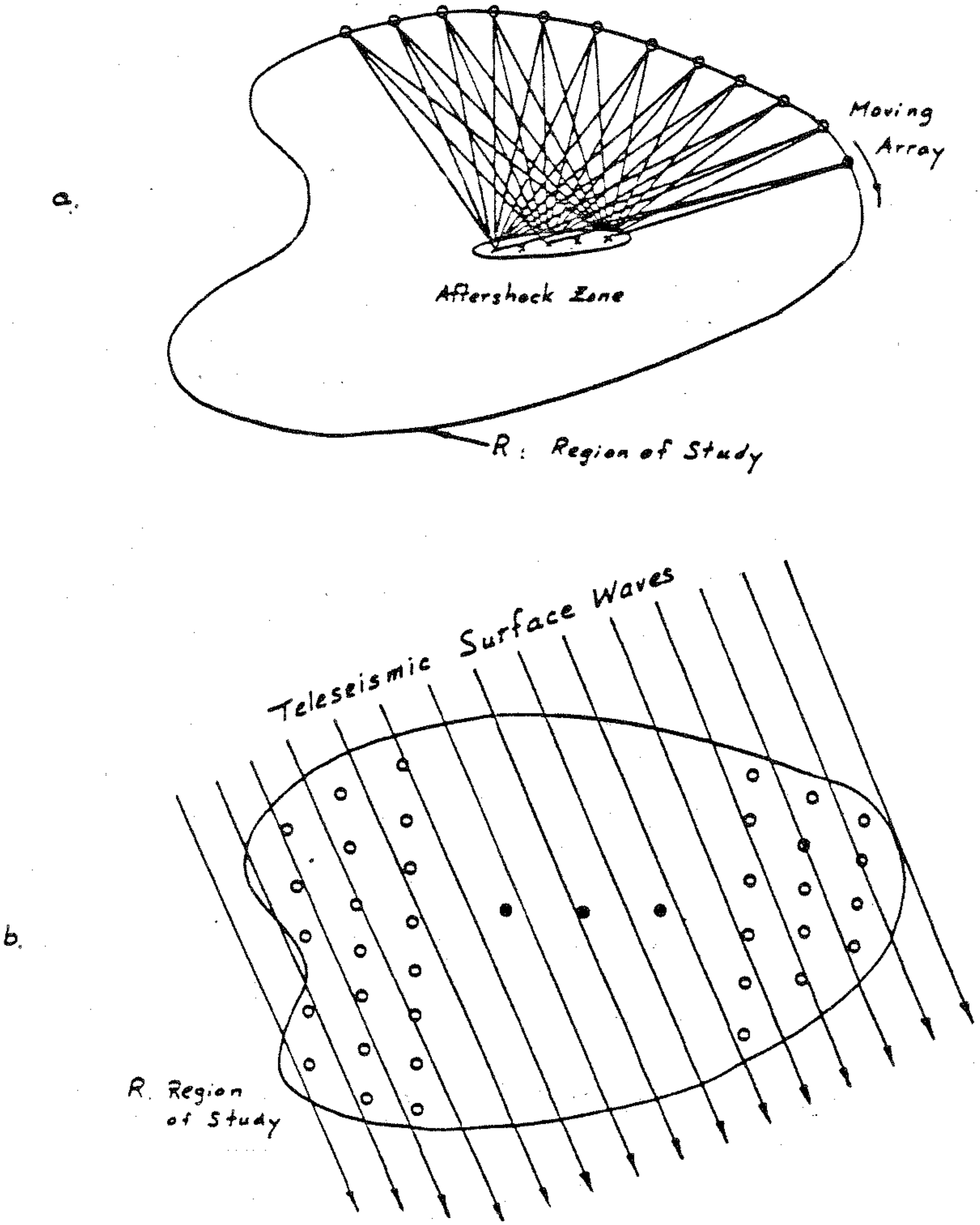


Figure 5-3. Geometry for regional tomography using surface waves. (Top) Using aftershocks as sources; (Bottom) Using teleseisms as sources.

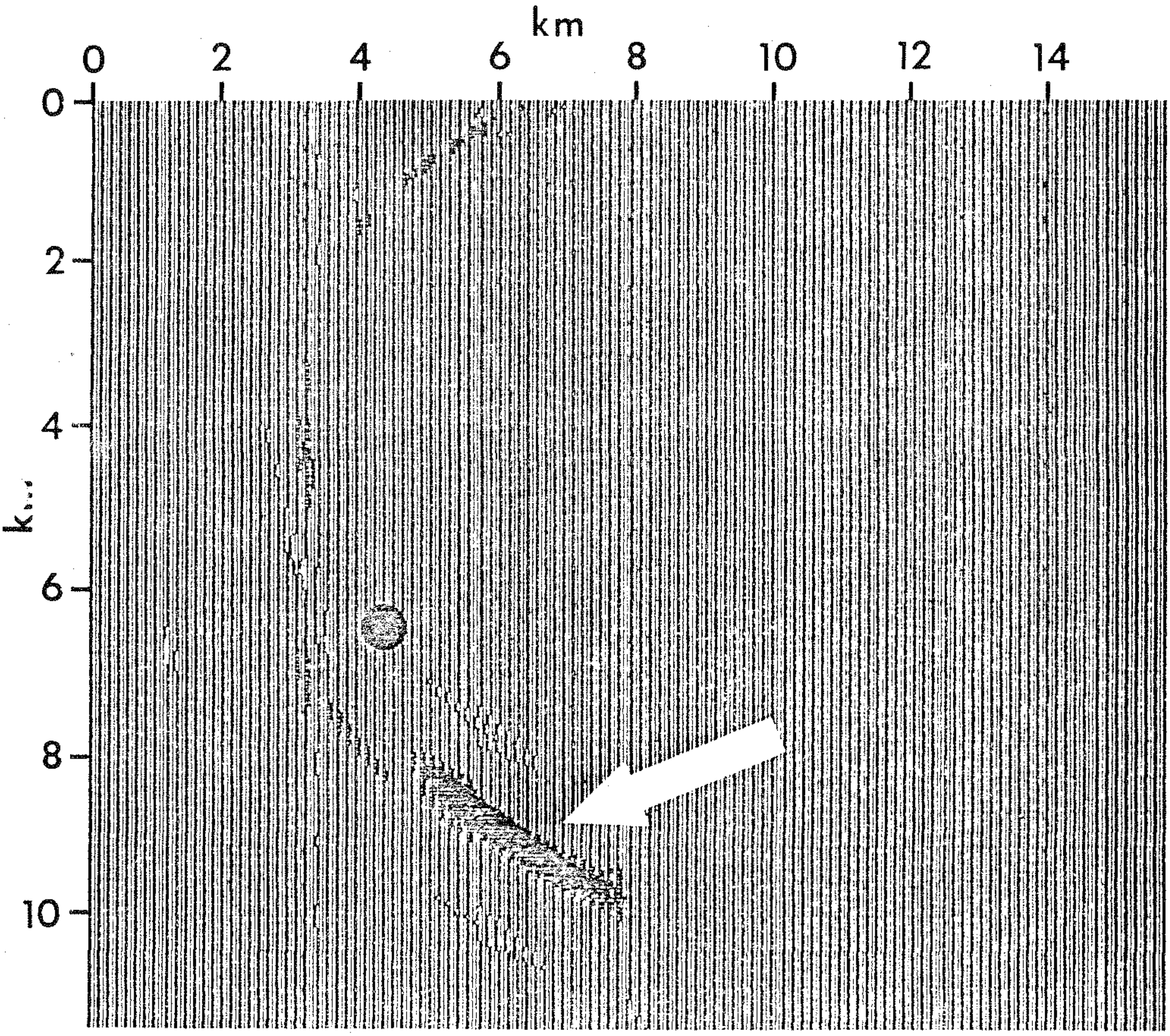


Figure 5-4. Imaging of an earthquake source by reverse time extrapolation. this plot contains a slice through the Earth near Mammoth Lakes, California. The image on this slice is of a real earthquake source obtained by reverse time extrapolation of the wavefield recorded at the earth's surface (after McMechan, Luetgert, and Mooney, 1984).

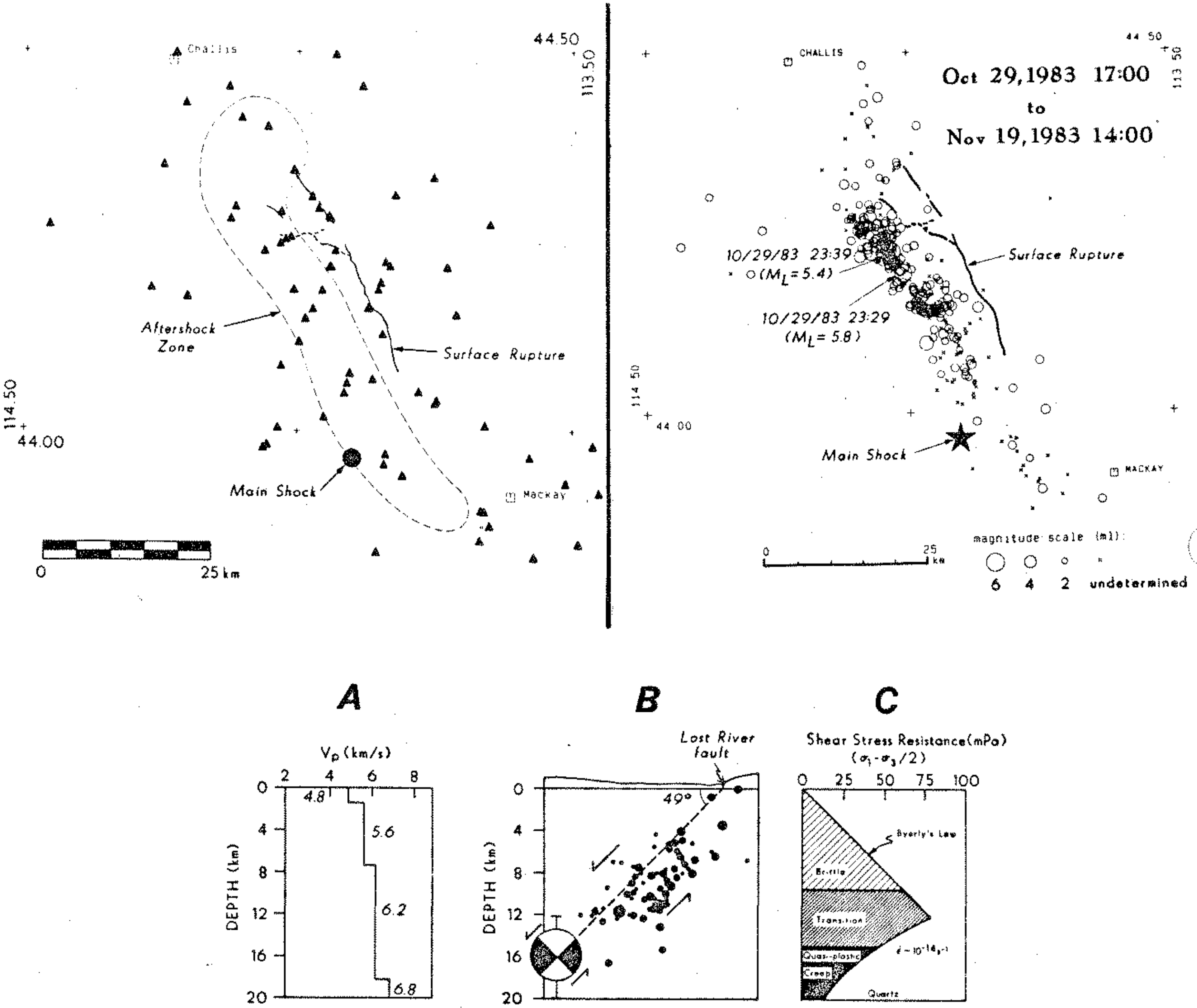


Figure 5-5. Earthquake monitoring of aftershocks of the Borah Peak, Idaho earthquake. Upper diagrams show locations of temporary continuous-recording and event-triggered seismographs, epicenters of the main shock and aftershocks for a twenty day period, and location of the surface rupture of the fault. Lower part of the diagram shows the velocity model used to locate the hypocenters (a), a cross-section with projected hypocenters of the aftershocks and location and fault-plane solution (vertical section) of the main shock (b), and a model showing the mechanical properties of the crust, indicating a brittle zone extending to about 12-15 km (c). (From Smith *et al*, and Richins *et al*. U.S.G.S. Redbook Conference on Borah Peak, October, 1984)

5.7. Anisotropy

It has long been known that the upper mantle consists predominently of rocks with preferred orientation of anisotropic minerals. In some cases, such as ophiolite sequences, the anisotropy is know to occur with a uniform symmetry over relatively large regions. The orientation of the symmetry axes in anisotropic materials in the mantle is thought to result from flow and recrystallization.

The extent to which anisotropy characterizes the material of the crust is uncertain, but is a challenge for future research. Metamorphic fabrics and structural features in the crust, such as sills and dikes are thought to give rise to an apparent anisotropy manifested in various ways in the characteristics of seismic waves.

Anisotropy can be studied in several ways. The velocities of body or surface waves, for instance, will vary azimuthally in every anisotropic material except that in which there is transverse isotropy with a vertical axis of symmetry. The inability to explain both Love and Rayleigh wave velocities with an isotropic model is another possible indication of anisotropy. Another well-known manifestation of anisotropy is shear-wave splitting. In addition, the polarizations of body and surface waves may be anomalous compared to polarizations predicted by isotropic models.

Although these effects can, in principle, be used to determine the extent and orientation of anisotropy in the earth, other factors, of which lateral heterogeneity is probably most important, can lead to erroneous interpretations of anisotropy where it might not occur in reality. To separate the effects of anisotropy form those of lateral heterogeneity, the use of well-calibrated three-component seismometers is required. Deployed as temporary arrays in different geographic regions for sufficiently long time intervals, they will provide the necessary data with which to study anisotropy and its regional variation beneath continental regions.

5.8. Attenuation Measurements

As seismic waves propagate through the earth their energy may be absorbed by intrinsic anelasticity of the material they traverse, or scattered by complexities in velocity structure. The attenuation of seismic waves caused by those mechanisms may be expressed by the intrinsic quality factor given by Q_α for compressional waves and Q_β for shear waves. In the continental lithosphere, these quantities are known to vary with depth, with geographical region, and with frequency at least above about 0.5 Hz. Moreover, the degree of frequency dependence of those parameters may also vary regionally.

Much progress has been made on these questions in recent years. There are, however, many regions which remain unstudied, and the way which Q varies with frequency over most frequency ranges is not known. It is likely that the regional variation of Q, as well as its frequency dependence, are affected by features produced during the tectonic evolution of the crust. To understand the relation between Q and crustal evolution will require an understanding of the mechanism of Q and to what extent intrinsic anelasticity and scattering contribute to seismic wave attenuation. To sort out the contributions of these factors in different regions and tectonic environments requires broad-band data from instruments (with high dynamic range) that can be deployed in arrays designed for specific signals and paths.

The limited distribution of permanent seismograph stations prevents the systematic study of regional variation of Q in the detail which is necessary for a causative understanding of that parameter. In addition, the narrow bandwidth of most traditional seismograph systems makes it difficult to study the frequency dependence of Q. These difficulties can be overcome using a relatively small number of broad-band instruments deployed within a single geologic province. Specific experiments should be devised to measure the attenuation of surface waves using either groups of two or more stations separated by distances of several hundred km or more, or single stations at some distance from an earthquake with a known fault-plane or moment tensor solution. The spectra of teleseismic body waves can be used to model lateral and vertical variations of Q throughout the lithosphere and asthenosphere.

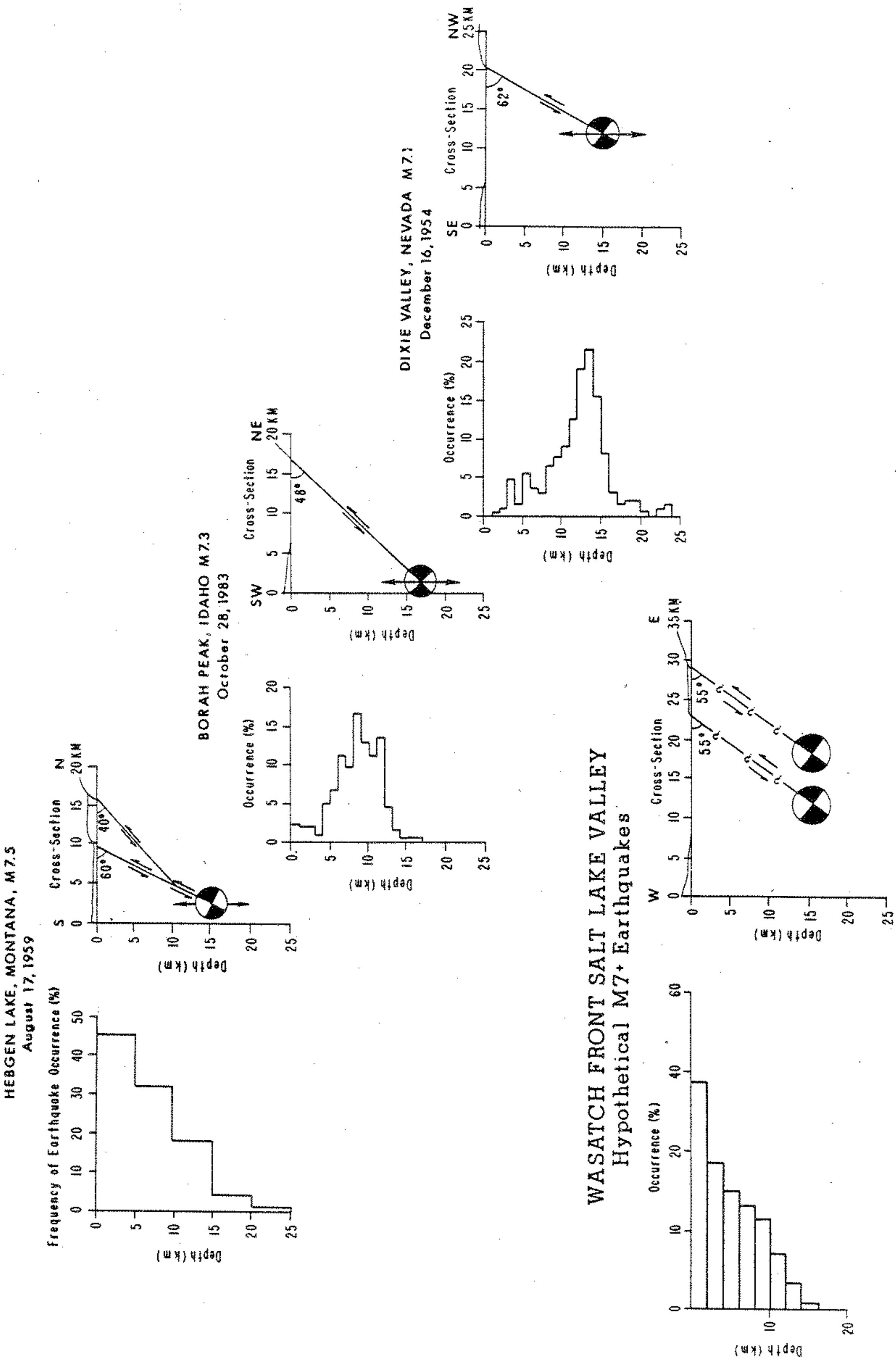


Figure 5-6. Fault-plane solutions for a number of extensional areas in western U.S. showing high degree of consistency of rupture angle from region to region. (From R. Smith, with permission, 1984)

5.9. Composition and Propagation of Oceanic Microseisms

The study of oceanic microseisms, considered to be a vital tool in oceanography and meteorology three decades ago, was more or less abandoned after the advent of satellites. However, many questions are still outstanding and only an instrumentation system such as the PASSCAL array can answer these questions, especially if used with satellite based systems simultaneously monitoring the source regions in oceans. Are microseisms generated beneath storms in the deep ocean or are they only generated by wave action near the coasts? What types of seismic waves are present in them? Microseisms fill a critical gap in the seismic wave spectrum (0.5—0.05 Hz) and deserve some attention. We suggest deployment of a 200-element subset of the PASSCAL array (L-shaped configuration) on an island where strong cyclonic storms occur nearby. Using frequency-wave number analysis the microseismic source(s) can be located and the composition of the waves determined. Dispersion curves of the surface-wave component of microseisms can be inverted to produce velocity models of the oceanic crust.

5.10. Three-Dimensional Modeling using Local Earthquake Data

Regional earthquake phases such as Pg and Sg, Pn and Sn, have long been used to obtain crude velocity models of the crust and upper mantle. Methods have been developed which utilize these phases as recorded by a regional array to obtain either plane-layered or three-dimensional models of the upper lithosphere beneath the region of the array. The implementation of these methods, to date, has suffered from the same shortcomings as those which adversely affect three-dimensional modeling using teleseismic data; less than ideal station coverage limits the resolution of detail and the absence of horizontal-component instruments has prevented the study of shear-wave structure. These shortcomings can be overcome with a dense network of three-component instruments that are being deployed in a seismically active region for a period of several months.

5.11. Body-Wave Apparent Velocity $dT/d\delta$ and P and S Delay Measurements; Imaging of Heterogeneities Using P and S Waves from Regional Earthquakes and Teleseisms

Vertically emerging bodywaves from regional earthquakes and teleseisms when recorded by a dense seismic array (such as a PASSCAL array) contains information on the three-dimensional heterogeneities beneath the array. The depth sampled is approximately the aperture of the array and the horizontal and vertical resolutions are about 5 km for P-waves and 25 km for S-waves. For example a 1000-element PASSCAL array when deployed in the form of a square with 5 km instrument spacing can be used to image a volume of 150 × 150 × 150 km^3 with high resolution. Several forward-and inverse-modeling techniques are available to process the data, the most commonly used being the linear inversion technique developed by Aki and colleagues. Numerous three-dimensional modeling experiments have been performed in the U.S.A. and other parts of the world. But there have been two major limitations: (a) lack of array density leading to severe restrictions in resolution of the models, and (b) lack of information on S-velocity. The PASSCAL system solves both these problems by (a) the availability of large number of instruments and (b) the wider bandwidth of the sensors which enable detection of shear-waves and computation of S-wave residuals. The three-dimensional P- and S-models generated using the PASSCAL array together with similar attenuation models can be translated into models of physical properties in the lithosphere and asthenosphere. Such results are needed to understand the deep processes associated with almost every tectonic setting, in addition to understanding localized or regional features, such as magma chambers, batholiths, rifts, or mountain roots.

The resolution limit (5 km for P-waves) can be increased by deploying a PASSCAL array in a dense configuration (30 km × 30 km grid with 1 km spacing, for example) and recording vertically arriving reflected waves generated by several explosions. Thus the PASSCAL array opens the exciting possibility of starting from a regional model and converging into a high-resolution model by combining passive and active techniques. To give a concrete example of application, imagine how much our knowledge of magma genesis in subduction zones and the origin of andesitic volcanos could be enhanced by a series of experiments using PASSCAL, say, in the Cascades or Alaska, starting from array spacings of 30 to 50 km and ending with array spacings of a few hundred meters!

5.12. Strong-Motion Seismology

The data loggers which form the core of the proposed PASSCAL instrumentation will also be usable for strong-motion earthquake studies. An array of 50, 100, or more data loggers coupled to strong-motion seismometers could easily be deployed in a profile or a two-dimensional pattern over an active fault zone to provide high-resolution observations of the wavefield from an earthquake. Two- and three-dimensional modeling, wavefield imaging, and tomography of data from this tightly spaced array of strong-motion instruments will yield detailed information on the earthquake's dynamical history and on the effects of lateral heterogeneity and local geological structure on near-field ground motions generated by an earthquake. In special cases, for instance, during after-shock sequences, response to incoming ground motions could be monitored not only under free-field conditions, but also in structures of engineering significance. For near-field strong-motion studies a different kind of sensor may be required. These sensors should be capable of sensing ground accelerations without significant distortion up to 1 or 2 g (1 g = 981 cm/sec) and at frequencies up to 50 Hz or more.

6. EXAMPLES OF THE USE OF LARGE ARRAYS OF PORTABLE INSTRUMENTS FOR GEOPHYSICAL STUDIES OF THE LITHOSPHERE

This chapter discusses some typical experiments that might be performed by the PASSCAL array. The purpose of the discussion is to illustrate the use of the array in specific cases, so that its modes of deployment and unique capabilities can be demonstrated. This chapter does not assert a priority for these experiments. Indeed, many other experiments of equal or greater interest may be conceived in the future. These examples are meant to merely cover a variety of geophysical targets; they range in scale and complexity, and they make use of diverse seismic techniques.

6.1. Major Lithospheric Experiments

6.1.1. Continental Growth by Terrane Accretion: The Trans-Alaska Lithospheric Investigation (TALI)

One spectacular finding resulting from the last decade of geologic research is the realization that an important process in the evolution of continents is growth by intermittent accretion of far-traveled, distinct "terranes." Most of Cordilleran western North America demonstrably has been accreted to the North American craton since the Paleozoic. The most bewildering assemblage of terranes so far identified from stratigraphic and paleomagnetic data shows that most of Alaska was assembled only since Mesozoic and Cenozoic times, and seismotectonic data demonstrate that terrane accretion is presently active (Figure 6-1).

While surface geology and paleomagnetics have proven that terrane accretion of Alaska is a fact, little is known about the processes at lower crustal and lithospheric levels that accompany terrane assemblage. It is clear that large-scale plate motions have provided the framework and driving forces for Alaska's crustal growth. But whether the crustal growth is thin-skin, and what its relation is to maturation of the lower crust and underlying mantle is shrouded by lack of data. To bring about a change, geologic and geophysical methods, especially deep seismic imaging must be jointly applied to illuminate the structures associated with terrane accretion over the entire lithospheric depth range. For this purpose TALI (the Trans Alaska Lithospheric Investigation) was born.

TALI is a multi-institutional, cooperative geological, geophysical investigation of the Alaskan crust and upper mantle that was inaugurated in 1984 as an informal consortium of academic and governmental institutes. Participating institutions presently include the University of Alaska, Rice University, Alaskan Division of Geological and Geophysical Surveys, and the U.S. Geological Survey. Many university groups are planning to join during the expected program duration of ten years.

The objectives of this multi-year program are to investigate the structure of the North American continent along a 1000 km long north-south transect across Alaska from the deep Pacific basin to the deep Arctic basin. The transect route (Figure 6-2) crosses the continent at its narrowest width. Here it samples a nearly complete suite of the key problems of continental geology, including continental accretion at a convergent boundary, the response of newly accreted terranes to continued subduction and collision, and transform faulting within the continental interior (e.g. Denali Fault). The transect then crosses a major fold- and thrust-belt orogen (Brooks Range), continues northward through a passive continental margin with its subsided sedimentary basins at the Beaufort Sea shelf.

The TALI program emphasizes the coordinated application of diverse, yet complementary geologic and geophysical methods and multidisciplinary interpretation and synthesis of data. Proposed field investigations include seismic refraction and reflection profiling (Chapter 14), both onshore and offshore; geologic mapping along the seismic profiles and special stratigraphic, structural, isotopic and petrologic studies; aeromagnetic and gravity surveys in selected areas; and magneto-telluric heat flow and in-situ stress measurements.

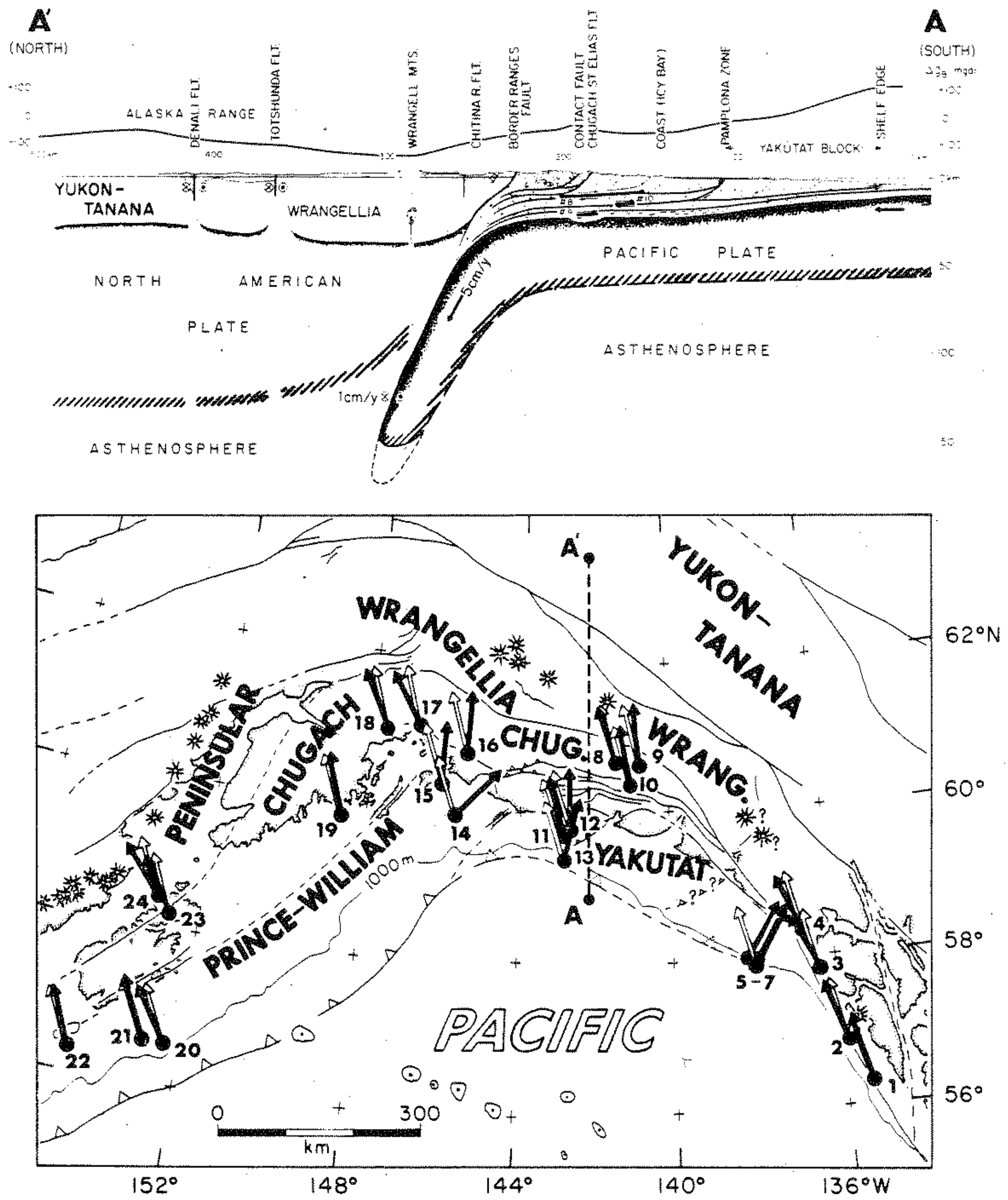


Figure 6-1. Map (bottom) and schematic cross section (top) showing active terrane accretion in the Gulf of Alaska. Solid arrows of numbered locations on map show actual slip directions during specific earthquakes and, for comparison, open arrows indicate Pacific vs. North American plate motions at the same locations as computed from global plate reconstructions. (modified from Perez and Jacob, *J. Geophys. Research*, 1980)

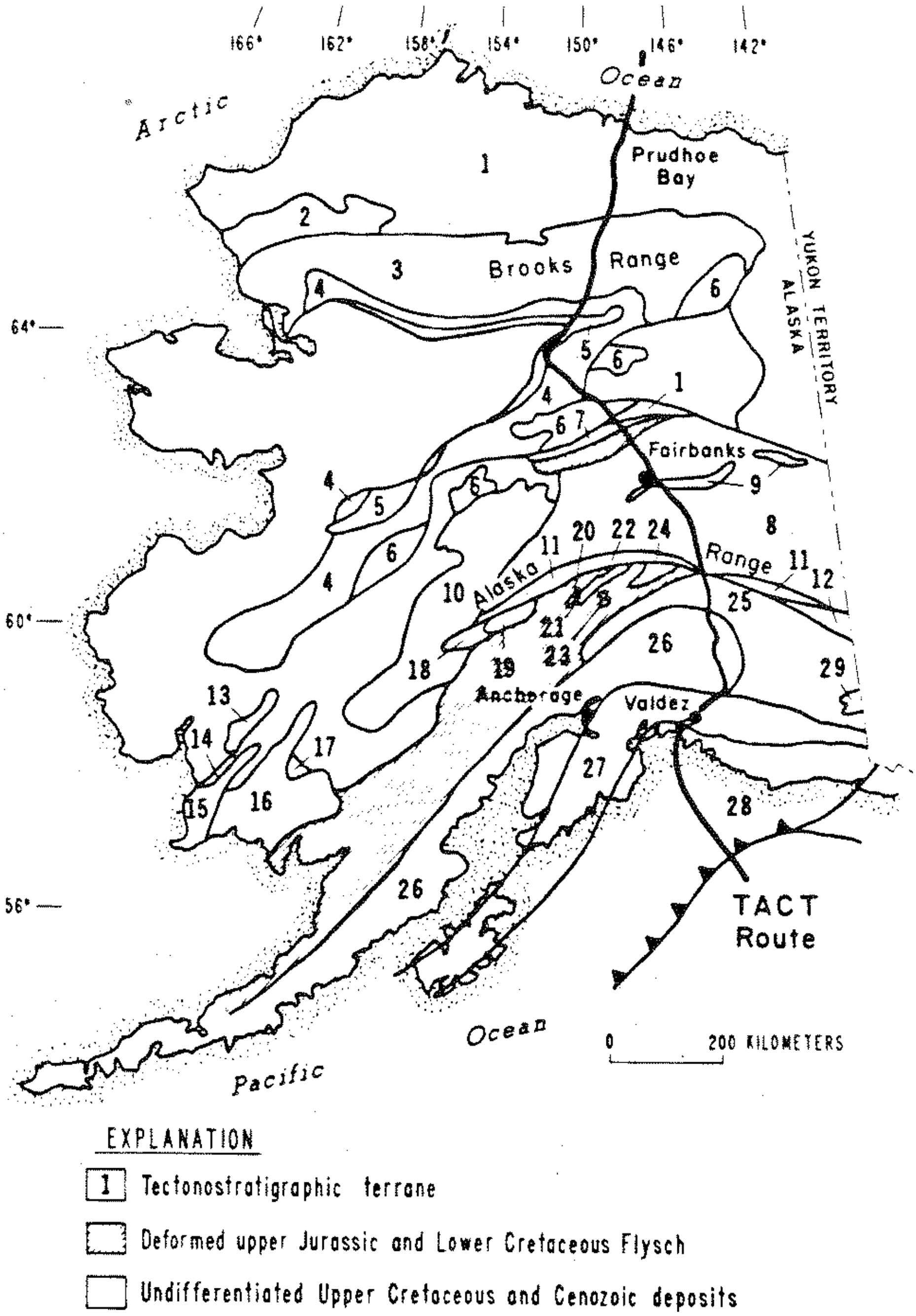


Figure 6-2. Route of the Trans-Alaska Crustal Transect shown in relation to tectonostratigraphic terranes (after Jones and Silberling, USGS Open-file Report 79-1200, 1979). Terranes along transect comprise: (1) North America; (3) Endicott; (4) Ruby; (5) Angayucham; (6) Innoko; (7) Livengood; (8) Yukon, Tanana; (9) 70-mile; Pingston-McKinley; (24) McLaren; (25) Wrangellia; (26) Peninsular; (27) Chugach; and (28) Prince William.

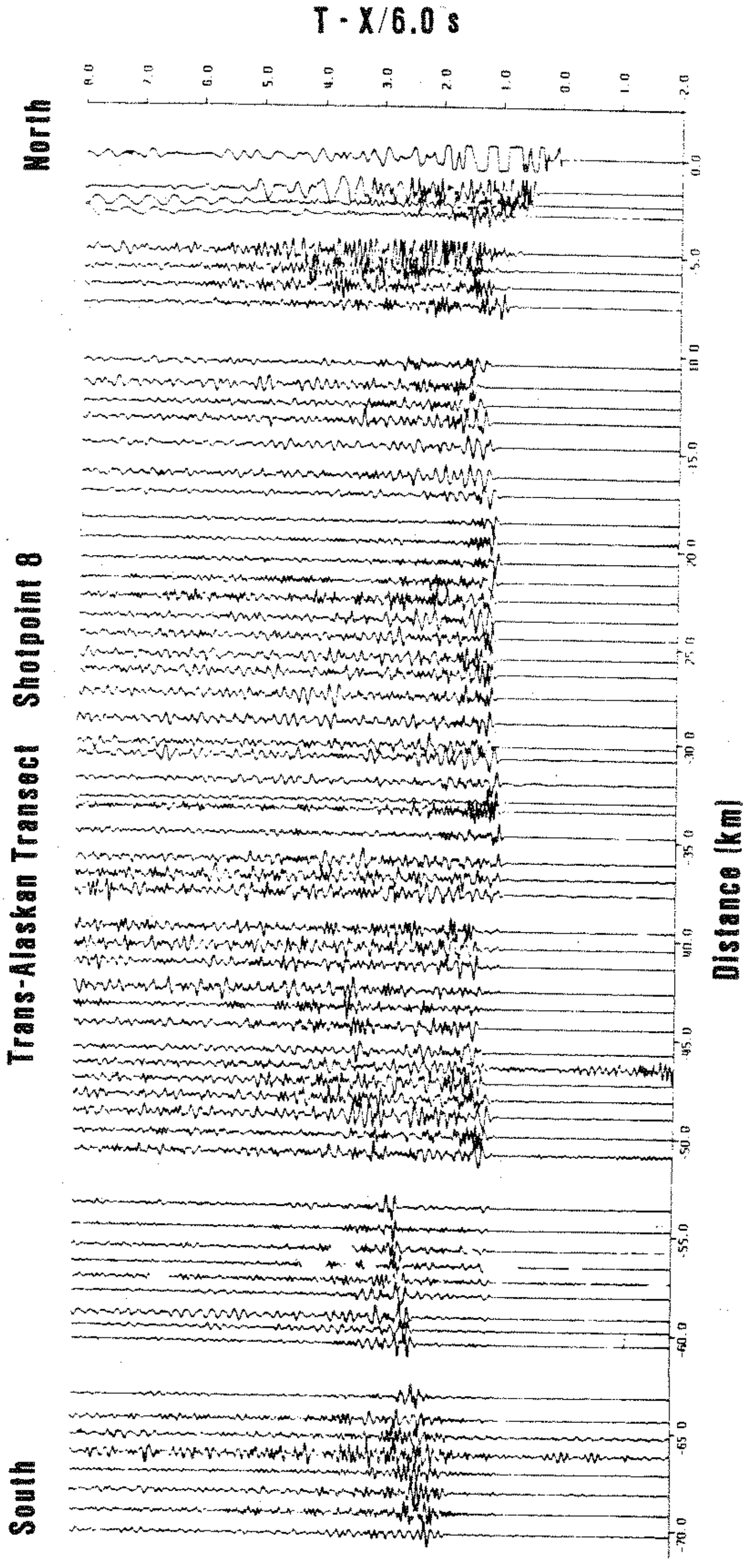


Figure 6-3. Seismic refraction profile recorded along the southern end of the TALI route. Note the very strong wide-angle reflection between 45—70 km range.

Seismic refraction profiles recorded in the summer of 1984 focused on the definition of representative seismic velocity structures in the accreted Chugach, Peninsular, and Wrangell terranes, and of the basements flooring the terranes; the nature and structure of the boundary or transition between the Peninsula and Wrangellia terranes beneath the Quaternary cover in the Copper River Basin; and the location and structure of the subducted and actively subducting Pacific lithosphere beneath the Chugach Mountains. Preliminary examination of record sections produced in the field yields encouraging results and shows numerous strong wide-angle reflections that may be from the top of the subducted lithosphere at depths of at least 10 to 15 km (Figure 6-3).

As spectacular as these preliminary results are, they illustrate several of the serious shortcomings of the existing instrumentation that will be overcome when sufficient numbers of PASSCAL instruments will be available. While the profiles show excellent continuity of energy between adjacent traces, the receiver spacing of the 120 analog instruments of about 1 km, is too broad to record an unaliased wavefield, which greatly limits the resolution of structural detail. The proposed set of PASSCAL instruments could fill a critical gap in the existing experimental plan by providing an array for the three-dimensional imaging of deeper structures along the transect route as illuminated by a variety of seismic sources including controlled explosions, local earthquakes and teleseisms.

As this program proceeds, it is certain that new tectonic questions will be raised by its results. For instance, presently it is not clear whether the Yakutat Block and Chugach Terrane, two of the youngest accreted terranes, are truncated at depth by a common, single detachment, whether this detachment coincides with the Moho of the subducted oceanic Pacific lithosphere, or whether some basement attached to the Yakutat Block has underridden the Chugach Terrane to any substantial depth. Superimposing hypocenter locations from passive experiments onto velocity sections will resolve the presently unknown location of the seismogenic shear zones relative to the preexisting structural units.

Focal mechanisms and seismicity studies in the Gulf of Alaska region by the Geological Survey and university groups indicate that the subducting Pacific slab may be torn into two diverging slab segments, one plunging to the NE beneath the Wrangell volcanoes, another to the NW beneath the Cook Inlet. Very detailed three-dimensional tomography and/or passive three-dimensional full wavefield studies using earthquakes and a few critically placed explosions using two-dimensional deployment of PASSCAL recorders should resolve the existence of a major gap or mantle window in the subducting slab.

Further inland the USGS refraction profiles, and during subsequent years, COCORP reflection profiling and deployments of PASSCAL instrument arrays will cross major active or fossil fault zones thereby zeroing in on crust and upper mantle structures beneath such major fault systems as the Denali, Tintina, and Kaltag faults. The profiles will traverse major terrane boundaries and probe whether the crustal terrane configurations as outlined by near-surface geologic and stratigraphic expressions find corollary expressions in their Moho and upper-mantle structures, or whether the terranes are thin-skinned, and do not have a one-to-one relationship to heterogeneities in the upper mantle.

Once the transect crosses the Brooks Range and reaches the North Slope many of the deeper crustal structures to be imaged underlie the sedimentary formations that are of economic interest because of their hydrocarbon potentials. They can be studied using seismic and stratigraphic sections (from surface and down-hole data), to be jointly analyzed for basin subsidence by modern back-stripping techniques.

In summary, the Trans-Alaska lithospheric investigation is a 10-year multidisciplinary program to study many facets of the origin of continental lithosphere primarily by accretion of far-travelled terranes. PASSCAL will have a special place by probing with high resolution at select localities the relation of upper mantle to crustal structure at all lithospheric depth ranges.

6.1.2. Long-Line Seismic Profiling in Selected Tectonic Regions of the U.S.

The availability of hundreds of matched, versatile digital seismographs will allow for significant new long-line refraction/reflection profiling experiments. One of the most successful aspects of the COCORP program has been the regional geologic and tectonic interpretation due to the recording of regional profiles hundreds of kilometers in length across several geological terranes. Examples include the Great Basin to Colorado Plateau profiles and the Southern Appalachian profiles. Similarly, new long-line refraction/reflection profiling can provide new insight on lithospheric structure, geodynamic processes, and lateral variations in structure. The long-line data will provide additional deep structural control (lower crust and upper mantle) as well as accurate velocity data (for both P and S) that are presently not available from conventional COCORP profiling activities.

A few limited long-line experiments have been performed in recent years, with significant results. Examples include the Yellowstone-Snake River Plain experiment in which significant crustal-structure anomalies and volcano-tectonic evolutionary processes were investigated. (See discussion in Chapter 4) Also, the Mississippi Embayment crustal study and the Saudi Arabian project, both by the USGS, provide good examples of the type and quality of interpretation that can be accomplished using long-line techniques.

The new PASSCAL instrumentation will substantially enhance the quality of data from long-line studies by making smaller station spacings possible (100—200 m) and will simplify the logistics and the data processing by permitting longer sections to be included in a single shot. Modern wavefield continuation methods and two-dimensional modeling methods are available to develop strongly constrained models for the underlying structure of the crust and upper mantle. Long-line profiles would be particularly valuable in the following areas:

(1) Southern Appalachians: Atlantic Coast, through Appalachians to Appalachian Basin.

(2) Ouachita Mountains: Midcontinent craton to Ouachita Mountains to Gulf Coastal Plain.

(3) Great Basin: Pacific Border to Sierras to Great Basin to Colorado Plateau.

(4) Columbia Plateau: Pacific Border to Cascade Mountains to Columbia Basin to Western Snake River Plain.

When the length of the long-line profile is taken to the range 400—2500 km, the recorded wavefields represent signals reflected at wide angles from within the sub-crustal portion of the lithosphere. Such data represents one of the best possibilities for defining the details of the geology below the Moho. A 500 km lithospheric profile in France and a 2500 km profile in the USSR showed a wavefield consisting of numerous "shingling" wide-angle reflections, while arrivals from beyond 2200 km behaved like simple "diving" waves in a velocity gradient. The sub-continental lithosphere is clearly characterized by this multiply reflective internal layering, while the mantle below 400 km seems to lack this complexity as far as we know it today. This kind of data should lead to a better idea of whether the lithosphere has deep roots (>150 km) under shields (tectosphere), and would clearly be important in characterizing the contrast in properties of the lithosphere across the Rocky Mountain front and the Appalachian orogen.

6.1.3. Thrust Belt, Southern Appalachians

The southern Appalachians are part of a Paleozoic orogenic belt that extends in a series of salients and recesses some 3,200 km (2000 mi) from Newfoundland to Alabama. Recent geophysical studies have yielded considerable information about the crust beneath the southern Appalachians and adjacent areas even though there has been much debate over these interpretations; particularly the deep seismic reflection surveys. These studies include deep seismic reflection profiles by COCORP and the U.S. Geological Survey, seismic refraction profiles, gravity interpretations, and magnetic interpretations.

According to some authors, the southern Appalachians are underlain by an east-dipping decollement zone from the Appalachian plateau to the continental shelf. Palinspastic restoration of structures west of the Brevard zone suggest a minimum shortening of 280 km (175 mi) for the Valley and Ridge and Blue Ridge provinces. Interpretations of the COCORP reflection profile indicates that the crystalline Precambrian and Paleozoic rocks of the Blue Ridge and Piedmont provinces constitute an allochthonous plate, 6 to 15 km thick, that overlies autochthonous, relatively flat-lying, 1 to 5 km thick sequence of sedimentary (or metasedimentary) rocks of the proto-Atlantic continental margin. It appears that the crystalline rocks were thrust at least 160 km (100 mi) to the west. The COCORP data also show the Brevard fault to be the surface expression of an east-dipping splay off the main basal thrust.

A USGS deep-reflection profile across the eastern Valley and Ridge, Blue Ridge, and western Piedmont provinces of Tennessee and North Carolina also indicate that crystalline rocks of the Blue Ridge and Piedmont are thrust westward over a thick sequence of sedimentary rocks that are exposed in the Valley and Ridge province.

The interpretations of the COCORP survey in the Southern Appalachians have sweeping implications for the tectonic history of the area and have led to the choice of an area in South Carolina as a possible deep drilling site. The site of the first deep drilling project totally dedicated to scientific research is a particularly appropriate place for an early effort by groups from PASSCAL to mount a major experiment. A fully integrated experiment combining the elements of both reflection and refraction technologies would provide a unique and powerful tool for determining deep and shallow earth structure in the proposed drill site area.

A preliminary experiment design has been formulated (Chapter 14) and includes a combined DSS/refraction/reflection study. A 300 km long DSS line with shotpoints at 25 km intervals would be run from the Blue Ridge to the Eastern Piedmont, with special attention given to the transition region (Figure 6-4). A seismic contractor with the ability to record 200 separate sites would be employed for the data collection, and preliminary discussions suggest that the U.S. Geological Survey may be able to provide the funds required for drilling and blasting. Rough estimates provided by the seismic contractor indicate that the cost of crew mobilization, data collection, and production of a standard format tape of the seismograms would be approximately $500,000. The use of the same contractor crew for collection of any reflection data desired would be cost efficient and advantageous because of the matching of instrumentation. In fact, this experiment and a reflection experiment could be conducted simultaneously to yield a truly unique data set.

6.1.4. A Three-dimensional Active-Passive Imaging Experiment in the Basin-Range

The objective of a seismic project in an active extensional regime is to resolve details of the upper-crust in an area of active faulting, by means of a unified experiment that combines controlled and natural sources with a two-dimensional array. This includes P- and S-velocity variations, apparent Q variations, and the precise location of earthquake hypocenters in a laterally variable velocity model. These parameters are necessary to resolve such features as listric faulting, the properties and structure of upper-crustal low-velocity layers, possible seismic identification of ductile layers, the correlation of hypocenters with subsurface faulting, the relationship of subsurface features to surface faulting, and the simultaneous inversion of passive-active data as a means of unifying the interpretations and constraining models that otherwise would be limited by single methods. Moreover, dense 3-component seismometer spacings permit unaliased recording of the wavefield. Because velocity structure is accurately determined as part of the experiment, the recorded earthquake wavefields can be downward continued to yield source time history, slip function, and geometry of the fault zone.

An active/passive seismic recording experiment provides an important opportunity to compare results of subsets of data typical of those routinely analyzed in network seismology (or in microearthquake field experiments) with "truth" established by the elaborate active/passive experiment.

The general experiment can be designed to fulfill the objectives of a three-dimensional active/passive seismic study. Such an experiment requires a geologic target area that has the following characteristics: (1) on-going earthquake activity, (2) geologic or subsurface verification that listric faulting and/or equivalent low-angle thrusting is present, (3) reasonable accessibility for simple and relatively inexpensive logistics, and (4) availability of additional

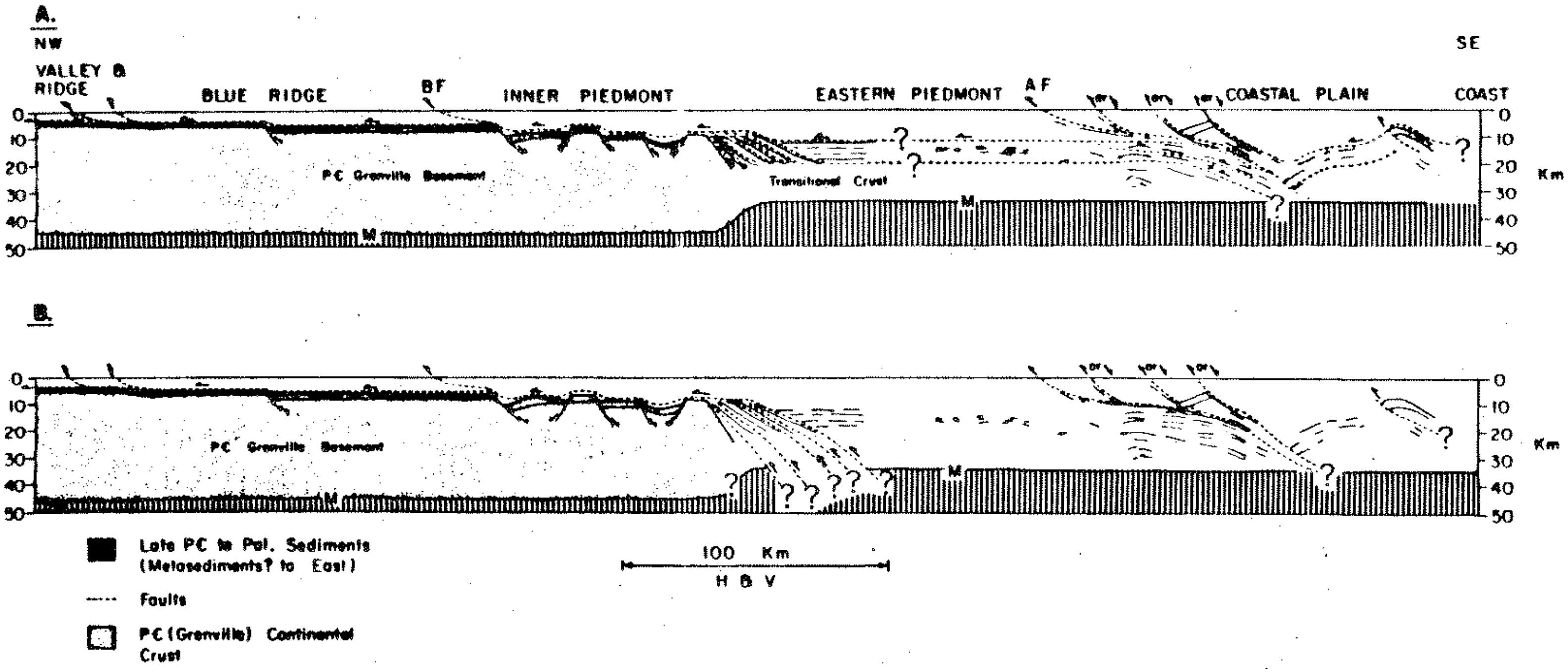


Figure 6-4. (Top) Schematic cross section from the Valley and Ridge to the coast, based on the COCORP data in which a subhorizontal detachment is interpreted to extend beneath the Coastal Plain. (Bottom) An alternate interpretation in which the thrust surfaces of the Inner Piedmont-Blue Ridge allochthon are interpreted to root near the Charlotte Belt (after Hatcher and Zietz, 1980). The shaded areas are interpreted as late Precambrian/early Paleozoic strata of the continental shelf and adjacent ocean basin; the lined pattern represents the mantle, and the hatched pattern represents continental crust.

geophysical and geologic information.

In approximately two months of recording, during which time full PASSCAL instrument array is employed, both active and passive phases of the experiment could be completed over a key area at least 50 km square within the extensional terrane. The combined data of artificial and natural sources permit the simultaneous solving for velocity structure (including detailed tomographic imaging of small-scale velocity heterogeneities), accurate hypocenters, and fault plane solutions. These results when coupled with wavefield imaging of the fault planes and rupture mechanisms will provide a comprehensive, and hitherto unobtainable, picture of the complex and important processes of continental rifting. Mechanisms of normal faulting are of great importance in understanding crustal extension. For example, do normal faults with steep dips in surficial sediments exhibit decreasing dip with depth? Do they remain planar or become listric? To what degree do they accomodate intraplate deformation? These and other questions pertaining to intraplate tectonism can be resolved only by developing seismic images of the subsurface fault zone and surrounding foot-wall/hanging wall rocks. Figure 6-5 shows a migrated seismic reflection profile across a normal fault in the Wasatch front. The fault exhibits steep angles near the surface, with decreasing angle of dip with increasing depth. Seismic imaging of faults is also critical in evaluating their relationship to deeper lithospheric structures such as detachment and thrust faults. Monitoring of active normal faults simultaneously with seismic imaging can aid in understanding the seismogenic mechanism and its relationship to structure.

6.1.5. Continental Volcanic Field, Columbia Plateau

One of the limiting factors in developing a consistent geologic and geophysical model for the crustal structure and tectonic development of the Pacific Northwest region, and specifically the Columbia Plateau, is the absence of detailed seismic data on the velocity structure of the crust and upper mantle of the large volcanic complex. Although the eastern and western Snake River Plain are now relatively well understood and have detailed seismic studies, the Columbia Plateau region in the High Lava Plains of central and eastern Oregon have only limited seismic information.

A large number of geological and geophysical studies of the tectonics of the Pacific Northwest have been performed in the last several years. One critical limitation of these studies, however, has been a lack of detailed crustal-structure information that prevented that plate tectonic-and crustal evolution processes could be related to the surficial geology which in turn is largely covered by the mid-Miocene plateau basalts. Most recent tectonic models have attempted to relate the complex Pacific Northwest kinematics to a model of distributed right-lateral shear in the western U.S. and to the docking of accreted terranes. The concept of a broad plate interaction zone for the right-lateral relative motion between the Pacific Ocean plates and the intraplate region of western North America provides an attractive starting model for understanding the complicated Pacific Northwest region.

Most models of the Pacific Northwest, in addition to considering the late Cenozoic plate interactions, also emphasize the extensional phenomena of the Basin and Range Province during the same time period. The style of volcanism, what little is known about the crustal structure of the Columbia Plateau region relative to the extensional terranes to the south, and the presence of the Blue Mountains as an uplifted province suggest that the Cenozoic tectonic development of the Columbia Plateau may be related to the overall distributed shear and extensional model of the western United States.

Lithospheric seismic refraction/reflection studies in the Columbia Plateau can provide critical data for the interpretation of the tectonics of the Pacific Northwest, crustal evolution of this plateau basalt province, docking of accreted terranes, and the relationship of the Columbia Plateau to the possible connection to the western Snake River Plain area. The availability of close station spacing, digital three-component data with adequate amplitude control will allow for greatly improved modeling techniques utilizing one-, two- and three-dimensional travel time and synthetic seismogram techniques to be applied to this data set for both P and S wave velocity structure determinations.

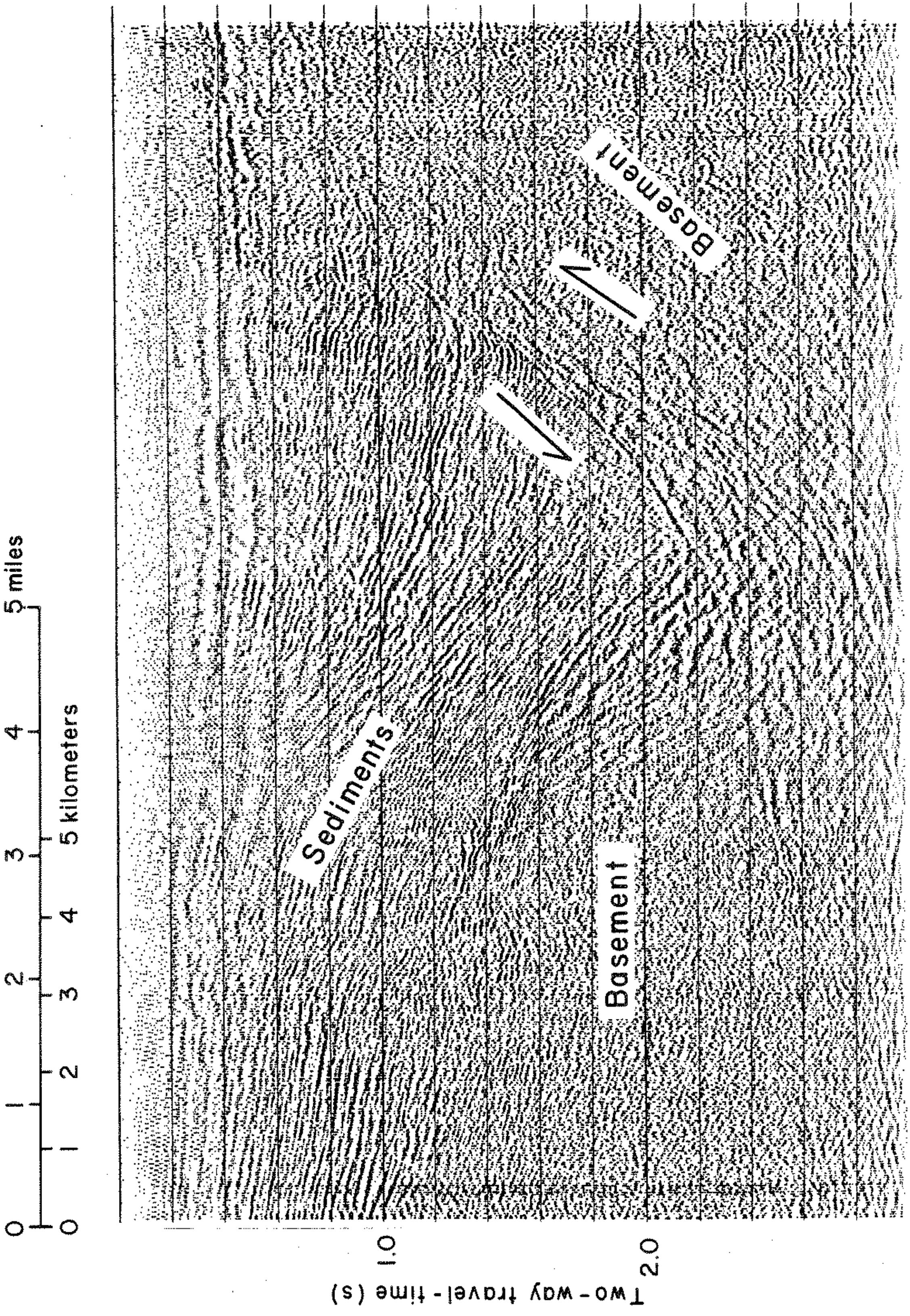


Figure 6-5. East-west reflection cross-section, Great Salt Lake, Utah. Horizontal extent about 12 km. Reprocessed migration before stack by John Vievros, University of Utah. (R. Smith, by permission, 1984)

6.1.6. Paleozoic Thrust Belt, Ouachita Mountains Area

The Ouachita system is a Paleozoic orogenic belt that extends westward from the Appalachian system in Mississippi, to at least the Cordilleran orogenic belt in Mexico. Although the system is buried for most of its length, major exposures occur in two salients of the system. These are the Ouachita Mountains of Arkansas and Oklahoma and the Marathon uplift of west Texas. Wells have yielded much information about the subsurface continuation of the Ouachita belt, but the gulfward extension of the system is unknown because it rapidly passes out of reach of present commercial drilling techniques.

A deep seismic reflection profiling experiment over the Ouachita system by COCORP has provided evidence for extensive thickness of sedimentary rocks near the southern edge of the orogen. However, several questions related to the deep structure of the orogen remain. A seismic refraction/ reflection survey utilizing digital seismographs spaced at about 250 m and recording controlled sources can be used to determine the nature of the lower crust and the transition of the craton to oceanic crust. The seismic experiment envisioned for the Ouachita Mountains area would extend the COCORP results in terms of both depth and lateral extent. As can be seen from COCORP data, there is considerable ambiguity about deep crustal structure which needs to be resolved. Perhaps the most important question is that of the thickness and extent of Ouachita facies metasedimentary rocks. For instance, a large thickness of these rocks would indicate an underlying, fundamentally oceanic crust which is not consistent with many tectonic models proposed for the development of the Ouachita system.

A wide-angle reflection-refraction (deep seismic sounding) experiment extending from the Benton uplift to the Gulf of Mexico would be ideal. If the remarkable on-going swarm of earthquake activity in northern Arkansas continues, the experiment could include an element of passive monitoring. An early experiment has been proposed (Chapter 14), which would be tied to the COCORP profiles, and an unified interpretation of the COCORP and wide-angle data would be undertaken. The experiment would provide complete two-dimensional wavefield coverage over a distance of about 150 km. The seismic data can be interpreted using two-dimensional travel time, inversion, waveform extrapolation, two-dimensional synthetic seismogram modeling, and CDP reflection processing. Of particular importance is the simultaneous interpretation of the wide angle reflection and refraction data and the COCORP reflection profiling data.

6.1.7. Subduction and Accretion at the Continental Boundary Beneath Cascadia

The coastal region of Washington, Oregon, and northern California represents an area of recent continental growth by accretion. The contemporary expression of this accretionary process is seismically active subduction of the Juan de Fuca plate beneath the Olympic mountains of northwestern Washington, and of the Gorda plate beneath the Coast Ranges of northwestern California. At these northern and southern extremeties of the Cascadia subduction zone, the most recently subducted pieces of the lithosphere are defined by active Benioff zones, but only to a depth of less than 100 km. The largest section of the subducted lithosphere between these two extremes has, at least during historic times, been completely aseismic. This apparent lack of great earthquakes at the plate contact may be an example of a recent change in the subduction process from brittle to ductile behavior, or if elastic strain is accumulating, it may represent a large and potentially dangerous "seismic gap." To assess the configuration of the subducted lithosphere and to seismically constrain the state of stress and probe the physical properties of the material along it's upper boundary will be the key to choosing between these two alternative interpretations.

Preliminary refraction work in cooperation with the Canadian COCRUST project has revealed a rough velocity model of this boundary in the Olympic Peninsula region and additional insight may become available soon from a COCORP profile planned for Oregon in connection with the EMSLAB program in that area. Since the crust in this region has apparently been assembled by a very complex accretionary process, it exhibits an unusually large amount of lateral heterogeneity. As a result, previous experiments involving only a few Ocean Bottom

Seismographs offshore and a few tens of land based seismographs have produced only a crude picture of the lithospheric structure. Only a hint of the configuration of the sub-crustal part of the lithosphere is currently provided by studies of teleseismic P delays, and long-period body wave modelling utilizing the existing, widely spaced regional seismic network. This area is thus a good target for a dense array experiment for a period of 3—6 months to record offshore explosions, local micro-earthquakes occurring in the subducted lithosphere, and teleseismic body waves. The diversity of sources that could be recorded here illustrates the need for flexible new instrumentation, since it would require recording specific times for the offshore explosions, triggered recording of micro-earthquakes, and triggered broadband recording of teleseismic body waves. It would also involve configuring the instruments' 6 channels for vertical-component recording of the explosions, and three component recording of the earthquakes for S wave analysis.

6.1.8. Deep Structure and Processes in the Western United States

Teleseismic and local earthquake travel time data collected at existing seismic arrays in the western United States have revealed the three-dimensional velocity anomalies relevant to the deep tectonic process under each array. For example, using the Central California network data, an inclined low-velocity zone was discovered dipping eastward from the San Andreas fault through the lithosphere into the asthenosphere. The zone may represent the seismic image of the proposed "window" in the subducted Farallon plate that forms as the Mendocino Triple junction migrates to the northwest. Similarly the inversion of data from the arrays in Alaska, Washington and Oregon have delineated the geometry of subducting plates under these respective areas. The most recent example, using the Southern California Array, consisting of 200 events at 200 stations distributed over a 400 by 500 km area, clearly defines a slab-like structure underlying the Transverse Ranges (Figure 6-6). The method used, a tomographic back-projection algorithm, exemplifies the kind of large scale data processing, with large data and model spaces, which is an intrinsic part of studies with large arrays.

In order to define the general geometry of currently subducting plates such as the Juan de Fuca plate and long disappeared plates such as the Farallon plate, we need a seismic array with spacing about 30 km. In order to cover the whole western U.S. from the eastern edge of the Rocky Mountains to the Pacific coast with this spacing, we need about 3600 stations. Since the teleseismic data needed for the inversion can be collected within about 3 months, the data for the whole western U.S. can be collected by 4 experiments each with 3 months duration.

The outcome of the data inversion will be a three-dimensional seismic image (distribution of seismic velocity including anisotropy) of the crust and mantle to the depth of about 1500 km with the resolution of about 30 km. The result will constrain the deep mantle processes responsible for the evolution of various geologic provinces in the western U.S. including the Columbia plateau, Cascade Range, Snake River Plane, Yellowstone Hotspot, Coast Ranges, Great Valley, Sierra Nevada, Basin and Range, Colorado Plateau, Rio Grande Rift and Rocky Mountains. For example, the entire window of the Farallon plate as proposed by Dickinson and Snyder can be delineated completely.

In addition to the P delay data, the experiment will produce the S delay data that can be used for shear velocity structure. three-component wave-form data that can be inverted to the layered structure under each station, amplitude spectra that can be used to estimate seismic attenuation, and the surface wave phase velocity data that can be used to estimate the vertical distribution of velocity and density under the station network. These data will further constrain the deep structure and processes under the western U.S. We can produce maps of various crust-mantle layer parameters including the map of Moho depth, map of seismic velocities for various layers, map of lithosphere thickness, map of quality factor Q, etc. These objective and quantitative characterizations of crust and upper mantle made uniformly over a broad region will form a firm ground upon which more detailed high-resolution studies can be initiated.

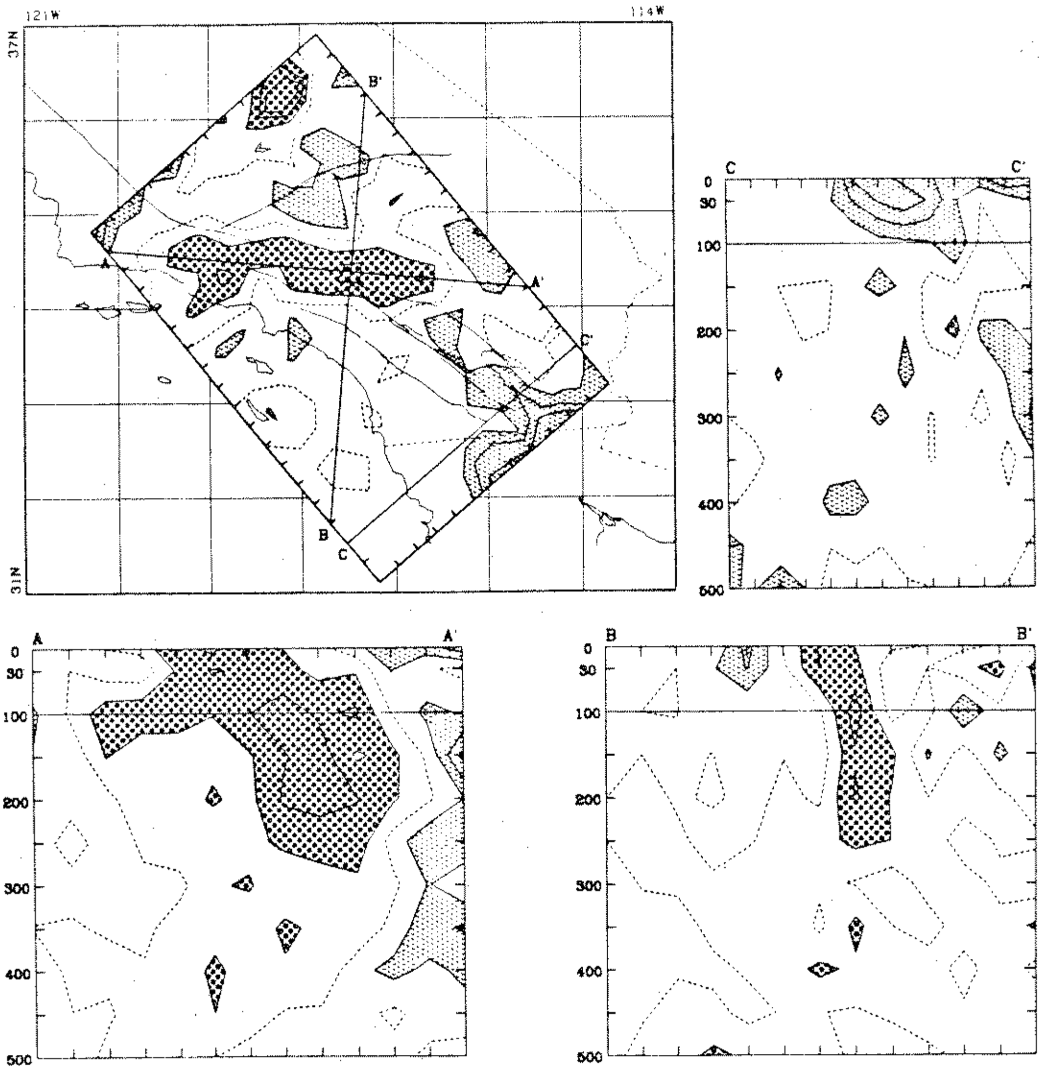


Figure 6-6. Results from the inversion of teleseismic P-delays. In the upper-left panel a horizontal section at a depth of 100 km is shown superimposed on a location map of southern California. The locations are shown for the three cross-sections that are displayed in the other panels. The tick marks surrounding the horizontal section show the locations of the block centers used in the inversion. All panels are displayed with no relative exaggeration. The contour inverval is 1.5% relative velocity deviations, with >1.5% indicated by dotted areas and <−1.5% by the hatched areas. The zero contour is dashed. In the lower-left panel a W−E cross-section (A-A') through the Transverse Range anomaly is shown. In this projection the anomaly appears as a wedge-like feature that is deeper on the eastern side. A S−N cross-section (B-B') through the Transverse Range anomaly is shown in the lower-right panel. The anomaly appears as a slab-like feature that dips slightly to the north. In the upper-right panel a SW−NE cross-section through the Salton Trough anomaly is shown. The anomaly is about 2−4% slow and extends down to 75−125 km.

6.1.9. Pan-Cordillera Experiment to Study Large Scale (100 km) Heterogeneities in the Upper Mantle from California to Alaska

This experiment is designed to study gross features of the lithosphere over a very large geographical area. The experiment combines several recently developed seismic analysis techniques and takes full advantage of the proposed high-quality digital seismographs with broadband and high dynamic range.

The area to be covered is the Cordilleran system including Rocky Mountains, Sierra Nevada, Coast Range and Colorado Plateau, and extends from Baja California to Alaska. A network of 1000 mobile seismographs can cover the whole area from the western edge of the North America craton to the Pacific coast at a station spacing of 100 kilometers.

The array would be operated for several months in order to collect about twenty records of teleseismic body waves and surface waves as well as records of local earthquakes. The teleseisms will be analyzed by a recently developed waveform modeling technique that gives a detailed shear velocity layer structure under each station. Excellent results using this technique have been recently reported. The analysis of surface waves will produce maps of phase velocity for periods from 20 to 100 s, which can be used to determine the gross structure of the lithosphere and uppermost asthenosphere.

The local earthquake data will be used to determine the quality factor of the lithosphere by the coda wave method, which has been successfully applied to various areas by many seismologists. It would be interesting to find the coda Q of the entire Cordilleran system, since it has recently been shown to vary from values higher than 1000 in the central U.S. to less than 200 near the west coast. Recent studies also demonstrate a significant precursory change of coda Q before major earthquakes in China and the Soviet Union. The coda map would serve as a base map for defining the normal values of Q and may help to further define major soon-to-break seismic gaps along the boundary of the Pacific and North American plates.

The proposed field experiment is an ambitious undertaking, but is probably not a formidable one, since the station density is sparse enough that easily accessible sites can be found for the instruments along roads.

6.1.10. Continental Plutonism, Idaho Batholith

The Idaho batholith is one of the major batholiths in western North America and is accessible for seismic research. This batholith is a large ($<40{,}000\text{-km}^2$) composite body, made up of numerous granitic plutons located in the northern Rocky Mountains of central Idaho and adjacent portions of Montana. There have been no detailed seismic studies of lithospheric structure in the Idaho batholith and only the crustal structure of the eastern Snake River plain to the south is known.

The study envisioned for the Idaho batholith would be of a multiple nature involving passive and active experiments in both two-and three-dimensional configurations. The rugged terrain of the batholith area would restrict some aspects of the study but would not be a major problem. As shown by recent studies, mining operations in the Challis, Idaho area can provide a source of energy for active array studies. The aftershocks of the Borah Peak earthquake (Oct. 28, 1983: $M_L = 7.2$) whose epicenter was near Mackay, Idaho have continued into 1984. It is reasonable to expect that these events will continue at a reduced level for several years and could serve as a source for passive experiments. A moving array of several hundred instruments could effectively employ these two sources. The topography in the area would indicate that the arrays be somewhat irregular in shape, but this should not be a problem with modern tomographic techniques.

Profiling experiments could be conducted in several areas, and in particular, care should be taken to insure that ties can be made to studies in adjacent areas. A calibration study in an area adjacent to the batholith should also be undertaken.

6.1.11. New Madrid, Missouri, Study of an Ancient Continental Rift

The New Madrid seismic zone is the most seismically active region in the United States east of the Rocky Mountains. It is a zone of high activity surrounded by the relatively stable crust of eastern North America. All earthquakes of that region are restricted to the upper crust and the zone of most intense activity occurs within the boundaries of an ancient Cambrian or late Pre-Cambrian rift. Crude models of the crust and upper mantle have been obtained from seismic reflection and refraction data, and three-dimensional inversions of teleseismic P wave data have yielded striking lateral changes in velocity in both the crust and upper mantle, some of which underlie the area of earthquake activity.

Although interest in the New Madrid region has been high in recent years and much new information has been obtained, results have been flawed by limited station coverage and the absence of any shear wave data. As a result, present models of the region are characterized by poor spatial resolution and are restricted to compressional velocities.

Because of the above limitations, it is not yet possible to relate earthquakes in the New Madrid region to structural features with any great confidence. On the basis of seismic refraction work, a high velocity 'rift cushion' has been proposed as occurring beneath the most seismically active portion of the seismic zone. Presently available teleseismic data, however, yield contradictory results that suggest that lower than average velocities underlie that zone.

To resolve these questions and relate seismic activity in the New Madrid region to fine-scale features of the crust and upper mantle, experiments capable of achieving a much finer resolution than is presently available are required. The New Madrid region is ideally suited for study with a large, 5-km-spaced two-dimensional array using tomographic techniques. In this way a three-dimensional image of this ancient rift system can be obtained, and regions of high or low P or S velocity can be identified. We anticipate that a major outcome of such a study will be to relate earthquake activity to major structural features and by this means to take a major step toward understanding intra-plate earthquakes within continental interiors.

6.1.12. Seismicity and Crustal Structure of the Rio Grande Rift

Recent geophysical investigations of the Rio Grande rift have been successful in identifying probable magma chambers in the middle and upper crust of the rift, and in characterizing the geometry of the faulted flanks of the rift. The magma chamber was detected using shear wave reflections from shallow (< 8 km deep) microearthquakes. Important additional data from controlled source P-wave reflection data indicate that the magma occurs in a thin, flat sill covering about 1700 km^2 at a depth of 19 to 20 km. Regional-scale surface-wave and seismic refraction studies show that the crust has been thinned by 10 to 15 km beneath the rift. High-resolution reflection profiles appear to resolve some of the major crustal features of the rifts, such as buried intragraben horsts, detachment faults, and intrusive bodies.

The faulting styles and seismicity associated with continental rifting can be well studied using a dense seismic array in the Rio Grande rift. Previous studies of the rift are limited by the sparsity of the existing seismometer network as well as by the limited wide-angle data. A small (20 km by 10 km) but dense (every 1 km) network of seismometers would provide the resolution necessary to locate hypocenters accurately and to determine focal mechanisms for microearthquakes over the magma chamber. This detailed seismicity can then be related to known structural features within the upper crust and used to better define the depth of the transition between brittle and ductile deformation. Reflections from the magma chamber observed on these earthquake records will serve to define the character of the mid-crustal magma chambers.

A more detailed crustal structure in the rift than is currently available can be obtained using seismic refraction profiling techniques. Moving this linear array and sources so that reflections from the magma chamber sample a common reflecting point with a wide-variety of angles of incidence will provide powerful constraints on the impedence contrast represented by the magma chamber. This experiment will require 200 instruments of the PASSCAL array for a period of 6 months to a year. For most of the experiment the array will be configured in a 20 km by 10 km rectangle where three-component instruments are spaced at 1 km intervals. The seismicity within the rift is sufficiently well-known to allow intelligent placing of this array. The active portion of the experiment will require less than a month of field effort and can be performed with only 100 instruments, each configured for 6 sensors at 100 m spacing. Explosive sources for the active portion of the experiment will allow definition of crustal structure to the Moho.

6.1.13. Refraction Study of the Northeast Passive Continental Margin

Combined onshore-offshore seismic experiments offer great potential for resolving the deep structure and stratigraphy of passive continental margins. Recent high-quality two-ship multichannel seismic refraction profiles collected during the Large Aperture Seismic Experiment (LASE) on the North American margin off-shore New Jersey define the apparent continuation of oceanic layer 3 (compressional velocity of about 7.2 km/s) landward to the commonly presumed ocean-continent transition. The actual landward extent, however, is unknown due to a lack of wide angle seismic data in the shallow water and land portions of the margin.

Current understanding of possible crustal structure differences between the now welded segments of the North America and African plates, the Meguma and Avalon zones in the Appalachians, are likewise limited by the sparsity of information in this region.

There are a number of places where a collaborative onshore-offshore seismic experiment could be performed. The landward extension of the LASE profiles into New Jersey is an obvious choice. The Gulf of Maine is another concrete example (chapter 14). Here an extension of the marine-based Common Depth Point (CDP) data onshore is already planned by the USGS. These data could be augmented by obtaining 20 to 30 expanding spread profiles along these marine-based profiles and by the collection of an equal number of refraction profiles along the land based CDP profiles. Using the land based array and marine sources one should be able to extend the crustal structure directly across the continental shelf and rise to the oceanic crust.

This experiment would require deploying 100 to 200 instruments from the PASSCAL array for 1 to 2 months. The high sampling rates possible with these instruments would ensure compatibility of the data with that from the marine instruments, which would facilitate combining these datasets. The uniformity of instrumentation would permit the results to be interpreted much more confidently than previous, less complete datasets have allowed.

6.2. Other Major Experiments

6.2.1. Aftershock Studies

Aftershock studies associated with major to moderate earthquakes can provide unique and abundant information in short periods of time. Rupture dimension, fault geometry, spectral content of ground motions, stress patterns, and crustal and upper-mantle structure are among the topics that can be studied. Many of these topics are not only of scientific interest but are useful for immediate seismic engineering purposes. When the availability of large numbers of PASSCAL portable stations is combined with the occurrence of hundreds or thousands of aftershocks, it is possible to extract a wealth of information in only a few days to weeks of recording. The following earthquake scenarios provide examples of key types of aftershock studies:

- a major catastrophic earthquake;
- an important moderate event;
- an earthquake occurrence in a region of otherwise sparse seismicity.

Major catastrophic event. Let us assume a major segment of an active plate boundary in California, Alaska or beneath Oregon-Washington breaks with a rupture length of a few hundreds of kilometers, leading to an earthquake of magnitude $M_w=8$ or larger, affecting major population centers directly or by generating a tsunami. In such an event of national importance and economic consequences, a PASSCAL array, initially of 100 instruments, could be immediately deployed, within 24 hours. The primary purpose of the stations located near the fault terminus would be to document any rupture extensions into still unbroken portions of the fault. Alternatively, the initial instruments could be deployed in places where the permanent array was particularly sparse or where the main event put parts of the network out of commission. Within the next three days, specific topic-oriented deployment of instruments would address questions such as the maximum depth of brittle stress release (important for joint interpretation with geodetic information), detailed mapping of the main and subsidiary faults by the distribution of aftershocks, and slip vectors from focal mechanisms, and the determination of the seismic response of selected engineering structures. If logistics permit, the entire pool of PASSCAL instruments with various sensor combinations (including strong-motion accelerometers) could be deployed, typically up to several weeks or a few months.

There is a fair chance that if a major earthquake were to occur within the next decade or so, it will occur without prior warning, even despite existing research programs in earthquake prediction. This fact may jeopardize and complicate the deployment of PASSCAL instrumentation in the aftershock zone, if a major PASSCAL experiment is coincidently being performed elsewhere. PASSCAL, in close coordination with the USGS, state, local, and federal agencies, and university seismological groups proposes to draw up emergency plans with contingencies for various scenarios for great earthquakes on a state-by-state basis. Universities have traditionally been able to field aftershock surveys within only a few hours of moderate sized earthquakes. Pre-planning by PASSCAL will enable the organization to respond similarly to events of national importance, or abroad if invited by an affected foreign country.

Important moderate events. We choose as an example an event on the San Andreas fault system near Parkfield, California, since long term predictions suggest the likelihood of a major earthquake in the time period 1987—1989. Aftershocks of a magnitude 6 to 7 earthquake, involving rupture on a fault 20—100 km long, could be adequately monitored with an array of about 500 instruments. These stations would supplement the existing 100-station permanent array to provide detailed faulting patterns with resolution in the 100 m range and focal mechanisms for both the shallow and deep aftershocks occurring on the main and subsidiary faults. Prospective PASSCAL instrument sites can be chosen now, so that after the main shock the array can be immediately deployed. Important problems that these data can address include brittle vs. creeping stress release during aftershock activity (important in conjunction with interpretation of geodetic measurements), strong-motion, micro-zonation, and structural-engineering projects. Close planning of this experiment by PASSCAL and its university members, the USGS and the earthquake engineering research community is a fundamental condition to the success of such a scenario.

Rare events. In regions of sparse seismicity, it is uneconomic to maintain telemetered networks for the long periods of time necessary to observe a significant number of events. Nevertheless, the seismicity in these areas is of fundamental importance in understanding the state of stress in the tectonically less active parts of the lithosphere. Furthermore, in many of these areas (eg. eastern North America) seismic hazard assessment needs to be improved for the safe design of critical facilities such as power plants. In such regions the fast deployment of PASSCAL instrumentation within hours of the occurrence of moderate size events ($m_b = 3$ to 5) can provide crucial information on the location of active faults heretofore unmapped, relation of faults to surface geology, attenuation laws for strong-motion parameters, the seismic Q structure, stress drops, stress orientations (from focal mechanisms), and crustal structure. For such aftershock studies, an initial set of about 20 to 50 instruments could be deployed by a single crew, and if sufficient aftershock activity is detected, the array could be enlarged to a few hundred instruments to remain deployed over a period of several weeks. The deployment could typically be carried out by a single university or a consortium of a few regional universities.

6.2.2. Observations of the Rupture Process of a Moderate-Sized Fault

Although it is well known that an earthquake is caused by slip on a fault plane, there are actually very few direct observations of that slip. The most commonly used method is based on directivity; it stems from the fact that the P (or S-) wave radiated in the direction of rupture propagation is higher in frequency than the wave radiated in the opposite direction (an effect akin to the doppler shift). To date, most directivity measurements have been made with long-period instruments at teleseismic distances, so the measurements are sparse. Only a few, gross source parameters can be inferred from these data. Furthermore, certain parameters such as fault size and rupture velocity cannot be independently resolved. In order to improve upon these reconstructions, it is necessary to observe the radiated waves over large portions of the focal sphere. This is perhaps most easily done with an array near the rupturing fault, since the upper hemisphere and parts of the lower hemisphere are accessible over a region no more than a hundred kilometers in diameter. These data can then be processed to yield estimates of the spatial and temporal history of rupture propagation, including rupture nucleation, behavior at asperities, stopping phases, and estimates of stress drops. One data processing technique can be cast in a form very similar to tomographic imaging. Alternatively, it is possible to downward-extrapolate the wave field by application of the wave equation, until it impinges upon the fault plane.

An example of a study of rupture propagation on a major fault is given by a recent USGS study of the Imperial Valley Earthquake. The USGS used a six-component linear array to observe the rupture of the fault. These studies produced new results, including the velocity of propagation and a suggestion of the interaction of the rupture process with possible asperities. This sort of information is important to test recent theoretical models of rupture initiation, propagation, and interaction with asperities and barriers. The Imperial Valley study was made possible with such a limited array by a fortuitous fault geometry. However, because the array was so limited in extent, it was impossible to observe many details of the rupture process (even distinguishing P and S waves was difficult). This limitation could be removed with a large array of stations (with strong-motion accelorometers as sensors) such as that envisioned under the PASSCAL program. In order to constrain the rupture history of the fault as tightly as possible, it is necessary to sample the radiated waves over as much of the focal sphere as is possible. For a typical California crustal structure, a 50 km long linear array (with 1-km spacing) can sample the azimuth of the focal sphere for angles of incidence between 0 and 135 degrees from the vertical. One-thousand instruments could be deployed in 20 such linear arrays arranged radially about the fault. These 1000 instruments should record all three components of ground motion, so that both compressional and shear waves are well recorded. This layout will also assist in separation of the P and S waves by using polarization data.

The most difficult aspect of this experiment is that it requires a moderate to large earthquake (body wave magnitude of at least 4.5) to occur on the chosen fault. Even on the most active faults, the repeat times for such earthquakes are on the order of several years. One potential candidate is the section of the San Andreas fault near Parkfield, California. This area experienced a $M_s=6.4$ earthquake in 1966 which ruptured a 20-km section of the San Andreas. Recurrence intervals and the recently developed concept of a "characteristic earthquake" suggest a similar event can be expected at Parkfield around 1988. A PASSCAL array would supplement the existing 100 station strong motion array and allow a very-high-resolution image of the rupturing fault to be formed. Given the uncertainty of this date, however, this experiment would be planned as a target for deploying the array during times when the array is not being otherwise used. While in this passive mode the array could also be used for imaging the crustal and upper-mantle structure near the fault using local earthquakes and teleseisms. For simultaneous seismicity studies it could produce precise locations of aftershocks and possible foreshocks.

6.2.3. Experiments to Test and Utilize Modern Wavefield Processing Techniques

Downward continuation techniques (seismic migration) play an important role in exploration seismology. However, their application to lithospheric seismology has been more limited,

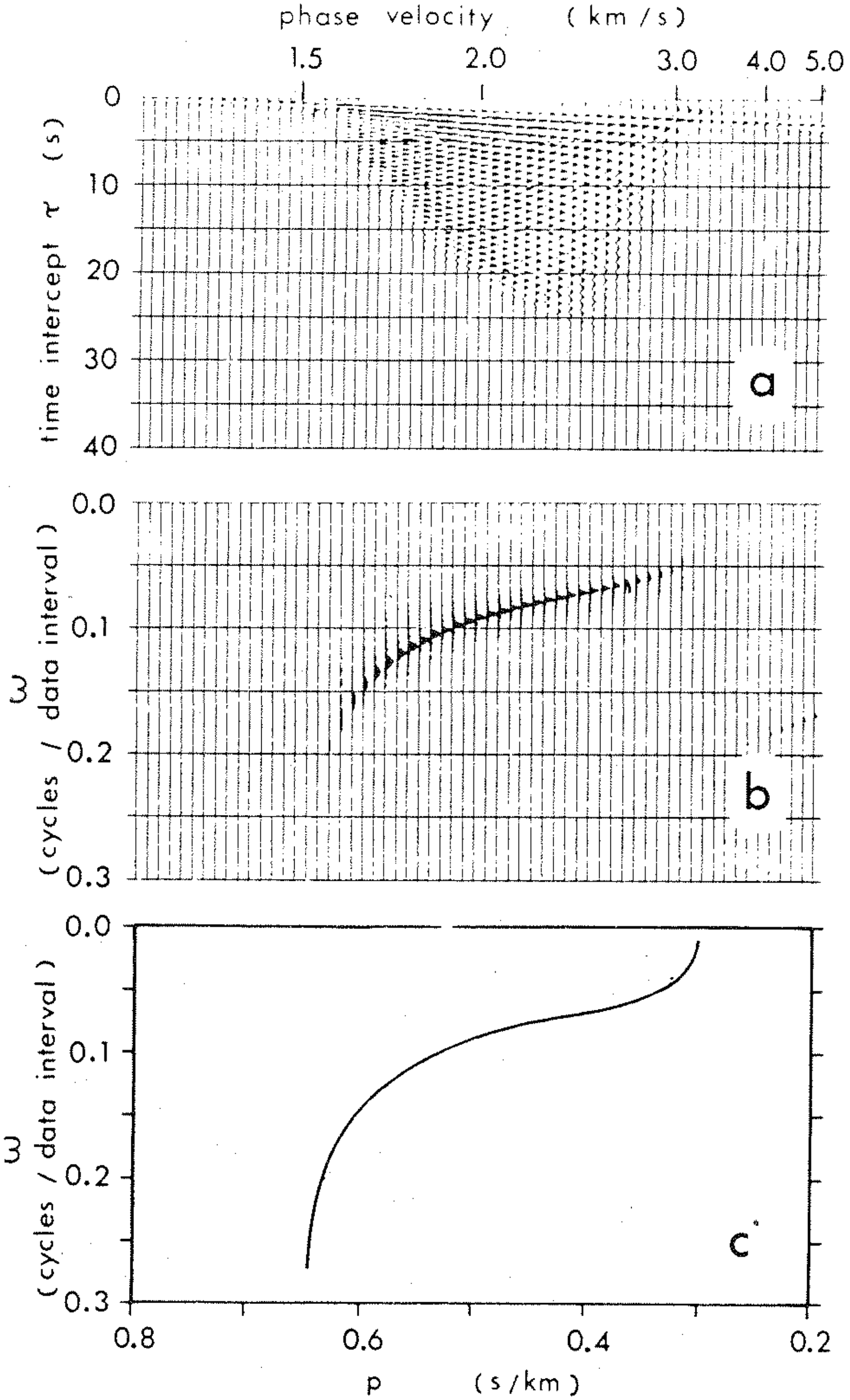


Figure 6-7. Analysis of dispersive waves by wavefield transformation: a synthetic example. (top) plane wave representation of the dispersed wavefield; (middle) the dispersion curve; (bottom) the original dispersion curve, for comparison. (After McMechan and Yedlin, 1980.)

in part because of the sparse, aliased data that was typical of past experiments. Nevertheless, these are important techniques, both because of their ability to extract new information from the data and because they can often be automated in a way that permits routine processing of very large datasets. PASSCAL arrays will provide the quality of data needed to employ these modern processing methods which include:

Downward continuation of teleseismic waveforms. Teleseismic arrivals that impinge on the earth's surface in the vicinity of an array can be thought of as plane waves that are subsequently scattered by the structure beneath the array. The travel times of the original transmitted energy can be imaged by tomography for velocity distribution, and the corresponding amplitudes for attenuation. A second process can then be applied to the later parts of the wavefield. The backscattered energy generated by reflection at the free surface can be migrated to produce an image of the reflectivity distribution through the earth. If the original event was sufficiently large, backscattered energy might be received even from the deep mantle beneath the array. The main restriction in this experiment is that each teleseism will generally contain only a few coherent plane waves. Thus for both tomographic and downward continuation purposes the data need to consist of a number of events at different distances and azimuths, so that plane waves of all orientations can be used.

Three-dimensional kinematic imaging. Migration of offset reflection data is very time consuming when implemented in full dynamic, three dimensional form. In many cases, however, much of the salient structural information can be obtained by a simple kinematic imaging of a single marker horizon or layer in the earth (or a number of these layers imaged in turn). This process can be implemented by a kinematic Kirchoff migration algorithm using a statistical imaging criterion to find the best fit position of the chosen reflector. This algorithm, which is a form of general pre-stack imaging, can be used with a passive or active experiment and places no restrictions on the source-receiver geometry. Limited experience with data from the Nevada Test Site indicate that this method may prove very useful when applied to PASSCAL data.

Imaging of dispersed waves. A wavefield containing dispersed waves, such as surface waves, can be transformed into an image of the corresponding one-dimensional velocity-depth function (Figure 6-7) This process involves a three-stage wavefield transformation. First, plane wave contributions are isolated by a slant stack. A one-dimensional Fourier transform is then performed on the time-intercept coordinate to produce an image of the dispersion curve. The final step is an iterative downward continuation that transforms the frequency axis into a depth axis. This process is conceptually parallel to methods used with refraction data, but could be applied to surface waves, seismic noise, and regional seismic phases.

Imaging of refracted waves. A wavefield containing refractions and post-critical reflections can be transformed into an image of the corresponding one-dimensional velocity-depth function. This transformation is accomplished in two stages. First the data are decomposed into component plane waves by slant-stacking. This process involves a series of stacks of the original data over families of sloping lines. The result is a new wavefield in the slowness-time intercept (tau-p) space. Each p-vector in the tau-p wavefield can then be iteratively downward continued to produce an image of the velocity-depth structure (Figure 6-8). When the structure used to generate the continuation coincides with the main energy band in the image, then the correct velocity is found. A recent example of this technique utilizing earthquake data is shown in Figures 6-9 and 6-10, where upper mantle is determined for the Gulf of California by means of wave field continuation of P-waves.

6.3. Small Experiments

6.3.1. Investigation of the Fine Structure of Velocity Transition Zones: The Continental Moho Discontinuity

The continental Moho has been investigated for many years, principally by refraction and wide-angle reflection data from earthquake and explosive sources. These relatively low resolution (2 km) methods suggest that the Moho is a relatively sharp boundary between the crust

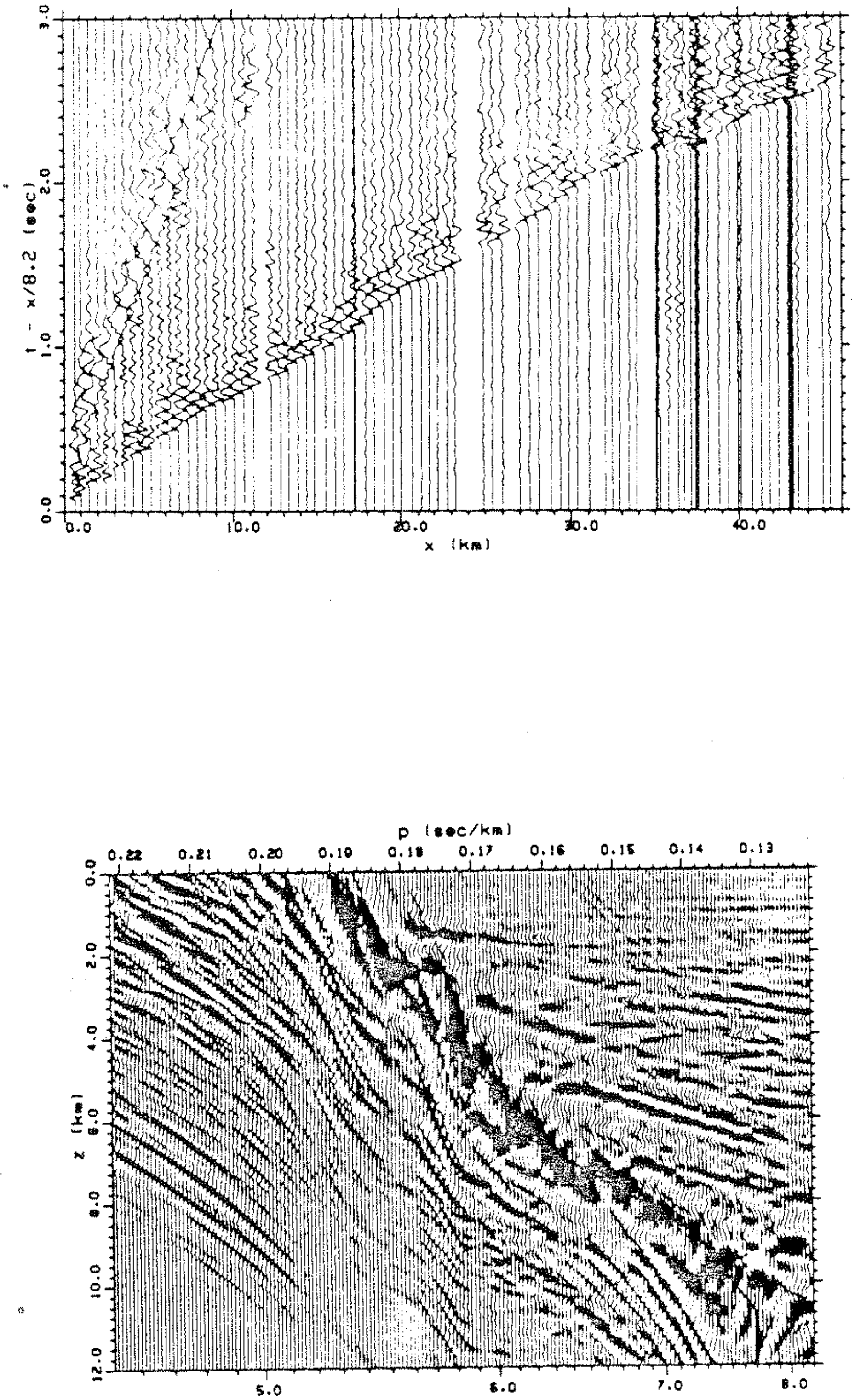
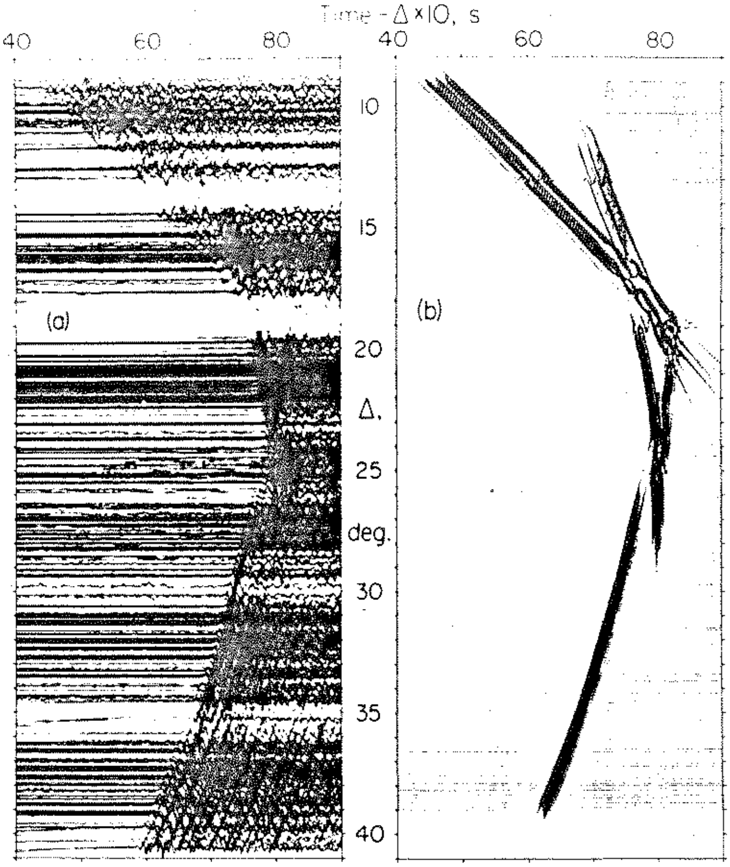


Figure 6-8. (Top) Refraction wavefield from the Mojave Desert. (Bottom) The wavefield has been slant-stacked and then downward continued, to produce a velocity model.



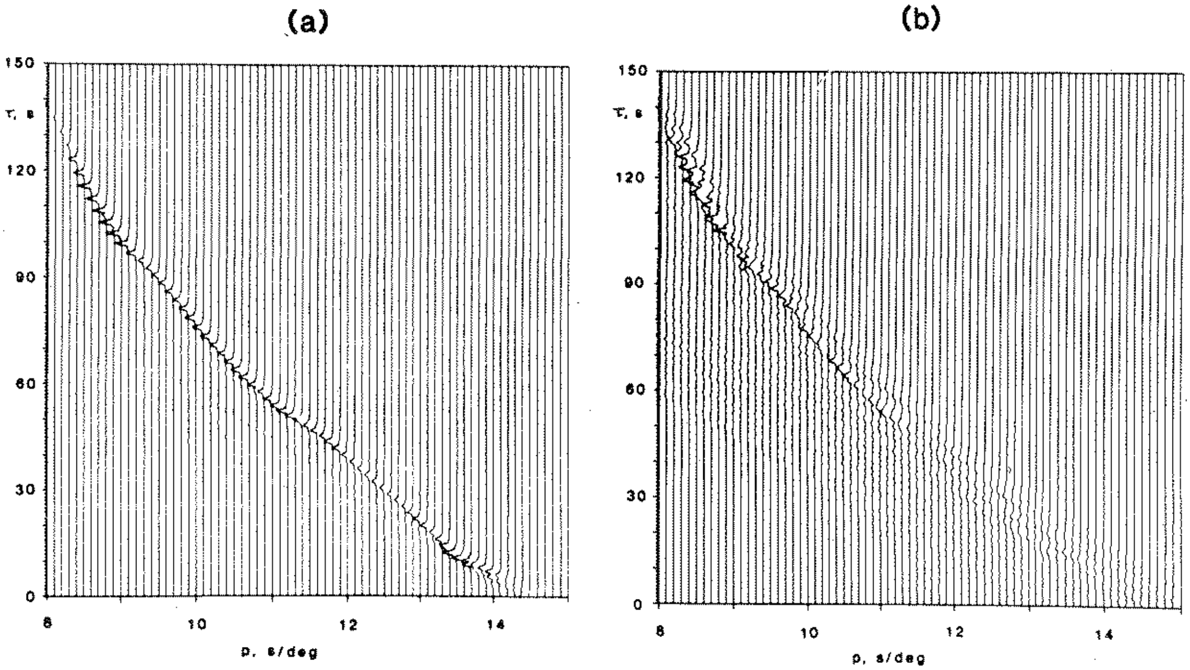


Figure 6-9. Seismic record section (a), 9 to 40 degrees distance, for 373 observations recorded on the SCARLET 200 element southern California digital network of 10 events beneath western Mexico and the Gulf of California. (b) Synthetic record section based on a previously determined velocity depth model. (From Walke and Clayton, *Bull. Seis. Soc. Am.*, 1984)

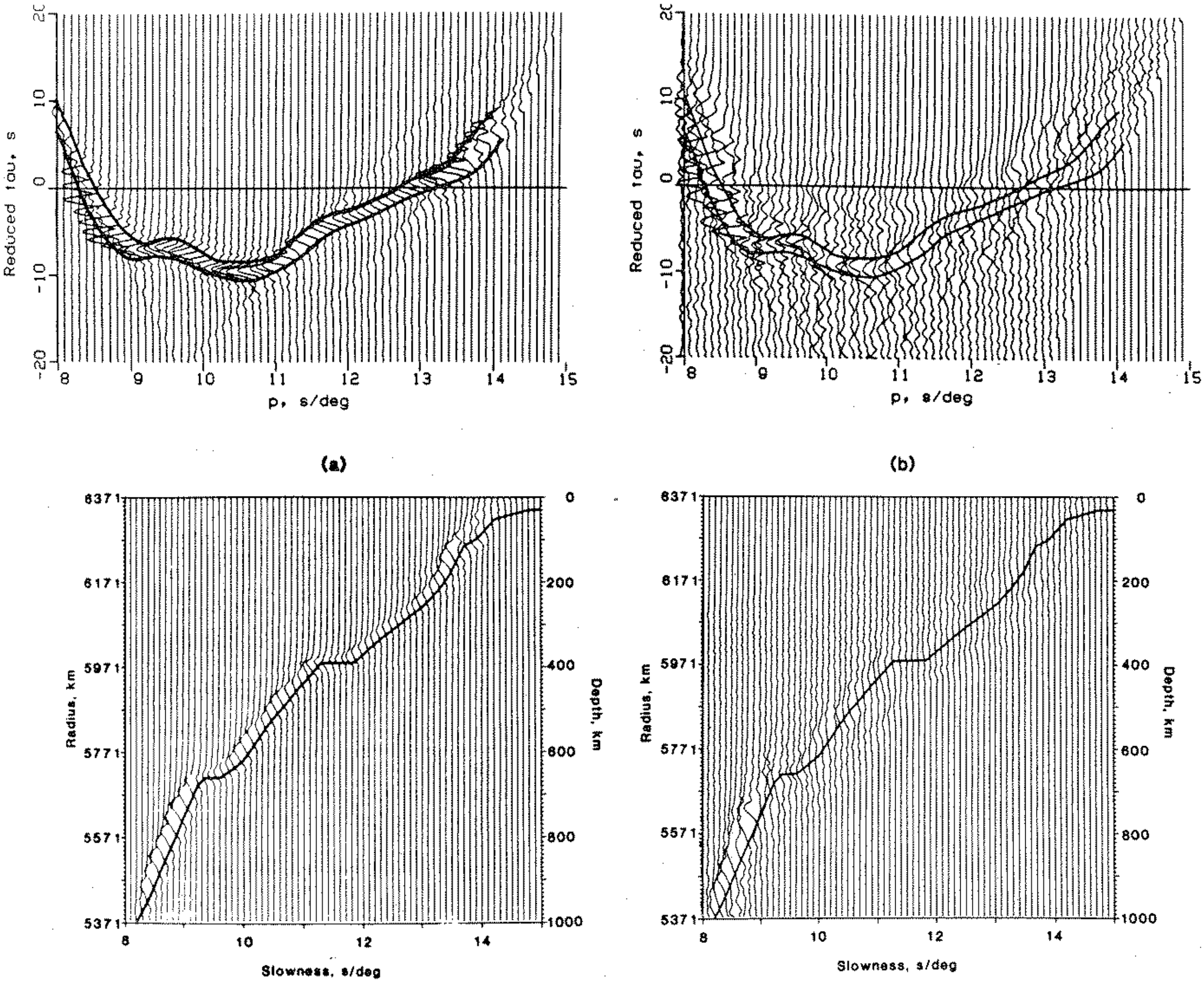


Figure 6-10 Top: Reduced tau slant stacks of record sections shown in Figure 6-9. (a) synthetic data, (b) observed data. Lines indicate region of large amplitudes on the synthetic stack, overlaid on both (a) and (b). Bottom: Downward wavefield continuation of reduced tau slant stacks shown at top for both synthetic (a) and observed (b) data. Results show that continued image of observed data is consistent with the velocity-depth model shown by the solid line. (From Walke and Clayton, *Bull. Seis. Soc. Am*, 1984)

and upper mantle that is generally continuous laterally. Recently, deep seismic reflection studies have indicated that the Moho is a few km thick and has fine structure, probably thin laminations. In addition, these studies suggest that the Moho is rather discontinuous laterally. This dilemma exists because the two methods used sample the Moho in quite different ways, and with substantially different resolution.

(1) Reflection profiling: Angle of incidence = <10°. Frequency = 10–30 Hz. Station spacing = 100 m.

(2) Refraction/wide angle reflection: Angle of incidence = 30–80°. Frequency = 1–20 Hz. Station spacing = 2–5 km.

These differences result in the reflection data being most sensitive to fine structure in a Moho transition zone and the refraction/wide-angle data being most sensitive to gross velocity structure. At present it is not at all clear whether the laminated events which are labeled "Moho" on reflection profiles actually come from the same depth as the zone of greatest velocity gradient.

With the capabilities of the PASSCAL arrays, it will be possible to collect a unified data set over an area on the Moho, with station spacing of 100 to 200 m, offsets ranging from 0 to 180 km, and broad bandwidth. By characterizing the transition in behavior of Moho reflections over the full range of angles of incidence, it will be possible to produce a unified inversion for the structure of the transition. A suitably designed large-scale imaging experiment should yield information on this question, if at least one line of this sort is included.

6.3.2. The Propagation and Source Mechanism of Harmonic Tremor

Seismographs located within a few tens of kilometers of an inflating or erupting volcano often record 'harmonic tremor', a phenomenon commonly felt to be associated with magma transport. Typical episodes of tremor last for several hours, and consist of wavetrains with frequencies in the range of a few Hz. The non-transient nature of the source has made the study of tremor very difficult. Unlike the distinct phases observed on earthquake seismograms, P, S, and surface waves from tremor are mixed together on the seismogram. Consequently, very little is known about either the source or mode of propagation of the waves.

Observations using sparse arrays of seismometers indicate that the amplitude of the tremor rapidly decays with distance from the center of the volcano. These observations cannot be interpreted as geometrical spreading of either pure body waves or pure surface waves, indicating that several modes of propagation are probably present. Polarization studies also indicate the presence of both P and S waves in the harmonic tremor wave train. Measurements of back-azimuth and phase velocity of tremor have been made from the Tolbachik, Kamchatka, USSR fissure eruption using a 24-element L-shaped array. The azimuths are consistent with the position of the presumed source region, and the phase velocities (while difficult to interpret since the distance to the source was unknown) seem indicative of P waves. Little is known about the source region or mechanism of the tremor. Observations of the size of the area of most intense tremor on Kilauea volcano, Hawaii, indicated that the tremor source can be very shallow and can move as shallow magma migrates. On a few occasions, onsets of tremor have allowed source locations to be established. Episodes of deep (40 km) tremor under Kilauea have been studied in this manner. However the available observations are not accurate enough to constrain the size or depth of the source in most instances. Several hypotheses have been proposed regarding the way in which growing tensional cracks and hydraulic instabilities in the magma chamber lead to tremor. The presence of numerous peaks in the tremor spectra has been used to support these hypotheses, but a quantitative explanation of the peaks has not been achieved.

The primary problem is understanding the mode of propagation of the tremor, so as to be able to distinguish P, S and surface waves. Once the various modes can be identified, the more fundamental question of the source characteristics can be tackled. The primary tool for discriminating these waves is a dense linear array of seismometers. This array can distinguish different modes of propagation, since it can simultaneously measure both the frequency and

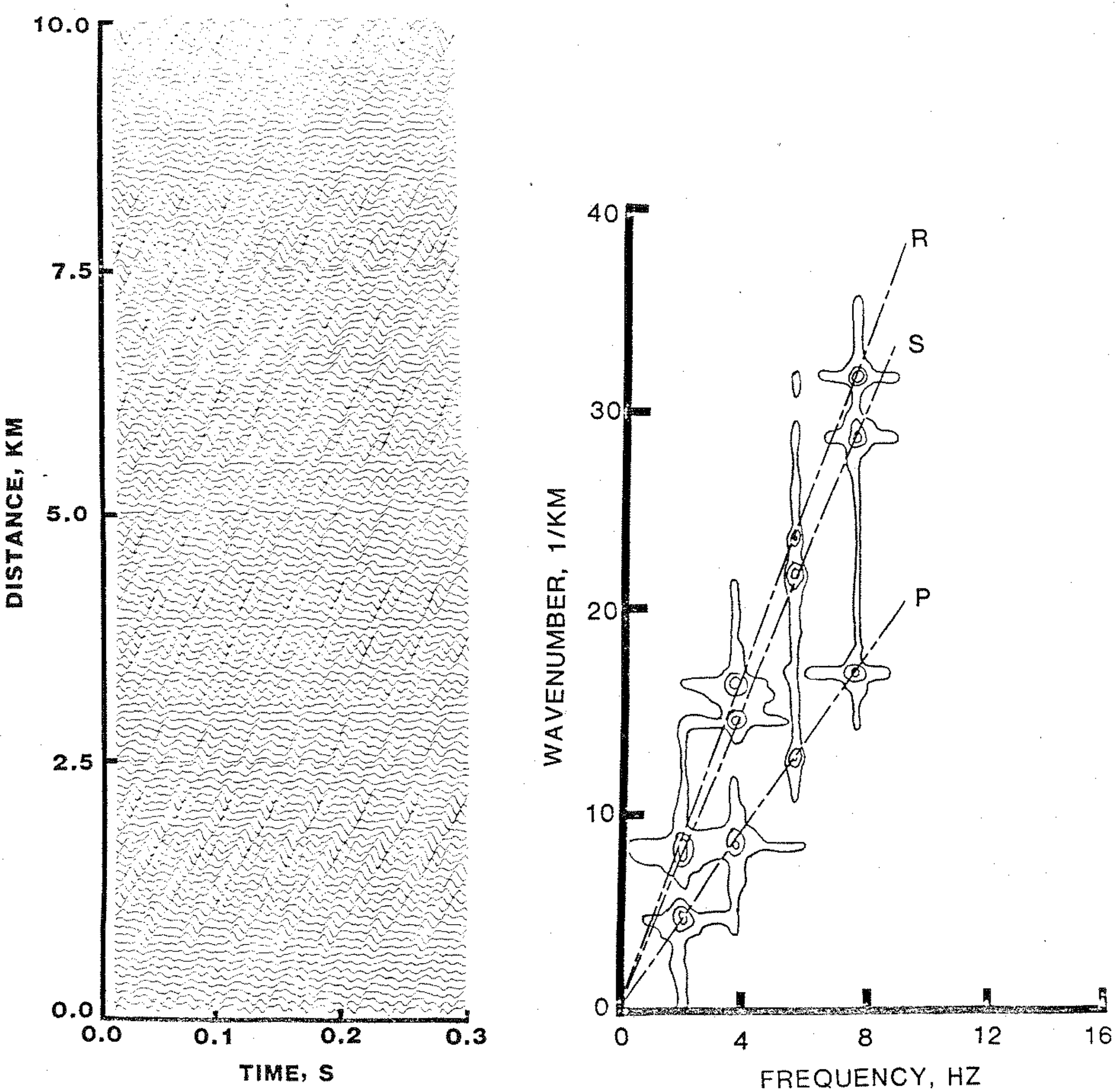


Figure 6-11. (Left) A synthetic record section for the vertical component of a hypothetical 128 element array some 20 km from the volcano and 10 km long. The source is assumed to radiate P, S, and Rayleigh waves with four distinct frequencies; 2, 4, 6, and 8 Hz. These waves were chosen with unit amplitude and random phase. Random noise of relative amplitude 0.1 was also added to the signal.
(Right) Frequency-wavenumber analysis of the data on the left reveals the P, S, and Rayleigh (R) waves that compose the time domain signal. The twelve contoured peaks in spectral amplitude correspond to the twelve component waves (four frequencies times 3 modes of propagation. The phase velocity and spectral amplitudes of each of the peaks can then be simply computed. (W. Menke, with permission, 1984)

horizontal wavelength of waves. The array must be capable of unaliased recording of P, S and Rayleigh waves in the range of 2—8 Hz (in a medium with a compressional velocity of 3 km/s). It must therefore be on the order of 10 kilometers long and have element spacing of about 80 meters (ie. 128 elements), and should be oriented radially with respect to the source. These instruments should record three components of ground motion, so as to permit both horizontally propagating P and S waves to be recorded. The array need only be deployed for a short time. A single hour's recording during an eruption would be sufficient for the basic experiment, although monitoring a complete eruption would be optimum for searching for changes in the tremor source location.

A synthetic record section for such an array, containing P, S and Rayleigh waves with frequencies of 2, 4, 6 and 8 hz is shown in Figure 6-11. The component waves in this record section can be identified through a frequency-wavenumber decomposition of the data, thus allowing the phase velocities and amplitudes of the component waves to be measured.

The amplitude data can be used to address fundamental questions about the tremor source mechanism. For instance, the relative amount of radiated P and S waves can be compared to theoretical models of the possible source mechanisms. The phase velocity data will provide information on the depth of the source (presuming that it occurs under the volcano and that the velocity structure is fairly well known). Changes in the source location can also be detected by changes in the phase velocity of the waves. To supplement these measurements, it would be useful to supplement the array with a few instruments deployed perpendicularly to it, so that azimuths can be measured, and to use a few controlled sources to determine velocity structure.

6.3.3. Observations of P Waves Diffracted About The Core-mantle Boundary

The PASSCAL array can not only be used for the immediately obvious purpose of constraining the structure of the continental lithosphere, but also to conduct transition zone and lower mantle experiments that are beyond the capacity of the Global Network program of IRIS. The 100-station Global Network, although potentially sensitive to frequencies as high as 10 Hz, does not possess a spatial distribution commensurate with the task of, for example, constraining the high frequency (1.11 Hz) phase and amplitude behavior of core-diffracted P and S waves. The elucidation of the detailed structure of the core-mantle boundary is important to the earth sciences today. The application of thermal boundary layer theory to the nature of the elastic structure of the mantle immediately above the core predicts the presence of a low velocity zone within 200 km of that boundary. Current seismic data relevant to the question are ambiguous. Although several popular models of this zone contain details that might be attributed to thermal or compositional heterogeneity, many counter-examples exist. A clear need exists for spatially coherent (instrument spacing of 1—2 km) data at high frequencies (1.11 Hz). Furthermore, the instruments must be well calibrated in order to accurately measure both the amplitude and phase of the diffracted waves.

The determination of the structure of the core-mantle boundary is further complicated by a surprising degree of aspherical heterogeneity in the lower mantle, as revealed by recent studies. These studies have use the currently available global travel time dataset in conjunction with tomographic methods to construct three-dimensional images of the heterogeneties. Although individual studies of the core-mantle boundary have previously provided disparate views of the structure of the boundary, the possibility existed that the 'heterogeneity' was simply an artifact of the limited data and variety of analysis methods.

Several experiments designed to collect broad-band data relevant to the structure of the core-mantle boundary should be conducted. A linear array of seismographs, as few as one hundred or the full PASCAl array, should be placed in a tightly spaced (1—2 km) northeast-southwest line in the western United States. The core-mantle boundary in the equatorial Pacific would be examined by recording events from the very active Tonga-Fiji trench. A portion of the array could be moved northward every few months into the deep diffraction shadow of the core. The core-mantle boundary in other regions such as beneath the north pole or Eurasia could be studied by similar deployments in Canada or northwestern United States and western

Europe, respectively. These experiments would not suffer from the use of dissimilar events and instruments that have plagued past studies of these phases.

6.3.4. Array Studies of Regional Seismic Phases

In contrast to the discrete phases usually associated with body waves at teleseismic distances, regional phases consist of a superposition of many waves that are multiply refracted and reflected in the lithosphere. Examples of some important phases commonly recorded on short-period seismometers include P_n, S_n, P_g, L_g, and coda waves. All of these phases are presumably rich in information on the structure of the crust and upper mantle. The phase L_g has recently also been used to discriminate nuclear explosions from earthquakes. Unfortunately, the potential of these phases to elucidate structure has never been realized because their complexity makes single-station observations difficult to interpret. Hence their mode of propagation in not completely understood.

Because of their relatively high frequency content (1—10 Hz), regional phases are susceptible to scattering from heterogeneties in the lithosphere. Thus, many of these phases cannot be modelled deterministically, but must be studied using statistical descriptions of the velocity structure of the medium through which they propagate and for the wave fields themselves. Regionalized coherence studies, which require dense array deployments, should provide important information with which to test theories of scattering that govern the propagation of these phases. The transition from the coherent to the incoherent portion of the phases may vary geographically and with frequency. A portable broad-band array will therefore permit the study of regional variations in the statistical properties of the lithosphere, perhaps mapping the scale lengths of the heterogeneties. In seismically active regions these experiments can be performed over time periods of only a few weeks. Typical array deployments would consist of 100 to 200 instruments that could be reconfigured during the experiment into linear, X-shaped and two-dimensional arrays with typical spacing of 50 meter. The variety of array shapes would allow several signal processing techniques to be applied to the data, including frequency-wavenumber decompositions.

7. INSTRUMENTATION

7.1. Philosophy

At the heart of the program to meet the scientific objectives of PASSCAL is a new generation of highly versatile matched portable broad-band digital seismographs. Advances in recent microprocessor and microelectronics technology now make feasible a modular digital instrument of unprecedented versatility, and seismologists worldwide are moving rapidly to capitalize on these technological advances. With existing technology it is now possible to construct a rugged, fieldworthy portable seismograph with the following capabilities:

- high dynamic range digital recording (120 dB)†
- highly accurate phase-lock time system (10 μsec, relative; 100 μsec, absolute)†
- variable recording bandwidths, user specifiable, within a very broad overall frequency band (0.01—200 Hz)
- multi-channel recording, with channel capacity expandable in modules.
- triggered event recording based on local, regional, or teleseismic wave onsets, or turn-commands based on preset or radio codes
- high speed memory to permit buffering and preprocessing of data
- continuous recording of decimated data
- automatic self-calibration of the instrument and tape storage of complete system parameters including sensor type
- self-diagnosis, including identification of problems at the module level
- high density recording media, with 160 Mbyte cartridge magnetic tape available now, 300 Mbyte magnetic tape cartridges forecast for the near future
- microelectronically controlled broad-band portable seismometer
- duplex data transfer between user and seismograph

The functional needs for field seismology and the general design principles have been discussed at some length in the SSCL report and in the Proceedings of the 1983 Utah workshop on Guidelines for Instrumentation (*References*). The systems we propose to bring into being are in accord with the strong recommendations of these two studies. Table 7.1, which is taken from the SSCL report, gives the requirements for a versatile, portable system which can record both controlled and natural source signals.

We propose that such a seismograph system be designed, built, and procured as the core of the instrumentation for large, portable lithospheric arrays. To meet the requirements for versatility (Table 7-1), the seismograph system is being designed around a communication bus structure (Figure 7-1). Various functions (analog-to-digital converting, filtering, triggering, recording, arithmetic operations, etc.) are performed by modules which have their own microprocessor "intelligence." The modular structure allows the the system configuration to be varied by adding or deleting modules without reprogramming the central microprocessor. Moreover, modular design allows the instrument configuration to be tailored to specific experiments; it is probable, for example, that seismograph units will be available in more than one package. In none of the proposed instrument configurations, however, is the seismograph unit expected to exceed about 30 lbs (exclusive of seismometers) and about 0.5 cu. ft. in volume.

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† Proceedings of the CCSS Workshop on Instrumentation, Los Altos, California, November 29—December 2, 1983.

Table 7-1 Portable Seismograph Requirements for Various Applications†

	Artificial Source		Earthquakes	
Requirement	Vibroseis	Explosion	Short-Period Local and Teleseisms	Broad-Band Body and Surface Waves
Time accuracy of any sample	250 μs	1 ms	1 ms	>1 ms
Minimum number of channels (maximum 12)	1	3	3	3
Bandwidth, Hz (exclusive of transducer)	5-200	2-200	500	0.01-20 Hz max. 0.1-20 Hz portable
Typical sample rate	4 ms/channel	10 ms/channel	10 ms/channel	40 ms/channel
Event length	20-60 s	1-5 min	10 s - 5 min	30 min to several hours
Dynamic range (exclusive of transducer)	120-140 dB	120-140 dB	120-140 dB	120-140 dB max.
Minimum resolution (exclusive of transducer)	12 bits	12 bits	12 bits	12 bits
Service interval	10 days (maximum)	10 days (maximum)	10 days (minimum)	10 days (minimum)
Typical number of records per service interval	1,000 sweeps or stacks	100	1,000/day worst case; 20/day typical	10/day or fewer
Special requirements	Radio command to initiate stacking	Programmed turn-on	"Smart" trigger	"Smart" trigger Digital filtering Special seismometers
Master communication	Radio turn-on and sync for T_0	Radio turn-on	--	--
Position	1 m	1 m	10 m	--
Minimum total capacity	10 mbytes	--	25 mbytes	--

† From proceedings of the CCSS Workshop on Instrumentation, Los Altos, California, November 29 - December 2, 1983.

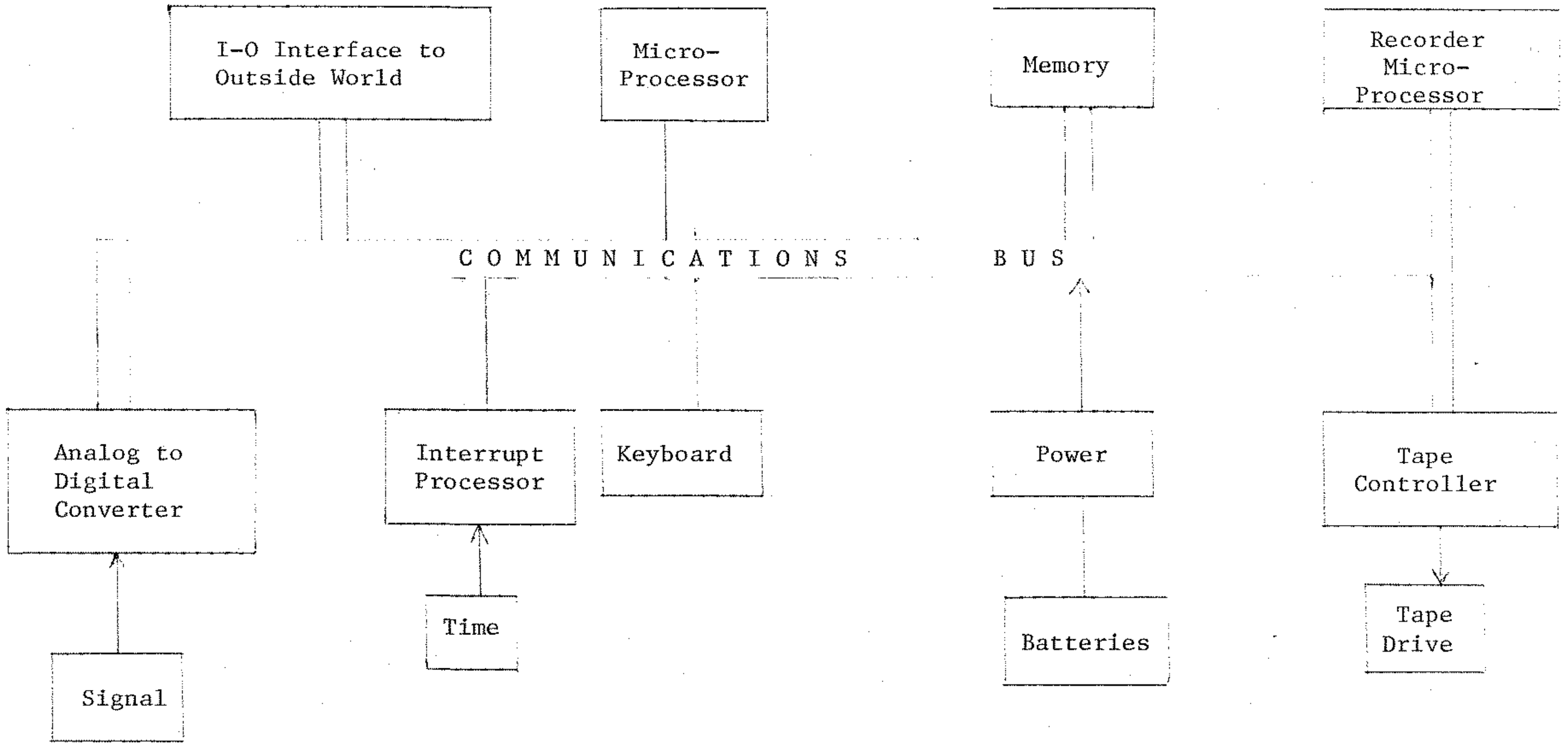

Figure 7-1: Architecture of a datalogger designed around a communications bus

A major consideration in the decision to employ a bus architecture is that it permits the system to "evolve" as new modules incorporating new features or improvements replace old modules without significant modification of the instrument or its software. By defining a comprehensive bus communication protocol, we can assure that general and special purpose modules, compatible with the instruments, can be developed industry-wide and marketed in the competitive marketplace. It is noteworthy that the seismograph industry regards the concept of modular bus design as it is to be incorporated in the new seismograph system to be of such general versatility that it may serve as an industry standard for a wide class of data-loggers and control instrumentation.

It would be extremely attractive if satellite telemetry could be incorporated into the system design, to permit direct downloading of array data to a data collection point. Extensive discussions with industry experts have brought out that no satellite telemetry technology now available meets industry needs for high data rate, acceptable costs, and low weight and power. All telemetry systems now in use by industry use line-of-sight radio, cable, or optical cable. These do not fill PASSCAL requirements, since the spacing of instruments and the overall size of the arrays deployed will frequently be too great to make use of these methods. Single side band is not an acceptable technology due to the large antenna required and the unreliability of the propagation paths to the ionosphere. For data storage and retrieval, therefore, we make use of the rapidly developing magnetic cartridge technology. Systems now being sent to China by the U.S.G.S. use a 67 Mbyte 3M cartridge. Another vendor is currently developing a 160 Mbyte cartridge. Amoco, which developed the Seismic Group Recorders (SGR), uses digital tape cartridges which are collected from the field daily and played back in special vehicles. Most PASSCAL experiments would not require retrieval of cartridges more often than once a week.

The present design decision, therefore, is to adopt magnetic tape technology for at least the first five year cycle in the development of this kind of instrumentation. While frequent visits to the instruments to retrieve data are not flashy high-technology, the SGR's provide an example where this approach works well. This decision will become firm at the time the first round of prototypes is bid in mid-1985. The modular nature of the instruments would permit adding telemetry systems to them at a later time when the capabilities and costs become appropriate.

7.2. Background and History

Start-up funds for defining and publishing full engineering specifications for the seismograph system and for designing the bus communication protocol have been provided by NSF for one year (July, 1984 to July, 1985) as part of the Phase Zero proposal of PASSCAL, administered by Carnegie Institution.

Instrument development has been the driving priority of the PASSCAL program and is already well advanced. The program for instrument development is based on results and recommendations which have emerged from two workshops held in the past year, one sponsored by NSF and hosted by the University of Utah[1] and the other an international meeting sponsored by the Commission on Controlled Source Seismology (CCSS) of IASPEI[2].

A general community consensus on scientific specifications was agreed upon in the course of those two workshops, and a set of provisional design guidelines are contained in the working group reports of the Los Altos CCSS workshop, Nov. 29—Dec. 2, 1983. One major conclusion of a strategic nature emerging from those intensive workshops is that the instrumentation industry must be involved in full partnership from the very inception of the design process for

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[1] Proceedings of a Workshop on Guidelines for Instrumentation Design in Support of a Proposed Lithospheric Seismology Program, May 4-5, 1983, Salt Lake City, Utah, Department of Geology and Geophysics, University of Utah.

[2] Proceedings of the International Workshop on Instrumentation, sponsored by the Commission on Controlled Source Seismology, Los Altos, California, November 29—December 2, 1983.

the instrument. This is absolutely essential to assure that the seismograph system as specified will be one which manufacturers will be prepared to build.

Substantial progress toward organizing a scientific and engineering design team was made during the open national meeting, Jan. 13—14, 1984, in Madison, Wisconsin, where the formal consortium for PASSCAL was organized. A 25 member instrumentation working committee was formed as part of PASSCAL during the Madison meeting and from that group was selected an instrument design team, headed jointly by R. Meyer (U. Wisconsin) and S. Sacks (Carnegie, DTM). In the course of the Madison meeting previous informal arrangements were firmed up for the PASSCAL instrumentation group to join in a loose-knit consortium with industry engineers from Kinemetrics, Teledyne/Geotech, and Sprengnether in a cooperative venture to set engineering specifications for a suitable communications bus.

The joint university/industry design team is an open committee on which membership requires only a commitment to devote at least one month per year to work on instrument development and to attend meetings of the instrumentation working groups (travel funds provided). The present design committee includes both technical experts within the seismological community who have experience building digital instrumentation, as well a lead group of research scientists with wide experience in instrumentation and field experiments (**Appendix C**).

The instrument definition process is proceeding well, and should be completed by early 1985. Several meetings of subgroups of the instrument design team have taken place over the past several months; the first, a three-man meeting at UCSB in February, 1984, produced a set of "straw man" specifications. A three day meeting of the full design team was subsequently held in April, 1984, hosted by Sprengnether Instrument Company in St. Louis. At that meeting the design team was divided into a number of specific working groups whose task it was to produce comprehensive reports on every aspect of the system. General (but not unanimous) agreement was reached at the St. Louis meeting that the task of the design team is to set both engineering specifications of the modules and complete hardware and software specifications for a communications bus.

A meeting with oil industry representatives was held 19—21 September 1984 in Dallas, Texas, organized by Ken Larner of Western Geophysical (who is also liaison representative of the Society of Exploration Geophysicists). A full presentation and review was made of major instrumentation systems in use by the oil industry. The meeting included discussions with manufacturers of exploration instruments to determine which parts of their technology are appropriate for PASSCAL. Several fruitful discussion were also held concerning interest on the part of manufacturers of exploration instrumentation in participating in the PASSCAL effort.

Summary: As of September 1, 1984, the Instrumentation Committee, with the unanimous consent of the Standing Committee, plans to go ahead with specifications for:

*engineering characteristics of the modules
*hardware and software definition for a communications bus

Following the Dallas meeting with industry representatives, the Standing Committee will appoint an outside panel of three non-interested experts to critique the instrumentation plans and provide feedback to us before the December AGU meeting. This should permit publication of the specifications in spring, 1985, as the first step in the implementation plan.

7.3. Implementation and Time Line

The specific timetable for instrumentation development is given in Chapter 14. Present plans call for specifications, including the hardware and software specifications of the communications bus, to be released April, 1985. At that time, RFPs will be issued to business for bidding to construct prototypes. Companies will be asked to manufacture a prototype of the basic instrument in two packages, a superlight package for backpacking applications and a "standard" package for operation in rugged but not unusually hostile environments. The basic instrument must contain:

* Analog amplifiers and self-calibration electronics
* 6 channel A-D conversion
* Arithmetic unit, including at least two trigger algorithms
and decimation software
* Delay memory (buffer)
* Recorder
* Bus arbitrator
* Clock and timing receiver

A review panel, empanelled by the PASSCAL Standing Committee expressly for that purpose, will select three companies to construct prototypes or parts of prototypes for at least 30 instruments which can be tested in the field. We anticipate instrument delivery in late fall or early winter of 1985, and estimate the price will be about $30K/unit. Depending upon the results of testing and the extent of required modifications during an anticipated 6 month evaluation period, the instruments could be in production by late spring, 1986, in time for limited use (with the prototypes already in existence) in some of the interim experiments being proposed in Chapter 14 of this document.

To meet this ambitious schedule, we are requesting additional funds starting Feb. 1, 1985, for design of the communications bus. The bus design is fundamental to all module designs, and in the view of the instrumentation committee must be public to ensure that modules can be produced by different manufacturers. Bus specification is, however, by far the largest of tasks remaining to be completed by the design team. The funds requested are in addition to ones already provided for in the Phase zero proposal*. Based on work now complete† Phase zero underestimated by at least $150K the resources necessary to complete the full design work on the bus. We are also requesting funds to design and prototype an Omega receiver with phase-lock time accuracy of 10 μsec. At the time Phase zero was submitted, unconfirmed reports suggested that such a timing module was already available in Europe. Subsequent investigations by R. Meyer in Europe established that the timing module in question did not meet our specifications. Specific personnel, timetables, and estimated costs for these two additional developmental efforts are detailed in Chapter 14.

The instrument design team considers 30 prototypes a necessary number of instruments to allow for testing under a variety of realistic field conditions while sufficient to allow useful scientific data to be obtained in actual small experiments. Members of the design team will oversee the laboratory and field testing of the instruments.
We anticipate that laboratory testing will be done primarily by university engineers and Bruce Ambuter. Field testing will be carried out as part of the PASSCAL program of interim lithospheric experiments, in conjunction with planned deployments of presently available instruments (see chapter 14).

The design team will have a number of continuing tasks that extend beyond the period of testing and modification of the prototypes. Technological advances, particularly in microprocessor technology, are occurring so rapidly that there will be opportunities for substantial upgrades in the performance and versatility of the instruments. Even now, it is possible to foresee that engineering investigations will continue into such areas as:

* evaluation of new or redesigned modules
* improvements in dynamic range
* lower power modules

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* Phase zero is a pre-IRIS grant to Carnegie Institution of Washington to fund design work on instrumentation and data management. See chapter 14 for a summary of this project.

† Technical Reports on Bus System, A to D, Recording, Arithmetic Unit, Filters and Triggers; PASSCAL subcommittee on Instrumentation, July, 1984. (S. Sacks, Dept. of Terrestrial Magnetism, Washington, D.C.)

- satellite telemetry
- alternatives to magnetic tape storage
- internal stacking of data

Among the PASSCAL program needs crucial to the final development of the multicapability seismograph is the ability within its basic module to trigger uniformly on the set of known seismic-event types, including the onsets of P waves and S waves at local, regional and teleseismic ranges. While a number of algorithms are published and/or available a relative evaluation is needed and consideration must given to their implementation within a physically small, low power portable digital seismograph.

Some resources, chiefly in travel, engineering salaries, and in consultant fees will have to be provided for continuous engineering upgrades to the instruments after commercial production begins. It is not necessary that all funds provided for that purpose come through PASSCAL, as independent efforts should be encouraged.

7.4. Sensor Development

The versatile dataloggers now under development and described in the previous section are being designed to accommodate the widest possible range of portable and semi-portable sensors currently available or under consideration for development. The datalogger will be capable of handling frequencies from 0.01 to 200 Hz, over 120 dB of dynamic range. In actual use, however, the datalogger is inherently limited by the capabilities of the sensors. The limitations take at least three forms:

- lack of portability
- spurious response characteristics
- narrow frequency and/or dynamic range

Portable 1 Hz seismometer: An important instrumentation need of the PASSCAL program is the acquisition (and/or development, if necessary) of a light weight, rugged, portable 1 Hz seismometer with acceptable response characteristics. We gain little in designing a highly compact light weight datalogger package if the accompanying seismometers can not meet the same standard. The popular 1 Hz HS-10 geophones, for example, weigh nearly 50 lbs per 3 component package with carrying case. Other lighter weight 1 Hz sensors currently available may prove satisfactory, but at least some have been suspected of poor response characteristics. In fact, portability and response fidelity are commonly rather exclusive, one being achieved at the expense of the other.

The first task of the PASSCAL subcommittee on sensor development will be to test and evaluate existing sensors, including some of innovative design which have recently been developed in Europe. The first steps toward sensor evaluation have already been undertaken and the nucleus of a sensor development team formed, consisting of J. Steim (Harvard), S. Sacks (DTM), Wielandt (Zurich), and O.D. Starkey (Teledyne/Geotech). Investigations of this group are currently supported with special money ($50K) from Carnegie Institution earmarked for the PASSCAL instrumentation program. While the Carnegie program was undertaken to investigate requirements for a broad-band portable sensor, efforts are now underway to involve scientists and engineers with expertise or interest in the whole spectrum of portable or semi-portable sensor design, but particularly those with expertise in lightweight sensor design.

The multi-year program to evaluate and develop portable sensors will make use of a set of shake tables at DTM whose characteristics are linear to about 1 kHz and are well calibrated because of prior work at DTM on design and construction of the broad-band permanent station seismometers. Other testing facilities will be available at Teledyne/Geotech. To be investigated are the entire suite of portable vertical and horizontal sensors in current use in wide angle reflection-refraction, surface wave and normal mode investigations of continental lithosphere as well as strong motion transducers. Of special concern is linearity as a function of amplitude, the possible presence of parasitic resonances, and cross-coupling response as a function of amplitude and frequency. The effects of temperature and external magnetic fields, and some quantitative estimates of durability will be sought. The results of these investigations will be published after consultation with the manufacturers. Continuing negotiations will be carried on with manufacturers to incorporate desirable design modifications in existing instruments. We anticipate that these negotiations will lead to improved transducers including those having lighter weight and significantly better response characteristics.

Broad-band portable seismometer: One important long-range objective of the PASSCAL program is to develop a broad-band long period **portable** seismometer. By "broad-band" we mean an instrument that ideally will give a usable response from 100 sec (perhaps 20 sec in the initial stages) periods to at least 5 Hz. Such a sensor would be the basic tool for recording regional and teleseismic earthquakes with PASSCAL arrays. It is needed for a wide range of studies that cannot be done with existing portable sensors, such as surface wave studies, studies of attenuation, and many kinds of earthquake source studies. While the development of a broad band sensor is not as urgent a priority as development of the datalogger, it is likely to require a longer time period and depend more critically on innovative design.

The development effort is being lead by Steim and Sacks, both of whom have extensive experience in the hardware development of broad-band seismometers. Steim, a recent graduate of Harvard, will be working on the fundamental technical design of the sensor. He has recently built a state-of-the-art broad-band system of non-portable design and is committed to developing a similar portable sensor. He will devote about six months, beginning in the fall of 1984, working with Sacks at DTM. Wielandt is expected to collaborate for at least two weeks during the fall or early winter of 1984 with Steim, who has already spent several weeks collaborating with Wielandt on permanent broad-band seismometers. Wielandt has indicated, however, that he is prepared to commit as much as six months or more of his time to developing a portable broad-band sensor, provided that effort is directed toward production of a fully operational field unit on a commercial scale (i.e., is not another laboratory instrument). There will also be extensive collaboration with some of the instrumentation firms, notably Teledyne/Geotech (O.D. Starkey), who are interesting in developing a commercial version of a broad-band seismometer.

We have no estimate in this early stage of the program of a timetable for development of a broad-band sensor, although we do expect that a 20 sec instrument can be developed relatively rapidly, while the 100 sec instrument will require considerable developmental effort. For the long term, the broad-band sensors will be used more sparingly than standard seismometers. For experiments where spatial aliasing is a concern, long-period instrument responses mean that station spacings may be proportionately greater. In the long term budget we are requesting funds for 400 three component instrument sets (1200 seismometers), which we judge adequate for most anticipated applications.

Multichannel geophone cables: While the six-channel capacity of an instrument can be utilized with one or two 3-component seismometers, it also leads to the possibility of enhancing the number of sensors in the full array by operating a string of six vertical geophones at each instrument. In an experiment where other constraints would dictate a 500 meter instrument spacing, this would give a sensor spacing of 100 meters and eliminate a great deal of aliasing.

This would suggest that PASSCAL have in stock a 500 meter cable with 6 groups of vertical geophones, for each instrument. It would, for example, increase the aperture of the unaliased array one could manage with 1000 instruments from 100 to 500 km. The problem is that PASSCAL would end up with 500 km of cable filling trucks and warehouses. Until the requirements of the science dictate more, we propose instead that 100 sets of cables be procured, to serve as support principally for experiments being conducted by individual Universities. It would permit a University with 100 instruments to deploy an unaliased string of sensors 60 km long, and leave it in place for any number of weeks or months for recording of artificial and natural sources.

7.5. Global Positioning System (GPS) in PASSCAL

The Global Positioning System (GPS), when fully operational in the late 1980's, will make highly accurate seismometer positioning practical for large-scale PASSCAL experiments, where thousands of array elements may be deployed. The dataloggers are being designed with an input port, through which geographic coordinates and elevation can be downloaded from portable GPS (or other satellite) receivers and stored directly onto the permanent recording medium of the datalogger.

The GPS represents a significant improvement over any previous positioning system, and its potential for revolutionizing geodetic surveying is well known. For PASSCAL, the advantages of GPS include portability, simplicity, and speed. With a single receiver, GPS gives instantaneous absolute positioning accuracy to better than 10 m (latitude, longitude, elevation) using the classified military (P) code. Instantaneous relative positioning to several meters is also possible using the unclassified civilian GPS code, but requires that two instruments are used.

GPS receivers already available commercially are fully portable (about 50 lbs., complete with antenna), but even that size is expected to decrease dramatically, as is price (e.g. see T.A. Stansell, Jr., "Civil GPS from a Future Perspective," Proceedings of the IEEE, 1983). Studies to develop hand-held equipment are already being funded through DARPA (Defense Advanced Research Projects Agency), and we anticipate that eventually a small GPS module can be incorporated directly into the dataloggers (or even specially designed sensor packages), making every instrument automatically self-positioning.

8. PASSCAL FACILITIES: OPERATION AND MAINTENANCE

The PASSCAL project proposes the acquisition and operation of a large complement of digital seismographs over the next six years, with a goal of 1000 by 1990. Effective operation and maintenance of these instruments require that essential support services and facilities be defined, and the principles of their management be established. We propose to establish as an operational division of IRIS, under the direction of the PASSCAL Standing Committee, a unit known as *PASSCAL Facilities*, whose day-to-day operations will be supervised by the Chief Engineer (chapter 10). The PASSCAL Facilities will have service responsibilities in the areas of maintenance, calibration, deployment, training, communications, data retrieval and preprocessing, transportation, and land work. Scientists from over fifty universities and institutions will be involved in using these Facilities, in experiments ranging in scale from large cooperative three-dimensional studies using 1000 instruments down to simple projects using 50—100 instruments for a brief period.

In the following sections of this chapter we set out a plan of operation for PASSCAL Facilities. We intend that these Facilities will be highly responsive to the needs of the researchers who use them. Thus, while day-to-day operations will be the responsibility of the Chief Scientist and Engineer, science policy, experiment design, and technical planning and innovation will remain the strict domain of the academic research community acting through the Standing Committee, the four permanent PASSCAL subcommittees (see Figure 10-1(b)), and other relevant subcommittees and panels.

8.1. Justification for Centralized Facilities in PASSCAL: Scope of Facilities and Services Supported by PASSCAL

The PASSCAL array can be seen to be analogous in many ways to a large oceanographic research vessel. There are many different institutional research people who need to use their time effectively, leaving the operation and maintenance of the ship and its basic facilities to a full-time staff. Centralization of support is easily justifiable on the ground that very few institutions could afford to provide the number of personnel required, and that the maintenance of many separate support staffs would be far more costly than the provision of a single central facility. The strength of the new system lies in having standard instruments with a low failure rate forming each array deployment. The requirement for maintenance and calibration standards is therefore a very strong constraint which leads to the central facility. Finally, the multitude of operational chores which arise during field studies involving a large array can be handled completely by the regular scientific and support personnel of only a few large institutions...the provision of optimum communications, the services of an experienced landman, and management of explosives, for example.

On the other hand, in many respects this system is not analogous to a research vessel. It can be divided into several groups which may be deployed as arrays in different places for different experiments. The many participating scientists have traditionally undertaken their field programs in small groups, operating independently of any central organizing body, subject only to the peer review process. It is broadly agreed that participation by PI's and by their students and associates in all phases of field data acquisition and processing is the most desirable way to maintain and foster high quality research. We set forth, therefore, the principal that this participation must be an intrinsic part of the process of experimenting with the PASSCAL instruments.

A working balance is achieved between these requirements for centralization and participation of individual scientists by considering the projected mix of large and small scale experiments (Chapter 6) and its economic impact. If PASSCAL were to equip and staff its Facilities adequately to conduct the larger, more labor intensive experiments, the cost would be prohibitive. The idea that a PI might "order up" data acquisition services on contract is therefore not only counter to the way good science is carried out, but economically unworkable.

The basic operational principles of the PASSCAL Facilities are therefore:

(1) Equipment will be centrally procured and managed, for all cases where standardized performance and centralized management is required. This would probably encompass nearly all the needed facilities except for vehicles owned by participating institutions and special gear incorporated into an experiment by a PI.

(2) Personnel will be maintained at levels which permit PASSCAL to operate the instruments in a low-level baseline of activity. This would include essential engineering, programming, and maintenance people, as well as a basic number of per-instrument staff for field and maintenance. In this baseline mode, it would be possible to supply a single maintenance/training technician to PI's using instruments for small-scale experiments. In general, personnel costs will be minimized by:

→ use of contracts to provide short-term services, like drilling and shooting.

→ use of contractors to provide continuing services, such as operating the maintenance facility.

→ use of PASSCAL employees only for supervision, contract monitoring, and liaison with PI's.

(3) For large scale cooperative experiments, the funding and logistical issues are more complex. We exploit the fact that such activities will come up about once a year for periods of no more than about three months.

→ *Funding* for the data acquisition itself will come through PASSCAL... as a part of its ongoing effort. Such support will come as an annual activity, in which the extraordinary costs of the annual large scale experiment are met for the (approximately) two months of the experiment.

→ *Field hands*, for deployment and retrieval work will be provided by the participating PI's. PASSCAL support would cover their travel costs. Wages of extra labor would also be covered.

→ *Permitting, drilling, shooting, communications*, and other specialized services would be provided through the Special Services branch of PASSCAL, with close collaboration between the PI and the Logistics Officer. The use of contractors or of PASSCAL employees would follow the guidelines set above for keeping personnel levels (and costs) down.

The philosophy for operation of the Facilities, therefore, leads to an economically optimal approach which requires that PI's be closely involved in the conduct of the field work. This requirement follows from grounds of simple economy, in addition to the basic requirement that the PI exercise responsible oversight in all phases of his research.

Specific questions of how these additional field hands are qualified for use of equipment will be decided by the Standing and Instrumentation Committees in consultation with the Chief Engineer. We do anticipate, however, that some studies might be conducted in the field entirely by the PI's own group. A 3-month fixed deployment of 100 instruments which required data retrieval only at one week intervals might easily be handled by 2—3 people with basic checkout in the use of the instruments and the field computer.

Management... the lines of advice and control which connect the PI, the Chief Engineer, the PASSCAL Standing Committee, IRIS, and the funding agencies, is spelled out in Chapter 10 of this Plan. PI's will become involved in large-scale experiments through participation in planning workshops run by the Science Planning and Coordination Committee. They will also be able to submit ordinary unsolicited proposals to funding agencies for support of smaller projects.

8.2. Functions of the PASSCAL Facilities

The PASSCAL Facilities, comparable to the other national facilities such as high energy accelerators, giant telescopes, and deep sea drilling vessels, are the instrumentation and operation backbone of the PASSCAL Program. They serve the following functions:

(1) *Hardware support functions...* maintain, repair, and implement modifications of instrument packages to ready them for field deployment. This includes calibration and diagnostic testing of dataloggers and seismometers. help deploy instruments and supporting hardware. help maintain & repair instruments in the field. maintain support facilities-vehicles and systems.

(2) *Data retrieval functions...* help with retrieval and replacement of data media (cartridges) in the field.

(3) *Data playback and monitoring...* help to playback field tapes validate instrument performance, perform initial data editing, and create standard format trace data on exchange media (e.g. 6250 bpi SEG Y tape). help in playback, plotting and analysis of portions of the data stream for early monitoring and evaluation of the progress of the experiment.

We also identify the critical area of data playback and preprocessing. These functions lie at the interface between the PASSCAL Facilities and the IRIS Data Management Center, and are discussed in Chapter 9. They represent specific operations and services for PASSCAL experimenters which must be available to PI's.

(4) *Edit and sort...* data into shot or event gathers, with verified parameter data, in a form suitable for archiving.

Some PI's will be able to handle the edit/sort preprocessing in the field computers; others will require facilities at the Data Management Center. In some cases, the workload will be so large that use of an industry contractor may be called for.

It is anticipated that there are many other services related to the field experiments which may be more efficiently provided by the PASSCAL Facilities than PI groups. These include:

Permitting for blasting and for instrument locations.

Contracting for shot-hole drilling and for shooting. (The PASSCAL Facilities might develop limited in-house capability for shot-hole drilling and blasting.)

FCC or overseas licensing for communications channels.

Land surveying and instrument positioning.

Radio data telemetry network design and set-up in the experimental area.

These above functions become increasingly more important to a successful lithospheric experiment when the scale becomes large.

8.3. Organization of the PASSCAL Facilities

Consider (Figure 9-1), a hypothetical deployment of a 1000-element array.

(1) The instruments themselves are dispersed geographically over an area of linear dimension as great as 1000 km. Subsets of 100 or so may be situated in other areas altogether. An appreciable number will be in maintenance status at the Central Maintenance Facility.

(2) The support crews, their vehicles, and computers must be headquartered in field centers in towns near the deployed array.

(3) The Data Management Center, in which the edited event data are to be archived, is in yet another distant central location.

There is, therefore, a flow of hardware outward from the central instrument facility, to the field centers, and to the field sites. A similar reverse flow of digital data inward from the field sites to the field centers and on to the Data Management Center.

It will be required, therefore, that the per-instrument support operating out of the field centers be vehicle-based, with adequate support personnel. Following the discussion of the different divisions of the support Facilities, we develop quantitative estimates of the magnitude of the support which will be required per 50-100 instruments as a basis for the budget plan in Chapter 13.

We adopt the following four-fold division of the PASSCAL Facilities (as described below in sections 8.3.1 through 8.3.4):

(1) The Central Maintenance Facility

(2) The Field Deployment and Maintenance Group

(3) The Data Support Group

(4) The Special Services Group

This organization is proposed as a model from which an actual working operation can be developed. Many details of how this is implemented cannot be settled at this time. In particular, many staff people, particularly those at the less technical levels, such as basic maintenance, driving, etc., may work in more than one of these divisions over the year, since the need for field personnel will fluctuate substantially. No unnecessary assumptions have been made about the business arrangements by which the PASSCAL Facilities are brought into service. Among these business options which PASSCAL might adopt are:

...use of contractor? for limited tasks, for entire facility?
...arrangements for space? rental, ownership, contractor space,
  university space, combination with other IRIS facilities?
...line of command linking PASSCAL management with contractors.

At this time, opinion in the Standing Committee favors having PASSCAL (IRIS) employees at least in the few important positions where policy has to be enforced. These questions are discussed in Chapter 10; in general, however, they can be worked out only in the coming year, following the creation of an IRIS Business Office, and the establishment of policies and protocols for purchasing and contracting.

8.3.1. Central Maintenance Facility (CMF)

In order to maintain high standards of instrument performance and low down-time, the CMF will be required to perform the following functions.

(1) Maintain inventory of instruments, and records on deployment and maintenance histories. Administer distribution of instruments and training of users.

(2) Schedule and conduct routine preventive maintenance. Do diagnostic instrument testing before instruments are returned to the field.

(3) Repair, maintain, and calibrate instruments returned from field duty.

(4) Maintain and administer field support crews, including vehicles, computers, etc.

(5) Administer acceptance testing when new instruments or components are delivered. Advise business office on enforcement of quality control in the purchasing and contracting process.

In addition, this central facility should probably have some capability beyond being a repair and maintenance shop. The top level technical people here will represent the most advanced capability in instrumentation on the PASSCAL payroll, and we will wish to integrate their proposals for technical improvements with those of the Instrumentation Committee and others in the research community. Over the years, the instrumentation will undergo various upgrades, and the program will want to field test various new technologies in telemetry, control, advanced A-D, data storage, etc.

The resource needs of the CMF will grow with PASSCAL, as more and more instruments are brought on line. Since instrument specifications are being developed at this time, a

Program Engineer should come aboard as soon as is practical, preferably around Feb. 1, 1986, as detailed in Chapter 14. The Program Engineer is needed to interact with the manufacturer(s) selected for instrument construction throughout the course of production, and with an augmented staff, to perform instrument acceptance tests and to take delivery. Space for all the PASSCAL Facilities will be focused at the CMF, since the Field Group and the Data Support Group will require some central administrative site. By the first delivery of 100 instruments in 1986, a physical plant of about 6,000 square feet will be needed to house the PASSCAL Facilities, about half for the CMF and half for the other three Groups.

8.3.2. Field Deployment and Maintenance Group (FDMG)

The backbone of the FDMG is a number of support vehicles which are equipped to handle all tasks connected with the deployment and visitation of instruments in the field. They will also be needed to handle field data retrieval, validation, and initial data preprocessing. Staffing of these facilities has to be subject to our policy given above, which minimizes the number of full time staff in accordance with a usage profile which fluctuates substantially over the year.

A structure for the FDMG facilities which minimizes the number of vehicles is as follows:

(1) Instruments will be transported to a field area *en bloc* in Instrument Vans, which are trailers outfitted for storage and cross-country transport. We assume 200 instruments per van. The use of vans minimizes the number of vehicles which must be owned for deployment to actual field sites. Vans to support 100 instruments may also be included as a more effective way of distributing smaller complements of instruments.

(2) Deployment will be done from rugged, field-worthy vehicles outfitted to transport about 25 instruments. A single deployment vehicle can support up to 100 instruments, if used in conjunction with the vans.

(3) Test vehicles will contain electronic support equipment, including test gear, possible SSB or satellite communications, and a field computer for initial data playback and monitoring. The number of instruments which can be tied to a single field computer is still a matter of much analysis; we set here a figure of one field computer for every 50 instruments.

With this organization, the FDMG will include 10 deployment vehicles, 5 instrument vans, and 20 test vehicles, for the full 1000 instrument system.

For a large-scale field exercise, staffing the FDMG will require personnel from both the PASSCAL Central Maintenance Facility and from PI groups. For smaller studies being handled by a single PI, most of the personnel would come from the PI's staff.

Two examples should be helpful. In the case of a passive 100 instrument network operating for local earthquake studies, the PI group would be assigned two test vehicles and one deployment vehicle and given full responsibility for the field activities. The instruments would be trucked out in a single van. Here, time pressure and the intensity of field effort are both minimal, and the need for PASSCAL support staff also minimal. In the case of a large-scale multi-institution effort involving 800 instruments for two months, with many different types of data, the time pressure and intensity of effort are maximized. We would project a PASSCAL provided support staff of one per hundred instruments and PI support staff of about 2—3 per hundred.

8.3.3. The Data Support Group

Once data cartridges are retrieved from the field stations, support services related to the playback and preprocessing of the data and to preparing the data for archiving and release will be provided by the Data Support Group. Although the line between this function and the hardware services of the FDMG must be somewhat arbitrary, and may be lost in practice, a separate discussion here serves to highlight the importance of Data Support services. Some of this discussion also overlaps that in Chapter 9, which deals with Data Management for PASSCAL.

Data Support services are needed to convert unedited data recorded on the field instrument media (cartridges) into edited event data resident in the IRIS Data Management Center. In **7.1**, above, we have argued that radio or satellite telemetry of data will not be an adequate solution to the data retrieval problem for several more years. We have adopted a data retrieval strategy based on the use of high density magnetic tape cartridges and physical retrieval by the support crew.

The Data Support functions are:

(1) Physical retrieval of cartridges.

(2) Initial playback of cartridges. Validation and editing of descriptive parameter data. Validation of instrument performance. Creation of initial edited trace data in standard format on standard exchange media (e.g. SEGY tape).

(3) Initial monitoring by the PI of the progress of the experiment.

(4) Final editing for event data sets. PI supervised editing of field data and creation of edited event data sets or profile data sets, suitable for inclusion in the Data Management Center archive.

The field computers. Each test vehicle in the field area will have a computer (either mounted in the vehicle or in a motel room) with facilities for playback, plotting, sorting, and output of data onto standard media. Justification for this element of the support program is spelled out in section 9.2. It is expected that the PI will be responsible for spelling out the procedures which need to be done on the data by the field computers. Either the technician in charge of the test vehicle, the PI, or any suitably trained field assistants will carry out the playback procedures, under the supervision of the PI.

Two PASSCAL senior programmers will be needed to help oversee the field computers as a standard system. Responsibilities would include the production, purchase, or integration of software needed for the baseline needs of quality control, initial sort, and instrument evaluation; also the maintenance of software and software documentation, and the training of participating scientists in the use of the software and hardware. The specific staffing plan or outside software procurement plan needed to meet these responsibilities will be developed by the Standing Committee and Data Management sub-committee in consultation with the senior programmers and the Chief Scientist.

The baseline facilities and personnel needed for Data Support are estimated at:

(1) One field computer per 50 instruments.

(2) One test vehicle, with driver-technician, per 50 instruments.

(3) One field computer at the CMF, for software debugging and prototyping, for backup service to the field systems, and for general use by the programming staff.

(4) A programming staff at the CMF, consisting of a senior programmer, and at least one other programmer-analyst. Two is an absolute minimum here, for a large experiment involving the entire network would need at least one software support person in the field and one in headquarters.

We emphasize that the initial definition of the field computers, the definition and writing of the baseline software, and whole process of getting these facilities started will require additional technical effort, probably through extramural projects and contract-written software. Details of prototype operations already quite well advanced are given in Chapter 14.

Support services at the IRIS Data Management Center. While the need for field computers to facilitate data flow and serve the PI in monitoring the experiment is overwhelming, the analysis in Chapter 9 of the requirements for preprocessing of PASSCAL array data also show clearly that a substantial fraction of this work will still need to be done at a facility with much more storage and speed than the field computers. We have, therefore, specified that the data stream from the PASSCAL array will require substantial centralized data preprocessing services (particularly sorting), and have recommended that this be done at the IRIS centralized

Data Management Center. In Chapter 9, we have estimated the nature and quantity of these needs. By agreement with the IRIS Executive Committee, all these services will be covered under the program of the Standing Committee for Data Management. PASSCAL will maintain its input into the vital functions being supplied by this program at the executive level through the IRIS Board of Directors and at the operational level through the PASSCAL Data Management subcommittee (chapter 10).

8.3.4. The Special Services Group

It is regarded as likely that PASSCAL will need to provide additional special services on the ground that the expertise required is highly specialized and/or intrinsically centralized. We identify the following candidate services, which would involve at least one professional level staff member working in the CMF.

(1) Communications services: Responsibility for PASSCAL radio communications, which will probably include long range message services (SSB radio or satellite mail) and line of sight field communications (UHF radios and relays). When telemetry becomes a significant mode of data retrieval or remote control, additional staff may be required in this section.

(2) Permitting and shooting: Responsibility for the specialized services involved in permitting for instrument sites, for drilling, for shooting, and the like.

(3) Time and position services: Responsibility for maintaining GPS receivers and timing systems on instruments. Technical expertise to implement special strategies for particular field experiments.

9. DATA MANAGEMENT

Perhaps the most frustrating, ubiquitous impediment to the seismologist engaged in field experiments is the time-consuming preprocessing of field data into a usable form. Equally frustrating can be the experience of attempting to acquire data from a data center. The frequency with which previous seismological programs have succumbed to the pitfalls inherent in managing substantial quantities of data clearly emphasizes the responsibility which PASSCAL and IRIS have to realistically define and implement their data management responsibilities.

In specifying the design and operational characteristics of a 1000 element seismic array, it is necessary to develop a plan for the flow of digital data from the sensors to the individual scientist. Data which are acquired in certain experiments can be expected to amount to more than 100 Gbyte, formed of up to 10^7 traces. Editing, sorting, and preparation of documented data sets from this quantity of information will require a flexible, high capability system and intelligent participation by the investigators. (For comparison with figures which develop later in this chapter, a 1000 station 6-channel PASSCAL array, running at 100 samples per second, would produce 80 Tbyte or 80,000 Gbyte in a year of continuous operation.)

First, we present **(9.2)** the **needs** which must be met by the components of a data management system. We discuss next **(9.3)** the **functional components** of the plan which is to be adopted by PASSCAL, along with the constraints and requirements which justify these components. We then present **(9.4)** **models of the data flow** from different types of field studies, and finally **(9.5)** the **projected demands** on the different components of the system.

The conclusions of this chapter are the design inputs to the PASSCAL ten year plan (Chapter 13), and serve as recommendations and inputs to the IRIS Standing Committee for Data Management, regarding the Data Management Center and its relation to PASSCAL.

9.1. PASSCAL and the IRIS Data Management Center

The need for large-scale, high performance data management services of a similar sort by both PASSCAL and the Global Seismic Network (GSN) has led the IRIS Board of Directors to establish a separate Standing Committee to implement and operate the centralized, common data management facilities. A division of operational responsibility for handling the PASSCAL data flow is thereby defined.

(1) PASSCAL will implement and operate all components of the data management system which are decentralized, and associated with the initial field data acquisition. This will consist of the seismometer packages and the field playback/computer systems which will normally be located at a support center near the deployed packages.

(2) The Data Management Standing Committee will implement and operate all components of the data management system which are centralized, with particular emphasis given to functions which are common to PASSCAL and the Global Network. We call this the Data Management Center.

Generally, then, the data will flow from the instruments to the field support centers under PASSCAL, and be passed on to the Data Management Center.

We call attention to the PASSCAL **organizational chart** in Figure 10-1. The PASSCAL Data Management Subcommittee will maintain responsibility for questions of data management as they affect PASSCAL operations and users. This subcommittee is expected to maintain close official liaison with the IRIS Standing Committee for Data Management.

9.2. Needs for Data Management Services

Raw data appearing in sequential form on cartridges from individual seismometer stations require a number of processing steps before the information is fully documented, sorted, and associated with other information in a data archive. The archive itself represents a repository of such documented data sets which exists to provide convenient access to the data by participating scientists. We list services (1) to scientists using the PASSCAL array for data collection and (2) to scientists using data archived in the Data Management Center.

9.2.1. Needs Associated with Data Dollection

Scientists participating in PASSCAL data collection will have need for the following:

(1) Intelligent functions in the instrument packages: Selection of channels, sampling rates, and filter settings; preprogrammed time windows; simultaneous multiple triggers; simple event picking; storage of parameter information in trace headers.

(2) Retrieval of data cartridges from instrument locations to field centers.

(3) Rapid response services: verification of integrity of cartridge data; verification of performance of recorders; verification of characteristics of recorded data; plotting and preliminary analysis of a limited subset of the total recorded information. In controlled source experiments, plotting of record sections or shot gathers is essential to verify that the design characteristics of the experiment are optimum, particularly the source characteristics. In natural source experiments, an early look at selected instruments is essential to develop a preliminary catalog of events recorded so that subsequent sorting and association of traces with events can be done smoothly.

(4) Sorting and event association: Data recorded on the cartridges is in effect cataloged by its instrument number and may be unidentified, if due to natural sources. For the data to be usable, the traces from the entire network must be resorted and associated with a catalog of events. Where the events are artificial sources, the number of traces will often be small enough and the complexity of the catalog simple enough that this is a simple process. When many natural events are recorded by an array, or when a major three-dimensional seismic reflection or tomography profile is involved, both complexity and quantity escalate substantially. Since much of the rationale for the PASSCAL array lies with its use for acquiring large, complex data sets, the need for well-thought-out sorting and event association provides a strong demand upon the overall data management system.

(5) Support for documentation activities by the P. I.: The process of converting the field data to a form useful for analysis and appropriate for the Data Management Center archive may also involve a second, more time consuming stage of producing event catalogs, plots of event gathers, and of thorough editing and preprocessing of the data for parameter inconsistencies, errors, and other grossly unacceptable perturbations of the data. This requires interactive access to large quantities of sorted or partially sorted trace data and availability of relevant software tools for this work.

The **sorting** process requires a few remarks. The rearrangement of large numbers of data traces on the basis of event rather than the basis of instrument number is equivalent to a large matrix transpose, say 1000×500 in dimension, where the elements to be rearranged in the transpose are digital data traces of, typically, 10^4 bytes. If it is demanded that the sort be carried out on a small computer, with quite limited memory and disk, then it is required that the original data cartridges be played back many times. Such a method is unacceptably demanding of time, wear on the cartridges, and on the operating personnel. If it is demanded that the data be fully sorted in one pass, to minimize these three penalties, then extremely large scratch disk storage, perhaps 2×10^{11} bytes, or 600 standard drives, would be required. This method poses an unacceptable cost, especially if such data sets occur relatively infrequently. The way of obtaining the sort at acceptable penalty levels for time and facility cost is a two or three-stage sort. In the PASSCAL context the field computers can be utilized during initial playback to provide the first level of sorting. At most data from 100 instruments could be sorted at that stage. The remaining stages of sorting would have to be carried out at a more powerful fixed facility.

Individual P.I.'s who are running experiments with a 100 element deployment and moderate rates of data may well be able to handle all sort functions at the level of the field computer. The experience of the U.S. Geological Survey with their 120 analog instruments confirms this projection.

9.2.2. Requirements for the Data Archive

What form should the archived data take? Although it is possible that a high performance data archive could manage with parameter (data base) information and trace data randomly stored on the archive media, common practice and common sense dictate that some basic principles of organization be adopted. The fundamental unit of seismic data is the individual seismic trace. Contiguous organization of traces into groups is general practice in all branches of seismology.

(1) In reflection seismology, traces are organized into *field gathers*, consisting of groups of traces with a common source. Field gathers are further blocked into groups corresponding to a contiguous portion of a survey. Stacked data are organized as *CDP stacks*, consisting of a set of stacked traces corresponding to a contiguous sequence of reflection points on a line. With three-dimensional surveys, the ensemble of stacked traces itself is a three-dimensional data volume consisting of traces corresponding to a grid of mid-points on the surface.

(2) In earthquake seismology, whether teleseismic or local, the traces are organized, if at all possible, by event, which must be determined by picking arrival times, identifying events, and associating them with the recorded traces.

(3) Certain special data sets will have no events to organize the catalog, or be too complex to readily organize by event. Examples would be harmonic tremor, extremely active earthquake swarms, and microseismic noise recordings. In such cases, traces would be organized at fixed length and catalogued by time.

What services are required by the scientific community? For scientists intending to retrieve data from the archive of the Data Management Center, the following services are needed:

(1) Catalogs, both printed and on-line, of data in the archive. On-line, the ability to search a catalog structure for basic information about availability and characteristics of data sets.

(2) Ability to preview representative trace displays of a given data set.

(3) Ability to obtain desired data sets or subsets in standard exchange media format in a reasonable time. With present technology, this would be overnight mail delivery of up to four reels of 6250 density 9 track tape, or about 500 megabytes on a one day basis. In the future, much larger quantities should be feasible.

(4) Dial-up access to the Data Management Center.

(5) Services for high resolution, high volume previewing of the archive, in the Data Management Center. It is premature to estimate the level of this kind of support. An obvious minimum would be that which would support the needs of the management of the Center.

(6) Adequate support of the software which provides the above services. This includes help features, manuals, a professional programming staff, and the ability to assess the need for and to develop new software tools.

9.2.3. Needs for Hardware and Software at P. I.'s Institutions

Ultimately, research on the data sets produced by the PASSCAL array will be done by scientists working at their own institutions. Unless each participating research group has access to a certain level of computer hardware and software for data analysis, much of the research will be frustrated. In Chapter 15, we discuss this issue at greater length.

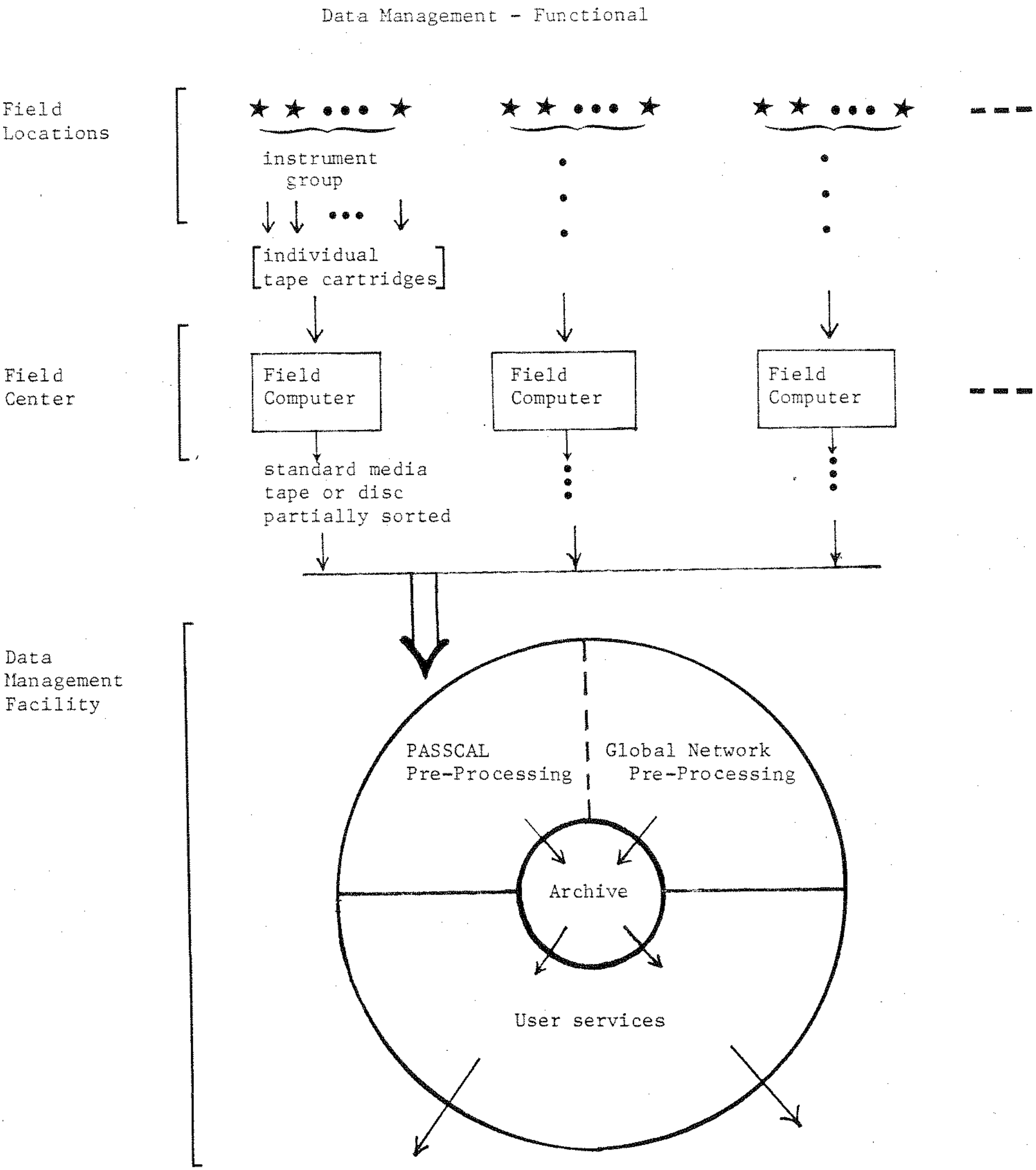

Figure 9-1: Functional map of PASSCAL data management

9.3. Functional Components of a Data Management System

From the preceding sections, we can define (Figure 9-1), the different components of the total PASSCAL-IRIS data management effort:

1. The instrument packages are to have a limited, but critical set of logical functions. These would be incorporated into the firmware of the different modules. Intelligent algorithms for event detection are now part of the arsenal of network seismology, and are the most general tool for restricting the volume of data at its source. For many experiments, however, multiple detection algorithms may be necessary, acting in an *or* mode; some development work lies ahead. In general, parameter information about each sensor will be loaded into trace headers, and information about the trace data itself might be extracted and also saved in the headers. The application of a P-picking algorithm for use in local earthquake situations and the storage of the picked times on trace headers could greatly simplify the subsequent preprocessing of the large data sets involved.

2. The field computers will be transportable systems equipped for playback of the data cartridges, perhaps with multiple input devices; otherwise they would carry memory, scratch disk, plotting hardware, and a device for the output medium†. Such systems can be assembled with available 32-bit microprocessor-based high performance computer workstations and peripherals, and fit in the physical space which would be available on a PASSCAL test vehicle. Identification of specific hardware will depend on what is available at the time bids are sent out, and will depend on qualifications for transportability and reliability. Immediate plans for testing existing field computer prototype systems, including software, are described in Chapter 14. One field computer will go into the field center to work with each 50 instruments (estimated). A uniform package of support software will be installed in the field computers.

A general philosophy for minimizing bottlenecks in data flow involves handling as many chores routinely, and as early in the data preprocessing, as possible. The field computers are intended to meet this need and to meet the need for the P.I. to conduct rapid inspection and evaluation of the data. It is adequate to set performance specifications for the field computers as follows: equal to those presently obtainable and qualified for the purpose (or better), at present price levels (or better). Clearly, availability of Gbyte levels of disk capacity and multi-megabyte memory is anticipated as a means of enhancing the ability of the field computers for first stage sort of trace data.

In terms of the needs posed in 9.2.1, the field computers will handle (1) rapid response functions and (2) first stage sort and event association. In perhaps a few instances, and at the discretion of the PI, it is possible that the mobile field computers can be dispensed with almost entirely, in favor of sending the field tapes directly to the playback facility at the Data Management Center.

3. The Data Management Center, operated by the IRIS Standing Committee on Data Management, needs to have facilities and support for completion of data preprocessing, ahead of the archive and data distribution functions (Figure 9-1). This preprocessing facility would be a compatible superset of the field computers, and would permit completion of whatever sorting, event association, and documentation chores (9.1.1) the PI was unable to complete using field computers. The performance specifications for the IRIS-operated facility would need to be based on typical recurring data volumes which are expected from a typical mix of field experiments. Where extraordinarily large, but relatively uncommon data sets become involved, the economics of cost and effort suggest that preprocessing may be better handled by an outside contractor.

Long term budget estimates and FY85—FY87 budget figures (chapter 13) for the PASSCAL data management effort reflect the cost of all operations located in the field.... the instru-

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† See also Chapter 8 of this Plan

ment packages and field computers, but not the central IRIS Data Management Center, which is covered by the program documents for the Data Management Standing Committee.

9.4. Models for Data Flow

We introduce a set of models for field experiments of various types. These lead to quantitative estimates of the data volumes and rates of data production by the array, from which we deduce the demands which these experiments place on the different components of the data management system.

9.4.1. Artificial Source Experiments

We first take up a set of controlled source experiments, in order of increasing data volume. In general, the management of controlled source data is simpler than for earthquake data since the shot time, location, and desired record lengths are known. As will be shown, however, the handling of the high data volumes produced by controlled sources may tax both field and central computers as much as do earthquake studies. We consider separately the demands on a field computer and the demands on the Data Management Center.

In Table 9.1 estimates of the data volumes and needs for data sorting are presented for four generic controlled source experiments. This table also provides parameters such as sample rates, number of events per day, etc., which were used to generate these estimates. These experiments are:

1) A quarry blast refraction study involving 100 seismometers;
2) A Deep Seismic Sounding (DSS) experiment involving 1000 instruments;
3) A three-dimensional seismic study involving 1000 explosive shots to 1000 instruments;
4) A three-dimensional seismic study where 800 vibrator points are occupied and individual vibrator sweeps are recorded by 1000 instruments.

In all cases it is assumed that the desired output from each of the field computers (about one per 50 instruments) will be common-source gathers.

Demand on field computers. The data volumes, and therefore the difficulty in obtaining common-source gathers in the field, are markedly different for each experiment. For example, the total raw data for the quarry blast experiment is on the order of 0.2 GByte, an amount that can easily be handled by a minicomputer. The demultiplexing, sorting, and plotting of field tapes for this small experiment by the field computer can be easily managed on a daily basis, or as frequently as the PI wants to collect the data cartridges. DSS experiments, however, collect roughly 5 times this amount of data per day, and the three-dimensional experiments roughly 50 times this daily sample rate. For explosive source DSS and three-dimensional studies, the main task for the field computer remains the demultiplexing, data quality control, and sorting and playback tasks.

The three-dimensional vibroseis experiment is posed as an experiment involving the maximum likely data volume for controlled source studies. The acquisition of uncorrelated individual sweep records without vertical stacking is a plausible scientific requirement, for various types of preprocessing of this raw field data have been shown to substantially enhance the signal/noise ratio of the final section: e.g., prewhitening, despiking, trace balancing, noise rejection. We ask whether this data load can be read by the field computers, preprocessed, vertically stacked, correlated, and sorted on a production basis. The result is a conditional yes, subject to the availability of high performance array processor units to expedite the number crunching, and subject to the limitation of the sort to 50 stations. This kind of experiment, which is very similar to an industry program using seismic group recorders (SGR's), is then conceivable with the projected PASSCAL field computers, even without the implementation of hardware for vibroseis correlation in the field units. After summation and correlation, the daily data volume output, would be of the order of 72 MBytes, which is easily sorted on a field computer. For a three-dimensional reflection survey with dynamite sources, daily data flow is comparable to the vibroseis survey, at the post-stack, post-correlation stage.

		CONTROLLED SOURCE EXPERIMENTS				NATURAL SOURCE EXPERIMENTS					
	TYPE OF EXPERIMENT	SS REFRACTION STUDY	DSS	3-D EXPLOSION STUDY	3-D VIBROSEIS STUDY	SS LOCAL EARTHQUAKE (LOW/HIGH)	SS LOCAL EARTHQUAKE (HIGH RATE)	LS LOCAL EARTHQUAKE (LOW/HIGH)	LS LOCAL EARTHQUAKE (HIGH RATE)	SURFACE WAVE TELESEISMS	LINEAR TELESEISMS
GROSS EXPERIMENT PARAMETERS	# of recorders	100	1000	800	800	100	100	1000	1000	500	500
	# of channels/recorders	6	3	3	3	3	3	3	3	3	3
	Total # of channels	600	3000	2400	2400	300	300	3000	3000	1500	1500
	Duration of Experimt.(days)	10	100	60	60	300	300	300	300	300	300
	Total # of sources	10	25	900	12000	1500	15000	1500	15000	600	600
	Ave. # of traces/recorder/day	6	0.75	45	600	15	150	15	150	6	6
	Ave. total # of traces/day	600	750	3.6	4.8×10^5	1500	15000	15000	150000	3000	3000
	Total # of traces	6000	75000	2.2×10^6	2.9×10^7	4.5×10^5	4.5×10^6	4.5×10^6	4.5×10^7	9×10^5	5×10^5
SAMPLING PARAMETERS	Digitizing rate(samples/sec)	250	100	250	250	100	100	100	100	2	20
	Trace length (sec)	30	400	120	50	100	100	100	100	4000	4000
	Trace size (kBy)	15	80	60	25	20	20	20	20	16	160
	Total volume of raw data(GBy)	0.09	6	132	725	9	90	90	900	14.4	144
FIELD SORT PARAMETERS	Duration of cartridge pickup (days)	1	16	1-30	1-5	100	10	100	10	300	150
	Traces/cartridge	6	12	45-1350	600-3000	1500	1500	1500	1500	1800	900
	MBy/cartridge	0.09	0.96	2.7-81	15-75	30	30	30	30	28.8	144
	Total data in field sort (GBy)	0.0045	0.048	0.135-4.05	0.75-3.75	1.5	1.5	1.5	1.5	1.44	7.2
DATA CENTER SORT PARAMETERS	Total raw data sorted in all cartridges (GBy)	0.005	0.5	3-70	7-60	15	15	150	150	16	80
	Estimated % of recovery	100	100	100	3	50	50	50	50	?	?
	Total output data volume(GBy)	0.01	1.0	6-140	.21-1.8	15	15	150	150		

Table 9-1

For the illustrative long line DSS experiment, average daily data rates are still lower, for most of the field time is spent moving the elements of the array. Quality control is especially important here, however, to insure that shots and receivers have performed up to expectation before the array is picked up for redeployment. Thus, during shooting period intensive data analysis consisting of demultiplexing and playback of data is required. The 5-day intervals between shots can be used to sort the data into common source gathers. Per shot, roughly 60 MBytes of data need to be sorted in each of the 5 days of nonshooting.

Demands on central facility. The demands for preprocessing made on the Data Management Center by these different experiments also vary widely. For small datasets the tapes received from the field computers will be ready for archival. For DSS or three-dimensional experiments the Data Management Center will need to combine data tapes which have been sorted by 100 element groups into combined 1000 element sorted gathers. Although further sorting by the PI of DSS data should provide no major difficulty, it is unlikely that PIs at most institutions can sort three-dimensional datasets into CMP gathers. This advanced sorting is a service that the Data Management Center must provide, either using its own facilities or through the services of a contractor.

9.4.2. Natural Source Experiments

Table 9.1 summarizes gross data properties of four model natural source experiments.

(1) A "small scale" local earthquake monitoring survey utilizing 100 short period, three-component stations.

(2) A "large scale" local earthquake monitoring survey utilizing 1000 short period, three-component stations.

(3) A tomography experiment utilizing 20 second surface waves recorded by 500 intermediate period, three-component stations arranged in a circular array.

(4) A teleseismic profiling experiment utilizing 500 three-component instruments deployed along a linear profile at 500 m intervals. The array would be moved 10 times to cover a 2500 km profile.

One peculiar feature about data from natural source experiments needs to be noted immediately. Present plans suggest these instruments would be individually triggered. As a result, unscrambling the data coming from the array is more complicated than it is for controlled source experiments for three basic reasons: (1) the instruments do not start or stop recording at a common time, (2) false triggers can be expected, and (3) not all stations will trigger on every event.

Demands on Field Computer. Natural source experiments pose somewhat different data management problems than controlled source experiments. The biggest difference in this regard lies in the demands placed on the field computer. It is required to handle:

1) demultiplexing field tapes

2) editing out dead traces

3) sorting traces into "common event gathers"

Demultiplexing is a standard process and needs no further comment. The other tasks, however, pose some unique problems. It is not trivial to sort traces from a large set of instruments that are individually triggered. There is a major association problem because the instruments are not synchronized to start at a common time. Consequently, the sorting algorithm must make some fairly complicated decisions to associate trace A with event B. Nonetheless, the sorting of likely-to-be-associated event data on the basis of trigger times using a "probable" correlation time window is a proven procedure. Files containing time of onset and duration of triggered events for each station need to be assembled separately from the time series data so that sorts for times of associated events can be made rapidly and with little computer power, prior to sorting traces into common event gathers.

A second major problem with the sorting the field computers must perform, is the very large data flow which may occur with certain experiments. If the currently envisioned 160 megabyte cartridges are used, a field computer assigned to handle the data from 50 instruments could need to sort over 5 Gbyte of data. Unless there is a dramatic change in field random mass storage capabilities, this is clearly impractical. It may be desirable in such cases to monitor only a small subarray (possibly telemetered) of perhaps 20 stations. Data from this subarray could be handled easily with existing digital network software to provide preliminary hypocenter locations, magnitude estimates, etc. This would be an input to the sort/edit task to be done in the Data Management Center.

The other unique problem of the PASSCAL array, when used to record natural events, is that of editing. Current experience with existing networks indicates that in some severe cases only 1 to 10% of the input data survive the winnowing process. Given the high data volumes flowing from natural source experiments (see Table 9.1), this is significant. In designing the PASSCAL data management system, however, we must recognize that the same editing percentages may not apply for two reasons.

(1) The array may be densely deployed over a small area. Very small focal earthquakes would be recorded by the whole network.

(2) For wavefield studies, deleting high noise traces may not be desirable. The only traces one might wish to throw away are those that are completely dead.

Consequently, proper editing may not always be possible in field computers and may occasionally fall on the data center.

Demands on central facility. The impact of passive earthquake recording experiments on the central facility is very dependent on the particular deployment and on the triggering modes used. It is most pronounced when the full array is deployed. We distinguish two situations.

1. In a deployment which is aimed at teleseismic events, such as a surface wave tomography study or a linear body wave profile, the number of events and the average number of events per day can be estimated in advance. Since most teleseisms show only a few limited duration high frequency body wave groups (band around 1 Hz), along with about an hour of fundamental mode surface waves, the sampling strategy at the instruments can limit the data flow in a predictable way. The predictability of this impact on the system is further enhanced by the likelihood that at least half of the PASSCAL system will be deployed in this mode for much of the year (see Chapter 13). The model estimates of 16—80 GByte/yr (Table 9.1) would settle down to a more or less steady stream, easily managed by a central facility.

2. From time to time a large number of instruments may be deployed in a dense array over a seismically active zone. Some of these experiments may be preplanned, while others may occur in response to large earthquakes or volcanic eruptions. It is quite impossible to predict the frequency of events from such deployments. It suffices to say that there exists the possibility that the array may capture intense periods of seismic activity which require the acquisition of data at the maximum sampling rate (about 250 /sec) for an appreciable fraction of real time. Data sets of 100-500 Gbyte may therefore arise quite unexpectedly. In such a situation, the scientists involved need to make policy decisions about the retention of data, based on projections about their ability to work with these quantities. It is quite clear that such cases, which lie at the statistical extreme, cannot be used to specify the preprocessing performance of the Data Management Center, and that special resources may need to be brought to bear in such situations through outside contract.

9.5. Model for Demand on the Data Management Center

A model for utilization of the PASSCAL instruments appears in Chapter 13, as Figure 13-1. (These figures are not policy figures, but represent unsubstantiated estimates of the average usage per year.) It assumes 3 months of deployment of the full array in a large scale cooperative experiment involving controlled and natural sources. For the remaining time, over half the instruments are deployed to record natural events... most often teleseisms, and the remaining instruments are on loan to smaller groups of P.I.'s in groups of 100 or less. The impact on the field computers is dependent on the particular type of study, but total figures are unimportant, since the field computers are defined by the requirements of size and cost at state of the art technology, and will be utilized as fully as possible. For all but certain experiments with 100 element arrays, however, the field computers may be insufficient to handle all the data preprocessing.

This model leads to estimates for the data flow into the Data Management Facility for preprocessing and archiving.

(1) Between 50 and 100 GByte per year from recording of teleseisms.

(2) Data from one large cooperative experiment per year. From 50 to 200 Gbyte per year, depending on the particular experiment.

(3) From six small scale experiments with 100 instrument arrays. Less than 50 GByte per year.

(4) From an unanticipated swarm of aftershocks or volcanic earthquakes: Rare data sets as large as 100-500 Gbyte.

The annual data flow into the Data Management Center would then be a fairly steady 150—350 Gbyte per year, augmented by unpredicted event swarms delivering an additional 100—500 Gbyte each. The general level could go up in a few years if the use of vibroseis caught on for tomographic and three-dimensional reflection studies.

The management of the large data volumes in an archive we leave to the Standing Committee for Data Management. We are, however, presently operating under the assumption that technologies for storage of multiple GByte data sets (laser optical media, vertical magnetic technology) will permit the archiving of 10^{12} bytes/year without unacceptable demand on the resources available.

9.6. Design and Policy Recommendations

9.6.1. User Data Management Plan for Each PASSCAL Experiment

It is recommended by the Standing Committee for PASSCAL that every scientist requesting PASSCAL facilities and services for data acquisition be required to submit a detailed Data Management Plan. This Plan would explain the nature and quantities of data expected, the methods to be used for preprocessing and sorting of data, the nature of the archive to be produced, and the requirements for support from PASSCAL and the Data Management Center, both for facilities and for software support. It is recommended that the Data Management Plan be incorporated when appropriate as a part of a funding proposal to U. S. Government agencies. PASSCAL would retain the power to approve, modify, or disapprove the proposed Plan. PASSCAL would offer to provide technical advice on the capabilities and services available.

9.6.2. Public Release of Data

The use of facilities funded by the U. S. Government carries an obligation that the data produced be made available to the public. On the other hand, individual PI's require time to prepare usable data for research and in an edited, documented form. The Data Management Plan, therefore, should include a proposed date or schedule for the release of the data to the Data Management Center for archiving and public release. By filing his Plan, the PI agrees to abide with the schedule for data release. Recognizing that the time factors involved will differ from experiment to experiment, PASSCAL will set guidelines regarding data release.

9.6.3. Summary Recommendation on the Data Management Center

The IRIS Data Management Center needs to have the capability to complete the sorting, event association, and editing of most PASSCAL data sets. The expected data flow (150—350 GByte/yr) from the predictable component of our array utilization model should be used as the basis for planning the baseline support services and facilities.

9.6.4. On Very Large Data Sets

The largest data sets (>200 Gbyte) must be treated as statistical outliers. The oil exploration industry has several years of experience and the large facilities required to manage such quantitites of data. In addition, industry is equipped for complete processing of three-dimensional reflection data sets. It is anticipated, therefore, that PASSCAL will find it appropriate in certain situations to contract with industry for processing services associated with uncommon, but very large data sets.

9.6.5. A Caution

By the time a full 1000 instruments are available, (1989, at the earliest), it is likely that evolution of technology and cost of mass storage, of laboratory computers, and satellite telemetry will make the data volumes discussed here seem rather unprepossessing. Continued aggressive development by the exploration industry of such technologies and of three-dimensional seismic reflection methods will probably move PASSCAL toward a comparable increase in emphasis of the three-dimensional imaging methods for which the PASSCAL array is most fundamentally suited, and a commensurate increase in the data flow through the system.

10. PASSCAL ORGANIZATION: TERMS OF REFERENCE

Functionally, the PASSCAL organization is much like the mugwump, and defies simple definition in terms of lines of command and responsibilities. This is because we are setting up an organization with line operational responsibilities for facilities and program, but one in which individual members of the scientific community are given maximum freedom to participate and to conduct their own research as they see fit. We address this issue here by writing an organizational plan and terms of reference based on extensive discussions at the PASSCAL Standing Committee meetings on 30 Jan—1 Feb 1984 and on 12—16 July 1984. Numerous parallels with other collaborative national programs, in particular, the Joint Oceanographic Institutions (JOI), simplify the task. Upon ratification by the Standing Committee, this chapter will constitute the legislation which sets forth lines of command, responsibility, advice, and liaison, and which provides a common framework for PASSCAL operations. The organizational chart in Figure 10-1(a-b) can be used for reference throughout the discussion.

10.1. PASSCAL Operational Responsibilities

The general categories of PASSCAL responsibility are:

(1) Long-term program planning. Proposal and budget preparation. High level liaison.

(2) Long-term science planning. Coordination of major scientific studies using the array. Liaison in the scientific community.

(3) Provide support facilities and services. These include maintainence and repair, scheduling, deployment, data playback, software support, and special services.

(4) Provide support for data preprocessing and management, in cooperation with the IRIS Data Management Facility.

(5) Provide support for continuing instrument development, and evaluation of new experimental and analytical techniques for data acquisition and interpretation.

(6) Provide information to the public, to government agencies, and the press about PASSCAL activities.

10.2. Policies and Guidelines

The organizational plan is based on the following policies:

(1) The operational part of the program... the instruments, facilities, and personnel, including subcontractors, must be managed evenhandedly to serve the whole of the seismological community, but with the same efficiency we expect from a business. Routine operations must be run by an IRIS manager with line responsibility.

(2) The Standing Committee is to serve in the role of a Policy and Management Committee to oversee all aspects of PASSCAL, operational as well as policy and planning.

(3) Scientists participating in the Program, through its Committees and Panels, bear the collective responsibility for setting scientific goals and coordinating plans for large-scale experiments using the PASSCAL instrumentation.

(4) PASSCAL serves as a facility for data acquisition and for maintaining portable seismic instrumentation at state-of-the-art levels. Principal Investigators planning to conduct research which makes use of the PASSCAL data acquisition systems will obtain support as follows:

    a. Funding of research projects should be undertaken through ordinary NSF or other agency procedures. PI's should find their own funding for all research costs except:

    b. most costs of data acquisition and of instrument development and acquisition, which will be covered by the PASSCAL budget.

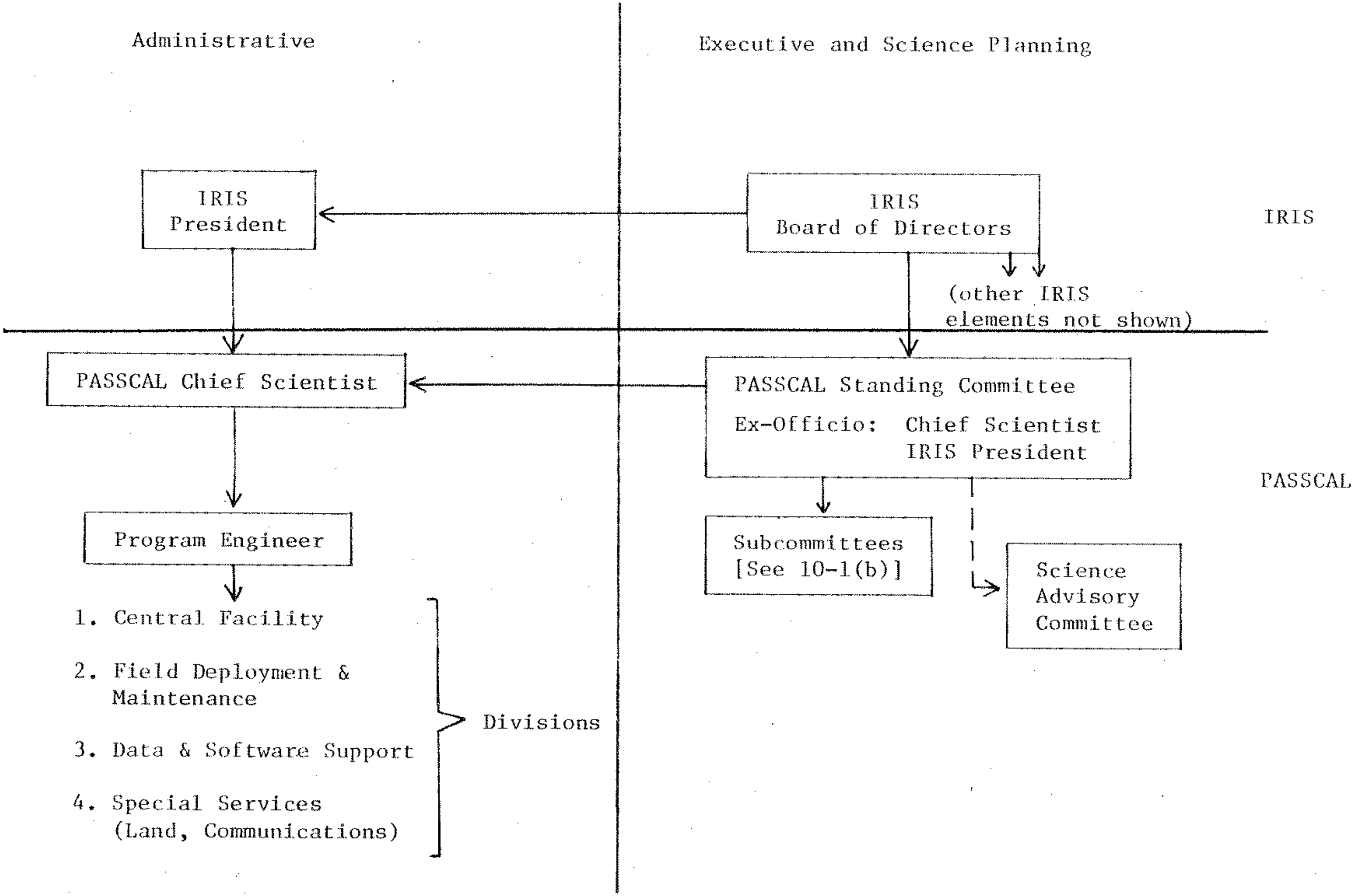

Figure 10-1(a). PASSCAL Organization

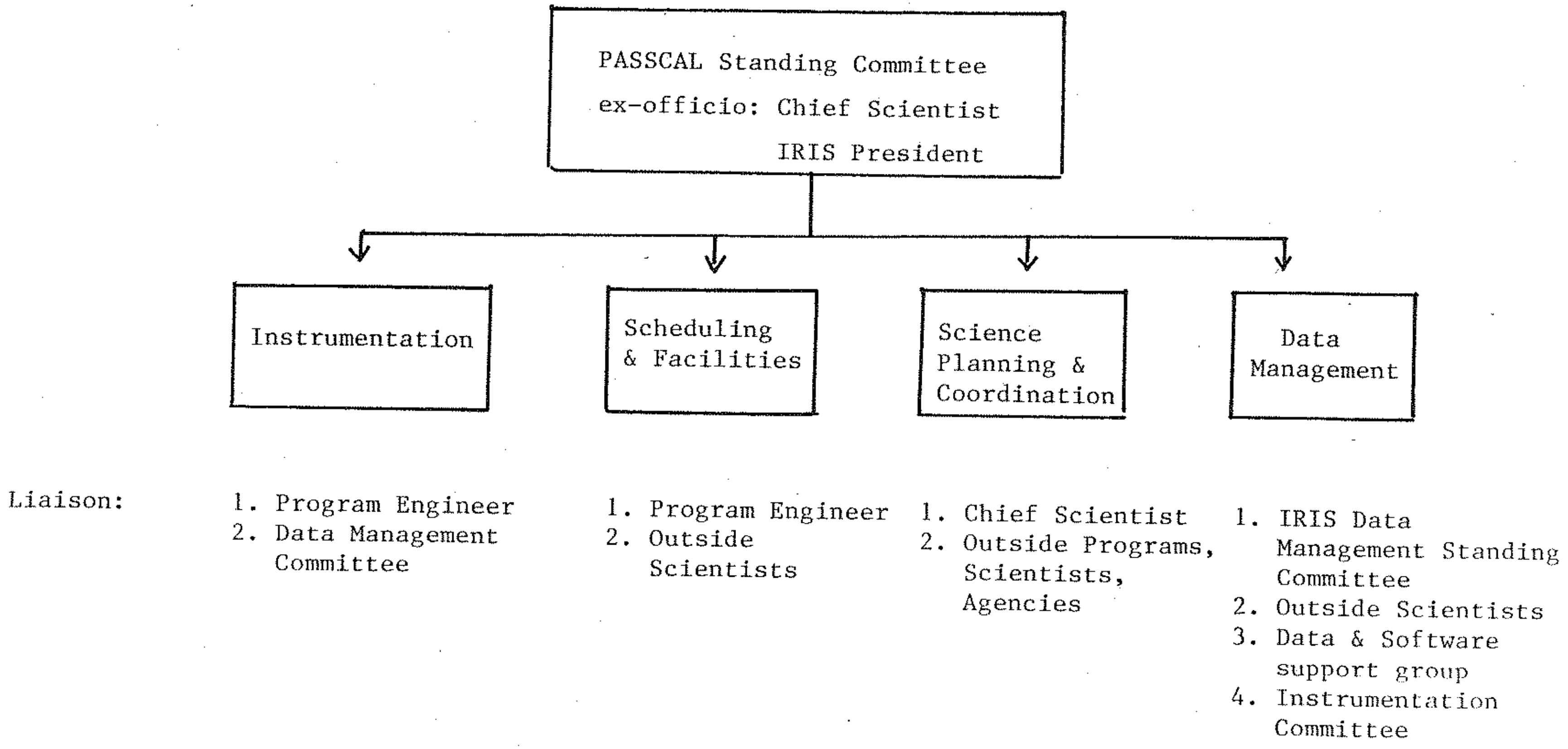

Figure 10-1(b): PASSCAL Subcommittees

Figure 10-1(b). PASSCAL Subcommittees

Since there are some ambiguities in this formulation, a more detailed description is given later in this chapter.

(5) PASSCAL will provide advice, if asked, regarding the scientific merit of proposals or programs, through an autonomous review committee.

(6) Individual PI's are to be extended the maximum degree of autonomy in planning and funding their own programs, subject only to PASSCAL needs for coordination and scheduling of the use of PASSCAL resources.

(7) The scientific community is to be provided standing mechanisms for participation in the governance of PASSCAL.

10.3. The Organizational Plan

In the PASSCAL organization chart (Figure 10-1), we show a side for administration and a side for executive and science planning functions. The administrative side, consisting of PASSCAL employees and facilities, along with contractors, forms a line of management headed by the PASSCAL Chief Scientist, who reports to the IRIS President. The executive/science planning side, consisting of scientists serving on committees, is headed by the PASSCAL Standing Commmittee, which reports to the IRIS Board of Directors.

10.3.1. Administrative and Operational

The PASSCAL Chief Scientist, an IRIS employee, will oversee the administrative and operational side of PASSCAL, including all facilities, services, and contracts. He/she will be hired by the IRIS President on the recommendation of the Standing Committee of PASSCAL. The Chief Scientist will be accountable to the IRIS President for administratively and fiscally effective operation of the PASSCAL facilities.

The Chief Scientist will be fully responsible to the PASSCAL Standing Committee for faithfully executing PASSCAL policies and programs as determined by the Standing Committee. He will sit ex-officio on the Standing Committee.

The Chief Engineer, who reports to the Chief Scientist, will be in functional charge of the facilities and services. These will be: (a) The Central Maintenance Facility, (b) the Field Deployment and Maintenance Group, (c) the Data and Software Support Group, and (d) the Special Services Group. The head of each division will report to the Chief Engineer.

There may also be one or more special officers, in areas such as bookkeeping and public affairs, who report to the Chief Scientist. Fiscal officers within the PASSCAL organization will report directly to the Comptroller of IRIS.

During field operations, the Chief Scientist will appoint a senior member of the operations staff or may himself serve as Party Chief. The Party Chief, like a ship's captain, will have ultimate responsibility for the safety and logistical integrity of field operations. Responsibility for the **scientific** conduct and integrity of experiments lies with the Party Scientist (see below) in consultation with other PI'S. Thus, the Party Chief and Party Scientist share authority for field operations according to their respective areas of responsibility.

10.3.2. Executive and Science Planning

The PASSCAL Standing Committee is the executive body responsible for setting policies and for passing these to the Chief Scientist or to relevant subcommittees or special appointees for execution. The Standing Committee will adopt these terms of reference, and may from time to time modify them to reflect new conditions. Where responsibilities arise which are not covered in these terms, the Standing Committee will have direct charge, until suitable standing arrangements are made. The Chief Scientist and the IRIS President will sit *ex officio* on the Standing Committee.

The Standing Committee will have direct responsibility for all aspects of operation of the program, including:

Long-term program planning
Proposal and budget preparation
High level liaison
Selection of Chief Scientist and Program Engineer
Setting of policy and fixing of Terms of Reference

The Standing Committee will oversee the deliberations of the four subcommittees. These are, as follows, with their responsibilities:

(1) **Instrumentation**. Planning, definition, and oversight of the instrument development program. Monitor performance of the field instrumentation and systems, and oversee quality control.

(2) **Scheduling and Facilities.** Coordinate requests by the scientific community for use of instruments and facilities with their availability, through the Program Engineer.

(3) **Science Planning and Coordination**. Sponsor planning activities designed to produce full plans for large-scale multi-institution cooperative studies using the full array. Coordinate with other initiatives, such as continental drilling, CALCRUST, and the like.

(4) **Data Management**. Work with PI's to develop adequate data management plans for array experiments. Coordinate with IRIS Data Management Center to insure that adequate preprocessing services are available to PI's as needed. Facilitate communication between PI's and IRIS Data Management Center. Oversee the data and software support services of PASSCAL.

10.3.3. The Science Advisory Committee

For a program which includes as large a fraction of the relevant scientific community as PASSCAL, issues of conflict of interest are almost impossible to avoid when scientific proposals are sent out for review by funding agencies. The Standing Committee proposes that a Science Advisory Committee be appointed for the purpose of conducting peer reviews of proposals or other submissions, when requested by an agency. The Science Advisory Committee is to have no members in common with the Standing Committee, and will give recommendations directly to the relevant agency. The Standing Committee may also from time to time request advice of a general or specific nature from the Science Advisory Committee.

10.4. The Annual Meeting

An annual meeting of participating scientists, to be held normally at the Western meeting of the American Geophysical Union, is to serve as a plenary session for discussion of issues relating to PASSCAL. This Meeting is to fill the role originally assigned to the "Senate" when this program was first organized in Madison, in January, 1984.[1] In IRIS, the plenary authority lies with the Board of Directors, which is composed of one representative from each member institution. The Annual Meeting of PASSCAL, therefore, can have only an advisory role, but it is an important one.

Subject to approval by the Board of Directors of IRIS, it is proposed that the Annual Meeting conduct each year an advisory process of nomination and election of 1/3 of the Standing Committee to three-year terms. A Nominating Committee is to be appointed in advance of the Annual Meeting by the Standing Committee. The Standing Committee will formally transmit the results of such election to the IRIS Board as a recommendation to the Board for appointments to the Standing Committee.

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[1] Program for Array Seismic Studies of the Continental Lithosphere, Minutes of the National Organizational Meeting, Madison, Wisconsin, Jan. 13-14, 1984, convened by University of Wisconsin - Madison and Department of Terrestrial Magnetism, Carnegie Institution of Washington.

10.5. Scientific Planning and Funding.

We set forth guidelines here to balance the tensions between the requirements for advance planning of array operations, for maximum autonomy of individual PI's, and for the effective use of the PASSCAL resources. Generally, PASSCAL will take a larger role in the planning of larger-scale cooperative experiments, and will reserve funds to assure that the data acquisition phase of these studies can be successfully consummated. Otherwise, PASSCAL will not serve as a funding agency for support of PI's projects. Support for most costs of participation and data analysis by PI's must be obtained through normal agency channels.

Point of Contact for the Scientific Community: As the senior scientist in the operational organization of PASSCAL, the Chief Scientist will serve as a point of contact for scientists needing information or services, and will be the most effective means of obtaining accurate information about programs, plans, and procedures.

Standing Committee Responsibility for use of PASSCAL Resources: The Standing Committee has ultimate responsibility to authorize the allocation of instruments and services to principal investigators. It is therefore required to go through a process of review of all requests; it may direct the subcommittee on Scheduling and Facilities to deal with most requests, but retains the authority to rule in case of schedule conflict or other difficulty. Where difficult conflicts exist, the review process may legitimately consider requests in terms of the overall balance and scientific priorities of the Program. The review may also take account of issues such as logistics, instrument upgrade schedules, and the like, which interact with particular experiments.

Request for use of resources. It is expected that every PI and every special consortium with plans to use the PASSCAL array will so advise the Chief Scientist, providing details of resources needed and the desired schedule. This will be necessary at the latest, when a project is funded, but will also be important at the earlier stages in planning a project, so that potential conflicts can be anticipated. PASSCAL will request that the PI have an adequate data management plan, and that the PI can commit adequate personnel to the field portion of the study for deployment and data retrieval.

Small project proposals by individual PI's: PASSCAL will encourage project proposals by individual PI's to funding agencies for support of experiments requiring small subarrays of instruments (typically 100). It is expected that most of the instrument pool will be available for such projects except during the course of major experiments. Long-term deployments, more than about one year, will need greater justification. While PASSCAL will provide the support services described in Chapter 8 of this Plan, PI's will normally need to arrange funding for their own staff and expenses in connection with these small-scale programs.

Planning and funding for large-scale experiments: The subcommittee on Science Planning and Coordination will be responsible for maintaining a science plan for the use of the array in large-scale multi-institutional collaborations. Consequently, the subcommittee will sponsor workshops for the advance definition and planning of prospective large-scale experiments. Prospective sponsoring PI's for large experiments will have to satisfy both the agency review process for funding and the review by the Standing Committee.

Availability of PASSCAL funds to support University participation: PASSCAL will maintain a budget line to support the special costs associated with the data acquisition in these large-scale studies. These will include permitting, drilling, blasting, and subcontracting for the large labor force required. In the last instance, where participating Universities provide needed people to take part in instrument deployment and retrieval, data retrieval and playback, or communications and liaison, subcontract money would flow from PASSCAL to the PI's University to defray the costs of providing this labor.

Realistically, the budget for these purposes will be limited, and it will probably be necessary to use it to support large-scale experiments and to support occasional smaller proposals to study methodology or instrument performance, which are of particular importance to PASSCAL.

Planning for passive deployments: PI groups desiring use of a large array (more than 250 instruments) for passive deployment will have to pass agency funding review and Standing Committee authorization to proceed. The Standing Committee will need to deal with competing demands for resources, and will have the authority to resolve such conflicts by authorizing projects which optimize the balance of use of the array over a longer period.

Party Scientist with authority in the field: For each experiment in which PASSCAL instruments are used, the team of investigators will select a Party Scientist who will exercise in consultation with other PI's, general authority in the field over the scientific conduct of the experiment. The Party Scientist will work jointly with the Party Chief in exercising field authority, and will have final authority, save in cases affecting safety or health of personnel or the integrity of the facilities.

10.6. Contingency Planning for Special Events

The subcommittee on Science Planning and Coordination is charged with developing plans for responding to unusual geophysical events quickly. A major earthquake or volcanic eruption would present an unusual opportunity for obtaining detailed seismic information on the post-event dynamics, using a large PASSCAL array. The planning process should take into account (a) special advance arrangements which could speed the deployment; (b) planning for specific high-risk sites; (c) cost of a rapid redeployment of the array; (d) priority protocols with respect to currently active experiments.

The importance of such a rapid response redeployment of the array may be such that PASSCAL should establish a funding plan in advance as well as assure that a small instrument pool is always available for immediate use. This might be through the raising of private funds or the establishment of an agreement with a government agency.

11. PASSCAL RELATIONSHIP TO OTHER EARTH SCIENCE PROGRAMS

In the discussions of the scientific applications of a large portable array (Chapters 3—6), it is evident that the most fruitful applications are large-scale cooperative projects with the full array, in which many different seismological tools can be applied to the same problem area. With such problem-focused studies, the PASSCAL array, which serves to provide regional imaging of velocity and structure, can serve as a catalyst for investigations using other seismological tools, as well as broader geological and geophysical investigations. In addition, the special capabilities of a large array of matched portable digital instruments, even at strengths of 100—200 instruments, make possible a number of experiments on the excitation and propagation of seismic waves in the crust and lithosphere which are of special interest to industry, to several government agencies, and to scholars specializing in wave propagation.

In this chapter, therefore, we discuss briefly the natural relationships which arise between PASSCAL and other major initiatives, agency programs, consortia, and industry. In many cases, the degree of common interest suggests that the PASSCAL Standing Committee may seek to develop formalized working arrangements and informal, but regular liaisons, to insure that PASSCAL and these other programs work together effectively and harmoniously. Undoubtedly, IRIS, the parent corporation to PASSCAL, will establish official liaisons at the Board of Directors level in many of these cases. We will not mention this obvious option again.

11.1. The COSEPUP initiatives

In 1983, the Committee on Science, Engineering, and Public Policy of the National Academy of Sciences (COSEPUP) developed research briefings in five fields of science for presentation to the White House Office of Science and Technology Policy, the National Science Foundation, and other government agencies. The report of the research briefing Panel on Solid Earth Sciences highlighted the study of the continental lithosphere as an area which was ripe for major initiatives, as mid-1980's technology makes possible substantial breakthroughs in our understanding of the continents. The five areas identified by this panel are:

...seismic studies of the continental crust and lithosphere
...global digital seismic network
...continental scientific drilling
...physics and chemistry of geological materials
...satellite geodesy

At the time of the writing of this Plan (July, 1984), the National Science Foundation Division of Earth Sciences has created a special Program for Lithospheric Studies, to serve as a vehicle for the building of support for new initiatives in each of these areas. This PASSCAL Plan is an organizational document for the first listed initiative. We briefly discuss current effort in respect to the other four COSEPUP initiatives and its relation to PASSCAL.

11.1.1. The Global Seismic Network (IRIS)

The Global Seismic Network is a cooperative enterprise similar to PASSCAL, organized (like PASSCAL) under the Incorporated Research Institutions for Seismology (IRIS) in May, 1984. There is more than 60% overlap between institutions engaged in these two programs, with many individual investigators having interests in both. The GSN seeks to arrange for a global network of 100 compatible, digital, broad band, telemetered seismic stations which employ the latest in analog, digital, and communications technology. Pilot experiments with available global data indicate that three-dimensional imaging of the density and elastic parameters of the earth can be expected at scales ranging from global down to about 150 km (vertical) and 2000 km (horizontal). The Science Plan for the GSN was released on April 15, 1984, and can be obtained from Jonathan Berger at UCSD.

PASSCAL and GSN, as programs of IRIS, seek to utilize common scientific interests and common technology needs cooperatively, to enhance the strengths of the programs and conserve resources. The spinoff of the Standing Committee for Data Management, and the plan to establish an IRIS Data Management Center are aimed at serving the data support needs of both scientific programs under a single roof. At this time, pending more detailed discussion of the tradeoffs, the option also remains of putting some of the hardware support facilities in the same place.

While initially conceived as a tool for controlled source imaging of the lithosphere, the PASSCAL array concept now gives approximately equal standing to imaging studies using controlled sources and to the use of natural sources for studies of both structure and earthquakes. It is expected that the deployment of over 500 instruments each year in a low-overhead mode of passive (triggered) recording will produce a quantity of earthquake data similar in volume to that to be produced by the Global Network. Such studies will provide important data on the lithosphere and the sub-lithospheric mantle and core which have substantially higher spatial resolution than is possible with the Global Network. We expect, therefore, that planning and execution of these large-scale regional passive deployments will be undertaken both for regional augmentation of the lithospheric program and for enhancement of the resolution of the global network.

11.1.2. The Continental Scientific Drilling Program (DOSECC)

The long-term focus of the CSDP is a series of deep drill holes in the continental crust, to depths (where appropriate) in excess of 10 km. The planning, site selection, drilling, regional studies, logging, downhole studies, and studies of core materials for each hole... probably a 3 year or longer effort... will, like the IRIS seismic programs, require substantial coordinated activity by participating scientists from many institutions. The medium for these purposes and for the management of the drilling activities will be the non-profit corporation "Deep Observation and Sampling of the Earth's Continental Crust" (DOSECC), whose members are universities and similar institutions interested in the CSDP.

The seismological tools of PASSCAL lend themselves very well to the kind of comprehensive regional study of the structure of the neighborhood of a drill hole. The particular ability of PASSCAL to determine velocities, by several independent methods, may provide the kind of correlation of lithology with velocity which is needed to interrelate measurements on core materials, downhole measurements, and seismic reflection profiles. Over the long haul, both programs have a major stake in understanding the geological significance of velocity determinations of all kinds, and of fine tuning the methods to the point where seismic velocity results can be of real geological significance. Elsewhere in this Plan we discuss as an example experiment, the use of a PASSCAL array for comprehensive seismic study of the Southern Appalachian drill hole area.

We plan, therefore, that the Science Planning subcommittee of PASSCAL will maintain continuing liaison with the corresponding group within DOSECC, with the expectation of combining forces from time to time as both programs evolve. In addition to drill site regional studies, PASSCAL may promote special experiments in seismic methodology which take advantage of the existence of sensors in the drill hole.

11.1.3. Physics and Chemistry of Geological Materials

This initiative is aimed at putting U. S. laboratories in the forefront of experimental work aimed at understanding the behavior of materials under the pressures and temperatures of the earth's mantle and core. The most interesting scientific relation with PASSCAL lies in the likelihood that structural and velocity anomalies in the subcontinental lithosphere (and deeper) will be able to be resolved with some confidence. Such seismic results have major impacts on models of mantle evolution, and will drive more refined experimental work to understand the systematics of velocity, density, and geological setting for various materials.

11.1.4. Satellite Geodesy

In this initiative, NSF and NASA are supporting the acquisition of ground instrumentation which can take advantage of the new Global Positioning System (GPS) satellites to measure plate positions at the centimeter level. The most direct benefit to PASSCAL lies in the projected availability of portable ground receivers which will enormously simplify the determination of the geographic coordinates of observing stations, permitting automatic downloading of identification and coordinate data to the instruments, for automatic recording on the data cartridges.

11.2. Reflection Profiling of the Continental Crust

The first "revolution" in geophysical studies of the continents was the development of reflection seismology as a technique for the routine profiling of continental crust. Through the **Consortium for Continental Reflection Profiling (COCORP)** thousands of km of section have been collected over areas of key geological importance since 1976. The great geological significance of these results has been widely discussed. The programmatic significance, however, is that routine two-dimensional reflection profiling using an industry standard vibrator crew is now established as a basic tool for any regional study of geology or tectonics which is concerned about the continental crust as a whole.

The information returned in a reflection profile of this sort is a pseudo-image of the crust, where image intensity is produced by strong local gradients or variability in the acoustic impedance in the subsurface. It is, thus, a representation of structure, since it principally sees boundaries or grating-like layering with dips less than 45°. The method is limited by signal/noise ratios which make the imaging of the lower crust a matter of luck (on land), and lead to inevitable ambiguities in interpretation. Despite this, however, the power of the method and its field technique... as a routine crew operation... lead us to conclude that a certain amount of two-dimensional reflection profiling will be an intrinsic part of every major PASSCAL experiment or other regional cooperative study.

At present, the ability to carry out reflection profiling depends on two resources: money and equipment. Within the community of groups studying the continental crust, we identify several places presently doing or sponsoring reflection profiling:

(1) Cornell University, home of the COCORP project, contracts a full time 96 channel vibroseis† crew, and operates a computer and analysis center for producing sections, under NSF support.

(2) The University of Wyoming, Virginia Polytechnic Institute, and the Colorado School of Mines have full equipment for multichannel vibroseis† profiling, and run occasional research profiles under outside support.

(3) The United States Geological Survey has for the past two years put resources into the acquisition of new field data and the reprocessing of industry lines.

(4) Regional consortia such as CALCRUST, and TALI have been formed to obtain seismic reflection lines in coordination with other geological and geophysical data. Funding has been on a project by project basis.

It is planned, therefore, that PASSCAL's planning process for large cooperative experiments will involve the solicitation of potential partners who can carry out the desired profiling. In some cases, routine reconnaissance work would be needed, in others, tight integration of the profiling crew with the PASSCAL array operations may be sought.

In many PASSCAL experiments, some element of reflection profiling may be implemented as a part of a larger experiment, using the array. A simple reconnaissance technique, for example, is to move a source (shots or vibrators) through an array of sensors. Reflection studies which cannot be carried out by the above-mentioned two-dimensional profiling

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† *Vibroseis* is a registered service mark of Continental Oil Co.

operations will be an important part of PASSCAL developmental field work. Among the modes of operation for which the PASSCAL array would be uniquely suited are:

(1) Three-dimensional surveys. The array is deployed once, in a grid along roads, and the source points are taken at each receiver point. For 800 instruments along crossing lines in a 40 km^2 area, 6-fold coverage of $(100\ \mathrm{m})^2$ bins can be obtained.

(2) Special explosion surveys. Recent results, including an explosion line in Australia, suggest that reflection imaging of the sub-Moho lithosphere can be done in land surveys if explosives are used as an energy source.

(3) Velocity surveys. In the context of two-dimensional profiling, this includes various field geometries which go to large offset, and which are discussed in chapters 4 and 6 of this Plan.

11.3. Marine Programs

Much of the impetus for organizing large new initiatives in continental studies has come from the realization of the successes achieved in marine geology and geophysics over the past 15 years by combining high technology with an organized scientific community. The remarkably different geological settings which typify continent and ocean and the dependence on such different logistics continue to put obstacles in the way of "unified" programs for study of the lithosphere.

Some critical areas of overlap do exist, however, and we call attention to them here.

(1) Emphasis in the studies of passive continental margins has moved into the deepest, thickest part of the sediment pile, where the Ocean Drilling Program (ODP) hopes to push back the frontier, particularly in the distal areas in deep water. Multichannel, multiship seismic reflection studies, using a variety of field geometries, such as expanding spread profiles (ESP) are aimed at more precise delineation of velocities and reflectors in the deepest parts of the pile, near the critical part of the continent-ocean transition.

(2) Many areas of crystalline continental crust lie under shallow water along the continental margins. Seismic studies of this "wet continent" have proven remarkably successful, owing to the desirable source characteristics of the marine airgun. A USGS profile on the Long Island Platform and the many reflection lines collected by the BIRPS group in the U.K. have been far more revealing of the nature of continental crust than have most of the land data.

A newly organized consortium for marine multichannel seismology, the National Oceanic Reflection Profiling Organization (NORPO), is aimed at bringing state of the art technology and adequate resources to a national capability for marine multichannel work. A liaison with PASSCAL at the science planning level would be the most workable way to plan for programs of joint interest on continental margins. In Chapter 6, we have briefly outlined a possible multiyear study across the passive margin of the U. S. east coast. A combined land-marine transect across the accretionary margin on the Washington-Oregon coast would also be of great scientific importance.

11.4. Regional Consortia

There is a clear trend toward the development of combined multi-institution research projects aimed at significant regional tectonic problems. The **CALCRUST** consortium has undertaken to combine special seismic reflection lines with geophysical profiles and geological studies to look at the regional tectonics of Southern California. The **TALI** program combines forces of the U.S. Geological Survey with a group of universities to conduct a multi-year multidisciplinary transect of Alaska. Other such consortia can be expected to arise as the normal way to organize and fund large regional programs.

This mode of organization is clearly complementary to that of PASSCAL, which is built around the capabilities of a new technology. A most natural procedure would be for certain large-scaled PASSCAL experiments to be developed in concert with a relevant regional consortium; this would involve more interested scientists in the work and provide obvious efficiencies of effort. It is our intention that the Science Planning subcommittee of PASSCAL maintain close liaison with these consortia.

11.5. U.S. Government Agency Programs

The capabilities of the PASSCAL array and the new research opportunities opened up by it suggest that many applications may exist which are of interest to government agencies other than the National Science Foundation. Our goal will be to provide government agencies the widest opportunity to participate in PASSCAL, through sponsorship of PASSCAL directly, through extramural sponsorship of scientific projects using the PASSCAL array, and through the direct participation of agency scientists in PASSCAL projects. Government scientists, acting as individual scientists, are invited to participate in the affairs of PASSCAL (Chapter 10), in committee or project matters, and are invited to participate in the plenary Annual Meeting.

11.5.1. U.S. Geological Survey

Individual scientists from the U.S. Geological Survey have taken an active role in the early stages of PASSCAL planning, and sit on the Standing Committee, as well as other subcommittees. Their participation reflects the existence in the USGS of major programs in network seismology, lithospheric tectonics, regional geology and geophysics, and earthquake studies. Continued, expanded liaison of this sort will be the most useful way to maintain close scientific collaboration between PASSCAL and USGS.

The existence in the USGS of active field programs of reflection and refraction seismology, of earthquake monitoring, and regional geophysics indicates that some formal understanding between PASSCAL and the USGS regarding the sharing of equipment, the planning of joint field programs, and the exchange and participation of individual scientists would be mutually beneficial. The array of 120 analog instruments which form the core of a strong USGS program in lithospheric refraction and reflection represents a major existing resource. Intelligent use of these instruments during the first 3 years of PASSCAL in pilot projects could be of great mutual benefit to preparing for a 1000 element array. The ongoing USGS effort in reflection profiling has acquired important lines in California, the Mississippi embayment, and the northern and southern Appalachians. It is planned to follow up initial discussions with USGS representatives this fall and draw up a memorandum of understanding regarding future USGS-PASSCAL cooperative efforts.

11.5.2. Defense Advanced Research Projects Agency (DARPA)

DARPA and the seismological community have a longstanding relationship centered around the technical problems of verifying the parameters of large underground explosions worldwide, and of distinguishing them from earthquakes. Current discussions between DARPA representatives and IRIS are focused principally on the Global Seismic Network and the Data Management Program, which have a very close parallelism with DARPA's main operational responsibilities for global monitoring.

The proposed PASSCAL instrumentation, however, provides a major increase in the capability for different kinds of research which are of importance to DARPA. The principal possibilities are:

(1) A large array, in a passive deployment, will have the capabilities associated with large fixed arrays, such as LASA and NORSAR, combined with portability.

(2) These instruments lend themselves particularly well to fundamental studies of the mechanisms of wave propagation and loss in the continental lithosphere. The ability to deploy the instruments along a long line in subarrays makes it possible to identify accurately the mode of propagation of each component of a complex wavetrain, and thereby remove the ambiguities which plague the analysis of regional earthquake phases.

(3) Reliable site calibration, using characteristic spectral functions from data observed at a single station, is a long-standing goal for the global monitoring effort. Detailed study of the site calibration process will be possible, using arrays of about 100 PASSCAL instruments with broad-band sensors. Again, the ability to use beam-steering to identify spatial modes of propagation brings about the big improvement in capability.

PASSCAL expects, therefore, to establish liaison with DARPA for the purpose of further defining areas of shared interest which are based on the 1000 element array.

11.5.3. Department of Energy (DOE)

The U. S. Department of Energy, through its Office of Basic Energy Sciences, has a major committment to the "thermal regimes" component of the Continental Scientific Drilling Program (CSDP). Under this initiative, DOE is currently funding a variety of shallow drilling projects in Long Valley, California, Valles Caldera, NM, and Salton Trough/Imperial Valley, CA. These projects are all oriented at attempting to understand the origin and evolution of volcanic hydrothermal-magmatic regions via a systematic examination of major silicic calderas. Requests for major increments in FY85-86 funding have gone forward to support anticipated drilling proposals to DOE/OBES in the near future.

The DOE, through its liaison membership on the NAS Board of Earth Sciences and Committee on Seismology, also supports in principal, generic seismological studies. In addition, specific projects related to nuclear test verification, seismometer instrument development, nuclear waste isolation, oil and gas stimulation, geothermal research, and the CSDP Program are also supported. The latter two programs have as a basic objective the understanding, through seismological techniques, of crustal and lithospheric processes related to the emplacement and evolution of high-level magmatic systems. These two programs are supported through the Division of Geothermal and Hydropower Technology and the Office of Basic Energy Sciences.

Clearly, the development of the PASSCAL instrumentation will have a significant impact on all these DOE programs. It may be anticipated, that scientific program support may become available through one or more of these offices for projects employing the PASSCAL system. Thus, DOE should be regarded as a strong supporter of the PASSCAL concept, although not as a lead agency for system development or program management. We expect to more fully define the relation between PASSCAL and DOE in meetings between agency representatives and the PASSCAL Standing Committee.

11.5.4. Nuclear Regulatory Commission

The Nuclear Regulatory Commission has a long-standing interest in obtaining detailed information about local seismicity, earthquake mechanisms, and related geological structures. The NRC, although a strong supporter of regional seismic networks, has been drawing back recently, due to the high cost of telemetry and the limits on performance of present networks. The PASSCAL array technology will permit the deployment for limited periods of time of movable networks with better capabilities than present fixed networks. Combined with active source studies, such networks may make it possible to accurately associate hypocenter locations with seismogenic crustal dislocations. It is likely that the NRC will find it economical in the long run to procure and operate standardized PASSCAL-technology instruments for longer term monitoring. While both NRC and PASSCAL are at present unable to use present technology to meet data telemetry needs at acceptable cost, the PASSCAL development effort will continue to explore the rapidly evolving possibilities of satellite telemetry, and help bring this capability to all users as quickly as possible.

11.5.5. Office of Naval Research (ONR)

The ONR has a long history of interest in the fundamental mechanisms of propagation of sound in the crust. The special capability of the PASSCAL instrumentation for studying in detail the modes of propagation in the continental lithosphere may be of particular interest to

ONR both as a demonstration of the capabilities of arrays of instruments in the band .01—50 Hz and for basic understanding of mechanisms of propagation and loss over long ranges.

11.6. Industrial Cooperation

The scientists and institutions who are involved in establishing the PASSCAL initiative have, over the years, enjoyed close relationships with the oil and gas exploration industry. This has taken the form of participation in SEG activities, in lectures and consulting at companies, in company recruiting visits, in project support from industry laboratories, and in high level grants for fellowships in the universities. The highly pluralistic nature of both the industry and university communities, combined with the very different boundary conditions under which they operate, leads to a system in which university-industry relations are dependent on a host of personal relationships built up over the years.

The overlap of interests between industry and PASSCAL is so multifaceted that we cannot begin to explore it here. The PASSCAL approach is a true hybrid between the use of networks for studies of natural sources and the use of closely spaced arrays for reflection seismology. The extension of the reflection array to the more flexible technology of separate instrument packages is now established, with the advent of various types of telemetered recording systems. The "Seismic Group Recorders" (SGR) developed by Amoco, and available commercially through licensees are similar in certain important respects to the proposed PASSCAL instruments, even though unsuitable for most PASSCAL purposes.

The full range of technical problems which are faced by the seismic reflection industry are also of concern to PASSCAL:

..engineering; source point characteristics
...data management techniques
...imaging techniques
...specialized technologies for data display and storage
...noise control techniques
...determination of velocity

The principal benefits which inhere in a close liaison with industry come from the exchange of non-proprietary information... research results, field experience, technology evaluation, and research ideas.

Participation by industry representatives goes back to the NAS Committee on Seismological Studies of the Continental Lithosphere, whose report forms the scientific charter for PASSCAL. In the preliminary PASSCAL organizational meetings during late 1983 and the first part of this year, representatives from industry have participated, particularly at the plenary meeting in Madison, Wisconsin in January, 1984. The meeting of the PASSCAL Standing Committee on 31 January — 1 February, 1984 was hosted by Western Geophysical Company in Houston. To continue these practices of open communication and participation, the Standing Committee has adopted the following policies to promote communication with industry:

(1) George McMechan has been appointed Industry Liaison Representative, and will assist the Standing Committee by maintaining a general contact list of interested individuals and companies.

(2) Ken Larner, who serves on the PASSCAL Standing Committee, is, in addition, a representative to PASSCAL from the Society of Exploration Geophysicists (SEG).

(3) Special joint workshops and meetings will be sought, both with industry groups and in connection with SEG meetings. PASSCAL can provide, as appropriate, exhibits, technical papers, and visiting lecturers to facilitate communication.

The relation of PASSCAL to industry requires special clarification in connection with the development of the instrumentation for the 1000 element portable array. At present, many of the requirements for performance of the PASSCAL array are not relevant to the preponderance of industry reflection work, either two-dimensional or three-dimensional. Consequently, available systems, such as the SGR's, lack capabilities which are part of the requirements we have set for PASSCAL. Moreover, the size of the initial market for PASSCAL instrument packages (1000) is probably too small to drive a major development cycle by vendors who specialize in industry reflection equipment. At the same time, the Instrument Development subcommittee of PASSCAL, as a part of its series of meetings on instrument definition, is planning a meeting with industry representatives for September, 1984, to define precisely their degree of interest in the PASSCAL instrumentation. (See Chapter 7 for further discussion).

12. INTERNATIONAL COOPERATION

Over the past 20 years, much of the leadership in active seismic sounding of the lithosphere has resided in Europe, where a strong international effort based on the "MARS" instruments has produced a number of important new profiles and results. The Yellowstone-Snake River Plain experiment of 1977 was made possible largely because of the cooperation of European colleagues in bringing MARS instruments to this country and participating in field work. As U. S. scientists organize PASSCAL to bring about a major jump in U. S. capability, it is critical that the international nature of these programs continue to be recognized, and that national plans for instrumentation and deployment not affect the long-term continuity of international programs in lithospheric studies.

12.1. Mechanisms of International Cooperation

The principal organ for maintaining international communication in controlled source studies is the Commission on Controlled Source Seismology (CCSS) of the International Association of Seismology and Physics of the Earth's Interior (IASPEI), which holds regular workshops in various countries. PASSCAL also plans liaison with national or multinational groups such as the European Commission on Explosion Seismology, COCRUST (Canada), and CERESIS (Andean South America). The Standing Committee will appoint a representative to the CCSS, and will work through the CCSS on matters requiring multilateral discussion. The International Commission on the Lithosphere (ICL) has a primary scientific interest in the dynamics and kinematics of lithospheric processes. PASSCAL will seek advice from ICL on field experiments and scientific studies of interest to the broad international community.

In the year past, the workshop on seismic instrumentation held at Los Altos, California, sponsored by the CCSS and co-convened by R.P. Meyer (U. Wisconsin), R.F. Mereu (U. Toronto, Canada), and J. Ansorge (Inst. of Geophysics, Switzerland), was attended by representatives from several countries other than the U.S., including Japan, England, Scotland, W.Germany, Sweden, Switzerland, and Canada. A number of real constraints make it unlikely that the next generation of instrumentation will be an international standard; the liaison through the CCSS is needed to maximize the exchange of information, and the degree of compatibility of instrumentation, and to insure that standards are developed for data exchange. PASSCAL seeks support for international workshops, on subjects both scientific and technical, to further opportunities for joint international experiments and to share information on instrumentation, on data management and on analytical techniques.

PASSCAL is establishing a Council of Foreign Associates, the members of which are invited to major PASSCAL meetings and workshops, and receive minutes and proceedings. We note also that membership on PASSCAL committees is not restricted to U.S. scientists.

12.2. International Scientific Experiments

In the long run, international cooperative experiments are inevitable since many of the most exciting areas for study lie outside the U. S. Multinational participation will be a necessity both because the experiments may take place on the territory of several countries, but will require personnel and equipment from several countries. We expect to coordinate international experiments with CCSS, the ICL, and other international organizations or agencies where appropriate. Examples of important studies which cannot be carried out on U. S. territory are:

(1) Study of a collisional orogen with deep focus earthquakes

(2) Study of certain stages of active continental rifting

(3) Study of double thickness continental crust

(4) Study of active accretion at a foreland fold-thrust belt

PASSCAL expects that a major cooperative international experiment using the 1000 instrument array could be possible early in the 1990's, and will seek discussions to define the first such effort. Already British participation in the instrumentation group has started, through collaboration with the British Geological Survey, Edinburgh office, regarding telemetering and triggering technologies. Special attention needs to be paid to maintaining communication with our Canadian colleagues, and their very active programs of crustal and lithospheric geophysics. Throughout the growth of PASSCAL, we can expect attractive opportunities for collaborative programs with Canada, and have already laid some groundwork. University of Wisconsin scientists participated at Canadian invitation in the COCRUST program in the summer of 1984, using Wisconsin's digital instruments.

13. TEN YEAR PROGRAM PLAN AND BUDGET

The ten year program plan consists essentially of a model budget, based upon the plans for the build-up and operation of PASSCAL which are described in Chapters 3—9.

13.1. Program Model

13.1.1. The Steady State Model

In the steady state, we assume that PASSCAL has attained its full complement of hardware, support facilities, and personnel. This includes 1000 seismometer packages, and adequate support in the form of support crews and vehicles, field computers (including field data management and analysis), a front end computer facility, and sensor options. The model (Figure 13-1) is based on the need for PASSCAL to support, through its array and facilities, a wide range of studies of the continental lithosphere. Priority in allocation of resources is to be given to studies which could not be done without PASSCAL resources, and which provide qualitatively new information about the continental lithosphere and mantle.

Over each one year cycle, the model allows for approximately 2 months in which nearly all array resources are dedicated to a particular large scale, intensive multi-investigator field study. These studies, which make fullest use of the PASSCAL capabilities, also place substantial demands on the time of many investigators and incur substantial costs. In a given study, it is estimated that the participating investigator groups would require two years to carry through the full cycle of preparation, data acquisition, data editing, and data analysis and interpretation. The model allows for one such study per year, as being compatible with projected numbers of investigators and with prospective available support.

Over the rest of the year, the model estimates that half of the array may be deployed in a major passive mode experiment, and most of the remainder is available for use by PASSCAL participating institutions for smaller scale studies with the latter having the higher priority. The mix of instruments used for passive mode deployments versus those used for specific investigations will vary according to the level of instrument requests from the research community. The example experiments discussed in Chapters 3—6 indicate that allocation of typically 100 instruments to a single institution is appropriate, providing excellent scientific return at an acceptable level of institutional effort.

The budget levels for the steady-state model are found in the columns for FY 1992—94 in the budget (Table 13-1). The most striking aspect of the steady-state budget is that the annual costs of maintaining the equipment pool at full strength, and of maintaining a reasonable flow of hardware enhancements nearly equal the annual costs of building the pool in the first place during FY 1987—1990.

13.1.2. Ramp-up to the Steady-state Model

An overview of the implementation schedule is given in Figure 13-2. The growth of PASSCAL will be governed by the magnitude of the instrument pool. With datalogger acquisition beginning in FY 1987 and proceeding at 200 units per year thereafter, the program will reach full size in FY 1992. Acquisition of other equipment... sensors, field computers, vehicles, and the like... will parallel this growth ramp in the datalogger pool.

PASSCAL supervisory and professional staff, not numerous in any case, will reach full strength by FY 1987. Contractor maintenance personnel and costs will ramp up through FY 1992 along with the equipment pool.

13.2. Budget Projections

A ten year budget projection for PASSCAL is given in Table 13.1. Table 13.1 is organized by Fiscal Year, with figures given in kilo-dollars. All amounts refer to uninflated FY 1985 dollars. Figures in parentheses indicate number of individual units purchased, or, in the case of

Planning model for annual use of PASSCAL array.

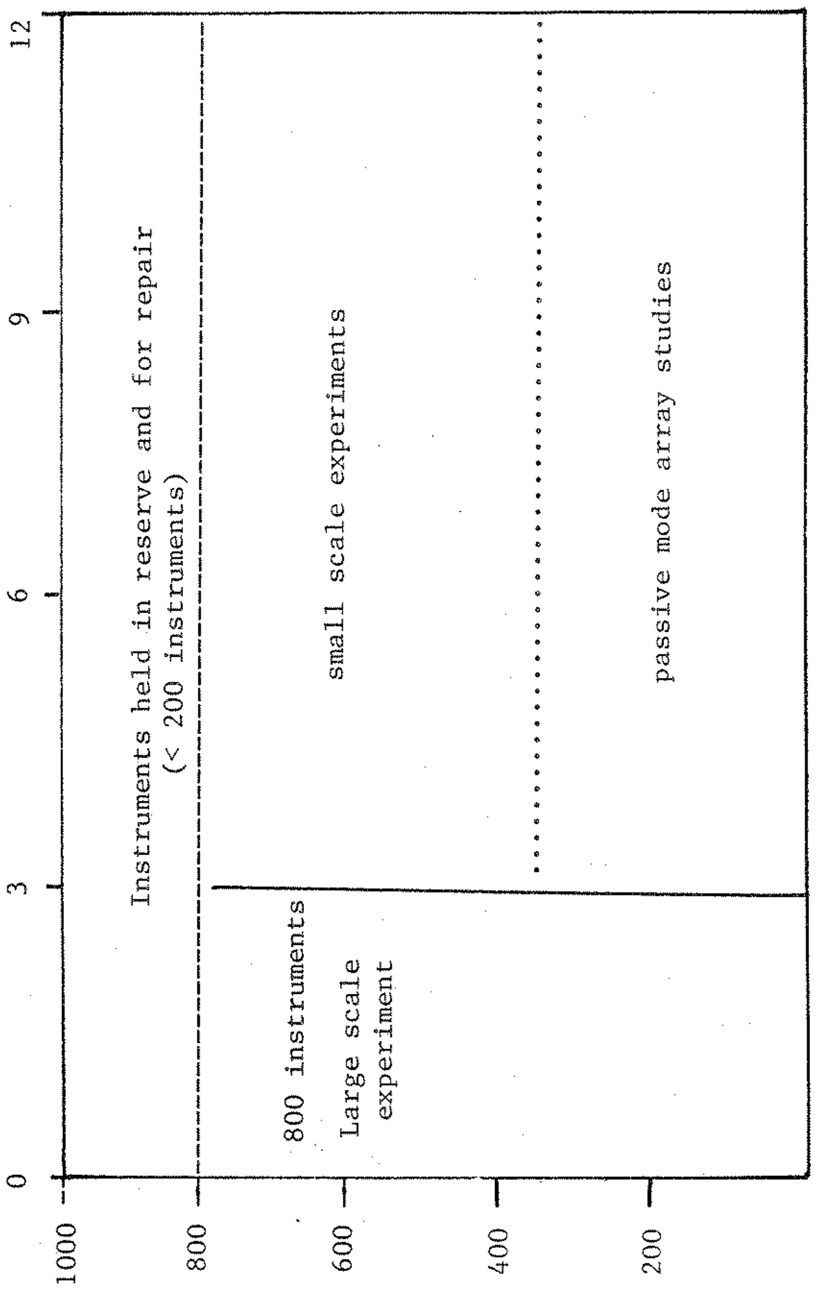

Figure 13-1

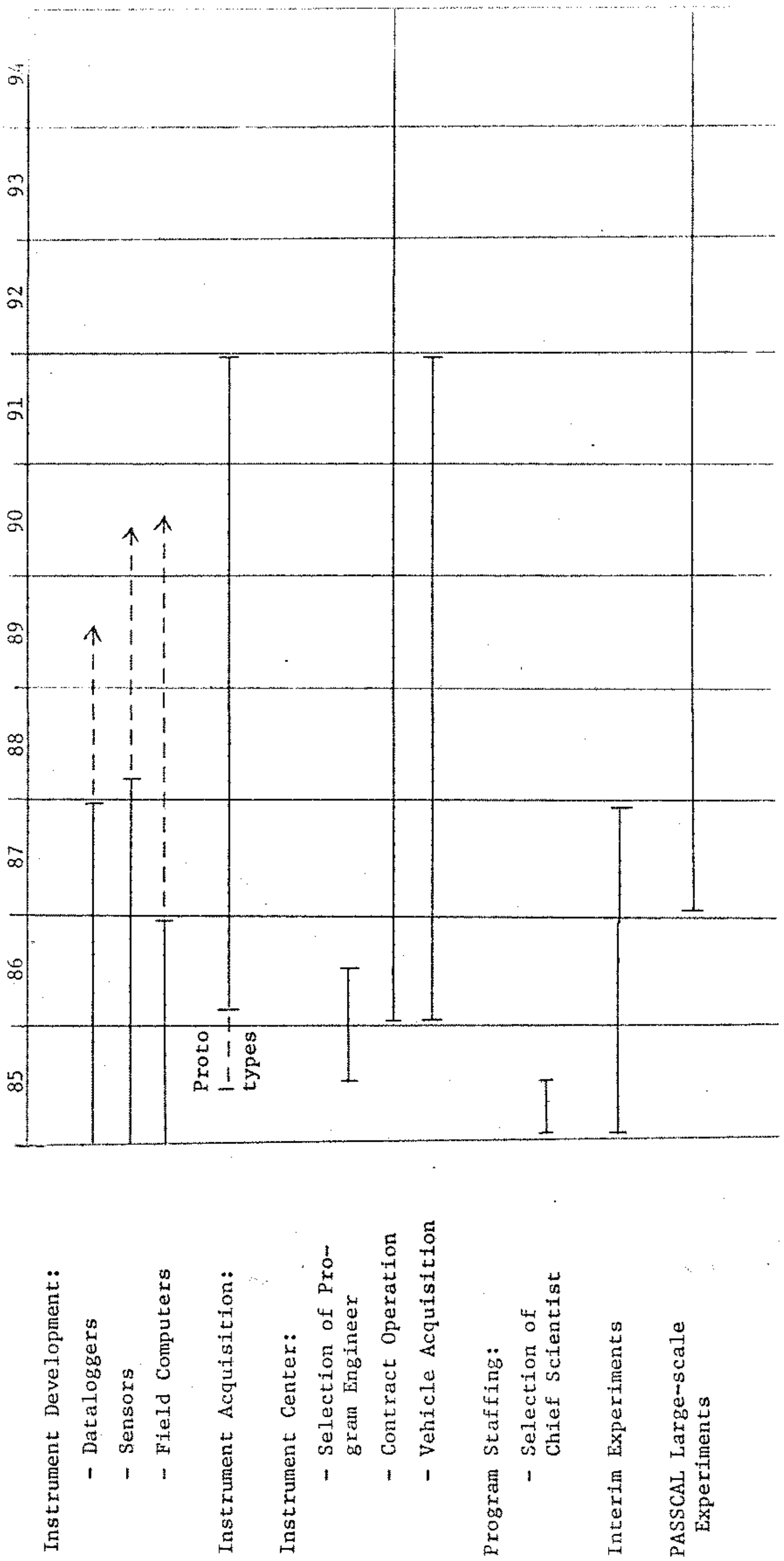
85
86
87
88
89
90
91
92
93
94
Instrument Development:
- Dataloggers
- Sensors
- Field Computers
Instrument Acquisition:
Proto types
Instrument Center:
- Selection of Program Engineer
- Contract Operation
- Vehicle Acquisition
Program Staffing:
- Selection of Chief Scientist
Interim Experiments
PASSCAL Large-scale Experiments

Figure 13-2

	FISCAL YEAR									
TASK	85	86	87	88	89	90	91	92	93	94
Instrumentation										
Seismograph (Datalogger) Development	350	200	200	100	100	100	100	100	100	100
Seismometer Development	100	200	200	100	100	100	100	100	100	100
Prototype purchase (Dataloggers)		900								
Seismometers (6/Datalogger)		480	1200	1200	1200	1200	900			
Dataloggers		750	3000	3000	3000	3000	2250			
Broad-band sensors		60	60	300	600	600	600	240		
Field Computer Development	235	200	50	50	50	50	50	50	50	50
Field Computers (1/50 instr.)	80	80	320	320	320	320	320			
GPS Receivers (1/100 instr.)			200	100	100	200	400			
Equipment Reserve against loss (10%/yr)								2730	2730	2730
Equipment Upgrades (10%/yr) (3 year log)				8	235	713	1205	1727	2259	2706
Test Vehicles (1/50 instr.)		80	160	160	160	160	120			
Deployment Vehicles (1/100 instr.)		20	40	40	40	40	20			
Vehicle maintenance, license, insurance		30	90	150	210	270	320	320	320	320
Vehicle Replacement					100	200	200	200	200	200
Instrument Vans (1/200 instr.)		22	22	22	22	22				
TOTAL	765	3022	5542	5550	6237	6975	6585	5467	5759	6206

All figures are in constant 1985 dollars x 10^3.

Table 13-1 (page 1 of 3)

	FISCAL YEAR									
TASK	85	86	87	88	89	90	91	92	93	94
Central Support Facility										
Equipment Maintenance (1%/month, total equipment)		282	856	1446	2072	2711	3247	3276	3276	3276
Fuel, Oil (15,000 mi/yr/vehicle) @ 10 mi/gallon)		6	19	32	44	57	67	67	67	67
Tractor/Truck Rental ($2000/experiment/van @ 3 experiments/yr)		6	12	18	24	30	36	36	36	36
Personnel										
Chief Engineer		45	47	50	52	55	57	60	63	66
Clerical Support		18	19	20	21	22	23	24	25	27
Logistics Officer			40	42	44	46	48	51	53	56
Software		38	40	42	44	46	48	51	53	56
Motor Pool		35	37	37	39	41	43	45	47	49
Benefits (@ 35%)		48	64	67	70	74	77	81	85	89
Office Support (xerox, comm.)		10	10	10	10	10	10	10	10	10
Space Rental										
Office @ $20/sq ft) (2000 ft^2/secretary)		40	40	40	40	40	40	40	40	40
Lab @ $20/sq ft (2000 ft^2/200 instruments		20	60	100	140	180	220	240	240	240
Garage @ $15/ft^2(80 ft^2/veh)		4	11	18	25	32	38	38	38	38
Travel										
Air Fare ($600/trip @ 5 trips/yr)		15	15	30	42	54	54	54	60	60
Car Rental ($40/day, 20 days/ trip @ 5 trips/yr)		4	8	8	12	16	16	16	16	16
Per Diem (20 days/trip @ 5 trips/ yr $50/day)		25	35	50	70	90	90	90	100	100
TOTAL	0	596	1313	2010	2749	3504	4114	4179	4209	4226

Table 13-1 (page 2 of 3)

	FISCAL YEAR									
	85	86	87	88	89	90	91	92	93	94
Management										
Chief Scientist	50	53	55	58	61	64	67	70	74	78
Clerical Support	18	19	20	21	22	23	24	25	27	28
Office Support (xerox,comm.)	8	10	10	10	10	10	10	10	10	10
Office Space Rental	40	40	40	40	40	40	40	40	40	40
Travel (10 trips/yr. @ $1000/trip)	10	10	10	10	10	10	10	10	10	10
PASSCAL (Chair., Sect., Office)	10	10	10	10	10	10	10	10	10	10
Science Planning Workshops	100	100	100	100	100	100	100	100	100	100
Travel (4 comm/10 people/ comm @ $1200/trip, 2 mtg./ yr)	96	96	96	96	96	96	96	96	96	96
TOTAL	332	337	341	345	349	353	357	362	367	372
Experiment Support Costs										
Large-scale cooperative experiment	400	700	1100	1600	2400	2400	2400	2400	2400	2400
Long-term passive deployment				250	250	250	250	250	250	250
Smaller-scale experiments... special studies	150	250	250	400	400	400	400	400	400	400
TOTAL	550	950	1350	2250	3050	3050	3050	3050	3050	3050
GRAND TOTAL	1647	4905	8546	10155	12385	13882	14106	13058	13385	13854

Table 13-1 (page 3 of 3)

travel, the number of personnel involved in the base-line travel projections. The Table includes the following major categories:

- Instrument development
- Instrument acquisition
- Equipment reserves against loss and equipment enhancements
- Vehicles
- Central Support Facility and support services operation
- Large-scale field studies
- PASSCAL Management, including operations of the Standing Committee, subcommittees and panels.

13.2.1. Instrument Development

Datalogger development is concentrated in the first three years of this program (FY 85 through FY 87) and, together with funds provided through the Phase zero proposal, is projected to cost nearly $1M. These costs apply not just to initial instrument development but to the substantial effort that is anticipated for evaluation and modification of prototypes and early production models of the instrument. For a steady-state (post FY 87) developmental program to define and specify new modules and to develop enhancements to existing ones, we have budgeted $100K/yr. Seismometer development parallels that of the datalogger, but with total estimated primary (FY 85 — FY 87) developmental costs approximately $600K. $100K/yr is provided for steady-state seismometer development (post FY 87).

Field computer and data management development, which includes hardware modifications and field testing of commercially available minicomputers and extensive software development, is expected to cost about $500K, including funds provided in Phase zero. A steady-state developmental budget of $50K/yr will provide mostly for software modifications and design of customized hardware enhancements, at least some of which will reflect future changes in the data acquisition or data transmission systems of the dataloggers.

13.2.2. Instrument Acquisition

Instrument acquisition is organized as a staged build-up over the period FY 86 through FY 91, at a rate of about 200 seismograph systems/year until a full complement of 1000 instruments is reached. Seismometers of varying type will be acquired at a rate of at least six/datalogger, to implement the full six channel capacity of the datalogger.

We estimate that 1 field computer will service 50 instruments (a basic field unit includes a two or three man crew and a complement of 50 instruments with vehicular and computer support). As mini- or microcomputers become increasingly powerful, the ratio of computers to instruments may well decrease.

The logistical requirements for obtaining highly accurate positions for hundreds or thousands of elements of a seismic array demand that Global Positioning System (GPS) receivers be utilized for instrument location. A minimum requirement will be one receiver/100 instruments, with at least one additional receiver serving as a reference point.

Costs: Costs associated with instrument acquisition are current best estimates, *expressed in constant 1985 dollars* , and will need to be updated periodically.

The first of the dataloggers will be acquired as prototypes, for which we anticipate costs to be high ($30K/unit), reflecting substantial developmental outlays by industry. Production models are projected to cost about $15K. That figure is based partly on experience with such instruments as GEOS (USGS) and partly on rule-of-thumb commercial formulas; which suggest final prices will be about three times the cost of materials.

Seismometers are to be acquired six per datalogger, at a cost of $1,000/component. In terms of the current market, this figure is low. The popular HS10s, for example, sell for about

$1800 per component; however, we anticipate that the price will be brought down substantially in response to the large numbers ordered.

Current costs of possible field computers (e.g. Masscomp, Sun, Apollo, etc.) as configured for field operations are at least $80K per unit, the figure used to calculate field computer acquisition costs; if prices come down, we prefer to augment the capability of the systems at that price level, since it is the field computer throughput limitation which constrains the whole process of data management.

We have calculated GPS receiver costs at a nominal $100K/unit; however, it is extremely difficult to project costs for GSP receivers, as the system is still in the experimental phase. The current price is about $150K/receiver, but experts familiar with GPS expect that to drop substantially over the next several years as GPS comes on line.

13.2.3. Equipment Reserves Against Loss and Equipment Enhancements

These two categories comprise the steady state support of the instrument pool. Equipment reserve against loss is calculated at 10%/year of the total instrument pool of nearly $28M. It takes effect in FY 92, after acquisition is complete. Losses incurred during the period of acquisition will be covered through a varying rate of acquisition. A loss rate of 10%/year is a conservative estimate, calculated to cover theft, vandalism, accidental breakage, and any other kinds of uninsured loss.

Equipment enhancements includes costs of adding new or modified modules to the instruments or of upgrading the instruments in other ways. Possible future enhancements might be a communication module for satellite telemetry or one for receiving GPS positioning code (so that every datalogger is automatically self-positioning). Installation of these and other enhancements as well as upgrading of the standard modules will by conservative estimate amount to at least 10%/year for the foreseeable future. Costs for equipment enhancements as presented in Table 13.1 are calculated with a built-in three year delay, so that the first request ($180K) appears in FY 89 for support of enhancements to equipment purchased in FY 86. Thereafter, funding for enhancements applies to the **equipment** instrument pool but with a three years lag time. Implicit in this formula is that instruments remain state-of-the-art for about three years, after which time they require periodic enhancements.

13.2.4. Vehicles

Acquisition of vehicles for field deployment and support of the seismograph systems parallels the staged build-up of instrumentation and concomitant growth of the Central Support Facility (CSF). Vehicles are essentially part of the CSF, but will be deployed most of the time in field operations. Three classes of vehicles have been defined:

(1) Test vehicles. These are specially equipped vehicles, the size of a large van, designed to transport field computers and all necessary maintenance hardware and electronics for support of 50 instruments. The cost of $40K/vehicle includes modification and outfitting.

(2) Deployment vehicles. These are rugged vehicles designed for rough terrain and equipped with racks for transporting seismographs in field sites. Both the test vehicles and deployment vehicles will be part of each experiment involving more than 50 or 100 instruments.

(3) Instrument vans. These are truck trailers equipped to carry large numbers of instruments (200), and which will be hauled by contract truckers to experiment sites.

13.2.5. The Central Support Facility

Development of the CSF is based on projected needs for technical and logistic support of the instrument pool during the period of equipment acquisition and later. The major cost item, equipment maintenance, is calculated simply on a standard commercial basis of 1%/month of the total value of the equipment. We are not yet prepared to translate those figures into technical staff and appropriate support facilities, but that task will be worked through over the course of the coming year.

13.2.6. Personnel

The CSF will be operated under contract (most contract costs are included under the category "Equipment Maintenance"), but will remain under the operational oversight of the Chief Engineer who is an IRIS employee. Additional IRIS employees include two programmers (for field computers and dataloggers), a logistics officer, responsible for permitting, site surveys, and the like, and a motor pool manager, responsible for seeing that vehicles are properly maintained. A nucleus for the CSF is projected to begin operation during the period covered by the FY 1986 appropriation. Funds provided in FY 85-86 are chiefly for start-up, including personnel, acquisition of equipment for the CSF, and for contract maintenance as needed with OEMs at their facilities.

Personnel costs are projected to total around $200 to $250K/yr starting in FY 86. Space requirements for laboratories and garage are calculated according to numbers of instruments and vehicles to be housed; total space rental for FY 92 and later projects to be about $300K/year. Travel costs are based on anticipated levels of participation by technical and other support personnel of the CSF in field experiments — one engineer/technician is assigned to a complement of 50 instruments during an experiment, and to 5 experiments/year of 20 days duration each. Thus, we estimate the technical personnel of the CSF will spend nearly half their working days in the field.

Annual costs associated with the CSF are projected to stabilize at about $4M after FY 92.

13.2.7. Special Data Acquisition Costs

The PASSCAL instruments are to be made available for experiments like a ship or some other large facility. Since the purpose of the instruments is data acquisition, PASSCAL includes in the budget a line which will support the experiment costs beyond those covered by providing instruments and support facilities.

Large-scale cooperative field studies: Much of the justification for PASSCAL arises from the capabilities of large arrays as they can be utilized in large-scale cooperative studies. The per-day costs associated with field operations and personnel can be substantial in the case of a large-scale experiment. A representative large-scale cooperative field study is envisioned once each year, and can be roughly characterized in terms of effort expended:

→ Duration: 2—3 months.

→ Number of instruments deployed: 900

→ Number of participating PI's: 15

→ Number of participating university personnel in the field: 50, with 15 university vehicles.

→ PASSCAL: 5 Vans, 20 test vehicles, 10 deployment vehicles, with 10 staff (see 13.2.4).

→ Sources: Natural events and an extensive blasting program.

The budget line for large-scale experiments is meant to cover incremental costs of deployment and operations only, since the budget lines for equipment, equipment maintenance, and vehicles cover equipment-related costs in an annualized fashion. These incremental costs are basically the per-day costs of an experiment. With the above parameters, we can estimate the budget requirements:

→ Per Diem and Travel expense: $400K

→ Supplemental Wages: $400K

→ Vehicle Fuel and Repairs (University vehicles): $75,000

→ Special integration costs... hardware, software, labor: $100,000

→ Drilling, blasting, permitting: $1,425,000.

→ Total: $2,400,000.

Substantial reallocation of these resources may occur in certain cases: for example $600,000 worth of contracted two-dimensional reflection profiling might be a key part of an experiment.

Major passive deployments: It is likely that at least one and perhaps many large-scale passive deployment will be a part of the experiment plan each year, with about 500 instruments being mobilized to record teleseisms and regional earthquakes. With data retrieval being required only infrequently, it is possible to run such an experiment at substantially less cost than an intensive, large-scale study using controlled sources. Nonetheless, some support will be required to insure smooth functioning of each experiment, particularly travel and logistical costs for members of the team of PI's, special integration costs, and personnel costs associated with the timely editing, sorting, and cataloging of the event data. $250K/yr is budgeted for this kind of support for large-scale passive experiments.

Special small-scale experiments: Throughout the course of the program, PASSCAL will be faced with special needs for smaller scale field studies which address various questions of methodology, such as :

comparison of sources
study of ground coupling and effect of surface layer
characterize response of well-exposed basement, for
  scattering, frequency response, etc.
intercomparison of parameter estimates from well logs,
  laboratory measurements, and local seismic surveys

In some cases, these studies may be needed to provide engineering information about the desirability of planned purchases or enhancements to the system. Often a minimum time lag between experiment definition and completion will be needed. We have, therefore budgeted $400K/yr to support about four such projects on the fundamental methodology of lithospheric seismology. Normally, the Science Planning and Coordination Committee in conjunction with the Instrumentation Committee, where appropriate, would form a working panel of participants, after announcement of opportunity to the community. In addition PASSCAL will support a limited number of small-scale experiments designed as preliminary studies to major experiments. We anticipate that these "pre"-major experiment investigations will in certain cases be a ncessary preliminary to large-scale studies in little known areas.

The figure of $400K/yr would apply from FY 1988 onward. The budget figures for FY 1985–87 are estimated to provide interim experiments using contracted commercial crews or rented instruments for a significant fraction of the effort (Chapter 14). In all cases, where monies flow from the PASSCAL data acquisition budget to universities, the support will be for the incremental cost of being involved in data acquisition. Normally, such involvement would be in addition to the normal complement of sponsored research at a university, funded through standard agency procedures.

13.2.8. Management

A fully operational management organization is projected to be in place from FY 85 onward. The three major areas of cost include the office of Chief Scientist, Science Planning workshops, and travel support for the four major PASSCAL working committees (Standing Committee, Instrumentation, Data Management, and Science Planning and Coordination). Travel for the Scheduling and Facilities Committee is provided for in the CSF Budget.

14. IMPLEMENTATION PLAN FOR FIRST TWO YEARS

During the startup of PASSCAL, two major lines of development are paramount:

(1) A **science** program of developmental experiments using arrays of available portable seismometers, to demonstrate and more fully understand the capabilities of the proposed new PASSCAL instrumentation, and to apply PASSCAL methodology at an early stage to key geological problems.

(2) A **functional** plan of program tasks, in the areas of instrument development, support facilities, and management, designed to bring a working complement of new instruments into full operation by 1987.

PASSCAL program tasks, including instrument development and acquisition, support facilities, initial experiments, data management, and science management have been defined in a general fashion throughout this document. In this chapter, we set forth the functional goals and task statements for the two year period beginning February 1, 1985. We begin with a **review** (14.1) of the program status at this time, including the tasks now being undertaken under Phase zero funding. This is followed by **summary plans** by functional area (14.2), and a **detailed breakout of tasks** for six month periods (14.3). We then discuss the **budget** and give detailed justifications (14.4).

The remainder of this chapter is devoted to the **scientific goal of a series of interim developmental experiments**, in which important geological problems are addressed with presently available resources (14.5). As an illustration of the kinds of interim studies which are possible, and to demonstrate the high degree of interest nationally in lithospheric seismology, we review a group of experiments by different groups of investigators which are targeted for the next 18 months (14.6).

For convenient reference, the proposed budget for the three fiscal years 1985—87 is extracted from the ten year budget plan (Table 13.1) and is included in this chapter as Table 14-1. The FY-85 budget figures apply to the period 1 February 1985 to 30 September 1985; FY-86 and FY-87 are for the full fiscal year, including, in the latter case, 8 months beyond the period being emphasized in this chapter.

14.1. Review of Current Program Status

14.1.1. Initial Steps: May 1983 – June 1984

This period was devoted largely to organizing the seismological community to unite behind the PASSCAL initiative, and to a series of workshops aimed at achieving an early definition of the PASSCAL instrumentation. Workshop reports are given in Appendix A.

1. The Workshop on Guidelines for Lithospheric Instrumentation, held 4—7 May, 1983, in Salt Lake City, began the process of developing a consensus in the seismological community on the functional requirements for the new generation of instruments.
2. The CCSS International Workshop in Instrumentation, held 29 November – 2 December, 1983, in Los Altos, reviewed technical characteristics of existing and planned instruments.
3. The National organizing meeting for PASSCAL, held in Madison, Wisconsin, elected a Standing Committee and other committees, and held technical discussions on instrumentation, data management, and experiment planning.
4. The Instrumentation Committee formed working panels which held meetings to define different aspects of the instrument systems. The panels have produced a series of technical reports (July 1984), giving the interim status of their deliberations.

TASK	FISCAL YEAR 85	86	87
<u>Instrumentation</u>			
Seismograph (Datalogger) Development	350	300	300
Seismometer Development	100	200	200
Prototype purchase (Dataloggers)	-	900	
Seismometers (6/Datalogger)	-	480	1200
Dataloggers ($15K/unit)	-	750	3000
Broad-band sensors		60	60
Field Computer Development	235	200	50
Field Computers (1/50 instr.)	80	80	320
GPS Receivers (1/100 instr.)	-	-	200
Equipment Reserve against loss (10%/yr)	-	-	-
Equipment Upgrades (10%/yr)	-	-	-
Test Vehicles (1/50 instr.)	-	80	160
Deployment Vehicles (1/100 instr.)	-	20	40
Vehicle maintenance, license, insurance	-	30	90
Vehicle Replacement	-	-	-
Instrument Vans (1/200 instr.)	-	22	22
TOTAL	765	2822	4452

Table 14-1. Budget: PASSCAL startup period, beginning 1 February 1985 (page 1 of 3)

TASK	FISCAL YEAR		
	85	86	87
Central Support Facility			
Equipment Maintenance (1%/month, total equipment)		282	856
Fuel,Oil (15,000 mi/yr/vehicle @ 10 mi/gallon)		6	19
Tractor/Truck Rental ($2000/experiment/van @ 3 experiments/yr)		6	12
Personnel			
Chief Engineer		45	47
Clerical Support		18	19
Logistics Officer			40
Software		38	40
Motor Pool		35	37
Benefits (@ 35%)		48	64
Office Support (xerox, comm.)		10	10
Space Rental			
Office @ $20/sq.ft. (2000 ft.^{2}/secretary)		40	40
Lab @ $20/sq.ft. (2000 ft.^{2}/200 instruments)		20	60
Garage @ $15/ft.^{2} (80 ft.^{2}/veh)		4	11
Travel			
Air Fare ($600/trip @ 5 trips/yr)		15	15
Car Rental ($40/day, 20 days/trip @ 5 trip/yr.)		4	8
Per Diem (20 days/trip @ 5 trips/yr $50/day)		25	35
TOTAL	0	596	1313

Table 14-1. (page 2 of 3)

	FISCAL YEAR		
Management	85	86	87
Chief Scientist	50	52	55
Clerical Support	18	19	20
Office Support (xerox, comm.)	8	10	10
Office Space Rental	40	40	40
Travel (10 trips/yr. @ $1000/trip)	10	10	10
PASSCAL (Chair.,Sect.,Office)	10	10	10
Science Planning Workshops	100	100	100
Travel (4 comm/10 people/comm @ $1200/trip, 2 mtg./yr)	96	96	96
TOTAL	332	337	341
Experiment Support Costs			
Large-scale experiments	400	700	1100
Small-scale experiments	150	250	250
TOTAL	550	950	1350
GRAND TOTAL	1647	4707	7456

Table 14-1. (page 3 of 3)

5. The Incorporated Research Institutions for Seismology (IRIS) was incorporated in Delaware on May 8, 1984, with 18 initial incorporating institutions. At the initial meeting of the Board of Directors of IRIS on May 13, 1984, in Cincinnati, the membership of the PASSCAL Standing Committee was duly appointed under IRIS auspices.
6. A series of open PASSCAL Committee meetings was held in Cincinnati, at the AGU meeting, to continue deliberations on data management, instrumentation, and experiment planning.

14.1.2. Phase Zero: July 1984 - Present - June 1985

The "Phase zero" PASSCAL project is an interim effort to continue program planning and instrument development during the period prior to initial funding of PASSCAL through IRIS. Phase zero is funded by the National Science Foundation through the Department of Terrestrial Magnetism, Carnegie Institution of Washington, at a budget level of $435,000 for the period July 1984 — June 1985. The principal tasks and budget lines for Phase zero are:

Instrument Design: Salaries, engineering consultants, meetings, components and hardware for testing. $235,000†

Data Management Study: Salaries, programmers, meetings. $125,000.

Planning and coordination: Coordinator part salary (D. James), office support, meetings. $75,000.

Progress in the instrument design work is reported in Chapter 7 of this Plan. The data management study, which involves the participation of J. Scheimer of Lawrence Livermore Laboratory and Carl Johnson of the U. S. Geological Survey, is discussed in the Plan and Proposal from the IRIS Data Management Standing Committee.

The requested funding and list of tasks for the initial IRIS/PASSCAL period, February 1985 — January 1987, does not duplicate tasks which are funded under Phase zero for the first half of 1985. Details are found in the the next section.

14.2. Task Summary by Functional Area

14.2.1. Program Management

The PASSCAL Standing Committee is the governing body for PASSCAL. Its responsibilities include oversight and support for scientific, technical, managerial, and organizational activities of PASSCAL. To support these activities funds are requested for the following:

→ Workshops for Science and Technical Planning. These workshops are primarily for planning & evaluation of proposed large-scale experiments and serve as a direct means of involving the interested scientific community in experiment planning. Workshop proceedings will be particularly important in the early phases of PASSCAL where the strategy for large multi-institutional experiments remains to be developed. Workshops which will be supported in the first two years include ones for planning experiments which can be done with existing instruments. Workshops are also expected to serve as a focus for planning of international experiments or as international forums for exchange of technical information on instrumentation. The first of these workshops will be held in December, 1984, as a part of the Phase zero activities of PASSCAL.

→ Travel for members of PASSCAL working committees and panels. We estimate travel expenditures based on two meetings per year for the four working committees, each of which is comprised of 10 members. One of the most crucial needs of these early years is to maintain community-wide communication and participation, a need fulfilled in large part by broad-based membership in active working committees.

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† The instrument design activities are funded out of NSF funds programmed for use in projects with industry participation.

→ Office of the PASSCAL Standing Committee Chairman. Modest funds ($10K) are requested to defray clerical and office costs associated with the official duties of the PASSCAL Chairman.

14.2.2. Search for Chief Scientist

An immediate task of the PASSCAL Standing Committee is to hire a Chief Scientist, whose charge it will be to serve as overall manager of PASSCAL (see 13.3.1). The Standing Committee proposes to select a Chief Scientist and establish an appropriate office by no later than mid-spring, 1985. This step is essential to the coherent operation of PASSCAL. At present, those tasks which properly fall under the purview of a Chief Scientist are distributed in an informal way between members of the Standing Committee and the Program Coordinator and Standing Committee Secretary (D. James). Under the plan proposed here, these distributed activities will be formalized and merged into the office of Chief Scientist. Funds for salary, clerical support, office space, and travel are requested for the Chief Scientist starting in FY 85.

14.2.3. Instrumentation

14.2.3.1. Dataloggers

The philosophy and background on development of dataloggers and sensors are contained in Chapter 7. The major task of the instrument design team continues to be the design of a communications bus. The cost of that development is only partially covered by the Phase zero proposal. Detailed proposals to implement particular bus architectures have only just been completed. The design committee has decided to proceed with the bus proposed by the working group headed by Pierce and Dearborn of UCLA. Full implementation of the bus design will require about $150K in addition to what has been budgeted in phase zero (see appended July, 1984, report of the instrument design team (reference S, Appendix A)). Included in that sum is salary support for Pierce and Dearborn (both of whom are on soft money), and some additional hardware and software costs of constructing prototype systems to be supplied to manufacturers for module testing.

Funds are requested in FY 85 for development of a phase-lock Omega receiver with absolute timing accuracy of 10 μsec. The receiver will be part of the timing module. At the time the Phase zero proposal was submitted, unconfirmed reports suggested that such a timing module was commercially available in Europe at a very low price. Subsequent investigation showed that the module does not exist at any price; consequently, Powell (U. Wisconsin) has begun to design and build a prototype receiver. Total time of development is estimated to be about a year at a cost of at least $50K.

Full module and bus specifications are to be completed by March or April, 1985. RFP's will be issued for bids to construct prototypes. The nonindustry members of the instrumentation committee in consultation with a special panel of outside reviewers will select three companies to construct 10 prototypes each (30 prototypes total) at an estimated cost of $30K/unit.

Delivery of prototypes is scheduled for late fall or early winter of 1985, and will be followed by a 6 month period of testing, evaluation, and modification. Laboratory testing will be done by members of the instrumentation group. We propose that field testing be done at least partially under realistic conditions of actual field experiments. We expect to include the prototypes in one or more of the interim experiments, but final planning will depend upon actual delivery schedules for the prototypes.

We expect production of instruments to begin in spring, 1986, perhaps in time for some to be incorporated in the fall, 1986, interim experiments. We are requesting funds to be allocated in FY 86 to purchase 100 dataloggers with seismometers.

14.2.3.2. Sensors

The program for sensor development has been described in detail in Chapter 7. The nucleus of a sensor design group has already begun work on an evaluation of existing sensors as preparatory to designing a long-period, broad-band portable sensor. Part of that evaluation will involve the measurement of amplitude and phase response of existing commercial instruments. J. Steim (Harvard) has the primary task of carrying out the technical research at DTM (Carnegie) in collaboration with S. Sacks (DTM), E. Wielandt (Zurich) and O.D. Starkey (Teledyne/Geotech). The work at present is focused on the broad-band sensor and is supported by Carnegie seed money which will be exhausted July 1, 1985. We expect the developmental phase of the broad-band sensor studies to continue, involving about 6 months/yr each for J. Steim and E. Wielandt over a period of at least two more years. We are requesting $100K/yr in FY 85 and $200K in FY 86 for sensor development, to continue the work already begun.

A second task of the sensor design group is to develop a reliable light weight "standard" (1 Hz) seismometer. As part of the sensor evaluation already under way, the design group proposes to determine if existing sensors can be modified to make them more portable or if some of the new force balance or other innovative light-weight sensors are suitable for PASSCAL studies.

The two year budget calls for purchase of 6 "standard" seismometers to accompany each of the 30 prototype instruments purchased. No decision will be made on make of sensor until after a trial period of testing and evaluation, but the instruments are expected to cost, even by conservative estimate, at least $1K/ component, possibly twice that. We are also requesting funds for purchase of 2 Wielandt 3-component broad-band permanent seismometers ($10K/component) which will be used for a number of testing and evaluation procedures involving the new data logger.

14.2.4. Support Services and Facilities

14.2.4.1. Field Computers and Field Data Management

With the proliferation of powerful, compact minicomputers it is already apparent that there will be a large number of alternative hardware solutions to the field computer problem. The strategy we propose here is to initiate an evaluation of existing and potential hardware systems. A panel on field computers, chaired by Gary Pavlis, has been created to perform that evaluation and to make recommendations to the Data Management subcommittee concerning specific hardware configurations.

At least two field computer prototypes in the process of development: one by the University of Wisconsin and the other jointly by Lawrence Livermore and Lawrence Berkeley Laboratories.

The system under evaluation by Wisconsin consists of a 68000 (32 bit) based Masscomp computer with 2 Mbytes of memory, a 440 Mbyte Fujitsu Winchester disk drive, and a graphics workstation with color monitors and a small Versatec plotter. Special hardware has been added to read field tapes into memory. The software, which will soon include the SAC package Scheimer and Johnson are merging for the PASSCAL prototype data center (see Phase zero and DMC documents), produces record sections, event tapes, and does other routine operations such as automatic picking and spectral analysis. The total cost of the system is about $80K. Though the system is complete, it cannot yet be used for field testing because the Wisconsin Geophysics department does not own the CPU. We are requesting $60K for that hardware acquisition so that field testing can begin.

The Wisconsin field computer system is expected to undergo several months of realistic field evaluation. The 15 Wisconsin portable seismograph units are well suited to a prototype testing operation, as they are triggered and programmed multichannel instruments capable of providing large amounts of earthquake data essential to evaluate the data flow capability of the computer and prototype software for data handling.

The joint LLL-LBL field computer is also a 68000 based 32-bit work station with a capacity in the range of a VAX750 to VAX780. One version of the field computer is already being used both for field operations and to implement the prototype data center, initial funds for which are already provided for Scheimer and Johnson out of Phase zero. Additional funds for the PASSCAL data management program are being requested under the DMC portion of this report. The Scheimer/Johnson effort also entails substantial amounts of software development. A second version of the field computer is planned by LLL and LBL for truck installation sometime around January, 1985. That system, too, will allow a comparison to be made between motel-based and truck mounted field computer operation. The LLL and LBL computers are already scheduled for use in controlled source experiments (the Long Valley experiment, Section 14.6). The results of field computers in those experiments will complement those from the natural and controlled source experiments of Meyer. The field computers will also be used in the experiments designed to test the prototype dataloggers, expected in late 1985 or early 1986.

The panel on field computers also has responsibility for making recommendations in areas other than computer hardware, including:

- software requirements
- number of instruments/computer
- customized hardware, such as multiple tape readers
- special vehicle requirements

We are requesting $10K in travel for support of the 4 member panel ($800/person/trip) to meet three times a year. Both that sum and the $60K for the Wisconsin hardware acquisition are included as part of the $235K for field computer development in FY 85.

Software development for the field computers will be a major task during FY 85 and 86 ($200K/yr), and will be overseen by the panel on field computers. Funds are requested to purchase 1 field computer in late FY 85, and one in FY 86 for software development and field testing. We estimate computer costs at $80K/ea. including hardware modification for field applications. Salary for two programmers is budgeted, to begin late in FY 1985. Present projections call for 1 field computer/50 seismic units. That estimate may be revised up or down when results of the fields tests are known.

14.2.4.2. Central Support Facility

The Central Support Facility (CSF) is expected to come into existence in FY 86. Plans for that facility and appropriate RFPs will be the responsibility of the Instrumentation and Scheduling and Facilities committees in conjunction with the Chief Engineer and Chief Scientist.

The Facility will begin full operation, including vehicles, in FY 86, in preparation for receiving, testing, and maintaining the first complement of 50 production seismograph units, field computers, and GPS receivers. We have chosen to calculate costs of technical personnel (apart from the Chief Engineer and Logistics Officer), testing equipment, electronic components, etc. under a general category of instrument maintenance, calculated on a basis of 1%/month of the value of the instruments. This complement of technical personnel will also be involved as support staff during data acquisition activities. To the extent possible, the operations of the CSF will be handled by a contractor.

Associated with the CSF will be a number of vehicles for the transportation and field support of the seismographs and field computers. First acquisition of such vehicles will be in FY 86 when the instrument center begins operation. The support of these vehicles will require a mechanic to manage the motor pool, and funds for that purpose are included in FY 86 budget.

The logistics officer included in the detailed budget for FY 86 is responsible for land permitting, site surveying, and other logistical tasks associated with the large-scale experiments.

14.2.5. Data Management

The data management development begun by Scheimer and Johnson (see, also, Field Computers, above) for PASSCAL are expected to continue during the ramp-up phase of both the experiment planning and the data center. A budget and specific plan is included with the DMC report.

14.2.6. Planning and Execution of Interim Experiments

In Section 14.5 we present a rationale for early and continuing experiments in Lithospheric Seismology during the PASSCAL start-up period. Consequently, the budget line in the long-term Plan for the support of data acquisition (experiment) costs of the large-scale cooperative experiments should begin immediately, with plans for interim cooperative experiments in late FY 1985 and late FY 1986. Additional data acquisition costs are budgeted for smaller field studies which are keyed to specific methodological problems, and which can be carried out with available instruments.

We have discussed experiment planning under 14.2.1 (management), and will be working actively with the Science Planning and Coordination Committee (SPCC) (Figure 10-1(b)) to begin the annual process of defining and planning for the initial PASSCAL field studies. The co-chairs of the SPCC, Bill Ellsworth and Larry Braile, plan to present a request to the seismological community in early fall, 1984 for informal, but thought-out proposals for interim experiments. At an open workshop at the western AGU, in December, the SPCC will try to develop a list of options for the FY 1985 and 1986 experiments, and to form teams of participants. Final selection of the FY 1985 experiments is planned by January 31, 1985.

The plan for interim experiments runs for three fiscal years. In each year, we plan about four small-scale experiments which will be aimed at sorting out problems of methodology and field practice. These experiments would use available recording systems and be conducted by individual PI's. The preliminary plan for large-scale interim experiments is as follows:

FY-1985 One six (6) week experiment using dynamite and 200 commercially contracted group recorders, in September, 1985.

FY-1986 One four (4) week experiment using dynamite and 400 commercially contracted group recorders, along with prototype PASSCAL instruments, in late summer, 1986. Also, one experiment using borrowed USGS analog recorders (100) in conjunction with prototype PASSCAL instruments.

FY-1987 One six (6) week experiment using dynamite and 400 commercially contracted group recorders, along with an initial complement of PASSCAL instruments, in summer, 1987. Also, one experiment using borrowed USGS analog recorders (100) along with newly available PASSCAL instruments.

14.3. PASSCAL Implementation: Two Year Timeline by Six Month Periods (Exclusive of Experiment Planning)

The requirement that all of the IRIS initiatives be coordinated and presented in a single proposal means these words are being written less than one month after the start of the one year Phase zero proposal, during the course of which specific timelines by task were to be developed. Many task definitions at this time remain incomplete and some target dates and costs, particularly those pertaining to prototype development, are necessarily imprecise.

PASSCAL implementation, summarized in six month increments below, is an amplification of the first two years of the ten year timeline and budget plans presented in Sections 13.3 and 13.4. This two year timeline for implementation serves as the basis for the budget explanation presented in Section 15.3 below.

14.3.1. 6-Month Period 2/1/85 — 8/1/85

14.3.1.1. Program Management

- Appointment of Chief Scientist, late winter 1984 or early spring, 1985.

- Scheduling and Facilities subcommittee appointed by PASSCAL Standing Committee to collaborate with Chief Scientist and instrumentation committee in defining location, hardware, and personnel requirements for Central Support Facility.

- Science and technical workshops begin for comprehensive planning of interim experiments, 1985 and 1986, and for supplemental input to instrumentation development. Workshop RFP's will be issued in fall, 1984.

- Initiate publication of a regular newsletter.

- Preparation and review of revised science and management plan, with budget, for FY 1986.

14.3.1.2. Instrumentation

- Conclude work on implementing communications bus, as begun under Phase zero. (Pierce and Dearborn, UCLA)

- Release of hardware and software bus specifications and engineering specifications for functional modules described in Chapter 7.

- RFP's to industry to build 30 prototype dataloggers.

- Conclude development of Omega phase-lock timing system with absolute accuracy of 10 msec. (Joint effort, Depts. of Geophysics and Meteorology, U. Wisc.)

- Broad-band sensor development under Steim, Sacks, and Wielandt, with industry collaboration. (Sacks, Stein, Wielandt, CIW)

- Testing and evaluation of commercially available portable seismometers. Collaboration begins with industry to implement desirable modifications.

- Field computer prototype testing and evaluation (Pavlis panel). (U. Wisc. and LLL field testing)

14.3.1.3. Data Management

- Evaluation of the Scheimer/Johnson and U.Wisconsin prototype data centers, funded under Phase zero, as applied to existing and Long Valley experiment data sets.

- Cataloguing and distribution of information on existing analytical software, compiled under Phase zero.

14.3.2. 6-Month Period 8/1/85 — 2/1/86

- Search committee nominates candidates for Program Engineer and Logistics Officer. Program Engineer appointment effective Oct. 1, 1985; Logistics Officer effective Feb. 1, 1986.

- Second round of workshops for 1986 and 1987 interim experiments.

- RFP issued for Central Support Facility following publication of requirements.

- Interim space rental for Program Engineer and clerical support staff.

14.3.2.1. Instrumentation

- Purchase of 30 datalogger prototypes.

- Purchase of 180 "standard" seismometers.

- Laboratory and field testing of datalogger prototypes. Collaboration with industry to implement modifications, and with Scheduling and Facilities committee to incorporate instruments in planned interim experiments.

- Initiate study of light weight portable sensors of non-standard design.

- Laboratory construction and testing of components for a very long-period portable sensor (response to 100 sec).

- Purchase of a field computer, for installation at the Central Support Facility for the purpose of fulltime software development.

14.3.2.2. Data Management

- Programmer hired (FY 86) to develop field computer software.

- Evaluation and grading of field computer operations by LLL/LBL and University of Wisconsin, carried out as part of summer, 1985 interim experiments. (Pavlis panel)

- Evaluation and grading of prototype data center based on summer, 1985, interim experiment. Evaluation by DMC Standing Committee and PASSCAL Data Management Subcommittee.

14.3.3. 6-Month Period 2/1/86 — 8/1/86

- Contract(s) let for purchase of first 100 production dataloggers.

- Contract let for Central Support Facility.

- Appointment of Logistics Officer effective 2/1/86.

- Preparation of submittal of FY 87 proposal with budget.

- Appointment of motor pool manager.

14.3.3.1. Instrumentation

- Purchase and testing of 1 GPS receiver, for both positioning and timing.

- Purchase of field computer (twin to computer already purchased for Instrument or Data Center software development) for 1986 field experiments.

- RFP's for manufacture of seismometer (probably force balance) with response to 20 second period.

- Contracted Central Support Facility start-up (with lead-time at least three months before delivery of first 100 instruments).

  * Purchase of testing hardware and software for Central Support Facility.
  * Purchase and outfitting of two instrument support vehicles.
  * Purchase of one deployment vehicle.
  * Purchase of one instrument van.

- Continuing (thru 2/1/87) development of ultra long period (100 sec) portable seismometer and light weight 1 Hz sensors.

- Evaluation and continued testing of production dataloggers (thru Jan., 1987).

14.3.3.2. Data Management and Computation

- Data Center operations under supervision of Standing Committee on Data Management.

- Software development for field computer deployment in summer, 1986, field experiment.

- Appointment of PASSCAL Panel to assess long-term needs for supercomputer facility.

14.3.4. 6-Month Period 8/1/86 — 2/1/87

14.3.4.1. Management

- Workshops, 1987 and 1988 multi-institutional experiments.
- Contract(s) let for purchase of FY 87 complement of 200 dataloggers.

14.3.4.2. Instrumentation

- Manufacture of prototype 20 sec portable seismometers (two 3-component sets) for field evaluation.
- Advanced instrument development, including new and enhanced datalogger modules, and modification of early production modules.

14.4. Discussion of Budget

The bulk of the first year (FY 85) budget is allocated for instrument and field computer development, and for science planning and management. FY 86 marks the start of instrument acquisition with the purchase of 30 prototype dataloggers, and the concomitant start-up of maintenance and support facilities.

14.4.1. Instrument Development.

Instrument development remains under the direction of the 15 member Instrument Design Team, a subgroup of the PASSCAL Instrumentation Committee (see Section 7.1) and is currently supported under Phase zero. Of the total of $350K budgeted for datalogger development in FY 85, $150K is dedicated specifically to completing the large and fundamental task of designing the system bus architecture (UCLA subcontract). The bus project is currently the full time task of D. Pierce and D. Dearborn of UCLA who are already committed to devoting 10 man months to the development under Phase zero. An additional 12 man months are necessary to complete development of the communications bus.

Additional base-line support of $150K for the instrument design team is requested for travel expenses and consultant services. Most of these expenses will be incurred in connection with contracting for and subsequent testing and modification of prototype dataloggers. Costs for those tasks will be determined over the next few months as the deliberations of the Instrument Design Team take the form of concrete recommendations. A comprehensive budget will be submitted, if necessary, in late 1984 as an addendum to this proposal.

Work has already begun to develop an Omega timing module (accurate to 10 μsec) by Meyer and Powell and colleagues in the Department of Meteorology at the University of Wisconsin. We are requesting $50K (see accompanying subcontract) to complete development of the Omega timing system.

Sensor development is currently being supported by CIW ($50K) for one year (through June, 1985). There are also very limited funds for sensor hardware ($5K) in Phase zero. Present sensor research by Steim, Wielandt, Sacks and Starkey (see Section 7.2) are directed primarily at development of a long period portable sensor. Additional tasks, related chiefly to developing a rugged light-weight portable "standard" seismometer, will be undertaken in the near future. We are requesting $200K/year for both long-period and light-weight sensor development.

Included in the FY 86 request are funds to purchase two 3-component Wielandt long-period seismometers (permanent installation). These seismometers will be installed and used for developing and testing the long-period features of the datalogger. The datalogger is specified to operate to periods of 100 sec or more and utilizes special filtering and decimation processes for long-period data. The Wielandt instruments give a well defined broad-band long-period output for examining and testing the low frequency operating end of the datalogger system. In addition, the Wielandt instruments will function as the nucleus of a permanent "standardized" facility dedicated in part to long-term datalogger and sensor development and evaluation.

14.4.2. Prototypes

The definition of formal PASSCAL policy vis-a-vis equipment vendors is still in the formative stages; procedures for requesting and evaluating proposals and letting of contracts remain to be implemented and documented through IRIS. In the absence of a formalized set of procedures, costs of prototypes have been estimated nominally to be double the projected cost of production models, with this estimate ($30K/unit) subject to substantial future adjustment. Funds are requested in FY 86 for 30 complete prototype systems, at a total (estimated) cost of $900K. Manufacture of prototypes is expected to involve at least three companies, each of which will produce all or part of 10 dataloggers.

14.4.3. Instrument Acquisition

Acquisition of production instruments begins in late FY 86. The plan for a staged buildup of resources over a 6 year period is contained in Section 13.4. For FY 86, funds are requested to purchase 100 dataloggers ($15,000/unit), 600 seismometers ($1000/unit), two additional field computers ($80K/unit), and the first two GPS receivers ($100K/unit). The basis for the cost estimates given here for this equipment is presented in more detail in the subsection on Instrument Acquisition in Section 14.4.

14.4.4. Central Support Facility (CSF)

Funds are requested in FY 86 to support the start-up phase of the Central Support Facility. Included in that request are funds to support a Program Engineer, a secretary, and a computer programmer. Facilities consist only of office space. In the first year of the program, "equipment maintenance," at least for dataloggers, will be handled through contract with the manufacturers. Maintenance (FY 86) is calculated using a standard commercial formula of 1%/month of the total value of the equipment.

The basic justification and costing formulas for the instrument center (including vehicles) and its various activities are given in Section 13.2.

14.4.5. Management

About $125K/year, starting in FY85, is required for the office of Chief Scientist. Included in that figure is a (nominal) $50K/yr salary for the Chief Scientist, $18K/yr for secretarial support, about $50K/yr for space rental and office facilities, and $10K for travel.

An additional $10K/yr is requested to defray office expenses of the Chairman of the PASSCAL Standing Committee.

PASSCAL support of science planning workshops is a key part of the PASSCAL program and a major link between PASSCAL support facilities and hardware and the scientific community. The early workshops (FY 85 and 86), especially, must be well supported to assure the articulation of a sound scientific and technical program. The total cost for workshops is calculated on a basis of 5—10 workshops/year at a cost of $10—20K/workshop.

Finally, travel funds of $96K/yr to support the work of the PASSCAL committees — Instrumentation, Scheduling and Facilities, Science Planning and Coordination, and Data Management — are included in this request. Travel costs are estimated on the basis of 2 meetings/year for each committee, 10 people/committee. This estimate is a conservative one, for included within the committee structure are numerous panels which will also require travel support.

14.4.6. Interim experiments

Cost figures for the interim experiments are highly preliminary, since the experiments will not be defined until after December, 1984. We use a model in which seismic group recorders (SGR) and full shooting and data preprocessing are contracted for the large-scale studies. While this is the most expensive technology, it is far closer to the planned PASSCAL array in number of instruments and portability than anything else available; moreover, we have recent quotations as a basis for cost estimation.

As a model for three years of interim experiments, we propose:

FY 1985 (1) A cooperative experiment, requiring a 200-instrument SGR crew for 6 weeks, at cost from Amoco in addition to available instruments from the research community: $400K.

(2) Smaller-scale studies using existing instruments, particularly triggered instruments, but also the USGS complement of 120 matched analog instruments: $150K.

FY 1986 (1) A major cooperative experiment, again using SGR's on loan and other available university instrumentation: $700K. August, 1986.

(2) Smaller-scale studies, as for FY 1985: $250K.

FY 1987 (1) A large cooperative experiment utilizing SGR's and the first complement of PASSCAL instruments: $1.1M. July, 1986.

(2) Smaller scale studies for FY 1987 will be the first serious round of deployment of PASSCAL instruments, and will be especially important as demonstration experiments and for the experience gained. $250K.

The mix of experiments using SGR's and experiments run by university investigators with available university or USGS instruments is planned to meet two goals which are not totally compatible during the interim period. The SGR studies will provide data having some important characteristics of data from a controlled source experiment with the PASSCAL instruments... large number of matched channels, adequate subsurface coverage to invert for three-dimensional structure. The other studies are needed to provide the seismological community with suitable experience in data acquisition.

The interim experiments should also be designed to evaluate technical and engineering needs associated with deployment of a large array. Some of these include:

1. Triggering schemes for recording local and distant earthquakes, particularly their relative reliability from instrument to instrument across arrays.
2. Evaluation of radio command, master/slave telemetering, and other mechanisms for simultaneous instrument turn-on.
3. Testing of alternative timing and phase-lock systems.
4. Effectiveness and properties of various sources, controlled and natural, for attacking specific problems.
5. The effects of alias filters under certain experimental conditions, particularly in noisy environments.

Prototype experiments well be needed to test the functional and interface requirements for the PASSCAL system. All experiments include the following functions:

- Planning, proposing, and scheduling
- Instrument preparation and maintenance
- Field data acquisition
- Data management
- Analysis and publication

Efficient operation therefore requires clear specification of each function and the interfaces between them. For small experiments (around 50 instruments), the implementation of these functions and interfaces may be reasonably familiar and executed almost entirely by one institution. Large experiments will involve an unfamiliar, complex system of many institutions and disciplines, involving instrument preparation and maintenance from the PASSCAL Central Support Facility (CSF), software and hardware support from the PASSCAL field computer and data management system, the IRIS Data Center, and the resources of the Principal Investigators' universities.

With the above functional groupings we can begin to explore the interface requirements. This process probably begins with asking questions about "what" and "how". How does an investigator learn the capability of the field acquisition and instrumentation systems provided by PASSCAL? How can one reconfigure the instruments for special purposes without impinging on simultaneous investigations? How can one be involved in developing and implementing new ideas for the instruments? How can one learn the capabilities of the IRIS Data Center and assist in their development? What mechanism can assure that all services can be extended to cover new requirements in the future? What are the specific responsibilities of the investigator to the PASSCAL supporting services? What media and formats are required to interchange data with the IRIS Data Center? How can the catalogs, media, and formats available from the Data Center be made to serve the needs of PASSCAL investigators? What communications are required between the field instrument and computer sites of a large experiment, and the field control center, the CSF, and the IRIS Data Center? What data streams must pass to and from the instruments to produce an efficient, understandable, managable system? The answers to these questions will have an impact on the functional specifications of the system, including the field recording instrument, yet many of the questions will require prototyping and testing under real circumstances.

A great deal of attention has already been given to the instrument and the details of some of its components. This exercise was a way of evaluating "what can be done" in terms of the feasibility of meeting various specifications. However, it results in specifications based more on what kind of IC chips are available than on the scientific and system requirements. Determining these requirements is very complex, and, like most PASSCAL problems, is not expected to have a static solution. It is clearly necessary to begin with prototype experiments that exercise the functions listed above and the interfaces between them. For example, if we recommend that Rosscomp tapes, which are expected to be the highest-capacity media used in the field, be added to current playback facilities, then interchange with the IRIS Data Center can begin, and we can evaluate media and refine formats at high levels before the large PASSCAL array makes extraordinary demands on young facilities. We suggest further that trial data sets should be taken and should contain the expected mix of natural-event and artificial-source data, involving refraction, reflection, surface wave, and teleseismic recording. This will require separation of the data from the various disciplines and result in critiques and linkages between investigators. In short, real experiments should be performed with a mix of existing instruments, which in toto approach the multiple capabilities expected of the PASSCAL instrument. This will reveal both the strengths and weaknesses of the proposed systems and clarify their functional and interface requirements.

Thus, we propose experiments within the first two years that test and exercise the functional and interrelational aspects of the entire PASSCAL and IRIS system, with representative data sets using natural and controlled sources. Three examples follow:

1 Collection of substantial amounts of continuous digital data in several areas of geologic significance, including areas of current earthquake activity, to form a broad-band data set for laboratory testing of PASSCAL instrument prototypes.

2 Collection of prototype multifaceted data using instruments currently available that in toto approach the capabilities of the PASSCAL instrument. For example, we must establish the system requirements for using local earthquakes as sources for profiling and three-dimensional studies, including the tomography deployments. With existing instruments, we can provide earthquake locations with a small number of instruments in active volumes, and profile with sufficient sensor density to result in unaliased two-dimensional profile data. Sufficient instruments to do this exist if we employ six-element data loggers in a linear array, which will be one of the basing modes for the PASSCAL instrument.

3 With existing instruments, we can prototype local arrays with data telemetered to a central computer. In reasonable circumstances, these data can then be used to decide in real time whether a suitable local earthquake has occurred. If so, the computer can use radio to activate a much larger array made up of seismic group recorders (SGR's) or, more

typically, of the PASSCAL-like instruments. The latter have delay memory and independent timing, so that the recording decision need not be made so fast. The SGR's, without delay memory, require a more rapid decision and response from the computer and more rapid turn-on than the PASSCAL-like instruments.

14.5. Scientific Goals for the 1985-87 Period

The main scientific goal of PASSCAL for its first two or three years is to conduct a series of cooperative studies of the lithosphere using existing instruments, with particular emphasis on triggered systems and matched instrument sets, including SGR's. These studies are to serve as demonstrations of the power of the newer methods of lithospheric imaging, of the complementary relationship of the methods to reconnaissance reflection profiling, of the ways in which data management can be successfully undertaken, and of how diverse, complementary data sets can be jointly interpreted. They will also provide PASSCAL with a baseline of practical experience in the most cost-effective ways of bringing resources to bear from those available in industry and universities.

These interim experiments are to be planned particularly for their geological value: a demonstration,, in this case, to geologists and tectonophysicists of the importance to earth science as a whole of an ability to study the lithosphere at high resolution.

The interim experiments will involve from 100 to perhaps 200 instruments or more. Available instruments fall into two broad categories. The first group includes triggered digital dataloggers, the predecessors to the PASSCAL instruments, which are available in relatively small numbers from universities and (possibly) from the USGS. These instruments are a critical component of the interim experiments. In addition, available instruments include 120 matched analog instruments owned by the U. S. Geological Survey, a number of digital instruments owned by academic institutions, a few 48 or 96-channel reflection trucks owned by academic institutions, and commercial crews 200 seismic group recorders.† The interim experiments will exploit the combination of closely spaced arrays with extensive use of explosives as a controlled source. Until the PASSCAL instruments are on-line, it will not generally be possible to collect sufficient data using natural sources alone. Explosives can provide a substantial enhancement in signal to noise ratio over vibrator signals, particularly at offsets beyond 20 km, and their use permits us to penetrate the lower crust and upper mantle more effectively.

Several significant benefits are envisioned from these field efforts. First, it is important to keep extending field acquisition techniques, data management techniques, and data analysis methods using available instruments during this stage so that maximum and timely advantage can be made of the new PASSCAL instrumentation. Second, there exist a number of scientifically important projects that can be performed with existing seismometers. These studies can provide key geological information despite the inadequate calibration, versatility, and numbers of instruments relative to the new PASSCAL system. Third, these smaller-scale experiments will allow PASSCAL to gain experience in organizing co-operative seismic experiments involving several institutions by providing basic logistic support for field efforts, pre-processing the data, and in running a centralized data facility. As time progresses, it is likely that PASSCAL will provide increasing amounts of support for field equipment, financial assistance for planning experiments, and logistical assistance for these projects. This is also the case for PASSCAL's support of hardware and software for initial pre-processing and even higher-

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† It is to be emphasized that available instruments, while numbering in the low hundreds, are wholly inadequate to function as the kind of system PASSCAL is developing. Few can record natural events. Few are digital. Only small numbers of instruments are matched, a requirement for waveform analysis. Many instruments are configured in multichannel cables suitable mainly for conventional reflection work. The USGS instruments are analog. Since no common time-keeping and synchronization hardware exists for this variety of instruments, putting all into the field for a single experiment may well be impractical, requiring numerous exercises in baling-wire-and-chewing-gum design. While the use of these instruments will advance our understanding of the capabilities of large arrays and clear up many questions regarding their performance, they suffer fatal shortcomings as an imaging system for state-of-the-art seismic studies of the lithosphere.

level data processing stages. Fourth, it is time to start planning for co-operative on- and off-shore seismic experiments of continental margins and hotspot volcanism, due to the long lead times required for oceanographic research. This coordination is required to insure that marine research is conducted in places where on-land work can be performed and vice versa. Fifth, field studies will be required starting in FY 1986 for testing of prototypes of the PASSCAL instrumentation under realistic conditions, and in a setting which permits comparison with existing instruments. advanced seismometer prototypes for testing and for field studies prior to the large-scale studies planned to start in FY88.

Potential Principal Investigators will be invited to prepare informal proposals to the PASSCAL Science Planning and Coordination Committee and to form collaborative groups to conduct interim experiments. The results of this SPCC planning exercise will be used not only to guide the support given by PASSCAL to PI's but should also be used to generate autonomous proposals to funding agencies. Proposed large-scale cooperative experiments will be evaluated both for their intrinsic geological merit and for the ways in which they embody the attributes of the planned PASSCAL system... multiple methodologies, multiple investigators, with emphasis on imaging the subsurface in some way. Proposed smaller projects will be weighed in terms of their support for basic research on the methods of data acquisition and interpretation. We emphasize that support for these research efforts will come directly from funding agencies to PIs via the normal peer review process. When funded proposals require PASSCAL resources, the PI will be expected to have discussed his/her anticipated needs in advance with PASSCAL.

14.6. Lithospheric Seismology Projects Currently in Progress or Planning

Even as PASSCAL is becoming organized, participants from many institutions are planning a number of studies of the continental lithosphere for the immediate future. While some of these are continuations of experiments from preceding years, others are new initiatives which directly support the PASSCAL goals for interim experiments. These projects address broad range of scientific targets and include both formal and informal consortia of research institutions that will conduct the experiments. These studies are illustrate the great scientific promise of lithospheric seismology, and represent possible candidates for future PASSCAL involvement with the new instrumentation or with focused interim experiments. They also illustrate the limitations of presently available instrumentation.

Examples of currently planned or other possible experiments with geological/tectonic goals include the following:

Ouachita System, Lithospheric Structure
Appalachian Drill Site Characterization
Long Valley, California Magma Chamber Study
Maine/Quebec Lithospheric Studies
Trans-Alaskan Lithospheric Investigations
Newberry Craters, Oregon Hydro-Magmatic System

The first two of these illustrate particularly the ways in which a large complement of versatile recorders might go well beyond the capabilities of reconnaissance-type reflection profiling. In the first case, the acquisition of refraction and wide angle reflection data of suitable quality using dynamite sources provides deep structural and velocity information. In the second case, the new reflection profiles and velocity determinations are being focused at high resolutions which could not be obtained from the original COCORP data.

Remarkably, although thousands of km of crustal reflection lines have been run in the U.S., thousands of km of DSS lines have been shot in the U.S.S.R., and thousands of km of refraction lines have been shot, principally in Europe, the U.S., and Canada, there still is no unified data set over the same line, containing narrow-angle reflection data, and wide-angle/refraction data. Consequently, the relationship between these types of data in the real earth is still poorly understood. Both the Ouachita and Maine studies described here show promise of providing unified data of this kind for the first time.

Of equal importance with the field experiments are studies that will test and evaluate seismic sensors and controlled seismic sources for use in the PASSCAL program. Major activities in FY-1985 will include:

Evaluation and Development of Sensors
Controlled Source Evaluation for Lithospheric Imaging

Note that no field projects have yet been annointed as official PASSCAL experiments. Further discussion of the scientific context for some of these studies is given in Chapter 6 of this Plan.

14.6.1. Ouachita System Lithospheric Structure

A seismic refraction/reflection project has been proposed for the Ouachita orogenic system. The experiment will utilize 200 seismic group recorders (SGR) available from industry in three deployments with explosive sources along a N-S profile through the southern margin of the Ouachita Mountains. The profile will be recorded with the digital, broadband SGR's at 250 m station spacing over a 200 km profile, to study the deep structure of this transition zone from the orogen (possible ocean-continent transition) to craton. The close spacing and redundancy of coverage provided by multiple shots offset from the seismograph array will provide complete wavefield coverage of refractions and wide angle reflections from interfaces in the 0 to 40 km depth range. A complete range of angles of incidence (near vertical to wide angle) will be recorded. Approximately 12000 seismic traces will be recorded. Interpretation of the data will be performed by (1) two-dimensional travel time inversion; (2) wavefield imaging utilizing the complete waveform for all seismograms; (3) forward modeling using two-dimensional synthetic seismogram techniques; (4) reflection processing with standard CDP stacking techniques for near vertical and wide angle reflections; (5) integrated interpretation of the seismic structure with gravity models and geologic interpretations.

This experiment represents an ideal interim experiment consistent with PASSCAL objectives for the following reasons:

(1) These will be the first data collected in a lithospheric study which meet the standards for deep imaging: digital, large dynamic range, close station spacing,† and spanning a broad range of angles of incidence.

(2) The profile will be recorded near the COCORP Ouachita line, allowing reprocessing of the COCORP data with the knowledge of the deep structure provided by the refraction/reflection results. The new data, which emphasize deeper structure, will benefit from the shallow intepretation from the COCORP results.

(3) The experiment is an ideal test and learning experience for large array studies; we will be facing all of the data management problems of large-scale seismic experiments but with the advantage that the recording format, instrumentation, and data management utilize industry standard technology. We expect that the preparation of an edited experiment data tape will be completed four weeks after the end of the field work.

(4) Because SGR crews are currently working in the Ouachita area, and because of a favorable agreement with industry, the planned experiment is highly cost-efficient, making it appropriate for an interim experiment.

(5) The data, combined with the COCORP data, will provide a unique resource for testing and analysis of new methods of interpretation from high-density array studies as envisioned for future PASSCAL experiments.

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† "Close spacing" in the context of the PASSCAL objectives always means that the recorded wavefield is unaliased spatially. For 20 Hz deep crustal signals at a surface slowness of .16 sec/km, 100 m or less is required.

14.6.2. Appalachian Drill Site Characterization

The first site planned for deep continental drilling under the CSDP and DOSECC lies in the Inner Piedmont of South Carolina, about 70 km east of the COCORP reflection profile and about 10 km southeast of the Brevard Zone. In this area it will be possible to drill through three distinct allochthonous lithostratigraphic terranes which are mapped to the northwest, through the master decollement (at about 10 km depth), and into the pre-Ordovician North American basement. The drilling program in this area opens up a host of opportunities for seismic studies of the crust, both passive monitoring of teleseisms and many types of controlled source seismology. With the deep drill hole and with other shallow test holes nearby, it will be possible to conduct hole to hole and hole to surface studies, in addition to the surface to surface mode.

A principal goal of seismic studies in the neighborhood of a deep drill hole is to develop detailed velocity and structural images which can be correlated with measurements on returned cores and with surface geological and geophysical studies. The correlation process can shed light not only on the familiar question of the relation between mineralogy and velocity, but is of almost greater importance in sorting out the effects of anisotropy, water content, crack distribution, and stress.

A consortium of investigators from University of South Carolina, Virginia Polytechnic Institute, Princeton University, Lamont- Doherty Geological Observatory, and Stanford University, under Robert Hatcher as Chief Scientist, has proposed to carry out an integrated geophysical and geological study of the crust in the neighborhood of the proposed drill hole, as an aid to detailed site location and to characterization of the crust. The study would emphasize higher resolution and greater velocity control than was obtained by the COCORP reconnaissance 50 km away. The planned studies include:

- 150 km of 48 fold reflection profiling
- 80 km (2 lines) of ESP velocity profiles along strike
- 20 km of high resolution profile near the drill site
- field mapping and detailed gravity lines to develop adequate detail in the area
- drilling of 6 shallow test holes for sampling lithology below the weathering zone and for heat flow and borehole stress measurements

The site characterization experiments listed above bring to bear the best techniques now available for the limited goal of studying the 12 km or so accessible to the drill. What is missing at this point is a regional perspective, which considers the structure of the orogen more broadly, down into the lithosphere and eastward across a major crustal transition into the core of the orogen. A combined DSS/reflection/refraction study using rented Seismic Group Recorders is under study by the Science Planning and Coordination Committee, and is described in Chapter 6 of this Plan.

14.6.3. Long Valley, California Magma Chamber Studies

The short term objectives of new and continuing studies in the Long Valley Caldera are to develop a better understanding of the location, geometry and physical characteristics of the shallowest magma bodies within the caldera, and to improve our understanding of the relationship between these features and deeper-seated processes (Figure 14-1). Institutions actively involved in the presently-coordinated seismic imaging experiment in Long Valley include University of Wyoming; Sandia National Laboratory; University of California, Berkeley; University of California, Santa Barbara; University of Southern California; Lawrence Berkeley Laboratory; E.T.H., Zurich; and the U.S. Geological Survey. In addition, the University of Nevada, Reno and the California Division of Mines and Geology are also actively engaged in other important, ongoing investigations at Long Valley. Interest in this program has also been expressed by researchers from Lawrence Livermore Laboratory, Caltech and University of Texas, Dallas. It is anticipated that some of these people, as well as others not yet identified,

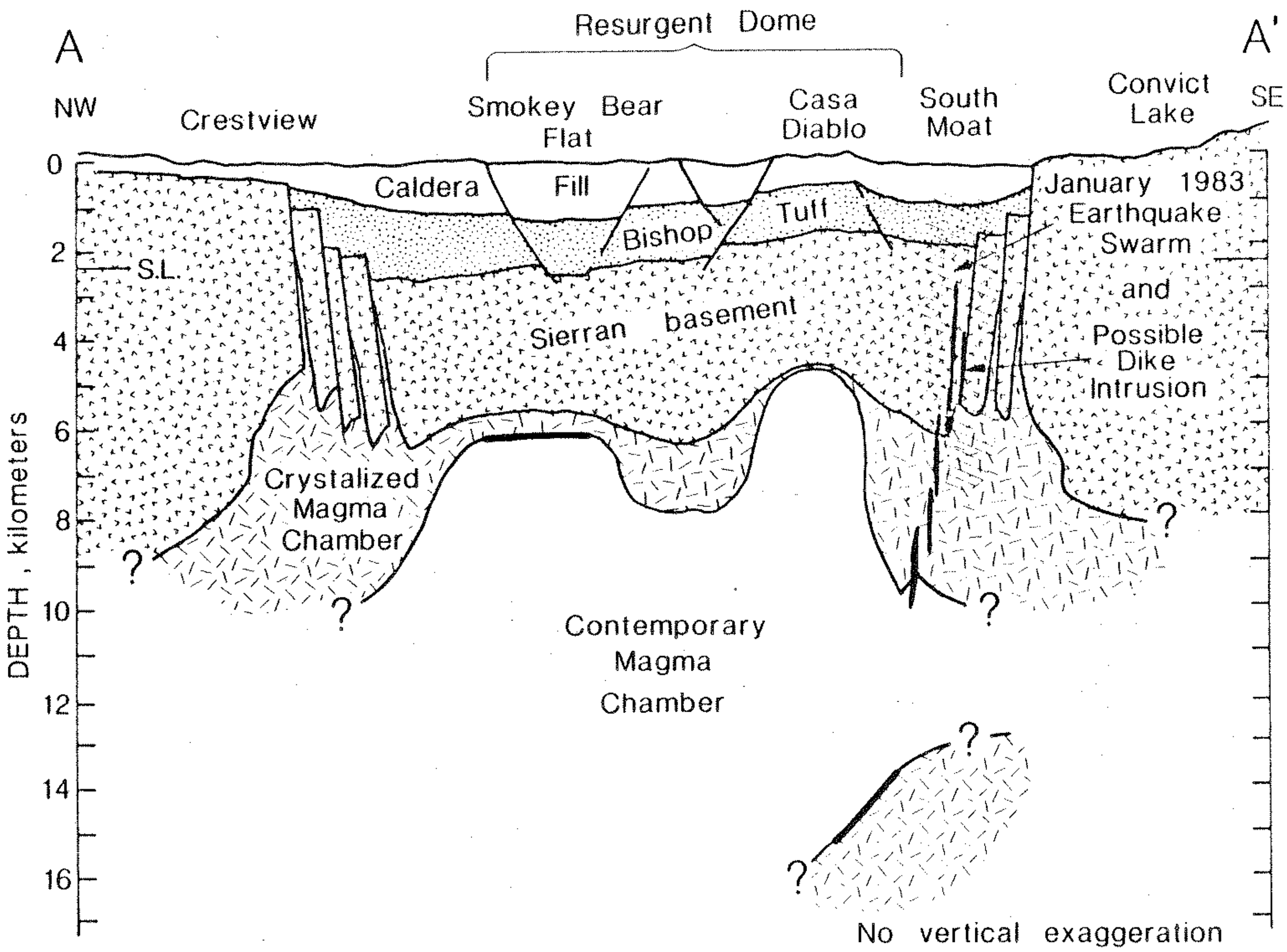

Figure 14-1. Schematic northwest-southeast cross-section through Long Valley caldera showing magma chamber geometry based on seismological evidence. Heavy lines indicate approximate positions of reflecting boundaries. Shaded pattern beneath south moat indicates approximate distribution of earthquakes in the January, 1983 swarm; dark vertical lines indicate approximate positions of dikes that may have been intruded during the swarm.

will join this program as it develops.

Experiments planned for FY-1985 include seismic reflection profiling across the magma chamber, shear wave reflection profiling at vertical incidence and at wide angle, vertical seismic profiling using both P-wave and S-wave sources in a 3000' drillhole, and expanded microearthquake coverage to the south and west of the caldera for use in geotomography. FY-1984 work was supported by the U.S. Geological Survey and the Department of Energy. Continued funding from agencies as well as new proposals to the National Science Foundation are anticipated in FY-1985.

14.6.4. Deep Crustal Structure Investigations in Maine and Quebec

The U.S. Geological Survey began a multi-year program to study the crustal structure of Maine using deep crustal reflection profiling and wide angle refraction profiling in 1983. The objectives in this region are to develop a complete geophysical transect of the Appalachian orogen. Completed already is a seismic reflection line from the St. Lawrence to the international border. The USGS line is planned to reach to the coast, to tie with an anticipated marine line across the Gulf of Maine.

Over 200 km of reflection data have collected with an 800 channel sign-bit recording system, and a parallel seismic refraction experiment will be conducted in the fall of 1984, using the 120 analog instruments. The refraction experiment will extend into Quebec and will tie together Canadian deep crustal reflection data with the Maine profiles. An important goal of this study is to collect and to try to understand unified reflection/refraction data along a single line. Participants in this work include the U.S.G.S. and Canadian scientists, along with people from Colby College and Princeton University.

14.6.5. Trans-Alaskan Lithosphere Investigations

The multi-year Trans-Alaskan Lithosphere Investigation† (TALI) along a 1000-km-long transect following the Alaskan pipeline route conducted its first active seismic experiments in 1984. Seismic studies planned for FY-85 will continue to focus on southern Alaska and its offshore continental margin, and are anticipated to include onshore refraction profiling, offshore refraction and reflection profiling, and passive array deployment to record local and teleseismic earthquakes for three-dimensional structure studies. Elsewhere along the transect geological and other geophysical studies will continue. Participating institutions in the past year's work include the U.S. Geological Survey, University of Alaska, Rice University and the Alaska Division of Geological and Geophysical Surveys. The participation of other institutions in this program has been actively encouraged at TALI workshops held in conjunction with national meetings of the AGU, SSA and GSA. Funding support derives from many sources including the U.S. Geological Survey, State of Alaska, National Science Foundation and an industry consortium organized by Rice University.

14.6.6. Newberry Craters, Oregon Hydromagmatic System

The Department of Energy (DOE) is sponsoring a series of controlled source seismic experiments at Newberry Craters designed to resolve the shallow crustal structure of the hydrothermal system and its relationship to heat sources at greater depth. The first seismic refraction experiment was conducted in 1983 by the U.S. Geological Survey (USGS) for DOE and was designed to test the feasibility of three-dimensional imaging of the crust by seismic undershooting. Later this year, the USGS will conduct an undershooting experiment with over 120 instruments deployed in a 10 km square on the volcanoes' summit using parameters defined by the 1983 study. All of the available resources for controlled source seismology of the USGS will be fully committed to this experiment, which leaves other important lithospheric investigations that could utilize the same sources totally undone. In the future, the PASSCAL

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† See also Chapter 6.

array could be utilized by interested scientists when special opportunities arise in future experiments. The PASSCAL program will also provide a forum for information exchange and experiment planning that will foster wider participation by the scientific community in similar experiments with their existing capabilities long before the first new instruments are available.

14.6.7. Evaluation and Development of Sensors

This multi-year program is supported by the Carnegie Institution of Washington and makes use of a set of shake tables whose characteristics are linear up to about 1 Hz. Development of these shake tables was a consequence of earlier work at Carnegie on design and construction of broad band permanent station seismometers.

To be investigated are the entire suite of portable vertical and horizontal sensors in current use in wide angle reflection-refraction, surface wave and normal mode investigations of continental lithosphere as well as strong motion transducers. Of special concern is linearity with amplitude, spurious resonances, cross coupling response (with amplitude and frequency as variables). The effects of temperature and external magnetic fields and some quantitative estimates of rugged ability will be sought. The results will be published after consultation with the manufacturers of the sensors. This leads logically to a study of improved transducers, particularly those of lighter weight, and with an enhanced range of linearity, both in amplitude and in frequency.

At this early stage of this work, it is already evident that PASSCAL needs to develop a broad band truly portable transducer operating in the period range from 0.1 or 0.2 to 50 or 100 seconds. In addition are needed ways to evaluate of the geophone plant in the field, and a study of the costs and benefits of various methods of planting including methods of improving the stiffness of coupling to the earth.

14.6.8. Controlled Source Evaluation for Lithospheric Imaging

A new program is in the planning stages to study the properties of controlled seismic sources for use with the PASSCAL array. The program will both review the available literature (public and proprietary, if available) and begin an experimental study of sources. This work is of critical importance at this time because the characteristics of appropriate sources, including ground motion amplitude, frequency content, duration and range will specify many of the design parameters for the field seismograph units.

Over the next few years PASSCAL plans to conduct a series of field studies of the characteristics of different types of sources. This is to start with the construction in 1985 of a modest test facility for recording ground motion from a variety of sources. A small borehole array for recording the outgoing or incident wavefield and small surface arrays with vertical and horizontal sensors will be the primary evaluation tool.

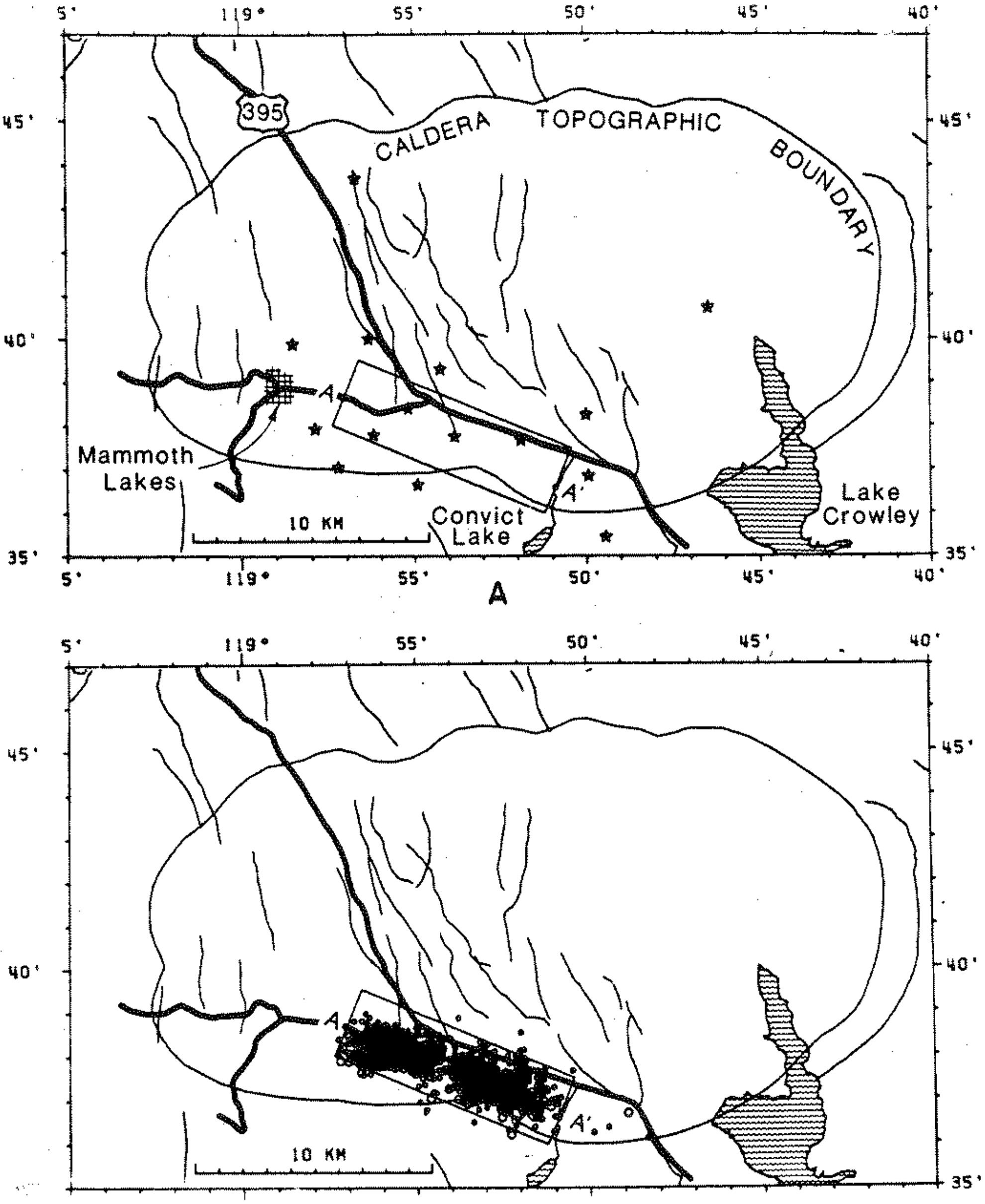

Figure 14-2. Locations of seismograph stations (stars) and earthquakes located during the January, 1983 swarm, and shown in Figure 14-3. (From Savage and Cockerham, *Jour. Geophys. Res.*, 1984)

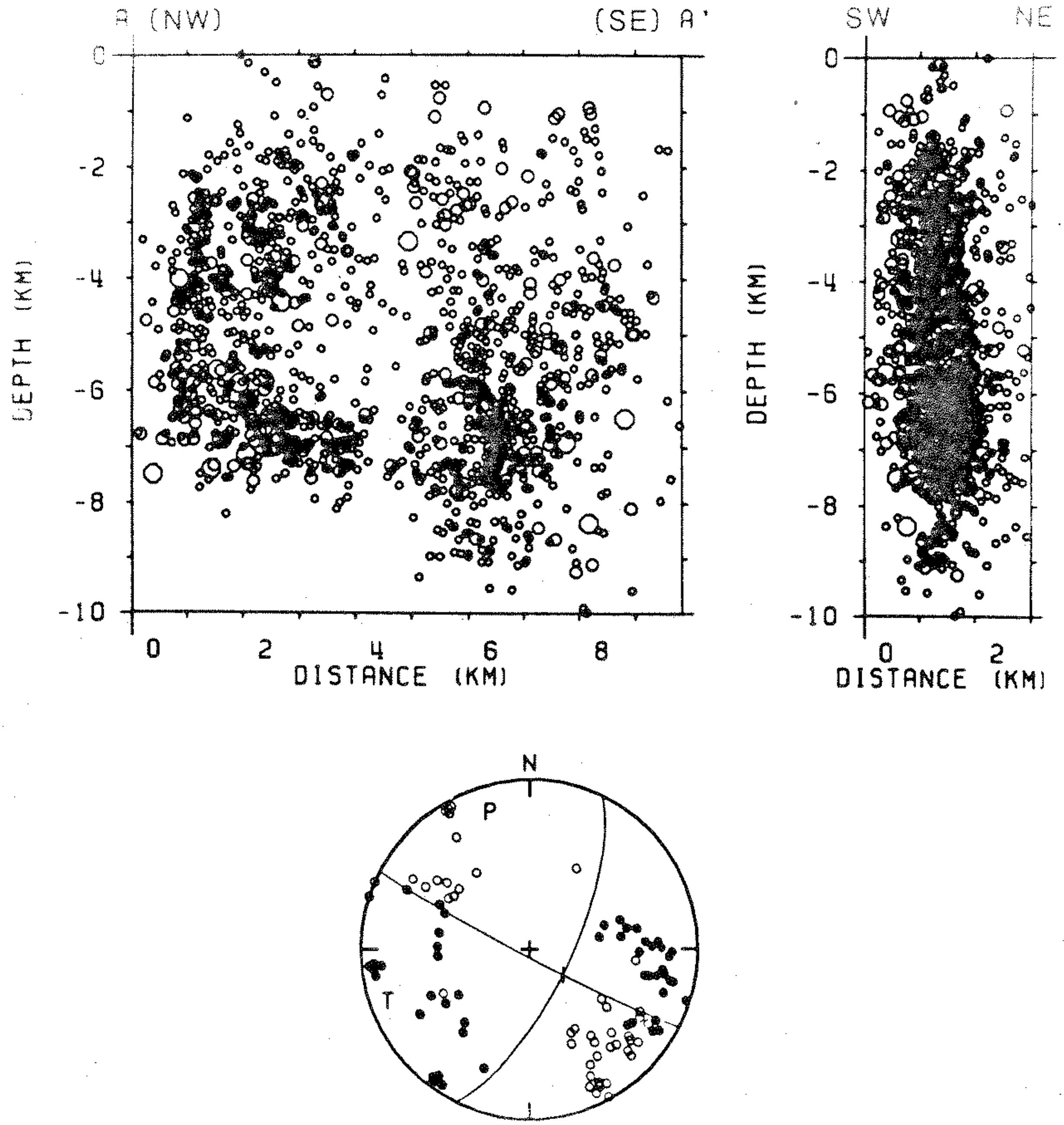

Figure 14-3. Top: Projections of hypocenters of earthquakes shown in Figure 14-2 onto vertical planes striking west-northwest and south-southeast. Cross-section A-A' is parallel to the trend of earthquakes in 14-2 and the other cross-section is perpendicular to it. Size of symbol used for hypocenters proportional to magnitude.
Bottom: Composite fault plane solution of events in the eastern half of the earthquake swarm shown in (A). Symbols are for lower hemisphere equal area projection. Solid circles are compressional first motion, open circles are dilational. Trend of earthquake epicenters, delineation of a vertical fault plane in the hypocenters and the west-northwest trending vertical fault plane of the fault-plane solution are all consistent with right lateral slip along the vertical fault plane associated with shallow injection of magma into a dike near the southern edge of the Long Valley caldera. (From Savage and Cockerham, *Jour. Geophys. Res.*, 1984)

15. SUPPORT FOR UNIVERSITY RESEARCH PROGRAMS

The major function of PASSCAL is to advance the scientific research capabilities of the academic community. Productive utilization of the PASSCAL array is possible only if enough researchers are able to participate in the planning, operation and data analysis of seismic experiments. While the plan for PASSCAL operations is aimed at minimizing the costs to PI's of participation in the data acquisition, this participation in the first instance depends on the PI having research support for students, computing, travel, summer salary, manuscript preparation, and so on.

15.1. Support for Planning, Interpretation, and Analysis

For PASSCAL to be a vigorous program, a number of strong research groups must be adequately supported for the "at home" component of the program. This might be divided into two sorts of groups:

(1) Those which are actively engaged in the workup of data which they have collected in previous field work... including much data housekeeping, processing, and modeling. The magnitudes of data flow from the array mean that each group must have full-time personnel working on the data to prevent the types of delay which are so common when scientists at universities have to split their funding over many sources. We model this by assuming ten PI groups are active at one time, at a level of $150,000 per year... one postdoc, one grad student, 2 summer months for the PI and other expenses. This cost of $1.5 million per year should be regarded as an intrinsic part of the total PASSCAL funding.

(2) Other groups engaged in analysis and interpretation of PASSCAL data. Programmatically, this research should probably be regarded as normal NSF (or other agency) project support, in competition with other conventional-sized projects. Adequate funding in this area will be important, however, since many participants in PASSCAL will be doing continuing research of this kind, and will require support. It is worth noting that these groups will constitute the bulk of the "users" who will be making use of the IRIS Data Archive for access to PASSCAL data.

Many if not most of these participants and data users will be "converts" from present seismological programs which use older fixed network data. Moreover much of their support will be sought through NSF project funding. The implication is that a substantial fraction all NSF project funding in seismology will support efforts which use PASSCAL... both new experiment efforts and later stage data analysis.

15.2. Need for Computers at the Universities

Easily overlooked in planning for a very large cooperative program is the availability of adequate data analysis resources to the end users of the data - to a large extent scientists in universities. Analysis of collected seismic data is a interactive and time-consuming operation, requiring on-site computer systems for participating universities. Such resources are available to some extent in the planned IRIS Data Management Program, and for large-scale studies, in the planned IRIS Seismic Supercomputer Program. However, the bulk of the continuing research done by academic scientists is in their own laboratories, where they have the discretion to allocate resources and tailor the hardware and software to their own research needs. Systems such as the PDP 11-70's which were given to some institutions by the USGS in 1979 are now grossly insufficient to handle the data flow from large arrays, not to mention existing earthquake networks. At that time, the record shows that bringing the computer power into the individual PI laboratories stimulated a number of major developments. More recently, systems like the VAX 11-780, the Prime, Perkin-Elmer 3230 have found their way into about 15 of the most active institutions in connection with projects in reflection seismology, often through industry programs, or through involvement with COCORP.

It will be necessary to insure that university research groups participating in PASCAL (and the Global Network) be able to raise their local computing power to present day capabilities. With the current generation of small work station or super work station machines (Ridge, Pyramid, Sun, Apollo, Masscomp and others), significant computing power can be made available at moderate cost ($100-150K) in the laboratories. Only a few institutions at this time now have resources at this level, and thus the ability to be at the forefront of many topics requiring intensive computation. Given the lead time required to bring such new systems up to speed, in particular, the time required to implement some of the more advanced capabilities in computer graphics, for example, it is important that continuing NSF support for acquisition of laboratory computers be available in the very near future.

Appendix A: References

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Appendix B: Abbreviations and acronyms

CALCRUST: A consortium of California earth science investigators with a cooperative program to apply reflection seismology to key problems of California tectonics.

CCSS: Commission on Controlled Source Seismology, a working commission of the International Association of Seismology and the Physics of the Earth's Interior (IASPEI).

COCORP: The Consortium for Continental Reflection Profiling, a program for reconnaissance two-dimensional Vibroseis reflection profiling of the continental crust, managed by Cornell University.

COSEPUP: The Committee on Science, Engineering, and Public Policy of the NAS.

CSDP: The Continental Scientific Drilling Program, a national effort coordinated by the Continental Scientific Drilling Committee of the NAS.

CSF: The Central Support Facility, the PASSCAL fixed facility for instrument and system maintenance and support.

DMC: The proposed Data Management Center, to be operated by IRIS under its own Standing Committee for the entire seismological community.

DOSECC: Deep Observation and Sampling of the Continental Crust, a non-profit Corporation of Universities which is to supervise the execution of the Continental Scientific Drilling Program.

DSS: Deep Seismic Sounding, used to describe a method of collecting crustal refraction and wide angle reflection used principally in the USSR. It is characterized by explosive shotpoints at intervals typically 40 km, which are fired into a multichannel array with receiver spacing 100-200 meters. The resources devoted to this method, and the quantity of data collected by the Soviets exceed by a factor of about 50 the comparable effort in the USA during the past 20 years.

GSN: The Global Seismic Network, an IRIS Program.

IRIS: Incorporated Research Institutions for Seismology, a non-profit Corporation of Universities which is to supervise the execution of large-scale cooperative programs in seismology.

JOI: Joint Oceanographic Institutions, a non-profit Corporation of Universities engaged in oceanographic research.

NORPO: The National Oceanic Reflection Profiling Organization, a new program organized under JOI for cooperative multichannel marine reflection projects.

PASSCAL: The Program for Array Seismic Studies of the Continental Lithosphere, an IRIS Program.

Phase Zero: A pre-startup funding period for PASSCAL, to run from July 1, 1984 to June 30, 1985, which was funded through the Carnegie Institution of Washington. D. E. James and S. Sacks, PI's.

PI: Principal Investigator

SSCL: Seismological Studies of the Continental Lithosphere, the 1984 National Academy report, written by a subcommittee of the Committee on Seismology chaired by George Thompson, which set forth the scientific rationale for a lithospheric seismology program and gave recommendations for its implementation.

TACT: Trans-Alaska Crustal Transect. See TALI below.

TALI: Trans-Alaska Lithospheric Investigation, a multi-institution collaboration involving the U. S. Geological Survey and several universities for geophysical, and geological studies on a trans-Alaska transect.

USGS: The United States Geological Survey. In this report reference is made specifically to activities originating at the laboratories in Menlo Park, California.

Vibroseis: A registered service mark of Continental Oil Company. The technique uses a truck-mounted hydraulic vibrator to input a swept-frequency chirp into the ground and subsequently uses digital cross-correlation to recover an equivalent pulse response seismogram.

Appendix C: PASSCAL Committees and Panels

Standing Committee

Robert A. Phinney (chair):	Princeton University
Keiiti Aki:	University of Southern California
Gilbert Bollinger:	Virginia Polytechnic Institute
Gregory Davis:	University of Southern California
William B. Ellsworth:	U. S. Geological Survey, Menlo Park
Kenneth Larner	Western Geophysical Company
Robert P. Meyer:	University of Wisconsin
Selwyn Sacks:	Carnegie Institution of Washington
Robert B. Smith:	University of Utah
David E. James (secretary, ex officio)	Carnegie Institution of Washington

Instrumentation Design Team

Scientists:

Selwyn Sacks (Co-chair):	Carnegie Institution of Washington
Robert P. Meyer (Co-chair):	University of Utah
William A. Prothero:	University of California — Santa Barbara

Engineers:

Bruce Ambuter:	Consultant
Yousri Barsoum:	Sprengnether
Jeff Bertram:	Sprengnether
Don Dearborn:	University of California — Los Angeles
Gray Jensen:	U. S. Geological Survey, Menlo Park
David Kodama:	Kinemetrics
David Pierce:	University of California — Los Angeles
Lee Powell:	University of Wisconsin
William Rihn:	Kinemetrics
William Schaecher:	Teledyne/Geotech
O.D. Starkey:	Teledyne/Geotech
Craig Ware:	Sprengnether

Data Management Committee

Robert A. Phinney (Chair):	Princeton University
Wang-Ping Chen:	University of Illinois
Robert Clayton:	Caltech
Klaus Jacob	Lamont Doherty Geological Observatory
Carl Johnson:	U. S. Geological Survey, Pasadena
Ken Larner:	Western Geophysical
Jim McClain:	University of California — Davis
Tom McEvilly:	University of California — Berkeley
George McMechan:	University of Texas — Dallas
Ken Olsen:	Los Alamos National Laboratory
John Orcutt:	Scripps Inst. Oceanography
Gary Pavlis:	Indiana University
Jim Scheimer:	Livermore National Laboratory
Paul Silver:	Carnegie Institute of Washington
John Zucca:	Livermore National Laboratory

Science Planning and Coordination Committee

Larry Braille (Co-chair): Purdue University
Bill Ellsworth (Co-chair): U. S. Geological Survey, Menlo Park
K. Aki: Massachussetts Institute of Technology
Roger Bowman: University of Colorado
Robert Crosson: University of Washington
Paul Davis: University of California — Los Angeles
John Ebel: Boston College
Gordon Frantti: Michigan Tech.
Joe Gettrust: NORDA
David Hill: U. S. Geological Survey, Menlo Park
Brian Isacks: Cornell University
H.M. Iyer: U. S. Geological Survey, Menlo Park
Klaus Jacob Lamont-Doherty Geological Observatory
Donna Jurdy: Northwestern University
Randy Keller: University of Texas — El Paso
Jim Luetgart: U. S. Geological Survey
Brian Mitchell: Saint Louis University
Walter Mooney: U. S. Geological Survey, Menlo Park
Rex Pilger: Louisiana State University
Paul Pomeroy: Rondout Associates Incorporated
Bill Prothero: University of California — Santa Barbara
Larry Ruff: University of Michigan
Paul Silver: Carnegie Institute of Washington
Bob Smith: University of Utah
Scott Smithson: University of Wyoming
Doug Stauber: U. S. Geological Survey, Menlo Park
Ta Liang Teng: University of Southern California
George Thomson: Stanford University
Anne Trehu: U. S. Geological Survey
Raymond Willeman: Texas A&M University

Appendix D: Chronology of Meetings

1. May 4—5, 1983. Workshop on guidelines for instrumentation design in support of a proposed lithospheric seismology program, Salt Lake City, Utah. Convened by R. Smith and W. Arabasz, 55 participants. [See Appendix A for reference to Proceedings volume]
2. Nov. 21—22, 1983. Meeting of the ad-hoc organizing committee for lithospheric seismology, Carnegie Institution of Washington, Dept. of Terrestrial Magnetism, Washington, D.C. Convened by D. James and S. Sacks, 12 participants.
3. Nov. 29 — Dec. 2, 1983. International workshop on instrumentation, Los Altos, California. Convened by R. Meyer, S. Mueller, J. Ansorge, H. Shimamura, and R. Mereu, 61 participants. [See Appendix A for reference to Proceedings volume]
4. Jan. 13—14, 1984. National organizational meeting for the Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL), Yahara Center, Madison, Wisconsin. Convened by Carnegie Institution and the University of Wisconsin, 78 participants. [Minutes available from D.E. James, Carnegie Institution]
5. Jan. 31 — Feb 2, 1984. First full meeting of the Board of Directors (now Standing Committee) of PASSCAL, Houston, Texas. Hosted by K. Larner, Western Geophysical, Inc.
6. February, 1984. Instrumentation meeting of the "Team of 3" to prepare a straw-man design for consideration on the April, 1984, meeting of the instrumentation working group, Los Angeles, California. [Report of the Team of 3 issued March 8, 1984. Available from D. James, Carnegie]
7. April 16—18, 1984. First meeting of joint university/industry instrument design working group, St. Louis, Missouri. Hosted by Sprengnether, 15 participants. [Interim technical reports distributed Sept., 1984. Minutes of meeting available from D. James, Carnegie]
8. May 13, 1984. First meeting of the Board of Directors for Incorporated Research Institutions for Seismology (IRIS), Cincinnati, Ohio. [Minutes available from G. Bollinger, VPI&SU]
9. July 12—19, 1984. Standing Committee meeting and workshop to prepare this PASSCAL Program Plan, Princeton, N.J. Convened by R. Phinney, 22 participants.
10. August 18, 1984. Standing Committee meeting to approve PASSCAL Program Plan and prepare material for IRIS proposal to NSF, Golden Colorado.
11. Sept. 19—21, 1984. Instrumentation working group meeting with engineers from the oil industry, Dallas, Texas. Hosted by Teledyne-Geotech, 26 participants. [Minutes available from D. James, Carnegie]