FOCAL MECHANISMS FROM SEISMOGRAMS

Faculty
Glenn Kroeger, Trinity
Timothy Vick, Carleton

Students
Robert Andrews, Wooster
Timothy Daughton, Colorado
Amy Larson, Smith
Laura Reiser, Beloit
Valerie Scruggs, Smith
Gregory Wimpey, Trinity

Visitor
Sam Root, Wooster

EARTHQUAKE FOCAL MECHANISMS FROM TELESEISMIC WAVEFORM ANALYSIS

Glenn C. Kroeger
Department of Geology
Trinity University
San Antonio, Texas 78212

Seismic Radiation from Earthquakes

Earthquakes occur when the Earth's lithosphere fails in a brittle manner releasing stored strain energy. This energy is radiated throughout the Earth in the form of seismic waves. The energy radiated at high frequencies corresponds to **body waves** which travel in packets along definable ray paths through the Earth. These body waves are either P waves with longitudinal vibration, or slower S waves with transverse polarization. The lower frequency energy can be approximated as **surface waves**, which travel along the surface of the Earth and sample the Earth to a depth that is a function of their wavelength. The surface waves can be separated into Love waves with horizontal vibration perpendicular to the direction of propagation, and Rayleigh waves with elliptical particle motion in a vertical plane that includes the direction of propagation.

Seismic energy is not radiated uniformly from the earthquake focus. The distribution of energy radiated in each direction is a function of the actual failure in the lithosphere, the **earthquake focal mechanism**. Over 90% of all studied earthquakes exhibit mechanisms that consist primarily of slip on a fault plane. The energy radiation pattern from such a failure is known as a **double-couple** mechanism. The P wave and S wave radiation patterns each have four lobes or maxima. In the case of P waves, the lobes are separated by the fault plane and a conjugate plane which is, perpendicular to both the fault plane and the direction of slip along the fault. The S wave radiation lobes are centered on these two planes. Adjacent lobes in each radiation pattern have opposite polarities of motion. Thus, in the case of the P pattern, two lobes represent initial **compressions** where the first motion of vibration is away from the focus of the earthquake. The other two lobes represent **dilatations** with initial motion toward the focus (Figure 1). A study of the actual pattern of radiated energy of an earthquake allows the determination of the geometry of the fault plane and the slip on that fault. This provides information about the stresses in the lithosphere around the focus and the tectonic forces responsible for the earthquake.

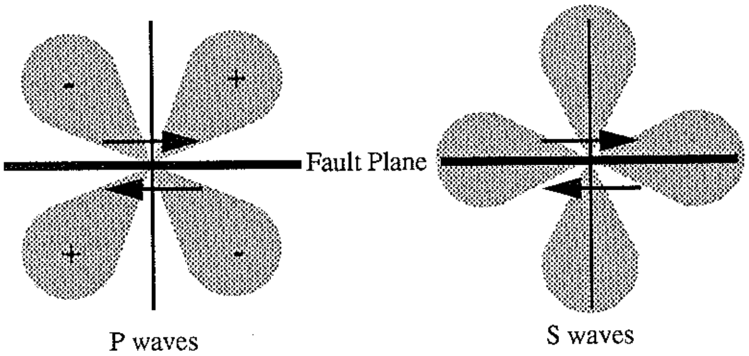

Figure 1. P and S wave radiation patterns

First Motion Mechanisms

The simplest way to study an earthquakes mechanism is to determine a first motion mechanism. In this procedure, the P wave arrival is located on a set of vertical component seismograms. An upward first motion represents a compression while a downward first motion represents a dilatation. The results are plotted on an equal area stereonet projection that corresponds to a sphere enclosing the earthquake focus. Each seismogram is plotted as a point where the ray path from the focus to the seismic station penetrated the sphere (Figure 2a). The azimuth of the point is determined by simple spherical geometry given the epicenter of the earthquake and the location of the seismic station. The plunge is the conjugate of the **takeoff angle**. This angle is calculated from the angular distance between the earthquake to the seismic station, Δ, and tables of measured travel times. Two orthogonal planes which divide the compressions from the dilatations are identified as the **nodal planes** of the earthquake mechanism (Figure 2b). One of these nodal planes is the fault plane, the other is the conjugate plane. There is no way from the seismic data alone to distinguish the two planes. This must be done on the basis of the geology or tectonic setting of the earthquake. Although straightforward, this method is not always successful in practice. Seismograms which represent rays leaving near the nodal planes have very small initial motions which are often misidentified on the records. Additionally, given the small number of seismic stations in the world, and their distribution on continents and islands, coverage of the focal sphere is often very poor. In many cases, particularly with thrust or normal faults, first motion mechanisms are inadequate to constrain the focal mechanisms. Finally, first motion mechanisms provide no information on the depth of the focus or the time duration of the rupture process.

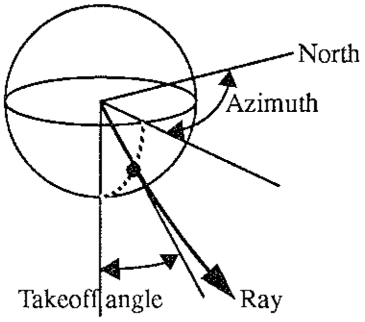

Figure 2a. Geometry of the focal sphere.

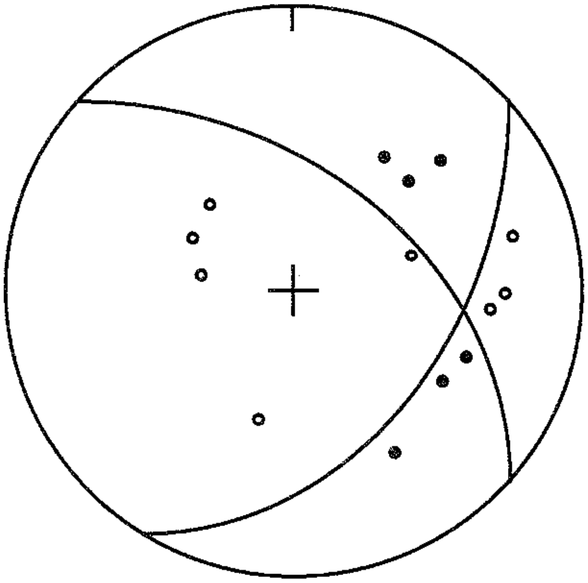

Figure 2b. First motion mechanism. Each station is plotted on an equal area net. Compressions are shown as filled circles. The orthogonal nodal planes divide the compressions and dilatations into quadrants.

Synthetic Waveform Modeling

In order to estimate focal depth, duration of rupture, and to cope with poor quantity and distribution of data, seismologists analyze more of the seismogram than the initial direction of motion. A powerful technique, that has been in use for about a decade, is the modeling of the first portion of the P wave or SH wave seismogram. A synthetic seismogram is constructed mathematically, with input parameters which include the focal mechanism, depth, crustal velocity structure around the focus, and the time history of the rupture. These parameters are varied until the synthetic seismograms at a set of seismic stations achieve a best fit to the observed seismograms. The synthetic seismograms include not only the direct body waves, P and SH, but also body waves that reflect off crustal structure near the focus before traveling to the receiver (Figure 3). The time spacing of these reflected phases, particularly the free surface reflections pP and sP, contains the information about the focal depth. In order to compute the waveforms using ray approximations, the body waves must travel without significant distortion along their path from the focus to the receiver through the mantle. In practice, this means that seismograms from stations in the angular distance range $30° \leq \Delta \leq 90°$ are used. At smaller distances, the rays bottom in the low velocity zone of the upper mantle where their waveforms are distorted. At greater distances, the rays are refracted along the core-mantle boundary where they are strongly attenuated.

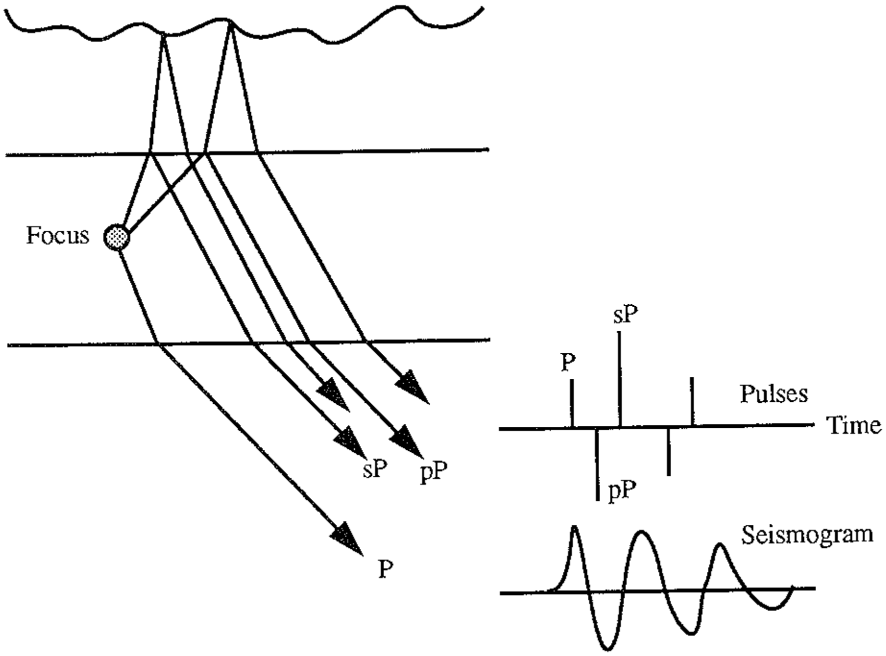

Figure 3. Synthetic seismograms are constructed by summing a series of pulses representing the direct ray and rays which reflect off crustal structure near the source. The timing of the rays contains information about the focal depth while the relative amplitude of the rays contains information about the fault geometry.

The 1989 Keck Projects

The first three weeks of the summer program included a significant amount of classroom work on the basics of earthquake seismology, concepts of signal processing, and programming. Working in groups, the participants produced C programs for the Macintosh that performed signal processing using Fast Fourier Transforms, the basis of the algorithms used in the seismic modeling code. During the last two weeks, increasing time was devoted to printing, digitizing and modeling seismograms. Tuesday evenings were devoted to bowling.

The earthquakes studied in the Keck summer program all occurred before the advent of modern digital seismographs. Seismograms for the earthquakes occurring after 1965 were recorded by the WWSSN seismic network. These seismograms were obtained on microfiche from the National Earthquake Information Center (NEIC) in Golden Colorado. Seismograms for the 1958, Huslia, Alaska earthquake were obtained directly from seismic observatories in the U.S. and Europe, and one Russian record was obtained from the Historical Seismogram Filming Project, administered by the NEIC. All of the microfilm and microfiche seismograms were examined on viewers, the P and SH wave arrivals identified, and the useful parts of the records were printed. All of the paper records and prints were then digitized on a digitizing table, smoothed, and sampled to produce digital records. The resulting seismograms were then modeled and the focal parameters of the earthquakes estimated.

Amy Larson (Smith College), Valerie Scruggs (Smith College), Laura Reiser (Beloit College) and Tim Daughton (Colorado College) worked on a series of aftershocks of the 10 June 1975 Nemuro-Oki tsunami earthquake located on the arcward slope of the Kurile trench. The mainshock produced anomalously large tsunamis for its seismic moment. This enhanced tsunamigenic efficiency has been attributed to a very long rupture which lasted in excess of 40 seconds. This slow rupture may result from rupture occurring in the sediments of the accretionary wedge. Because of the complex rupture of the mainshock it is difficult to model and its depth beneath the seafloor is not well constrained. Determining the depths of the aftershocks is critical to understanding this slow rupture process. In the process of modeling these aftershocks, it was found that they too have anomalously long rupture times for their size. Preliminary results of this modeling were presented at the Fall 1989 American Geophysical Union Meeting. Amy and Valerie have continued to refine these models and present the results in their abstract in this volume.

After the summer session, Laura tackled the analysis of the 7 April 1958 Huslia, Alaska earthquake. This proved to be a great challenge as that available data was scarce and much of it was of poor quality. An additional problem was the lack of standardized instruments in 1958. This earthquake is the largest non-subduction related earthquake ever recorded in Alaska. Some early analysis was carried out in the 1960's, but the techniques and theories applied are now known to be in error. It is therefore critical to use modern techniques to look at the data that still exists from this major event.

Since his return to Colorado College, Tim Daughton has analyzed the 22 November 1969 Kamchatka earthquake. This earthquake turned out to be significantly larger than had previously been determined. It is an important earthquake as it lies at the corner between the Kurile arc and the Aleutian arc. In this location it may represent residual motion on a now inactive subduction zone. Understanding the tectonics of this region is critical to the delineation of the North American-Asia plate boundary. He sought to verify previous work on the focal mechanism and to make the first accurate determination of the depth of this earthquake. Previous estimates of depth were based only on crude locations and qualitative analysis of the seismograms.

During the summer session, Robert Andrews (College of Wooster) and Greg Wimpey (Trinity University) began an analysis of the 30 June 1975 Yellowstone earthquake. This relatively small event (M_L= 6.1) event has never been studied using teleseismic records. Reported first motion data were inconsistent and there was some question whether this earthquake represented a double-couple source. The records showed very weak arrivals making this a very difficult event to analyze. Robert has completed a careful study of the P waves in which he shows that this earthquake is indeed a double-couple event and that the effects of a low velocity diapir under Yellowstone must be included in the modeled seismograms. Greg has modeled the SH waves in order to better constrain the strike and slip-angle of the event, two parameters which were relatively poorly constrained by the P waves. Greg continues to work on the surface waves from this event.

During the summer session, Tim Vick and Glenn Kroeger spent the majority of their time removing bugs from software which the students were so kind as to find. I am especially indebted to Tim for his music, his software development, and for managing Sunday breakfasts. Finally, all of the participants in the earthquake seismology project wish to thank the Keck Foundation for the funding that made this experience possible.

A TELESEISMIC P WAVE ANALYSIS OF THE 30 JUNE 1975 EARTHQUAKE AT YELLOWSTONE NATIONAL PARK, WYOMING

Robert E. Andrews
Department of Geology
The College of Wooster
Wooster, OH 44691

At 18:54:13 Universal Time on 30 June 1975 an earthquake of magnitude 6.1 (M_L) occurred in Yellowstone National Park, Wyoming. This earthquake was part of a sequence consisting of 5 foreshocks, 1 main shock, and 91 aftershocks occurring through 19 July 1975. An analysis of this earthquake sequence was done by Pitt et al. (1979) utilizing mainly local seismic recordings and a few teleseismic recordings. However, Pitt et al. (1979) never fully constrained the main shock. Therefore, the purpose of this study was to reexamine the teleseismic P wave recordings in order to constrain the main shock of this earthquake sequence.

GEOLOGIC SETTING

Yellowstone National Park, spanning 9,000 square kilometers, is located on the Yellowstone Plateau in the northwestern portion of the state of Wyoming and parts of Idaho and Montana. The plateau, formed at the intersection of three Late Cenozoic tectonic trends, is located directly above a mantle diapir or hot spot. During the Pleistocene, this hot spot caused a period of volcanism to begin within the plateau. This volcanism, lasting two thousand years, consisted of three major cycles each climaxing in a violent pyroclastic caldera-forming eruption of rhyolites and ash flow tuffs. The last eruption resulted in the formation of a large collapsed caldera 75 kilometers by 45 kilometers in size. Because of this hot spot Yellowstone lies within one of the most seismically active regions of the Rocky Mountains. The vast majority of the earthquakes in this area result from regional tectonic movement and/or activity within the magma chamber underneath Yellowstone. It is believed that another period of volcanism is developing within Yellowstone (Towell, 1980; Smith and Christiansen, 1980).

LOCATION

The epicenter of the main shock was centered near Norris Junction on the north-central boundary of the Yellowstone caldera (Fig. 1). Located just north of the epicenter is an exposure of a slump surface that dips southward into the caldera. At some lateral distance and depth, this slump surface intersects more steeply dipping ring-fracture zones which were the principal outlets of the last major pyroclastic eruption 600,000 years ago. No visible faults are present in the vicinity of the epicenter, however, numerous north-to-northwest trending normal faults exist north of the epicenter (Pitt et al., 1979).

PREVIOUS ANALYSIS

Pitt et al. (1979) determined that most of the focal mechanisms for this sequence indicated normal faulting striking north-northwest. Some focal mechanisms, however, did show a strike-slip component. Pitt et al. (1979) believes that the 30 June earthquake sequence combined with the trends of previous activity south of Norris Junction indicates that two buried subparallel fault zones exist underneath the north-central boundary of the caldera. In addition, Pitt et al. (1979) believes that this earthquake sequence demonstrates that seismicity within the northern part of the Yellowstone caldera relates to a regional stress system and that the caldera is capable of supporting major block tectonics, a feature common throughout the region. Pitt et al. (1979), however, does not believe that the 30 June earthquake sequence reflected any current activity within the magma chamber underneath Yellowstone.

DATA ANALYSIS

Eight Canadian and twenty-eight WWSSN long period vertical and horizontal seismograms recording this earthquake were obtained from the National Earthquake Information Center in Denver, Colorado. Additional data were also obtained from the International Seismological Center (ISC) Bulletin (1975).

A first motion analysis was attempted of the Canadian and WWSSN seismograms in order to determine a double couple mechanism for this earthquake. However, because most of the recordings had low amplitudes it was extremely difficult to determine the first motion polarity of the P waves. Consequently, a double couple mechanism could not be determined from this data. First motion data from the ISC were then analyzed to augment the Canadian and WWSSN data. Because the ISC data were inconsistent both internally and with the Canadian and WWSSN data, it was unable to augment the Canadian and WWSSN data. Thus, from first motion analysis it seemed that this earthquake did not result from a double couple source as previously determined by Pitt et al. (1979).