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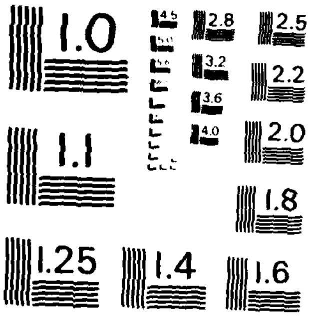

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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8. An analysis of the correspondence between documented teleseismic earthquakes and mapped faults in Pakistan.

SUTURE ZONES, SEISMIC WAVE PROPAGATION, AND TECTONICS OF CENTRAL ASIA

Lamont-Doherty Geological Observatory
of Columbia University
Palisades, New York 10964

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Abstract

During the past six months of this contract, research was conducted in the following areas of interest to the contract.

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Semi-Annual Report

1. Relative P-wave residuals calculated from nuclear explosions and teleseismic earthquakes recorded at short-period stations in New York and adjacent states are examined in an attempt to correlate them with tectonic structural features, gravity anomalies and other geophysical parameters. The residuals for events from NTS, Novaya Zemlya, and the Aleutians support the findings of Fletcher et al. (in press) that travel time residuals for stations in northeastern New York are negative, i.e., the arrivals are early as opposed to the state as a whole. The relative residuals for one Aleutian earthquake vary by more than 3 sec across the state. For events of eastern and southern azimuth the range in residuals is on the order of a second and the northeastern stations are not always negative with respect to the western stations. This residual pattern, particularly the wide range of residuals for some events, requires that there must be large-scale laterally inhomogeneous structures in the crust and upper mantle. It is possible that an ancient suture zone consisting of high velocity oceanic crust material imbricated in the lithosphere along the New York-Vermont border might explain these observations. (E. Cranswick and L. R. Sykes)

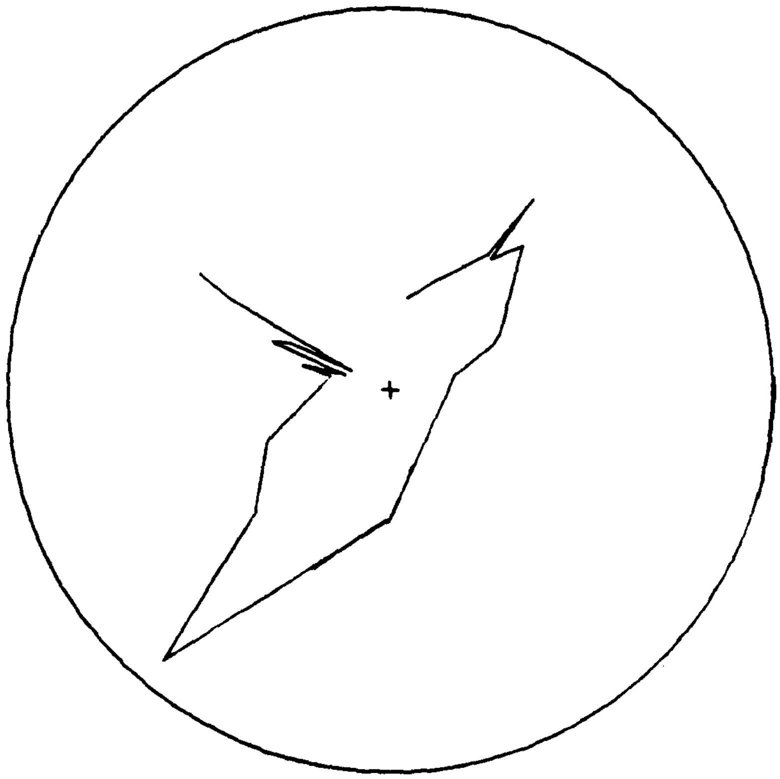
2. A study has just begun to investigate anomalous relative residuals for P and PP arrivals from earthquakes with reflection points beneath the Tibetan Plateau. Some residuals are significantly larger (more positive) than those expected for a double crust: anomalous material may exist to a depth of about 200 km. No anomalous travel-times were observed for arrivals with reflection points in Asia beneath the Tien Shan Mountains and the Indus Basin. (Y. Aggarwal)

3. The focal mechanisms of earthquakes near or on the mid-Atlantic ridge contain important information about the small-scale motions of the lithosphere near the spreading center. Problems are often encountered in studying focal mechanisms in this region because few earthquakes have magnitudes greater than 6.0, an approximate minimum magnitude for calculating good quality focal mechanisms for this region from P-waves alone. This project attempts to obtain focal parameters of earthquakes on the mid-Atlantic ridge between 25°N and 36°N from the analysis of surface waves.

Rayleigh waves of a magnitude 5.0 earthquake occurring on April 17, 1974 at 35.2°N and 35.37°W were analyzed from the vertical component of 25 WWSSN stations. Amplitude densities of period 35.1 second were obtained from moving window analysis, and were equalized to 3000 kilometers with instrumental, geometrical spreading and attenuation corrections. These quantities were plotted as a function of epicentral azimuth (Figure 1). Dashed lines represent nodal planes constrained by the three lobe-like radiation patterns. The azimuthal distribution of these stations ranges about 270°, and locate on the European, South American and North American continents. It appears to be evident that the maximum amplitude densities appear almost exactly 45° from each nodal plane. These results make us believe that it is a four lobe radiation pattern of a strke-slip fault striking about N83°E. It is noteworthy that the amplitudes observed on the records from the North American

<u>Figure 1</u>

Plot of observed Rayleigh wave amplitude density at 35 sec vs. azimuth from epicenter for 25 stations in Europe, North America, and South America. Three observed lobes of the four lobe strike-slip pattern coincide approximately with the central azimuth to each continent.



EVEVT A1,RAYLEIGH WAVE 35.1SEC.

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Figure 1

stations vary more with azimuth than the amplitudes from the European and South American stations. Because attenuation and geometrical spreading corrections were made isotropically to all the data and because group velocities were corrected for slower velocities along continental paths passing through both Europe and North America, we think that the variation of observed amplitudes with azimuth may be the result of lateral refraction along ray paths to North American stations.

We are attempting to work out the observational radiation patterns of Rayleigh and Love waves in this region, starting from the largest earthquakes which have focal plane solutions from body waves already. These studies are believed to be a necessary step to understand the actual path effects of surface waves from this region, and it will be greatly helpful to solve source mechanisms. We have built the confidence from previous work to obtain at least two source parameters, i.e., the fault type and strike of earthquakes with magnitude larger than 4.6. This study will also enable us to determine the fine-scaled spreading patterns in this region, which are not completely understood at the present time. (S.-K. Ho)

4. An approximate method for calculating the reflection and transmission coefficients of normally incident Rayleigh waves across two welded quarter-spaces was previously outlined by Alsop, Goodner and Gregersen (hereafter abbreviated as AGG). We have revised two of the concepts presented in AGG then extended the revised method to allow for oblique incidence. The results for normal incidence are in agreement with previous experimental and theoretical results (McGarr and Alsop, 1967; AGG, 1974).

For two media with a phase velocity ratio of 1.16, we found that the transmitted energy follows a reciprocity relation; that is, if the same propagation path is followed, the energy transmitted from medium I to medium II is the same as that from medium II to medium I. Theoretically, this reciprocity relation should exist between any discrete eigenfunction on either side of a transition zone. The transmitted energy decreases from near 100% at normal incidence to 50% at about 40° (Figure 2a). The reflected energy is less than 1% and decreases with increasing angle of incidence (Figure 2b). Since we did not take boundary conditions on the free surface into account, we believe that the calculated energy for reflection/transmission will be reduced by diffractive effects, and our results probably represent an over-estimate for the reflected and transmitted energy. (T. Chen)

5. House and Boatwright have analyzed two moderate earthquakes (M_b = 5.7, 6.0; M_s = 5.1, 5.3) that occurred in the Shumagin Islands (a group of islands off the Pacific coast of the western tip of the Alaskan Peninsula) on April 6, 1974 at 0153 hrs and 0356 hrs, respectively. These events were located at 54°52.18'N, 160°17.37'W and 54°54.33'N, 160°17.71'W at depths of 37 and 40 km. Arrivals at six stations with epicentral distances of 39 to 110 km were used to locate these events. These stations are a subset of a large short-period telemetered network operating in the Shumagin Islands region. The two earthquakes were not preceded by locatable foreshocks but were followed by some

Figure 2

a) Plot of transmitted energy vs. angle of incidence for a plexiglass to polystyrene interface and for the reverse.

b) Plot of reflected energy vs. angle of incidence for the same two interfaces as in Figure 2a.

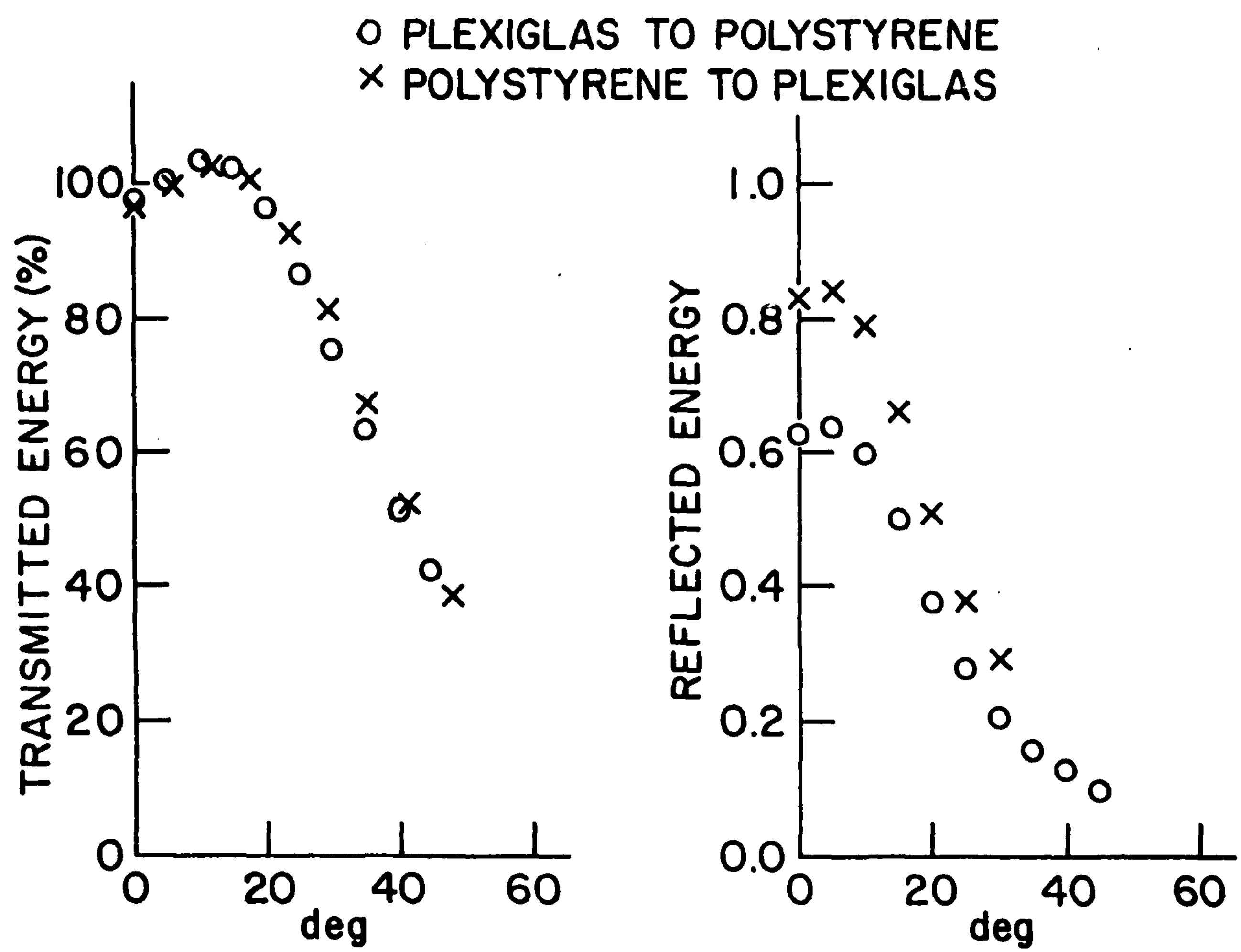

Figure 2a

Figure 2b

30 aftershocks which delineate a diffuse zone of activity roughly parallel to the Benioff zone (strike 240°, dip 32°N) and to one of the nodal planes of the focal mechanism (strike 244°, dip 30°N) for these two events. The focal mechanism for the 0356 event was determined from the P-wave first motions and S-wave polarizations at 62 stations of the WWSSN and Canadian network. The 0153 event had fewer, but identical P-wave first motions and S-wave polarizations, and is assumed to have the same focal mechanism. The T and P axes are oriented 334°, 75° and 154°, 15°, respectively.

Both events triggered a SMA-1 instrument sited at Sand Point, on Popof Island, at a hypocentral distance of ≈ 64 km. We have analyzed the SV components (Sand Point is at an SH node) from these records using the technique proposed by Richards and Boatwright (personal communication). The two events are remarkably similar, with moments of $M_o = 2.5 \pm .2, 4.9 \pm .4 \times 10^{24}$ dyne-cm; radiated energies of $E_s = 4.2 \pm 1.0, 5.5 \pm 1.3 \times 10^{19}$ dyne-cm; and stress drops of $.55 \pm .2$ and $.4 \pm .15$ kbars, respectively. The combined rupture area of 16 ± 5 km^2 is considerably smaller than the area of the aftershock zone (≈ 100 km^2).

These results are significant as determinations of the state of stress in this subduction zone and seismic gap, since the events resulted from a nearly pure underthrusting of the Aleutian arc by the Pacific plate. Using an energy balance approach, it is possible to estimate a lower bound for the average shear stress (resolved across the fault plane) of ≈ 5 kbar. (L. House and J. Boatwright)

6a. Both historical (non-instrumental) and modern (instrumental) data are compiled and critically reviewed to document the known seismicity of Pakistan, Afghanistan, NW India, SE Iran and small portions of the USSR, People's Republic of China, and Arabian Sea. The region studied is bounded by lines of latitude 20° and 38°N and lines of longitude 60° and 80°E. Intermediate-depth earthquakes in the Hindu Kush and Pamir region are excluded from consideration in this study.

The historical data consist of about 350 accounts and felt reports concerning earthquakes which occurred as early as 25 A.D. These data are interpreted in terms of the modified Mercalli intensity scale. The modern data consist of arrival times and hypocenters found in various earthquake catalogs for about 675 events which occurred between January 1914 and April 1975. Modern events occurring between 1914 and 1965 are systematically relocated. Magnitudes for most modern events are either determined from ground-displacement amplitude and period information given in the bulletins of some stations (e.g., Uppsala and DeBilt) or are compiled from other sources.

For some of the larger events in both historical and modern times it is possible to estimate the orientation and length of the zone of rupture. In a few cases an approximate value of the seismic moment is also estimated.

The patterns of seismicity which are observed can be summarized as follows:

(1) The frontal fold and thrust belt, associated with the collisional boundary between India and Eurasia, is seismically active along its entire length. Some segments of this zone have ruptured in large earthquakes in the historical past.

(2) The seismicity of the Makran region of southern Pakistan and southeastern Iran is consistent with the interpretation of this region as a zone of active subduction of the Arabian plate beneath continental material to the south. The Makran coast was the site of a great earthquake in 1945.

(3) The Murray Ridge-Owen fracture zone, the probable plate boundary between the Arabian and Indian plates, is a seismically active feature.

(4) Geomorphically prominent strike-slip faults in the Eurasian hinterlands of the frontal fold and thrust belt (e.g., the Chaman and Herat faults) have shown only minor levels of teleseismic activity, but some have experienced infrequent large earthquakes.

(5) Seismic activity in the Indo-Ganges basin, which is the foredeep associated with the frontal fold and thrust belt, is observed.

(6) The coast of India is characterized by a general low level of activity, but has been the site of at least one large earthquake in the historical past. (R. C. Quittmeyer and K. H. Jacob)

6b. Evidence from seismology and plate tectonics indicates that the Quetta-Sibi syntaxis of Pakistan may have developed as a result of right-lateral movement on a broad shear zone extending southwest from Quetta. Three large earthquakes have been associated with the Kachhi plain of Pakistan in the past 100 years. Intensity data for the two earlier events (1872, 1909) and aftershock data for the most recent one (1931) indicate that earthquakes in this area are caused by rupture of faults with a southeast orientation. A focal mechanism for an event in 1973, located within the inferred shear zone, is consistent with right-lateral movement along a fault plane parallel to those inferred for the large events. Such movement is compatible with the large-scale features of the Quetta-Sibi syntaxis observed today. Consideration of the current plate motions suggests the development of the syntaxis may be a natural consequence of the changing angle between the India-Eurasia plate boundary and the northerly direction of relative plate motion. In southern Pakistan plate motion is parallel to the plate boundary, but to the north the motion becomes more and more oblique. This oblique motion may decouple into thrusting combined with dextral shear (associated with crustal shortening) in the Quetta-Sibi syntaxial region and sinistral shear along the Chaman fault. Similar zones of convergence associated with oblique plate motion along the San Andreas fault in California and the Alpine fault in New Zealand were discussed by Scholz (1977). (R. C. Quittmeyer)

7. The historical and modern seismicity of Pakistan and its vicinity is examined in terms of its relation to mapped surface faults. There are found to be three categories into which the seismicity may be classified: 1) earthquakes with large source dimensions that are associated with faults on the basis of either surface rupture of a mapped fault or aftershock areas of focal mechanisms that define a trend that is consistent with a mapped fault; 2) narrow, elongate zones of earthquakes that may be related to movement along a single, continuous fault or a group of similarly oriented smaller faults; 3) diffuse activity that is not clearly related to any individual fault. The seismicity of this last category may in some places be the result of the scatter of epicentral locations of earthquakes occurring along shallow-dipping thrust faults. The seismic activity also defines portions of the Indus basin as seismically active even though no surface faults are mapped there.

Care must be employed when using only documented seismic activity to evaluate seismic hazards within Pakistan. The seismic record may be short when compared to the recurrence intervals for large earthquakes. Geologic evidence of recent fault movement and geodetic measurements will help alleviate this deficiency of the seismic record. (R. C. Quittmeyer, A. Farah and K. H. Jacob)

8. Geophysical and geologic data indicate the Makran region of Pakistan and Iran is an active subduction zone. Oceanic portions of the Arabian plate subduct towards Eurasia with rates of about 5 cm/yr. Most of the tectonic features of the Makran arc-trench system are somewhat anomalous. The anomalies include: The arc-trench gap measures 500 $\pm$ 100 km, twice the width of a typical arc-trench gap. The Benioff zone is only weakly developed to a depth of about 80 km with no reliably located seismicity at larger depths. Yet two focal mechanisms in the deepest documented part of the Benioff zone indicate down-dip tension in the descending slab. The 400 km long volcanic arc shows wide spacing (> 100 km) between its major volcanic centers. A large portion of the accretionary prism is subaerially exposed rather than submarine. The geologic record indicates that this active continental margin may have developed through most of the Cenozoic, and the large portions are still underlain by an oceanic infrastructure. (K. H. Jacob and R. C. Quittmeyer)

List of Personnel

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T. Chen
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L. House
R. Quittmeyer

Problems Encountered:

None

Action Required by the Government:

None

References Cited:

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