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History of Seismology

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1. Introduction

At present seismology is the study of seismic sources (mostly earthquakes), the waves they produce, and the properties of the media through which these waves travel. In its modern form the subject is just over 100 years old, but attempts to understand earthquakes go back to the beginnings of science. The course of seismology, more than that of many other sciences, has been affected by its object of study: From Lisbon in 1755 through Kobe in 1995, destructive earthquakes have provoked scientific interest, and, quite often, social support for seismic studies. Table 1 lists some earthquakes (and one explosion) that have had an impact on seismology.

This article describes the history of seismology up to about 1960, with a brief sketch of major themes since then. To cover this history in the space available requires a fair amount of selection. Any reading of the older literature shows that a great many ideas were suggested long before they became generally accepted: For example, the ideas that shaking is a wave propagated from a source, that some earthquakes (at least) are

TABLE 1 Some Events of Significance to the History of Seismology

Name	Date	Location	Magnitude	Importance
	143	Gansu, China	7	Possibly first instrumental record of unfelt shock
Lisbon	1755 Nov. 1	Azores-Cape St Vincent Ridge	8+	Widespread seiching and tsunami: basis for theories of wave propagation
Calabria	1783 Feb. 5	Southern Italy	7+	First event studied by a scientific commission
Basilicata (Neapolitan)	1857 Dec. 16	Southern Italy	7	Detailed investigation by Mallet
Yokohama	1880 Feb. 22	Near south coast of Honshu, Japan	5.8	Led to Seismological Society of Japan
Casamicciola (Ischia)	1883 Jul. 28	Tyrrhenian Sea	6	Led to foundation of Italian seismological service
Vyernyi (Alma-Alta)	1887 Jun. 9	Lake Issyk-Kul, Krygyzstan	7.3	Stimulated Russian study of earthquakes
North Canterbury	1888 Aug. 31	South Island, New Zealand	7+	First scientific observation of strike-slip faulting
	1889 Apr. 18	Near south coast of Honshu, Japan?	7+?	First teleseismic recording
Nobi (Mino-Owari)	1891 Oct. 28	Western Honshu, Japan	8.4	Large surface rupture; led to Imperial Earthquake Investigation Committee
Assam	1897 Jun. 12	Northeastern India	8.7	Recognition of teleseismic primary and secondary phases
San Francisco	1906 Apr. 18	Central California	7.7	Large surface rupture; geodetic detection of off-fault motions; led to Seismological Society of America
Kulpa Valley	1909 Oct. 8	Northwestern Balkan region	6	Discovery of crustal phases
Kanto (Kwanto)	1923 Sep. 1	Near south coast of Honshu, Japan	7.9	Led to foundation of Earthquake Research Institute (Tokyo)
Buller (Murchison)	1929 Jun. 16	South Island, New Zealand	7.8	Stimulated local earthquake recording in New Zealand; inner-core phases in Europe
	1946 Apr. 1	Unimak Island region	7.2	Led to tsunami warning system
Ashkhabad	1948 Oct. 5	Turkmenistan–Iran border region	7.2	Stimulated Soviet earthquake program
	1952 Nov. 4	Off east coast of Kamchatka	9.0	First suggested observation of free oscillations
RAINIER	1957 Sep. 19	Southern Nevada	4.0	First underground nuclear explosion, helped stimulate VELA-UNIFORM program
Chilean	1960 May. 22	Off coast of Central Chile	9.5	First detection of free oscillations
Alaskan	1964 Mar. 28	Southern Alaska	9.2	Stimulated US earthquake-hazards program
Niigata	1964 Jun. 16	Near west coast of Honshu, Japan	7.5	Stimulus for modern Japanese earthquake programs
Xintiang	1966 Mar. 22	Northeastern China	7.0	Stimulated Chinese earthquake program

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caused by faulting, and that the Earth contains a liquid core. I have therefore focused less on the earliest occurrence of an idea than the time when it became something seriously considered within the seismological community. To make the narrative more readable, the sources for particular statements are given in a separate set of notes, referenced through footnote numbers; these notes, the reference list, and a bibliography of the history of seismology, are all included on the attached Handbook CD.[1]

2. Early Ideas about Earthquakes

The most common explanation given for earthquakes in early cultures was the same as for any other natural disaster: they were a manifestation of divine wrath. In European thought this idea did not disappear from scientific discussion until well into the 18th century. But two premodern cultures, the Chinese and the Greek, also developed naturalistic explanations for seismic shaking. Greek natural philosophers suggested a variety of causes for earthquakes; the most influential (and extensive) treatment extant was by Aristotle (ca. 330 BCE), who attributed earthquakes to winds (driven by an "exhalation," the pneuma) blowing in underground caverns. The classical authors also attempted to classify earthquakes by different types of shaking: something that remained a mainstay of seismology for a long time, and still survives in popular terminology.[2]

Chinese ideas about earthquakes were put forth by various thinkers at roughly the same time as the Greek ones, the dominant idea also being that shaking was caused by the blocking of a subtle essence (the *qi*). After the Han dynasty (200 BCE), Imperial state orthodoxy associated natural disasters with dynastic decline; this led to systematic preservation of accounts of earthquakes in the official annals. China's technology also produced the first seismoscope, invented in AD 132 by Zhang Heng. This well-known device, which reportedly signaled the direction of an earthquake as well as the occurrence of shaking, is supposed on at least one occasion to have responded to unfelt shaking; the mechanism of its operation remains obscure.[3]

The Aristotelian view of earthquakes (as of many other aspects of the world) remained the primary theory during the medieval periods of both Islam and Europe. With the decline of Aristotelian thought in early modern Europe, other ideas were put forward, though many of the writers were from northern Europe and so (unlike the Greeks) had little direct experience of earthquakes. They did, however, know about gunpowder: This new technology of chemical explosives suggested that earthquakes might be explosions in the Earth (or in the air); of the various chemical theories put forward, the most popular involved the combustion of pyrites or a reaction of iron with sulfur. Such theories also explained volcanic action; that the most seismic part of Europe, namely Italy, was also volcanic helped to support this association. In the 18th century the development of theories of electricity, and especially their application to lightning, provoked several theories that related earthquakes to electrical discharges. In England, much of this theorizing was stimulated by the occurrence of several damaging earthquakes in the year 1750.

However, the greatest stimulus to seismological thinking was undoubtedly the Lisbon earthquake of 1755, partly for its destructiveness, but even more for providing evidence of motion at large distances: It caused seiches over much of Europe. At least two writers, J. Michell (1761) and (much more obscurely) J. Drijhout (1765), proposed that this distant motion was caused by a wave propagating from a specific location, thus more clearly than before separating the earthquake source from the effects it produced. The type of wave envisaged was like a traveling wrinkle in a carpet; Michell also suggested that the vibrations close to the source were related to waves propagated through the elasticity of the rocks, as sound waves were known to propagate through the elasticity of the air. The elasticity and pressure of gases, more specifically of high-temperature steam, also provided Michell's driving force for the earthquake itself, which he took to be caused by water vaporized by sudden contact with underground fires. (This steam also supported the propagation of waves to great distances.) Michell attempted to locate this "place of origin" by comparing the times of the seiche-inducing wave and the observed sea wave, and also hazarded a guess at the depth. While these ideas were not forgotten, they did not lead to any additional research, and certainly did not replace older theories of earthquakes.[4]

3. The Nineteenth Century to 1880

The expansion and professionalization of science in the 19th century meant that earthquake studies, like many other parts of science, could become a specialization, at least for a few scientists for part of their careers. One type of research that began in this period was the accumulation of large volumes of data, with the aim of finding underlying patterns—a style that has been called "Humboldtean" when applied to the Earth, but was in fact much more general. For earthquake studies, this meant the first systematic catalogs of shocks (as opposed to lists of catastrophes); leaders in this were K.A. Von Hoff and A. Perrey, the latter being a disciple of A. Quetelet, one of the founders of statistics. Many of these compilations were used to look for possible correlations between earthquake occurrence and astronomical cycles or meteorological events; this was one of the main topics of 19th-century seismology. Along with these catalogs came studies of individual shocks: Most European earthquakes after about 1820 stimulated some sort of special study, by individuals (often local professors) or by commissions set up by governments or local scientific societies. The first such commission was established after the Calabrian earthquake of 1783; a century later, one earthquake

(in Andalusia, 25 December 1884) would bring forth three commissions, one each from Spain, France, and Italy.

These special studies developed many of the tools and vocabulary still used to describe the felt effects of a large earthquake. One such tool, quite in keeping with the overall trend in science toward quantification, was scales of intensity of shaking: the first by P. Egen in 1828, followed by many others, notably those of M. de Rossi, F. Forel, these two working together, and G. Mercalli. The first cartographic application of an intensity scale, creating the isoseismal map, was by J. Nöggerath in 1847; in turn, the accumulation of maps stimulated questions about why the distribution of shaking was as observed, and to what extent it could be explained by waves radiating from a central source.

This period also saw the first efforts to relate earthquakes to other geological processes. Von Hoff was explicitly interested in this relationship and in the English-speaking world it was promoted most assiduously by C. Lyell, whose program of reducing all past geological change to current causes was aided by showing that earthquakes could cause vertical motions over large areas. Prominent examples of such motion in Lyell's treatment were the 1819 Rann of Cutch (India) and 1822 Chilean earthquakes, and later the 1835 Chilean and 1855 Wairarapa (New Zealand) earthquakes. The 1819 and 1855 earthquakes produced some of the earliest known examples of a break at the surface, though the first scientific observations of fault rupture did not take place until much later, by A. McKay in 1888 (North Canterbury) and by B. Koto in 1891 (Nobi).[5]

In retrospect, the basis for a different approach to earthquake study can be seen to have begun in 1829 to 1831, with investigations by S.D. Poisson into the behavior of elastic materials. He found that in such materials wave motions could occur, and were propagated at two speeds; the slower wave had particle motion perpendicular to the direction of propagation, and the faster one included dilatation of the material. A wave motion with transverse vibrations was of great interest because it offered a model for the recently discovered polarization of light, and many of the 19th-century investigations into elastic wave propagation were in fact made with optical observations in mind, attempting to explain light as transverse waves in an elastic "luminiferous ether." Notable examples were the study of G. Green (1838) into wave transmission across a boundary, and of G.G. Stokes (1850) on radiation from a limited source.[6]

These results were applied to earthquake studies by W. Hopkins (1847), and by R. Mallet (1848 onwards). Hopkins showed how timed observations of wave arrivals could be used to locate an earthquake, but went no further than this purely theoretical exercise. Mallet, a polymathic engineer, not only coined the term seismology but tried to develop it systematically as a science of earthquakes, observed through the waves they generate. Mallet constructed one of the most complete earthquake catalogs to date, which he summarized in a map (Color Plate 1) that clearly delineates the seismic and aseismic regions of the world (1858). But Mallet aimed to do more than describe: Whenever possible he argued for the application of quantitative mechanical principles to determine how much, and in what direction, the ground moved in an earthquake. This quantitative emphasis is perhaps most notable in his 1862 study of the 1857 Basilicata (Neapolitan) earthquake, in which he attempted to estimate the direction of arrival of the shaking at many points, and so infer the location (and depth) of the source. It is also apparent in his earlier attempts (1851) to measure actual wave velocities from explosions and compare these with known elastic constants; he obtained much lower values than expected, which he attributed to inhomogeneity but which were more likely caused by insensitive instruments. Like Michell, Mallet believed that earthquakes were caused by the sudden expansion of steam as water met hot rock; because of the explosive nature of such a source, he believed that the earthquake waves would be almost entirely compressional.[7]

What was lacking in Mallet's otherwise comprehensive program was an adequate method of recording earthquake motion; though he and others proposed possible ways to do this, few of these schemes were actually built and even fewer were used by more than the inventor—though it was recognized early (for example, by Hopkins) that a network of instruments was really what was needed. The first instrument to automatically record the time and some aspects of the shaking was the seismoscope of L. Palmieri (1856), used in Italy and Japan. However, the first network of instruments, set up in Italy starting in 1873, was not intended to record earthquake shaking. Rather, these "tromometers," developed by T. Bertelli and M. de Rossi, were used to measure ongoing unfelt small motions, looking for changes in the amplitude or period of these related either to weather or to earthquakes, a study called "endogenous meteorology."[8]

4. The Birth of the "New Seismology": 1880–1920

With its emphasis on background vibrations, the substantial Italian effort turned out to be less fruitful than what happened in Japan as a consequence of the Meiji restoration of 1868: the establishment of modern science in a very seismic region. This was begun by the Japanese government bringing foreign experts (*yatoi*) to Japan, including professors well trained in the latest methods of physics and engineering. Of these, the most important for seismology was John Milne, who arrived in Japan in 1876 to be a professor (aged 26) at the Imperial College of Engineering in Tokyo. He made seismology his main interest after the earthquake of 22 February 1880, which also led to the foundation of the Seismological Society of Japan, with Milne as its effective leader. Such organization among the foreign experts

was soon paralleled by similar initiatives from the Japanese: the Meteorological Agency established (or rather, took over from Milne) a regular reporting system in 1883, and S. Sekiya became the world's first professor of seismology in 1886. The routine reporting of earthquakes allowed Sekiya's successor, F. Omori, to develop his law for the decay of aftershocks from data for the 1891 earthquake.

Even before the 1880 earthquake, attempts had been made by foreign scientists in Japan to record the time history of felt shaking. This developed into a rivalry between J.A. Ewing at the University of Tokyo, and Milne (with his colleague T. Gray). Ewing applied the horizontal pendulum to get the first good records of ground shaking (at what would now be regarded as the lower limit of strong motion) in 1880–1881. These records showed the motion to be much smaller than had been assumed, and also much more complicated: nothing like a few simple pulses and not the purely longitudinal motion envisaged by Mallet. Thus, as soon as seismologists had records of ground motion, they faced the problem that has been central to the science ever since: Explaining observed ground motion and deciding how much of the observed complication comes from the earthquake and how much from the complexities of wave propagation in the Earth.

While Milne may not have been the first to record earthquake shaking, he soon became a leading seismologist, not so much from any new ideas he brought to the subject as from his energy and flair for organization. Like Mallet, Milne aimed to study all aspects of earthquakes and elastic waves, but he added to Mallet's quantitative emphasis a regular use of instrumental measurements, often designing the instruments for the occasion. This regular use of quantitative instrumental records (not just by Milne) led contemporaries to term these activities "the new seismology."[9]

These instrumental improvements were largely focused on local shaking, but they formed the basis of quite different studies under the stimulus of an unexpected result. In Germany E. von Rebeur-Paschwitz had built sensitive horizontal pendulums for measuring tidal tilts, his interest being primarily astronomical. These showed transient disturbances, and he was able to correlate one of these, on 18 April 1889 (Fig. 1) with a Japanese earthquake reported in *Nature*. This demonstration that distant earthquakes could be recorded led to new developments in seismic instrumentation in Italy, by G. Agamemnone and A. Cancani, and in Japan, by Omori and Milne. Milne returned to England in 1895, bringing an enthusiasm for global seismology, a design for an inexpensive seismometer, and a long association with the British Association for the Advancement of Science (BAAS). Both he and von Rebeur-Paschwitz proposed in that year a global network of seismic instruments, but it fell to Milne, capitalizing in large part on the geographical reach of the British Empire and his BAAS connection, to install the first such network, with himself and an assistant as (in modern terms) data and analysis center combined.

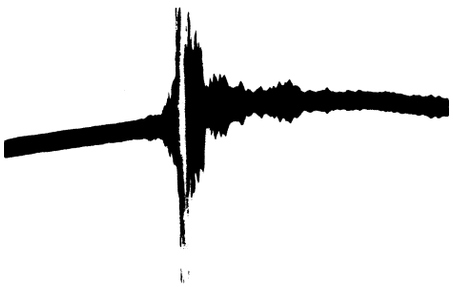

FIGURE 1 The first recording of a distant earthquake. This photo reproduction is from von Rebeur-Paschwitz (1895) and is clearer than the engraving used in his 1889 article. This earthquake is often said to have been "in Tokyo," since the one report available was from there, but the description (see also Knott 1889) makes it clear that the shaking was just barely felt, so the shock must have been offshore. The magnitude in Table 1 is estimated from this record, applying the instrumental constants in Abe (1994).

Unfortunately, the global scope of Milne's network was not matched by the quality of his instruments: These low-gain undamped sensors, registering on a low-speed record, were adequate to detect large shocks but not to show the details of the waves from them. Major advances in instrumentation came from two physicists who had turned to seismology. The first was E. Wiechert, who (following a study of Italian instruments) introduced in 1904 his inverted-pendulum sensor, the first seismometer to be properly damped—something Wiechert's own theoretical developments, themselves new, showed to be important. The second was B.B. Golicyn (Galitzin), who, beginning in 1906, applied electrodynamic sensors and photographically recording galvanometers to create instruments of unprecedentedly high sensitivity and accuracy.[10]

As these and other instruments were installed at observatories around the world, seismologists faced a new problem: sorting out the different "phases" observed, and relating them to different kinds of waves propagating inside the Earth. Theorizing about the Earth's interior was an active subject in the 19th century, but (rather like cosmology today) one in which a maximum of ingenuity was applied to minimal amounts of data. It was agreed that the depths of the Earth were hot and dense, but what parts were solid or liquid (or even gaseous) was the subject of much debate, though by the 1890s there was general agreement (from Kelvin and G.H. Darwin's tidal studies) that a large part of the Earth must be solid, and thus capable of transmitting the two known types of elastic waves, along with the elastic surface wave proposed by Rayleigh in 1885. But it was not known which of these wave types would actually occur, and how much they might become indistinguishably confused during propagation. Given that the Earth was an inhomogeneous body, and that rocks were anisotropic, seismologists had a wide range of options available to explain the observations.[11]

The most obvious distinction was between the large "main phase" and the preceding "preliminary tremors," which

were early suggested to be surface waves and body waves, respectively. In 1900 R.D. Oldham, using measurements of the 1897 Assam earthquake, classified the preliminary tremors into two phases, which he identified with longitudinal and transverse body waves, the main phase being a surface wave. That this is the same identification that would be now made should not obscure its controversial nature at the time. For one thing, measurements of particle motion in the main phase showed motions quite different from Rayleigh's theory; for another, there was disagreement about the extent to which the records reflected tilting as opposed to horizontal motion. Perhaps because of these disagreements, in the proposal by Wiechert and van dem Borne in 1904 for designators, the letters *P*, *S*, and *L* referred only to the timing or form of the waves, not to their type.

This was by no means Wiechert's only contribution to global seismology; it would be fair to say that the work he and his students at Göttingen did between 1900 and 1920 made them the leaders of the subject. Already expert in optics and electrodynamics, Wiechert was able to apply his knowledge to waves in the Earth. With G. Herglotz, he developed the first solution to the geophysical inverse problem of deducing wave velocities from travel times (the forward version of this had been discussed by H. Benndorf). Another student, K. Zöppritz, determined a set of travel times that were used for some years, as well as working out the equations for transmission of elastic waves at an interface (earlier solved for wave energy by C.G. Knott). B. Gutenberg used the Herglotz–Wiechert method to determine a velocity profile—and in particular, to find the radius of the core (a region of decreased wave speed first proposed by Oldham in 1906) at a value very close to the modern one. And L. Geiger showed how to determine earthquake locations from distant observations using least-squares. Many of these names are still familiar, attesting to the extent to which Wiechert's group laid foundations for the field that have in many ways endured.

Of course, there were others contributing to wave-propagation studies. One was A. Mohorovičić, who used data from the 1909 Kulpa Valley earthquake in Croatia to study travel times at relatively short distances, and found additional phases which he explained by assuming a velocity discontinuity at about 50 km depth. A related development was the demonstration in 1911 by the mathematician A.E.H. Love that surface waves with particle motion transverse to the direction of propagation were possible in a layered Earth, thus satisfying the characteristics of the main phase in seismograms.[12]

5. The "Classical" Period: 1920–1960

In the forty years from 1880 to 1920, seismology had thus gone from being primarily a descriptive natural history of earthquakes to having a large (and mathematical) component concerned with the wave propagation within the Earth. The next forty years (roughly) might well be called the "classical" period: A time during which many of the ideas first developed before 1920 were refined and improved, but without any substantial changes in aims or techniques. This period spans what is often taken to be a huge change in science (especially in the United States), from low-tech poverty before World War II to high-tech affluence after it; but while this change did occur for physics, it does not seem to have applied to much of seismology.

5.1 General Developments

Despite setbacks from both World Wars, the number of seismic stations increased substantially over these four decades; and the wider use of radio time signals after 1920 made timing more accurate (even if still poor by later standards). However, this growth was not at all standardized: individual organizations would set up one, or in a few cases, several new stations. The most "global" organization engaged in seismology at this time was probably the Jesuits, some of whose schools included seismological observatories. In the United States these observatories formed their own organization (the Jesuit Seismological Association), which provided one of the first rapid determinations of global epicenters. There were also international organizations: The International Seismological Association was founded to promote international cooperation in 1904, though it ceased to exist with the start of World War I. When revived in 1922, it created what was perhaps the most important entity for global seismic research, namely the International Seismological Summary (ISS), in many ways the continuation of Milne's efforts in earthquake location, which had been continued after his death by H.H. Turner and the BAAS. Through the occasional exchange of records, the regular exchange of station bulletins, and the ISS, information collected worldwide was available to individual researchers. Seismologists thus had what would now perhaps be called a "virtual" global network, something which greatly stimulated studies of seismic waves at great distances.[13]

While such wave-propagation studies were a great research opportunity for many scientists, they were also a departure from seismology's previous focus on earthquakes and their effects—and were viewed by some as an abandonment of the most useful part of the subject. One response was to develop instruments appropriate for studying nearby earthquakes, a strategy pursued by H.O. Wood in southern California in the 1920s. This resulted in a new and more sensitive instrument developed by himself and J.A. Anderson, as well as more sensitive electromagnetic seismometers, and the strain seismometer (both invented by H. Benioff). The Wood–Anderson, in particular, made southern California a model local seismic network, in a style soon copied from northern California to New Zealand. The quality of data available in California helped to attract the most productive of Wiechert's pupils, B. Gutenberg, to a position in Pasadena in 1930, a move which

(as in other parts of science) transplanted the outstanding quality of German science to an American setting.[14]

Another shift from Germany to America happened in this period, namely the application of seismology to subsurface exploration, usually for oil. The pioneer here was yet another student of Wiechert's, L. Mintrop, who had for his thesis developed a portable seismograph to measure waves generated by a falling weight. After wartime experiences in artillery location (also influential for many Americans), he formed an exploration company, which began work along the Gulf Coast (Mexico and United States) at about the same time as several US groups. From this beginning, exploration seismology grew rapidly and became a field dominated by US companies.[15] Another "applied" area in which much early work was done in the United States was the recording of strong ground motion, begun in the 1930s (and treated in detail in an accompanying article).

5.2 First-Arrival Seismology: Global and Local Earth Structure

The main problem of instrumental seismology in this period remained that of relating observed bursts of energy on the seismic record ("arrivals") to elastic waves in the Earth. This was, for global seismology, a period of rapid progress: By 1940 the seismic-wave velocity structure of the mantle and core had been worked out in terms that remain little altered. Many travel-time investigations were "special studies" of global recordings from particular earthquakes: usually those that could be well located from other data. H. Jeffreys and K.E. Bullen took a quite different approach, using global data from the International Seismological Summary to iteratively construct improved epicenters and travel times, with due attention to statistical problems throughout. This analysis (and improved timekeeping) showed that many of the complications invoked by earlier seismologists were superfluous: The Earth is in fact a nearly spherically symmetric body, with only a few major internal discontinuities. One of these, the core–mantle boundary, was shown by Jeffreys in 1926 to separate a solid from a fluid region, based on the difference between mantle rigidities found seismically and whole-earth rigidities from earth tides. That the core itself contained a discontinuity was shown by I. Lehmann in 1936, using records of New Zealand earthquakes antipodal to the densely spaced stations of Europe. This finding of the inner core may be said to have completed the discovery phase of exploration of the inside of the Earth, though not its detailed mapping.

On more local scales there were a number of studies of crustal velocity structure using earthquakes and the occasional large explosion (usually detonated for some other purpose, or an accident). The results were interpreted in the framework given by Mohorovičić, finding the depth of crust–mantle discontinuity and sometimes of other velocity discontinuities (notably one first suggested by V. Conrad) as well. This is one branch of seismology that did change significantly after World War II: There were then several programs that used large-scale seismic refraction to determine crustal structure. In the United States the pioneering postwar land-based program was by M. Tuve and H. Tatel. A program of land-based "deep-seismic sounding" was begun in the USSR before World War II by V.A. Gamburtsev, and greatly expanded after it. A similar pattern, of modest prewar beginnings and huge postwar expansion, also applied to seismic measurements at sea, led by M.N. Hill in Great Britain, and M. Ewing and R.W. Raitt in the United States.[16]

5.3 Seismic Geography

While the compilation of earthquake catalogs in the 19th century reached its culmination in the massive (and mostly unpublished) lists of F. Montessus de Ballore, the global picture of seismicity stood to be greatly improved by instrumental recording—though for many decades errors in the data and travel times combined to give a picture that, while more complete, was rather blurred. The first major advance from instrumental measurements came from the dense local network in Japan, which enabled K. Wadati to distinguish (in 1927) between deep and shallow earthquakes. Wadati's results, combined with global travel-time data (which had suggested great depths for some earthquakes) cleared up the longstanding problem of earthquake depth, and showed that deep earthquakes were relatively restricted in their distribution. The other advance in seismic geography grew out of the sensitivity of the local network in southern California, which detected many small earthquakes that had to be clearly distinguished from larger, damaging ones. This led C.F. Richter, transforming another idea of Wadati's, to develop a "magnitude" scale for the size of the earthquakes: As any seismologist who has had to explain it to the public knows, it is not such an obvious concept as it might seem. Gutenberg and Richter soon extended it from southern California shocks to earthquakes throughout the world. The magnitude scale, combined with the distinction between earthquakes of various depths, and the more reliable locations possible with improved travel times, came together in Gutenberg and Richter's study of the seismicity of the Earth (1941, and later revisions). This delineated, better than before, the belts of major seismicity and large aseismic regions, giving a synoptic view of current global activity that influenced tectonic theories. The magnitude scale also made possible estimates of the distribution of earthquakes by size: This magnitude–frequency relation and its parametric description (the *b*-value) remain a basic relationship of seismology.[17]

5.4 Earthquake Mechanism

If earthquake distribution was greatly clarified between 1920 and 1960, the same could not be said of seismologists' understanding of what actually happened at the source of seismic

waves. By the 1920s there was little doubt that earthquakes and faults were closely related, though a respectable minority of seismologists maintained that the faulting associated with earthquakes was not the cause but an effect. In this matter seismologists tended to be influenced by the earthquakes and faults they knew best, so for Americans the paradigmatic event was the 1906 California earthquake. This exhibited large motions not just on the fault but also at a distance, leading H.F. Reid to state (1910) the theory of elastic rebound, according to which the earthquake is caused by the release of stress built up along a fault.

The problem for seismologists was, as it still is, to relate what happened at the earthquake source to the seismograms observed. Given that Golicyn (Galitzin) had shown that the first motion of the *P* wave pointed directly toward (or away from) the epicenter, seismologists looked for patterns in the first motion as recorded at an observatory, or seen at several observatories around an earthquake. The latter approach required a large number of stations, which were available only (for local records) in Japan; Japanese seismologists for some time were the leaders in studying this topic. The first observational results were from T. Shida, who in 1917 showed a pattern of first motion divided into quadrants separated by nodal lines—though he found other patterns as well (Fig. 2). The first theoretical treatment was by H. Nakano in 1923, in a paper which examined the first motion from isolated forces and couples. Of little influence in Japan (nearly all copies were destroyed in the fire after the 1923 Kanto earthquake), a copy of this paper reached P. Byerly in California. By 1938 Byerly had developed a method (extended distances) for plotting the distribution of first motions recorded globally in such a way as to identify nodal planes at the source. Apparently because of its intuitive match with the elastic rebound concept, he chose from Nakano's source models the single couple as representative of faulting.

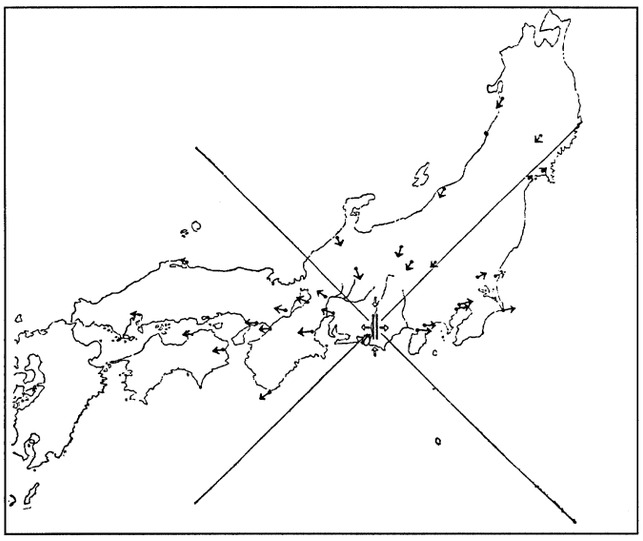

FIGURE 2 An early plot of first motions, from Shida (1929), showing one example used in his unpublished 1917 work. Note that the source pictured, while equivalent to a double-couple, is not shown as one.

Starting from Shida's initial investigation, there was a rapid development of first-motion studies in Japan, both theoretical and observational. It was soon observed, by S.T. Nakamura and S.I. Kunitomi, that the nodal lines coincided with geotectonic trends, strengthening the idea that seismic waves were produced by faulting. H. Honda showed that one implication of the simplest interpretation was false, namely, that the amplitudes of first motions would be largest close to the plane corresponding to the fault. Honda also argued that a double-couple system of forces was required to represent stress relaxation at the times of earthquakes; such a mechanism would produce two indistinguishable nodal planes. This view was itself soon challenged by M. Ishimoto, who argued that the distributions of first motions for many earthquakes were in better accord with conical nodal surfaces rather than planes, implying a distribution of forces that would now be called a compensated linear vector dipole. Ishimoto explained this as being consistent with magma intrusion causing both the earthquake and the faulting.

Ishimoto's interpretation of nodal lines created a controversy restricted to Japanese seismologists, perhaps because the associated magma theory was unappealing elsewhere. But other questions of earthquake mechanism were debated more widely—though with a tendency for the positions taken to coincide with nationality. After World War II earthquake-mechanism studies in Japan, led by Honda, favored a double-couple of forces as the source representation. An independent Soviet program on this subject began after 1948 under the leadership of V.I. Keilis-Borok, and developed methods for mechanism determination that made use, in principle, of first motions and amplitudes of both *P* and *S* waves; their results were interpreted as showing, most often, a single-couple source (for which the *S*-wave distribution, unlike that of the *P*-wave, differs from that for a double couple). Both Soviet and Japanese seismologists worked with local earthquakes. The systematic application of Byerly's techniques to large global earthquakes was undertaken by J. Hodgson and co-workers in Canada, with the results largely being interpreted both in terms of fault planes (taken to imply a single couple) or stresses (a double couple). Attempts to use *S* waves to discriminate between these models were not especially successful, nor were efforts to compile maps of inferred stress directions and relate these to regional tectonics.[18]

5.5 Surface Waves

Though the period from 1920 through 1960 can be viewed as the heyday of "travel-time seismology," it was not without attempts to interpret other parts of the seismogram. Once it was

clear that what had been called the "principal part" was a combination of Love and Raleigh waves, it became possible to use measurements of their velocities to determine shallow structure—a possibility made difficult by the computational burden of finding wave velocities for even very simple structures. Early results by G.H. Angenheister (yet another of Wiechert's students) showed Rayleigh-wave velocities that were higher along oceanic than along continental paths. Subsequent studies through 1940 confirmed that oceanic paths showed faster velocities, implying a thinner crust—though the estimates of ocean crustal thickness varied, from 40 km to less than 10 km. Much about the observations, notably the long coda often associated with Rayleigh waves, remained unexplained.

The 1950s saw further developments in surface-wave studies, most notably in the program led by M. Ewing and F. Press. Ewing had had considerable experience with dispersive wave propagation through his ocean-acoustics work during World War II, and also had seismic refraction evidence against a thick crust under the ocean. He and Press were able to show that the structure seen from refraction indeed fit observations quite well, even explaining the coda. They and their coworkers went on to study surface waves over a variety of paths, to develop a new design of seismometer for better recording of the longest periods, to install several such instruments in a global network intended for surface-wave studies, and to publish a treatise covering the entire subject of elastic waves propagating along boundaries. This treatise included, though it did not emphasize, the improved computational method that N.A. Haskell had developed for computing dispersion in multilayered media—a method that was to become the basis for many later developments in seismic-wave computation.[19]

6. From 1960 on: The Modern Era

In many ways the 1960s brought major changes, and much growth, to seismology. Rather than trying to cover every subject, I sketch new trends that can be seen, retrospectively, to be important; I have not tried to associate ideas with individuals. The most important new development is that seismology became what physics had been since the 1940s, a science viewed as relevant to national security—in this case not for the weapons it could build, but for those it could detect. The first nuclear explosion, in 1945, was detected seismically, and US investigations of detection included seismology from their beginnings in 1947; but in an era of atmospheric testing seismic methods took third place to infrasound and radionuclide collection (though even third place was enough to produce significant funding in the United States). With the pressure to move testing underground, seismic methods became more important—and the results from the RAINIER test, and the US–Soviet debates over how to interpret them and data from other underground tests, showed the inadequacy of existing knowledge. A US government panel (led by L.V. Berkner) recommended a large-scale program of "fundamental research in seismology." This resulted in the creation in 1960 of the VELA-UNIFORM program—which, though a project funded by the US government, provided support to a large number of seismologists outside the United States. The interest in this project, and in seismic means of detection, only increased with the Limited Test Ban Treaty of 1963, which moved most tests underground. A large fraction of the VELA-UNIFORM funds went for improved instrumentation, including a considerable amount for seismic array development (also pursued by test-detection groups in the UK and the USSR). VELA-UNIFORM's most important instrumental contribution to seismology was certainly the World Wide Standard Seismograph Network (WWSSN). This provided seismologists, for the first time, with easy access to records from standardized and well-calibrated sensors spread around the world. These data improved old results (e.g., on earthquake distribution) and made possible new ones; every subsequent global network has been modeled on the WWSSN style of operation.[20]

Much of what seismologists did with WWSSN data would not have been possible without the other tool that became common at the time: rapid computation. As computing costs fell, and available funds rose, seismologists were able to speed up calculations that previously had taken up much time (epicenter location) and begin to do things that the labor of computation had ruled out before, such as compute surface wave dispersion in realistic structures. But the effect of the computer was not just to allow seismologists to model complex structures; it also gave them new ways to look at data. The ideas of signal processing and Fourier analysis, developed largely by statisticians and electrical engineers, began to make their way into seismology, to show what could be done with waveforms beyond timing them.

The year 1960 brought an impressive demonstration of this new style of seismology, with the first detection of the Earth's free oscillations. The oscillations of an elastic sphere had been investigated by S.D. Poisson in 1829 (before he studied elastic waves), and some approximate periods of oscillation for a somewhat realistic (but homogeneous) Earth were worked out by H. Lamb (1883) and A.E.H. Love (1911). Following a large earthquake in 1952 H. Benioff believed that he had observed the gravest mode of oscillation, with a period of 52 minutes. But to see how this result compared with that expected it was necessary to compute the periods for a realistic Earth. This was done in 1959 by Z. Alterman, H. Jarosch, and C.L. Pekeris, using an early electronic computer. The occurrence of the 1960 Chilean earthquake spurred several groups to apply the novel techniques of Fourier analysis to their records. The demonstration, at the 1960 IUGG meeting, that the peaks in these transformed records matched the computed periods of oscillation, is a marker of the advent of new seismological techniques. Free-oscillation investigations flourished from then on, contributing to more precise Earth models, to the

advent of digital recording of seismic data, and (by being the first substantial demonstration of geophysical inverse theory) to the methodology of geophysics: All important aspects of the last few decades of seismology.

But perhaps the most important change for seismology since 1960 was, as for most of the earth sciences, the change in our picture of the Earth created by sea-floor spreading and plate tectonics. Though most of the data that went into this theory came from nonseismic measurements, earthquakes did play a role in two ways. The first was through oceanic seismicity: The more accurate epicenter locations got, and the smaller the magnitude threshold became, the greater the extent to which oceanic earthquakes appeared to occupy only a very narrow and continuous zone along the ocean ridges. The match between this narrow belt of earthquakes and (in some places) a deep median rift helped to focus attention on these narrow zones. The second contribution, especially important for the development of plate tectonics, came from focal-mechanism studies. The debate between single-couple and double-couple mechanisms was settled in 1964 by the demonstration that only the latter was compatible with a dislocation source (first applied to earthquakes by A.V. Vvedenskaya in 1956), and the WWSSN data made possible much more reliable solutions, for smaller earthquakes, with much less effort. Awareness of sea-floor spreading stimulated a study of the mechanism of oceanic earthquakes, which showed that oceanic fracture zones behaved as transform faults, connecting segments of spreading ridge. On a much larger scale, the first published paper suggesting plate tectonics showed that slip vectors of earthquakes around the North Pacific were consistent with the rigidity of this large area. This emphasis on earthquakes as indicators of motion rather than stress rapidly became the norm: only ten years from the time when focal mechanisms were difficult to estimate and confusing to interpret, they had become a routine tool for elucidating tectonics. Indeed, the largest effect of plate tectonics on seismology was to integrate earthquake occurrence (in many areas at least) with other evidence of deformation in ways not done before: Seismicity was finally felt to have been explained, not just described. This was perhaps most true for deep earthquakes: Though the physics of such deep sources was not resolved, the concept of subduction zones changed deep shocks from something that just happened to occur in some places to a consequence of the geometry and history of plate motion.

These conceptual breakthroughs gave a sense that what was going on at the earthquake source was far better understood than before. This, and the increasing level of damage earthquakes produced in a more urbanized world (in which growth has outpaced applications of seismically resistant construction), has created a steadily stronger desire to apply seismology to problems of seismic hazard. One consequence of this was the construction of many local seismic networks, to detect smaller earthquakes and so improve the description of seismicity. Most such networks use telemetered data, a technique first applied by P.G. Gane and others in 1949 to a network for studying rockbursts in South Africa. The increased interest in hazard, and the increased understanding of seismicity, created new interest in the possibility of earthquake prediction. Prediction studies (and the problem of discriminating earthquakes from explosions) have made studies of the earthquake source, and the mechanics of rock deformation associated with it, into a major part of the seismology of the last forty years, though earthquake prediction belongs to the future, not the history, of seismology.[21]

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Editor's Note

The numbered footnotes and bibliography are given on the attached Handbook CD under the directory \01Agnew. Readers are encouraged to read: Chapter 2, Historical View of Earthquake Engineering, by Housner; Chapter 3, The Jesuit Contribution to Seismology, by Udias and Stauder; Chapter 4, International Seismology by Adams; and Chapter 79 on centennial national reports to IASPEI, especially from Germany, Japan, Russia, the United Kingdom, and the United States, edited by Kisslinger. Biography of many persons mentioned in this chapter is given in Chapter 89, Biography of Notable Earthquake Scientists and Engineers, edited by Howell.