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Magnitude, moment, and measurement: The seismic mechanism controversy and its resolution

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A R T I C L E I N F O

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A B S T R A C T

This paper examines the history of two related problems concerning earthquakes, and the way in which a theoretical advance was involved in their resolution. The first problem is the development of a physical, as opposed to empirical, scale for measuring the size of earthquakes. The second problem is that of understanding what happens at the source of an earthquake. There was a controversy about what the proper model for the seismic source mechanism is, which was finally resolved through advances in the theory of elastic dislocations. These two problems are linked, because the development of a physically-based magnitude scale requires an understanding of what goes on at the seismic source. I will show how the theoretical advances allowed seismologists to re-frame the questions they were trying to answer, so that the data they gathered could be brought to bear on the problem of seismic sources in new ways.

1. Introduction

What is an earthquake? An event happens at a fault, usually deep beneath the earth's surface, where it cannot be seen directly. This event generates elastic waves that propagate through the earth and reach its surface. An earthquake, in the ordinary sense of the word, occurs when these elastic waves reach us, and they are experienced by us as ground motion, or recorded by seismometers. Because of its salience for us, this ground motion is the main thing that comes to mind when we think of an earthquake. But if we want to understand how earthquakes occur, or perhaps even to predict them, we need to understand the event that happens at the origin of the earthquake, at the fault, deep within the earth. This event is called the *seismic source*. The main way in which we obtain knowledge about the source is by taking observations made at the earth's surface by seismometers, and trying to extract information about the source from these observations.

The acquisition of this knowledge is made difficult by two circumstances. First, seismic sources are usually buried deep within the earth, so we do not have direct access to them. All of the processes that happen at the seismic source are hidden from us. Second, what happens at the seismic source is a complicated process, presumably involving rock fracture at a fault which itself has a complicated structure. How, then, do we obtain knowledge about the seismic source from observations at the earth's surface? One way to try to do it is hypothetico-deductively—make hypotheses about what goes on at the seismic source, deduce predictions from these hypotheses about the observations that we ought to see at the earth's surface, and then compare these predictions with observations. This method, however, is subject to well-known problems such as under determination, which I will not go over here. The other way to try to obtain knowledge is through measurement. The problem, in our case, is that in order to make a measurement, we need to have a model of the seismic source—but, of course, how can we have such a model without some prior knowledge about what the seismic source is like?

This paper will cover a period during which seismologists moved from a more or less hypothetico-deductive way of trying to obtain knowledge about the seismic source, to being able to measure some of its physically meaningful parameters. This story will advance through two threads that will come together at the end. The first thread involves the development of a scale for measuring the size of earthquakes. For a long time, such scales were entirely empirical—there was no direct connection between these scales and actual physical parameters of seismic sources. It took a theoretical breakthrough in the 1960s for measurement of such physical parameters to become possible, and a physically-based magnitude to be developed. The second problem concerns our understanding of what happens at the seismic source. There were two basic models for the mechanism of the seismic source, and during a period from the 1930s through the 1960s, there was a controversy

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concerning which of these models best described its target. The controversy was finally resolved in the 1960s via the same theoretical breakthrough already mentioned. These two problems are linked, because the development of a physically-based magnitude scale requires an understanding of what goes on at the seismic source. The theoretical breakthrough has even greater significance, however, because for the first time it allowed seismologists to start bringing seismic wave observations directly to bear on their determinations of the physical processes at work in seismic sources.

The rest of the paper consists of four sections. Section 2 examines the history of earthquake intensity and magnitude scales up to the 1960s. All of these scales were empirical, in the sense that they were defined in terms of what happens locally, near seismic instruments, not in terms of physical processes that occur at the seismic source. Section 3 concerns studies of the seismic source. Here, I focus on the concepts of the single couple and the double couple, and the seismic mechanism controversy, a decades-long dispute over whether the single couple or the double couple is the proper way to represent the seismic source. A significant issue that I discuss here is the role of intuition in this controversy. Section 4 details theoretical advances in the 1960s that finally allowed the controversy to be resolved, and the development of a physically-based magnitude scale. Finally, Section 5 concludes the paper by discussing how the theoretical advances enabled new ways of bringing data to bear on understanding the mechanisms of seismic sources.

2. Earthquake intensity and magnitude scales[1]

At the seismic source, the occurrence of a certain kind of sudden motion along a fault results in the generation of seismic waves. I will first briefly discuss these waves before turning to intensity and magnitude scales, which are the main subject of this section. Seismic waves propagate outwards from the source through the earth's interior and along its surface, and they are detected by seismometers located at various points on the earth's surface. In 1889, Ernst von Rebeur-Paschwitz recorded seismic waves in Potsdam that he later proposed emanated from an earthquake that had happened minutes earlier in Tokyo. This was the first recording of seismic waves that had traveled deep through the earth's interior. By the end of the nineteenth century, a well-developed theory already existed for the treatment of waves that travel through an elastic solid medium, owing to the fact that physicists earlier in the century had taken the luminiferous ether to be such an elastic solid. In 1828, Simeon Poisson showed that the interior of a homogeneous elastic medium would support two kinds of waves; dilatational waves (known as P waves in seismology), and shear waves (S waves). Lord Rayleigh and A. E. H. Love later showed that in addition to these, a third and fourth kind of wave, respectively called Rayleigh waves and Love waves, can be created at the surface of such a medium. P waves and S waves are collectively referred to as "body waves," while Rayleigh waves and Love waves are referred to as "surface waves". Richard Oldham identified what he took to be P, S, and Rayleigh waves on seismographic observations of a large Indian earthquake in 1897, and Love waves were identified on seismograms after Love proposed their existence in 1911. The recording of seismic waves from large numbers of earthquakes became routine in the first couple of decades of the twentieth century.

The intensity of the shaking we feel from an earthquake can vary widely, from barely perceptible tremors to the kind of strong shaking that can bring down buildings and highway overpasses. We might thus think of recording the size of an earthquake in terms of the kind of effects that we observe on the ground. Early work on such scales was carried out in the earthquake-prone country of Italy. The first widely used scale for recording earthquake intensity, the joint work of Michele Stefano de Rossi and Francois A. Forel, was published in 1883. It was a ten-degree scale, ranging from degree I, which is a shock that can only be felt by an experienced observer, through degree V, which can be felt by everyone and causes some disturbance to furniture, to degree X, which involves "great disaster, ruins, disturbance of strata, fissures in the earth's crust, rock falls from mountains" (Howell, 1990, p. 100). Giuseppe Mercalli invented a similar scale with twelve degrees in 1887, a scale which, with minor alterations, was adopted by Harry Wood and Frank Neumann in 1931 for their investigations of earthquakes in Southern California. The Wood-Neumann version of the Mercalli scale is still in use today in the United States.

Intensity scales are based on subjective judgments of felt motion and phenomena such as damage to buildings. They tell us how much the ground shakes at a particular place on the surface of the earth, so they are quite useful for the general public, who naturally want to know how much the ground shakes where they actually are. Seismic intensity is not, however, a direct indicator of the size of the seismic source. As one might expect, the farther one is from the source, the weaker the shaking will be. If what one wants to measure is not the amount of shaking at some particular place on the surface of the earth, but the size of the event at the seismic source, one needs a different scale.

The kind of scale that is taken to correspond in some way to the size of the seismic source itself is called a *magnitude scale*. When an earthquake occurs, the shaking caused locally at various places on the earth's surface is recorded by seismometers. Because the shaking from an earthquake is stronger the closer you are to the source, the maximum amplitude recorded on a seismometer will generally be larger as one gets nearer to the source. In 1931, the Japanese seismologist Kiyoo Wadati first noted that there is a roughly logarithmic relation between this maximum amplitude and the distance from the seismic source to the seismometer on which the shaking is recorded. Charles Richter (1935) later proposed a scale in which the logarithm of the maximum amplitude recorded on a seismometer at 100 km from the source of an earthquake would be used as the measure of the size of the earthquake. This scale is now known popularly as the Richter scale. Seismologists refer to earthquake magnitude as measured on this scale as *local magnitude*, or M_L. The amplitude here is defined in terms of the amplitude recorded by a particular kind of seismometer, the Wood-Anderson torsion seismometer, which was the instrument being used by Richter and his colleagues in the 1930s. The main reason that Richter developed this scale was to provide a convenient way of comparing the relative sizes of earthquakes in Southern California. The aim was not to measure any physical parameter of an earthquake, and in fact the only substantive difference between magnitude and maximum intensity was in its being defined in terms of instrumentation rather than subjective reports of observed effects at the epicenter (Howell, 1990, p. 104). That the local magnitude is defined in terms of a particular kind of seismometer results in various shortcomings. Seismometers differ in their frequency response characteristics, so it is not a straightforward matter to convert magnitudes measured using other types of seismometers to local magnitude (Howell, 1990, p. 106). Further, the Wood-Anderson seismometer responds best to ground motion with a period of less than one second, but wave amplitudes for larger earthquakes with a magnitude beyond 7.0 begin to saturate in this range, and this can make local magnitude inaccurate for larger earthquakes (Beroza & Kanamori, 2009, p. 4).

[1] For the historical details in this section, I have drawn on Howell (1990; esp. ch. 6, pp. 97–118).