3. IRIS SCIENTIFIC PROGRAMS

3.1. GSN Scientific Program

3.1.1. Introduction

One principal objective of seismology is to determine the earth's structure as a function of radius and position. For this we need a global distribution of stations that sample different parts of the earth's interior. Another principal objective is to determine the location, origin time, and mechanism of earthquakes. Observations of amplitudes of the waves recorded at many points around the globe are necessary for the detailed studies of the properties of seismic sources.

The Panel on Global Earthquake Monitoring wrote in its report published in 1977: "Global seismic networks are as basic to seismology as the telescope is to astronomy and the accelerator is to physics. Without this instrumentation, seismologists are 'blind' to subsurface earth processes and properties and the very survival of the science would be threatened. Support of a modern global network of seismic stations is clearly in the national interest." Comparison of a seismic network with a telescope is quite realistic, other than the network represents an 'inverted' telescope. This is illustrated in Figure 3.1, showing a family of rays of the compressional (P-) waves covering the teleseismic distance range (from 25° to 180° of arc). This simple picture demonstrates why seismologists need a global network.

On the basis of results obtained from the analysis of available data, seismologists became convinced that significant advances in many problems of fundamental importance to earth sciences could be achieved with a network of some 100 globally distributed modern seismographic stations with digital recording. In particular, the first attempts at a full reconstruction of three dimensional earth structure offer a promise of solving some of the basic problems of geodynamics. The density of coverage of the earth's surface with seismographic stations must increase in order to achieve the necessary resolution of detail.

Progress in application of electronic control methods and digital data acquisition, developments in digital mass storage methods, advances in satellite communications and availability of large computing facilities make deployment of such a network operationally and economically feasible.

A group of 36 seismologists from 17 institutions prepared a **Science Plan for a New Global Seismographic Network** (Appendix 1A). Copies of this Plan were disseminated in April of 1984 to over 300 scientists in this country and abroad with a request for comments. Replies are reproduced in Appendix 1B. Following incorporation of IRIS and activation of its committees and sub-committees, the Technical section of the Science Plan has been revised, updated and the budget formulated. These issues are presented briefly in Sections 4.1 and 6.1 of this proposal; presentation of Design Considerations as Appendix 1C; draft of a Letter of Agreement between IRIS and USGS as Appendix 1D.

3.1.2. Global Networks: Past and Present

The need for global coverage of the earth's surface by seismographic stations had been recognized as early as the beginning of this century when the first, very sparse, networks were established. One of the first networks was supported by the British Association for the Advancement of Science; the first uniform network of seismographic stations in North America was established in 1908–1911 by the Jesuit Seismological Service. Seismological research was very much facilitated by the establishment of the International Association of Seismology in 1905 and the publication of the International Seismological Summary with the first issue covering the year 1918; systematic determination of epicenters of the world's large earthquakes can be traced back to 1899.

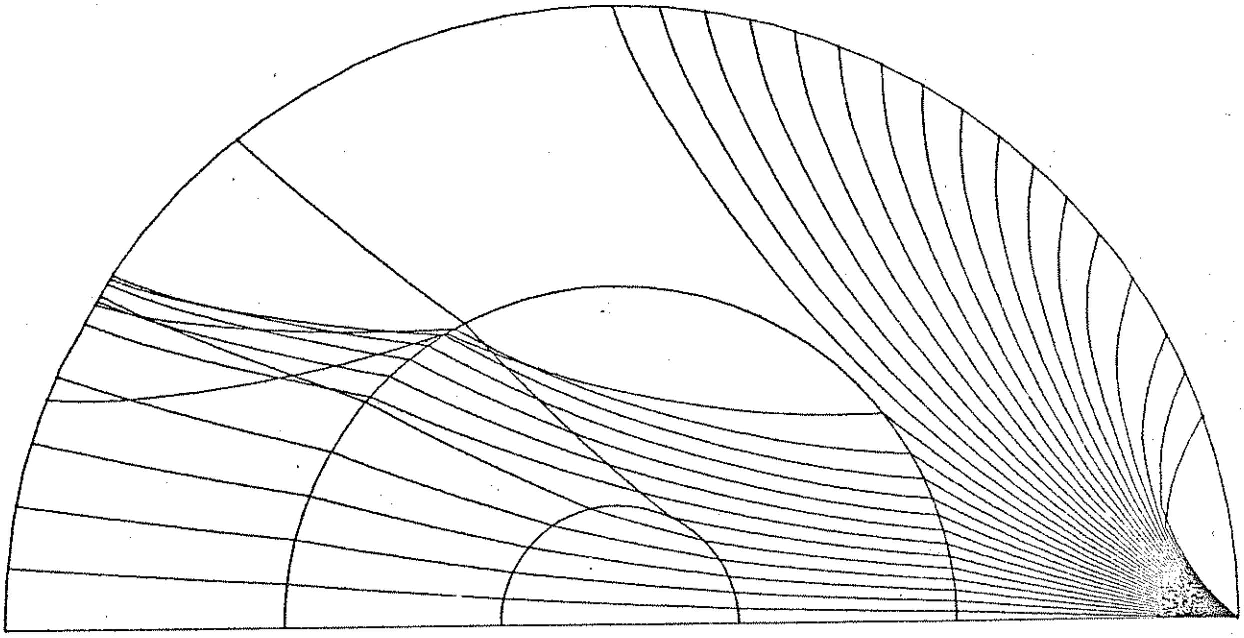

Figure 3.1. The outermost circle is the surface of the earth, the core-mantle boundary is next and the innermost circle has the radius of the inner core; discontinuities in the upper mantle are not shown. The velocity varies as a function of radius. The seismic source is placed at the surface and the rays show paths of the P-waves radiated at incidence angles varying from 0° to 30° with a 1° step. Major perturbations in the ray path occur due to abrupt changes in velocity. The core-mantle boundary, where a change by more than 40% occurs, represents the most dramatic example.

The World-Wide Standardized Seismograph Network (WWSSN), installed in early 1960's was by far the largest of the global networks and it had a profound impact on modern seismology. The cause of its success was the fact that copies of records from over 100 stations could be ordered at low cost from a single central location. Several research institutions within the United States and abroad maintained complete libraries of microfilmed WWSSN recordings. The existence of WWSSN was a key factor in studies of global seismicity and radiation patterns of earthquakes, which formed the cornerstone of the plate tectonic theory. Also, hand-digitized analog WWSSN recordings were used in various quantitative analyses of seismic waveforms and the results provided a strong stimulus for the development of digitally recording stations.

The first of the current generation of globally distributed digital stations were installed in 1975. There are presently over 50 operational stations; those managed by the U.S. institutions and the French GEOSCOPE network are shown in Figure 3.2.

The Global Digital Seismographic Network (GDSN) is operated by the United States Geological Survey and comprises three different types of instruments from very sensitive borehole seismographs to nearly 25 year old WWSSN sensors equipped with digital recording. The International Deployment of Accelerometers (IDA), operated by the University of California, San Diego, is an ultra-long period network of 18 LaCoste-Romberg gravimeters. It was specifically designed to record free oscillations of the Earth excited by major earthquakes. The Regional Seismic Test Network (RSTN) consists of 5 installations in the U.S. and Canada and is operated by the Department of Energy. These stations transmit data via satellites in real-time and the entire data stream can be received by anyone within the range of the satellite. In this sense, the RSTN network could be considered the prototype of the new Global Network. Also, the RSTN stations were designed for unmanned operation — a solution that may have to be adopted in the deployment of seismographs in inaccessible areas such as oceanic islands or uninhabited interiors of continents. The French GEOSCOPE network has now 5 operational stations and another 15—25 are planned. These stations utilize 3-component instruments, characterized by a large dynamic range. There is continuous recording of very-long period data (1 sample per 10 seconds) and triggered recording of broad-band data (5 samples/second) is to be implemented in the near future.

Other organizations operate regional arrays of digital seismographs and new stations are now being deployed or are in the planning stage. It is expected that records from these networks will be generally available and that a total of some 80—90 stations will be operational in 1986—99. This is very close to our goal of 100 stations. Why, then, do we believe that the new network is needed?

The reason is that *none* of the operational stations satisfy *all* the needs of basic research in seismology. None of the stations combine the dynamic range needed to record a great earthquake with magnitude above 8.5 and, at the same time, resolve the ground noise with the bandwidth necessary to cover the range of frequencies from a fraction of a millihertz to 5—10 Hz. Such data are needed for studies of the earth's structure and earthquake mechanism. All the technology required to construct three-component instruments with a dynamic range of 140 db and continuous recording in the pass-band from tidal frequencies to 5—20 Hz is currently available.

3.1.3. Scientific Objectives

Despite the limitations of the existing stations, the digital data recorded during the last 7—8 years led to many important results and the research plan described in Appendix 1A is largely based on the success of the existing networks. While the section "Scientific Objectives" occupies 80 pages of the Appendix 1A, only a few issues will be highlighted here; when appropriate, the reader is referred to a particular section of the Science Plan.

In what follows, we shall, somewhat artificially, separate the problems related to the studies of earthquake source mechanisms (Appendix 1A, section 3.2) and the earth's structure (Appendix 1A, section 3.3). In reality, each seismic recording is affected by both; the overall progress in seismology is impossible without advances in both domains.

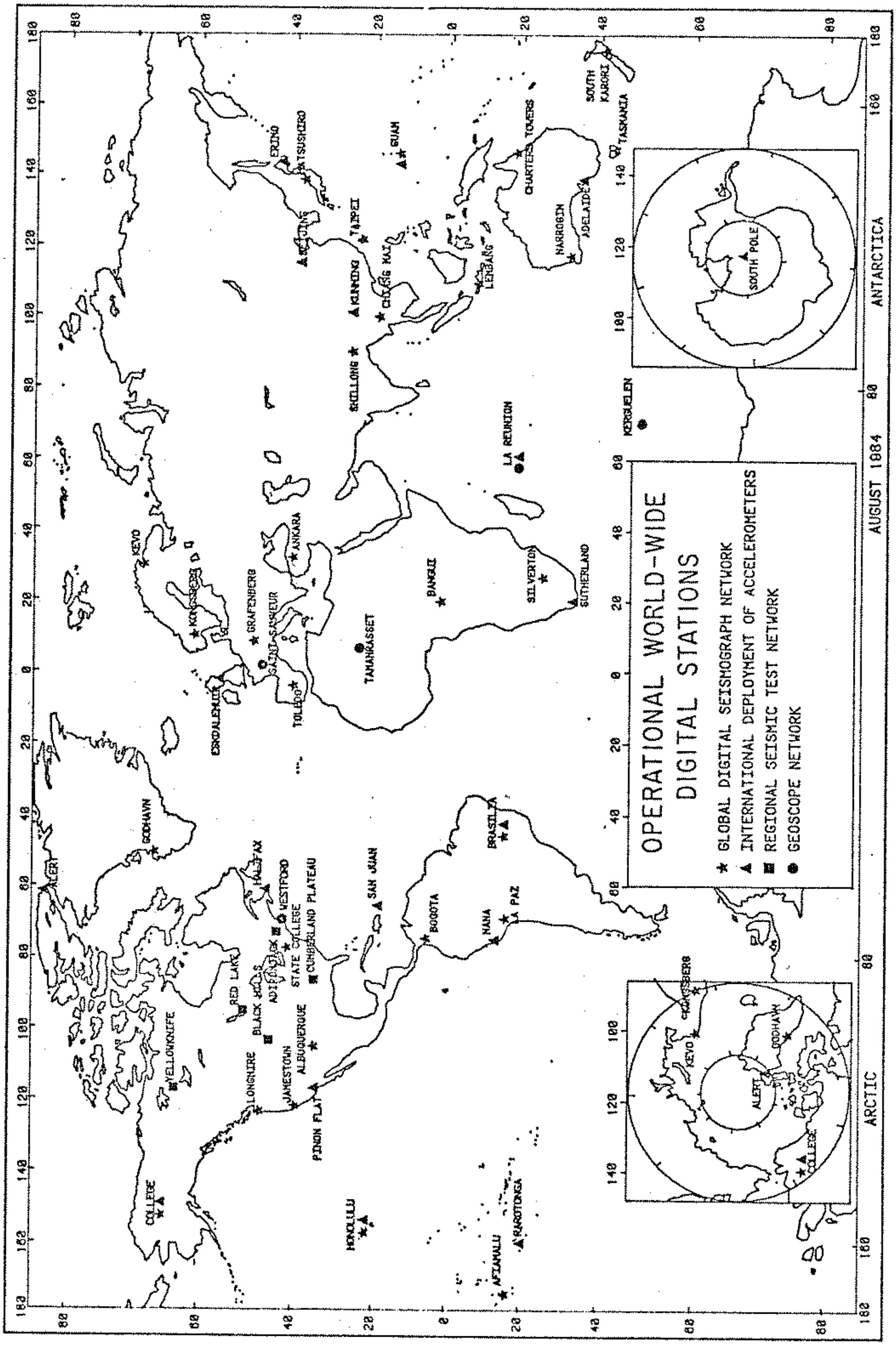

Figure 3.2. Distribution of the operational world wide digital stations.

The simplest mathematical representation of an earthquake is the "point source," characterized by the permanent change of stress in the source region (Appendix 1A, section 3.2.1). While locations of earthquakes have been performed routinely for many decades, the systematic determinations of the moment tensor are relatively novel, and, on a scale of several hundred events per year, would not be possible without digital data. The following is an example of how systematic investigations of the source mechanism can be used to monitor the dynamic behavior of seismicity in a particular region.

Figure 3.3 shows the double-couple representation of moment tensor solutions obtained for the Kurile Islands region for the years 1977— 1983 using the digital data provided by the IDA and GDSN networks. The radius of each "beachball" is a linear function of magnitude; the pattern of nodal planes and darkened areas determine the nature of faulting. There is a distinct gap in seismicity between the islands of Simushir and Onekotan, covering some 300 km of the trench axis, with no major earthquake in this region since, at least, 1915. The existence of this gap has been recognized for some time. The major burst of seismic activity occurred as a sequence of large thrust events from March 22 to 24, 1978, with the largest events exceeding magnitude (M_w) of 7.5. The pattern of seismicity following this series seems to be consistent with the hypothesis of stress diffusion along a subduction zone.

The normal fault, outer rise, event on 4/30/81 is consistent with the concept of relaxation of stresses in the subducted lithosphere following a major thrust earthquake. The seismicity migrates towards the northeast with a magnitude 6.9 earthquake on 12/31/80 and 7.1 on 6/30/82. The most recent event illustrated (5/1/83) is a thrust on the southwestern edge of the gap itself. The northeastern end of the gap borders the fault area of the 1952 Kamchatka earthquake. This area has been quiescent since 1977, except for three outer rise events in 1981. Two in the northeast were tensional, but one near the southwestern end was compressive, perhaps diagnostic of the overall high stress in the entire region. Then, in 1983, two thrust events occurred on the southwestern end of the gap: M_w of 6.3 on 2/26/83 and M_w of 6.5 on 4/4/83.

Whether this pattern of migrating seismicity is indicative of an impending major event in the Simushir-Onekotan gap is an open question. Increase in seismicity at the edges of a gap was noted before some major events (1952 Kamchatka $M_w = 9.0$, 1964 Alaska $M_w = 9.2$). What this example shows is that one can distinguish spatio-temporal patterns, with the source mechanism being an important parameter. Development of a global telemetered digital network would allow for the real-time monitoring of seismic gaps.

The real-time aspect of the proposed network (Appendix 1A, section 3.2.5) is important for several reasons. The ability to predict tsunami effects, to assess possible damage in remote areas in order to plan disaster aid programs, to predict the potential of occurrence of damaging aftershocks, are all issues of importance to the society. The ability of scientists to rapidly assess the tectonic significance of a large earthquake in order to inform the public, to plan post-seismic experiments and to make better hazard reduction plans are other valid reasons for real-time data transmission and analysis. The recent large earthquake in Japan (May 26, 1983; $M_w = 7.8$) represents a good example: the source mechanism was not known for several days, even though Japan is one of the countries with the best seismic instrumentation in the world and the level of scientific preparedness is very high.

Derivation of point source parameters is only the first step in earthquake analysis. It is necessary to recover the spatial and temporal history of faulting for a given event to obtain understanding of the physics of the rupture process (Appendix 1A, section 3.2.2 and 3.2.3). The recent controversy about the nature of the Mammoth Lakes earthquakes, 1978— 1980, could have been fully resolved had the data from the planned network been available. The long period data clearly indicate that the overall process of stress release in the main shock of the May 1980 sequence deviates significantly from the double-couple mechanism (plane shear failure). A dike injection of magma or steam was proposed to explain the mechanisms obtained from the analysis of digital data that contained very little energy at periods below 10 seconds. On the other hand, the analysis of hand-digitized WWSSN records, having better response at

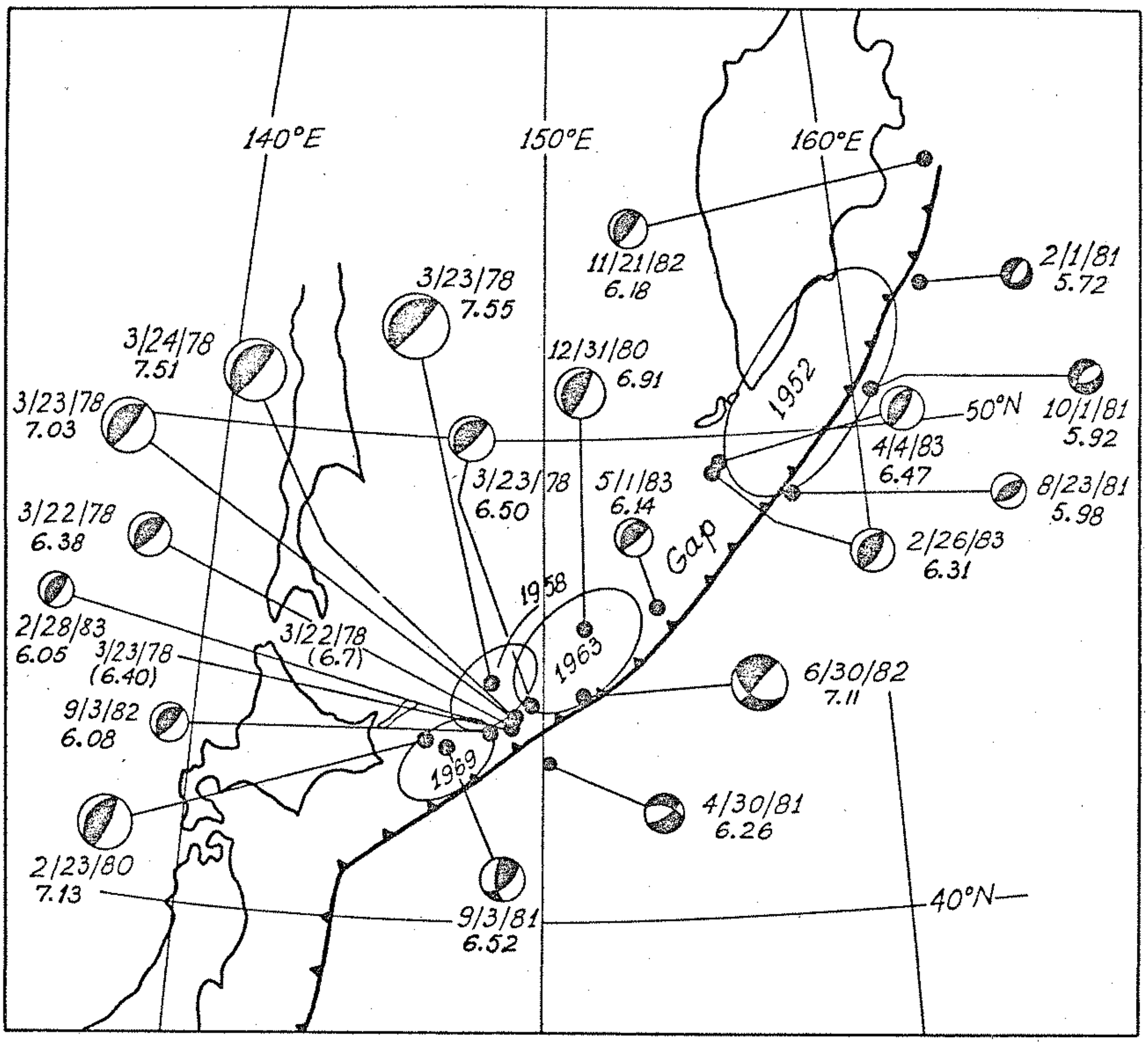

Figure 3.3. Seismicity of the Kurile Islands trench for years 1977-1983. All source mechanism solutions were obtained from analysis of digital data. (Kanamori and Dziewonski, with permission)

shorter periods, led some researchers to propose a complex mechanism consisting of normal faulting followed, in about 6 seconds, by a strike-slip event. The stress release obtained by adding these two subevents is, essentially, the same as the one obtained from the analysis of long-period data. Yet, because of the poor distribution of WWSSN stations for this event and the low quality of some analog recordings the ambiguity remains. A set of digital broadband records would allow us to answer unequivocally the important question of the nature of the tectonic stress release in this region.

The digital data collected during the last few years have led to the first applications of seismic methods to quantification of volcanic eruptions (Appendix 1A, section 3.2.4). The most complete data have been obtained for the Mt. St. Helens eruption of May 18, 1980. The real-time capability of the proposed network would allow rapid assessment of the magnitude of an eruption even in a remote location, which would be useful in predicting its effect on atmospheric processes.

Finally, the high quality data of the planned network could be important in studying "exotic" sources such as ultra-low frequency events that escape detection through the usual seismological procedures (so called "silent" or "slow" earthquakes), meteorite impacts and gravitational waves (Appendix 1A, section 3.2.4.3).

The anticipated impact of the planned global network will be at least equally important on the studies of the earth's structure (Appendix 1A, section 3.3). As in the studies of earthquakes, the digital data accumulated over the last few years have been used in studies that demonstrate the potential of high quality digital data.

The structure of the upper mantle, which extends from the base of the crust to a depth of about 700 km, has been the subject of intensive studies for several decades, partly because the properties of this region determine the large-scale dynamics of geological processes observed at the surface. The studies are complicated by the presence of low velocity zone, multiple discontinuities and regions of steep gradient as well as significant lateral heterogeneity. Most likely, the progress in studying the fine structure of the upper mantle will be made through the deployment of large scale portable arrays; the global network will be used to identify the anomalous regions. The lateral variations in the radii of discontinuities and the velocity contrast across them, however, can be studied using individual broadband stations (Appendix 1A, section 3.3.1, 3.4.1, 3.4.2).

The structure in the vicinity of the core-mantle boundary is important for better understanding the process of the formation of the core and the present day dynamics of this most dramatic boundary within the earth (Appendix 1A, section 3.4.3). Studies of the core structure would have a significant impact on some of the key problems in the geodynamo theory (Appendix 1A, section 3.4.4). Recent results on the anomalous structure of the outermost 200–300 km of the inner core (Appendix 1A, section 3.4.5) brought forward a suggestion that this region is not solid but that it consists of a viscous fluid with the relaxation time increasing with pressure. Availability of the broadband data is essential in testing this hypothesis since, if it is valid, the apparent radius of the inner core should show frequency dependence.

Dramatic progress has been made during the recent 2–3 years in studies of lateral heterogeneities in the earth's interior (Appendix 1A, section 3.3.2). The potential impact of these results exceeds the interests of seismology itself and promises to provide critically needed data for geodynamics, petrology, and geochemistry. Even with the limited resolution of the initial studies, the three-dimensional pictures of the earth's interior, unbiased by assumptions of continuation with depth of the surface tectonics, illustrated new and unexpected features. Examples of such preliminary findings are: most stable continental areas are underlain by faster than average mantle to depths of about 400 km; the depth expression of mid-oceanic ridges is highly variable; the pattern of anomalies in the transition zone (400–700 km depth) bears no resemblance to the surface tectonic expression; the level of velocity anomalies significantly increases near the core-mantle boundary (Appendix 1A, section 3.3.2.3).

With the current digital network, the half-wavelength of resolvable anomalies ranges from 3500 to 2500 km; in order to make these results more relevant to geological observations, the half-wavelength should be reduced to approximately 1000 km. This could be accomplished with 100 well distributed stations. Additional data, such as the long-period body waves can be included in future analyses and, as the models improve, the frequency content of the analysis could be broadened, leading to higher resolution with depth and, in particular, more detailed global representation of the lithosphere. This would provide the framework for high resolution studies including the use of the portable array. Figure 3.4 shows a slice through the mantle of a model obtained by inversion of the ISC travel time data (Appendix 1A, section 3.3.2.2). The coverage by the sources and stations is very uneven. In some areas it is possible to obtain much higher resolution, and tomographic studies applied on regional scale are already providing new tectonic insight (Appendix 1A, section 3.3.2.1).

Very low-frequency seismology (periods longer than 100− 300 seconds) presents another set of research opportunities (Appendix 1A, section 3.5). Measurements and interpretation of the splitting of the spectral peaks of free oscillations of the earth due to lateral heterogeneity is an important area of research. The full normal mode theory provides an important test of the proposed models or approximate solutions. Some observations, such as the anomalously large splitting observed for some modes of low angular order cannot be reproduced using the surface wave approach.

The recent results from seismology are having an important impact on research in other branches of earth sciences. For example, the three dimensional velocity models have been used to explain the low order geoid field (Appendix 1A, section 3.6.1), assuming that the perturbations in velocity and density are proportional. These calculations, which involve a finite viscosity, can lead also to the establishment of constraints on the radial distribution of viscosity. Much better correlation with the gravity field is obtained if a tenfold increase in viscosity across the 670 km discontinuity is assumed than either for a constant viscosity model or for a hundredfold increase. The level of the statistical significance of the hypothesis that the principal source of the gravity anomalies of degree 2 and 3 is located in the lower mantle is about 99%. With the known models of density and viscosity, it is possible to calculate deformation of the core-mantle boundary. The predicted amplitude of this deformation is of the order of 5 km − sufficient to exert a significant effect on the flow in the outer core. Thus the results from seismology contribute to providing critically needed answers in interpretation of the earth gravity field, magnetic field, its rheology and convection within the deep interior.

Seismology is also a petrological and chemical probe (Appendix 1A, section 3.6.2). By comparing seismic velocities with laboratory data on various minerals, and correcting for the effects of temperature and pressure, it is possible to discuss the composition of various regions of the mantle. By three-dimensional mapping of velocity anomalies it is possible to make inferences with respect to the depth of reservoirs of mid-ocean ridge basalts and hotspots. The question of the layered *vs.* whole mantle convection could be addressed by investigating the pattern of anomalies on both sides of the 670 km discontinuity. The results so far are inconclusive, but the critical experiments, involving simultaneous inversion for the whole mantle, have not yet been performed.

The planned network will have major impact on the studies of the lithosphere (Appendix 1A, section 3.7), particularly in conjunction with the operation of the large portable array. Global digital data will allow us to improve on global maps of lithospheric thickness, velocity, attenuation, anisotropy and stress. Even with the present data we have maps of lithospheric structure and have learned that simple tectonic regionalization is misleading. Detailed studies of the lithosphere in a few places cannot answer general questions; they need to be put into a global context.

Detailed reflection and refraction experiments and global studies are complementary. The situation is similar to the detailed geological and geophysical mapping which was put into context when the more global perspective was obtained from plate tectonics. The global digital array will provide the third dimension of the global view.

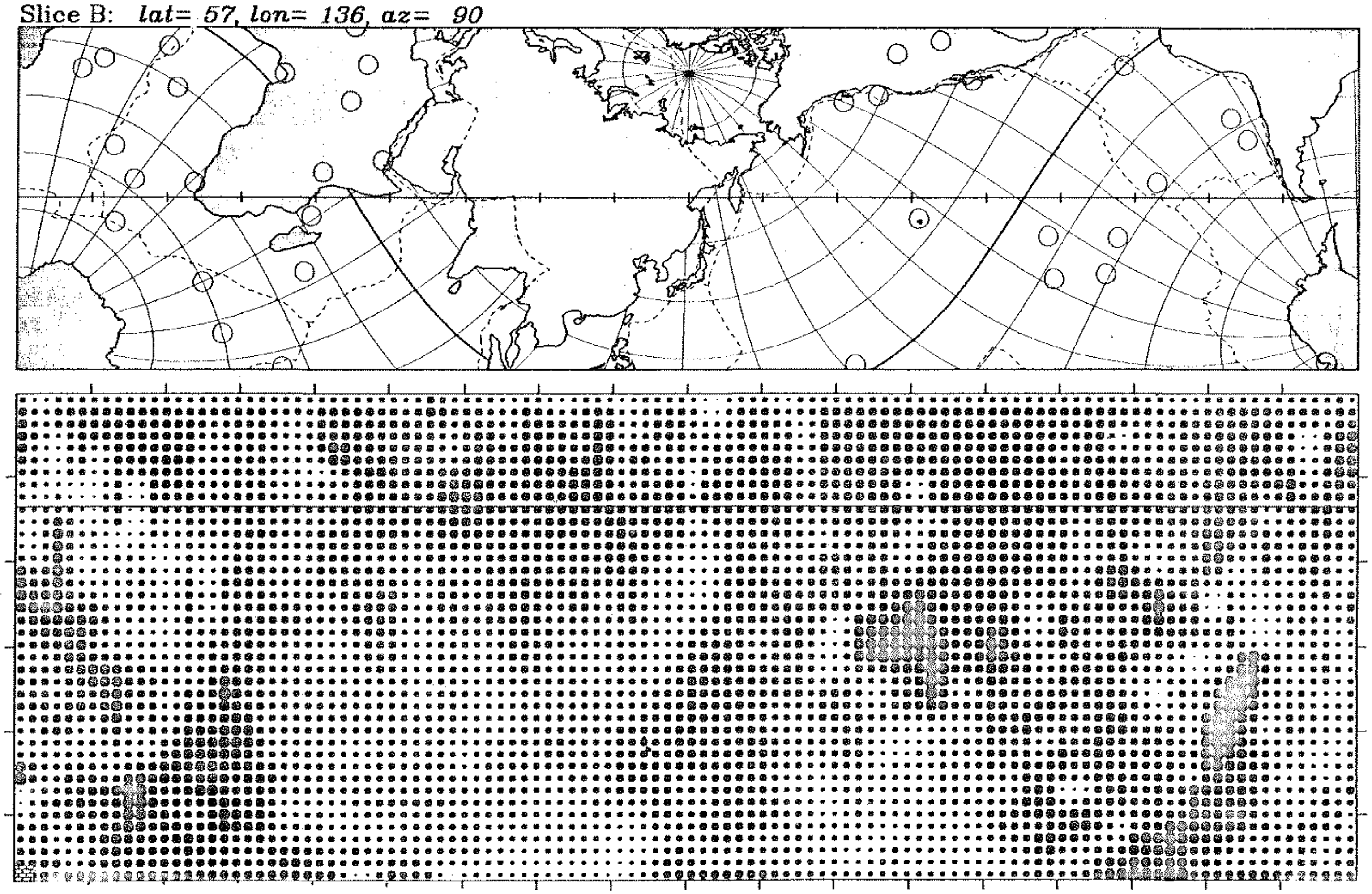

Figure 3.4. Results of the global tomographic inversion of the ISC trave time data. The display is a cross-section of the mantle along the great circle path shown on the map. The top and bottom of the section are the earth's surface and core-mantle boundary respectively. The tick marks on the vertical axis are 500 km apart. The light regions indicate fast velocities, and the dark regions are slow velocities. The open circles are hotspots. (Clayton and Comer, with permission)

In addition to the understanding of earthquakes and, therefore, lithospheric stresses, and providing maps of the third dimension, the digital network will permit high resolution studies of the downgoing lithosphere and discontinuities in the surface lithosphere.

In the discussion here and the Science Plan we have stressed the deeper mantle because of limitations of the present data set. With increased dynamic range, a broader frequency response and better station distribution we anticipate that global maps of the lithosphere (thickness, velocity, structure, density, anisotropy) will emerge very quickly. Short-period surface waves and reflected phases from teleseisms are ideal for this task.

There are many very fundamental questions about the lithosphere that require the global approach and which will not be answered until we have improved global and transportable networks.

We expect that in addition to providing the much needed data for the basic science, the GSN program will renew the interest in seismic instrumentation within the academic community. Investigations and development of innovative techniques for the acquisition, telemetry or management of data is one of the many responsibilities of IRIS.

3.2. PASSCAL Scientific Program

3.2.1. Introduction

The **Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL)** represents an unprecedented national collaboration among seismologists from over 40 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.

Many of the most important questions about earth history now revolve around the history and structure of the continents. The availability at this time of the new technologies for data recording and processing makes seismic imaging of the continental lithosphere an extremely powerful tool for addressing these questions. This initiative is aimed at this timely and appropriate new technology, with the expectation of obtaining significant new knowledge about the earth, while revolutionizing the methods and capabilities of seismology.

The scientific rationale for this new initiative was recently given in the National Academy of Sciences Report *Seismological Studies of the Continental Lithosphere*[1], which appears as Appendix 2B of this IRIS proposal. IRIS is the organization formed by the scientific community to bring into being, coordinate, and operate this new initiative in continental lithospheric seismology as strongly recommended in that Academy report.

PASSCAL proposes to make a major advance by mobilizing the power of a 1000 element collection of portable digital 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 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. The capability for operating such a system at regional or even continental scale gives it the power to complement the

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[1] 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.

global studies of the earth planned for the Global Seismic Network (GSN) by developing a ten-fold or better increase in resolution for the subjacent mantle. By the same token, PASSCAL arrays can be operated at extremely local scales, permitting 3-dimensional reflection and tomographic imaging of critical geological targets within the crust. It also becomes possible to conduct a number of fundamental studies of the physics of wave propagation in the real earth, at significantly high frequencies. Once the imaging of the lithosphere reaches a geologically interesting 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 should represent an ingenious and cost-effective scientific solution to the needs for society to understand the nature of the earth beneath our feet.

In capability and emphasis, PASSCAL is complementary to other initiatives in lithospheric studies, particularly COCORP[2], the Continental Scientific Drilling Program (CSDP), and regional geological consortia. The the great flexibility and power of the portable array technology can make it a basic tool for studies of many different kind. Within the seismological community itself, PASSCAL offers the opportunity for participation by scientists from institutions of all sizes, through both large-scale cooperative projects of up to 1000 instruments and studies by individual investigators using 50-100 instruments.

This Proposal 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 IRIS Proposal for a Global Seismic Network, is similarly the work of the entire community of U. S. seismologists engaged in global studies of the earth's interior.

A full Program Plan for PASSCAL has been prepared as a separate document, and appears in this IRIS proposal as Appendix 2.A. The material in this section of the IRIS proposal and in section 4.2 (Technical Plan for PASSCAL) is taken from the Program Plan, to which readers should refer if more detailed information is sought.

3.2.2. Summary of PASSCAL Proposal

1. It is proposed to bring into being and operate a system of 1000 versatile, portable digital seismic recording units for studies of the continental lithosphere. PASSCAL, through its staff and contractors, will provide and maintain instrumentation and support facilities, and will provide baseline logistical support for projects using the instruments. (Discussed principally in section 4.2 of this IRIS proposal).

2. It is proposed that a continuing national program of field studies of the continental lithosphere be implemented. Such studies are to range widely in terms of scale, methodology, and geological problems considered. PASSCAL, through its participating scientists, will coordinate a planning process whereby such projects are conceived and scheduled.

3. The period from FY 1985 through 1987 will entail the development of the new instrumentation, the acquisition of prototypes, and the definition and startup of support facilities. A program of field studies of the lithosphere using presently available equipment will address a number of significant geological and methodological problems during this interim period.

4. The period from FY 1988 through FY 1994 will involve the growth of the instrument complement to 1000 (by 1991) and the conduct of a continuing program of seismological studies of the lithosphere using these instruments.

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[2] The Consortium for Continental Reflection Profiling

3.2.3. Scientific Justification for PASSCAL

The justification for a new generation of portable seismic instruments deployed in large arrays is very simple indeed; it will produce qualitative new breakthroughs on a wide variety of fundamental problems in the study of the continental lithosphere. The variety of different seismic methods which have developed over the years can all be brought to a much higher level of performance than has been possible with conventional instruments. Moreover, the flexibility and standardization inherent in the new instrumentation makes it possible to conduct unified studies, in which these methods are simultaneously employed on the same target. It must be emphasized that both natural source and controlled source data are equally amenable to such studies; indeed, we expect that most major experiments would be planned to utilize both.

For each of the most widely used seismic methods, we can point to a great increase in power which has been demonstrated when the methods are used with dense arrays of large numbers of sensors.

(1) Refraction and wide-angle reflection: Wavefield continuation methods now make it possible simultaneously to determine velocity structure and to image the reflection (turning point) levels of these signals. Full use is made of the recorded wavefield, not just of the arrival times and amplitudes.

(2) Travel time analysis: Methods of analyzing refraction time anomalies (time term) or teleseismic P-wave anomalies are now equivalent to the tomographic methods first widely used in medical imaging. (Figure 3.5)

(3) Surface wave phase delays can now be analyzed tomographically, either by means of a large ring array or an area deployment. This can provide well-constrained and detailed S-wave structure, to complement P-wave velocities determined by other methods.

(4) Reflection profiling: While reflection studies are already conducted using array methods, (COCORP profiling, for example), the number, flexibility, and portability of the PASSCAL instrumentation will permit near-vertical reflection studies at a variety of scales, and with the areal deployments which permit 3-dimensional imaging. Extensive use of explosive sources for certain studies will also enhance the depth which can be detected relative to vibroseis methods.

(5) Network studies of local and regional earthquakes: With the network transformed to an array, this kind of earthquake data will be equivalent to controlled source data, and could be processed by wavefield and tomographic methods to produce not only detailed velocity and structural models but also dynamical images of the sources themselves.

(6) Studies of wave propagation: Dense arrays will permit special studies, using either controlled or natural sources, in which particular modes or wave groups can be accurately tracked over large distances. This will make it possible to investigate attenuation, scattering, and mode conversion in detail, and to conduct other fundamental studies of the effects of earth structure on particular phases.

The scientific flexibility of the PASSCAL instrumentation can also be considered in terms of logistical issues.

1. Large-scale cooperative studies. The greatest scientific return will be obtained when the full complement of 1000 instruments is deployed (and perhaps redeployed) over a problem area for a multi-method, multi-investigator cooperative study.
Examples (from the Program Plan, Appendix 2A):

a) Reflection and tomographic study of the active normal faulting in the Basin-Range, to trace surficial faults to depth, to examine the structural style of an active fault, and to determine the deep crustal and lithospheric structure across this boundary. This experiment would use local earthquakes, teleseisms, and controlled sources.

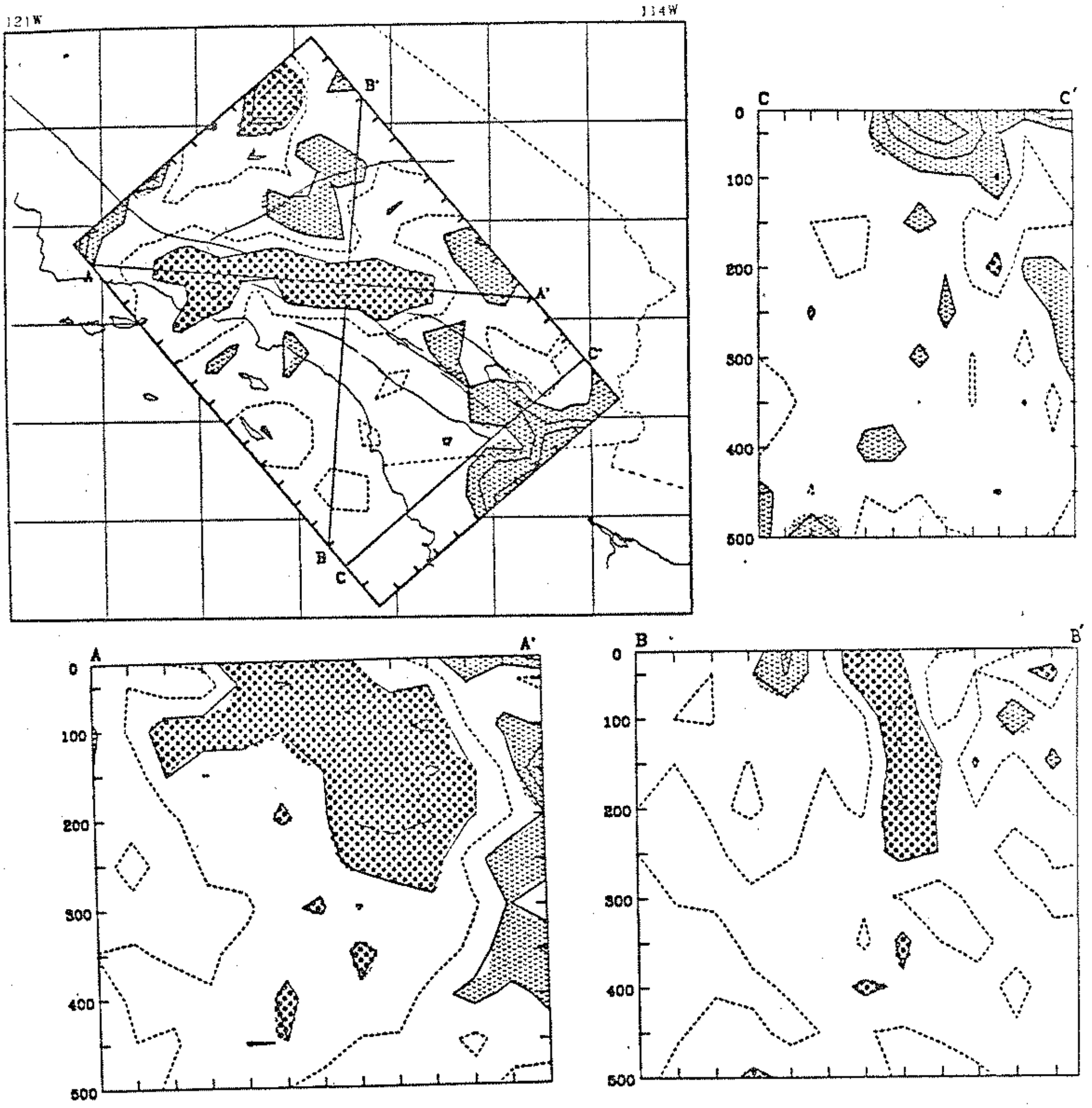

Figure 3.5. Cross-sectional images of the crust and upper mantle through the California Transverse Ranges were produced by tomographic analysis of teleseismic travel times at the Southern California array (200 stations). The availability of a versatile, portable array of 1000 instruments makes this capability available for any area at many different scales. 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 interval is 1.5% relative velocity deviations, with $> 1.5\%$ indicated by dotted areas and $\leqslant 1.5\%$ 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. (Humphreys, Clayton, and Hager, *Geophys. Res. Lett.*, *11*, 625–627, July 1984).

b) Long Valley, California multi-method controlled and natural source study of a shallow magma body and its related fault systems, in combination with boreholes and a fixed array.

c) Study of continental accretion in Alaska: Linear and areal deployments for narrow to wide angle reflections and velocity determinations. Use of natural and controlled sources.

d) Passive/active monitoring of the recent large earthquakes such as M= 7.3 Borah Peak (October 28, 1983) earthquake area. Use of area arrays for imaging aftershocks and tomographic reconstruction of the causitive fault. Detailed linear reflection lines for tracking an active fault.

Studies of this sort will engage a large fraction of the interested scientific community and of the funding. It is therefore envisioned that less labor-intensive modes of operation be employed for most of each year. This is achieved by putting out a large number of instruments in an array which is fixed for several months, to record regional and teleseismic earthquakes (passive array) or by farming out smaller groups of instruments (50– 100) to individual Principal Investigators for local studies.

2. Passive array deployments: Large regional arrays for study of mantle and crustal structure can be deployed in different patterns, depending on the resolution requirements and the methods to be emphasized... as circular arrays, grids, or networks. In every case, relatively small station spacing is emphasized at least in one dimension. Methods to be employed would include tomography using P-wave delays, wavefield continuation of body waves, surface wave phase tomography, and detailed modeling of regional events. Some supplementation of the data by controlled sources would be extremely useful.
Examples (from the Program Plan, Appendix 2A):

a) Colorado Plateau crustal and upper mantle structure using an area deployment with station spacing on a grid of about 20 km.

b) Pan-cordilleran experiment to study large-scale heterogeneities in the upper mantle from Alaska to California.

c) Surface-wave phase velocity tomography of the central U. S, using a near-circular array of 500 instruments.

3. Studies with smaller arrays: Groups of 50-100 instruments will be readily manageable by university research teams, given the logistical support facilities planned by PASSCAL. This will make it possible for investigators to conduct field studies of local geological targets, or in pursuit of some particular problem in wave propagation or experiment methodology, with minimum incremental cost.
Examples (from the Program Plan, Appendix 2A):

a) The mode of wave propagation and source mechanism of volcanic tremor.

b) Portable array for aftershocks studies of a 4.5 magnitude earthquake in eastern North America.

c) Mapping the Moho and the base of the Appalachian basin in the central Appalachians, using quarry blasts and a few explosions.

d) Monitoring the rupturing of a hydrofracture during a stress measurement in a drill hole.

e) Detailed studies in support of site selection associated with the continental deep drilling program.

In conclusion: The Program Plan for PASSCAL (Appendix 2A) contains a more extensive discussion along these lines, with many more examples. The National Academy Report (Appendix 2B) contains a thoughtful, basic discussion of key problems in the structure, processes, and history of the continents, and shows how the higher resolving power of a 1000 element array is perhaps the most versatile and powerful tool for obtaining fundamental new data. We endorse these discussions, and adopt them as an intrinsic part of our justification and plan.

3.2.4. Technical Justification for the PASSCAL Array Instrumentation

The impressive performance of a system of 1000 instruments is possible because for the first time instruments can be closely enough spaced on the ground to resolve subsurface details of geological interest and to 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 high bandwidth, dynamic range and resolution
- Its multicomponent, multipurpose sensors
- Its flexibility and portability
- Its calibration and standardization.

While existing arrays embody 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. Two distinct abilities arise from the large number of instruments. The availability of hundreds of instruments leads to an improved resolution of subsurface geologic features at scales mapped by geologists at the surface. For example, the difference between about 10 km resolution possible with current lithospheric tomography and the 1 km or better which is possible with PASSCAL is the difference between a fuzzy 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 determination of earthquake locations, focal mechanisms, and rupture mechanisms far more precisely than is now possible. A significant qualitative breakthrough occurs because enough sensors would be available to adequately sample the wavefield without spatial aliasing at frequencies up to 30 Hz. This opens up the full range of powerful wavefield processing methods which have been so important in reflection prospecting for hydrocarbons, in medical imaging, and in radio astronomy. Seismic imaging techniques (eg. migration and waveform inversion) that were hitherto used only for seismic exploration data can be applied to a wider frequency band and 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 another essential feature, since it allows large data sets to be rapidly analyzed 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 source to be observed in a single experiment. This ability is essential in large multidisciplinary experiments, which may consist of several simultaneous individual experiments.

The versatile sensors will allow three components of ground motion to be recorded, so that both P and S waves and their polarizations can be studied. While previous experiments have often treated the earth an an acoustic (fluid) body, the recording of 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 source studies.

The flexibility of the instruments, owing to their programmability and portability, 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. Another use of PASSCAL instruments will be in augmenting existing regional seismic networks with broadband standardized digital recorders. This capability can in part fulfill the NSA initiative for a National Digital Network.

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

3.2.5. Plan for Utilization of the PASSCAL Arrays

PASSCAL is organized to meet a need for high-resolution seismic studies of the earth's interior, and is conceived as a facility which is to be mobilized for a wide variety of studies proposed by the scientific community. The Science Plan for PASSCAL, therefore, is not a prioritized list of scientific targets, along with a planned ten-year time line, but is a meta-plan... a plan for organizing the scientific community so that it may most effectively bring forward projects and make use of the facilities and support services which are provided by PASSCAL. However, since the greatest power of a 1000 instrument system can be realized by deployment in a large-scale multi-method, multi-institution effort, the responsibility for PASSCAL to organize and plan is not trivial, particularly, if we seek to maintain the broadest degree of initiative and autonomy by the many participating Principal Investigators.

3.2.5.1. Organization of PASSCAL[1]

PASSCAL has two very distinct areas of functional concern: (1) The coordination of scientific plans and the formulation of policy through the participation of scientists from many different institutions; and (2) the management of an instrument pool, and support facilities, along with management supervision of instrument and software development, and field subcontractors.

For science planning and policy, the PASSCAL Standing Committee has the broadest discretion in setting the directions for the Program. Consisting of participating scientists chosen by the community and appointed by The IRIS Board of Directors, the Standing Committee oversees the work of its subcommittees:

Science Planning and Coordination
Instrumentation
Data Management
Scheduling

The operational branch of PASSCAL will be headed by a Chief Scientist, who reports to the Standing Committee and to the President of IRIS. Under the Chief Scientist will be a Chief Engineer, a programming staff, a logistics officer, and maintenance and deployment facilities run by a contractor (see Section 4.2).

3.2.5.2. Science Planning and Coordination

The PASSCAL instrumentation and support services constitute in effect a **national facility**, like an oceanographic vessel, which investigators or teams of investigators seek to use for data acquisition. The scope of PASSCAL operations, and the budget therefore, is defined by the requirement that PASSCAL support and underwrite the costs of data acquisition. While most of the **budget** is concerned with instruments and facilities, we have set out a budget category for **Special data acquisition costs**. These are costs which are specific to each experiment, and not appropriate for inclusion as a part of the baseline permanent staff and facilities. They include such costs contracting for drilling and shooting, per-day costs for extra field personnel (from participating universities), and special integration costs. An estimate of $3.05 million per year of these experiment-specific costs appears in the **ten year budget plan** (Chapter 6 of this proposal and Chapter 13 of the Program Plan). It is somewhat carefully defined to include experiments which require substantial integration by PASSCAL, and which therefore incur major costs, and to omit the spectrum of small-scale projects whose incremental field costs (beyond PASSCAL baseline services) are relatively small. This division has the effect that the majority of investigators with individual small projects would still fund their full project costs by unsolicited proposals to NSF or other agencies.

For investigators whose projects fall into the area where major PASSCAL resources and careful long-term planning and scheduling are required, the interface between PASSCAL and

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[1] Chapter 10. of the Program Plan (Appendix 2.A).

the individual investigator must be well-defined, and must equitably balance the traditional prerogatives of the investigator community with the PASSCAL needs for coordination and planning. Final authority on the scheduling of instruments and on the expenditure of resources for experiments will lie with the **Standing Committee**. The **Science Planning and Coordination Committee** (SPCC), however, will be the principal organ for coordinating the needs of prospective principal investigators and authorizing the major cooperative experiments.

Two mechanisms are being established to help bring this about.

(1) The SPCC will hold regular open **workshops** for the discussion of potential experiments and to facilitate the formation of investigator teams for the major experiments. One or two of these workshops will be regularly scheduled per year, and others may be called to initiate advanced planning for specific projects. The regular workshops will be held in conjunction with AGU national meetings, and will be used to encourage innovative approaches.

(2) The SPCC, like PASSCAL as a whole, will make extensive use of an electronic mail and bulletin board service, for exchange of ideas, for circularization of interested scientists, and for insuring that all who desire to participate are able to do so.

The formalities of the process of final authorization and scheduling of the major experiments still remain to be worked out by the Standing Committee in consultation with the SPCC. It is generally, but not universally, felt that a community-oriented consultation and consensus process for defining and selecting major projects has many long-term benefits. A similar situation exists in the oceanographic community, where scheduling ship time continually forces investigators to compromises which work for the maximum overall benefit. PASSCAL is open to the possibility that a strictly competitive "shoot-out" may be an appropriate step in the scheduling process, but plans to develop some initial experience in planning experiments for the interim period FY 1985–87, before settling all such issues.

3.2.5.3. Lithospheric seismology experiments FY 1985–87[1]

Over the past four years, adequate extramural support for major lithospheric field studies from government agencies has been quite lacking; the U. S. Geological Survey projects using 120 analog instruments have been the only significant source of innovative new array-based field work outside of industry but are not generally available to the University community. This hiatus in support has been justified on the ground that such major projects and large costs can only be supportable if they represent a truly national program.

PASSCAL is exactly that national program, as recommended before the 1984 National Academy Report. In consequence, it is necessary for the U. S. to return to a regular flow of major seismological field studies of the lithosphere. With a significant number of the new PASSCAL instruments planned for acquisition by 1988, it is particularly important that interim studies be carried out to:

(1) Develop a base of experience with the operation of large numbers of instruments.

(2) Develop a base of experience in coordinating and utilizing many investigators and simultaneously applying several seismic methodology.

(3) Develop a base of experience in managing and interpreting data from large integrated experiments.

At the PASSCAL organizational meeting in Madison, Wisconsin on January 13–14, 1984, 77 representatives from 55 institutions strongly urged that this program of interim experiments be given an early start and high priority.

The Science Planning and Coordination Committee (SPCC) has begun the process of planning for three annual cycles of interim experiments. A list has been compiled of lithospheric experiments planned for the present year, to serve as a starting point for defining the

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[1] Chapter 14 of the Program Plan (Appendix 2.A).

interim PASSCAL experiments.

Long Valley, California magma chamber study
Maine/Quebec deep lithospheric studies
Trans-Alaska Lithospheric Investigations
Newberry Craters, Oregon hydro-magmatic system
Southern Appalachian drillsite characterization
Ouachita System, deep lithospheric structure

The SPCC is preparing a calendar to announce its plans for defining interim experiments, to elicit some partially-defined projects from the scientific community, and to meet at the December 1984 AGU meeting to begin formulating a schedule of experiments. 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 judged 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. Single investigator small-scale projects will be important to continue and will continue to receive high priority. It is hoped to announce the schedule for the first year of interim studies in January, 1984.

Interim experiments: goals and approaches

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. 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. Available instruments include 120 matched analog instruments owned by the U. S. Geological Survey, several dozen 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 online, it will not be possible to collect appropriate data using natural sources. 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.

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† It is to be emphasized that these instruments, while numbering in the low hundreds, are wholly inadequate to function as the kind of system PASSCAL is developing. None can record natural events. Many 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, it will also illustrate their inadequacy as an imaging system for state-of-the-art seismic studies of the lithosphere.

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 1000 element system. *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-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 FY86 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.

Interim large-scale experiments: calendar and cost

Cost figures for the interim experiments are highly preliminary, since the experiments will not be defined until early 1985. We use a model in which seismic group recorders (SGR) are employed and 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.

The large-scale experiments are budgeted at \$400K, \$700K, and \$1100K, respectively, for FY85–87. The costs are proportional to the expected total effort as measured by sources (dynamite and vibroseis), by participation, and by time spent in the field.

Small-scale development programs

A number of specifically technical issues need elucidation before a full-scale program can be mounted with the new instruments. Among these issues are:

(1) Calibration of the performance of different sources with respect to narrow and wide-angle signals for depth of penetration, frequency characteristics, and site dependence.

(2) Statistical (spatial) characteristics of deep reflections on two-dimensional receiver patterns: needed to judge the tradeoffs involved in design of three-dimensional investigations.

(3) Development and testing of trigger algorithms for passive monitoring mode. These need to cope with multiple event types and with natural events mixed with artificial ones. Most of this work would be done using existing data from long- and short-period networks.

(4) Sensor comparisons under realistic field conditions.

A budget line has been set aside for these activities which can be carried out by individual universities as subcontractors. It is planned to issue an invitation to participating institutions to submit proposals for projects in these areas. We expect that a comprehensive invitation which encourages initiative will be preferable to a series of narrowly focused RFP's. This invitation will be formulated and distributed to the scientific community in early calendar year 1985. Budget figures of \$150K, \$250K, and \$250K, respectively are proposed for FY85–87, under *Experiment support costs: Small-scale experiments.*

3.3. Data Management Center Plan

The function of the Data Management Center (DMC) is to assure that the high-quality data sets generated by the GSN and PASSCAL data collection systems together with appropriate data subsets obtained from other U.S. organizations and from other countries are made available to the seismological user community in a timely manner and in a tractable form. The goal is to make it possible for a researcher to concentrate primarily on the analysis and interpretation of data rather than the assembly of usable data sets. Thus, effective dissemination of data to research seismologists is the single priority that drives the overall Data Management Center requirements.

The extraordinary advances in all aspects of digital computing technology over the past decade have provided the technical resources to handle the data volumes anticipated under the IRIS programs. As in most large data gathering efforts, the real challenge is effective data management. The rationale for structuring the proposed Data Management Center is that effective distribution of data to users in desired forms for analysis and interpretation must drive the data management system that is developed. Provisions for incorporating further advances in computer hardware and software capabilities, as needed, are also important ion structuring the Data Management Center.

The guidelines used in establishing the functional requirements of the proposed DMC included in Appendix 3A come from the discussions of the scientific data needs that appear in the accompanying GSN and PASSCAL plans and from the recommendations of recent National Academy of Sciences reports concerned with data management problems in seismology (Ref. 7) and related areas. The proposed IRIS Data Management Center will serve the seismological user community through the dissemination of both IRIS-generated data, and certain selected seismological data collected by other U.S. organizations and by other countries. It will serve the role of a national data center for digital seismological studies in the sense recommended in Reference 7, but it is not intended to provide a comprehensive archival source of all available digital seismic data that are being collected nationally or internationally.

The Data Management Center will be required to handle and distribute digital data that span the spectrum from fixed network recordings (GSN and subsets from other U.S. and foreign networks) to controlled-source portable array recordings generated by PASSCAL experiments and selected data from other U.S. or foreign experiments. Liaison and data exchange with other countries or international organizations engaged in data collection activities of importance to the IRIS program, will be an important aspect of the data management center's activities. In some respects, the mixed mode of fixed and portable array recordings of earthquakes (or explosions) over a protracted time interval will present the most challenging data management problems. Close communication and coordination with the GSN and PASSCAL standing committees will be essential from the beginning of the IRIS program to assure that the scientific needs that prompted the GSN and PASSCAL initiatives are met. Continuous feedback from users is planned and will be strongly encouraged to help assure effective dissemination of the data.

The approach proposed is to develop in the first 18 months the detailed design requirements for the Data Management Center that will be needed to accommodate the schedule of data collection anticipated under the GSN and PASSCAL science plans (Sections 3.1 and 3.2 and related appendices). Allowing time for procurement and installation, the resulting facility would become operational during the third year (FY87).

The Data Management Center must be developed early in the IRIS program to provide for effective and timely distribution of IRIS data and supplementary related data to users. However, there is a critical immediate need to disseminate digital data already being collected with existing seismic systems of both GSN and PASSCAL types.

Therefore, while the IRIS data center facility is being developed, early data distribution and data management experiments are planned for the first two years using existing facilities that have been developed for other purposes. These experiments will serve to provide useful prototype IRIS data to the seismological community immediately for use in current research and to get important feedback on which modes of distribution are likely to be most effective when the IRIS data collection systems are complete and in full operation.

The functional requirements of the DMC, as elaborated in Appendix 3A, include:

a. Comprehensive data directory that provides information on the holdings of the Center and attributes of the data sets available.

b. A digital waveform data base consisting of IRIS data supplemented with other selected waveform data from U.S. or international sources.

c. An effective relational data base management system that can accommodate the spectrum of anticipated user requests.

d. The capability to complete the processing of large PASSCAL data sets to make event associations and sort the data for each source.

e. The capability to process GSN data in near-real time for event detection, location, and source parameter estimation and to rapidly disseminate selected signals for large earthquakes.

f. Communications interfaces that can access other data bases and that allow users to access the Center's data bases remotely.

g. Modes of distribution that can accommodate both the least and the most sophisticated types of user access (e.g., written request to dedicated high-speed links to the DMC).

h. User services that facilitate access to data and information held at the DMC in forms most useful to the researcher (e.g., quick look of browse for waveform data, or assembly of multiple channels of data into desired configurations for analysis). User guides and training or help sessions must be routinely available.

i. Provisions for visiting scientists to be in residence at the Center for varying intervals of up to approximately one year.

j. Capability to exchange data and information with counterpart data centers in other countries in such a way that there are no barriers to user access to desired data sets.

k. Ongoing development and upgrading of both hardware and software to keep pace with advancing technology and user demands for IRIS data.

The DMC will operate under the direction of a Program Manager who will be responsible fore the proper performance of all data center activities as defined by the DMC Standing Committee of IRIS. Close coordination and interaction with the GSN, PASSCAL, and Computational Facility activities and with counterpart international data centers will be essential.

3.4. Geophysical Computational Centers

3.4.1. IRIS Computational Requirements

The computational needs for IRIS spans the range from mini-computers thru class 6 super-computers. In this discussion, the focus is on the need for large computational requirements. Requests for computers associated with: 1) field playback, 2) routine data processing, 3) engineering design, and 4) limited single-institution computing are not addressed as major elements in this proposal but are addressed as justified in the specific program plans.

The general needs for IRIS super-computers fall primarily into three classes: 1) synthetic seismograms, 2) inversion of seismic data, and 3) special data processing. For example PASSCAL and GSN requires large-scale computing for tomographic inversion and migration of two- and three-dimensional data sets while reconstruction of earthquake sources requires a great deal of now unavailable computing power. Synthetic seismograms, from two- to three-dimensional ray theory thru finite-difference/finite element techniques, necessitate large computers and vector processors. Special data sorting, editing and merging for three-dimensional reflection/refraction data, now used by industry, are best addressed by large-scale computers and will be required in the Data Management facility. There is clearly a demonstrable need for class 6 super-computers (or equivalent) that are readily accessible to individual users as well as the general IRIS operation.

How and where the large-scale computational facilities are located or distributed cannot be addressed until the main program elements are developed and in place. However more than 50% of the IRIS member institutions were involved in the recent submissions to the NSF Super Computer initiative for support of seimological computations and demonstrates the need for an identifiable and separate initiative for IRIS super-computing needs.

3.4.2. Supercomputers

Given the quality and quantity of data forthcoming from PASSCAL and GSN, it is obvious that seismologists will be deeply immersed in data and signal processing and will be plunged into three dimensional modeling on a scale very much greater than the present one. The seismologist and the computer will become a team of complementary members. A humorous summary of that complementarity, as given by T. Wipke, is:

	Scientist	Computer
Memory:	slow, unreliable	fast, reliable
Experience:	biased	unbiased
Evaluation:	global	local
Searches:	heuristic	exhaustive
Motivation:	high level	very low level

One of the major questions to be answered by the scientist is — what kind of computer should be on the team? In a recent comparison S. Hagstrom used a variety of programs to evaluate the performance of computers, large and small, in quantum chemistry software. The following cost comparisons of his are taken from a report to NSF from the International Symposium on the Impact of Computers on the Quantum Theory of Matter (Palm Coast, Florida, March 13, 1984)

Table 3.1

System	Price	Rel. Speed	Price/speed
IBM PC/8087	$ 4,000	0.1	$ 40K
IBM XT/8087	6,500	0.1	65K
VAX 11/730+ FPA	50,000	0.25	200K
VAX 11/750+ FPA	120,000	0.6	200K
VAX11/780+ FPA	200,000	1.0	200K
CDC 855	2,500,000	10.0	250K
VAX 11/750+ FPS164	500,000	10.0	50K
CDC 855+ CYBERPLUS	4,200,000	60.0	70K
CRAY 1M	4,500,000	100.0	45K

(Maintenance and operational costs are not included in the comparison.) The disappointing (i.e. expensive) part of the price/speed range is in the regime of supermini to mainframe. These least cost effective machines are convenient to use, which must account for their appeal. Once the machines in the other, cost effective categories become more convenient to use, one presumes that they will become more popular. Since the microcomputers are convenient to use at the present time it is the larger machines that are worth discussing. These are: 1) the supermini or mainframe with attached processor, and 2) the supercomputer.

An article by K. Berney in Electronics (July 12, 1984 pp 4546) describes an IBM project, directed by E. Clementi, in which three 4000 series computers and 10 FPS-164 array processors operating as a distributed system almost match the speed of a Cray 1S. This is a very interesting development that deserves to be closely watched by the seismological community. At present the convenience of using the IBM system is difficult to assess. What is wanted is a compiler and operating system that automatically adapt the user's code to the multi-mainframe, multi-attached processor system. Then the convenience will match that of a typical supermini if the system can operate in a time sharing mode.

In the US there are two major supercomputer vendors, ETA Systems, a spinoff of Control Data Corp., and Cray Research, Inc., essentially a CDC spinoff, also. In the quantum chemistry report, mentioned above, is a summary of a presentation by M. Kascic on the ETA GF-10, a 10 Gflops (giga floating point operations per second) successor to the CDC CYBER-205. The system will consist of 8 processors with a maximum of 32 Mword (64 bit) memory, and 256 Mword shared memory. Each processor will have a vector "pipeline" (800 Mflops using 64 bit words) and a scalar arithmetic unit (200 Mips). Shipment will not occur before 2Q 1987. The end of the product line is planned to be the 30 Gflops GF-30 planned for LQ 1990. The planned machines are very impressive but their convenience of use is impossible to assess.

There are now no CDC CYBER-205 machines with a time sharing operating system. However, the older CDC Star-100 and 7600 machines at Livermore do operate under LTSS, the Livermore Time Sharing System. The former is one of the first "pipeline" processors. Thus, there is reason to hope that the GF-10 will have a convenient time sharing system by 1990. Estimates of the effort involved to develop such a system range between 2 and 20 man years.

Cray Research Inc. (CRI) has moved beyond the 1A, 1M and 1S machines which are single CPU, vector mode machines. There is the Cray 2, supposed to be a GaAs based machine of advanced architecture about which little is known. A direct outgrowth of the Cray-1 series in the multiprocessor Cray X-MP. The X-MP clock rate is 9.5 ns versus 12.5 ns for the -1 series. This gives each processor of the X-MP a nominal rate of about 210 Mflops. The current "top of the line" is the model 4-8, a 4 processor machine with 8 Mwords of memory. Shipment is scheduled for 4Q 1984 or sooner. Benchmark tests conducted at Los Alamos show one X-MP processor to be 200 to 850 times faster than a VAX 11/780+ FPA, depending on the type of code being tested. Future plans call for the model 16-32, a 16 processor machine with 32 Mwords of memory, to have a 4.5 ns clock. This would give each processor in excess of 400 Mflops performance with over 7,000 Mflops, or 7 Gflops, for the whole machine.

The -1 series at Livermore and Los Alamos operate under a system now called CTSS, the Cray Time Sharing System. This means that the Cray computers are as convenient to use as a supermini. Furthermore, CTSS is being modified for the X-MP series. It is not yet possible in FORTRAN/CTSS to do multitasking or concurrent processing (i.e. access 2 or more processors from a single program). It is possible in FORTRAN/COS (Cray Operating System, a batch mode system) and within the next several months CTSS should accommodate multi tasking. This means that the user can have convenient, time sharing access to a multiprocessing, multi tasking supercomputer.

Therefore, the seismological computing needs for PASSCAL and GSN are most likely to be met by a supercomputer facility operating a time sharing system. It should be very cost effective, as well as convenient. Also it would have the mass-store/tape library facilities to support the seismological databases.

As an example of cost consider a facility based on the Cray X-MP model 4-8. Each processor can deliver about 8,000 hours/year for a total annual amount of 32,000 CPU hours. The cost of operating such a facility is roughly \$16M–24M depending on the number of remote sites, and the size and number of the other peripheral equipment (S. Karin, GA Technologies, personal communication, August 22, 1984). This translates to less than \$1,000/CPU hour for a processor at least 200 times faster than a VAX 11/780+ FPA. The price-performance figures in Table 3.1 are borne out in this comparison. It is doubtful if one can operate a supermini for $5 or less per CPU hour.

Fortunately for the interested scientist, there is a new NSF program in Advanced Scientific Computing. The program is expected to receive $40M in FY85 and select to fund between 0 and 3 supercomputer facilities in 1Q 1985. Full scale operation should begin about one year thereafter.

From the point of view of IRIS it is prudent to approach NSF with the request that IRIS be served by more than one of the supercomputer facilities to be established. IRIS should ask in 1Q 1985 for supplemental equipment for some of the specialized needs of seismological computing. The advantage of this mode of behavior is that the experience gained by using one or more of the NSF sponsored supercomputer facilities could serve in future years as a basis to answer the question whether IRIS ultimately wants to operate a dedicated seismological supercomputer facility.

At the present time the IRIS plan should be to gain experience at one of the NSF supported facilities. For data and signal processing and for arithmetically intensive computing it is very desirable that the facility have a flexible, interactive, time sharing operating system. At Los Alamos 95% of the supercomputer CPU time is delivered to the user by the time sharing system.