PRELIMINARY REPORT OF SEISMIC REFRACTION SURVEY ALONG THE EAST SIDE OF THE SAN FRANCISCO BAY, ALAMEDA COUNTY, CALIFORNIA

by

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The U.S. Geological Survey conducted a seismic refraction survey along the east side of San Francisco Bay in Alameda County, California, during the summers of 1972 and 1973. The area included in the survey extends from 1 mile south of the Dumbarton Bridge to 5 miles north of the San Mateo Bridge (fig. 1A and 1B). The purpose of the seismic investigation was to determine the velocity and nature of the material overlying the bedrock and the velocity, depth, and configuration of the bedrock surface. This information can be used by persons concerned with land use, ecology, and earthquake hazards and contributes to the geologic knowledge of the San Francisco Bay area.

A 24-trace refraction seismograph, mounted in a four-wheel drive vehicle was used to obtain the seismic records. The reversed profile method of shooting was used to make the seismic refraction field measurements. In this method, the geophones are arranged in a straight line, and an explosive charge is detonated alternately in the shotholes at the ends of the line. The shotholes were drilled to a depth of 20 to 25 feet with a gas-powered auger, mounted on a trailer. The geophones were spaced at 100-foot intervals, and the profiles ranged in length from 2500 to 7200 feet. Small charges of explosives, averaging a few pounds per shot, were sufficient to provide adequate seismic energy. Seismic profiles were limited to the levees or areas where it was possible to obtain a straight-line distance of the length necessary for the ray paths to reach the bedrock surface and where conditions made it possible to drill shotholes and detonate explosives.

The general geologic framework of the San Francisco Bay, including the area of the seismic survey, is described by Nichols and Wright (1971). A summary description of the "young bay mud" by Schlocker (1968, p. 24-25) states:

> "The youngest deposits are mostly soft clay and silt (mud) and minor amounts of sand and gravel. The soft muds, the most common modern sediment, vary considerably in thickness. They are generally less than 10 feet thick near the shore, but are more than 100 feet thick offshore--for example, between San Francisco and Yerba Buena Island and in Richardson Bay. In the Redwood Shores-Bair Island area, soft muds are about 10 feet thick near Bayshore Freeway, but about 60 feet thick near the eastern shore of Bair Island, 3 miles to the northeast. At many places, mud is more than 60 feet thick only 1/2 to 1 mile from the landward edge of the marshlands. Near the mouths of such streams as San Mateo, San Francisquito, and Alameda Creeks, mud interfingers with sand, gravel, and silt brought into the Bay by the streams."
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> "In addition to sand layers and lenses, significant peat and shell beds occur within the young bay mud in many areas. In the subsurface, young bay mud locally may extend well inland of of the marsh line where the mud interfingers with alluvial deposits of the principle drainages such as the Alameda Creek fan in Fremont."

Sediments beneath the young bay mud are a thick sequence of beds defined as an old bay mud consisting of sandy clay and clayey sand, alluvial layers of sand or gravel, and complexly interlayered beds of varying composition that are substantially denser and stronger than the young bay mud.

The bedrock underlying these units is presumed to be the Franciscan Formation consisting of marine sandstone, shale, chert with some conglomerate and limestone lentils, greenstone, diabase, and serpentine.

On the time-distance curves for two layers (figs. 2-5), the velocity of the geologic units overlying the bedrock is 5500 feet per second and the average bedrock velocity is 12,000 feet per second. The time-distance curves from shotpoint 38 to 39 (fig. 6) about 5 miles north of the San Mateo Bridge, are for three layers; the velocity of the near-surface material is 5500 feet per second, that of the intermediate layer is 7000 feet per second, and that of the bedrock is 11,200 feet per second.

Interpretive cross-sections showing the depth and configuration of the bedrock surface and the average velocities (fig. 7) were made by an iterative method described in detail in the Appendix. Shotpoint numbers are shown on the cross-section and the position of the shotpoints at the ground surface is represented by triangle symbols. The letter S on the sections indicates the computed position of the point at which a down-going seismic ray from the shot enters the bedrock. The plus signs and diamonds indicate the exit points of the rays travelling up to the geophones; plus signs are used for geophones to the right of the shot and diamonds for geophones to the left. The plus signs and diamonds represent the migrated control points on the bedrock surface. A consistent interpretation requires that S symbols lie along the interface defined by the other symbols; the degree to which this condition is met is a measure of the consistency of the interpretation.

Approximate corrections for the effect of very near-surface, low-velocity material were obtained by averaging the intercepts of the 5500-foot-per-second branches of the travel-time curves from opposite ends of the profile. These corrections were subtracted from the travel-time data before the cross-sections were prepared.

The method used for preparing the cross-sections (see Appendix) works only for two-layer profiles. For the profiles showing three layers on the time-distance curves, the cross-sections given in Figure 7 were done in two stages. First, the configuration of the top of the intermediate layer was determined by treating this layer and the near-surface one as a standard two-layer profile. Then the bedrock surface was determined, using the bedrock velocity and a value for the overburden velocity chosen to represent an overall average for the material overlying the bedrock.

The cross-sections (fig. 7) show results for all the profiles shot in the survey except for shotpoints 26, 40-41, and 42-43. No depth was obtained from shotpoint 26 because it was not possible to increase the length of the spread a sufficient distance to obtain the bedrock velocity; only the 5500-foot-per-second, near-surface velocity appeared on the record. The minimum depth to bedrock is estimated at 700 feet with the actual depth unknown.

Lack of space made it impossible to extend the profile for shotpoints 40-41 more than the 5000-foot distance, and no bedrock velocity or depth to bedrock was obtained. A velocity of 5500 feet per second for the near-surface material and an intermediate layer with a velocity of 7000 feet per second indicated a depth of 420 feet to the top of the intermediate layer; no depth was obtained for the base of this layer, but the minimum depth to bedrock is estimated at about 1200 feet with the actual depth unknown.

Shotpoint 42-43 was 6800 feet long, and it was not possible to extend this profile. The velocity of the near-surface material is 5500 feet per second, and the calculated depth to the top of the 7000-foot-per-second intermediate layer is 420 feet. A bedrock velocity was not obtained from this profile, but the minimum depth to bedrock is estimated at about 1200 feet with the actual depth unknown.

In the area covered by this survey, all the seismic profiles from Alameda Creek to 1 mile south of the Dumbarton Bridge show two layers, with the velocity of the near-surface geologic units averaging 5500 feet per second and the bedrock velocity exceeding 10,000 feet per second with the average about 12,000 feet per second. A drillhole (fig. 1A) recorded bedrock at a depth of 632 feet and is consistent with the data from the seismic profiles from shotpoint 27-28, 2000 feet to the west.

All the seismic cross-sections from the San Mateo Bridge to 5 miles north of the San Mateo Bridge (the northern boundary of this survey) were three layers and are illustrated by the time-distance curves of shotpoint 38-39 (fig. 6) and the interpretive cross-section (fig. 7). The velocity of the near-surface material is 5500 feet per second, the velocity of the intermediate material is 7000 feet per second, and the bedrock velocity is 11,200 feet per second.

The area from Alameda Creek north to the San Mateo Bridge appears to be a transitional zone because both two- and three-layer profiles were recorded. South of the Alameda Creek, all the cross-sections indicate two layers are present. In the transitional zone, where three layers occur, they are not necessarily continuous and may appear on one end of the cross-section and not on the other (fig. 7).

APPENDIX

Method of Plotting Refraction Cross-Section

The method used for plotting a cross-section for the refraction profile (as described by Hazlewood and Joyner, 1973) is based on the assumption of a layer of velocity, V_1, with varying thickness, overlying a layer of higher velocity V_2. Under that assumption, the path of a seismic ray from shot to geophone is diagrammed in Figure 8. The completed cross-section consists of symbols plotted at the points at which the seismic ray enters and leaves the subsurface refractor. The point of entry is marked by the letter S, and the point of exit is marked by a plus sign for lines shot toward the right-hand end of the profile and by a diamond for lines shot in the opposite direction. Every point on the V_2 branch of the travel-time curve is thereby used to construct a depth point on the refractor, and the depth points are migrated to their true subsurface positions. The depth and offset distances for plotting the symbols are determined from the travel-time data in the following way.

For a given shot-geophone pair, the travel time, T_t, corrected as necessary for near-surface low-velocity effects, can be expressed as (fig. 8):

$$T_t = L_S/V_1 + L_2/V_2 + L_g/V_1$$

Since the distance L_2 is not known, it is convenient to rewrite the equation using the distance D between shot and geophone. If the dip of the interface is small,

$$T_t = (L_s/V_1 - X_s/V_2) + D/V_2 + (L_g/V_1 - X_g/V_2)$$

Introducing the definitions,

$$T_s = L_s/V_1 - X_s/V_2$$

$$T_g = L_g/V_1 - X_g/V_2$$

we can write

$$T_t = T_s + D/V_2 + T_g \tag{1}$$

In the nomenclature of the time-term method (Scheidegger and Willmore, 1957), T_s and T_g represent the shot- and geophone-time terms, respectively.

The point at which the downgoing ray enters the refractor is determined by the coordinates X_s and Y_s (fig. 8). X_s and Y_s can be expressed in terms of T_s and the velocity values V_1 and V_2. Likewise, X_g and Y_g can be expressed in terms of T_g, V_1, and V_2. Thus, if the dip of the interface is small,

$$\sin\Theta = V_1/V_2$$

and referring to Figure 8,

$$X_s = L_s \sin\Theta \tag{2}$$

$$Y_s = L_s \cos\Theta. \tag{3}$$

Combining equation (2) with the defining equation for T_s, we obtain

$$T_s = L_s(1/V_1 - \sin\Theta/V_2).$$

Solving for L_s and substituting in equations (2) and (3) give

$$X_s = T_s \sin\Theta/(1/V_1 - \sin\Theta/V_2) \tag{4}$$

$$Y_s = T_s \cos\Theta/(1/V_1 - \sin\Theta/V_2). \tag{5}$$

An analogous argument gives

$$X_g = T_g \sin\Theta/(1/V_1 - \sin\Theta/V_2) \qquad (6)$$

$$Y_g = T_g \cos\Theta/(1/V_1 - \sin\Theta/V_2) \qquad (7)$$

The first step in the interpretation is the determination of V_1 and V_2 from the travel-time plots in the conventional manner. Then, trial values are assumed for T_S for each shot. The velocity values and the trial values for T_S, along with the corrected travel-time data, are the input to a computer program that generates a plotted cross-section. For each shot, equations (4) and (5) are used to determine the coordinates for plotting a symbol to mark the point at which the seismic ray enters the refractor. Then, for every geophone, equation (1) is solved for T_g; equations (6) and (7) are used to determine the coordinates of the point where the seismic ray leaves the refractor.

An error in the trial value for T_S shows up on the plotted cross-section as an inconsistency between the plotted entry point for the ray from a given shot and the exit points for rays from other shots, especially the reverse shot. These inconsistencies are removed by modifying the original T_S values, and a new cross-section is plotted. The procedure is repeated, if necessary, until a consistent solution is obtained. This process yields an unambiguous solution, provided that the shot and geophone coverage is adequate. The adequacy of the coverage can be readily evaluated by inspection of the plotted cross-section.

One simple way of obtaining a starting value for T_S is to assume in equation (1) that T_S and T_g are approximately equal. On that assumption, T_S is approximated by one-half the zero-distance intercept of the V_2 branch of the corrected travel-time curve.

If an incorrect value of V_2 is used in preparing a cross-section, the sequence of depth points generated by lines shot in one direction will cross at an angle to the sequence of points generated by lines shot in the opposite direction. Under some circumstances, an improved estimate of V_2 can be obtained by adjusting the initial value to enhance the consistency of depth points from reversed shots.

In deriving the equations for computing the coordinates of the migrated depth points, the assumption was made that the dip of the interface could be neglected. That assumption has been tested by applying the procedure to synthetic travel-time data graphically determined for dipping interface models where V_1 = 5500 feet per second, V_2 = 10,000 feet per second, and the interface dipped at 5° and 10° from a depth of 400 feet beneath the up-dip shotpoint. The maximum error of the plotted points in depth was 30 feet for the 5° dip and 80 feet for the 10° dip. The error in the 5° test is negligible compared with other sources of error in shallow-refraction surveying. Even in the 10° test, the error is tolerable, particularly since the errors for up-dip and down-dip lines are of opposite sign; if good reverse coverage is available, the plotted points will bracket the true position of the interface.

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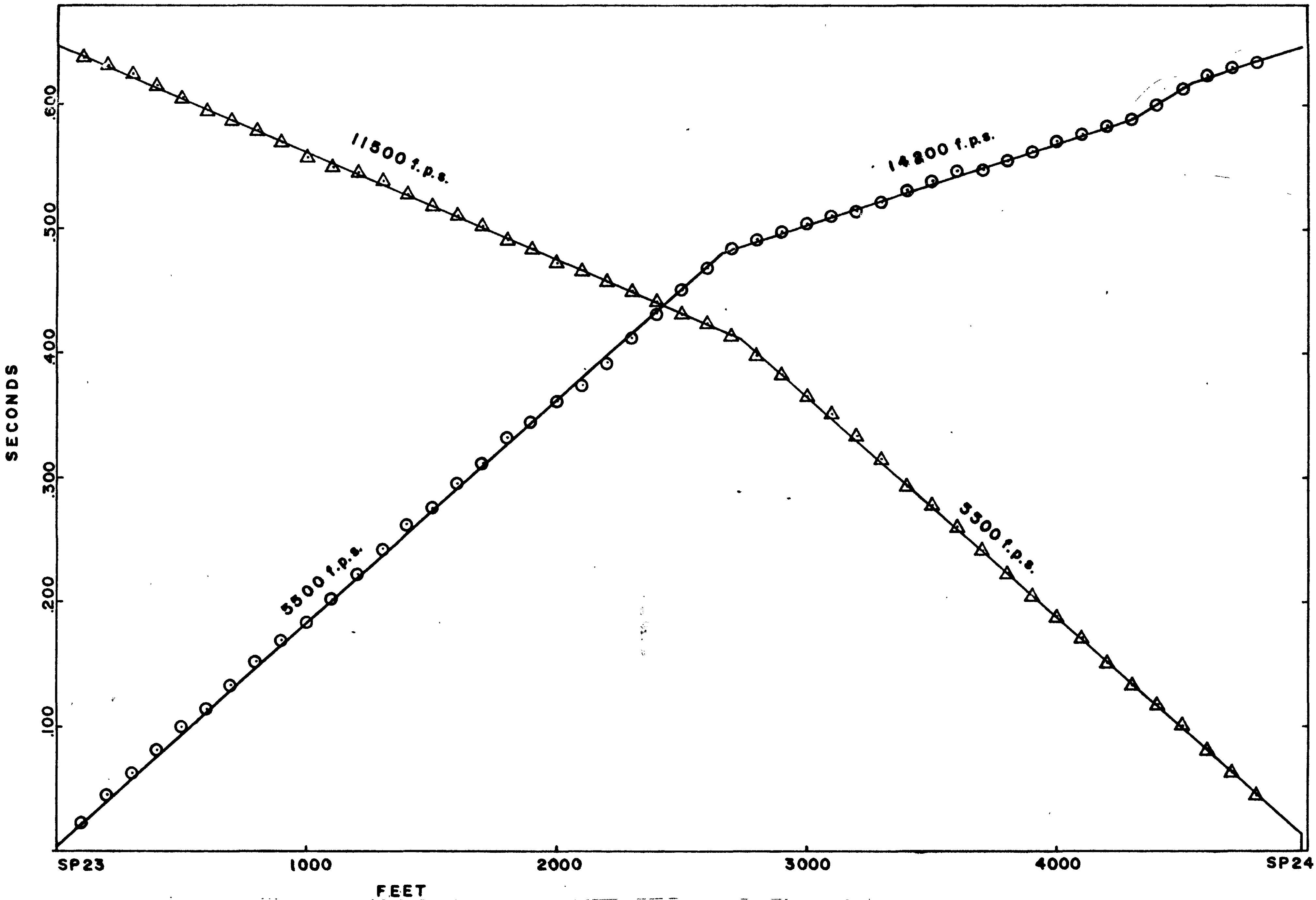

Figure 2. Time Distance Curves for Shotpoints 23 and 24, Alameda Creek, Alameda County, California

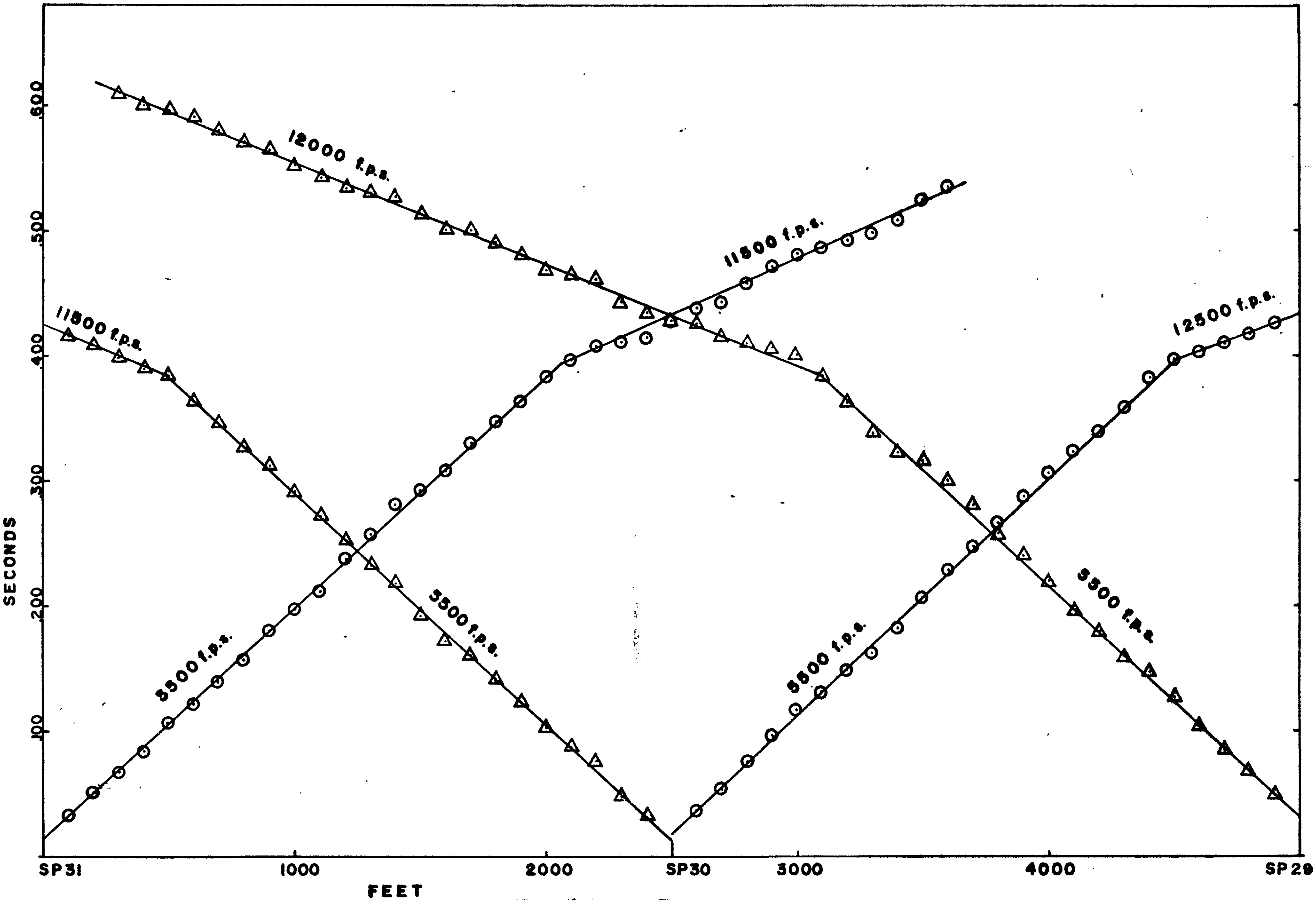

Figure 3. Time Distance Curves for Shotpoints 31, 30 and 29, Coyote Hills, Alameda County, California

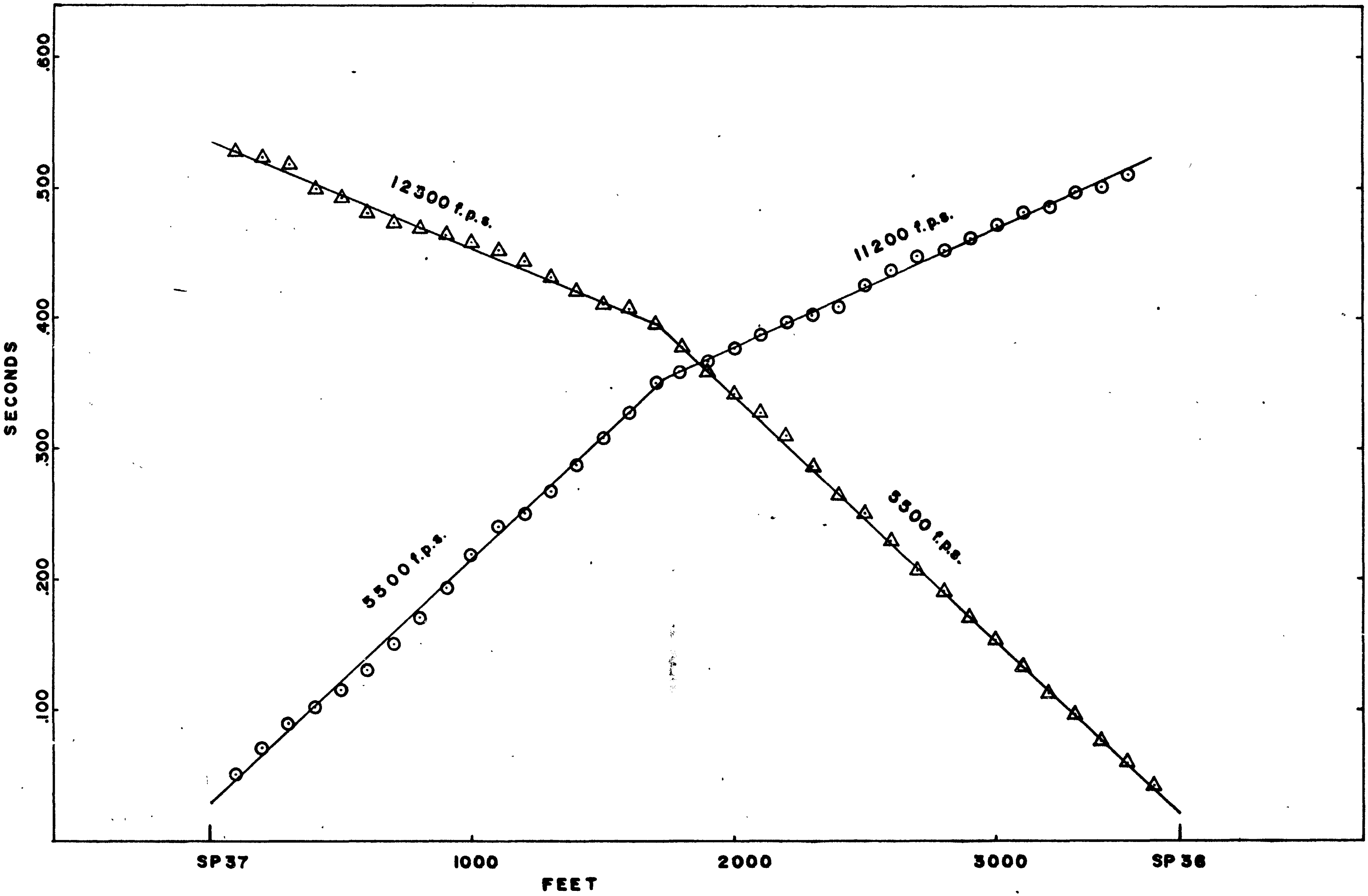

Figure 4. Time Distance Curves for Shotpoints 37 and 36, Coyote Hills, Alameda County, California

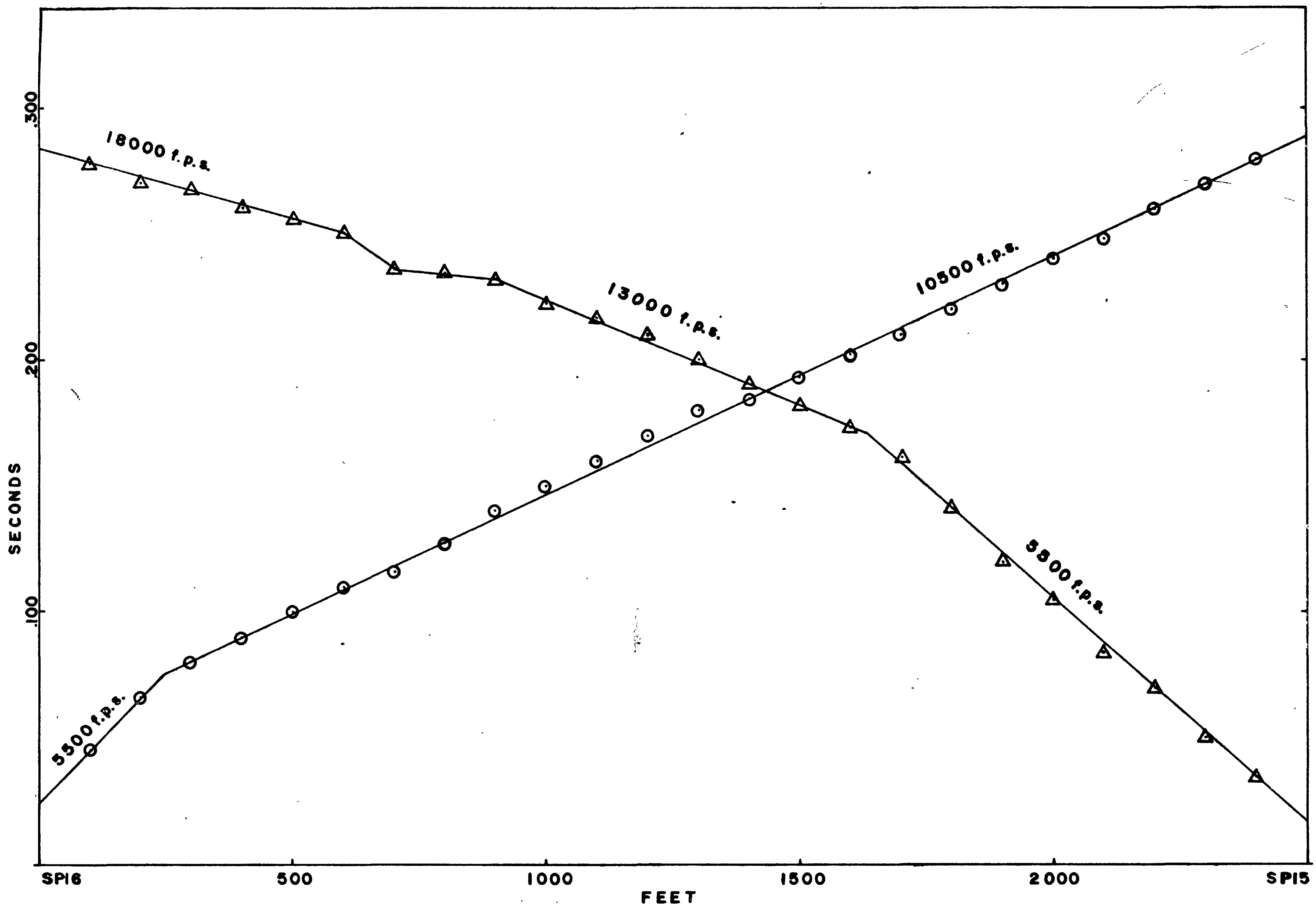

Figure 5. Time Distance Curves for Shotpoints 16 and 15, Coyote Hills, Alameda County, California

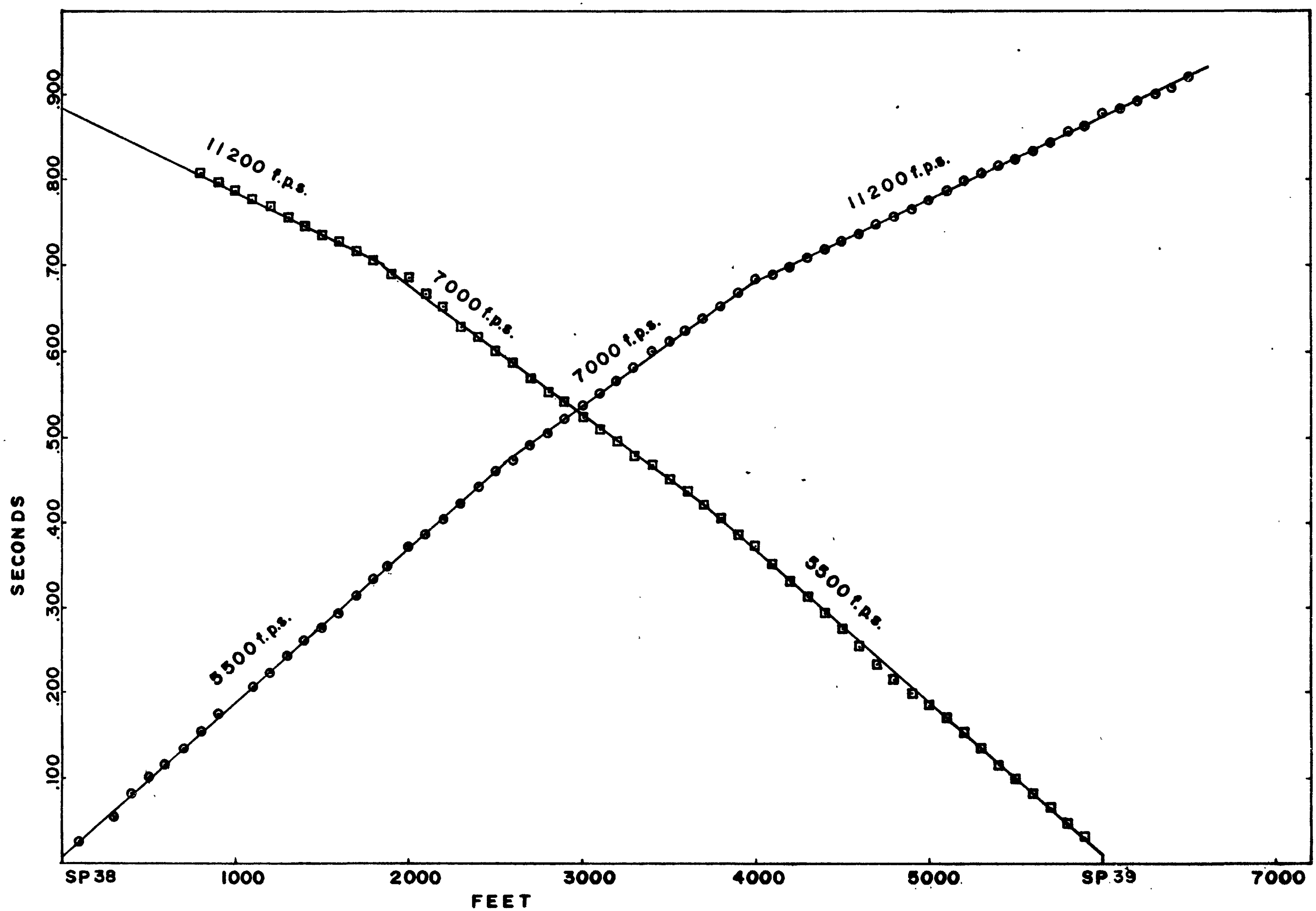

Figure 6. Time Distance Curves for Shotpoints 38 and 39, Alameda County, California

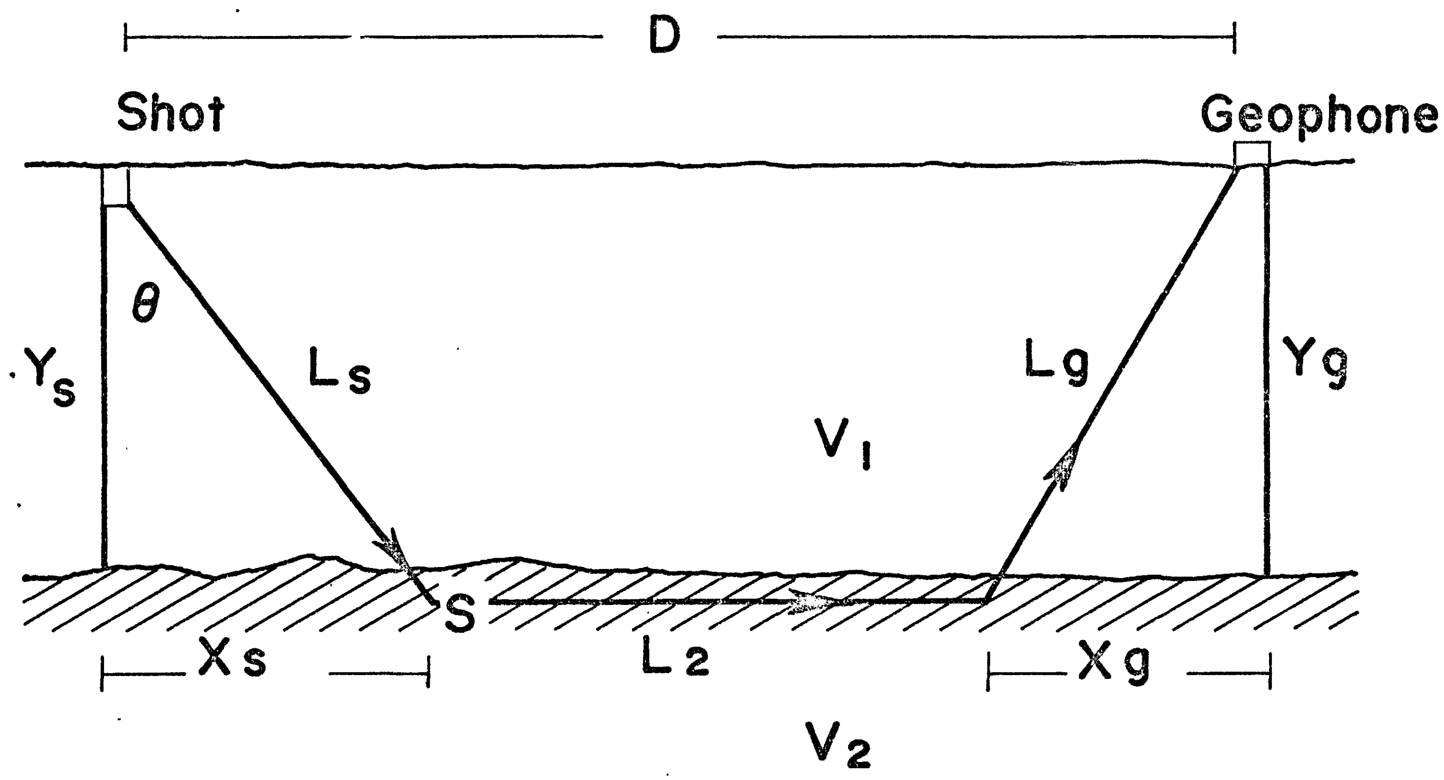

Figure 8