Chapter 79.33 Japan

Centennial Report of Japan
Part 2. Historical Development of Seismology in Japan

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Contents

Abstract

This article introduces the main seismological achievements produced in Japan over the 100-year interval before the establishment of plate tectonics. The development of seismographs and the installation of a nationwide seismic network during the late 19th and early 20th centuries contributed greatly to the investigation of spatial and temporal distributions of earthquakes including the first confirmation of deep-focus earthquakes. The dense network also facilitated earthquake mechanism studies from radiation patterns of seismic waves, which led to the double-couple source model in 1930s. Theoretical studies of seismic wave generation and propagation were intensively carried out in Japan since 1920s. Other important studies include studies of crustal deformation related to major earthquakes, statistical studies of earthquake occurrences (e.g., the power-law distribution in space, time, and energy), studies of earth structure (e.g., lateral inhomogeneity beneath island arcs). Advances in seismology of Japan after the establishment of plate tectonics are not described, because the contributions in this period are too numerous and diverse to review individually, but most of them have received international recognition.

1 Introduction

Japan is an earthquake country. About one-tenth of the large earthquakes ($M_w > 6$ or 7) in the world occur in Japan and the adjoining sea areas. During the past 200 years, 33 earthquakes are known to have killed more than 100 people in Japan, 17 of which killed more than 1000.

Although earthquakes have been great concern among the people of Japan, and numerous documents describing the effects of earthquakes have been preserved since old times, scientific studies of earthquakes began a few years after the Meiji Restoration (1868). This article reviews the development of seismology in Japan during the 100 years preceding the establishment of plate tectonics. This interval will be divided into the following four periods: (1) the late 19th century (1868–1900), (2) the early 20th century before the 1923 Kanto earthquake (1901–1922), (3) between the Kanto earthquake and World War II (1923–1945), and (4) the two decades preceding the establishment of plate tectonics (1946–1967).

Seismology in Japan before World War II is not very well known outside Japan, because of the inaccessibility of some literature then published. The last one-third of the 20th century is not included here for the following reasons. (1) In this period, important seismological papers in Japan have been published in forms accessible to international audience. (2) These papers are too numerous and diverse to review individually. (3) Many of these will be introduced in the institutional reports in this handbook. (4) Most research objectives were studied both in and outside Japan in close interaction.

To write this article, I have consulted many articles dealing with the history of seismology in Japan, Fujii (1967), Hagiwara (1981, 1982), Hamamatsu (1981), Ikegami (more than ten articles published mostly in “Chigaku-Kyoiku (Education of Earth Sciences)” between 1974 and 1981, partially summarized in Ikegami, 1987), Kayano and Suzuki (1981), Usami (1981), Usami and Hamamatsu (1967), and others, all were written in Japanese.

Books and review papers written in early years of seismology contain interesting views on earthquake phenomena (e.g., Imamura, 1905, 1924, 1929; Kikuchi, 1904; Kusakabe, 1927; Matuyama, 1925; Omori, 1907; Terada and Matuzawa, 1926). Biographical writings on three founders of seismology in Japan, J. Milne (Herbert-Gustar and Nott, 1980), S. Sekiya (Hashimoto, 1983), and A. Imamura (Yamashita, 1989) are also valuable. No single book for the biography of F. Omori is available, though his work can be appreciated through his 400 articles (see e.g., Ikegami, 1981).

2 The Late 19th Century

2.1 Earliest Seismic Observations in Japan

A few years after the Restoration (1868), the government of Japan began to engage foreign scientists and technicians, mostly from Europe, some from the United States, as teachers in national colleges and agencies. It was natural that some of them had a special interest in the frequent earthquakes in Japan. In 1872, G. F. Verbeck tried to record earthquake motion by using an instrument consisting of four crystal balls on a horizontal marble plate of smooth surface and a heavy wooden block put on the balls. E. Knipping also made earthquake observation using a pendulum in the same year. No successful results from these observations have been left in literature.

In 1874, L. Palmieri’s seismoscope (using mercury-filled glass tubes) was imported from Italy. In 1875, the Geographical Survey was established, and its Meteorological Section was informally called the Tokyo Meteorological Observatory (TMO). The TMO continued the observation with the Palmieri seismoscope for 1875−1883.

On February 22, 1880, a locally damaging earthquake hit the Yokohama area. This earthquake stimulated the organization of the Seismological Society of Japan. Its first formal meeting was held on April 26, in which I. Hattori was elected as the president, and J. Milne and J. A. Ewing gave lectures on seismology in Japan and a horizontal-component seismograph, respectively. Milne emphasized that the discovery of the method for predicting earthquakes is one of the aims of seismology. In the same year, the Seismological Laboratory was set up in the University of Tokyo. Its main staff members were Ewing and S. Sekiya.

Ewing, Milne, Sekiya, and T. Gray developed several types of seismographs (e.g., Ewing, 1883; Dewey and Byerly, 1969). Ewing succeeded to build both horizontal and vertical pendulums having relatively long free periods (horizontal pendulum and Ewing-type vertical-motion pendulum). Milne continuously collected the data on felt earthquakes throughout Japan (e.g. Milne, 1895). It can be said that the first seismograph capable of practical use was constructed in Japan with the help of Japanese craftsmen and the first systematic investigation of seismicity based on the routine reporting of earthquakes started in Japan.

Milne conducted experiments on the propagation of seismic waves using falling bodies and explosives. In 1883, Ewing returned to England and C. G. Knott arrived as the successor. In this year, the Palmieri seismoscope at the TMO was replaced by the Ewing-Gray-Milne seismograph (often called Gray-Milne seismograph).

In 1884, Sekiya devised a four-grade seismic intensity scale. Near the end of this year, the TMO began to collect observational data from all over Japan. In 1885, the Seismometrical Section (headed by Sekiya) was started in the Geographical Survey. Sekiya was appointed as the first professor of the Institute of Seismology, University of Tokyo in 1886.

In 1886, the first volume of “Jishin Hokoku (Seismological Bulletin)” for the year 1885 was published. In 1887, the TMO was renamed the Central Meteorological Observatory (CMO). The data collected by the TMO/CMO were mostly felt intensity reports from public offices of prefectures, counties, towns and villages. The number of such reporters reached about 1000 in 1900. Many county offices installed an inexpensive seismoscope with smoked sheet-glass recording, but the distribution of these instruments is not well known now. The number of weather stations equipped with seismographs was about 20 in 1891 (the year of the Nobi earthquake).

2.2 The Nobi Earthquake of 1891 and Establishment of the Imperial Earthquake Investigation Committee

On July 28, 1889, the Kumamoto, Kyushu, earthquake (*M*6.3) occurred. Sekiya tried a field observation of aftershocks using a seismograph. On October 28, 1891, the Nobi (or Mino-Owari) earthquake (*M*8.0) caused heavy damage in Gifu and Aichi Prefectures in central Japan. This event was investigated intensively by F. Omori, B. Kotô, and others.

As a consequence of this earthquake, the Imperial Earthquake Investigation Committee (IEIC, H. Kato, Chairman) was organized in the Ministry of Education in June 1892. The Seismological Society of Japan was disbanded. The 18 objectives proposed at the beginning of the IEIC indicate that the committee intended to study earthquakes, tsunamis, volcanoes, and related phenomena using various approaches (seismology, geomagnetism, geothermy, geodesy, gravimetry, and geology), and the main target was to develop the methods for predicting the earthquake occurrence and for mitigating the earthquake disaster. The activities of the committee can be traced by reading the published articles in four publications, Report of the IEIC, Publication of the IEIC, Bulletin of the IEIC, and Seismological Notes. The first one was most voluminous but written in Japanese.

It is now generally accepted that the Nobi earthquake was due to the left lateral movement of the Neodani fault system. Kotô (1893) suggested that the faulting was the cause of the Nobi earthquake. Omori (1894) published a law on the decay of aftershock frequency with time, $n(t) = K(t+c)^{-1}$, on the basis of the data on the 1891 Nobi and the 1889 Kumamoto earthquakes.

2.3 The Last Several Years of the 19th Century

Within five years of the establishment of the EIC, northern Japan suffered two destructive earthquakes (the 1894 Shonai and 1896 Rikuu earthquakes) and one great tsunami (the 1896 Sanriku tsunami); the tsunami took 22,000 lives. It was often considered in those days that the tsunami was generated by the proper oscillation of bay water. However, Imamura (1899) suggested that the primary cause of tsunami was the vertical crustal movement at the sea bottom accompanying the earthquake. Later, Sano and Hasegawa (1915) explained the tide gauge records of Sanriku tsunami by the theoretical waveforms calculated for the sudden depression of sea bottom around the epicenter.

Omori developed a horizontal-component seismograph of smoked-paper recording type, but the installation of the Omori seismographs at various places in Japan started in 1900. Near the end of the 19th century, about 50 weather stations in Japan were equipped with seismographs (mostly the Gray-Milne type). These stations sent the observational data to both the CMO and the IEIC.

Since the timing accuracy of seismographs was low in those days, the epicenters were estimated from the distribution of seismic intensities. Omori (1899) suggested a linear empirical relation between the duration of preliminary tremor and the epicentral distance. However, it had not clearly been recognized until about 1910 that the preliminary tremor is the *P* wave train before the emergence of *S* wave. The durations (*S*–*P* times) had been used as the main data for the hypocenter determination in Japan until about 1960.

Early efforts to measure the velocity of seismic waves from explosions and earthquakes were continued by Ewing, Milne, Omori, and Imamura. They published at least ten papers on this subject before 1900.

3 The Early 20th Century before the 1923 Kanto Earthquake

3.1 Seismicity Studies

The IEIC continued its activity until 1925. A large part of the research activities of the IEIC was due to Prof. Omori of Tokyo University, who had been the secretary of the committee since 1897 and took the acting chairmanship in 1917. His work was rather limited to describing seismic and volcanic phenomena, preparing earthquake catalogs, and their statistical investigation. Although statistical methods were especially important tools in early years of seismology, the conclusions of many papers by him, seasonal and daily variation of seismic activity, relations to tides and meteorological conditions, etc., were inevitably questionable in the sense of statistical significance.

A statistical study by Terada (1918) dealing with the distribution of time intervals between successive earthquakes was a pioneering work in this field. He used a lognormal distribution and a sum of two exponential distributions.

Omori conceived a novel idea as follows. (1) Meizoseismal areas (suffering ground acceleration of about 200 gals or more) of past large earthquakes in a seismic zone do not overlap each other. (2) The earthquakes occur in parts of the seismic zone not occupied by meizoseismal areas of previous earthquakes. (3) If the whole seismic zone was filled by the meizoseismal areas of past earthquakes, the zone loses the capability to produce earthquakes, and the seismic activity moves to a different seismic zone. He developed this idea quoting various examples in more than ten papers published between 1906 and 1922. Although clause (3) is misleading, his idea is similar to the seismic gap hypothesis advocated in the 1960s. Omori (1909) showed that in central and southern Italy, meizoseismal areas of 12 earthquakes occupied the main seismic zone leaving three gaps. He considered these gaps as possible sites of future large earthquakes. Actually the devastating 1915 Avezzano earthquake (M_s6.9) occurred in one of them.

One of the main objectives of the IEIC was the collection of historical materials on earthquakes. Tayama (1904) published the collected materials under the title of "Dainihon Jishin Shiryo (Historical Materials of Earthquakes in Japan)". This 1200-page article contains about 2000 earthquakes between 416 and 1866.

3.2 Experiments on Rock Deformation – Relation to Aftershocks

Studies of the velocity structure of the earth were scarcely done in Japan before 1923. On the other hand, important studies were made concerning the occurrence mechanism of earthquakes. Experimental studies of the elasticity and anelastic deformation of rock were performed by H. Nagaoka and S. Kusakabe. Kusakabe of Tôhoku University wrote more than 10 papers by 1906. Kusakabe (1904) considered that the aftershock activity represents the recovery of strain after the reduction of stress as a result of the occurrence of the main shock. The frequency of aftershocks is proportional to the rate of strain recovery. He obtained an empirical equation for the creep of rock. The Omori formula can be derived approximately from the time derivative of this equation.

Kusakabe (1915, 1927) was of the opinion that earthquakes were closely related to the strain of crustal rock, which would control the seismic wave velocity. Observable velocity change might occur before the large earthquake, which lead to the prediction of earthquakes. However the time accuracy was too low to provide effective data for testing this hypothesis.

3.3 Distribution of the Direction of Initial Motion and the Earthquake Mechanism

During about 1905–1910 it gradually became clear that the initial part of a seismogram represents the longitudinal waves. In 1917, T. Shida of Kyoto University (famous for the Shida number in earth tide studies) made an important discovery. The direction of first motion was found to be either compression (C) or dilatation (D) at 29 stations in Japan in the case of the Shizuoka, Central Honshu, earthquake (M6.3) of May 18, 1917. The two kinds of stations (C or D) showed a distinctive geographical distribution. Two perpendicular lines crossing at the epicenter divided the earth's surface into compressional and dilatational quadrants. He presented this discovery at the meeting of the IEIC, but he did not publish it in any article. We can see only his letter including a map showing the distribution of the directions of initial motion sent to the Seismological Institute of the University of Tokyo dated June 25, 1917 (see reminiscences by Shida, 1929).

Such quadrant type distributions were also obtained in the 1918 Omachi, 1919 Miyoshi, 1922 Shimabara earthquakes, but the 1923 Kanto earthquake exhibited a different pattern because the faulting was not strike-slip. For a detailed description of early studies of earthquake mechanisms, see a review by Kawasumi (1937).

3.4 Crustal Deformation Accompanying Earthquakes

The relation between earthquakes and crustal deformation revealed by geodetic surveys was first discussed for the Nobi earthquake of 1891. The precise leveling surveys were repeated after the 1891 Nobi, 1984 Shonai, 1909 Anegawa, 1918 Omachi, 1922 Shimabara, 1923 Kanto earthquakes, etc. The triangulation was done after the 1914 Sakurajima eruption and earthquake and the 1923 Kanto earthquake. These survey results and the records of upheaval or subsidence of seashore at the time of some historical earthquakes provided indispensable information on the processes of earthquake generation.

4 Between the 1923 Kanto Earthquake and World War II

4.1 The Kanto Earthquake

The Kanto earthquake of September 1, 1923 destroyed southern Kanto district including the Tokyo-Yokohama area, killing 146,000 people. This earthquake had a great impact on seismology in Japan. The Seismological Institute was established in the Faculty of Science, University of Tokyo in December, 1923. The EIC was discontinued and the Earthquake Research Institute (ERI) of the University of Tokyo was established in January, 1925. The results of the investigations into this most disastrous earthquake in Japan's history were published in Volume 100 (Parts 1–6, 1925–1926) of the Report of IEIC in Japanese. Geodetic and seismic data obtained for this earthquake were utilized in source studies in the 1970s, revealing that this quake was an interplate earthquake due to the oblique subduction of the Philippine Sea plate beneath the North American plate with a seismic moment of about 8×10^{20} N·m (M_w7.9).

4.2 Seismic Observation: Instruments and Networks

The network of seismic stations kept by the CMO was gradually improved. In 1942, 60 weather stations had the Wiechert Seismographs of both horizontal and vertical components and other 50 weather stations had less sensitive horizontal-component seismographs, forming the densest nationwide network of seismic stations in the world. Most of the 110 stations also had so-called strong-motion seismograph of the CMO type. This is not an accelerometer but a displacement-meter with a free period of about 5 seconds and a static magnification of 1 or 2.

In the ERI, unique instruments for seismic and crustal-deformation observations were developed. These include a silica-pendulum tiltmeter (Ishimoto, 1927), an acceleration seismograph (Ishimoto, 1931), a velocity seismograph (Hagiwara, 1934), a water-tube tiltmeter (Hagiwara, 1947).

Observation of aftershocks by seismometers temporally set up near the epicenter of a large earthquake had been tried since the 1889 Kumamoto earthquake. Successful results were obtained for the 1927 Tango earthquake by Nasu (1929 and several later papers). In this earthquake, both the main fault (Gomura fault) and its conjugate fault (Yamada fault) were ruptured at the same time. The aftershock hypocenters do not cluster around the fault rupture. The aftershock observations were carried out after the 1930 Kita-Izu, 1931 Nishi-Saitama, 1939 Oga-Hanto, 1943 Tottori, 1948 Fukui, and 1949 Imaichi earthquakes by the staff of the ERI and other institutes.

In Kyoto University, K. Sassa initiated the continuous recording of tiltmeters to detect crustal movement associated with earthquake occurrence. The anomalous tilting recoded a few hours before the 1943 Tottori earthquake has been regarded as an early example of instrumentally recorded earthquake precursors (e.g., Sassa and Nishimura, 1951)..

4.3 Deep Earthquakes and Their Regular Spatial Distribution

European and Japanese seismologists suggested the existence of earthquakes with focal depth greater than 100 km in the 1900s and 1910s. Shida thought that the depth of some earthquakes (such as the south of Honshu event on January 21, 1906) exceeded 300 km. The International Seismological Summary (ISS) edited by H. H. Turner for the year 1918 (published in 1923) and for the later years reported a number of earthquakes with focal depths between $0.015r$ (96 km) and $0.08r$ (510 km), where r denotes the earth's radius. However, some of them seem to be shallow earthquakes. Work of Wadati (1927) at the CMO afforded an indisputable evidence for the existence of deep earthquakes. The significant difference in iso-P lines and iso-$S–P$ lines between two earthquakes having the epicenters at almost the same place indicated the large difference in depth between the two.

Wadati (1935) provided a map showing the iso-depth lines of earthquake foci in and around Japan. This map clearly showed that deep earthquakes occur within a layer that dips westward beneath the Japan arc. This inclined layer was identified in the late 1960s as the subducting oceanic plate having relatively high seismic velocity and low seismic attenuation. Deep earthquakes produce clear *ScS* phases at short epicentral distances. Honda (1934a) confirmed the liquidity of the core using the relative amplitudes of *ScS* waves.

4.4 Double-Couple Model for Earthquake Mechanism

Another important achievement was accomplished by the seismologists in the CMO in the analyses of earthquake mechanisms. Sagisaka (1929) emphasized that faulting motion occurred at the source of a deep earthquake on the basis of the directions and amplitudes of first motions observed at many stations in Japan. In later papers he verified this using *P* and *S* waves from shallow and deep earthquakes. Sudden faulting within the earth had often been considered to be equivalent to a couple of forces applied at the focus (single couple model) in the mode of seismic wave generation. Honda (1931, 1932, and several later papers with colleagues) asserted that most earthquake sources show quadrant-type focal mechanism, and these were represented by two couples of forces perpendicular each other (double couple model). He used abundant data on the azimuthal distributions of the directions of initial motions as well as the amplitudes of both *P* and *S* waves observed by the dense network of the CMO. Honda (1934b and several later papers) reported that the direction of maximum pressure (or tension) derived from focal mechanism solutions showed regular distribution closely related to the trend of island arcs in the region of Japan.

Against the quadrant type focal mechanism proposed by the CMO group, Ishimoto (1929, 1932) of the ERI maintained the cone type focal mechanism that correspond to a dipole force system at the focus. He considered sudden magma intrusion. Important studies of earthquake mechanism were also done by Kawasumi (1934), Matuzawa (1936), Minakami (1935), and others. There has been much discussion of what would be an appropriate model for earthquake sources. Even with the dense network of the CMO, it was difficult to discriminate between mechanism types owing to the narrow shape of the Japanese Islands. It took about 30 years for Honda's double couple model to receive worldwide acceptance.

4.5 Travel-Time Studies

Wadati (1925) and Matuzawa (1929) published early papers on crustal structure in Japan. Standard travel-time tables useful for hypocenter determination were constructed by seismologists in the CMO for regional and global scales (e.g., Sagisaka and Takebana, 1935; Wadati and Masuda, 1934; Wadati and Oki, 1933; Wadati *et al*., 1933).

4.6 Theory of Seismic Waves

Theoretical studies of generation, propagation, and particle motion (waveforms) due to various combinations of simple forces applied at the focus were performed in the 1920s and 1930s. Nakano (1923) wrote an important paper on this problem, but most of the printed copies were lost in the fire caused by the Kanto earthquake. He also published several valuable papers, e.g., on the generation of Rayleigh waves (Nakano, 1925). Sezawa (1927 and many later papers) made a number of theoretical studies on various aspects of seismic waves including the discovery of M_2 surface wave (e.g., Sezawa and Kanai, 1935). Other important theoretical work includes papers by Inouye (1936), Kawasumi (1933), Matuzawa (1926), Nishimura (1937), Sakai (1934), and Shono (1938).

4.7 Statistical Analyses of Earthquake Occurrence– Power-law Distributions

There were some marked progresses in statistical seismology. A method used by Matuzawa (1936) for the periodicity of earthquake occurrence was an advanced one over the Schuster criterion, because the effect of clustering was largely reduced. Matuzawa and followers claimed the periodicity (annual, semi-annual, diurnal, semi-diurnal, etc) in some data samples at high confidence levels. Some of them may be attributed to the preferential selection of data.

The power-law distributions are now frequently used in statistics of the quantities related to earthquakes. In recent years, such distributions have been analyzed under the concept of fractals. Omori's law (Section 2.2) is the earliest example. Wadati (1932) published a paper discussing the frequency distribution of earthquakes with respect to radiated energy E. He assumed a power law distribution of E, i.e., $n(E) \propto E^{-w}$, and estimated the exponent w as 1.7–2.1. Although his method was based on several assumptions, this is equivalent to Gutenberg-Richter's relation log $n(M)=a-bM$ published in the 1940s, if the earthquake magnitude M is related to E by log $E=\alpha+\beta M$.

The power-law distribution of maximum amplitude A recorded by a seismograph at a station, $n(A) \propto A^{-m}$, was published by Ishimoto and Iida (1939). If magnitude is defined by $M=\log A+f(\Delta)$ where $f(\Delta)$ represents a calibrating function of epicentral distance Δ, Ishimoto-Iida's relation is equivalent to Gutenberg-Richter's relation with $m=b+1$ (Asada *et al*., 1950).

Kawasumi (1943) devised an earthquake magnitude scale M_k using seismic intensity at the epicentral distance of 100 km. He showed that M_k has an exponential distribution. Nakamura (1925) reported an exponential distribution of seismic intensity for the aftershocks of the Kanto earthquake. Since the seismic intensity is linearly related to the logarithm of ground acceleration α, these studies indicate a power-law distribution of α. For more power-law distributions proposed by Japanese seismologists, see Section 5.6.

4.8 Historical Earthquakes

K. Musha put a great effort into the collection of documents on historical earthquakes. These materials were published between 1941 and 1950 in four volumes of "Dainihon (or Nihon) Jishin Shiryo (Historical Materials on Earthquakes in Japan)". These are largely extended versions of Tayama's collection (see Section 3.1). About 6400 earthquakes occurring before 1868 are listed. These volumes include Tayama's collection.

It may be appropriate to note here that since 1975 T. Usami and collaborators intensively collected historical materials on earthquakes. The collected materials have been published by the ERI between 1981 and 1994 in 21 volumes of "Shinshu Nihon Jishin Shiryo (Newly Collected Historical Materials on Earthquakes in Japan)" totaling more than 16,000 pages. Additional 1500 pages have been published as "Nihon no Rekishi Jishin Shiryo Shui (Gleanings of Historical Materials on Earthquakes in Japan)". These volumes do not contain Musha's collection.

4.9 Seismic Cycles

The data on historical earthquakes were very important in studies of repeated occurrence of large earthquakes in the same region. Imamura, the successor of Omori at the Seismological Institute of the University of Tokyo, noted the recurrence of great earthquakes along the Nankai trough and the deformation cycle of the source region (e.g., Imamura, 1928). He expected the occurrence of a great earthquake like the 1854 Ansei earthquake in near future. In December 1944, a leveling survey was conducted to record the preseismic data along the Kakegawa-Omaezaki route. It is known that during this survey, anomalous disturbances suggesting the precursory aseismic slip were observed a few days before the Tonankai earthquake of December 21, 1944 (M_s 8.0).

4.10 Ultimate Strain

The triangulation survey conducted after the Tango earthquake of 1927 revealed the crustal deformation accompanying this M_s7.6 earthquake. Tsuboi (1932) analyzed these data and reached the conclusion that the crust ruptured in the region where the crustal strain reached the order of 2×10^{-4}. He considered the earthquake as a phenomenon of strain release stored in a crustal volume. From the size of the crustal deformation accompanying an earthquake, the energy released in the earthquake can be estimated. He estimated that the largest earthquake with the source volume of 100×100×30 km^3 releases the energy of 10^{24} ergs. This idea was generalized later (Tsuboi, 1956) by combining the empirical relation between magnitude and aftershock area by Utsu and Seki (1955). The Tango earthquake also provided an earliest example of the postseismic slow movements of the fault (Tsuboi, 1931).

5 Two Decades Preceding the Establishment of Plate Tectonics

5.1 The 1946 Nankai Earthquake

During the five-year period from the second half of 1943 through the first half of 1948, western Japan suffered from five destructive earthquakes, each of which caused more than 1000 deaths. Investigations into these earthquakes were relatively few because of the exhaustion brought by the war. Repeated geodetic surveys by the Geographical Survey Institute provided fairly detailed picture of the crustal deformation caused by the 1946 Nankai (or Nankaido) earthquake. Moreover, significant postseismic recovery of the deformation was found through leveling surveys repeated several times on the Muroto peninsula. These data were used in the 1970s and later to construct source process models for the Nankai earthquake. Earlier on, Sawamura (1953) proposed the Nankai thrust which was responsible for the great earthquakes recurring off the Nankaido region.

5.2 Microearthquake Studies

Asada and Suzuki (1949) carried out a seismic observation in the aftershock zone of the 1948 Fukui earthquake by using seismographs very sensitive in the frequency range higher than 10 Hz. The observation revealed that very small earthquakes ($M \approx 0$–3), called microearthquakes, occur very frequently and the amplitudes of these earthquakes follow Ishimoto-Iida’s relation.

Field surveys of microearthquake activity were conducted by several national universities in the 1960s. The most intensive study was made in the case of Matsushiro earthquake swarm starting in 1965 and lasting several years. These observations led to the installation of the microearthquake networks by several national universities and the National Research Center for Disaster Prevention (NRCDP) in the 1970s. NRCDP was renamed the National Research Institute for Earth Sciences and Disaster Prevention (NIED) in 1990.

The CMO changed its name to the Japan Meteorological Agency (JMA) in 1956. In 1960 the JMA began to replace Wiechert-type and other mechanical seismographs by electronic seismographs with crystal-controlled timing systems, but the sensitivity of the JMA network was kept relatively low, because its main purpose was to observe earthquakes of magnitude 3.0 or above in Japan.

5.3 Seismic Survey of Crustal Structure

Studies of crustal structure in Japan conducted in the late 1920s and the 1930s had provided rather slow P velocities in the uppermost mantle of Japan. The first systematic long-range observation of seismic waves from an explosion was performed in 1950 using a 50-ton quarry blast at the construction site of Ishibuchi Dam. Since then the Research Group for Explosion Seismology (the members are seismologists from several universities and government agencies) conducted the experiments every year in various parts of the Japanese islands and explored the crustal structure. For the interpretation of the results obtained before 1967, see for example Mikumo (1966) who used both seismic and gravity data.

Studies of crustal structure beneath the sea floor using ship-based instruments were carried out by S. Murauchi, N. Den, and colleagues since 1963. Development of the ocean-bottom seismograph (OBS) in Japan began in the late 1950s. The OBS grew to be a powerful tool for detailed studies of structure and seismicity in the 1970s.

5.4 Studies of Seismic Waves

After about 1960, the use of electronic computers permits the numerical calculation of complicated curves such as spectral curves, dispersion curves, synthetic seismograms, etc. Important theoretical studies of seismic waves, especially surface waves and free oscillation of the earth, were done by Hirasawa and Stauder (1965), Matumoto (1953), Saito (1967), Sato (1961), Satô (1955), Takahashi (1955), Takeuchi (1959), Tazime (1965), Usami *et al*. (1965), Yamaguchi (1961), Yamakawa and Satô (1964), and others. Only one paper for each author published between 1946–1967 is quoted here, though it is not easy to select a representative one. For more information, see Takeuchi and Saito (1972), Satô (1978) and Lapwood and Usami (1981).

The analyses of observed surface waves for crust and upper mantle structure were also advanced. Important work before 1967 includes Kaminuma (1966), Kanamori (1963), Satô (1958), and Santo and Satô (1966).

5.5 Upper Mantle Heterogeneities

Some pieces of evidence suggesting the regional difference in seismic wave velocity and attenuation in the upper mantle beneath Japan were obtained in the 1930s (e.g., regional distribution of travel-time residuals; the absence of $sScS$ phases near the epicenter of deep earthquakes). As early as 1918, K. Hasegawa reported that some earthquakes occurring on the Japan Sea side were felt only on the Pacific Ocean side. This strange phenomenon (abnormal distribution of seismic intensities) was studied in detail by T. Ishikawa and others between 1926 and 1933. Katsumata (1960) remarked that the seismic waves passing through the seismogenic parts of the earth travel faster with less attenuation than the waves traveling through the aseismic parts. In 1966, Utsu systematically studied the seismic intensity distributions for deep and shallow earthquakes around Japan and concluded that the Q contrast between deep seismic zone and the aseismic upper mantle beneath Japan reaches 10 times or more. He also obtained a 5% difference in velocities of both P and S waves. For more details on the heterogeneous structure of the island arcs of Japan, see a review paper by Utsu (1971).

5.6 Statistical Studies of Seismicity

Following a few power-law distributions described in previous sections, more empirical power laws were proposed. These are $f(s) \propto s^{-q}$ by Tomoda (1952) and $f(n) \propto n^{-\delta}$ by Suzuki and Suzuki (1965) both for the spatial distribution, and $n(t) \propto t^{-p}$ by Utsu (1957) for the temporal distribution of aftershocks (see Chapter 43 for the meaning of these distributions). Spatial and temporal variations of some parameters such as m in Ishimoto-Iida's relation, b in Gutenberg-Richter's relation, δ and p in the above relations were discussed (e.g., Mogi, 1962a; Suyehiro *et al*., 1964). Aki (1965) and Utsu (1965) showed a method for estimating the b value.

Other statistical studies made in this period include the investigation of foreshocks, aftershocks, and earthquake swarms (e.g., Mogi, 1963; Utsu, 1961). Kawasumi (1951) did pioneering work on seismic ground-motion hazard mapping of Japan using his catalog of historical earthquakes. Inouye (1965) showed some examples of seismic quiescence before some large earthquakes in Japan.

5.7 Rock Fracture Experiments

Ishimoto-Iida's relation which is equivalent to Gutenberg-Richter's relation holds good in the shocks (acoustic emissions) caused by microfractures during deformation/fracture experiments of rocks and other brittle materials. The temporal patterns of microfracture activity include sequences similar to foreshocks and aftershocks. The similarities between microfracture and earthquakes intensively studied by Mogi and others in the early 1960s indicate that the rock fracture experiments provide important suggestion on earthquake generation mechanism and prediction (e.g., Mogi, 1962b, c).

5.8 Seismic Source Studies

The idea that earthquakes are caused by dislocation sources (represented by the double couple model) became supported during the 1950s and the early 1960s. Honda, Ichikawa, and others obtained the fault plane solutions of numerous earthquakes in Japan. Their studies confirmed the regular distribution of the orientation of P axes (or T axes). See summary papers by Honda (1962) and Ichikawa (1971). The faulting origin of earthquakes was also advanced by the quantitative studies of crustal deformation accompanying earthquakes by Kasahara (1957) and surface wave radiation patterns by Aki (1960). Maruyama (1963) theoretically showed the equivalence between the dislocation source and the double couple source.

Study of the 1964 Niigata earthquake by Aki (1966) is noted for the introduction of the seismic moment. This quantity is now widely used in the quantification of earthquakes. The earthquake source model based on a simple dislocation along a fault was established in this period. Aki (1967) published another important work on the scaling law of source spectrum.

5.9 Earthquake Prediction Plan

It had been reported by Kyoto University group that anomalous crustal strain and tilt changes were recorded before several large earthquakes in Japan in the 1940s and 1950s. These observations, together with foreshocks, changes in groundwater, etc. observed before some earthquakes, were considered to be worth studying more intensively for earthquake prediction. In the 1960 spring meeting of the Seismological Society of Japan, Wadati proposed to start the discussion on the possibility of earthquake prediction. The discussions held among the SSJ members were summarized by Tsuboi, Wadati, and Hagiwara in 1962 as a pamphlet titled "Prediction of earthquakes – Progress to date and plans for further development".

The plans included geodetic surveys, continuous observations of tilt and strain, seismicity studies, observations of temporal variation in seismic velocity, studies of active faults, geomagnetic and electric observations, rock fracture experiments, heat-flow studies. Later hydrological and geochemical studies, crustal structure studies, and collection of historical materials were added.

Soon after the first Japan-U.S. conference on earthquake prediction held in Tokyo and Kyoto in March 1964, the Alaska earthquake and the Niigata earthquake occurred in both countries. The government of Japan approved the budget in 1965 for all items listed in the plans but in reduced amounts. Several government agencies (Geographical Survey Institute, JMA, NRCDP, Geological Survey, Marine Safety Agency, etc.) and several national universities have continuously received the budgets every year.

6 A Brief Note on Seismology in Japan in the Last Three Decades

During the last three decades Japanese seismologists were active in almost every aspect of seismological research. These contributions are not referred to here, because of the reasons described in the introduction of this article. The recent researches in Japan (as of 1993) are summarized in Special Issue of Journal of Physics of the Earth (Vol. 43, Nos. 3-5, 1995). Special Issues of Zisin (J. Seism. Soc. Japan), Vol. 44 (1991) and Vol. 50 (1998) carrying 30 and 24 review papers and several other review papers in the same journal during the 1990s are also useful to evaluate recent seismological researches in Japan, but these are written in Japanese.

In recent years, more than 300 papers have been presented at every meeting of the Seismological Society of Japan held twice a year. I only cite some of the research objectives for which Japanese seismologists have made significant achievements.

Instrumentation and observation

- Dense telemetered seismic networks including the cable type OBS stations.
- Dense networks of digital strong motion seismographs.
- Quick determination of source parameters and early warning system.
- Broadband seismic networks in the western Pacific area.

Earth structure and seismicity

- Seismic refraction and reflection studies in land and sea areas for crust and mantle structure.
- Tomographic images of velocity and Q structure in local, regional, and global scales.
- Detailed distributions of earthquake foci in subduction zones (e.g., double seismic zones of intermediate-depth earthquakes) and its relation to global and regional tectonics.
- Seismic coda waves, seismic anisotropy, free oscillation of the earth, etc.

Earthquake source studies

- Theoretical studies of static and dynamic dislocations.
- Source processes and their complexities and diversities by analyses of seismic waves, tsunami data, and geodetic data.
- Slow earthquakes, silent earthquakes, and interplate coupling.
- Experimental and theoretical studies of rupture nucleation and growth. Frictional properties of faults.
- Scaling laws for quantities related to seismic sources and quantification of earthquakes.
- Rock fracture experiments. Computer simulations of seismic activity.

Tectonic activities and crustal movements

- Crustal movements by repeated geodetic surveys, continuous observation using GPS networks, strainmeters and tiltmeters. Relations to the plate motion and earthquake occurrences.

- Observational, theoretical, and simulation studies of seismic cycles at plate boundaries.

Earthquake hazard and prediction

- Recurrence patterns of earthquakes from active faults, marine terraces, tsunami deposits, historical earthquakes, etc.
- Earthquake sequences, seismicity patterns, and probability of earthquake occurrence.
- Earthquake triggering by stress changes by tides, earthquake dislocations, etc.
- Earthquake precursors in geochemical, hydrological, geodetic, electrical, and seismic data.
- Simulation of strong ground motion waveforms.

7 References

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