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I. Introduction

The major research accomplishments under this grant have been established in a series of scientific papers which are listed at the end of this report. Technical details have been reported in quarterly progress reports.

The present report summarizes results in the following categories:

1. Structure of the Earth - body waves
2. Structure of the Earth - surface waves and free oscillations
3. Body wave and surface wave theoretical studies
4. Nonelastic properties of the Earth
5. Source studies
6. Instrumental development
7. Digital and analog recording

In the following sections of this report we briefly summarize results in each of the above categories. These summaries serve to introduce the abstracts which follow.

II. Structure of the Earth - Body Waves

Objectives: To develop and apply techniques for the determination of earth structure from body waves using arrays and nuclear sources.

Accomplishments: The ability to locate natural or artificial seismic sources depends on having very precise information regarding travel times of seismic waves. Travel time information is particularly confused in the critical distance range of 10° to 40° . We have shown that this situation is due to large amplitude later arrivals. The travel time curve in this region is not a smooth curve, but is very complex, involving triplications and cusps. These features are due to the low-velocity zone and to three pronounced second-order discontinuities in the upper mantle. The discontinuities near 400 and near 650 km are quite satisfactorily explained in terms of solid-solid phase changes in silicates. We have been able to estimate the composition and temperature in the mantle from the location of these discontinuities. Structures of the lower mantle and the core mantle boundary have been derived from studies using the Tonto Forest Array.

Several detailed investigations of the velocity structure of the upper mantle have been completed. In one study, body wave amplitudes and travel times were obtained from three events, the Bilby and Shoal nuclear explosions and the Fallon earthquake, using automated signal detection and analysis methods developed earlier. The travel times and amplitude spectra of first and later arrivals along four distinct profiles were interpreted in an integrated manner and provided details of the upper mantle compressions velocity variation with depth and the intrinsic anelastic properties of the material as a function of depth and frequency. Regional differences in mantle structure were observed, particularly in the character of the low velocity zone. The results of this study show that the mantle in the western United States may be characterized in general by a low velocity zone, whose depth extent and velocity is highly variable from one geologic province to another, and by narrow zones of rapid velocity variation in the regions from 350-400 km; 600-650 km and possibly in

the region between 950-975 kms. The first two transition zones show small variations in depth location for different regions and in the magnitude of the velocity variation. Between these sharp transition zones the velocity variation with depth is slowly and monotonically increasing. The anelastic properties of the medium as characterized by the dissipation function, Q , were obtained from the amplitude data in the frequency range between 2 cps to .2 cps. Present results suggest a frequency dependence for Q , although work is continuing on this phase of the project at the present time. The Q structure in the crust, in the low velocity zone "lid" and in the low velocity zone itself shows a rapid decrease in the Q of the material at the crust-mantle boundary with a slow decrease of Q in the lid followed by a rapid decrease within the low velocity zone. The velocity- Q behavior strongly suggests a partially molten low velocity zone followed by various phase transitions deeper in the mantle. Correlation of these upper mantle properties with geologic regions have suggested mechanisms of crustal formation involving the low velocity zone and the low velocity zone "lid"; for example, extension of the low-velocity zone to the base of the crust with differentiation of the melt from the mantle material and formation of crust. In addition to interpretive questions involving the geological and geophysical significance of the structures obtained, the structures themselves have been used to remove the effects of propagation from the source radiation field in order to study the source itself. In particular, the radiation patterns for the nuclear events studied show the expected symmetry and amplitude decrement with distance once the properties of the medium have been accounted for. The study also shows that later arriving phases, with large amplitudes, can also be useful in studying the source since they are more clearly observed at many distances than are the first arrivals. This type of observational work is continuing in conjunction with theoretical source studies.

Various inversion methods designed to obtain velocity structure from body wave travel-time observations are under development. An iterative perturbation method previously developed has been extended and is now in the process of being applied. A similar method for the determination of Q at a fixed frequency versus depth is being tested.

A velocity structure for P waves in the earth's mantle has also been derived from $dT/d\Delta$ measurements with the extended array at the Tonto Forest Seismological Observatory in Arizona. Travel times, $dT/d\Delta$, and amplitudes were measured for over 200 earthquakes in the distance range 0 to 100 degrees. Corrections for the crust underlying the array have been applied by using crustal models derived from seismic refraction and gravity data. Considerable attention was given to the later arrivals on the seismograms so that a fairly complete $dT/d\Delta$ curve has been constructed. This was inverted to obtain a velocity structure for the entire mantle. The resulting structure is consistent with travel times from nuclear explosions and published amplitude data. The important features of the new velocity structure include three regions with high velocity gradients near depths of 150, 400, and 650 km. There are smaller discontinuities near 835, 1000, 1240, 1550, 1910 and 2350 km.

Body wave parameters such as travel times, apparent velocities and amplitudes have been computed for all standard body wave and surface wave mantle models. The differences between models are primarily due to neglect of later arrivals. The scatter of data near 20° is shown to be due to high amplitude second and

third arrivals which, for small events, can easily be mistaken for first arrivals. An accurate mantle structure cannot be determined on the basis of first arrivals alone.

Abstracts;

Toksoz, M. N., M. A. Chinnery, and Don L. Anderson, "Inhomogeneities in the Earth's Mantle," Geophys. J., R. Astr. Soc., 13, 31-59, 1967.

Using seismic body and surface waves, the velocity structure of the Earth's mantle is determined with the emphasis on regions of anomalous variations (so-called 'discontinuities'). In the upper mantle, the interpretation of Rayleigh and Love wave dispersion curves yields shear velocity profiles with discontinuities at depths 350 km and 700 km, and a low-velocity zone extending to 350 km. In the lower mantle P-velocity profile is determined from $dt/d\Delta$ measurements using large aperture seismic array and travel times from Long Shot nuclear explosion for the Japan-Kuriles-Aleutian-Montana path. The velocity structure shows anomalous gradients or 'discontinuities' at depths 700, 1200 and 1900 km, indicating that the lower mantle is not homogeneous.

Lateral variations of the velocity structures are investigated. For the upper mantle studies the Earth is divided into three regions: oceanic areas, continental shields, and tectonic zones. Pure path phase velocities of Love waves are extracted from the composite dispersion data. The pure path shear velocity profiles obtained from these data are characterized by lower velocities under the oceans in the uppermost portion of the mantle. Shields have the highest velocities. These velocity differences are interpreted in terms of temperature variations. At a depth of 110 km the temperature of the oceanic mantle is higher (by 100-500°C depending on the temperature coefficient of the velocity) than that of the mantle under the shields. The presence of lateral heterogeneities in the mantle is demonstrated qualitatively by the differences of $dt/d\Delta$ vs Δ curves for two separate paths.

Undulations of the geoid as determined from satellite observations are investigated for determining the sources of the anomalies. It is concluded that the main sources of lateral density variations must be in the mantle at depths greater than about 100 km.

Johnson, Lane R., "Array Measurements of P Velocities in the Upper Mantle," J. Geophys. Res., in press.

A velocity structure for P waves in the upper mantle has been derived from $dT/d\Delta$ measurements with the extended array at the Tonto Forest Seismological Observatory in Arizona. Short-period P waves from earthquakes in the distance range 0 to 30 degrees have been used. Corrections for the crust underlying the array have been applied using crustal models derived from seismic refraction and gravity data. By including later arrivals on the seismograms a fairly complete $dT/d\Delta$ curve has been constructed and this inverted to obtain a velocity model for the upper 750 km of the mantle. The model includes a low-velocity zone with a high velocity gradient near its lower boundary. Two other regions with high velocity gradients are located near depths of 400 and 650 km and consist of 9 - 10% increases in velocity spread out over 50 to 100 km. Travel times and amplitudes calculated for this model are consistent with observed data.

Anderson, Don L., "Latest Information from Seismic Observations," Ch. 12, THE EARTH'S MANTLE, ed. T. Gaskell, Academic Press Inc., London, 1967.

This article summarizes the recent seismic data regarding the structure and composition of the mantle and correlates it with relevant data from the laboratory. New developments, such as the use of amplitudes and later arrivals are stressed. Recent free oscillation and surface wave data is tabulated.

The evidence for the large upper mantle discontinuities is presented and interpreted in terms of phase changes. Some new body wave data in support of anomalous velocity gradients in the transition region is given.

The seismic equation of state is used to estimate the composition of the mantle. The possibility of a wide-spread P wave low-velocity zone is discussed.

Anderson, D. L., "Phase Changes in the Mantle," presented at 4th Annual Upper Mantle Mtg. on Theory and Computers, Trieste, Italy, Sept., 1967.

The great spread of the C-region of the upper mantle has always been difficult to explain in terms of a phase change hypothesis. Recent high pressure synthesis experiments reinforce the conclusion that the olivine-spinel transition in the mantle should be relatively sharp, on the order of 50 to 100 km in thickness. Seismic data now indicates that there are two relatively sharp discontinuities in the transition region, each one involving a velocity jump of 10 - 15% spread over a depth interval of 50 - 100 km. The depth and breadth of the upper discontinuity, near 400 km, is consistent with an olivine-spinel phase change in a magnesium rich $(\text{Mg, Fe})_2\text{SiO}_4$ system. The velocity jump associated with the discontinuity near 700 km is consistent with a further collapse of the spinel structure to a form which is about 9% denser. The lower mantle has a mean atomic weight higher than the upper mantle and it appears likely that the upper discontinuity involves a change in both phase and composition.

Julian, Bruce R., and Don L. Anderson, "Travel Times, Apparent Velocities and Amplitudes of Body Waves," Bull. Seism. Soc. Am., in press.

Surface wave studies have shown that the transition region of the upper mantle, Bullen's Region C, is not spread uniformly over some 600 km but contains two relatively thin zones in which the velocity gradient is extremely high. In addition to these transition regions which start at depths near 350 and 650 km, there is another region of high velocity gradient which terminates the low-velocity zone near 160 km. Theoretical body wave travel time and amplitude calculations for the surface wave model CIT11GB predict two prominent regions of triplication in the travel time curves between about 15° and 40° for both P and S waves, with large amplitude later arrivals. These large later arrivals provide an explanation for the scatter of travel time data in this region, as well as the varied interpretations of the "20° discontinuity."

Travel times, apparent velocities and amplitudes of P waves are calculated for the Earth models of Gutenberg, Lehmann, Jeffreys and Lukk and Neresov. These quantities are calculated for both P and S waves for model CIT11GB. Although the first arrival travel times are similar for all the models except that of Lukk and Neresov, the times of the later arrivals differ greatly. The neglect of later arrivals is one reason for the discrepancies among the body wave models and between the surface wave and body wave models.

The amplitude calculations take into account both geometric spreading and anelasticity. Geometric spreading produces large variations in the amplitude with distance, and is an extremely sensitive function of the model parameters, providing a potentially powerful tool for studying details of the Earth's structure. The effect of attenuation on the amplitudes varies much less with distance than does the geometric spreading effect. Its main effect is to reduce the amplitude at higher frequencies, particularly for S waves, which accounts for their observed low frequency character.

Data along a profile to the northeast of the Nevada Test Site clearly show a later branch similar to the one predicted for model CIT11GB, beginning at about 12° with very large amplitudes and becoming a first arrival at about 18°. Strong later arrivals occur in the entire distance range of the data shown, 11-1/2° to 21°. Two models are presented which fit these data. They differ only slightly and confirm the existence of discontinuities near 400 and 600 kilometers.

A method is described for predicting the effect on travel times of small changes in the Earth structure.

Archambeau, C. B., E. A. Flinn, and D. G. Lambert, "Mantle Structure from Body Waves." To be submitted to J. Geophys. Res.

Lateral variations in the upper mantle have been studied using body wave techniques. The study indicates:

- 1) Lateral variations are strong and tend to have sharp (lateral) boundaries, most if not all variation is in the upper 150 km and involves the LVZ. Differences in V_p are noted to depths of 800-900 km but resolution is marginal. The magnitude of the variations tends to decrease with depth.

2) Three basic structural types are distinguished: Basin and Range type with no lid on LVZ and Moho velocity 7.7+; shield type with no LVZ in V_p with Moho at ~ 8.1 ; transitional or mountain type with $P_{11} = 8.1$ and approximately 50 km thick lid plus LVZ. All structures have a sharp velocity increase at 150 km to 8.35 km/sec which terminates the LVZ when it exists at shallower depths.

3) All structures show, with minor variations, sharp velocity gradients in the ranges: 375 km to 400 km; 625-650 km both of about 8-9% and another smaller (2%) increase in the 950-975 km range. These are zones of possible phase changes.

4) Structures indicate that velocity gradient for V_p is quite possibly negative throughout the range from the base of the crust (averaging 30 km) to 160 km (somewhat below the first sharp velocity jump) with the exception of the depth region affected by what appears to be a phase change ending at 150 km. This later zone appears to extend from 100 km to 150 km, but may be sharper.

Johnson, Lane R., "Array Measurements of Velocities in the Lower Mantle," presented at the Annual Mtg., Seism. Soc. Am., Santa Barbara, Calif., 1967.

The extended array of the Tonto Forest Seismological Observatory in Arizona has been used to investigate the velocity structure of P waves in the lower mantle. Travel times, apparent velocities, amplitudes, and rates of change of amplitude with distance have been measured for the short-period P waves of 200 earthquakes in the distance range of 50 to 100 degrees. Attention has been paid to possible second and third arrivals on the seismograms and also the phase PcP. The measurements have been corrected for the effect of the crust underlying the array on the basis of crustal models derived from seismic refraction and gravity data.

With these results and also published travel times for P and PcP from nuclear explosions, an attempt has been made to construct a velocity model for the lower mantle which is consistent with all of the data. A model of the upper mantle which resulted from a similar analysis of local and regional earthquakes is assumed in making the computations for the lower mantle. Irregularities in the apparent velocities at distances of approximately 36, 52, 64, 71, and 88 degrees are interpreted in terms of second-order discontinuities in the lower mantle. The deepest one is very pronounced and is apparently associated with the core-mantle boundary.

Presented at the XIV General Assembly, Int'l. Union of Geodesy and Geophysics, Zurich, Switzerland, Sept. 25 - Oct. 7, 1967;

Johnson, Lane, "Measurement of Velocities in the Mantle with a Large Seismic Array."

Earthquake data recorded with the extended array at the Tonto Forest Seismological Observatory in Arizona have been studied in an effort to obtain the velocities of seismic waves in the mantle of the earth. The apparent velocities of short-period P waves from over 200 earthquakes in the distance range of 0 to 100 degrees have been measured. These data are inverted to obtain a velocity structure for P waves in the mantle, and the result is

compared with travel times from nuclear explosions and published amplitude data. The important features of the resulting velocity structure are an upper mantle low-velocity zone, three regions with relatively large velocity gradients in the upper mantle, and several regions with increased velocity gradients in the lower mantle.

Apparent velocities of S waves have also been measured and are presented, but the quantity of data is insufficient to allow a complete velocity solution. Data pertaining to the core radius and velocities within the core are also presented.

Anderson, Don L., "Composition of the Earth's Interior."

The speculations of Birch and Ringwood regarding phase changes in the transition region of the upper mantle and the crystal structure of the lower mantle are now on firm ground. Phase equilibrium studies on magnesium-iron silicates at high pressure have provided the data necessary to estimate the variation of elasticity and density through the transition region. An earth model is constructed which takes into account the effects of temperature, pressure, composition and phase change on the seismic velocities and density. The parameters in this model depend on the crystal structure and the zero-pressure density. These parameters are adjusted until the seismic data, including estimates of density from free-oscillation data, are satisfied. The final results are given in terms of mean atomic weight and crystal structure for the various regions of the mantle.

The top of the C-region, at 400 km depth, is a discontinuity both in phase and in composition. The iron content of the lower mantle is substantially higher than the upper mantle.

Brune, James N., "Travel Times and Higher Normal Modes of the Earth."

This paper describes the physical relationship between the normal mode and ray representations of body waves, and develops equations and experimental procedures for analyzing body waves in terms of normal modes. Higher mode dispersion points may be determined experimentally from the phase spectra of successive reflections of body waves of a given phase velocity (e.g., S at a distance Δ and SS at a distance 2Δ). Results from 12 examples indicate regional variations in S wave travel times of the order of 5 seconds.

Presented at the 48th Annual Mtg. of the Am. Geophys. U., 4/17-20/67, Wash., D. C.:

Brune, J. N., C. B. Archambeau, "A Refraction Line Along the Axis of the Sierra Nevada Using Aftershocks."

Aftershocks of the Truckee earthquake of September 12, 1966, were used to obtain a refraction line along the axis of the Sierra Nevada from Ebbets Pass to Isabella, a distance of about 450 km. Precise epicentral locations were obtained from near source stations operated by the University of Nevada and the U.S. Geodetic Survey. Preliminary analysis of the arrivals gives the following travel time equations: $P_0: 0.2 + \Delta/5.95$; $P_1^*: 1.1 + \Delta/6.2$; $P_2^*: 4.3 + \Delta/6.85$;

P_3^* : $5.3 + \Delta 7.19$; P_n : $8.2 + \Delta 8.0$; S_g : $0.4 + \Delta 3.61$. The P_n arrival was long period and only observed for aftershocks with magnitude greater than 4-1/2. The crustal thickness is about 47 km. This result verifies the existence of the root to the Sierra Nevada. This crustal thickness is about 6 km less than found by Eaton for the eastern margin of the Sierras. The crustal velocities increase with depth from 6.0 to 7.2 km/sec. South of the Sierras the P_n arrivals are about 3 seconds early, reflecting the change in crustal structure leaving the Sierras. Aftershocks are inexpensive, multiple seismic sources rich in shear wave energy and thus may be used very effectively in the study of Earth structure.

Anderson, Don L., Lane R. Johnson, "The Nature of the Discontinuities in the Transition Region of the Earth's Mantle."

The presence of two major discontinuities in the upper mantle between 350 and 800 km is now well established by a variety of seismological data. The depth, thickness, and velocity jumps associated with these discontinuities are remarkably consistent with recent high pressure experiments on solid-solid phase changes in the $Mg_2SiO_4 - Fe_2SiO_4$ and related systems. The depth to the discontinuities, their sharpness, and their shape is controlled by the composition and temperature. These constraints plus the absolute values of the velocities and densities supplied by travel time, surface wave, and free oscillation data permit bounds to be placed on the composition and temperature of the upper mantle insofar as the laboratory phase-equilibria data are to be believed. Large amplitude arrivals between P and pP from distant deep focus earthquakes are used to study the location and details of these transition regions.

Johnson, Lane R., "Array Measurements of Velocities in the Upper Mantle."

See abstract on Page 3.

Archanbeau, Charles B., E. A. Flinn, D. G. Lambert, "Fine Structure of the Upper Mantle from Seismic Observations."

An Earth structure consistent with much of the amplitude and time information contained in the seismic field can be obtained by inversion of the travel times and spectral amplitude data from both first and later arrival body phases by perturbation techniques, starting with structures that are in agreement with surface wave dispersion data. In this way the fine structure of the upper mantle can be resolved, in addition to the average properties obtained from surface wave studies, to yield more precise determinations of velocity gradients. These estimates can then be used to infer, with more confidence and uniqueness, the properties and composition of the material within this important region. Regional structures for the upper mantle determined in this manner are obtained in this study and show, collectively, rather sharp zones of transition within the upper mantle. In particular, compressional velocity structures appropriate to the mantle under mountains show low velocity zones and sharp velocity gradients near 400 and 700 km with remarkably low velocity gradients between these zones. The variation of structures between regions suggests relatively strong lateral variations in the character of the low velocity zone, the pronounced low velocity zone under a mountainous crust and its absence under tectonically stable regions suggesting a close relationship between the properties of this zone and crustal tectonics.

Anderson, Don L., "A Review of Upper Mantle Seismic Data."

Body wave, surface wave, and free oscillation data, especially those pertinent to the upper mantle, are reviewed. Low-velocity zones are important features of most recent studies, and there is strong evidence for lateral variations in the upper mantle. The conditions for velocity reversals are discussed, and it is concluded that compositional changes or partial melting or both are required to produce the observed low velocity and high attenuation. High-pressure and shock wave data are used to estimate temperature and composition throughout the mantle. The mantle is zoned, both in phase and composition.

III. Structure of the Earth - Surface Waves and Free Oscillations

Objectives: To develop and apply techniques for the determination of Earth structure from surface waves and free oscillations.

Accomplishments: Long period great circle surface wave data has been used to obtain mantle structures for oceanic, tectonic and shield areas. The velocities in the vicinity of the low-velocity zone are lowest under oceans and highest under shields. These results have been combined with the results of the body wave studies to generate standard mantle models for these three types of regions. Body wave parameters and perturbation parameters for both body waves and surface waves have been generated for these standard models. In the future, body wave and surface wave residuals can be used to modify the standard models to give a model appropriate for the region being studied.

All of the surface wave and body wave studies have regions of very high velocity gradient near 150, 400 and 650 km. The one at 150 terminates the low-velocity zone and probably represents a change to a more refractory mineral assemblage. A theoretical study of phase equilibria in olivine and the equation of state of silicates has been used to construct theoretical mantle models. These theoretical models are in remarkable accord with the results of the seismic investigations. The discontinuity near 400 km is probably due to the collapse of olivine to a spinel structure. The one near 650 km is probably due to the collapse of spinel to a defect NaCl structure. Furthermore there is an indication that the iron content increases through the transition region.

Several mantle models have been constructed which are consistent with body wave and surface wave data. These data supply accurate values for the body wave velocities in the Earth. The periods of free oscillation have been used to determine a density structure for each of the standard mantle models.

Abstracts:

Brune, James N., "The Sa Phase from the Hindu Kush Earthquake of July 6, 1962," Pure and Applied Geophysics, 62, 81-95, 1965.

The Hindu Kush earthquake of July 6, 1962 produced an Sa phase (vertical component or Rayleigh type) which was clearly recorded at stations in North America in the distance range 90° to 110° . The propagation of this phase was studied in detail, both by the usual method of measuring velocity of first arrival and also by determining group velocities from the derivative of the

phase of the Fourier transform (in the period range 20 to 80 seconds). The energy in the Sa phase propagates in a manner intermediate between that of a single ray and that of a single isolated mode. The expected interference effects which vary as a function of distance are observed and complicate a straight-forward measurement of group velocities. The results are most reliable if only the group velocities corresponding to parts of the spectra with relatively high amplitudes are used.

The results show a regional variation in the velocity of the Rayleigh type Sa for continental areas, being higher under shield areas than under areas of more recent tectonic activity. The results are compared with theoretical calculations for the Gutenberg, Jeffreys-Bullen and Canadian Shield models of the Earth and the results indicate regional variations in shear velocity in the upper mantle extending to depths of several hundred km under continents.

Presented at the XIV General Assembly, Int'l. Union of Geodesy and Geophysics, Zurich, Switzerland, Sept. 25 - Oct. 7, 1967:

Brune, James N., "The Sa Phase from the Hindu Kush Earthquake of July 6, 1962."

See abstract above.

IV. Body Wave and Surface Wave Theoretical Studies

Objectives: To improve our understanding of seismic wave propagation phenomena in order to extract more information from the seismic record.

Accomplishments: We have reached a level in seismology where classical ray theory is no longer adequate for our needs. This is particularly true for S-waves because of negative shear velocity gradients in large regions of the upper mantle and the long periods of shear waves. A 20-second shear wave travelling in the upper mantle has a wavelength of about 88 km, which is greater than the thickness of the transition regions in the upper mantle. A higher order ray theory or a model approach is required in order to adequately interpret shear body waves. Interpretation of P wave amplitudes and periods and phenomena near caustics also involve a better ray theory.

The physical relation between P and S travel time curves and torsional and spheroidal dispersion curves for a homogeneous sphere was demonstrated by deriving interference conditions for multiply reflected waves in a sphere and showing that these were equivalent to the normal mode period equations. Using the generalized interference equations, it was possible to develop an experimental procedure for analyzing body waves in terms of normal modes. Higher mode dispersion points are obtained from the phase spectra of successive reflections of body waves of a given phase velocity (e.g. S at a distance Δ and SS at a distance 2Δ). Results from numerous examples indicate S wave travel times approximately in agreement with the Jeffreys-Bullen tables, but with regional variations of as much as 8 seconds for a given distance. These results are in general agreement with results of Doyle and Hales, and thus confirm the large regional variations in S wave travel time. The overall results of the study have clearly outlined the connection between body waves

and higher normal modes and indicated that little if any information can be obtained about the structure of the Earth from very high mode dispersion studies that cannot be directly obtained from body wave studies. The study explains the peculiar oscillations in the spheroidal mode group and phase velocities.

A comprehensive study was made of published surface wave dispersion data. Summary dispersion curves were obtained for Love and Rayleigh waves for distinctive crustal types. It was concluded that a satisfactory classification of structures could be obtained by dividing the crustal structures into six types: shield, mid-continent, basin range, alpine, island arc, and oceanic ridge, and dividing the mantle into stable or unstable types.

A variety of other mathematical approaches to the solution of the equations of elastic motion in a radially heterogeneous planet are being investigated in order to bridge the gap between ordinary ray theory and the usual (exact) mode theory solutions. The ray theory is convenient for interpretation, but very inexact; while the mode theory is exact but inconvenient (inconvenient = impossible in some cases). Methods currently under investigation are applicable (convenient) in certain situations. They include decomposition of the equations of motion (involving some approximations) to simple (scalar) equations with variable coefficients corresponding to continuously variable velocity depth functions and solution of these equations by approximate methods (WKB, etc.). These approximate solutions are chosen to give ray-like solutions with frequency dependent amplitudes and show how measured velocity (by ordinary T- Δ methods) is related to real (intrinsic) elastic velocities, also will give the desired amplitude dependence on elastic parameters and frequency needed in observational-experimental studies. Other approaches involve asymptotic wave theories which are modifications and extension of Karal-Keller approach, and modified mode representatives where the mode sums are replaced by more rapidly convergent representations, obtained by various integral techniques. Important especially for S waves, but also in the region of a cusp for P, and for frequency effects.

The perturbation theory appropriate for the description of the effects of lateral variations in the elastic properties of an otherwise radially inhomogeneous gravitating earth has been formulated.

Applications of this formulation are being made in the simplest cases. In particular the expected changes in the eigenfrequencies for torsional oscillations are being calculated for the case of a lateral inhomogeneity with ϕ symmetry. This can be used to crudely approximate a continental land mass. More complicated variations will be considered later. The interpretation of these perturbations in terms of measured eigenfrequencies and phase velocities is being studied. It appears that the perturbations can realistically be interpreted in terms of certain averages of measured phase velocities or eigenfrequencies at various points on the Earth's surface.

The universal dispersion curve theory has been extended to handle group velocity and amplitudes. It has also been extended to spheroidal oscillations of an inhomogeneous gravitating sphere. Tables have been prepared which allow the interpretation of spheroidal and toroidal oscillations and Love and Rayleigh waves and their overtones. By use of these tables the inversion of all published free oscillation and surface wave data can be done on a desk calculation.

Abstracts:

Archambeau, Charles E., and E. A. Flinn, "Perturbation Methods for the Inversion of Body Wave Travel-Time Data," J. Geophys. Res., in press.

Estimation of the internal elastic structure of the earth from body wave travel times ordinarily uses both arrival time data and the slope of a curve fitted to the observed travel times. There are well known difficulties in fitting such curves, particularly in cases where the observed travel times suggest a multivalued travel time function. A perturbation method is described in which an initial velocity distribution, which may be chosen to be in agreement with surface wave dispersion data over the region in question, is perturbed iteratively until the theoretical travel time function is in agreement, in the least-squares sense, with the observed data. The method does not require any estimate of the curve slope or multiplicity, nor does it require a particularly dense and complete data coverage over the entire distance range. Several phases can be used simultaneously.

The initial velocity distribution is taken to be in the form $V(r, \alpha_k)$ where the α_k are a set of parameters to be determined from the observational data, the functional form of $V(r, \alpha_k)$ being fixed. At each step in the iteration process, variations in the α_k are computed from the travel time residuals δT at fixed distance, from the relation

$$\left(\frac{\delta T}{T}\right)_{\Delta} = - \sum_k \left(\frac{T_k}{T}\right)_{\Delta} \left(\frac{\delta \alpha_k}{\alpha_k}\right)$$

where T_k represents the travel time integral with a weighting factor $\alpha_k/v \left(\frac{\partial V}{\partial \alpha_k}\right)$.

Teng, T. L., and F. T. Wu, "A Two-Dimensional Ultrasonic Model Study of Compressional and Shear-Wave Diffraction Patterns Produced by a Circular Cavity," Bull. Seismol. Soc. Am., in press.

Diffraction patterns of compressional (P) and shear (SV) waves produced by a circular hole were experimentally obtained on a two-dimensional ultrasonic model. The shapes of the Fresnel patterns were found to depend on, 1) a/λ , the ratio of the radius of the cylinder to the wavelength; and 2) the wave type. The transitional zone between the illuminated and the shadow regions broadens, and the half-amplitude point shifts away from the geometrical shadow as a/λ decreases. For comparable a/λ the shadow boundary of the SV wave appears to start much earlier than that of the P wave.

Anderson, Don L., and David G. Harkrider, "Universal Dispersion Tables, Pt. II. Variational Parameters for Amplitudes, Phase Velocity and Group Velocity for First Four Love Modes for an Oceanic and a Continental Earth Model," Bull. Seismol. Soc. Am., in press.

The universal dispersion theory, presented in Part I is extended to allow computation of group velocity and amplitude partial derivatives. Tables giving the effect of a change in any parameter on phase velocity, group velocity and amplitude are given for two earth models, one oceanic and one continental shield. Tables are given for the fundamental and first three higher Love modes.

These tables make it possible to compute dispersion parameters for the first four Love modes for any realistic earth model or to invert observations to an earth model. Attenuation of Love waves for an arbitrary distribution of Q versus depth can also be computed by using techniques previously described

V. Nonelastic Properties of the Earth

Objectives: To determine the attenuation of seismic waves in various regions of the Earth and to determine the response of the Earth to long term forces.

Accomplishments: Seismic signals decay as they propagate because the Earth is not perfectly elastic. Other effects such as geometric spreading and dispersion, unrelated to anelasticity, also contribute to the observed amplitudes of seismic waves. Methods have been developed to determine the anelasticity of various regions of the Earth from the decay of body waves, surface waves and free oscillations. We have determined the quality factor, Q , throughout the mantle by use of these techniques. The important results are that the upper mantle, in the vicinity of the low velocity zone, is highly attenuating and shear waves are attenuated more strongly than compressional waves. There are suggestions that the transition regions in the upper mantle and at the base of the mantle are also highly attenuating.

A new method has been developed for obtaining the attenuation of the free oscillations of the Earth. It was discovered that increased absorption occurs near 0^T_7 , 0^T_{20} , 0^S_{12} and 0^S_{23} . This can be tentatively interpreted in terms of increased absorption near 400 and 800 km depth in the mantle. These depths are near the discontinuities in elastic properties and it is possible that energy is being lost in the mixed phase regions of the mantle.

We are doing theoretical and experimental studies to determine the effects of pressure, temperature, and partial melting on attenuation.

Abstracts:

Anderson, Don L., "The Anelasticity of the Mantle," Geophys. Journ., 14, 135-164, Oct., 1967.

The attenuation of seismic waves provides the most direct data regarding the nonelastic properties of the Earth. Recent experimental results from body waves, surface waves and free oscillations provide estimates of the anelasticity in various regions of the Earth. Results to date show that the upper mantle is more attenuating than the lower mantle, the maximum attenuation is in the vicinity of the low-velocity zone, a rapid increase in attenuation occurs in the vicinity of the C-region of the mantle and compressional waves are less attenuated than shear waves. A frequency dependence of Q has not yet been discovered.

Most laboratory measurements of attenuation have been performed at ultrasonic frequencies on pure specimens of metals, glasses, plastics and ceramics. A general feature of laboratory measurements is an exponential increase of attenuation with temperature on which are superimposed peaks which can be attributed to dislocation or other defect phenomena. Measurements on natural rocks at atmospheric pressure can be attributed to the presence of cracks. The intrinsic attenuation of rocks

as a function of temperature and pressure is not known. However, on other materials grain boundary phenomena dominate at high temperature. This can be attributed to increased grain boundary mobility at high temperatures. High pressure would be expected to decrease this mobility. If attenuation in the mantle is due to an activated process it is probably controlled by the diffusion rate of defects at grain boundaries. Estimates of attenuation in the lower mantle then yield an estimate of the activation volume of the defects contributing to the loss. If the lower mantle is assumed homogeneous the estimated activation volume is a small fraction of the presumed molal volume of materials making up the lower mantle. Stress induced migration of small point defects is a possible loss mechanism consistent with the observations.

Kanamori, Hiroo, "Spectrum of P and PcP in Relation to the Mantle-Core Boundary and Attenuation in the Mantle," J. Geophys. Res., 72, 559-571, Jan. 15, 1967.

Spectrum analyses were made of the records of the short-period vertical component of P and PcP phases on seismograms of array stations at Tonto Forest, Arizona, for twenty-one earthquakes over the range $\Delta = 47^\circ$ to 83° . Generally, as has been reported by other investigators, the trace amplitude ratio of PcP to P is significantly larger than the theoretical ratio. The pulse width of PcP is narrower than that of P. Both of these facts can be explained by taking into account an appropriate attenuation distribution in the mantle. Taking Q_β for S waves, which has been determined by Anderson, Ben-Menahem, and Archambeau using different methods as a standard, the Q distribution for P waves, Q_α can be determined as $Q_\alpha \sim Q_\beta$ at the period of about 1 sec. A matrix method is applied to calculate the complex reflection coefficient of a transitional mantle-core boundary. Impulse responses calculated therefrom and comparison of the waveforms of P and PcP lead to the conclusion that the major discontinuity at the mantle-core boundary is sharp and is probably less than 1 km thick. The effect of a more gradual transition region superposed upon such a sharp discontinuity is also discussed. The possibility of the existence of a soft layer terminated by a sharp boundary cannot be totally ruled out.

Kanamori, Hiroo, "Spectrum of Short-Period Core Phases in Relation to the Attenuation in the Mantle," J. Geophys. Res., 72, 2181-2186, April 15, 1967.

Spectral analysis is made of the records of the short-period reflected core phases from array stations at Tonto Forest, Arizona. Three earthquakes having $\Delta = 32.5^\circ$, 49.0° , and 62.8° are studied. Spectral ratios of ScS to ScP and PcS to PcP are calculated in order to estimate the differential effect of attenuation on P and S waves. The possible maximum value of average Q for shear in the mantle, Q_β is about 324 for the period range 1.5 to 5 sec. Using the value of Q_α , average Q for P waves, that was previously estimated as 435 through the spectral analysis of PcP phase Q_β and Q_α / Q_β can be estimated at 230 and 1.90, respectively.

McKenzie, D. P., "Forced and Free Convection within the Earth's Mantle," Geophys. J., in press.

An analysis of zonal circulation in a rotating homogeneous compressible sphere shows it to be more important than was previously believed. However, such flow is probably unable to produce the observed nonhydrostatic equatorial bulge as Mcke has suggested. The basic equations of the problem are nonlinear, but may be linearized if the viscosity is sufficiently high. The conditions

which must be satisfied before this approximation is valid are examined in detail because of their importance in the problem of convection in the mantle. This discussion shows many of the terms in the full equations may be neglected, and the simplified, but highly nonlinear, equations governing convection in the upper mantle are obtained. The boundary conditions on both the temperature and velocity are discussed but no numerical solutions are obtained. Analytic solutions for the temperature and velocity fields are obtained for an extremely simple model for forced convection, and demonstrate that the gravitational acceleration is reduced over the rising limb of a convection cell in this model.

McKenzie, Dan P., "Some Remarks on Heat Flow and Gravity Anomalies," J. Geophys. Res., in press.

Heat flow anomalies on the oceanic ridges and the large free air gravity anomalies observed from the earth's surface and from satellites are often believed to be surface expressions of high temperatures and flow within the mantle. However, a simple model for the temperature within a spreading sea floor can reproduce the shape and magnitude of the observed anomalies. Thus a hot upper mantle beneath ridges is not required to account for the observations, though it could still do so. A similar model may be used to relate the free air gravity anomaly to the stress in the lithosphere. The results show that the long wavelength harmonics of the external gravity field cannot be supported by the strength of the lithosphere. Most free air anomalies observed on the surface can be maintained in this way, except possibly the largest of those over trenches.

Teng, T. L., "Attenuation of Body Waves and the Q Structure of the Mantle," J. Geophys. Res., in press.

The variation of Q_α with depth is studied using the spectrums of a large number of P waves from two deep earthquakes. Two assumptions are made: (1) the normalized source spectrum is not a function of the angle of radiation; (2) Q_α is independent of frequency, at least within the band of $f = 0.01$ to 0.2 cps. Spectral ratios of two body waves are used to eliminate the source effect and the effect of the wavefront divergence. It is shown that when instrumental and crustal effects are removed, the logarithm of the spectral ratio is a linear function of frequency. The coefficient of the linear term, called the differential attenuation, is used to invert for a Q_α -depth structure. Two possible Q_α models are presented; both of which have a low-Q upper mantle about 950 km deep with an average Q_α of about 93. This is followed by a high-Q middle and lower mantle where Q_α varies from 250 to 1000. Both models suggest a low-Q layer of about 200 km thick near the bottom of the mantle with an average Q_α of about 150. The Q_α models represent preliminary attempts to deduce the Q_α structure of the earth, and should be regarded as tentative, in particular the portion of the model near the bottom of the mantle. Results of the present study are comparable with the Q values obtained by other authors. Major sources of errors are discussed in light of further refinement of the experiment.

Kanamori, Hiroo, "Attenuation of P Waves in the Upper and Lower Mantle," Bull. Earthquake Res. Inst., Japan, in press.

Difference of Q specific quality factor, for P waves in the upper and the lower mantle is determined around the period of 1 sec by the spectral analysis

of P, PcP, pP and pPcP phases from nine aftershocks of the Alaska earthquake of March 28, 1964. The effects of crustal layerings are removed by Haskell's method. From relative spectral ratios P/PcP and pP/pPcP, the maximum of the average Q for P waves, \bar{Q}_α is estimated as 800. The ratio of the average Q for the upper 870 km of the mantle, \bar{Q}'_α , to that for the rest of the mantle, \bar{Q}''_α , cannot be larger than 0.3. Combining the previous estimate of \bar{Q}_α , the average Q for S waves, and taking the range of the ratio $1.8 \leq \bar{Q}_\alpha / \bar{Q}_\beta \leq 2.5$ suggested by surface wave studies, the probable range of \bar{Q}_α and $\bar{Q}'_\alpha / \bar{Q}''_\alpha$ can be determined as $410 < \bar{Q}_\alpha < 630$ and $0.04 < \bar{Q}'_\alpha / \bar{Q}''_\alpha < 0.12$ respectively.

Smith, S. W. and D. L. Anderson, "Attenuation of the Earth's Free Oscillations," presented at the XIV General Assembly, Int'l. Union of Geodesy and Geophysics, Zurich, Switzerland, Sept. 25 - Oct. 7, 1967.

The attenuation function for discrete modes of vibration of the earth has previously been measured from the bandwidth of the spectral lines and from a series of spectral density measurements made at successively later times after an earthquake. The principal errors that arise in these measurements are due to aftershock excitation of free oscillations and non-stationary earth noise. The effects of aftershocks and noise on the excitation of a particular mode of oscillation can best be seen by passing the seismogram through a very narrow band pass filter centered at the appropriate frequency for that mode. This operation produces an exponentially decaying sinusoidal signal in which a beat pattern due to the effect of the rotation of the Earth can be seen. Two important features of the seismogram are immediately discernible in such a signal: 1) increases in excitation due to aftershocks and other sources; and 2) the level at which the decay is no longer observable and the signals fall below the background noise.

The filters used in this analysis were a high Q resonant type; the digital realization of these filters was accomplished by a recursive operation. Preliminary results using this technique indicate that Q of low order spheroidal and toroidal modes is significantly higher than has been previously reported.

New values for Q are obtained for the great Alaskan and Chilean earthquakes, both by the above technique, which treats the seismogram as a standing wave, and by Fourier analysis of successive group velocity windows which treats the data as a travelling wave. This data is inverted to give the Q as a function of depth in the Earth, both in compression and in shear.

Teng, Ta-Liang, "Measurement of P-Wave Attenuation and Inversion of a Q-Depth Structure," presented at the 48th Annual Mtg. of the Am. Geophys. U., 4/17-20/67, Wash., D. C.

Measurements on the differential attenuation of teleseismic P-waves from the Peru-Bolivia deep shock of November 3, 1965, show good consistency with previous results from the Western Brazil deep shock of November 9, 1963. The replicability of these experiments seems to indicate that the assumption of isotropic source radiation, upon which the experimental method is based, holds at least for deep earthquakes of magnitude $M < 7$. With the addition of the new data a curve can be described which is used to invert for a Q-depth structure of the entire mantle. Several methods of inversion are discussed. In particular, it is shown that the inversion problem can be reduced to one of inverting a travel-

time matrix whose elements are functions of transit times through each layer. A Q-depth structure which is appropriate for long-period P-wave propagation is given. Its main features are (1) a low-Q upper mantle, (2) a high-Q middle-lower mantle, and (3) the Q value reduces sharply toward the core-mantle boundary.

VI. Source Studies

Objectives: To determine the properties and distributions of seismic sources.

Accomplishments: Continued progress has been made in our ability to obtain useful information about the seismic source from records written at teleseismic distances.

1) The seismograms of the Alaskan earthquake of 28 March 1964 were characterized by multiple P-phases not predicted by the travel-time curves. An analysis of these seismograms indicated that six events occurred after the initial event. These events were located and gave an average rupture velocity of 3.5 km/sec.

2) A straightforward method for computing rates of slip from earthquakes in major fault zones was developed. Rates obtained are in good agreement with other data where available.

3) Measurements of permanent tilt and strain have been made for six earthquakes and one large explosion. The results show consistently longer tilts and strains than are predicted by using a simple dislocation and half-space model.

Theoretical studies on the source mechanism are continuing. The effect of the radial variation of density and elasticity on excitation has been computed for three Earth models: tectonic, shield and oceanic. A method has been developed, related to the universal dispersion curve theory, for computing the effect of small changes in the Earth model on the excitation of surface waves. Extensive tables have been generated which allow one to compute the excitation for a variety of modes for any realistic Earth model.

The relaxation theory of seismic source radiation is being extended to include a failure criteria and a rheology in order to be able to predict onset of rupture, velocity of rupture and post-rupture relaxation. The theory is also being extended to handle a growing elliptical region.

Present computer programs are being modified to handle excitation of free oscillations from tectonic models of a growing region of stress relaxation. Since the source does not in general have any symmetry properties, this constitutes an extension of Harkrider's work.

Abstracts:

Vlaar, N. J., "The Field from a SH Point Source in a Continuously Layered Inhomogeneous Half-Space. II. The Field in a Half-Space, J. Geophys. Res., 56, No. 6, 1305-1315, Dec., 1966.

The propagation of waves due to the presence of an SH point source in the interior of a piecewise continuously stratified half-space is studied. The physical parameters governing the wave propagation, i.e., the rigidity and the

density, are assumed to be arbitrary piecewise continuous functions of depth with constant finite limiting values as depth goes to infinity. The analysis is based on spectral theory of boundary value problems associated with ordinary linear second order differential equations. It is found for the time harmonic case that the final field representations are given in the form of a finite residue series, plus a branch line integral, the first representing the normal mode contribution to the field. The field expression appears to have a symmetrical form with respect to field point depth and source depth, involving solutions connected with free wave propagation. This enables one to draw immediately conclusions regarding the influence of the source depth and the frequency on the spectral excitation of the normal modes if numerical knowledge of free Love waves is assumed to be known.

Liebermann, R. C., C. Y. King, J. N. Brune, and P. W. Pomeroy, "Excitation of Surface Waves by the Underground Nuclear Explosion Long Shot," J. Geophys. Res., 71, 4333-4339, Sept. 15, 1966.

The underground nuclear explosion Long Shot, detonated beneath Amchitka Island in the Aleutian Island chain on October 29, 1965, generated surface waves equivalent to those of an earthquake of surface wave magnitude $M_s = 3.9$. The body wave magnitude for this event is $m_b = 6.1$. Comparison with earthquakes from the same geographical and tectonic region, as well as comparison with the M_s versus m_b relationship of Gutenberg and Richter, indicates that the surface wave generation by Long Shot was significantly less than that of earthquakes of comparable body wave magnitudes. Since the body waves from Long Shot also contain less long-period energy relative to the earthquakes, we conclude that Long Shot did not efficiently excite the long-period part of the seismic wave spectrum. This result is in agreement with previous studies of underground nuclear explosions.

Brune, James N., and Clarence R. Allen, "A Micro-Earthquake Survey of the San Andreas Fault System in Southern California," Bull. Seism. Soc. Am., 57, 277-296, April, 1967.

The eight portable seismograph systems financed by the Air Force were used to make a micro-earthquake survey of the San Andreas fault in southern California. Micro-earthquakes were systematically recorded with magnitudes down to -1.3 at more than 60 sites along the San Andreas fault system in southern California during intervals of 2 days to 1 year, representing more than 35,000 hours of usable records. Noise levels averaged about 0.1 μ amplitude of ground motion.

Observed micro-earthquake activity varies from virtually nil along the central section of the San Andreas fault to more than 75 shocks daily in the Imperial Valley. Quietest is the 300-km segment between Cholame and Valyermo; more than one year of recording at Lake Hughes indicates an average of only one micro-earthquake within 24 km every nine days. Activity increases northward from Cholame toward Hollister, and southward it increases abruptly near Valyermo and continues high along major branches of the fault southeast into Mexico, with the exception of the Banning-Mission Creek fault southeast of Desert Hot Springs. Most areas where regional strain or fault creep have been demonstrated by geodetic measurements are also areas of high micro-earthquake activity. Existence of an area of minimal micro-earthquake activity within a broad region of active tectonism, and indeed along the very segment of the fault

that broke in the great 1857 earthquake, suggests that short-term micro-earthquake activity is not necessarily positively correlated with long-term activity and with earthquake hazard, and in some areas the relationship may be inverse. However, areal distribution of micro-earthquake activity is grossly similar to that of larger earthquakes ($M \geq 3$) during the past 29 years, and in many areas micro-earthquake activity can be approximately predicted by extrapolation of 29-year recurrence curves based solely on larger earthquakes.

Brune, James N., and Chi-Yu King, "Excitation of Mantle Rayleigh Waves of Period 100 Seconds as a Function of Magnitude," Bull. Seism. Soc. Am., in press.

The excitation of mantle Rayleigh waves of 100 seconds period as a function of magnitude was studied using data from 91 earthquakes in the magnitude range 5.0 to 8.9. The data were recorded on a wide variety of instruments including Milne-Shaw horizontal pendulums and modern long-period high-gain inertial seismographs. The larger earthquakes studied range in time from 1923 to 1964. Mantle Rayleigh wave amplitudes are corrected to a distance of 90° and plotted as a function of surface wave magnitude. The data are compared with theoretical curves based on a moving source model and two statistical models discussed by Aki. It is concluded that for large earthquakes the source may be approximated by a point couple which propagates a distance given approximately by the length of the aftershock zone.

Kovach, Robert L., and Don L. Anderson, "Study of the Energy of the Free Oscillations of the Earth," J. Geophys. Res., 72, 2155-2168, April 15, 1967.

The energies of the radial, torsional, and spheroidal free oscillations for a Gutenberg model earth were studied. Each mode of oscillation has a characteristic radial distribution of elastic and kinetic energy that fixes the parts of the earth that contribute most heavily in determining a particular resonant frequency. An examination of the partitioning of energy among compressional, shear, and gravitational energy as a function of mode number and depth immediately explains the persistence of the purely radial mode compared with the other normal modes of the earth. Only the first few spheroidal modes are sensitive to the density of the inner core; they are particularly sensitive to the density of the outer part of the core. The low-order spheroidal modes also exhibit a rapid rise of potential energy near the base of the mantle; this rise will permit improved estimates of the velocity to be obtained in this region, which is difficult to examine with body waves. The tabulated results allow estimates to be made of the previously neglected energy contained in the free oscillations excited by the great Alaskan shock suggests a value of 10^{23} ergs over the period range from 450 to 830 sec, implying that the energy density increases toward high frequencies in the total energy in the earthquake was of the order of $10^{24} - 10^{25}$ ergs.

Brune, James N., "Seismic Moment, Seismicity, and Rate of Slip Along Major Fault Zones," J. Geophys. Res., in press.

A straightforward method for computing rates of slip from earthquakes in major fault zones was developed. The slip rate is calculated from the sum of moments for the earthquakes. Rates obtained are in approximate agreement with rates obtained from geodetic measurements or magnetic anomalies provided long-time samples are considered and provided adjustments are made in the vertical

extent of the zone of earthquake generation. For some fault zones, particularly deep island arc shear zones, strain perhaps is being relieved by steady creep while in others, e.g. the San Andreas, strain is accumulating for a large earthquake. The zone of earthquake generation for oceanic transform faults may be as little as 5 km in vertical extent.

Wu, Francis T., "Parkfield Earthquake of June 28, 1966 Magnitude and Source Mechanism," J. Geophys. Res., in press.

The Parkfield earthquake of June 28, 1966 (04:26:12.4 GMT) is studied using short period and long period teleseismic records. It is found that: (1) $M_b = 5.8$ and $M_s = 5.4$ as compared to $M_b = 5.4$ and $M_s = 5.4$ for the fore-shock (04:08:54), (2) both the Rayleigh and Love wave radiation patterns conform to those of a double couple at a depth of about 8.6 km, (3) the main shock can be represented by a series of shocks separated in space and time.

The near field strong motion data support the last conclusion. Based on strong motion seismograms, and the surficial evidence of the dimensions of the fault, the energy is found to be 10^{21} ergs.

Davies, John B., and Stewart W. Smith, "Source Parameters of Earthquakes, and Discrimination Between Earthquakes and Nuclear Explosions," to be submitted to Bull. Seism. Soc. Am.

The first part of this study describes a technique by which the source parameters of an earthquake can be obtained from the spectrum of compressional waves. The source parameters defined are fault length, fracture velocity, and fault plane attitude. Two large, deep earthquakes are examined using this technique. The source parameters determined compare favorably with those obtained previously using different techniques. In the second section a method is proposed for discrimination between underground explosions and earthquakes. The technique utilizes the ratio of the spectra of the two classes of events where the path of propagation is common to both. On the basis of the analysis of the SHOAL event and a nearby shallow earthquake, it appears that the duration as determined from the spectral ratio is almost 10 times smaller for an explosion than it is for a comparable earthquake.

Wu, Francis T., "Source Mechanism of 1966 Parkfield Earthquake from Surface Waves," presented at the Annual Mtg., Seism. Soc. Am., Santa Barbara, Calif., 1967.

The Parkfield earthquake of June 28, 1966 provides us with excellent Rayleigh wave data; Love waves are relatively small. WWNSS records from stations in North and South America, Hawaii and northern Europe are transformed into frequency domain to obtain the surface wave radiation patterns; a double couple source representation is arrived at by trial and error. The rupture velocity and the fault length are found by observing the shift of spectral minima as a function of the azimuthal angle. These results are compared to the geological field observation and the near field seismic data.

Presented at the 48th Annual Mtg. of the Am. Geophys. U., 4/7-20/67, Wash., D. C.:

Smith, Stewart, Charles Sammis, Wayne Jackson, "Microearthquake Source Dimensions and Energy Release."

A temporary seismic array was operated by Caltech and the U. S. Geological Survey on the San Jacinto fault in the vicinity of Anza, California. Micro-earthquakes with magnitudes between . and 1 were detected within 10 km of the array. The spectrum of P and S waves in the band 1-40 cps was calculated for four earthquakes and one explosion located in the fault zone. The earthquake spectra were peaked at about 25 cps, and the explosion gave almost a flat spectrum. Using several different hypothetical fault models, the peak frequency was converted to a source dimension, which turned out to be about 50 meters under a wide variety of assumptions. Fault lengths of this size for magnitude 0 to 1 earthquakes are about 10 times larger than would have been predicted by extrapolation from earlier work on larger earthquakes. Energy release was calculated directly by integration of the velocity spectrum. Using the fault dimensions and energy release, the stress drop for these microearthquakes was determined to be about 0.5 bar.

Brune, James N., and Chi-Yu King, "Excitation of Mantle Rayleigh Waves of 100 Seconds Period as a Function of Magnitude."

The excitation of mantle Rayleigh waves of 100 sec period as a function of magnitude is studied. Seismograms from Milne-Shaw, Weichert, Columbia-IGY, WwSSN, CIT-ULP, and Columbia ULP-filtered instruments were used. Amplitudes were read directly from the records and corrected for instrument response and distance effects to a distance of 90°. The corrected amplitudes were plotted as a function of Richter magnitude. The magnitudes ranged from 5.0 to 8.9. The results were compared with theoretical curves derived from the directivity function, assuming fault lengths versus magnitude curves as given by Tocher and by Iida, and a rupture velocity of 3.0 km/sec.

Presented at the XIV General Assembly, Int'l. Union of Geodesy and Geophysics, Zurich, Switzerland, Sept. 25 - Oct. 7, 1967:

Brune, James N., and Clarence R. Allen, "A Micro-earthquake Survey of the San Andreas Fault System in Southern California."

See abstract on Page 17.

Smith, Stewart W., and John R. McGinley, "Permanent Tilts and Strains Associated with Earthquakes."

Recent measurements of permanent tilt and strain have been made for six earthquakes and one large explosion. The epicentral distances for the earthquakes range from 0 to 560 km and the magnitudes range from 2.5 to 7.5. Fault dimensions have been estimated from field observations and aftershock patterns. The results show consistently larger tilts and strains than would be predicted by using a dislocation of an elastic half-space as a model for the fault. It is shown that layers of low rigidity in the crust or upper mantle may be an explanation of this fact, since they can produce a significant increase in the permanent displacements associated with faulting. In the case of two of the earthquakes (magnitudes 2.5 and 7.5), the instruments were close enough to have observed precursor events had they occurred, but no change in the tilt or strain was discernable prior to the onset of these earthquakes.

Archambeau, Charles P., "Elastodynamic Source Theory: Part 1. General Theory," Rev. of Geophys., in press.

The most important and interesting source of elastic radiation in geophysics is an earthquake, or tectonic source, in that the radiation field from such an energy source provides information on the largely unknown stress field within the earth. In addition, the actual mechanisms or processes of material failure are undoubtedly described parametrically by the radiation field in terms of rupture velocity, rupture geometry, and the initial and residual stress within the region of failure. Accurate estimates of stress and the parameters of failure are, therefore, of particular significance in any description of the physical state of the material and would not be unrelated to the larger scale dynamical processes taking place within the earth. Thus, a number of methods and theories are presently used to give estimates of some of these parameters. The present study is intended to extend the dynamical theory of tectonic sources to provide a more complete description of earthquakes in terms of these basic parameters of rupture, including pre-stress, while at the same time making no assumptions concerning the nature of equivalent forces at the source or of their time dependence. The theory predicts the spatial and temporal form of the radiation field in terms of the initial pre-stress field and the basic rupture parameters and follows from the recognition that an earthquake is a relaxation source and that such a phenomenon is described analytically as an initial value problem. Consequently, such a source satisfies the conservation of energy and linear and angular momentum conditions required for a spontaneous source. The radiation field itself arises from the continuous reduction of stored potential strain energy in the elastic medium surrounding a growing rupture zone, where it is assumed that the rupture, or at least a part of the total rupture zone, has a well defined boundary at a given time, such that boundary conditions are applicable. The compatibility of this geometrically sharp, time varying boundary condition with probable failure processes in the earth is examined and judged to be good. Analytical expressions for the radiation field from an arbitrary source of elastic radiation are given and within the framework of this formulation the properties of a spontaneous tectonic source are contrasted with "applied force" sources and their special properties, as well as with some of the field observations of earthquake radiation fields. These considerations demonstrate the necessity of a more general and complete description of tectonic sources in order to explain all the observations, and more fundamentally, in order to deduce more precisely the nature of the physical processes of failure in the earth. It is concluded that a relaxation theory will provide the flexibility required to describe the characteristics of the observed radiation field, and will also provide estimates of rupture parameters bearing on the processes of failure and the state of the material.

A complete development of the dynamical relaxation theory for tectonic sources, including considerations of the total energy release and the final equilibrium field, constitutes the main result of this study, providing explicit expressions for the dynamic and static displacement and energy fields. It is shown that, in general the radiation field will have a frequency dependent shape, dependent to first order on the ratio of rupture length to radiation wavelength. A relatively simple example is considered and the radiation pattern, displacement and energy spectrums computed. The radiation pattern is contrasted with the pattern from a more complicated rupture geometry and serves to demonstrate the pattern-shape dependence on frequency, rupture geometry and pre-stress. The

energy and displacement spectrums are also found to have maxima and minima, the number dependent on the rupture geometry; their location and spacing dependent on rupture length and velocity.

VII. Instrumental Development

Objectives: Development of new instrumentation as required by needs of grant objectives.

Accomplishments: 1) A prototype tiltmeter for use in a borehole was constructed and bench tested. The objective was to determine if using conventional techniques one could make a tiltmeter small enough for operation in a typical heat flow hole, and achieve sensitivities required for the study of tectonic tilts (10^{-7} radian/year).

The instrument is an inverted pendulum with a 3 cm moment arm. The mass is cubical in shape with pairs of conventional capacity type transducers mounted on opposite sides. The outside diameter of the device is 2.5 inches without a remote leveling mechanism or hole lock. The electronics used would allow operation at pressures up to 5000 psi and temperatures up to 125°C.

The prototype model had a system noise level of less than 10^{-7} radians/cps. Improvement can be expected in this type device by adding electrical period lengthening. Further development has been suspended, however, until alternative approaches have been evaluated.

2) An improved ultra-long-period vertical pendulum has been installed at Isabella. Modifications include improvements in the feedback circuitry and the mechanical suspension. With a device such as this there is no standard for comparison of ground noise in the period band 60-3000 seconds. In order to determine if the present signal output in this band is limited by ground noise or system noise, an identical instrument has been installed on the same pier. Tests are currently in progress to evaluate this system.

VIII. Digital and Analog Recording

Objectives: To automate processes of seismic interpretations.

Accomplishments: Operation of the five component long period systems at Isabella and Nana has been continued. Permanent records of all large earthquakes are now being made by means of the Ambilog computer. Digital filters are applied to the data from the three pendulum and two strain instruments. Each instrument has a separate filter such that all data is equalized to the same frequency pass band. In the case of the strain instruments, plane waves with constant phase velocity are assumed and the equivalent ground displacement is calculated from the strain. When the epicenter is known, the separate strain and horizontal pendulum outputs are rotated to form longitudinal and transverse components. Separation of wave types, calculation of particle motion, and even estimation of apparent phase velocity can be made by using these combined strain-pendulum records. A collection of approximately 20 large earthquakes ($M = 6\frac{3}{4}$ -7) recorded on digital magnetic tape at Isabella and Nana is now available.

Each of these stations has a five component strain-pendulum system. Free oscillations and Q studies are planned for this body of data.

Operation of the eight station portable array in regions where micro-earthquake swarms occur and in the epicentral areas of large recent earthquakes produce a volume of data which cannot be easily processed by hand. For some problems, reliable and consistent data from thousands of such events is necessary, so an automatic system for searching magnetic tapes and calculating the epicenter has been completed. Briefly, the analog tapes are scanned and an event detector determines possible earthquake occurrences, which are transferred to digital magnetic tape. Event times from all stations are then used to validate an event as an earthquake. For local earthquakes, the P phase is picked by an amplitude threshold penetration. The S phase is estimated by applying a filter constructed from the shape of the P wave. At the completion of the process a seismologist can view the seismogram and make corrections if necessary.

In order to evaluate the effectiveness of this type of processing, the array was operated for two weeks in a high active seismic region in the vicinity of Anza, California where the rate of micro-earthquake occurrences is more than 10 per day. This was the first complete field evaluation of the magnetic tape recording systems. With the addition of a tape synchronization channel the system operated successfully, although the procedures for quality control of data are much more elaborate than required for film recording. A portable oscilloscope was purchased for field checking the tape recorders before each setup.

Automatic detection and location of microearthquakes was accomplished with this data using both the Ambilog and IBM 7094 computers. Vertical components only were available and thus the automatic identification of S waves was unreliable. Improvements in the processing technique will be necessary, however, to make it faster and more convenient if this type of automatic processing is ever to be a useful tool for seismicity studies.

Work has been completed on the interface between the telemetry terminal for the southern California array and the Ambilog computer. Experiments are underway, but not yet completed, on the automatic detection and location of events in real time. Initially, on detection of a possible event, data from the six stations will be stored on digital magnetic tape along with timing information from WWVB broadcasts. We expect to significantly improve the capabilities of the southern California stations for $dt/d\Delta$ and amplitude studies by means of this type of recording. Field programs which depend upon rapid knowledge of an approximate epicentral location in the California region will be assisted by such a system when it is connected with an automatic telephone dialing device.

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