Progress in Seismology: Turning Data into Evidence about the Earth's Interior

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Abstract:

This chapter gives an account of progress in seismology between 1889 and 1940. I argue that the difficulty of seismology is that seismic wave recordings are extremely information-rich but extremely complex, and progress in seismology during this period was the result of advances in methods for extracting information from complexly structured data. In particular, I divide the rough half-century in question into three periods. In the first period, seismological research focused on the question of whether the waves that are recorded by seismographs are correctly theoretically characterized. In the second period, the research focused on accounting for anomalies in the seismic wave recordings by finding an interpretation for each significant anomaly. In the third period, the research focus was on making inferences from interpreted seismic wave recordings to features of the earth's interior. In particular, I draw a contrast between British and German seismology, showing that progress in British seismology was stifled by the lack of methods for properly interpreting seismic wave recordings.

1 Introduction

In 1889, a German physicist, Ernst von Rebeur-Paschwitz, recorded anomalous signals on sensitive devices set up for measuring the lunar pull of gravity in Potsdam and Wilhelmshaven. Having chanced upon a report about an earthquake that occurred in Tokyo the day he recorded the signals, he inferred that his devices in Germany had picked up seismic waves that had originated in Japan. This discovery, and its later corroboration by other seismologists through the detection of waves from other distant earthquakes, led to the following questions. Do these waves pass through the earth's deep interior? And if so, can they be harnessed to extract information about the vast unexplored region beneath our feet?

These questions gave rise to a series of investigations by seismologists over the next few decades that successively revealed more and more about the earth's interior. The following half-century would see the identification of all the major features of the earth's interior, including the crust, the mantle, and the inner and outer cores, as well as the development by 1940 of two independently developed models of the earth's interior—the Jeffreys-Bullen model and the Gutenberg-Richter model—that were in close agreement with each other, and would continue to be used in seismological applications throughout the remainder of the 20th century.

The aim of this chapter is to give an account of how this rapid progress in seismology became possible, but before I give this account, let me briefly explain what makes seismology difficult. Earthquakes occur when a section of a fault suddenly ruptures. These ruptures typically occur between 10 to 100 kilometers beneath the earth's surface—far too deep to be directly accessible. The mechanism by which such ruptures occur are complex, and little was known about it during the period this chapter covers. The rupture creates seismic waves that radiate outwards in all directions, some of which travel deep into the earth's interior before being recorded by seismographs at the earth's surface. As I have already mentioned, the earth's interior contains complex structures, none of which were known to exist in 1889. Seismic wave recordings thus are the downstream effects of a complex rupture process, modulated by the properties of the complex structure through which the waves have propagated. They are, on the one hand, extremely information-rich, but also extremely complex.[1] The task of extracting the information from the complexity is difficult, and progress in seismology was the result of breakthroughs in methods for doing so.[2]

The view about progress in seismology that I will present in this chapter is closely related to certain views about progress in astronomy. In work on the history of celestial mechanics after Newton, both George Smith (2014) and William Harper (2011) use the phrase "turning data into evidence" to refer to an important aspect of progress in astronomy. The motions of the planets are extraordinarily complex, depending as they do upon the combined forces from all the massive bodies in the solar system, each of which is itself moving in a complex way. The way in which, according to Smith and Harper, astronomers after Newton dealt with this complexity was by using theory as a means for turning data into evidence—that is, theory is used to *interpret and decompose* observations, and then the interpreted observations are used, in conjunction with theory, as a means for making inferences about the solar system. I will not here go into the details of how this is done in astronomy. I will merely make the claim here that something similar went on in seismology. It turns out that, in seismology too, theory was needed as a means for turning complex data into evidence about the earth's interior.

The story I will tell in this chapter focuses on how seismology developed, in a series of three steps, the methods for doing so. I accordingly divide the rough half-century from 1889 to 1940 into three periods. In the first period, which took place roughly from 1889 to 1906, seismological research focused on the question of whether the waves that are recorded by seismographs are correctly theoretically characterized as elastic waves of a certain type. Although there were difficulties along the way, seismologists came to the conclusion that this is indeed the case, which laid the groundwork for the next step. In the second period, which took place roughly from 1906 to 1926, the research focused on complexities in the seismic wave recordings—anomalies that did not quite fit with the theoretical characterization. The research problem then became to find what I will refer to as an *interpretation* for every such anomaly. Typically, such interpretations were tied to postulated features within the earth's interior, such as the boundary between the earth and the core. There were, again, significant difficulties, but seismologists eventually gained confidence that the most significant anomalies could be accounted for in this way. This then led to the third period, which took place roughly from 1926 to 1940, during which the research focus was no longer on anomalies, but in making inferences from seismic wave recordings to features of the earth's interior.

This chapter will focus on the first and second periods. For each of these periods, I present a core research problem. As Shan (2019) has emphasized, scientific progress requires two intertwined sets of activities: *problem defining* and *problem solving* (Shan 2019, p. 745). Accordingly, for each of the two periods, I show how the problem came to be defined precisely, and then how the problem came to be solved. As we will see, it turns out that in seismology, the major obstacles to progress came in the problem-solving phase of research activity. In particular, in the second period, the development of mathematical techniques that were required for solving the problem was of immense importance, a fact that becomes obvious when a comparison is made between British and German seismology during this period. Finally, the focus of this paper is not on social or political aspects of seismology, but

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[1] On top of this complexity is the standard noise that occurs along with any measurement process, but I will not, in this chapter, get into the problem of dealing with noise.

[2] This chapter will focus on the problem of extracting earth structure from seismic wave observations. See Miyake (2017) for an account of the history of the parallel problem of extracting information about seismic sources from seismic wave observations.

given the nationalities of the protagonists in my story, and the period during which it takes place, political events unavoidably play a major role in it.

2 First Period (1889-1906)

I place the beginning of the first period in 1889, with Rebeur-Paschwitz's discovery of seismic waves from distant earthquakes. I take the research focus of seismology during this period to be on the question of whether these waves are correctly theoretically characterized as elastic waves of a certain type. The precise formulation of this question requires a theory of elastic waves. Fortunately, such a theory had already been developed decades earlier. Earthquakes had been a topic of interest for British geologists since the early 19th century. In 1847, William Hopkins worked out the theory of seismic wave propagation in mathematical detail under the assumption that they are waves in an elastic solid medium. He relied heavily on work from the 1820s and 1830s by Poisson and Cauchy on light waves, which were then conceived of as waves in an elastic solid medium, the ether. According to the theory of Poisson and Cauchy, an isotropic elastic solid medium will support two types of waves—longitudinal waves and transverse waves. Hopkins (1847) gives equations for the respective velocities α and β of these two types of waves, which I have put here in a modern form:

$$\alpha = [(K + 4\mu/3) \,/\, \rho]^{1/2} \qquad (1),$$

and

$$\beta = (\mu/\rho)^{1/2} \qquad (2).$$

Here, ρ is the density of the medium, K is the bulk modulus, and μ is the shear modulus. The two moduli represent elastic properties of the medium.

Throughout this paper, I will refer to the waves described by Equation (1) as *pressure waves* and the waves described by Equation (2) as *shear waves*.[3] Since the bulk and shear modulus are always positive, pressure waves should travel faster than shear waves. These equations open up a tantalizing possibility—if the earth's interior can be approximated as an elastic solid medium, and these wave velocities can be measured, such measurements might yield information about the density and elastic properties of the earth's interior. At the time Hopkins wrote the paper, however, seismic wave observation techniques had not yet been sufficiently developed.

When Rebeur-Paschwitz observed waves from distant earthquakes, then, the theoretical framework was already in place in which to formulate precisely a question regarding the physical nature of these waves: *Are seismic waves elastic waves of the sort described theoretically by Equations (1) and (2)—i.e., pressure waves and shear waves?* A positive answer to this question would open the door towards extracting information about the earth's interior by means of Equations (1) and (2).

Answering this question is easy in principle. If one hypothesizes that seismic waves are elastic waves of the type described by Equations (1) and (2), then two waves—a pressure wave and a shear wave—ought to emanate from any earthquake, and these waves ought to travel at different velocities that depend on the density and elastic properties of the medium through which they are propagating. If the earth's interior is homogeneous and isotropic to a first approximation, then an earthquake would generate two roughly spherical wavefronts that propagate at two different constant velocities. These velocities, being dependent only on the density and elastic properties of the earth's interior, would be the same for all earthquakes.

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[3] What are now called pressure waves and shear waves often were referred to respectively as "condensational waves" and "distortional waves" in the 19th and early 20th century. In order to avoid confusion, I am sticking with modern terminology throughout.

Obviously, one cannot directly track the wavefronts as they travel through the earth's interior, but if a large number of seismographic stations can be established throughout the earth's surface, one can hope to detect the wavefronts as they pass various points on the globe. By recording the times at which each wave passes these various points, the wave velocities can be determined. If it can be shown that there are two distinct velocities at which these waves travel, this would be evidence for a positive answer to the question.

In practice, answering the question turned out to be much more difficult. For starters, it required the establishment of a global network of seismographic stations. Fortunately, this was made possible by rapid developments in observational seismology, led by a group of British scientists in Japan. The most prominent of these early seismologists was John Milne, who had been experimenting with seismographs since arriving at the Imperial College of Technology in Tokyo in 1876 (Wood 1988). Rebeur-Paschwitz's discovery prompted Milne to invent and perfect a seismograph for recording distant earthquakes, and he promoted the idea of having a global network of seismographs in the Report of the 1895 Meeting of the British Association for the Advancement of Science: "a ring of twelve or twenty-four stations situated round our globe would in a very short time give us valuable information, not simply about its crust, but possibly also about its interior" (Milne 1895, p. 153).[4] The 1897 Report of the newly-created Seismological Committee of the British Association contains a letter to be sent to various investigators worldwide, requesting their cooperation, and states that the "first object in view is to determine the velocity with which motion is propagated round and possibly through our earth" (p. 137). By the time of the 1898 Report of the Seismological Committee, arrangements had been made for seismological instruments to be established at 22 stations all over the globe.

Setting aside the organizational problem of establishing a global network of seismographic stations, the major difficulty of the method I have just described is that it assumes that pressure waves and shear waves can be clearly identified on seismic wave recordings, but this was not yet the case. At the time, there were no standard ways of interpreting the raw data that was recorded on seismographs. Seismic waves were recorded as complex sets of squiggly lines. There were two robust features of these squiggles that seismologists in the 1890s, such as Milne, focused upon. Seismograms typically start off with rumbling motions of a very small amplitude, which are then followed by much more pronounced motions that look like rolling waves. The initial rumbling motions came to be called *preliminary tremors*, while the later motions came to be called *large waves*.[5] Because preliminary tremors always precede the large waves, and since Equations (1) and (2) imply that pressure waves always have a higher velocity than shear waves, one might think that the preliminary tremors are recordings of the pressure wave as it passes through, while the large waves are recordings of the shear waves that arrive a bit later. Complicating matters, however, was the theoretical postulation of a third type of wave by Lord Rayleigh in 1885. This type of wave would propagate along the surface of the earth, and it would travel with a velocity slower than pressure and shear waves. So an alternative is to identify large waves with these surface waves. But what, then, are the preliminary tremors—pressure waves or shear waves?

The way to answer this question is to measure the velocities of preliminary waves and large waves by plotting the time it takes them to travel to various locations on the earth's surface. These plots, called *travel-time curves*, became an important tool of early 20th century seismology. Whenever a large earthquake occurred, preliminary tremors and large waves would be recorded by stations distributed globally. Such recordings could be used to

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[4] Rebeur-Paschwitz also had the same idea at around the same time (see Schweitzer 2003).

[5] Sometimes called "long waves".

make plots of the time it takes such waves to travel various distances in degrees of arc along the earth's surface. If either preliminary tremors or large waves are surface waves that travel at constant velocity, then one would expect these plots to be linear. If they are, on the other hand, body waves that travel at constant velocity along the chord from the earthquake source to the observing station, these plots would not be linear, but one can easily calculate what these plots would look like, and the wave velocities could be determined from the plots.

The first travel-time curve presented by Milne was in the 1900 Report of the Seismological Committee. His diagram contained three curves—one for the beginning of the preliminary tremor, one for the beginning of the large waves, and one for the difference between them. The curve for the large waves was close to a straight line—which, as I have mentioned, is to be expected if they are surface waves. The Report, however, contains an extended criticism of the identification of large waves with surface waves, by C. G. Knott, a Scottish physicist who had also been stationed in Japan. Knott favored the view that the large waves are shear waves that have traveled through the earth's interior. The near-linear travel times for the large waves could be accommodated by throwing out the assumption that shear waves travel at constant velocity—a reasonable suggestion, given that shear waves are dependent on the density and elastic properties of the medium, and there is no reason to think that these are constant throughout the earth's interior. The Report ultimately comes to the conclusion that the data is inconclusive.

A major breakthrough came in a 1900 paper published by Richard Oldham, a British geologist who was then Director of the Geological Survey of India. Oldham had, in 1899, published a 500-page report on a major earthquake that had occurred in the Indian state of Assam in 1897. In preparing this report, he carefully studied recordings of seismic waves from this earthquake that had been made on seismographs located in Italy. He found that he could identify two distinct *phases* of the preliminary tremors, which he suggested treating as two different waves. He subsequently examined Italian seismograms for eleven other earthquakes, and identified these two phases on all of them. The 1900 paper contains a plot of the travel times for the two phases of preliminary tremors, showing that distinct travel time curves can be plotted for the two phases. He concludes that the *first phase* can be identified with pressure waves, and the *second phase* can be identified with shear waves.

He makes one other suggestion in this paper that is of great significance for the history of seismology. Noting the possibility that the earth might have a metallic core, he suggests that an investigation of travel times of the first and second phases of the preliminary tremors, under the assumption that they are respectively pressure and shear waves, might reveal the existence of such a core.

Oldham's distinction between two phases of preliminary tremors appears to have been quietly accepted by Milne. The 1902 Report of the Seismological Committee, written by Milne, contains a plot with three travel time curves: the first phase, the second phase, and the large waves. It also contains (pp. 65-67) an excerpt from a letter from Knott, grudgingly acknowledging that the large waves are likely to be surface waves ("facts are chiels that winna ding" he writes, quoting Robert Burns), and that the data for the first phase of the preliminary tremors appear to be consistent with their interpretation as a wave that travels at constant velocity within the earth's interior, along the chord between two points on the surface of the globe. Knott comments that the data for the second phase shows much less agreement. By 1902, then, Oldham appears to have convinced Milne that there is good reason to think that the first phase corresponds to pressure waves and the second phase to shear waves.

By no means, however, was this established beyond all doubt. As Milne, Knott, and Oldham all well knew, the observations at the time were not entirely reliable. The first and second phase of the preliminary tremors were not always clearly distinguishable. The origin times of most earthquakes were not directly known—they were typically inferred—and thus most of the travel times were inferred. The data itself was meager and biased. The suggestion of Oldham was based on just seven earthquakes, and relied heavily on data from just a handful of seismographic stations, mostly in Europe. By 1905, Knott had become convinced that the first and second phase are respectively pressure and shear waves, but he (Knott 1905, pp. 577-580) also found it worthwhile considering in great detail the views of a group of Japanese seismologists who considered all seismic waves to be transmitted along the surface of the earth. Within a few years, however, seismology turned to a different set of questions, raised in 1906 by Oldham.

3 Second Period (1906-1926)

By the beginning of the second period, seismologists now had some confidence in the theoretical characterization of the first and second phase of the preliminary tremors as, respectively, pressure and shear waves. In coming to this conclusion, however, most of the immensely complex structure in actual seismic wave recordings was ignored. The key to unlocking more information from the seismic wave recordings lay in now *assuming that the theoretical characterization of seismic waves is correct, and using theory as a tool for making sense of these complexities*. More specifically, theory was used to make predictions about what the seismic wave recordings ought to be like, and research then focused on anomalies[6] that stood out against such predictions. As seismologists at the time well knew, such anomalies could be the effect of as-yet unknown structures within the earth, so they held the promise of unlocking new discoveries.

The greatest obstacle to progress during this period was that in order to make predictions about seismic wave recordings, one needed mathematical techniques for calculating wave paths in the earth's interior, and these had to be developed. As we will see, the lack of such techniques stifled progress in British seismology during this period. German seismologists were able to develop such techniques, but were unable to make much progress for an entirely different reason, as we will see.

I date the start of the second period in 1906, with the presentation by Oldham of a paper titled "The Interior Constitution of the Earth as Revealed by Earthquakes" before the Geological Society of London. There are three significant features of this paper. First, Oldham explicitly states that, although the identification of the first and second phase of the preliminary tremors is not established with certainty, he will proceed under the assumption that it is correct: "I shall take it that the first-phase waves are condensational [i.e. pressure waves]—this being generally acknowledged—and that the second-phase waves are distortional [i.e. shear waves], an assumption which I regard as more probable, and on these assumptions it is possible to estimate the proportion which the modulus of rigidity bears to the bulk-modulus, or resistance to compression [within the earth]" (Oldham 1906, p. 466). Second, Oldham presents new travel-time curves for the first and second phases for fourteen earthquakes (p. 462), but notes a major anomaly in the travel time curve for the second phase—a sudden jump in the travel time between 120 and 130 degrees of arc. Third, in order to account for the anomaly in the second phase, Oldham postulates (p. 468) the existence of a central core in which the velocity of shear waves is significantly lower than in the outer layer. Based on the fact that the jump occurs at around 120 degrees, and assuming for simplicity

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[6] I am aware of the Kuhnian overtones of my use of the term "anomaly". I am broadly sympathetic to a Kuhnian (or a functional) way of understanding how progress was made in this case, but I will lay aside the obvious question about whether this marks the rise of a seismology paradigm because I think it is beside the point I want to make in this chapter.

that the path taken by the second phase in the earth's interior is a chord, he proposes that the earth has a central core with a radius 0.4 times that of the earth.

This paper displays what I take to be the key features of research during this period—namely, it makes the assumption that the first and second phases are correctly theoretically characterized as pressure and shear waves, it focuses on an anomaly (more specifically: a deviation between what one would expect seismic wave recordings to be like based on the assumption, and what the actually recorded seismic wave data looks like), and it postulates a feature of the earth's interior to account for that anomaly. The anomaly that Oldham points out is just one of many anomalies in the seismic wave data that were identified by seismologists during this period.

I take progress during this period to be the result of the pursuit of the following research problem: *For each robust anomaly in the seismic wave recordings, find an independently confirmable interpretation for that anomaly.* By *robust*, I mean that steps must be taken to ensure that the purported anomaly is not a mere artifact—always a possibility at the time given the very small number of observations, the limited distribution of seismographic stations, and the instrumentation then available. By *interpretation*, I mean an account of how that anomaly arises that is consistent with the theory of elastic waves. In most cases, it involves the postulation of some feature of the earth's interior. In Oldham's case, the anomaly as interpreted as being the result of the retardation of the shear wave as it travels through a central core. The requirement that the interpretation be *independently confirmable* is to prevent the possibility of simply accommodating the data. Once a feature such as a central core was postulated, seismologists were then tasked with finding ways of independently confirming whether it exists. I claim that it is through the pursuit of this research problem that seismologists gradually came to grips with the complexity of seismic wave recordings.

As I have already mentioned, the greatest obstacle to progress during this period was that in order to characterize the anomalies precisely, one must have a means for calculating the expected seismic wave recordings precisely, and for that one needs mathematical techniques for calculating wave paths in the earth's interior. Oldham and many of the British seismologists active at the time (with the exception of Knott) did not have the requisite mathematical training for developing such techniques, and it was German seismologists who were doing the research that turned out, in hindsight, to be the cutting edge.

Particularly important was a group at the University of Göttingen including the physicist Emil Wiechert and his students, among whom are a number of major figures of 20th century seismology, such as Karl Zoeppritz, Ludwig Geiger, and Beno Gutenberg. In 1907, Wiechert and Zoeppritz published the first in a series of papers with the title "Über Erdbebenwellen" ("On Earthquake Waves"). Their aim was the same as Oldham's—to use seismic wave observations as a tool for making inferences about the earth's interior. The paper is highly theoretical in its approach, covering in detail the theory of elastic waves, including derivations of Equations (1) and (2), treatments of the reflection and refraction of elastic waves at boundaries within the earth, and possible wave paths in an earth with varying density and elastic constants.

A section of the paper, written by Wiechert, discusses Oldham (1906), and is dismissive of his inference that there is a central core. Wiechert's criticism involves the realization that, in addition to pressure and shear waves that travel directly from the earthquake origin to the observing station, there are also *surface reflections*—pressure and shear waves that travel from the origin to a point on the earth's surface approximately halfway between the origin and point of observation, reflect off the surface, and then travel to the point of observation.

Here, in order to simplify the exposition, I shall use modern terminology for the first and second phase.[7] According to modern terminology, the pressure wave that travels directly from the origin to the point of observation is called the P phase. The shear wave that similarly travels in a direct route is called the S phase. The pressure wave that reflects once off the surface is called the PP phase, while the once-reflected shear wave is called the SS phase. Waves that undergo two or more reflections at the surface are represented by increasing the number of letters—e.g., the PPP phase is a twice-reflected P wave, the SSS phase is a twice-reflected S wave, and so on. Importantly, when an elastic wave (whether pressure or shear) is reflected, it produces both pressure and shear waves. Thus, the PS phase is a wave that is a pressure wave at the origin, and is converted into a shear wave upon reflection. The SP phase is the reverse of this. One can also have, e.g., the PSP phase, the SPS phase, the PSS phase, and so on.

Wiechert and Zoeppritz (1907, p. 518) claim that Oldham's anomaly can be explained as a case of misinterpretation. What Oldham had taken to be the S phase for observations beyond 120 degrees was, in actuality, the SS phase. The modern view is that Wiechert's criticism of Oldham is correct (see Brush 1980, p. 711). More importantly, Wiechert had made clear that in order to correctly interpret anomalies, one must be able to correctly identify the P and S phase on seismograms, but this requires being able to pick them out from a tangle of other phases for which they might be mistaken.

The way to do this is to come up with estimates of their travel times, as well as those of the phases for which they might be mistaken, such as SS or PP. This is complicated, however, since by then it was clear that the velocities of both pressure and shear waves vary as a function of depth within the earth, and this would result in curved wave paths. If that function could be determined at least approximately, then the wave paths could be determined, and the expected travel times for various phases calculated. The Göttingen seismologists thus concentrated their efforts on solving the following mathematical problem: *Determine, from travel times of pressure and shear waves, their velocities as a function of depth within the earth.* This problem was solved through a method developed in 1907 by the Göttingen mathematician Gustav Herglotz (Schweitzer 2003). Wiechert simplified the method and applied it to seismology, and it is now known as the Herglotz-Wiechert method. Using this method, Wiechert claims, "it was easy to find reflections in the tangle of earthquake waves."[8]

There is one further historically important paper by a member of the Göttingen group. Beno Gutenberg (1914) used techniques he developed with Ludwig Geiger for determining seismic velocities in order to make inferences about the earth's interior. The paper argues that the earth has a core with a distinct boundary, and calculates travel times for various *core phases*, which are waves that either travel through the core or reflect off of it. For example, the phase he calls P_cP is a phase that starts off as a pressure wave, is reflected as a pressure wave off the core, and returns to the surface as a pressure wave. An example of a phase that travels through the core is the S_cP_cS phase, which starts off as a shear wave, is a pressure wave within the core, is converted back to a shear wave upon emergence from the core, and is observed at the earth's surface as a shear wave.

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[7] The word "phase" when used in modern seismology in terms like "P phase" and "S phase" always means an elastic wave that follows a particular wave path in the earth's interior. In the first decade of the 20th century, however, the word "phase" just meant a portion of the seismogram (as in "first phase of the preliminary tremor"). Sometime after 1910, the word appears to have shifted its meaning towards the modern usage.

[8] This is my translation of the original German: "Da war es denn nach alledem leicht, die Reflexionen in dem Gewirre der Erdbebenwellen aufzufinden, zu identifizieren." (p. 519)

Gutenberg calculated theoretical travel times for core phases, used these travel times to identify core phases in seismographic data, and then used these core phases to calculate details about the core, such as its size. In this way, Gutenberg was able to identify a large number of phases, determine their travel times, and make inferences about the earth's interior. Gutenberg (1914) represents in many respects the culmination of the style of research being done in the second period of using sophisticated theoretical techniques to make sense of complexities in seismic wave recordings and thence to make inferences about the earth's interior.

Unfortunately, this work had virtually no impact in seismology for more than a decade. The year Gutenberg's paper was published, Europe was plunged into a devastating war, which made it difficult for the members of the Göttingen group to continue doing seismology (Schweitzer 2003, p. 17-18). Geiger lost his job as a seismologist (among a number of unfortunate events, including being taken as a prisoner of war and being accused of being a spy) and eventually became a successful businessman. Gutenberg also lost his job as a seismologist and spent the next decade as the manager of a soap factory while working on geophysics at night. He remained remarkably productive given the circumstances, but he would not land a permanent academic position until Caltech hired him as chair of geophysics in 1930. Another effect of the war was that it disrupted communication between British and German seismologists until the mid-1920s. This would have a significant impact on the progress of seismology.

The importance of the mathematical techniques developed by the Germans for progress in seismology becomes particularly clear when one examines British seismology during the second period. While I have given credit to Oldham for first developing the approach of the second period, he failed to convince any of his British colleagues of the existence of a core. Knott (1908, p. 232) took the Oldham anomaly to be an effect of the steep angle at which seismic waves emerge at longer arcual distances, and states that in any case "we can hardly regard Oldham's hypothesis as at all convincing until a great many more observations are to hand." G. W. Walker's (1913) *Modern Seismology*, strongly influenced by continental approaches, contains a discussion of both SS waves (p. 42) and PS waves (p. 41), arguing that these phases tend to be confused with the S phase, and as a result it makes the detection of S difficult at certain distances. Without naming Oldham, Walker writes: "It has indeed sometimes been asserted that S never reaches beyond a certain distance, and to explain this an impenetrable core of the earth has been assumed. We see that no such hypothesis is at all necessary to explain the observations" (p. 45).

The Oldham core seems to have fallen by the wayside by the mid- to late 1910's. The only significant British writing I can find from this period that mentions it favorably is Knott (1919), his view about it having changed by then.[9] There is no mention of even the possibility of a core existing in the Reports of the Seismological Committee of the BAAS in the 1910s.

Meanwhile, the Seismological Committee concentrated its efforts on the collection and reduction of seismological data flowing in from the global network of seismographs. For the purpose of reducing data, the Seismological Committee adopted a table of travel times for the P and S phase created by Walker (1913) by interpolation from the travel times for a set of well-determined earthquakes given in Zoeppritz (1907). H. H. Turner then set about comparing these travel times with the observed travel times for newly recorded earthquakes in order to make corrections to the tables.

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[9] Knott (1919) is a very interesting paper which not only revives the Oldham core, but argues that it is liquid—anticipating the ideas of Harold Jeffreys that were to appear in the mid-1920s.

In the late 1910s and into the 1920s, Turner inspected the residuals—that is, the difference between the expected travel times for the P and S phase according to the travel time tables and the actually observed travel times—and noticed several significant anomalies in these residuals. For example, in the 1915 Report of the Seismological Committee of the British Association for the Advancement of Science, Turner reported on a set of deviations of the S phase from the standard tables. These seemed to be systematic, and it was suspected that there was some other phenomenon that was being mistaken for the S phase. Various suggestions were made, including the idea that it was a PS phase, or that it was a pressure wave that had undergone multiple surface reflections, but no conclusive identification could be made. Turner labeled it the *Y-phenomenon*, and it was the subject of much discussion in the BAAS Seismological Reports of the late 1910s. The Y-phenomenon is just one of several other anomalies that are mentioned in the Seismological Reports of this period.

In hindsight, very little progress appears to have been made in British seismology in the 1910s and well into the 1920s. Of course, some of this lack of progress can be attributed to the effects of the war, but another major factor was the lack of a well-developed set of mathematical techniques for calculating travel times, something that is needed for properly interpreting seismic wave recordings. Nothing illustrates this better than the ultimate resolution of the question of the Y-phenomenon, which remained unresolved until 1926.

The BAAS Seismological Report for that year, written mainly by Turner, recounts that he had been examining the residuals for the S phase for an earthquake that had occurred on October 11, 1922, and had noted that the readings from between 80 degrees to 110 degrees probably were the result of a phase mis-identification. The question was: which phase? Turner had just tabulated these results when “a letter was received from Dr. Harold Jeffreys calling attention, in enthusiastic terms, to [Gutenberg (1914)], and it was at once seen that the readings tabulated as S refer to Gutenberg’s ray S_cP_cS; that is, a ray which travels as S until it reaches the liquid core of the earth, is then transformed into P, and finally emerges as S.” (Turner 1926, p. 271) It was found that the S_cP_cS phase would arrive slightly *before* the S phase at great distances, and is approximately the same amplitude. Because stations usually would record, as the S phase, the earliest wave arriving at around the time S was expected, the S_cP_cS phase was mis-identified as S, and in fact Jeffreys, looking back on this period, states that at angular distances of over 83 degrees, “there were hardly any genuine readings of S” (Jeffreys 1952, p. 86).

The British seismologists at the time well knew of the work of Wiechert and Zoeppritz, but they apparently were not aware of the important later papers of Geiger and Gutenberg from just prior to the start of World War I. The war is an obvious factor—not only did Geiger and Gutenberg lose their jobs, but German seismologists were prevented for political reasons from participating in international seismological conferences throughout the 1920s (Schweitzer 2003, p. 12) The British were thus unaware of the theoretical work on core phases and its significance for resolving some of the problems with travel time tables until Jeffreys pointed it out in 1926. Turner, who was revising the tables, and Jeffreys, who took on the task after Turner’s death in 1930, immediately saw the importance of the work of Gutenberg, including not just the core phases but the method that Geiger and Gutenberg had developed for determining seismic velocities from phase amplitudes.

The re-discovery of Gutenberg changed the nature of the question being pursued by seismologists once again. The new central question became: *Assuming that the observations have been properly interpreted, where are the major discontinuities within the earth, what phases do they give rise to, and what are the travel times for these phases?* The next significant period of seismology, in which this question was at the forefront, covers the period 1927 to 1940.

Harold Jeffreys, a particularly adept applied mathematician, was equipped with the right set of tools to become one of the two leading seismologists of this period, along with Beno Gutenberg, newly hired by Caltech. During this period, Jeffreys began revising the travel time tables, adding a large number of phases including surface reflections and core phases. Jeffreys was joined by his student Keith Bullen in the 1930s, and their work culminated in the publication of the Jeffreys-Bullen travel time tables of 1940 (Jeffreys and Bullen 1940). This period is worth examining in its own right, but I shall end my account of the progress of seismology in 1926.

4 Turning Data into Evidence in Seismology

Let me recap my account of progress in seismology. Understanding how progress was made requires understanding exactly what makes seismology difficult. At the beginning of this chapter, I stated that seismic wave recordings are, on the one hand, extremely information-rich, but also extremely complex. One must find a way to make sense of the complexity and unlock the information within—to turn data into evidence. The way this was accomplished in seismology is in a series of three steps.

In the first step, most of the complexity was ignored, and the aim was to determine whether a pre-existing theoretical characterization of seismic waves could plausibly account for major features in the seismic wave recordings. The major breakthrough in this period was the recognition by Oldham that the preliminary tremors contain finer-grained structures—the first phase and the second phase—which support the theoretical characterization when interpreted respectively as pressure waves and shear waves.

In the second step, seismologists, now confident in the theoretical characterization of seismic waves, focused on the complexities in the seismic wave data. In particular, for each significant anomaly, seismologists used theoretical tools to seek out an interpretation that could properly account for the anomaly. Because seismologists were by now examining finer-grained details in the seismic wave data, the development of mathematical tools for determining wave paths and travel times within the earth was crucial. The major breakthrough during this period was the development of these tools by German seismologists, but the tumultuous political events of the period led to a delay in recognizing the importance of this work, especially the important pre-war work of Gutenberg, until its re-discovery by Jeffreys. This opened the door to the third step, in which the focus was no longer on anomalies, but on making inferences from interpreted seismic wave data to features of the earth's interior.

What does all this show, more generally, about scientific progress? My view is that for two sciences at least—astronomy and seismology—an understanding of how progress was made requires coming to grips with the complex relation between theory and observation, especially the role of theory in interpreting data. The history of development of methods for extracting information from complex data, among which I count methods of idealization and approximation in astronomy and the earth sciences, is underappreciated by philosophers. A better understanding of how such methods were developed in individual sciences will give us a more complete picture of scientific progress.

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