Kiyoo Wadati and Early Research on Deep Focus Earthquakes: Introduction to Special Section on Deep and Intermediate Focus Earthquakes

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This special section of the Journal of Geophysical Research is dedicated to Kiyoo Wadati. This paper evaluates his contribution to our knowledge of geophysics and, especially, deep earthquake phenomena. In at least three areas, Wadati wrote several papers before 1936 which profoundly influenced modern geophysics. First, his work provided the first convincing evidence that deep earthquakes existed. Second, he was a leader in the construction of travel time tables and the determination of mantle velocity structure. Finally, he published the first accurate description of the inclined planar zone of deep earthquakes which extends from trenches beneath volcanic island arcs. Wadati's work strongly influenced research of many other scientists both before and after World War II, particularly, Jeffreys, Gutenberg, and Benioff. Several of the questions raised by the research of Wadati and others before 1940 are still unanswered today.

INTRODUCTION

About 60 years ago, Wadati published the first of a series of observational papers which initiated a revolution in scientific thought about the earth's mantle. His observations proved conclusively that deep focus earthquakes occurred and these results stimulated some of the most memorable research of the finest scientists of that time, including Jeffreys and Gutenberg. Forty years later his observations provided fundamental support for the theory of plate tectonics. As the collection of papers in this issue attests, Wadati's observations still stimulate research by earth scientists today. Thus it is appropriate to dedicate this special section of the *Journal of Geophysical Research* to Kiyoo Wadati.

To commemorate Wadati's work, this paper will examine the contributions that he and others made, mostly prior to 1940, toward understanding the significance of deep earthquakes. I will organize this discussion in terms of five questions raised by Wadati and others about deep earthquakes and related problems. This paper will evaluate only peripherally how research since 1940 has changed the answers to the five questions, as the papers and references collected in this special section constitute a broad overview of current research on deep earthquakes and related phenomena. In particular, this paper will not attempt to review the vast literature which has appeared since 1965 linking deep earthquake phenomena and plate tectonics, as it is familiar to most modern readers.

During most of the early history of seismology, the focal depth of "normal" earthquakes was a topic of speculation, although the existence of surface faulting for some events and the relatively small area of intensive damage for others suggested that the focal depth must be quite shallow. Nevertheless, a few investigations of first motions or of intensities found focal depths in excess of 100 km. For

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Paper number 6B6329. 0148-0227/87/006B-6329\$05.00 example, *Pilgrim* [1913] calculated focal depths from apparent velocity for 10 events including the 1906 San Francisco earthquake, which he found to be at 140 km depth. *Walker* [1921] studied emergence angles for *P* phases and concluded that typical focal depths were about 1250 km. However, there was considerable interest in a paper by *Turner* [1922], who directed publication of the *International Seismological Summary* (ISS). In this paper Turner analyzed travel times for a number of events and suggested that some earthquakes were as much as 400 km deeper than "normal", and other "high focus" events were as much as 130 km shallower than "normal". Thus the usual depth of normal seismic activity must exceed 130 km.

Although some scientists initially were inclined to believe Turner's [1922] observations [e. g., Wrinch and Jeffreys, 1922], other scientists expressed doubt for a variety of reasons. By modern standards the data and analytical tools available to Turner were quite primitive. Timing errors of a minute or more were common, there were no standard tables, and many seismic phases such as those of the core phases, core reflections, and surface reflections had yet to be identified. Perhaps the most damaging criticism, however, came from Banerji [1925]. He noted that Lamb [1904] had shown that deeper earthquakes should have weak or absent surface waves, whereas these waves were reported quite abundantly for Turner's events in his own ISS bulletins. In addition, Jeffreys [1928] noted that analysis of mountain elevations and other topography in terms of isostasy demonstrated that the earth had no strength at depth. From this he concluded that the earth could not support the stresses necessary for earthquakes. These results, as well as analyses such as Oldham's [1926] study of the spatial falloff of intensities of several Italian earthquakes indicated that "normal" earthquake focal depths were less than about 35 km

However, during this period the Japan Meteorological Agency (JMA) operated the world's best regional network of seismic stations, and some JMA scientists such as Wadati and Shida had become aware of discrepant observations of a few events. Indeed, in a speech presented in October 1926



Fig. 1. S-P isochrons for (left) the shallow North Tazima earthquake of May 22, 1925 ($m_B = 6.25$), and (right) the deep earthquake of January 15, 1927 (h = 420 km, $m_B = 6.5$) [from Wadati, 1928a].

at the dedication of the Beppu Geophysical Laboratory at Kyoto, Shida observed that since P arrivals are longitudinal waves, then the first motions of some Japanese earthquakes showed that they must have focal depths near 300 km. He presented specific data for an earthquake that occurred on July 27, 1926, which was especially well recorded, and the earthquake of January 21, 1906, which was especially large. However, Shida did not publish these results, and the text of his speech was not published until more than 10 years later [Shida, 1937].

THE CONTRIBUTION OF KIYOO WADATI

1928-1931: "Shallow and Deep Earthquakes" - Three Papers

At about the same time, Wadati [1927a] published a paper in Japanese which proved quite convincingly that some Japanese earthquakes had focal depths of about 40 km, while others had depths of about 300 km. However, the western scientific world became aware of this research only when Wadati [1928a] published it in the first volume of the Geophysical Magazine. Students of seismology even today can learn from this classic observational study, where Wadati developed new methods and presented several different types of data to support his conclusions. Because timing was often too unreliable to trust P times, Wadati relied heavily on S-P intervals. To obtain hypocenters for shallow events, he used an ingenious method which makes no assumption about the P and S velocities other than that they are approximately constant. He noted that if the S-P interval observed at one station is a factor R larger than that observed at a second station, then the locus of points stations is comparable to the depth.

To show unequivocally that some earthquakes are deeper than others, Wadati presented three types of observations. First, he plotted S-P isochrons for two events with nearly identical epicenters (Figure 1). These were the North Tazima event of May 23, 1925, known to be shallow from several investigations, including a previous study by Wadati [1927b], and a contrasting deep event which occurred on January 15, 1927. Although the minimum observed S-P times occur at nearly the same epicenter for the two events, the isochrons are clearly different. While the minimum S-P for the 1925 event is less than 10 s, the 1927 event has a minimum S-P exceeding 40 s, and a much greater distance separating the isochrons.

Second, Wadati described differences in the distribution of seismic intensities. The known shallow events had extremely high intensities near their epicenters, falling off quickly and predictably with distance (Figure 2). In contrast, the events with large minimum S-P possessed "abnormal distribution of seismic intensity", i. e., no regions of extreme intensity but zones of relatively high intensity separated by zones where the event was not felt. Finally, Wadati noted that the seismograms of the anomalous events differed in appearance from those of shallow earthquakes. Seismograms of the apparent deep events always had impulsive, larger S phases, shorter predominant periods, and a less well-developed coda. In the discussion, Wadati asked whether there exists a particular "deep earthquake zone" in Japan where all deep earthquakes originated.

about the P and S velocities other than that they are approximately constant. He noted that if the S-P interval observed at one station is a factor R larger than that observed at a second station, then the locus of points consistent with the observed ratio is a sphere. As the intersection of three spheres will be at a point, three pairs of S-P intervals will fix the hypocenter. The degree of uncertainty in the depth is small if the distance between stations is comparable to the depth. In his next paper in English, Wadati [1929] found that the occurrence of deep earthquakes was not limited to a particular, localized zone beneath 300 km. Once again, these results appeared in Japanese journals [Wadati, 1928b, c] prior to their publication in Geophysical Magazine. In these papers he showed that earthquakes occur at all depths down to about 500 km. He proposed a scheme for classifying earthquakes as shallow, intermediate, or deep, which is essentially still in general use today:





Fig. 2. Distribution of seismic intensity for (left) the North Tazima earthquake of May 22, 1925, and (right) the deep earthquake of July 26, 1926 (h = 360 km, $m_B = 6.75$). The intensity scale is that used by Japanese investigators of the time, where VI corresponds to a modified Mercalli intensity of X or XI [from Wadati, 1928a].

The name of shallow is given to such earthquakes which...generally situate at the depth of within about 60 km... . The name of deep is generally given to such earthquakes which are considered to take place at the deeper part than the case of shallow ones.... Among deep earthquakes, such ones of more than 300 km deep are comparatively frequent and they are called 'deep earthquakes' in a narrow sense or 'very deep earthquakes' if it is required to avoid the confusion. On the other hand, 'intermediate earthquakes' whose depths are about 100-200 km are not so numerous as one expected.

Two years later, Wadati's [1931] paper concentrated primarily on comparing the distribution of amplitude with distance for shallow and deep events. However, modern readers will be more intrigued by his maps of P wave residuals, which show that the "regions where the P wave arrived sooner than normal" generally occurred on the eastern side of Japan. He noted that these regions correlated with the regions of abnormal distribution of seismic intensity and also with regions of anomalously high gravity. He interpreted these observations in terms of "hard" and "soft" regions in the mantle and crust, which affect seismic waves differently.

1932-1934: "On the Travel Time of Earthquake Waves"-Six Papers

Compilations of travel times are important in seismology for two reasons: as an aid in identifying phases and locating events, and as basic data for the determination of earth structure. The existence of deep focus earthquakes explained some of the gross discrepancies in observed travel times that troubled early investigators. As more data became available, scientists at several centers turned their attention to the construction of concise, self-consistent travel time tables. Of these investigators, the most notable efforts were by Jeffreys in Great Britain, Gutenberg in the United States, and Wadati in Japan. Jeffreys was clearly the most accomplished applied mathematician, with immediate access the Herglotz-Wiechert method to obtain the velocities of P

to the data collected by Turner for the ISS bulletins. Gutenberg and Richter probably had the best collection of seismograms at teleseismic distances. However, at regional distances, the JMA network provided Wadati with data that were superior to any in the world for both shallow and deep earthquakes.

Although Wadati [1928a, 1929] had already begun to use travel times of deep earthquakes to infer the velocity in the mantle, this became the central objective for his next series of six papers. In the first paper, Wadati et al. [1932] presented travel times for P for distances between 0 and 1500 km and for depths from 0 to 500 km. He determined these from Honda's [1931] velocity structure, obtained by the Herglotz-Wiechert method from observations of the shallow focus North Idu earthquake of November 26, 1930. In his next paper, Wadati [1932] noted that deep earthquakes are ideal for the determination of S travel times because their S phases are generally so large and impulsive. He showed how plots of P arrivals versus S-P intervals, now called Wadati diagrams, can be used to determine the origin time of an unlocatable event, as well as the V_P/V_S ratio.

Next, Wadati and Oki [1932] noted that one can avoid missing weak phase arrivals by using only large earthquakes to determine travel time tables. They then proceeded to construct P tables for teleseismic distances using several large shallow Japanese events. For this work, Wadati and Oki used arrival times of Japanese events reported in the ISS bulletins, although they determined the hypocenters with data of the Japanese network. Wadati and Oki [1933] presented a continuation of this work for S waves, using the large deep earthquake of March 28, 1928, exclusively to avoid phase misidentification. They compared the resulting "Japanese mean-time distance curves" for P and S to preliminary tables by Krumbach [1931], Turner in the ISS bulletins, Gutenberg [1929], and Jeffreys [1932]. They used





Fig. 3. Comparison of P and S velocity in the mantle as detrmined by Wadati and Oki [1933] (thick solid line), Jeffreys and Bullen [1940] (dashed line J-B), and Dziewonski et al. [1975] (thin solid line, parametric earth model PEM, oceanic structure).

and S as well as Poisson's ratio from the earth's surface to the core. These results differ surprisingly little from the results accepted today (Figure 3). In the remaining two papers, *Wadati and Masuda* [1933, 1934] used this velocity structure to calculate tables for 19 additional phases, including surface reflections, core reflections, and core phases.

1935: "On the Activity of Deep Focus Earthquakes in the Japan Islands and Neighbourhoods"

Jeffreys [1928] had originally argued against the existence of deep focus earthquakes on the grounds that the mantle had insufficient strength to support brittle fracture. However, by now Wadati was well aware the mantle might be laterally heterogeneous, having different mechanical properties in different areas. Indeed, he had previously suggested this to explain discrepancies between his travel time tables and those of other investigators. To pursue this problem, it was necessary to undertake detailed investigations of particular large deep events [e.g., Wadati and Isakawa, 1933] and to obtain accurate catalogs of deep-focus events [Wadati, 1935, 1940]

Wadati's [1935] paper is perhaps most remarkable, however, because of its surprisingly modern description of the geometry of the deep earthquake zone. Here he presented the first contour map (Figure 4) ever published of the inclined zone of hypocenters. He compared this to a map of volcanic activity and noted that for intermediate depth earthquakes:

...contour lines and the distribution of active and dormant volcances have a close connection with one another.... Generally speaking, the possibility of drawing contour lines of the focal depth suggests that there exists in the crust something like a weak surface at where the earthquake outburst is liable to occur. This surface extends slopewise in the crust near the Japanese Islands.... Contour lines corresponding to larger depths lie on one side of the active volcanic chains and those of small depth on the other side. It is interesting that the volcanic activity seems to have no connection with the occurrence of shallow-focus earthquakes, but closely connected with that of earthquakes having rather deep foci.... Generally speaking, volcanoes are found in chain running nearly parallel to the continental margin and earthquakes occur also in a zone along a volcanic chain. But deep-focus earthquakes are apt to take place on one side nearer to the continent and shallow focus ones on the other side where is in most cases bordered on a very deep sea. This tendency seems to be observable in many volcanic regions in the world. Of course, we cannot say decisively but if the theory of continental drift suggested by A. Wegener be true, we may perhaps be able to see its traces of the continental displacement in the neighbourhood of Japan consulting the figures of contour lines as well as the distributions of volcanoes....

Most of Wadati's papers published after World War II are extensions of his previous work. They include updated maps and cross sections of intermediate depth activity [Wadati and Iwai, 1954], discussions of amplitudes and magnitude determination for local deep earthquakes [Wadati and Hirono, 1956] and the relationship between earthquakes and volcanic activity [Wadati and Takahashi, 1965]. In his last fulllength paper in English, Wadati et al. [1969] investigated amplitude and attenuation for rays traveling along the zone of deep seismic activity. They found a close relationship between zones of low attenuation and earthquake activity and concluded finally that "the well-known phenomenon about the abnormal distribution of seismic intensities in Japan was explained from the results of this investigation".

FIVE QUESTIONS

In the decade following the appearance of *Wadati's* [1928a] paper, scientists began asking a number of questions about deep earthquakes and related phenomena. In this section I compare the answers found in the literature of 1928-1940 to the answers one finds today.

1. How Deep Within the Mantle Do Earthquakes Occur?

Wadati's work convinced nearly everybody that some earthquakes were deep, especially after Stechschulte [1932] and Scrase [1933] studied seismograms for Wadati's events recorded at teleseismic distances. In addition, Scrase [1931] analyzed a number of events and convincingly showed how pP and sP phases could be used to determine depth even if timing was uncertain. Several investigators further developed methods of using travel time differences to determine depth, including Wadati and Masuda [1934], Kadoya and Hidaka [1934], Miyamoto [1934], Gutenberg and Richter [1934, 1936a, 1937], and Berlage [1935]. Meanwhile, Stoneley [1931] looked carefully at seismograms from stations reporting surface waves for Turner's [1922] deep events. He noted that the alleged absence of surface waves argued against a deep focus, citing a reciprocity theorem from normal mode theory. Since surface waves are superpositions of normal modes, and since surface focus events had negligible amplitudes at depths, then deep focus events must have negligible amplitudes at the surface. However, Stonely found that the surface waves reported in the bulletins were indeed absent, or of negligible amplitude. What managers had read as surface waves turned out to be S, SS, SSS, and other phases. Gutenberg and Richter [1934] noted that Zoeppritz [1912], in a paper published 4 years after his death, had commented on the existence of two types of earthquakes, those with and without surface waves. Studies of particular individual events showed clearly that body waves of deep earthquakes were exceptionally well recorded



Fig. 4. Wadati's [1935] map showing contour lines of equal focal depth for deep focus earthquakes near Japan.

and that surface wave amplitudes fell off as events became clearly described most of the features of morphology and deeper [Blum, 1936; Westland, 1936; Lynch, 1938; seismicity that we recognize today as typical of an island arc Heinrich, 1939]. Subsequently, careful attention to Turner's subduction zone. This study strongly influenced other [1922] "high focus" events revealed that all were poorly recorded and could be explained as events of normal depth [Visser, 1936a, Tillotson, 1938].

It soon became clear that large deep earthquakes occurred at depths as great as 550-650 km in several different areas [Visser, 1936a, b], including South America, Tonga-Kermadec [Brunner, 1938], the Sea of Okhotsk [Wadati and Isakawa, 1933], the East Indies [Berlage, 1937], the Marianas, the Celebes, and the Philippines. In their comprehensive geographical review, Gutenberg and Richter [1938] reported the Flores Sea earthquake of June 29, 1934 as the "deepest known shock", and assigned it a depth of 720 km. Subsequently, Gutenberg and Richter [1954] included it among their best constrained events after studying reports of Koning [1942], Berlage [1936], the ISS bulletins, and other information. However, much the same information was available to Jeffreys [1942], who pointed out a number of inconsistencies if such a great depth is adopted and suggested a depth of 650 km. In spite of the uncertainty about the depth, the value of 720 km has been widely quoted, perhaps because neither Gutenberg and Richter [1954] nor Richter [1958] ever referred to Jeffreys' [1942] paper.

The information available to us today has produced surprisingly few changes in the methods used to determine celestial phenomena or tidal stresses [e. g., Cotton, 1922; earthquake depth, or in the maximum depths determined. Conrad, 1933; Landsberg, 1933; Stetson, 1935, 1937; Recent reviews by Stark and Frohlich [1985] and Rees and Visser, 1936a]. However, subsequently nearly all belief in Okal [1987] found no focal depths exceeding about 680-690 earthquake periodicity disappeared as more data became km, as determined from pP-P intervals, from comparison of available and as seismologists became more familiar with digital seismograms with synthetics to find event locations the statistics of small samples. Particularly notable is a [e. g., Giardini, 1984], or from relocations of historical paper by McMurray [1941], who found no significant events using modern location methods. Furthermore, it has periodicity in a study of 320 deep earthquakes. Also, become even clearer that occasional very large deep Jeffreys [1938] correctly evaluated the likelihood that earthquakes, with moments exceeding 1027 dyn cm, occur in random events will appear to possess periodicity, and further widely different geographic areas at depths of 630-650 km. noted that the presence of any aftershocks will cause a The only such area known today and not known to Fourier analysis to incorrectly find apparent periodicities. Gutenberg and Richter [1938] is Spain, where a single major thus explaining away the results of many earlier deep earthquake occurred at 630-km depth on March 29, investigations. Jeffreys [1939a] favored the hypothesis that 1954.

2. What Is the Tectonic Significance of the Distribution of **Deep Earthquakes?**

When seismologists finally recognized that deep earthquakes really occurred, they quickly began making catalogs of deep earthquake events and drawing maps to determine their geographical extent [Turner, 1930; Conrad, 1933; Visser, 1936a, b; Leith and Sharpe, 1936; Hayes, 1936; Yamaguti, 1937; Davison, 1937; Gutenberg and Richter, 1938, 1939]. These maps show most of the features known today about the geographical distribution of deep earthquakes. For example, Hayes' [1936] map has deep hypocenters in nearly every area they are known today except for the Mediterranean region. Gutenberg and Richter [1938, 1939] noted isolated deep events in Romania and in Italy. However, some of the early maps [e. g., Hayes, 1936] report isolated hypocenters in the northeastern United States, Africa, and a few other places where they are no longer believed to occur, and even Gutenberg and Richter [1938] reported deep events in the South Atlantic. As noted previously, Wadati's [1935] study was the most intensive investigation available for a particular geographic area. He

investigators, such as Visser [1936b], who said,

Wadati's rule of deep-focus distribution in Japan holds good in other regions, especially in South America, near the Tonga Islands, in the Isle of Mindanao and in the Aleutian Archipelago. They are intimately connected with the most important deep troughs of the Pacific Ocean... . Other less important troughs do not develop a strong bathyseismic activity Where troughs are wanting, the deep foci are wanting also.

However, Visser [1936b] and Lynch [1936] also noted that the earthquakes in the Hindu Kush region are a clear exception to this rule.

Why did deep earthquakes occur, and why were they associated with deep ocean trenches? Holmes [1933] speculated that convection occurred within the earth's mantle, explaining a number of geological phenomena including the existence of deep earthquakes. He says,

If these deep-seated disturbances are not in some way a result of currents operating far down in the zone of flowage where great masses of eclogite may be fractured as their strength is overcome, it is difficult to conceive an alternate mechanism for them.

A number of investigators in this period suggested that deep earthquakes were periodic and thus might be linked to cooling caused earth contraction, which he calculated should provide significant tensional stresses down to about 700 km. He suggested that cooling occurred more quickly in the oceanic regions because the crust there contained less radioactive material. This explained why the oceans were deeper than continents and why deep earthquakes commonly occurred on the boundary between oceanic and continental regions.

Very few new data or hypotheses had become available when Benioff [1949, 1954] wrote that deep events were caused by gross density differences between blocks of oceanic and continental material. His papers were widely read, and represent the most favored hypothesis of his time. He said,

Evidence of this kind...indicates that the Tonga-Kermadec and South American sequences of earthquakes originate on great faults which dip under the continental masses. The faults are approximately 2500 km and 4500 km in length respectively. Their transverse dimensions are approximately 900 km each. They both extend to a depth of approximately 650 km-more than one tenth of the radius of the earth. The oceanic deeps associated with these faults are surface expressions of the downwarping of their oceanic blocks. The upwarping of their continental blocks have produced islands in the Tonga-Kermadec region and the Andes Mountains in South America.

masses, he suggested that hydrostatic stress differences blocks; thus

Acting over a sufficiently long interval of time this differential stress pattern produced a distortion of the two masses which resulted in a configuration (such that) the originally vertical surface (becomes an) inclined surface.

Of course, today nearly all scientists believe that subduction, and the associated deep earthquakes, form the cold downgoing limbs of convection cells; indeed, this result was one of the principal triumphs of plate tectonic theory. Several research projects reported in this issue use deep or intermediate events to investigate the properties of subducted lithosphere in specific regions [Engdahl and Gubbins, this issue; Schneider and Sacks, this issue; Smalley and Isacks, this issue]. A still unresolved question concerns the depth extent of the convective flow, as this has important implications for mantle evolution [e. g., see Anderson, this issue; Kincaid and Olson, this issue; Hamburger and Isacks, this issue]. Some investigators cite the cessation of deep earthquake activity near 690 km as evidence that convection in the upper mantle does not extend into the lower mantle [e. g., Richter, 1979]. Alternatively, others use residuals from deep earthquake seismic phases to argue that convection does extend beneath the deepest events [e. g., Jordan, 1977; Creager and Jordan, 19841.

A second important area of research today concerns the existence and significance of deep earthquakes not related to subduction. For example, Hatzfeld and Frogneux [1981] and Chen and Molnar [1983] have investigated earthquakes at depths of 50-200 km in northern Africa and elsewhere. It is even possible that occasional earthquakes at much greater depths, such as the Spanish deep earthquake of March 29, 1954, may be unrelated to subduction. In the present volume, Curchin and Pennington, [this issue] are once again asking whether deep earthquakes might at least be triggered by tidal stresses, an idea which has more appeal since Nakamura [1978] confirmed that tidal stresses apparently cause the deep moonquakes.

3. How Do Phase Transitions in the Mantle Affect the Deep Earthquake Source?

Almost as soon as Japanese scientists became convinced of the reality of deep earthquakes, they began studying their mechanism [Sagisaka, 1930; Honda, 1934a, b]. Honda's [1932] description of the first motion pattern of deep earthquakes contains nearly all the basic features of the first motion pattern known today. After carefully studying seismograms from the superb JMA network, he says

The magnitude of the initial motion and the amplitude of the longitudinal waves are minimum in the region (N-region) near the nodal line or nodal circle, and maximum in the middle region (I-region) between two neighbouring nodal lines. The amplitude of the transverse waves is maximum in the N-region and minimum in the I-region... Various types of the distribution of the initial motion are derived from the supposition that the radial displacement proportional to sin20 coso, being expressed in spherical coordinates, occurs in the hypocentral region The results of the calculation basing on the above assumption coincide very well with the facts obtained from the investigations of the distribution of the magnitude of the initial motion observed on the earth's surface. And we can explain also the magnitude of the transverse waves and consequently the existence of the various types of the seismograms (N-type and Itype and so forth) basing on the same assumption as before.

Because of different densities of continental and oceanic Meanwhile, seismologists elsewhere showed less interest in the first motion problem, possibly because they did not develop along the originally vertical boundaries between the have domestic sources of deep earthquakes. For example Scrase [1931], Stechschulte [1932], and Brunner [1938] did not even mention first motions in their comprehensive studies of seismograms of particular deep earthquake events.

> However, scientists outside of Japan were aware of the Japanese work and of the possibility that deep earthquakes might be related to phase transitions. For example, Stechschulte [1932] said

The apparent predominance of shear waves must be taken into account in any hypothesis that one might put forth in regard to the mode of origin of a shock at so great a depth as 410 km. The records would seem to preclude anything in the way of a mere explosive activity. The question arises whether possibly changes in volume by crystallization may take place and at such a rate that the resulting stress differences cannot be quickly enough realized by plastic flow and relief must be had in the earthquake shock.

However, Leith and Sharpe [1936] concluded that "polymorphic transitions" played no essential part in the deep earthquake process, and said

Of particular importance, when the significance of deep-focus earthquakes comes to be discussed, is the fact that no earthquake has been observed for which the initial surface motion was everywhere away from, or everywhere toward, the focus... . Clearly defined patterns are much more difficult to observe in the case of shallow earthquakes, owing to the generally much more complicated nature of the waves, the effects of crustal discontinuities on the waves, and the necessity of having a much denser network of observing stations.

In spite of the absence of clear evidence in the seismograms themselves that phase transitions caused deep earthquakes, the appeal of this hypothesis remained strong. Jeffreys [1936; 1937] suggested that a change in slope of the P travel time curve near 20° could be explained by a velocity increase in the earth near 480-km depth. He also noted Bernal's [1936] suggestion that common olivine might undergo a phase transformation to a denser spinel structure in the mantle. Bridgman [1945] noted that

Conditions are conceivable in which a transition might run catastrophically because of a change in equilibrium conditions associated with crustal movements, thus giving rise to deep seated earthquakes, but the chance for this sort of thing appears more remote than the chances for a catastrophic release of stress by a fracture phenomenon after a critical stress has been built up slowly by progress of a transition.

However, the existence of phase transitions and zones of high velocity gradient in the mantle was not universally believed for about 30 years, when Ringwood and Major [1967] produced a phase transformation on olivine samples in the laboratory, and several studies of multiply refracted Parrivals [e. g., Golenetskii and Medvedeva, 1965; Johnson, 1967; Archambeau et al., 1969] confirmed the presence of velocity increases

At present, considerable uncertainty remains concerning the relation between phase transitions and deep earthquakes, although it is clear that double-couple sources fit most deep earthquakes extremely well. Benioff [1963], Dziewonski and Gilbert [1974], and Gilbert and Dziewonski [1975] evaluated very long period data and found evidence for a precursory isotropic compression in the source mechanism of some very large deep earthquakes. However, subsequent investigations have been unable to confirm these results [e. g., Okal and Geller, 1979]. Randall and Knopoff [1970] and Knopoff and Randall [1970] noted that it was possible for an earthquake source to be non-double-couple and yet have no

isotropic component. Such a source might occur if a phase transition caused a sudden change in the shear modulus of mantle material under stress. Recent studies [e. g., Silver and Jordan, 1982] find a few deep events which have nondouble-couple components in their moment tensors. However, the size of these components is comparable to the systematic uncertainties in their determination. One problem is that the kinetics of the appropriate transitions are highly uncertain and highly dependent on temperature and composition of the subducting material [Sung and Burns, 1976a, b]. Two papers in the present volume concern the relationship between phase transitions and the deep earthquake zone. Kirby [this issue] considers the possibility that polymorphic phase transitions in subducted lithosphere may occur which enable certain types of shear instabilities to happen, causing deep earthquakes down to about 670-km depth. Goto et al. [this issue] investigate the relationship between phase transitions and the thermal-mechanical processes that occur in the subducted slab.

4. What Is the Significance of (the Absence of) Aftershocks of Deep Earthquakes?

Initially, there was little unanimity concerning the existence of aftershocks of deep earthquakes. For example, Gutenberg and Richter [1938] said

Additional evidence for the uniformity of origin of deep and normal shocks is provided by the occurrence of aftershocks of the larger deep shocks... Although aftershocks are reported less frequently for deep shocks than for normal shocks, the writers are of the opinion that their frequency of occurrence is not significantly different. Even large aftershocks of deep-focus earthquakes are readily overlooked on the seismograms of ordinary long-period instruments, owing to the practical absence of surface waves, and to the small registered amplitudes of the short-period body waves.

Gutenberg and Richter may have been influenced by the event of May 26, 1932, at a depth of 600 km in Tonga. This event, which is one of three events at such great depth to be assigned an m_B of 7.5 [Abe, 1981], possessed at least eight aftershocks mentioned in Gutenberg and Richter [1938], including three large enough to be localized by the rather sparse global network of the time. In contrast, Leith and Sharpe [1936] observed that while shallow earthquakes may have a thousand or more aftershocks, aftershocks are "rarely observed" for deep focus earthquakes. They went on to suggest that aftershocks may be more common for shallow events because the crust is more heterogeneous than the mantle and because the "containing pressures" within the mantle are sufficient to "heal fractures quickly".

Today we know that deep earthquakes with as many as eight teleseismically observed aftershocks are rare, and virtually none possess well-developed sequences of numerous aftershocks as often occur for shallow events [see Page, 1968]. However, numerous studies have shown that deep events are not randomly distributed in time, but occasionally occur as doublets or multiplets [see Frohlich, this issue]. Unfortunately, we have made little progess since Leith and Sharpe concerning the reasons for this difference. Heterogeneity in material properties and strength has been used to explain source complexity and aftershock behavior for shallow earthquakes [e. g, Das and Aki, 1977; Lay and Kanamori, 1981]. It is possible that future research can extend these ideas to deep events.

5. Mechanically, How Can Deep Earthquakes Occur at All?

In their reviews of deep earthquake phenomena, Leith and Sharpe [1936], Gutenberg and Richter [1938], and Jeffreys [1939a] were all puzzled by the nature of the deep earthquake failure process. Experimental progress during the preceding decade showed that the strength of rocks and other crystalline materials increased with pressure, decreased with temperature, and depended on the duration of the applied stress [e. g., Griggs, 1936]. Experiments of this kind made the existence of sudden stress release at depths seem unlikely, as they suggested failure should occur by ductile means. Jeffreys, in particular, was well aware that the mantle appeared to flow over long time periods, as shown by the existence of glacial rebound and by isostasy. However, the reviewers were also aware of experiments by Bridgman [1936], who placed various materials in a torsion press and found that even at pressures equivalent to 166-km depth some samples would experience sudden stress releases between episodes of ductile failure. This occurred as a "snapping" or "jumping" of the sample and press. These experiments suggested that the mode of failure at great depth might differ in some fundamental way from the process of shallow earthquake generation.

In the half century since these reviews appeared, there has been an enormous amount of laboratory work investigating the nature of rock failure at shallow depths; however, there has been very little improvement in our understanding of the mechanical failure process appropriate to deep earthquakes. One possibility suggested by Raleigh and Paterson [1965] is that fluid phases trapped within the pores of subducted lithosphere reduce the effective confining pressure, so that brittle fracture may occur as in "dry" materials at shallow depths. A more attractive possibility is that stressed materials may release seismic energy by suddenly accelerated creep, occurring either with or without accompanying partial melting. This was explored qualitatively by Orowan [1960], Griggs and Baker [1969], and in more detail in the present volume by Kirby [this issue] and Ogawa [this issue]. However, it is possible that deep events are completely unlike shallow events, i. e., deep earthquakes may not involve dislocation along a planar fault surface. For example, Willemann and Frohlich [this issue] are unable to show that deep earthquake aftershocks occur preferentially along the nodal plane of initial shocks, as would be expected for shear faulting.

While there has been no breakthrough concerning the mechanism of deep earthquakes, a great deal of information has accumulated concerning the spatial and temporal extent of deep earthquakes [see Schneider et al., this issue] and concerning the accompanying stress and moment release [see Silver and Jordan, 1982; Giardini, 1984; Apperson and Frohlich, this issue; Trifu, this issue].

DISCUSSION

While it is seldom possible to attribute a major scientific advance solely to the observations of one man, it is clear that Wadati's research prior to 1936 had a profound influence on the thinking of his contemporaries and on our scientific thought today. Of the five questions about deep earthquakes, Wadati clearly made the most influential, early contribution to two, namely, concerning the depth and the geographical distribution of deep earthquakes. In addition, he participated



Fig. 5. Number of papers published about deep or intermediate earthquakes each year since 1922. Included are all papers primarily about deep earthquakes or closely related phenomena, or papers where one third or more of the events studied have reported focal depths exceeding 70 km. Solid bars are papers identified by the author in a thorough search of 18 selected journals. The most current names of these journals are Bulletin of the Disaster Prevention Research Institute, Bulletin of the Earthquake Research Institute, Bulletin of the Seismological Society of Amererica, Geophysical Journal of the Royal Astronomical Society, Geophysical Magazine, Geophysical Research Letters, Gerlands Beitrage Zur Geophysics, Journal of the Faculty of Science of Hokkaido University, Series 7 (Geophysics), Journal of Geophysics, Journal of Geophysical Research, Journal of Physics of the Earth, New Zealand Journal of Geology and Geophysics, Physics of the Earth and Planetary Interiors, Pure and Applied Geophysics, Reviews of Geophysics, Tectonics, Tectonophysics, and Tohoku Geophysical Journal. Open bars are papers found in other journals without a systematic search.

extensively in some of the most remembered work of the prewar era, i. e., the preparation of travel time tables and determination of a mantle velocity structure. Prior to the appearance of his 1928 paper, the best studies concerning the depth of seismicity offered reasons why earthquakes could not occur substantially beneath the crust [Banerji, 1925; Jeffreys, 1928, 1929]. Afterwards, the most intensive research concerned ways to measure earthquake depth [Scrase, 1931; Stechschulte, 1932], the above mentioned travel time tables [e. g., Gutenberg and Richter, 1935a, b; 1936a, b; 1937; Jeffreys and Bullen, 1940] and possible explanations for the occurrence of deep events [Holmes, 1933]. Scientists also found means to use deep earthquakes as sources to measure other properties of interest, such as the depth to the core, and the structure of the earth's crust [Sharpe, 1935; Robertson, 1937; Jeffreys, 1939b].

Furthermore, Wadati's [1935] map (Figure 4) and description of the deep earthquake zone agree in all essential respects with our observations today. This paper appeared prior to similar descriptions by other scientists, who generally referred to his work [e. g., Visser, 1936b; Berlage, 1937; Gutenberg and Richter, 1938]. Although it was more than 30 years before the plate tectonic theory provided an explanation for the significance of Wadati's inclined zone of deep focus hypocenters, these 30 years provided no substantial change in the observational picture as presented by Wadati [1935].

provides a rather humbling commentary concerning the ISC events, and line is for events with m_b greater than 5.5.

extent that scientific thought is stimulated by innovative ideas, as opposed to political, economic, and social events. Wadati's 1928 paper clearly initiated the peak in publication between 1930 and 1940. The peak between about 1968 and 1972 apparently occurred in response to the appearance of plate tectonics, as scientists explored the role played by deep earthquake zones. However, the social and political forces clearly dominate. The effect of World War II was to virtually eliminate publication of deep earthquake papers for almost a decade. Indeed, between 1945 and 1960, much of the basic research which did appear was primarily a survey of work done before World War II [see Gutenberg and Richter, 1938, 1941, 1954; Honda, 1932, 1934a, b; 1951, 1957]. The resumption in research activity about 1955 may be indirectly related to governmental concern about the detection and monitoring of nuclear explosions. The U.S. response was to provide more funding concerning earthquakes and earth structure and to install an extensive global seismograph network, the World Wide Standard Seismograph Network (WWSSN). Microfilmed seismograms from the WWSSN provided access to data for a much larger group of seismologists, producing a steady increase in the number of earthquake publications after 1955.

In light of the number, importance, and longevity of Wadati's published contributions, it is ironic that his inclined zone of deep hypocenters has become known as the Benioff zone. The name was first applied by Dickinson and Hatherton [1967], although for several years most papers used only descriptive names such as "slab-like zone" or "deep seismic zone" [e. g., Isacks et al., 1968]. W. R. Dickinson and T. Hatherton (personal communication, 1986) both make it clear that they were strongly influenced by the publications of Benioff and Gutenberg and were largely unfamiliar with Wadati's publications. Hatherton notes that he was influenced by his association with Benioff while spending a year at Caltech, and also by a paper of Wilson [1954], which states

Benioff [1949] has shown that the earthquakes occurring beneath the Andes and the Tonga-Kermadec Islands lie along zones extending to depths of 700 km....

Dickinson states that since 1969 he has referred to them only as "inclined seismic zones", partly because he now feels it is inappropriate to give them any man's name and partly "because the term Benioff zone has been distorted by



Fig. 6. Fraction of earthquakes reported by the International Seismological Centre (ISC) between 1964 and 1981 having focal Surveying the literature on deep earthquakes (Figure 5) depths in excess of the value plotted on the x axis. Solid black is all

papers in this special section of the Journal of Geophysical Research, and in all my own future papers concerning deep earthquakes, I shall follow the suggestion of Uyeda [1971] and call them Wadati-Benioff zones.

Research concerning deep and intermediate focus earthquakes continues to be important for at least four different reasons. First, deep earthquakes constitute a surprisingly large fraction of all reported seismicity. About one fifth of all the events reported by the International Seismological Centre have focal depths exceeding 70 km (Figure 6). Of these 10 or more events with magnitudes of 5.0 or greater occurred in 131 of the 729 Flinn and Engdahl [1965] geographical subregions.

Second, several of the five fundamental questions about deep earthquakes still remain largely unanswered at this time. In particular, what is the nature of the mechanical failure Conrad, V., Die zeitliche Folge von Beben mit tiefen Herd, Gerlands process that occurs at the deep earthquake source? How, if at all, does it relate to the presence of phase transitions in the mantle? These are the same questions that troubled Jeffreys [1928], Leith and Sharpe [1936], and Bridgman [1945]. A half century of research has not answered them, although it half century of research has not answered them, although it mantle, J. Geophys. Res., 89, 3031-3049, 1984. has eliminated some possible answers and greatly improved Curchin, J. M., and W. D. Pennington, Tidal triggering of the resolution of the available observational data.

Third, it is clearer now than ever that the regions where deep earthquakes occur have a significant role in mantle dynamics and evolution. agreement as to whether subduction/convection proceeds beneath the depth of cessation of earthquake activity, or Dickinson, W. R., and T. Hatherton, Andesitic volcanism and whether this depth marks a phase or a compositional change in the mantle. Finally, because the deep earthquake source produces relatively impulsive seismic body waves, these body phases are used proportionally more often than those of shallow events as a probe for studying the structure of the earth's crust, deep mantle, and core.

Acknowledgments. I thank Yosio Nakamura for his excellent translation of the paper by Shida. Ruth Buskirk, William Dickinson, Flinn, E. A., and E. R. Engdahl, A proposed basis for geographic and Trevor Hatherton, Benjamin F. Howell, Seth Stein, Seiya Uyeda, and two anonymous reviewers provided encouragement as well as critical Frohlich, C., Aftershocks and temporal clustering of deep suggestions to improve earlier versions of this paper. During this research the author was supported by National Science Foundation Giardini, D., Systematic analysis of deep seismicity: 200 centroidgrants EAR-84-10352 and EAR-86-18406.

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> (Received November 20, 1986; revised March 13, 1987; accepted March 27, 1987.)