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Bulletin of the Seismological Society of America. Vol. 55, No. 3, pp. 579–586. June, 1965

MICROEARTHQUAKE CRUSTAL REFLECTIONS, SOCORRO, NEW MEXICO

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ABSTRACT

About 25 per cent of the microearthquakes which originate close to Socorro (*S* minus $P \leqq 2.5$ secs) produce seismograms with two sharp arrivals about 2.5 and 5.0 seconds after the direct *S*-phase arrival. The best interpretation of the time-distance data for these late phases is that they are the S_rP and the S_rS reflections from a crustal discontinuity at a depth of 18 km. The amplitudes of the reflections, which average 0.21 and 0.32 of the direct *S*-phase amplitude on vertical-component seismograms, are far greater than theoretical amplitudes found by assuming uniform radiation from the focus and reflection of a plane *SV* wave from a horizontal discontinuity.

Introduction

For several years, high-magnification seismographs located 3 miles west of Socorro, New Mexico, have been recording nearby microearthquakes (*S* minus $P \leqq 2.5$ sec) at a rate of about 600 events per year (Sanford and Holmes, 1962). In addition to direct *P* and *S* phases, about 25 per cent of these close events have two sharp arrivals which follow direct *S* by about 2.5 and 5.0 seconds (Figures 1 and 2). The amplitudes of these late arrivals average 0.21 and 0.32 of the direct *S* amplitude on vertical-motion instruments. Although these amplitudes are quite large, the best interpretation of the time-distance data is that these late arrivals are the reflected phases S_rP and S_rS from a crustal discontinuity at a depth of 18 km.

Observations of crustal reflections at very small epicentral distances are apparently quite rare. The only reference the authors have been able to find is a paper by Kamitsuki (1956) in which he discusses and reproduces seismograms of four shocks that have identifiable *S*-phase "Moho" reflections at epicentral distances ranging from 4.0 to 11.5 km. For the event recorded at a Δ of 4 km, the ratio of S_MS to direct *S* on a vertical-component seismograph is 0.32. Reflection amplitudes for the other close events are not given, but on the basis of the reproductions, they also appear to be large and comparable to the reflection amplitudes observed at Socorro.

Location of Socorro Microearthquakes

The epicenters and hypocenters shown in Figures 3 and 4 were calculated from high-speed (25 and 60 mm/sec) records of microearthquakes taken over the closely spaced network of stations shown in the insert on Figure 3. In an earlier paper (Sanford and Holmes, 1962), locations were determined from tripartite records (Stations 1, 2, and 3) assuming a uniform distribution of velocity beneath all stations. Recent geologic mapping (Smith, 1963) and recordings of nearby surface explosions indicate that the total thickness of low-velocity rocks beneath each station varies considerably from station to station. To offset the differences in geologic setting and elevation, individual station corrections based on explosion records are now applied to the arrival times at each station. Direction to the focus is determined from the corrected P arrival times, assuming straight-line travel from the focus to the stations at a velocity of 6 km/sec. Distance to the focus is determined from the S minus P interval with the assumption that Poisson's ratio is 0.25.

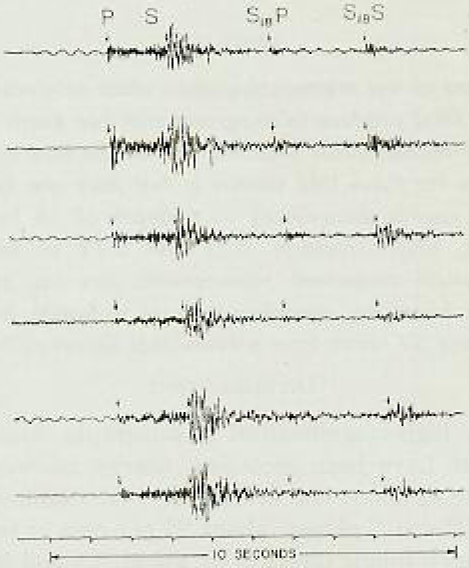

FIG. 1. Strip-chart seismograms (vertical component) of microearthquakes with $S_{18}P$ and $S_{18}S$ phases. Recording speed 15 mm/sec.

The number of stations used at Socorro for location of microearthquakes has ranged from three to five. In the case of five station recordings (10 examples), five combinations of three stations each were available for calculation of direction vectors from the stations to the focus. An analysis of the dispersion in these direction vectors for the best five station records gave an average standard deviation in azimuth of 5 degrees and an average standard deviation in angle of emergence of 6 degrees. The latter values indicate that the station corrections are fairly good and that most of the error in location arises primarily from errors in timing and identification of first motion on the records.

The grading of locations on Figures 3 and 4 is based on the number of stations recording the event (from three to five) and the quality of the records (from very poor to excellent). For example, a three station recording of good quality rates a grade of "fair," whereas a five station recording of fair quality rates a grade of "good." The precision of location is believed to range from less than 1 km for an "excellent" grade to less than 4 km for a "very poor" grade. These are errors in the relative positions of the shocks. Errors in absolute location, which may arise from incorrect assumptions as to the geometry of the ray paths from foci to stations, cannot be estimated.

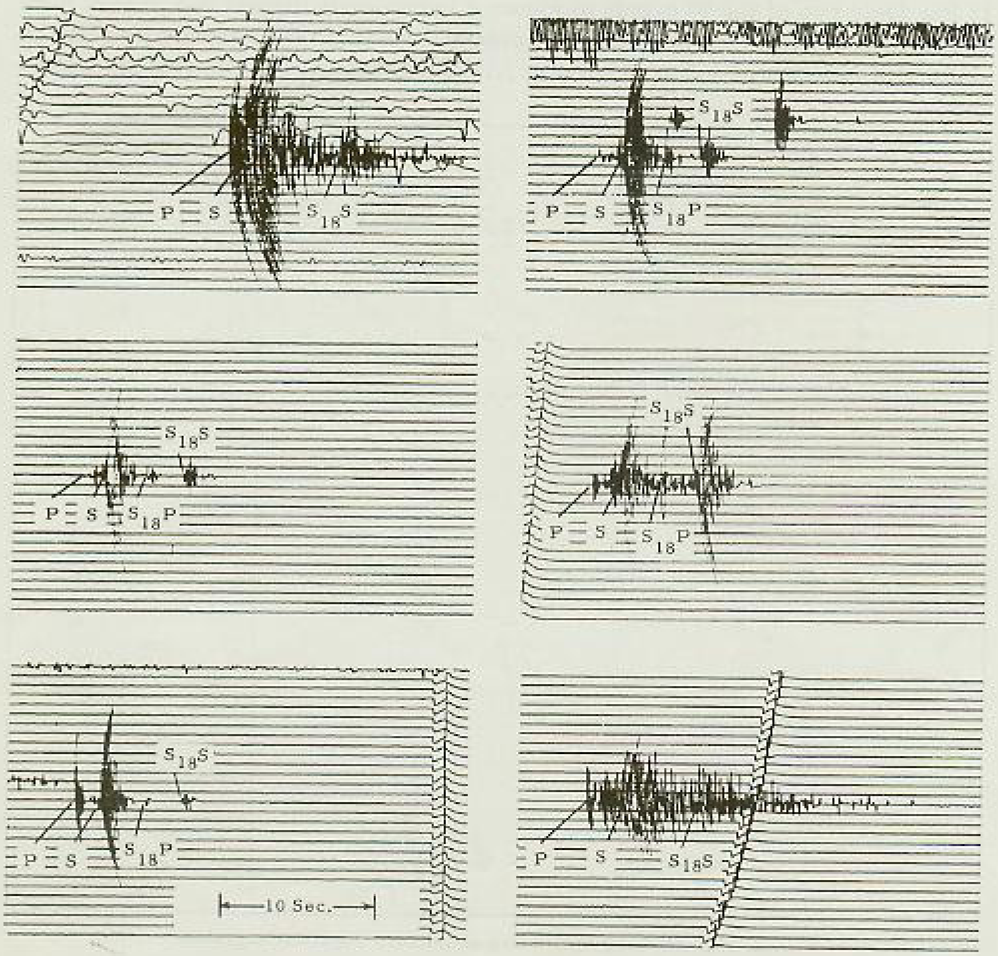

FIG. 2. Portions of helical seismograms (vertical component) showing microearthquakes with $S_{18}P$ and $S_{18}S$ phases. Recording speed 3.33 mm/sec.

The distribution of earthquakes shown in Figures 3 and 4 is considered a good representation of the distribution of all nearby Socorro shocks, inasmuch as the events located are a fairly random sample of the activity over a three-and-one-half-year period (September 1960 through March 1964). In Figure 3, 85 per cent of the epicenters are within an 80-square-kilometer area centered about 7 km southwest of the stations. This region of fairly intense activity is located on the southwestern flank of Socorro Mountain.

Figure 4 shows all the foci projected onto a vertical east-west section. The focal depths range from 0 to 13.5 km and average 5.7 km; 17 per cent of the foci are between 0 and 4 km, 68 per cent between 4 and 9 km, and 15 per cent between 9 and 14 km. Only two of the 34 events in Figure 4 have clearly defined S_xS phases, both with depths of focus near 8 km. At the present time, there is no explanation for the absence of foci east of a line which dips 55 degrees toward the Rio Grande valley.

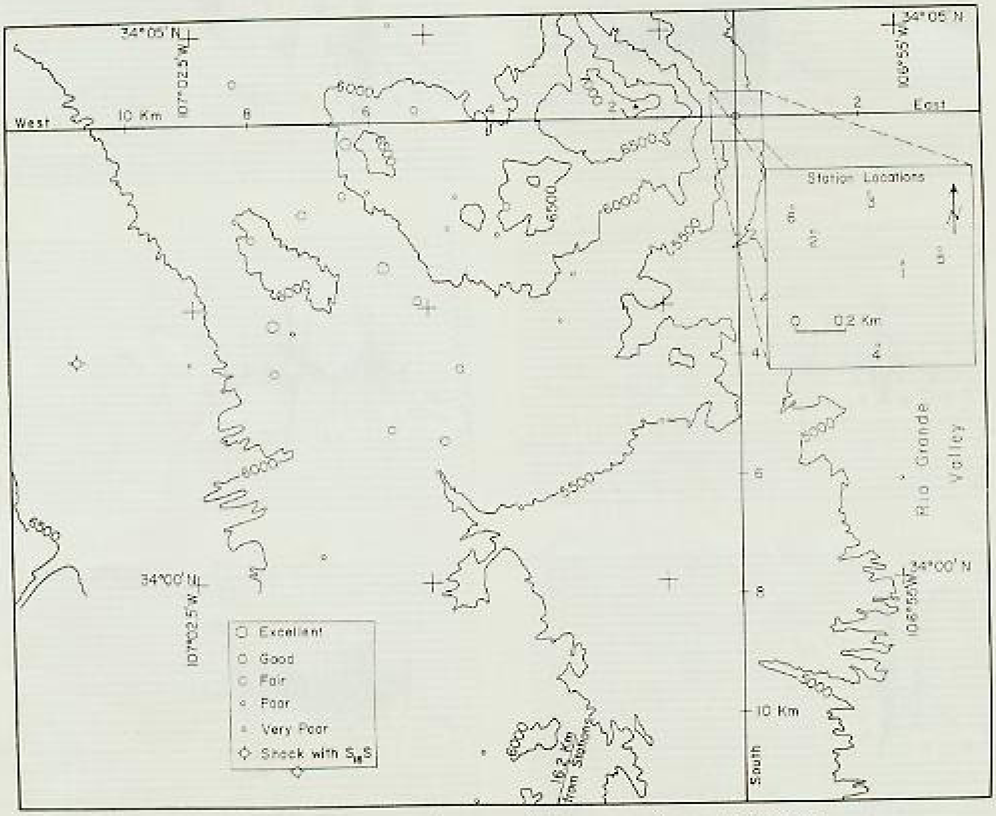

FIG. 3. Map showing epicenters of Socorro microearthquakes.

TIME-DISTANCE DATA

Figure 5 is a graph of the travel times of S_xP and S_xS versus the S minus P interval which is used as a measure of distance. Data from 56 vertical-component seismograms are plotted on this graph. Most of the data, circles on Figure 5, are from strip-chart seismograms taken at recording speeds of 15, 30, and 60 mm/sec. The remaining data (crosses), which are from low-speed (3.3 mm/sec) 24-hour helical records, were selected to extend the range of data available from the strip-chart records. All data points are graded on the basis of the quality of the reflected phase on the seismograms.

The distribution of reflection times shown in Figure 5 is representative of all shocks showing reflections. In the continuous monitoring of activity near Socorro, about 150 microearthquakes with reflection phases are recorded annually. Two-thirds of these events have *S* minus *P* intervals between 1.3 and 1.8 seconds, whereas only one quarter of all the nearby events detected (about 600 annually) have *S* minus *P* intervals within the same time limits.

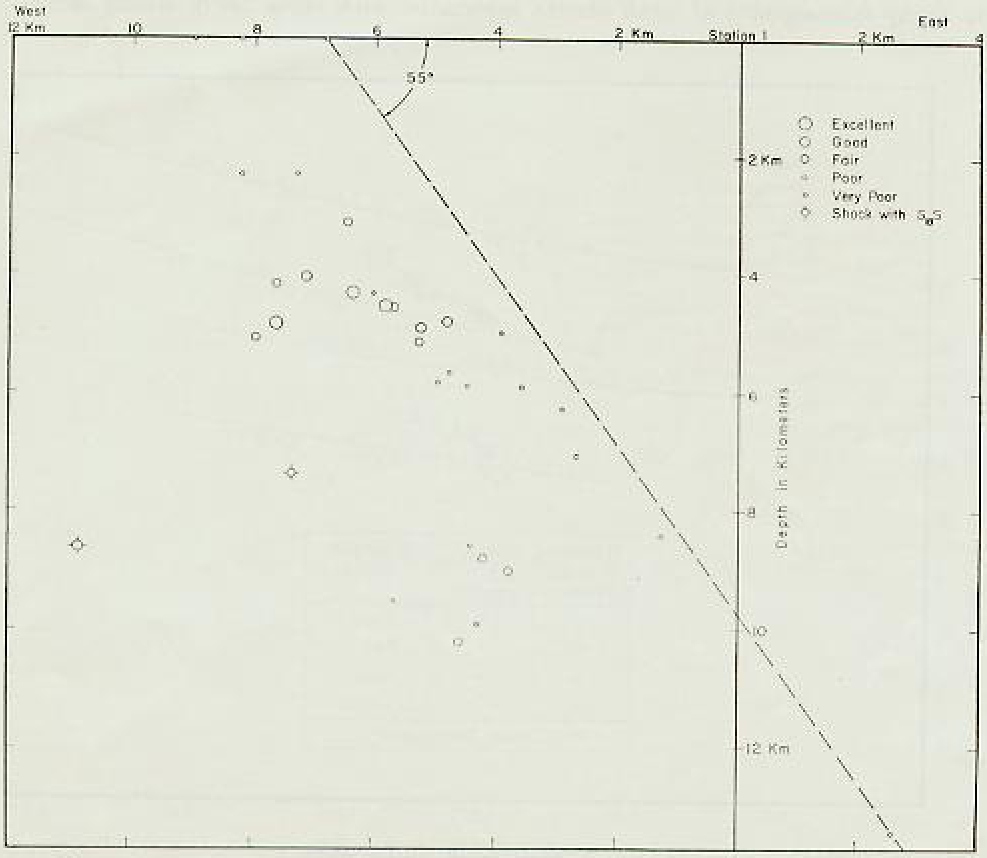

FIG. 4. Projection of Socorro microearthquake foci onto an east-west cross-section.

Theoretical curves for S_zP and S_zS reflections from a horizontal velocity discontinuity at a depth (z) of 18 km have also been drawn on Figure 5. Two curves for each reflected phase are given, one for a 4 km depth of focus (h), the other for a 9 km depth of focus. The left-hand ends of each curve are the theoretical limits of observable reflections at the specified depth of focus. All curves were computed using a *P* velocity of 6.0 km/sec and an *S* velocity of 3.46 km/sec.

In general, only one combination of h and z values will produce theoretical curves that fit the S_zS and the S_zP data equally well. In this particular case, the theoretical curves bracket both S_zS and S_zP data in about the same way, so that little adjustment in the values of h and z is possible. The theoretical interpretation shown appears good, inasmuch as the values of h for the curves are in general agreement with the distribution of depths of focus and no data fall to the left of the theoretical limits of the observable reflections.

OTHER EVIDENCE FOR REFLECTIONS

The presence of a strong S_xS phase does not appear to be restricted to seismograms of shocks very close to Socorro. In 1960, a probable S_xS phase was identified on many seismograms of weak shocks associated with three fairly strong earthquakes in central New Mexico (Sanford and Holmes, 1961). The weak and strong shocks of this series originated in the Sierra Ladrones 35 km north of Socorro. In the case of these more distant shocks, the amplitudes of the reflected shear phase generally equalled the amplitude of the direct shear phase on vertical-component seismograms. These strong reflected phases could be reflections from a discontinuity 18 km deep, provided the foci had a mean depth of 4.8 km. Although this depth appears abnormally low, it is certainly not out of line with depths of focus found for weak shocks near Socorro. Unfortunately, the S_xP arrivals for these shocks cannot be used to confirm the depths of focus and reflection because this reflected phase and the direct shear phase arrive simultaneously.

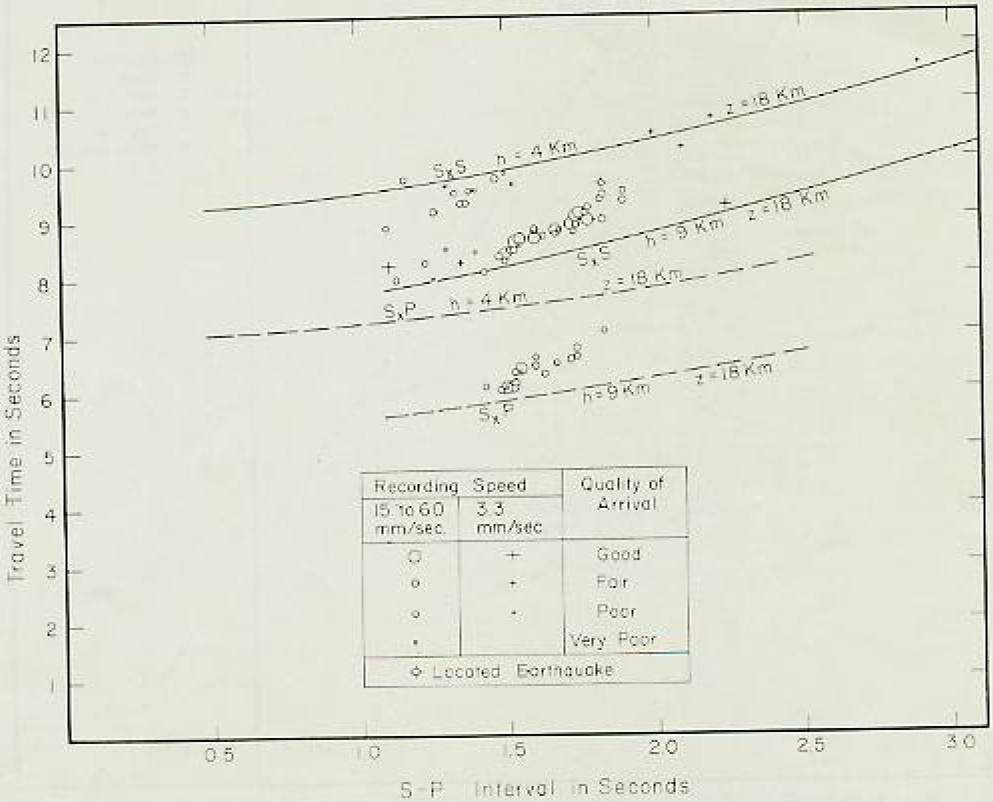

FIG. 5. Observed and theoretical travel times of S_xP and S_xS versus $S - P$.

The character of the S_xS phase also appears to support the reflection interpretation. On the vertical-component seismograms, the S_zS phase has the general appearance of the S-phase except for a reduction in amplitude. The frequency content of the two phases (on the basis of a visual inspection of the best high-speed records) appears approximately the same, although in some instances the higher frequency components are less prominent in the reflected phase than the direct phase (Figure 1).

AMPLITUDES OF THE REFLECTED PHASES

The primary objection to the reflection interpretation is that the observed amplitudes of the reflected phases are far greater than expected on the basis of standard theoretical calculations. Theoretical amplitudes are generally calculated from the Zoeppritz relations (Richter, 1958). With these relations, it is possible to determine the theoretical amplitudes C and D relative to B for a plane SV wave impinging on a velocity discontinuity. The quantities C, D, and B are the total amplitudes of the S_zP, S_zS, and SV phases, respectively.

In using the Zoeppritz equations to calculate theoretical amplitudes of reflection phases at Socorro, two assumptions were made: (1) the amplitude of the radiated SV phase at a given distance from the focus is the same in all directions and (2) the earth's free surface does not have an effect on the amplitudes of the direct or reflected phases. The first assumption, which is probably incorrect, was made for lack of information on the exact pattern of radiation from the focus. The second assumption is justified because the observational data on amplitudes were obtained from a detector located 360 feet beneath the free surface (Station 1 in Figure 3) or about one full wavelength of a 19 cps oscillation (the dominant frequency component of the S-phase of a nearby microearthquake) traveling at the S-phase velocity of the surface layer.

The actual values of the ratios C/B and D/B were obtained from the Zoeppritz curves of McCamy, Meyer, and Smith (1962), using an upper layer compressional velocity of 6.0 km/sec and lower layer velocities ranging from 6.54 to 8.0 km/sec. The angles of incidence on the velocity discontinuity were based on a 6 km depth of focus (h), an 18 km depth of reflection (z), and a 12 km distance to the epicenter (Δ). With the above conditions, the theoretical values of the ratio C/B ranged from 0.040 to 0.120 and the values for D/B ranged from 0.020 to 0.035. The corresponding observed ratios were 0.242 (with a standard deviation of 0.161) for C/B and 0.776 (with a standard deviation of 0.247) for D/B. The C/B ratio is based on data from 9 high-resolution records; the D/B ratio on data from 14 high-resolution records. The total phase amplitudes required for the observed ratios were calculated from the measured vertical components and angles of emergence at the station based on the mean distance to the foci (13.4 km), a 6 km depth of focus and an 18 km depth of reflection.

The discrepancy between the theoretical and observed ratios is very large, and it would be even greater if a correction were applied for geometrical spreading of the wave front. Better agreement might be obtained by considering the effect of a low-velocity surface layer which is known to exist at the point of the observations (Station 1 in Figure 3). However, we have one good record of an event with strong reflections which shows the same S_zS/S ratio for Station 6 as for Station 1 even though no low-velocity material exists beneath Station 6. This observation appears to exclude the low-velocity surface layer as an explanation for the large reflection amplitudes.

Kamitsuki (1956) believes the S_MS reflections he observed at short epicentral distances appear strong because the vertical component of the direct SV phase recorded at a free surface is sharply reduced for a narrow range of distances close to the epicenter. He presents theoretical curves showing the relative amplitudes of the vertical components of the two phases as a function of epicentral distance (using a depth of focus of 11 km). The curves show a very narrow distance range (about 1 km) centered at Δ equal to 8 km, where S_MS is large relative to direct S on vertical-component seismograms. The minimum in the vertical component of the direct SV occurs at an angle of incidence near 36 degrees, which is in agreement with curves published by Gutenberg (1944, Figure 3, p. 99).

Kamitsuki's explanation cannot be applied to the strong reflection amplitudes observed at Socorro. As stated earlier, the vertical-component detectors for the seismograms used in the analysis of reflection amplitudes at Socorro are not on a free surface but in tunnels 360 feet beneath the surface. Further, if the foci for the Socorro shocks are fairly uniform in distribution (Figures 3, 4), only a very small number of the shocks would have locations that give an angle of incidence near 36 degrees at the station. However, 25 per cent of all near events recorded at Socorro have clearly defined S_2S reflections. The actual percentage of events with reflections is certainly larger, as weaker S_2S phases are generally obscured by noise.

Two possible explanations for the strong reflection phases at Socorro are (1) asymmetrical radiation of S-phase energy from the foci and (2) focusing of reflected energy due to curvature of the discontinuity at 18 km depth. No direct evidence in support of either of these ideas has been found.

ACKNOWLEDGMENTS

We are indebted to the American Petroleum Institute for financial aid during the first few years of microearthquake research at NMIMT and to the National Science Foundation for present support of our research program.

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Manuscript received January 27, 1965.