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

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13. ABSTRACT

The study of anomalous events has succeeded in clarifying many of their puzzling aspects. Careful attention to the details of body wave magnitude computations has markedly reduced the number of anomalous events on the Asian continent. The remaining anomalous events display the same short period surface wave characteristics as intraplate events and because of their focal depth and the continental crustal structure there is the strong likelihood that Love wave surface magnitudes will provide a good discriminant.

The propagation of Love waves from one layered structure to another has been solved by a very efficient computational method giving excellent agreement with observations. A new technique of analyzing multi-mode surface wave dispersion has been developed which makes it possible to separate fundamental and higher mode Love waves from earthquake sources, given many observations. The technique permits mapping the horizontal variations of Love wave phase velocities.

The relation of earthquake focal mechanisms to global tectonic patterns has been extended to include the heretofore perplexing plate boundaries in the South Atlantic. Focal mechanism studies in the Scotia Sea have succeeded in defining the position and relative motions of the presently active plate boundaries, and thus added a needed constraint to the global pattern of plate motions.

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MAJOR SCIENTIFIC ACCOMPLISHMENTS

In the following paragraphs, scientific accomplishments for January through June 1974 are summarized following the itemization in the statement of work of this contract.

Line - Item 1a

Operation of the Lamont-Doherty network of three long-period and intermediate-period seismographic stations (the Palisades, Sterling Forest, and Ogdensburg) has continued during the last six months.

Line - Item 1c

The relation of earthquake focal mechanism to global tectonic patterns has been a constant theme in our work for many years. The tectonic pattern of the plate junctions in the South Atlantic Ocean has never been clear, however. Earthquake focal mechanisms have succeeded in defining the nature of the plate boundaries in this region.

Focal mechanism solutions for 46 earthquakes that occurred in the South Atlantic Ocean, in the Scotia Sea, and in southern Chile during the period 1963-1973 have been examined. The slip vectors of shallow earthquakes indicate that the South American plate is moving directly west with respect to the Antarctic plate at the ridge-fault-fault triple junction in the South Atlantic. The directions of motion of Africa with respect to the South American and Antarctic plates at the triple junction are N70°E and N47°E, respectively. The SA-ANT relative motion between the triple junction and the South Sandwich trench is best described by a pole of rotation at 80°S, 166°W, with angular rotation rate of 0.24 deg/my.

Shallow earthquakes along the South Sandwich trench indicate the oceanic portion of the South American plate is being thrust under the South Sandwich arc in an E-W direction. Most of the earthquakes at the northern end of the arc are due to hinge-faulting or bending stresses within the underthrust oceanic plate. The focal mechanisms of intermediate depth events beneath the arc indicate downdip extension in the northern end of the downgoing slab and downdip compression in the southern end. This change in the stress pattern may be caused by reduced negative buoyancy forces in the younger, southern half of the subducted plate. The seismicity and mechanism solutions suggest that the SA-ANT relative motion in the Scotia Sea region is taken up on both the North and South Scotia ridges. However, the plate boundaries in this area and in southern Chile are not well-defined. There does appear to be a consistent pattern of horizontal compressive stress directed ENE-WSW throughout the Scotia Sea region, probably induced by the convergence of the South American and Antarctic plates.

The SA-ANT relative motion observed in this study is not consistent with the motion predicted from the summation of motions observed on other plate boundaries. This discrepancy may be due to (1) systematic errors in the data, (2) a recent change in plate motions, or (3) minor, non-rigid plate behavior. The third explanation is preferred, because internal deformation of the plates at very slow strain rates can explain other examples of seemingly inconsistent plate motions, and may also account for the existence of diffuse, intraplate seismicity. The apparent relative drift of hot spots may also be due to internal deformation of the plates after the seamont chains are created. This work has been submitted to the Journal of Geophysical Research.

Line - Item 1f

1. Amplitudes of Horizontally Refracted Love Waves

Love wave transmission is studied numerically for propagation from one layered structure into another layered structure. By a new method of approximation the transmission coefficients can be computed for propagation directions differing from normal incidence. The method treats the steady state case. A Love mode is viewed as a superposition of propagating plane SH waves in those surface layers that have S-velocity smaller than the phase velocity, and inhomogeneous plane SH waves in layers having S-velocity larger than the phase velocity, notably in the lower halfspace of the layered structure. The term inhomogeneous plane waves is introduced in this study in agreement with the notation for electromagnetic waves that are solutions to the wave equations; they propagate in one direction in space and fall off in a direction perpendicular to it. The inhomogeneous plane waves are reflected and transmitted at a boundary just as are propagating (homogeneous) plane waves. The method is based on satisfying all boundary conditions on the vertical interface between two layered structures and computing the coupling between the interface stress-displacement field and the transmitted Love modes. The computations are done rapidly on a computer. The results of the present approximation method compare favorably with finite element computations reported in the literature, which require far more computer time.

Love wave amplitude observations were made at the seismic stations OBS on the ocean bottom northwest of San Francisco and BKS in Berkeley. Amplitudes and corresponding periods were read visually from the seismograms, and a few of these readings are supported by Fourier analysis results. The average trends of the observations are an increase of BKS/OBS amplitude ratio with decreasing period in the interval 60 - 20 seconds, and almost no dependence on angle of incidence between 0 and 60 degrees. These trends are common for propagation from the ocean to the continent and vice versa.

By comparison of the observations with computations for different layered structures a physical explanation is given of the observed trends. The amplitude vs. depth curves for Love waves in an oceanic structure have different shapes than those in a continental structure. The fundamental mode in the oceanic structure has large amplitudes in the low velocity channel, while in the continental structure it has the largest amplitudes at the surface. The difference between the amplitude vs. depth curves of the two fundamental modes becomes larger as the periods become shorter in the interval of interest, 60 to 20 seconds. At the continental margin energy is transmitted up or down. For periods shorter than approximately 25 - 30 seconds the first higher modes with large amplitudes in the low velocity zone play an important role in the transfer of energy. For transmission from the continent to the ocean, the first higher mode also has a surface amplitude larger than that of the fundamental mode. For the periods between 20 and 30 seconds there is a significant amount of mode conversion at a continental margin. The horizontal transmission of energy cannot be evaluated separately from the vertical transfer of energy caused by the different amplitude-depth curves of the ocean and the continent.

The suggestion in the literature that the transmission of energy is the same for propagation back and forth between a normal mode in one structure and a normal mode in another structure is verified. Reflections can be computed by the method of this paper. The reflection coefficients computed for a few suggested models are close to zero except for angles of incidence close to or beyond critical, which is beyond 60 degrees for these models. Beyond 60 degrees the simple transmission in the form of normal mode coupling is probably complicated by surface waves horizontally refracted along the continental margin.

2. A New Method for the Analysis of Multi-Mode Surface Wave Dispersion: Application to Love Wave Propagation in the East Pacific

A new technique has been developed for simultaneously measuring the average, regional phase velocity of two or more surface wave modes, even if they travel with the same group velocity. Many observations are required over paths of varying length with earthquake sources of known focal mechanism. The phase of the signal observed at each station can be predicted if the initial phase of the source and the phase velocity and relative amplitude of each mode is known. The square of the difference between the observed phase and the predicted phase is summed over all paths for a set of trial phase velocities. The trial velocities which give the minimum sum correspond to the average phase velocity of each mode.

By applying this technique to Love wave data from the east Pacific, the dispersion of the first higher Love mode was measured for the first time in an oceanic area. The phase velocity of the fundamental mode was found to increase with increasing age of the sea floor, probably as a result of the cooling of the oceanic lithosphere. The region was found to be anisotropic for Love wave propagation, with the fastest velocities roughly perpendicular to the ridge. The degree of anisotropy appears to increase with increasing period. This has been submitted to the Bulletin of the Seismological Society of America.

Line - Item 1g

The study of anomalous, intraplate events in the eastern Himalayas has succeeded in clarifying many of their puzzling aspects.

The region under consideration, defined by the Conference of the Committee on Disarmament (CCD) (1972) report, ranges from 92° to 100° east longitude and from 27° to 34° north latitude. This area occupies a region of the eastern Himalayas where the Great Boundary Fault, Main Thrust Fault and the Indus Suture Zone converge toward an intersection with the northern extension of the Andaman Trench and the Ninety-East Ridge. In spite of the complex tectonic setting, the orientation of the horizontal projection of the maximum compressive stress component appears to be rather uniform throughout this limited region.

All seismic events that occurred in this area are reported in the Preliminary Determination of Epicenters (PDE) published by the National Oceanic and Atmospheric Administration (NOAA). The authors of the CCD report have assigned surface wave magnitudes (M_s) to many of these events, and comparing these surface wave magnitudes to reported PDE body wave magnitudes they have grouped these events into three categories: 1) Type I events, those earthquakes that fall clearly in the earthquake population on an M_s-m_b plot. 2) Type II events, those earthquakes that are statistically indistinguishable from the explosion population on an M_s-m_b plot, and 3) Type III events, those earthquakes that fall in the Central Asian explosion population on an M_s-m_b plot. These three regions of the M_s-m_b plot are defined as:

I: $M_s \geq m_b - 1.0$

II: $m_b - 1.0 > M_s \geq m_b - 1.5$

III: $M_s < m_b - 1.5$

and are separated by dashed lines in Figures 1 and 2. Figure 1 is an M_s-m_b plot using the M_s values computed by the authors of the CCD report. The m_b values used in this plot, the same as those of the CCD report, are taken directly from the PDE reports with no further consideration of station location or distribution taken into account.

The formulation used in the determination of body-wave magnitudes reported in the PDE was changed on 31 October 1966, and hence two different methods of m_b computation are included in Figure 1. The two formulas yield slightly different values of body-wave magnitude. To remove the inconsistency m_b has been recomputed for all the events before 31 October 1966 using the new formula.

An additional problem in computing consistent PDE body-wave magnitudes using the Gutenberg and Richter formula results from including observations at stations less than 20° from the epicenter. Evernden (1967) considered some of the problems resulting from using near stations and concluded that body-wave magnitudes overestimated by as much as 1.5 magnitude units frequently occur because of failure to take into account such effects. He cites a Vermont earthquake as a striking example of this problem. Very few stations

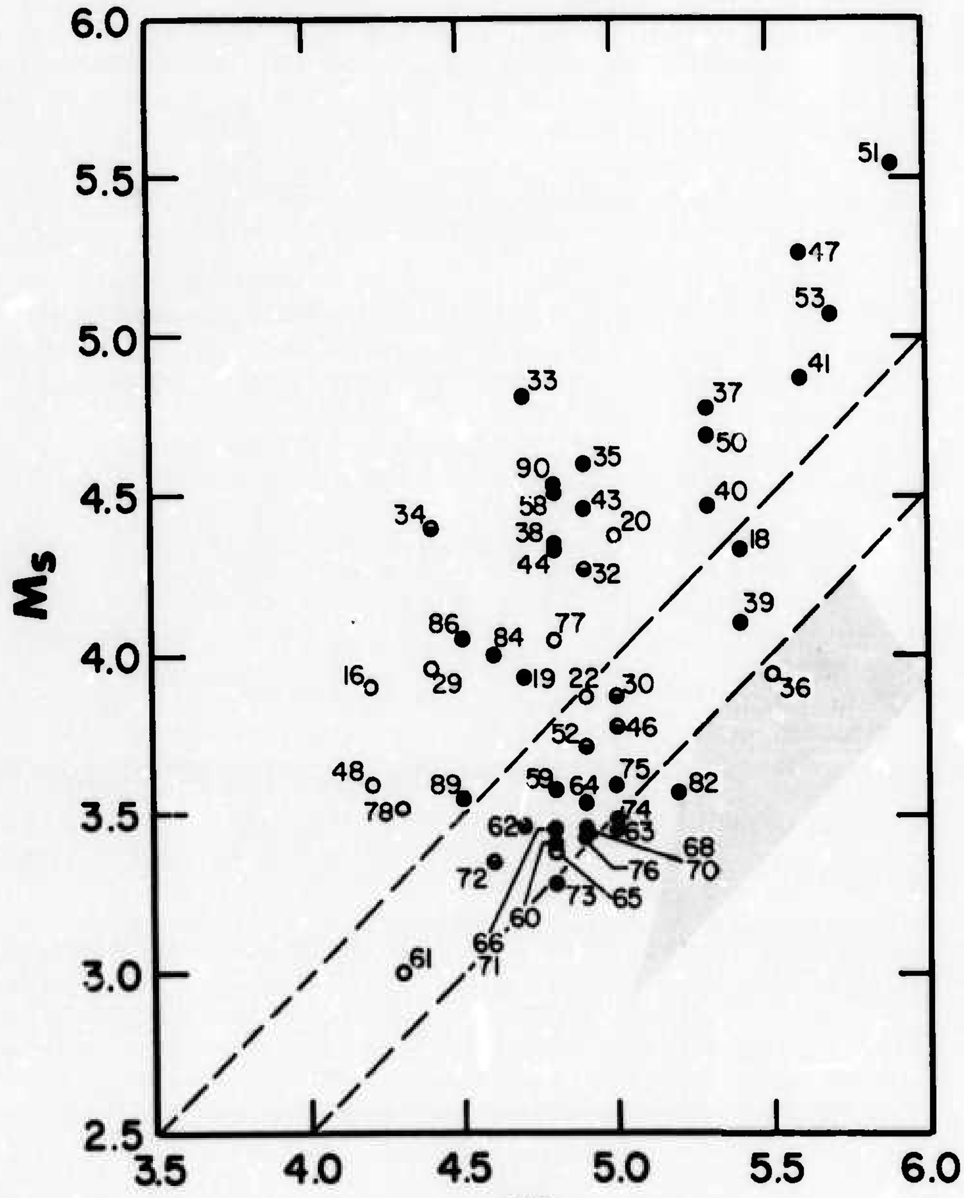

Figure 1 M_s-m_b plot of the eastern Himalayan events reported by the CCD (1972). M_s values were computed by the authors of the CCD report, and m_b values were taken directly from the Preliminary Determination of Epicenters (PDE). The stippled area contains Marshall and Basham's (1972) observations of explosions in eastern Kazakh and Sinkiang. Dashed lines separate three regions of this plot as discussed in the text.

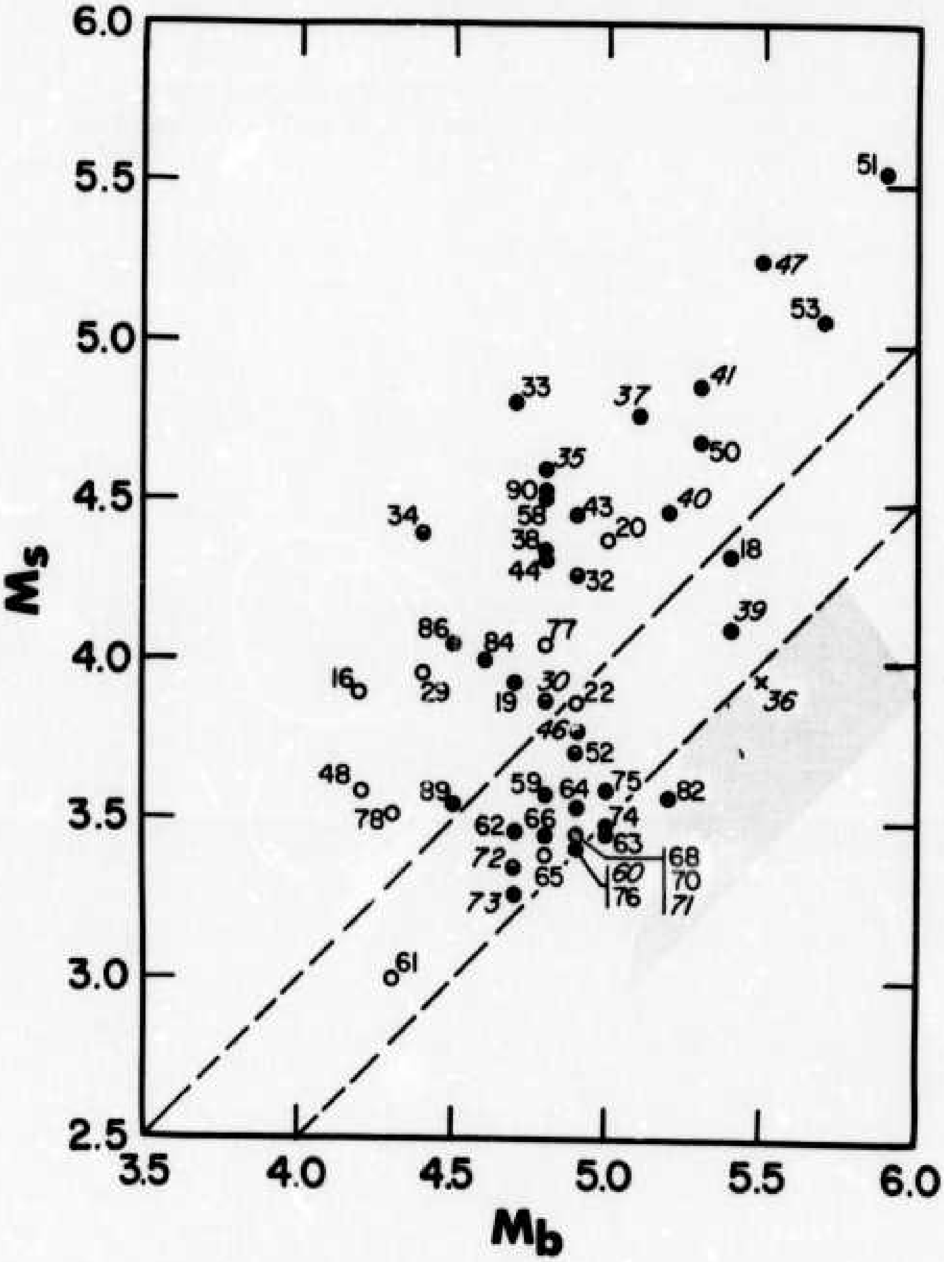

Figure 2 M_s-m_b plot of data in Figure 1 with m_b values recomputed after excluding all observations at epicentral distances less than 20°. Events whose body-wave magnitude has changed from Figure 1 are indicated by slanting numerals. The X denotes events with no m_b observations at epicentral distance greater than 20°. All other symbols are the same as those in Figure 1. Note that event 36 can no longer be defined as an anomalous event, and that the remaining, smaller magnitude, anomalous events group more tightly in a relatively well defined area of the M_s-m_b plot.

observed the Vermont event, the most distant being 2017 km. Five computed magnitudes ranged in value from 3.3 to 5.4, the average being 4.7. An earthquake of this magnitude should have been well observed at teleseismic distances, and hence an inconsistency existed. Recomputation of the magnitude using a more reasonable formula for the observed distance range reduced the magnitude to 3.8 or 3.9, removing the apparent inconsistency.

Taking Evernden's results into account, the body-wave magnitudes for the eastern Himalayan events under consideration here were recomputed dropping all magnitude calculations at epicentral distances less than 20°. The results of this further recalculation are shown in Figure 2 with index numbers for those events whose m_b value change from either of the two previous plots shown in slant numerals. This plot should be more consistent than the previous two, and will be the standard used here for definition of anomalous events in this particular region of the eastern Himalayas.

Discussion of changes There are a few events whose position on the M_s-m_b plot change rather significantly as a result of the recomputation of m_b values. Specifically, event 36 no longer has an m_b, and hence its potential as an anomalous event is unknown. Recomputation of the body-wave magnitude of this event (36) yields an m_b of 4.5, which places it well within the Type I natural earthquake population. Further, the surface-wave magnitude for this event, and others in the same sequence, may well be underestimated. Examination of surface waves generated by these events shows that Love waves are very well developed on several different azimuths, and Love wave amplitudes average three times the Rayleigh wave amplitudes for at least one observing station. Surface-wave magnitudes based on Love wave observations, as well as Rayleigh wave observations, may well improve the M_s-m_b characteristics of these events, and should be considered in any seismic event detection scheme.

Event 73 has changed from a Type III event to a Type II event, and event 30 has changed from a Type II event to a Type I event. Earthquakes in the 1968 sequence (most of events 59 through 84) are grouped in closer proximity on the revised plot, and with the removal of event 36 as a Type III event, all of the clearly anomalous events (Type III) are contained in this sequence. In general, the improved plot of Figure 2 shows better separation of groups of events than the original plot, thus more clearly defining some of the m_b-M_s problems.

The surface waves generated by the anomalous events share some striking similarities, particularly a predominance of short-period energy with a dominant period generally less than 10 or 15 seconds. Sykes and Sbar (1973) have noted that intraplate earthquakes efficiently generate short-period surface waves, and Tatham (1973) has successfully exploited this observation to examine shallow crustal structure. Tatham suggested that this short-period characteristic of intraplate earthquakes is sufficiently universal to allow these types of events to be used for shallow crustal structure on a nearly global scale.

The surface waves generated by the reliably identified anomalous events, those still remaining outside the natural earthquake population after the m_b recomputations, display the same short-period surface wave characteristics as the intraplate events. Tectonically, this observation could suggest that the earthquakes occurring at a continent-continent collision type of a plate boundary may have more in common with intraplate earthquakes than they do with earthquakes occurring at other types of plate boundaries. Also, the thick crust (~ 70 km) in the Tibetan plateau region may further complicate surface-wave magnitude determinations in this area. The fact that earthquakes can occur at rather substantial hypocentral depths could significantly reduce the amplitudes of the generated surface waves. This problem of attenuation with focal depth could be especially acute for these intraplate type events because only the short-period surface waves are created initially, and this is precisely the portion of the surface-wave spectrum that is most severely attenuated, even at rather moderate focal depths. Fortunately, Love wave amplitudes are less strongly attenuated with focal depth than are Rayleigh wave amplitudes, and hence Love waves should be considered in computing surface-wave magnitudes. In addition, the thick crustal section may contribute toward a stronger wave-guide effect than exists in other areas of the world, and thus Love wave development and transmission may be favorably enhanced. The fact that well developed Love waves are observed for many of the natural earthquakes occurring within the area under consideration supports these hypotheses and increases the likelihood that Love wave magnitudes could be useful in the reliable and consistent determination of surface-wave magnitudes.

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Problems Encountered:

None

Action Required by the Government:

None

Future Plans:

Future plans call for the continuation of the research outlined above and in other areas specifically related to the VELA-UNIFORM program.

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