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Lamont Geological Observatory
Columbia University
Palisades, New York 10964

CONTRACT NO. AF19(628)-4082
PROJECT NO. 8652

FINAL REPORT

PERIOD COVERED: 1 August 1964 - 31 July 1968
DATE OF REPORT: September, 1968

Contract Monitor: Clent Houston, Maj. USAF
Terrestrial Sciences Laboratory

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Prepared for

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
BEDFORD, MASSACHUSETTS 01730

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RESEARCH DIRECTED TOWARD THE USE OF LONG AND INTERMEDIATE PERIOD SEISMIC WAVES FOR THE IDENTIFICATION OF SEISMIC SOURCES

by

KEITH McCAMY

Lamont Geological Observatory
Columbia University
Palisades, New York 10964

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Abstract

In the period covered by this report, Lamont Geological Observatory has made significant advances towards the use of long and intermediate period seismic waves for the identification of seismic sources. Our increased understanding of many features of the seismogram has enhanced its utility in detecting and identifying small seismic events. The recently stated principles of global tectonics have shed new light on the problems of world seismicity, source mechanisms and the location of seismic events. The structure and causes of seismic noise which limits the effectiveness of all detecting instruments are now understood so well that much of the noise can be predicted. A large network of long and intermediate period instruments has been operated, and new high sensitivity, broad-band, low noise instruments have been developed which have proved especially effective for detecting small events. A study of the relative excitation of surface waves by earthquakes and explosions revealed it to be a powerful discriminant between the two sources. The steady development of computer programs has permitted rapid and sophisticated analysis of both conventional and Large Aperture Seismic Array data. Thus many of the goals of this research have been attained and important progress has been made toward detecting and identifying seismic events.

In the following paragraphs, scientific accomplishments under Contract AF19(628)-4082 during the period 1 August 1964 through 1 August 1968 are summarized following the itemization in the "Statement of Work" for the contract.

Item 1 - "Investigation of the applicability to intermediate (2 to 10 sec) and long (10 sec and greater) period seismic waves of phase compensation techniques for the purpose of determining an effective source polarity as a function of azimuth. In this connection worldwide charts or tables of phase and group velocity for surface waves of various periods will be compiled."

A compilation of all representative phase velocity dispersion data published in the literature has been made by Dr. J. Dorman and a completed manuscript entitled "Seismic Surface Wave Data on the Upper Mantle" has been submitted for publication. This constitutes a comprehensive survey and covers all areas of the world where studies have been made. Dispersion data were plotted for various period ranges and were separated on the basis of geological differences. The data indicate that important regional differences within the continents and between continents and ocean basins are present in the upper mantle as well as in the crust. Numerous data confirm the observation that wave velocities for ocean basins are intermediate between low values for mountain tectonic regions and high values for continental shield regions. The dispersion characteristic for tectonically disturbed regions is consistent with observations of higher heat flow in these regions. More phase velocity data based on regional differences are required in order to effectively utilize phase compensation techniques.

Item 2 - "Development of high speed computational techniques for the solution of the normal-mode propagation problems and the Fourier analysis and synthesis problems that arise in connection with Item 1."

The following scientific data processing programs have been developed with the support of the two contracts.

A) An algorithm due to Cooley and Tukey makes it possible to reduce the number of basic operations (multipication and addition) in a Fourier analysis from N^2 to approximately $N \log_2 N$. A program that makes use of this algorithm has been constructed for the IBM 360. Comparisons in computing time and quality of the spectra of free oscillations were made with spectra obtained by the usual method. The new algorithm was found to be much superior in these respects, particularly in saving computer time.

B) A program has been developed for IBM 1800 for computing and plotting travel-time curves for an earth model in which seismic velocity is a continuously varying function of radius. The velocity model is specified as a table of velocity vs. depth. Discontinuities in the velocity structure are permitted. A surface focus calculation is operational and a deep focus feature is being debugged. The curves are plotted on an attached Calcomp plotter. Boundaried of shadow zones, multiple branches, and other complications are defined in the output.

C) A program which fits amplitude and time for an arbitrary combination of pulses against an observed phase from a seismogram has been rewritten for the IBM 1800 digital computer to include variable width of trial pulse, representing a stopping phase, generated by superposition of the theoretical response of a layered half space and seismograph to a source represented by a step function of stress in time.

D) Magnetic tapes containing the parameters of principal seismic stations and the data for about 32,000 earthquakes located by the USCGS for the entire world for the period January 1, 1961 to March 31, 1968 have been prepared both in chronological order and by geographical location. The tapes are being continuously updated. Subroutines were developed for rapid searching, for incrementing the file, and for plotting the data on a Calcomp plotter using an IBM 1800 computer. These tapes are being used extensively in making seismicity studies of the hypocenter file itself, for selecting events for study from the WWSSN film-chip library, and for other studies. Detailed seismicity maps of selected regions using the entire USCGS epicenter file have been made and a manuscript, "World Seismicity Maps Compiled from ESSA, Coast and Geodetic Survey, Epicenter Data, 1961--1967," is in press.

E) A review manuscript entitled "Computer Methods in Seismology" which reviews all significant developments in this field, was included in the 1967 report of the U. S. National Committee to the International Union of Geodesy and Geophysics (Dorman, 1967).

F) A computer program has been written for the IBM 1800 to plot focal mechanism data automatically on an equal-area projection.

Item 3 -- "Develop techniques for analyzing microseismic data and conduct studies of the microseismic spectra."

Work carried out in this area is discussed under LASA data, Item 7.

Item 4 -- "Development of seismic instrumentation with increased sensitivity in the long-period range and with improved discrimination against noise in the dominant microseism band."

Three long-period Sprengnether seismometers were installed in the Ogdensberg Observatory and initially were run as a standard 30-100 system. Concurrently, a long-period Geotech seismometer was installed in the Palisades seismic vault, and its response was made similar to the instruments at Ogdensberg. High-quality signal-to-noise records were obtained at both sites. Both system magnifications were then increased to 80,000 in the period range 20-80 seconds by the use of Geotech long-period photo-tube amplifiers. These instruments have been operated continuously since their installation with numerous changes in coupling and filter parameters. The records from these systems have been examined for surface waves recorded from small magnitude events, but the studies are still preliminary.

During the past quarter year the operation of the N-S and vertical Sprengnether long-period, high-gain control seismometers has continued in the mine at Ogdensberg, New Jersey. With a gain of approximately 100,000 at 30 seconds and a frequency response of a 30-100 instrument, waves within the period range 15 seconds to a few minutes are regularly recorded.

Of particular interest was the presumed French explosion of August 24, 1968, from which long-period body phases, P, S, SKS, SS and surface waves were clearly recorded. The signal to noise ratio of the surface waves at 40 sec was 5 to 6 to 1 on the high-gain vertical. Periods as long as at least 60 seconds are easily recognized.

Within the past month two of three matched long-period seismometers were installed in separate pre-stressed, air-tight tanks in a newly developed sealed drift in the mine. These instruments are the E-W and verti components. Each is equipped with 3 transducers: two coil and magnet assemblies and one capacitor-plate transducer.

To date, one coil and magnet assembly from each component provides a standard 6000 gain 30 - 100 recording. Photo-tube amplifiers will be added to the second velocity transducer on each component and gains of 500,000 will be attempted together with strip-chart recording.

The capacitor-plate transducers have already provided records of tidal tilts and gravity changes from the E-W and vertical components respectively. The ability to look at this extremely broad spectrum of frequencies is a result of the well-controlled environment.

The N-S component will be installed shortly.

<u>Item 5</u> - "Operation and maintenance of the widely distributed network of long- and intermediate-period seismic stations that were initially put into operation in connection with the International Geophysical Year plus the central station at Palisades, with such changes in numbers, location, and instrumentation as may be deemed desirable for the performance of the contract. Changes in the numbers and locations of stations are not to be made without the prior written approval of the Contracting Officer."

The operation of the Lamont Geological Observatory's worldwide network of long-period seismograph stations including Palisades and Sterling Forest continued under the support of the present contract and will terminate 30 April 1969. Stations of this network include the following:

Station Code	Station Name	Latitude	Longitude
PAL	Palisades, N. Y.	41 00 25.0 N	73 54 31.0 W
SFO	Sterling Forest, N. Y.	41 12 30.0 N	74 15 00.0 W
BAA	Buenos Aires, Argentina	34 35 30.0 S	58 29 00.0 W
LWI	Lwiro, Congo	2 14 18.0 S	28 48 00.0 E
ELI	Elizabethville (Karavia) Congo	11 38 00.0 S	27 25 00.0 E
*HUA	Huancayo, Peru	12 02 [illegible].1 S	75 19 22.1 W
*HON	Honolulu, Hawaii	21 19 18.0 N	158 00 30.0 W
HKC	Hong Kong (WWSSS)	22 18 12.8 N	114 10 18.8 E
PIE	Pietermaritzburg, S. Africa	29 37 12.0 S	30 23 48.0 E
TOO	Toolangi, Australia	37 34 17.0 S	145 29 26.0 E
UPP	Uppsala, Sweden	59 51 29.0 N	17 37 37.0 E
RDJ	Rio de Janeiro, Brazil	22 53 42.0 S	43 13 24.0 W
*MTJ	Mount Tsukuba, Japan	36 12 39.0 N	140 06 36.0 E
*BOK	Bokaro, India	23 50 00.0 N	85 48 00.0 E
EIC	Easter Island, Pac. Ocean	27 09 29.0 S	109 26 04.0 W
*CAN	Canberra, Australia	35 19 15.0 S	148 59 55.0 E
COL	College, Alaska	64 54 00.0 N	147 47 36.0 W

Item 6 - "Investigation of the general characteristics of seismograms such as presence or absence of phases, dominant surface wave periods, duration, etc., as a function of source mechanism, region and focal depth, and the relation of these features to the problems of detection and identification of seismic events."

A) Relative excitation of surface waves by underground explosions and earthquakes.

The relative excitation of body and surface waves by Longshot and 29 earthquakes which occurred in the Aleutian Island chain were analyzed and compared. Longshot produces surface waves equivalent to those from an earthquake of surface wave magnitude $M_s = 3.9$ and body waves equivalent to those from an earthquake of body wave magnitude $m_b = 6.1$. The empirical relationship between M_s and m_b of Gutenberg and Richter predicts a surface wave magnitude of $M_s = 5.7$ for an earthquake of body wave magnitude $m_b = 6.1$. This is much higher than the observed surface wave magnitude of $M_s = 3.9$ which means that Longshot generated surface waves which were 50 times smaller than would have been predicted from the body wave magnitude. The 29 earthquakes verified the relationship between M_s and m_b of Gutenberg and Richter for the tectonic province of Longshot.

Surface-wave magnitudes (M_s) of 4.1 and 3.2 were subsequently determined for two events in southern Algeria. The corresponding body-wave magnitudes (m_b) were 5.8 and 4.9 respectively. The surface waves from these events are much smaller than would be expected from most earthquakes of comparable body-wave magnitudes, which fact suggests that these waves were generated by underground explosions.

The study of the relative excitation of surface waved by underground explosions and earthquakes was then extended to include events from 5 distinct geographical and tectonic regions of the world: the western United States: the Aleutian-Kamchatka area: southern Algeria: central Asia: and Novaya Zemlya.

Initially, a detailed analysis of events in the western United States was performed to evaluate certain identification criteria. For the limited population of events, the surface-wave magnitude (M_s) of Gutenberg provided a greater capability for separation of the earthquake and explosion populations than the AR parameter introduced by Brune, Espinosa, and Oliver. On this basis, the analysis of surface-wave magnitudes was extended to events in other regions of the world.

For all of the events and regions studied ($m_b > 5$), it was found possible to separate the underground explosions and earthquakes on the basis of their surface-wave and body-wave magnitudes. The M_s versus m_b data for events in the western United States are anomalous with respect to world-wide averages for both the earthquakes and underground explosions. This has led to the conclusion that it is necessary to compare the M_s M_s versus m_b data for explosions with earthquake data from the same region.

A detailed discussion of the source characteristics of earthquakes and underground explosions was undertaken to explain the observed M_s versus m_b behavior. With the help of theoretical models the amplitudes of P waves and Rayleigh waves were related to the dimensions of the source in space and time. The ω-square earthquake model of Aki and the explosive-source analyses of Ben-Menahem and Cisternas and Harkrider lead to theoretical M_s versus m_b curves which adequately account for the general features of the empirical data.

A manuscript summarizing the results of this study, "Relating Excitation of Surface Waves by Earthquakes and Explosions" by R. Liebermann and P. W. Pomeroy, has been submitted for publication to the Journal of Geophysical Research.

B) P and PcP for explosions and earthquakes.

Amplitude spectra were obtained from short-period PcP and P phases from sev seven explosions and six earthquakes. The results are summarized in a paper, "Amplitude Spectra of PcP and P Phase," by G. R. Buchbinder which is in press.

PcP and P amplitude spectra for both explosions and earthquakes are similar for any one event; therefore, station and core-mantle boundary effects are small and the general shape of the spectra is related to the source. All of the explosions studied have characteristic spectra with a pronounced minimum in the spectrum near one second. The period of this minimum increases with magnitude of the event. Short-period amplitude spectra from some intermediate- and deep-focus earthquakes resemble those from explosions. Spectra from the other earthquakes studied differ markedly from those of explosions: they have either no minimum in the spectrum near one second or very little energy for periods less than one second. The characteristics of the spectra may be of help in the classification of sources. On a plot of magnitude m_b versus period of the minimum T_d in the spectrum of explosions, the data form a straight line. Earthquakes with an amplitude spectrum similar to that of an explosion are randomly distributed on the plot of m_b versus T_d. Systematic effects of focal depth were not observed. Layering at the core-mantle boundary was not detected.

C) Focal Mechanisms.

The work on the focal mechanisms of earthquakes on the mid-oceanic ridges by Sykes (1967, 1968) shows that source mechanism solutions of high precision can now be obtained for a large number of earthquakes with magnitudes as small as 5.5. When first motions were read from long-period instruments of the WWSSN, Canadian and Lamont networks, less than 1% of the data were inconsistent with a quadrant distribution of the first motions of P and PKP phases. The earthquakes on the oceanic ridge system and along the continental extensions of this ridge system into Siberia and East Africa were characterized by a predominance of either normal faulting or strike-slip faulting. Hence, at least some of the stations recorded dilatations from these events. The source mechanism of all of these events falls into the category of earthquakes and not explosions. One of Sykes' best examples of normal faulting was the earthquake of August 25, 1964 near the coast of northern Siberia (m = 6.1). A focal mechanism study based on P and S wave first-motions has been completed for 22 recent earthquakes in the Indian Ocean by Banghar and Sykes. The data used in this study were also obtained from the long-period instruments of the World-Wide Standard Station Netowrk. A similar study of mechanisms of earthquakes near the west coast of the United States has been published by Tobin and Sykes (1968). Studies of source mechanisms of earthquakes such as these are of the greatest significance to the VELA-UNIFORM program.

D) Seismology and the New Global Tectonics.

Isacks, Oliver and Sykes (1968) have made a comprehensive study of the of the observations of seismology and found widely based strong support for an earth model that they called the New Global Tectonics. This model is founded on the hypotheses of continental drift, sea-floor spreading, transform faults, and underthrusting of the lithosphere at island arcs.

Seismic phenomena are explained, in general, as the result of interactions and other processes at or near the edges of a few large mobile plates of lithosphere that spread apart at the ocean ridges where new surficial materials arise, slide past one another along the large strike-slip faults, and converge at the island arcs and arc-like structures where surficial materials descend.

Study of world seismicity shows that most earthquakes are confined to narrow continuous belts that bound large stable areas. In the zones of divergence and strike-slip motion, the activity is moderate and shallow and consistent with the transform fault hypothesis; in the zones of convergence, activity is normally at shallow depths and includes intermediate and deep shocks that grossly define the present configuration of the downgoing slabs of lithosphere.

The downgoing slabs were found to be zones of extremely efficient propagation of seismic waves, particularly high-frequency waves. In the Tonga arc, for example, signals 100 to 1000 times larger than normal are found for paths along the deep seismic zone. These zones of efficient transmission may be of great importance to the detection and identification of seismic events.

Molnar and Oliver have examined the presence or absence of these high-frequency seismic waves for several thousand paths throughout the earth. They have identified zones of high and of low attenuation in many areas.

Seismic data on focal mechanisms give the relative direction of motion of adjoining plates of lithosphere throughout the active belts. The focal mechanisms of about 100 widely distributed shocks give relative motions that agree remarkably well with Le Pichon's simplified mode model in which relative motions of six large and rigid blocks of lithosphere covering the entire earth were determined from magnetic and topographic data associated with the zones of divergence.

Two principal types of mechanisms are found for shallow earthquakes in island arcs: the extremely active zone of seismicity under the inner margin of the ocean trench is characterized by a predominance of thrust faulting, which is interpreted as the relative motion of two converging plates of lithosphere; a less active zone in the trench and on the outer wall of the trench is characterized by normal faulting and is thought to be a surficial manifestation of the abrupt bending of the downgoing slab of lithosphere.

Several different methods yield average rates of underthrusting as high as 5 to 15 cm/year for some of the more active arcs. The thickness of the seismic zone in a part of the Tonga arc where very precise hypocentral locations are available is less than about 20 km for a wide range of depths. This extreme thinness apparently is typical of at least some other island arcs (Sykes, Oliver and Isacks, in press) and is of great importance in the identification of events from these regions as earthquakes.

The interaction of plates of lithosphere appears to be more complex when all of the plates involved are continents or pieces of continents than when at least one is an oceanic plate. The New Global Tectonics suggests new approaches to a variety of topics in seismology including earthquake prediction, the detection and accurate location of seismic events, and the general problem of earth structure.

E) Depth and Time Distribution of Aftershocks and Microaftershocks.

An analysis of the magnitude distribution of aftershocks following the 1964 Alaska earthquake indicated a serious bias in the magnitudes computed by the U. S. Coast and Geodetic Survey. Revised magnitudes were computed from the magnitudes published in the Geotech bulletin for AFTAC array stations. The distribution of revised magnitudes yields a b value of 1.1 with a 95% confidence of 0.1. This value is based on 293 aftershocks occurring in 1964 and 1965 after the first day of the aftershock sequence. The magnitudes of the aftershocks and the microaftershocks are distributed according to the Gutenberg-Richter magnitude-frequency relationship with b values of between 0.8 and 0.9 and are consistent with a single distribution equation for magnitudes between $m = 6$ and $m = 0$. Within the accuracy of the data, both aftershocks and microaftershocks occur at shallow depths (less than 35 km). The second observation is in agreement with findings from recent aftershock studies that have featured the accurate determination of aftershock hypocenters. As an outgrowth of this study, a paper (Page, 1968) presented evidence for the hypothesis that prominent well-defined aftershock sequences occur only at shallow depths within the earth's crust. At present, this hypothesis is substantiated by recent aftershock studies in Japan, Hawaii, and the western United States that have featured very accurate hypocentral determinations of aftershocks.

F) Microearthquakes.

A manuscript, "Microearthquake Activity Following the Parkfield, California, Earthquake of June, 1966," by T. J. Fitch is now in press. A high sensitivity microearthquake recording station was established 10 km from the epicenter of the magnitude 5.5 Parkfield earthquake of 1966. Beginning 43 hours after the main shock, an hourly average of 22 microaftershocks in the magnitude range 1.5 < M < -0.5 was recorded for a period of 13 days. The amplitude distribution suggests that there was a smaller percentage of small shocks in the Parkfield microaftershock series than has commonly been reported for Japanese and other California aftershock series: b values between 0.8 and 0.9 are commonly reported while the average b value for the Parkfield microaftershock series was 0.6. The spatial distribution of microearthquake activity is shown to be strongly non-uniform within the aftershock zone. The microearthquakes, in general, did not cluster in time about the larger aftershocks (M > 2.0). Of 24 aftershocks with M greater than or equal to 2.0 only one event gave evidence of triggering a secondary aftershock series. Assuming that secondary foreshock and/or aftershock series imply the creation or reactivation of a secondary fault, one is led to the conclusion that secondary faulting was a rare occurrence in the Parkfield aftershock zone. Field recording of this sequence showed that hundreds of microaftershocks per day can be recorded in the epicentral region of moderate size earthquakes using ultra-sensitive seismographs.

G) PL and S-coupled PL waves.

A manuscript "On the Synthesis of Shear-coupled PL Waves" by Chander, Alsop, and Oliver will be published in the December, 1968 issue of the

Bulletin of the Seismological Society of America. In this paper, using the shear-coupled PL wave hypothesis of Oliver as a basis, a method has been developed for computing synthetic long-period seismograms between the onset of the initial S-type body phase and beginning of surface waves. By comparing observed and synthetic seismograms, it was shown that this hypothesis can explain, in considerable detail, most of the waves with periods greater than about 20 sec recorded during this interval. The synthetic seismograms are computed easily on a small digital computer; they resemble the observed seismograms much more closely than the synthetic seismograms obtained through the superposition of normal modes of the earth that have been reported in the literature. The synthesis of shear-coupled PL waves depends on a precise knowledge of the phase velocity curve of the PL wave and travel-time curves of shear waves. Hence, in principle, if one of these quantities is well-known the other can be determined by this method. Phase-velocity curves of the PL wave were determined for the Baltic shield, the Russian platform, the Canadian shield, the United States, and the western North-Atlantic ocean, on the assumption that J-B travel-time curves of shear waves apply to these areas. These dispersion curves showed the type of variations to be expected on the basis of the current knowledge of the crustal structures in these areas. Examples were presented to show that J-B travel-times of shear waves along paths between Kenai Peninsula, Alaska and Palisades, equatorial mid-Atlantic ridge and Palisades, and Kurile Islands and Uppsala need to be revised. Shear-wave travel-time curves that are not unique but that give synthetic seismograms in agreement with the observed seismograms were obtained. The new S curves were compared with the J-B travel-time curves for S and they all predict S waves to arrive later than the time given by J-B tables for epicentral distances smaller than about 30°. The new S curve for the Alaska to Palisades path appeared to agree with one of the branches of the multi-branched S curve proposed recently by Ibrahim and Nuttli for the "average United States", insofar as travel-times are concerned; but there were some differences in the slopes of the two curves.

A second paper entitled "The Generation of Coupled PL Modes," by Alsop and Chander is in press. In this paper, the method of steepest descent was used to study the generation of PL modes. It was shown that coupling between body phases and PL modes is obtained, whenever a PL pole lies near the saddle point corresponding to the physical condition that the respective apparent surface phase velocities are almost equal. Direct PL modes are shown to come into existence at a point for which the travel times of the PL mode and the direct P arrival are the same, just as for Rayleigh waves. On the basis of this study, it should be possible to synthesize a long-period seismogram from a suitable combination of ray arrivals, normal modes, direct PL, and coupled PL modes.

Since the submission of the above two papers, the study of shear-coupled PL waves has been extended much further. A major part of the new effort has been the study of shear-coupled PL waves that have propagated across oceanic areas. By scanning the WWSSN seismograms, it has been observed that the oceanic shear-coupled PL waves are much more variable than the continental Pl waves. At distances less than about 50°, the oceanic S-coupled waves have very much shorter periods (10-20 sec) than continental ones (60 - 20 sec). At distances larger than 52°, S- coupled PL waves of periods 40 to 50 sec were observed at several of the above stations. The cause of this discrepancy is being currently investigated.

From this work, one result of importance to VELA-UNIFORM is already apparent. The absence of long-period S-waves from the seismograms of explosion recorded at certain stations may be caused by the path of propagation.

An observational study of compressional P-coupled waves has been initiated. In addition to the observational study of shear-coupled PL waves, further theoretical work is under way. Part of this effort concerns the checking and modification of Abramovici's computer program for calculating the dispersion curves of locked and leaking modes of an elastic wave guide by tracing the poles of the period equation for complex frequencies and real wave numbers.

H) Multiple Events.

A paper is in preparation in which it is established that the deep earthquake of August 15, 1963 consisted of at least three and probably four events. The earthquake of July 26, 1958, has been interpreted in the light of these results. It is inferred that it, too, was a multiple earthquake composed of as many as eight distinct events. Multiplicity may be an important diagnostic for distinguishing earthquakes and explosior

I) Seismicity.

Tobin and Sykes relocated the epicenters of about 300 earthquakes in the northeast Pacific for the period 1954-1963. The study included the regions near and off the coasts of southeast Alaska, British Columbia, Washington, Oregon, and northern California. The epicenters as well as solutions of earthquake mechanisms have helped to delineate a series of oceanic ridges and fracture zones in the area north of the Mendocino fracture zone. A scientific paper on this subject has been published. One of the significant results of this and of other seismicity studies by Sykes is that activity in many areas has been shown to be concentrated in narrow zones. Any search of a region then involves a line source rather than a distribution over a surface.

With all the hypocentral solutions of the USCGS available in digital format, a new study using digital computers to plot the seismicity for any part of the world for any time period has been initiated. It is anticipated that this study may show significant variations in the temporal distribution of seismicity.

J) Source Size.

Chander observed that the Rayleigh wave trains from certain earthquakes originating on the mid-ocean ridges show the normally dispersed oceanic Rayleigh waves superimposed on the inversely dispersed Rayleigh waves of periods between 40 and 90 sec. In certain other earthquakes, which also originated on the ridges, only shorter-period Rayleigh waves were observed. Since there is considerable evidence that earthquakes on mid-oceanic ridges are of shallow focus, these longer-period waves from the first group must have been excited by sources of abnormally large size. Efforts are now underway to find a method of computing the size of the earthquake source in these cases. This study should shed more light on the topic of source size of earthquakes, hence is of considerable interest in distinguishing explosions and earthquakes using the observed seismic signals.

K) Amplitude Variations of Long-Period Surface and Body Waves.

Two studies supported by this contract have important bearing on the feasibility of monitoring surface waves from distant seismic events using high-gain, long-period seismographs located on a tectonic environment different from that of the seismic event under study.

In the first study seismograms from Berkeley and from a site on the deep ocean bottom off California were compared to ascertain the effect on Rayleigh waves of propagation across the continental margin. Amplitude ratios as a function of period were formed by dividing the spectral component of one recording site by that of the other recording site. In the period range from 14 to 25 seconds and for near-normal incidence, the amplitudes of vertical displacement on the ocean bottom were 2/3 to 1/3 as large as those at Berkeley.

Comparison of the experimental amplitude ratios with ratios that were calculated by using a variational technique suggests that there is a striking contrast in structure between Berkeley and the ocean bottom site which is about 235 km WNW of Berkeley. The velocities and densities of the lower crust and upper mantle beneath the oceanic site are much higher than those beneath Berkeley.

In the second study, amplitudes of the vertical component of ground motion caused by Rayleigh waves with periods of about 20 seconds were measured with an array consisting of the 25 stations of the WWSSN in the

United States: the Rayleigh waves were produced by shocks in selected regions of the Pacific and one area along the mid-Atlantic ridge. Amplitudes were plotted as a function of azimuth from epicenter to station and on outline maps centered on the epicenters. Patterns of amplitude of 20 sec surface waves measured by the array are highly sensitive to epicentral location; a pattern changes continuously with change in epicenter. The amplitude generally show variations of a factor of 10 or more within the array. These striking fluctuations of amplitude appear to be largely produced by focusing caused by lateral variations in phase velocity; they cannot be explained by other factors such as an asymmetrical radiation pattern at the source. Analysis based on a simple model of a horizontal variation in phase velocity yields theoretical amplitude patterns that explain the size and character of the most prominent variations in amplitude. Results of this study indicate that the most reliable estimates of amplitude are those measured at sites closest to the seismic events. Evidence of this study also suggests that amplitudes of Rayleigh waves from distant events measured at a single array such as LASA may be very unreliable because of possible effects of lateral refraction. Although they were not studied extensively, the amplitudes of long-period P waves do not appear to exhibit as large a scatter as the amplitudes of 20 second surface waves.

L) Descriptions of seiches which occurred along the Gulf Coast of the United States and in Norway at the times of the Alaskan earthquake of 1964 and the Assam Earthquake of 1950, respectively, have been reviewed.

An analytical expression has been derived for the effect of seismic surface waves on a water channel of width L and depth H. The expression was used to explain many of the observations of Norwegian seiches and also to compute a theoretical marigram which was compared to an actual marigram recorded in a channel at Freeport, Texas. The horizontal components of seismic surface waves were shown to be the dominant cause of seiches due to teleseisms. The maximum seiche amplitudes vary as (1) the seismic wave amplitude, (2) H, where H is the channel depth, and (3) the degree of resonance between seismic waves and the natural periods of oscillation of standing water waves in the channel. The seismic surface waves from the Alaskan Earthquake provided enough energy to produce all of the observed seiches in the Gulf Coast area. The seiche observations were limited to the Gulf Coast region because the thick sediments unique to this area are necessary to provide sufficient seismic wave amplification for the production of seiches.

M) Radius of the Earth's Core.

A new model of the boundary between the core and the mantle of the earth has been hypothesized on evidence from the low-order free vibrations of the earth. Periods of the spheroidal oscillations of orders 3 to 9 exceed the corresponding theoretical periods for a standard earth model by an amount greater than the standard deviation of each observation. The corresponding discrepancy between observed and theoretical periods is not as conspicuous in the torsional oscillations, though it exists for orders 3 and 4, while the spheroidal and torsional periods of order 2 are so poorly defined experimentally that they do not exceed the respective theoretical values significantly. The observed data considered were previously obtained from spectral analysis of free oscillations excited by the Chilean earthquake of May 22, 1960. A core slightly larger than that found by Jeffreys and Gutenberg, surrounded by a thin soft layer at the base of the mantle, can explain the discrepancy in a way which is consistent with the pertinent data on seismic body waves. Reasonable numerical values are a 10-kilometer increase in the core radius and a 30-kilometer soft solid layer surrounding the modified core.

Item 7. "Using LASA data, detailed studies of wave propagation, of source characteristics, and of surface waves of short and long periods originating at teleseismic distances with particular emphasis on regions with complicated crust and mantle structure such as island arcs."

A) There are two computers available to analyze LASA data. The one at Lamont, an IBM 1800, is used to read the tapes, to filter the data, perform beam forming and frequency analysis, and to plot the data on both analog and digital plotters. The larger IBM 360 is used to perform more complex operations on LASA data: frequency wave-number analysis, Hankel spectra, and rapid plotting of many traces. With these many programs and program packages, the Lamont Observatory has become uniquely equipped to perform efficiently all the operations necessary for the thorough analysis of LASA data.

B) <u>Background Noise at LASA.</u>

The investigation of the structure and sources of the microseismic background at LASA (undertaken in collaboration with R. A. Haubrich of La Jolla) has produced several new results. The modal structure of the low-level earth motion can now be summarized. Between 40 and 100 mHz (primary frequency, PF) the earth noise is dominated by fundamental mode Rayleigh and Love waves, with the Love waves accounting, on the whole, for more than half the horizontal power.. Higher mode Rayleigh waves are present in the upper part of this band, but their power is several db below that of the fundamental mode. Between 100 and 170 mHz (double frequency, DF) the fundamental mode surface waves are still predominant but here, on the whole, the Rayleigh mode accounts for more than half the horizontal power. As frequency increases in this band, the power in the higher Rayleigh modes rises, until at 170 mHz it is equal to that in the fundamental mode. Between 170 and 300 mHz the higher Rayleigh modes comprise the large wave number earth motion, and body waves comprise the low wave number motion. Body waves are also present in the other bands.

The low wave number body-wave noise is generated at sea by storms. Two mechanisms seem predominant: rapidly moving storms over-run their swell and leave behind a wake rich in oppositely travelling waves that generate leaking modes by the Hasselmann interaction mechanism; storm waves reflected from coastlines interact in the same way with the incoming waves. Thus, with improved knowledge of the state of ocean swell, it may be possible to predict the body wave noise distribution on a synoptic basis.

The primary frequency Rayleigh waves are generated at coastlines as was proposed by Hasselmann in 1963. The double frequency Rayleigh waves appear to be also generated at or near the coastline despite the fact that the opposed wave mechanism is effective anywhere in the ocean. The conclusion is that reflection of waves from the coastline is the dominant means of generating opposed swell, at least in the DF band. Because of this, the average directional distribution of the fundamental-mode Rayleigh-wave noise can, with little difficulty, be predicted at a continental site by considering the distribution around the site of coastlines that face open ocean. The higher mode surface waves appear to be isotropic on the average except for a tendency to decrease in directions where there is no open ocean.

Under normal conditions there is no significant noise with periods longer than 22 seconds, suggesting that instruments with elevated long-period response and low internal noise could be run at unusually high magnification.

A manuscript describing this work is in the final stages of preparation and will be submitted to a journal in the immediate future.

C) Pattern Recognition.

Joint cooperation with the pattern recognition group of the IBM Research Laboratories, Yorktown Heights, New York, is continuing. The initial attempts at applying Karhunin-Loeve techniques to separate out depth phases in the P-wave train were unsuccessful. Present interest is concerned with detecting nuclear events concealed in the train of an earthquake signal.

For this purpose sample records for the 21 center seismometers were prepared with the P-wave of Longshot buried in the P-wave train of a Kamchatka earthquake of comparable magnitude. The Longshot signal was attenuated by different factors in separate samples. Although the two events are separated by more than two beam-widths, a simple beam pointed at Longshot does not enhance the Longshot energy very much compared to that for the Kamchatka event. The optimum filtering technique of Capon of Lincoln Laboratories and another technique that makes a best estimate of the interesting event and subtracts it from the records have been applied. Signal enhancements of the order of 10 to 12 db result.

It is planned to study the techniques and obtain estimates of signal enhancement as a function of distance between the sources of the signal and the interfering event.

D) Record Sections.

A complete plot of Longshot seismograms for all 525 seismometers of LASA were plotted together on one sheet by a Calcomp plotter. Different color inks were used for different subarrays. On this presentation it is possible to trace the progression of separate arrivals across the array. These arrivals are now being studied and their velocities are being compared with velocities of events detected by standard array techniques by the group at Lincoln Laboratories. A search is being conducted for new seismic phases.

E) A study of the relative generation of long-period body waves (such as P, PP, PPP, S, SS, SSS, PS, etc.) was undertaken with the following objectives:

a) to determine the attenuation of these waves in the period range of 2 - 25 seconds as a function of distance,

b) to determine the generation of body waves in this period range as a function of magnitude,

c) to observe qualitative and quantitative differences in the generation of these body waves between underground explosions and earthquakes of similar short-period body wave magnitude m_b.

Data from the high-gain, narrow-band, long-period instruments at LASA as recorded in analog form on 16 mm film have been utilized in this program. Specifically, for the study of item (a) above, the magnitudes m_b of 20 earthquakes in the distance range from 5° to 90° for which long-period body waves were well recorded at LASA were determined, and the amplitudes of the long-period waves were then normalized to $m_b = 5.0$. Separate plots of the amplitude variation as a function of epicentral distance for each of the long-period body waves were then prepared. These graphs will be used to determine correction factors in the studies below.

D) The short-period LASA data for the Denver earthquake of November 21, 1965 has been retrieved from the data tapes. These data are plotted for graphical display. The distances and azimuths from the earthquake epicenter to the various seismometers of the array have been computed and related to the arrival times to determine travel time anomalies.

Item 9. "Evaluation of the Feasibility of Using a Worldwide Array to Conduct Studies."

Preliminary steps have been taken for application of the array technique to measure the torsional oscillations of the earth.

Spectra of the torsional oscillations of the earth have been computed from horizontal long-period pendulum seismograph recordings obtained at six Chilean earthquake of May, 1960. Longitudinal and transverse components of the ground motion at the stations were synthesized by appropriate vector addition of the horizontal component seismograms. Harmonic analysis was used to obtain spectra of the torsional oscillations from the synthesized transverse component of motion. The new torsional oscillation data have been combined with those previously reported by various authors to obtain a more precise period and dispersion curve for Love waves in the period range corresponding to torsional oscillations of order $\ell = 2$ through $\ell = 23$. Four standard models of the earth (M1, J-BB, J-BA, and G-BA) were examined in the light of this new information; model M1 appears to be a better fit to the data.

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- LIST OF PERSONNEL -

Scientists:

L. E. Alsop	G. Latham	R. Page*
H. J. Dorman	K. McCamy	P. Pomeroy
M. Ewing	T. Matumoto	G. Sutton
V. Gabriel	J. Nafe	L. Sykes
B. Isacks	A. Nowroozi	D. Tobin*
J. Kuo	J. Oliver	G. White

*Graduate students, then scientists

Graduate Students:

B. Auld	M. Fliegel	W. Mitronovas
A. Banghar	F. Gumper	P. Molnar
G. Boucher	T. Katonak	R. Piermattei
G. Buchbinder	J. Kelleher	J. Rudnick
R. Chander	J. Lahr	J. M. Savino
P. Davis	R. Liebermann	L. Seeber
T. Fitch	A. McGarr	H. Von Veen

Engineers:

G. Hade
W. McDonald
F. G. van der Hoeven
L. Von Hemelryck

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13. ABSTRACT

In the period covered by this report, Lamont Geological Observatory has made significant advances towards the use of long and intermediate period seismic waves for the identification of seismic sources. Our increased understanding of many features of the seismogram has enhanced its utility in detecting and identifying small seismic events. The recently states principles of global tectonics have shed new light on the problems of world seismicity, source mechanisms and the location of seismic events. The structure and causes of seismic noise which limits the effectiveness of all detecting instruments are now understood so well that much of the noise can be predicted. A large network of long and intermediate period instruments has been operated, and new high sensitivity, broadband, low noise instruments have been developed which have proved especially effective for detecting small events. A study of the relative excitation of surface waves by earthquakes and explosions revealed it to be a powerful discriminant between two sources. The steady development of computer programs has permitted rapid and sophisticated analysis of both conventional and Large Aperture Seismic Array data. Thus many of the goals of this research have been attained and important progress has been made toward detecting and identifying seismic events.

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