Understanding Seismograms by Constructing Numerical Models

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At the turn of the century a number of rudimentary seismographs were constructed. Why scientists became interested enough to obtain proper measurements at this particular time is not clear, but it may have had something to do with the relatively large number of Great Earthquakes that occurred then. A Great Earthquake, magnitude 8 or greater, can be felt over 500 km. With modern instruments, even a relatively small event, such as the Borrego Mountain earthquake of 1968, produces sufficient motion to be recorded at the most distant station. This event, which occurred on the San Andreas fault near the Salton Sea, had a magnitude of 6.4, which is similar to that of the more recent San Fernando earthquake.

Seismograms for the Borrego event as recorded by a World Wide Seismic Seismograph Network (WWSSN) station are shown below. The distance between the seismic event and the recording station is usually indicated in degrees, Δ, as measured at the earth's center. One degree is roughly 110 km along the earth's surface.

Today's standardized instruments, which are later generations of instruments developed at Caltech, are installed around the world and are an important source of data for seismologists. These stations record the three components of motion over two frequency bands: short period (lower trace) centered at about 1 second (SP), and long period (upper trace) at 15 seconds (LP).

Until recently, such seismograms were not used to their full advantage. Conventional measurements included determining the time of first arrival of the seismic wave (for travel-time considerations), the direction of the first motion to ascertain the direction of faulting, and the amplitude of the largest peak in the first few seconds of the short-period vertical motion (SPZ), which is used in assigning a body-wave magnitude to the event.

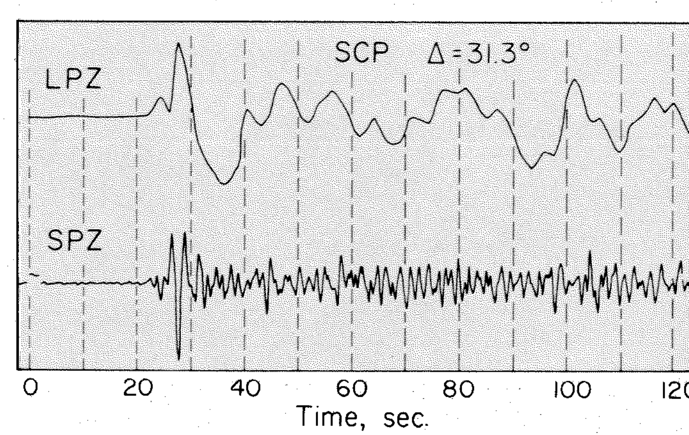
Seismologists in earthquake-prone regions such as southern California have a public responsibility to report immediately the location and magnitude of local events. But this kind of information is only the first step in the scientific study of earthquakes and the interior of the earth. Clearly, the seismograms contain much more information, and we are now attempting to interpret every wiggle. Seismologists are now faced with much stronger demands, such as:

(1) To determine whether a given seismogram was produced by an explosion or by some natural phenomenon;

(2) To determine the detailed structure of the crust, mantle, and core so that solid state geophysicists can speculate on the earth's composition and thermal history, and possibly infer large-scale dynamic processes based on lateral variation in these parameters;

(3) To determine the details of earthquake mechanisms to be used in predicting the nature of the strong motions likely to occur locally during future earthquakes as well as in predicting their occurrences;

(4) To determine stresses in the crust as one step in a program of earthquake prediction.



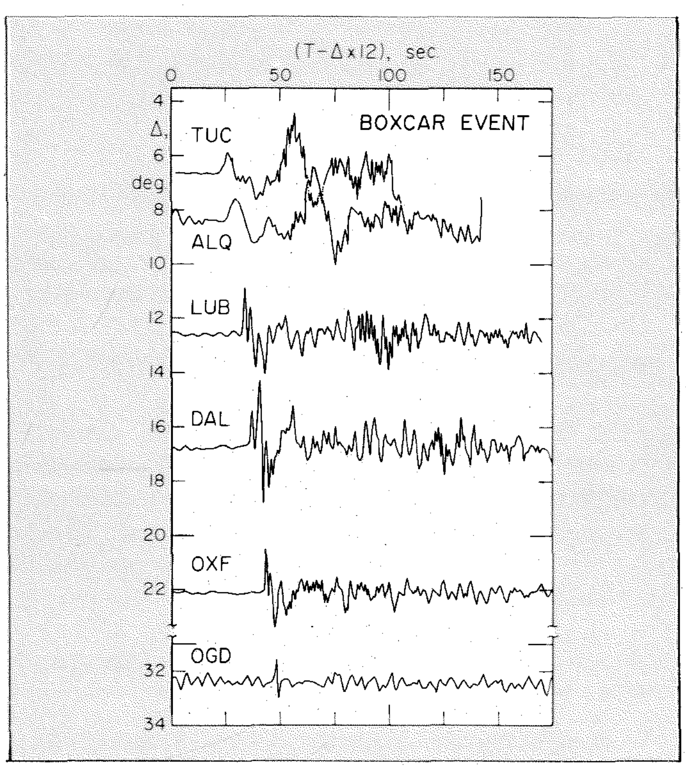
Vertical motion (Z) of long-period (LP) and short-period (SP) waves, recorded by the World Wide Seismic Seismograph Network station at State College, Pa. (SCP), during the Borrego Mountain earthquake of 1968.

Studying seismograms is the first step in the scientific study of earthquakes and the interior of the earth. Now, seismologists are generating synthetic seismograms to help explain why observed seismograms look the way they do

These demands require new techniques, and they have created a new branch of seismology. Many modern seismologists are experts in wave propagation and rely heavily on large computers to understand and explain the wiggles on seismograms. Some of these wiggles are due to complexities of the earthquake itself, and some are due to complications inside the earth. Seismologists are now generating synthetic seismograms, simulated inside computers, attempting to explain why observed seismograms look the way they do, and to see what can be learned about the problems I have mentioned. Admittedly, however, we are still developing the necessary theory and techniques.

Modeling Earth Structure

By studying seismograms produced by known sources, we can discover some of the effects produced by the earth in transmitting the motion from the source to the recording site. Buried nuclear explosions provide an excellent source of energy for this purpose. Since the locations of these explosions and the exact time of their occurrence are well known, they have proved invaluable in earth structure determinations. A profile of long-period recordings from the Boxcar event is given below.

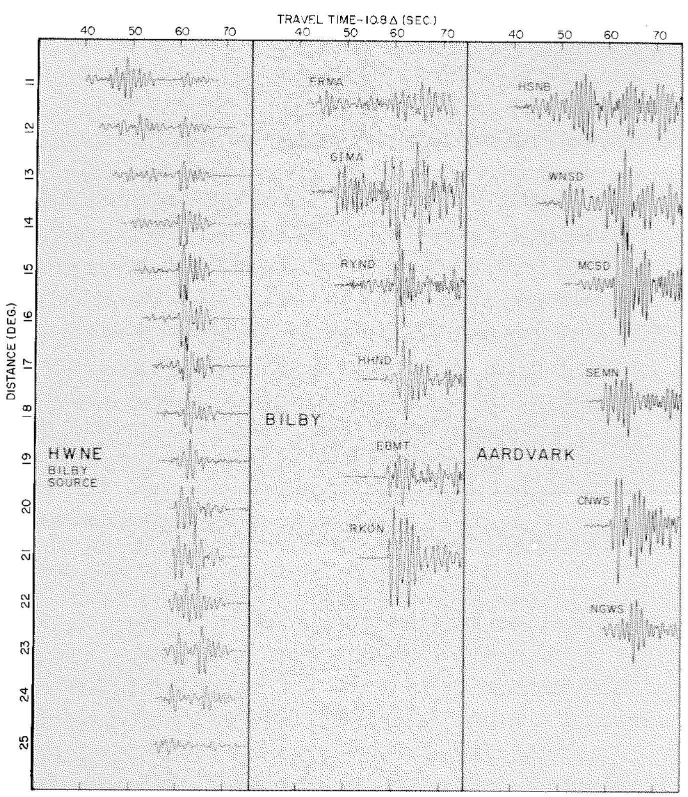


This type of display, common in seismology, shows the variation in amplitude and waveshape as a function of $\triangle$. Distance increases from top to bottom. These recordings are similar to those produced by other explosions fired at the Nevada Test Site. Note the complicated wave forms and how they change with distance.

Explosions, as seismic sources, have been studied extensively in anticipation of a nuclear test ban treaty, and they are reasonably well understood. Essentially, the explosion sends a compressional pulse (P) downward, and this is followed by a surface reflected pulse (pP) with opposite polarity. The separation of these two pulses tells us about the depth of burial. The reflection coefficient that controls the size of pP depends on the takeoff angle (the angle the ray makes with the vertical). For ranges greater than 30°, this angle becomes small, and the phase pP tends to cancel P. The net effect is a pressure pulse that lasts somewhat less than a second, depending on source depth. Further complications are caused by upper mantle triplications (three arrivals at one distance), as will be demonstrated shortly. The absence of short-period energy arriving in the first 20 seconds of motion near 9° is explained by a shadow zone caused by a low velocity zone (LVZ), a feature of the upper mantle discovered by Beno Gutenberg.

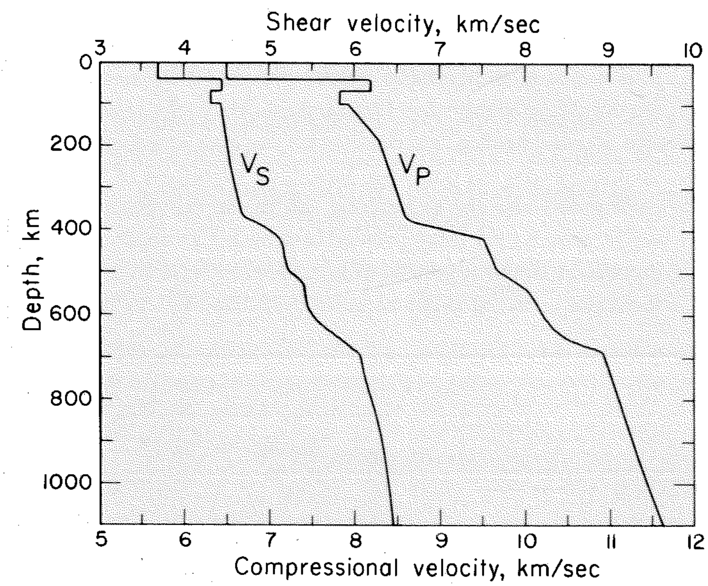
A profile of World Wide Seismic Seismograph Network observations of the "Boxcar" explosion fired at the Nevada Test Site in 1968. Stations represented here are located at Tucson, Arizona (TUC), Albuquerque, New Mexico (ALQ), Lubbock, Texas (LUB), Dallas, Texas (DAL), Oxford, Mississippi (OXF), and Ogdensburg, New Jersey (OGD).

A further windfall produced by nuclear testing has been the installation of the Long Range Seismic Measurement (LRSM) network. These instruments respond well to seismic waves that have a period of about one second. Examples of this type of seismogram from the Nevada Test Site events Bilby and Aardvark are displayed below. At about 15° two signals are readily apparent. The first arrival is small and rather emergent, followed by a larger signal about 12 seconds later.



A comparison of synthetic seismograms (left) with short-period observations made by stations of the Long Range Seismic Measurement Network. The last two letters in each name indicate the state or province where that station is located. "Bilby" and "Aardvark" are two explosions fired at the Nevada Test Site. The synthetics were generated for a particular model, HWNE, using the source function appropriate for the Bilby event. The relative intensities of the various arrivals together with the travel-time information is crucial in model determinations.

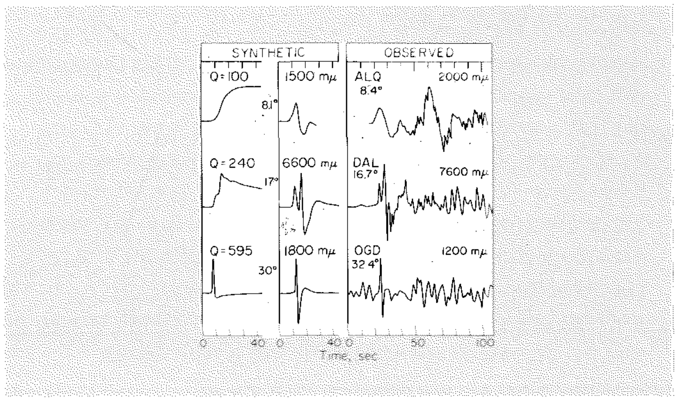
Such a phenomenon is easily explained in terms of upper mantle structure (below). Models containing velocity jumps such as this produce travel-time triplications—that is, multiple signals arriving at the same location at different times. Each of these signals has traveled a different path through the earth's upper mantle. At a range of 15° the first arrival penetrates to a depth of 250 km, whereas the larger second arrival is reflected off the so-called "400 km transition zone" defined by the rapid increase in velocity near that depth. The amplitude and time separation changes with range, producing a rather interesting interference pattern. Unraveling these rays to determine upper mantle structure is no easy task.



Compressional and shear velocities plotted as a function of depth in the earth's mantle.

The determination of upper mantle structure has been a major research effort of geophysicists at Caltech for many years. Several models have been proposed. The variation in models is partly due to lateral differences in the earth and partly due to inadequate data and differences in techniques of interpretation. The earth model presented here has been determined by computing and recomputing synthetic seismograms until they match the observed seismograms. By obtaining this agreement, we learn much about both the earthquake or explosions and the structure of the earth.

Working with many observed seismograms, taken over many paths, we can isolate the features of the seismograms that are due to earth structure. These features require essentially three transition zones in the earth's mantle near 400, 500, and 650 km depth. The sharpnesses of these transitions are still in contention. At the shallower depths, between 50 to 150 km, the earth is known to vary laterally. The velocity model presented here applies to the western United States. Synthetic seismograms for this model assuming the Boxcar source description are below.

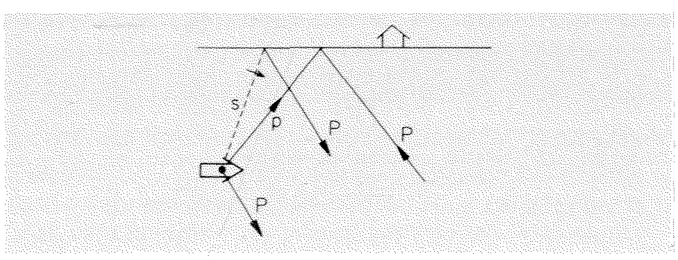


Comparison between synthetic seismograms and observations. The synthetics on the left are the time integrals of the vertical displacement before interaction with the WWSS instrument response.

Earthquake Source Descriptions

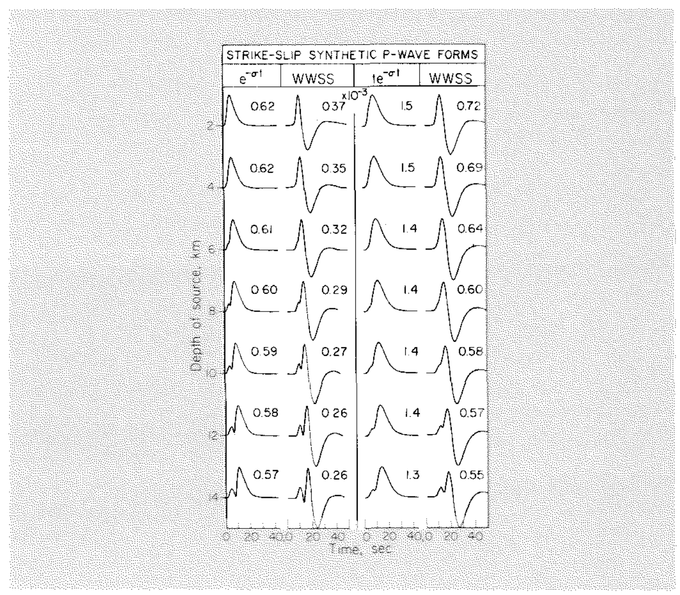
Earthquakes radiate not only P waves but S (shear) waves as well. For this reason, seismograms like that of the Borrego Mountain event on page 26 are more interesting than those produced by explosions. Most earthquakes are quite complicated but are thought to be adequately described by a series of shear dislocations. For example, the two sides of the San Andreas fault are being driven in different directions, with the eastern side moving south relative to the western side. When the stress reaches a critical value, the fault breaks, with one side moving relative to the other side (dislocation), producing an earthquake.

A simplified diagram indicating the seismic waves generated by this type of strike-slip dislocation is given below. Due to the proximity of the earth's surface, essentially three compressional pulses are radiated: P, pP, and sP. These three arrivals interact in a complicated manner, depending on the source depth. Numerical models of these pulses can be generated by assuming various time histories; that is, the time function that describes the motion across the fault.



Displacements produced by a strike-slip dislocation including free-surface interaction, with arrows indicating polarities.

The effective P wave containing the sum of the above three pulses as a function of depth is given below. Two time histories were assumed; the columns on the left are appropriate for a step jump in displacement followed by an exponential decay, whereas in the columns on the right, we supposed a linear buildup followed by an exponential decay. At the shallow depths, all three phases arrive simultaneously. At greater depths, the phase sP falls behind and can be identified as the large second peak. The sizes of the various pulses are controlled by the orientation of the fault. In this particular example, sP is about five times more energetic and overwhelms the other two phases. A comparison of the Borrego Mountain observation at SCP (State College, Pennsylvania) with the synthetics suggests a source depth of about 12 km.



Variation in the effective synthetic P-wave form as a function of source depth.

The synthetic seismograms presented above are examples of the so-called forward problem, the model of both the source and earth structure being assumed. These synthetics prove quite useful in understanding real records, but they can also be used more demonstratively in formal inversion. That is, in solving the inverse problem, given a set of observed seismograms, what source and earth model combination produces the best synthetic fit to the data? Scientists at Caltech's Seismological Laboratory are currently attempting to solve this problem. □