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BORN IN A COUNTRY OF EARTHQUAKES

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1. NATURAL PHENOMENA—MY LIFELONG FRIENDS

My country, Japan, is favored with a mild climate and with sufficient precipitation. We enjoy this gift of nature heartily, even though we also suffer from violent natural phenomena: earthquakes, typhoons, and volcanic eruptions. I was born in 1902 in Nagoya, during a raging typhoon. I think I was fortunate to have been born in this wonderful country that exhibits such a wide range of natural phenomena.

When I was six years old and sitting on the veranda of my grandfather's home in Hamamatsu, I suddenly felt strong earthquake shocks. I was surprised by these and rushed to the garden, where the family had already gathered. They looked anxious. Fortunately, the shock was not violent enough to cause damage to the house, but still it impressed me with the terror of earthquakes. The magnitude of this earthquake was 7.0; 41 victims died in the epicentral region, which was about 150 km distant from our home.

I would also like to tell about a volcanic eruption. When I was a small boy in elementary school in Osaka, one morning in the winter of 1914 I was surprised to find the school grounds and roofs entirely covered by white powder. I was told that this was ash from a large eruption of Volcano Sakurajima, which is far away, about 550 km from Osaka. It seemed very strange to me to think that those ashes had come flying from such a distant place.

During my school and college days, I used to spend my whole summer vacation at the seashore of Hamana Bay near Hamamatsu. There I had an opportunity to become intimate with marine life and to observe closely various kinds of natural phenomena in the air and sea, such as tidal

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motion, sea waves, typhoons, and storm surges. Perhaps these experiences remained in my mind and latently influenced me throughout my life.

On October 1, 1917, a violent typhoon struck our house in Tokyo. The strong wind destroyed the window glass, and the storm rushed into my room. This typhoon was the strongest to have attacked Tokyo in recent years. Unusually heavy flooding, originating from storm surges, caused heavy damage, especially in low coastal areas.

The most impressive natural disaster that I ever experienced was the great Kwanto earthquake of September 1, 1923. I was a student of physics at Tokyo University at that time. As I sat at a desk in a second-floor room of my wooden house, I suddenly felt very strong earthquake shocks accompanied by awful earth sounds. Then the mud began to fall from the wall, and the bookshelf at my side fell down. Fortunately, my house was damaged only slightly and my family was safe. Our house was in a high section of Tokyo, where the earthquake shocks were not so strong as those in the downtown area. There, a terrible fire added to the damage directly caused by the strong shocks. Consequently, there was a great loss of life. For several days after the earthquake and fire, I walked about the ruins under the leadership of professors investigating the effects of the shocks and fire. Looking back, this opportunity may have been important to my becoming a geophysicist.

At that time, Professor A. Imamura, taking the place of Professor F. Omori, lectured on seismology at Tokyo University. In an examination he asked us a question concerning the possibility of practical earthquake prediction. I answered that this might be attained if we try to identify premonitory events by combining precise seismological observations with the measurement of minute crustal movements. Now, it is with feelings of emotion that I realize that since then, 60 years have passed, and that now research on earthquake prediction is being seriously carried out in many countries, directed toward or actually realizing its practical use.

2. ON DEEP-FOCUS EARTHQUAKES

After I graduated from the university I went to the Japan Central Meteorological Observatory in Tokyo, which at that time dealt not only with meteorology but also with seismology, oceanography, terrestrial magnetism, and other geophysical subjects. I became a member of the seismological section and engaged in observation and research on earthquakes.

After about one month, on May 23, 1925, a strong earthquake occurred in the northern part of Hyogo Prefecture, and 40 persons died. Many aftershocks were observed afterwards, and there occurred among them an unusually big earthquake. This earthquake was publicly mentioned as the largest aftershock, but with no other special comment. I was attracted to the fact that this earthquake showed a special wave propagation feature, areas of high seismic intensity extending far from the epicenter.

On looking back now, I realize that this was a memorable earthquake. Not only did I feel it with my body, but I also noticed its characteristic nature, and this led me to investigate deep-focus earthquakes. (By the way, the focal depth of this earthquake was 400 km and the magnitude was 6.9.)

My routine job at that time was mainly to reduce the seismological reports sent from local observing stations and determine the positions of the foci of the respective earthquakes. While occupied in this work, it seemed to me that the current way of doing this was unsatisfactory, because insufficient attention was paid to the depth of focus. At that time, earthquakes were generally considered to occur at depths no greater than 60 km. Accordingly, when deep earthquakes actually occurred, such as at depths of 300 km or more, we had much trouble locating the positions of their epicenters.

In those days, we could not keep accurate time. Furthermore, it was sometimes difficult to know the accuracy of the phase determinations reported by the observing stations. In addition, these stations were confined to a long chain of islands, and we had almost no observations from oceanic areas. Finally, at that time we did not have sufficiently accurate values for seismic wave velocities in the crust and upper mantle, especially for some parts of the Japanese Islands. Such being the case, the results obtained in those days concerning the locations of earthquake foci were not always accurate, particularly in the case of deep-focus earthquakes.

In the end, it was the precise investigation of seismic wave propagation that made me gain confidence in the existence of deep-focus earthquakes. But actually, what gave me an impressive early hint was the irregular distribution of seismic intensities, a phenomenon that had been known among us for a long time. That is, seismic shocks were felt by persons in irregularly distributed regions, sometimes at places far from the epicenter. These regions were usually along the Pacific coast of North Japan.

Two early papers that strongly attracted my attention were those of Dr. K. Hasegawa and of Prof. F. Omori. The former reported that shocks of an earthquake that occurred in the northern part of the Japan Sea were felt only by persons on the Pacific side of Japan. The latter, entitled "Seismograms Showing No Preliminary Tremors," described seismograms of an earthquake that clearly showed large *P*-waves but no *S*-waves. Needless to say, these properties are exactly those of deep-focus earthquakes as we know them today.

Well, numerous earthquakes occur in and near the Japanese Islands, and these earthquakes are mostly shallow ones, with foci at depths less than 60 km. In addition, there also occur some earthquakes at any depth down to about 600 km. These facts, now generally well known, were my conclusions 60 years ago from my investigations of the abundant seismological data of the previous years in this region.

I first published a paper in Japanese on these results of my research and then a series of papers entitled "Shallow and Deep Earthquakes" in 1927, 1929, and 1931. These papers attracted the attention of geophysicists in several countries, and many investigations were then made concerning deep-focus earthquakes (for instance, Dr. F. J. Scrase's paper entitled "The Characteristics of a Deep Focus Earthquake: A Study of the Disturbance of Feb. 20, 1931").

3. DEEP-FOCUS EARTHQUAKES AND DEVELOPMENT OF SEISMOLOGY

While making a map showing the epicenters of deep-focus earthquakes, I noticed that the epicenters of these earthquakes were located in zones. In the region of Japan and its neighborhood there are two deep-focus earthquake zones that meet at nearly right angles with each other. One traverses the Japanese main island, and the other extends northeastward from the northern part of the Japan Sea. Also, there is another deep earthquake zone along the southwestern islands of Japan.

By examining precisely the distribution of the foci of these deep-focus earthquakes, as well as those of intermediate depth, I found that these earthquake foci are distributed quite regularly within the Earth's interior. Thus, isopleth lines for the earthquake foci could be drawn, and these showed that the foci of deep and intermediate earthquakes are confined to a surface or thin layer in the interior of the Earth.

My paper concerning this problem was published in 1935, entitled "On the Activity of Deep-Focus Earthquakes in the Japan Islands and Neighborhood." In this paper, it is also noted that these isopleth lines and the distribution of active volcanoes have a close connection with each other—that is, the volcanic belts coincide with the isopleth lines of 120–200 km for the foci of intermediate-depth earthquakes.

As time passed, the theory of plate tectonics has been developed and the problem mentioned above has come to be considered anew. Especially in discussion of island-arc tectonics, this distribution of earthquake foci is closely related to the subduction of the oceanic plate or the sinking lithosphere. I feel honored that the name Wadati-Benioff zone is sometimes used in this connection, and am much impressed by the recent studies on subduction zones and the concept of "comparative subductology."

These deep-earthquake zones are now observed in various parts of the world, but the subduction angles, the focus of the deepest earthquake, and the magnitudes of the related large shallow earthquakes are different in different regions. The recent development of plate tectonics theory has led to many remarkable results concerning the structure and activity in the crust and upper mantle. Certainly, seismology has played an important role in this, together with all fields of Earth science. Studies of the mechanism of earthquake occurrence, the propagation of seismic waves, and other phenomena concerning earthquakes are contributing to the recent progress in solid-earth science, but still the precise spatial distribution of earthquake foci is, I think, the fundamental matter.

When I first studied deep and intermediate earthquakes, it was difficult to obtain the precise spatial distribution of their foci, even in the region of the Japanese Islands, as the observational data were not very accurate. But gradually the observations have improved, and now the foci of deep and intermediate earthquakes are being observed clearly on both the upper and lower sides of the downgoing thrust sheet.

Now, the seismic waves propagating from the foci of deep earthquakes usually show very elegant features on the seismograph. Phases of *P*, *S*, and their reflected and refracted waves can clearly be observed. By studying these waves, we can obtain the velocity variation and also the effect of absorption in the interior of the Earth. I sometimes noticed that the wave amplitudes, especially for *S*-waves, of some deep earthquakes were observed to be much smaller than expected theoretically from the focal mechanism of these earthquakes, and I considered this to be the result of the wave passing through an especially soft layer in the Earth's interior. Many studies have been made of the attenuation of seismic wave amplitudes caused by internal friction in the upper mantle. In the Japanese island-arc region, for example, a detailed study was reported by Prof. T. Utsu in his paper "Seismological Evidence for Anomalous Structure of the Island Arcs with Special Reference to the Japanese Region" (*Rev. Geophys. Space Phys.*, 9: 839–90, 1971).

I hope for future developments in the study of this part of the upper mantle that is closely related to volcanic activity. As is well known, earthquakes generally take place in the neighborhood of volcanic regions, but if we look closely, shallow tectonic earthquakes very seldom occur at places very near the active volcanoes, whereas intermediate earthquakes occasionally do.

In Japan, it is very important to predict volcanic eruptions and also to promote countermeasures against those disasters. One must realize that at present there occur many great disasters caused by volcanic eruptions in various parts of the world. A concerted effort of researchers in various branches of science is required because in most cases, areas of active volcanoes are densely populated.

As for the magnitude of earthquakes, although its definition is fixed and is generally used for each earthquake, it is sometimes difficult to determine the magnitude of earthquakes from observations made at small epicentral distances, especially for earthquakes of deep origin and for those occurring in island-arc regions. I have tried often to find some formula to determine the magnitude of earthquakes in Japan, but I did not succeed because seismic waves propagate in such a complicated way in this region. I was only able to obtain the variation wave amplitude as a function of epicentral distance for earthquakes of various focal depths, and for those in different areas. It seems to me that there still remains room for further study of the magnitudes of intermediate and deep earthquakes.

4. PREDICTION OF EARTHQUAKE AND VOLCANIC ERUPTION

Looking back at the development of seismology, it may be pointed out that there have been two major schools. One school developed in countries of high seismicity, and the other in countries of low seismicity. In the former, the subject of studies has been local earthquakes and studies related to the prevention of earthquake damage, focused on earthquake motions and related phenomena, and eventually on earthquake mechanisms. In the latter, along with studies of earthquakes, more emphasis has been placed on studies focused on the internal structure of the Earth.

I was born in a country of high seismicity and have studied earthquakes, feeling these shocks frequently with my body. So I have been mostly interested in such subjects as seismic motion, seismicity, magnitude, upheaval and subsidence of the ground, tsunamis, landslides, and groundwater levels, bearing in mind the problem of earthquake prediction.

The study of earthquake prediction has been enthusiastically carried on since the early days of seismology, and researchers in Japan have discussed effective ways for the prevention of disasters. By their incessant effort, the importance of this project was clearly recognized, and since 1965 the Japanese government has appropriated a budget for it. Research on earthquake prediction has been pushed forward as a national project, aimed toward its practical use. As this project advances, various new seismological observational facilities have been established year after year.

Furthermore, in 1976 the Headquarters for the Promotion of Earthquake Prediction was established by the Japanese Cabinet, and in June

1978, the Large-Scale Earthquake Countermeasure Act was concluded to take effective actions to intensify the system for disaster prevention in case a major earthquake prediction is made. This Act was made on the premise that the occurrence of a large-scale earthquake as large as magnitude 8 class will be predicted.

As mentioned above, prediction at present is mainly aimed toward earthquakes in the magnitude 8 class, but it is rather important to also predict such destructive earthquakes in the magnitude 7 class, which occur more frequently in the densely populated areas. We are now endeavoring to establish a prediction system for those earthquakes.

To carry out the work of earthquake prediction, a complete observational network is indispensable, especially in Japan, and it is important to extend the observational network to the sea area. Thus, at present two systems of submarine seismographs are located off the coasts of the Boso and Omaezaki Peninsulas. No formal earthquake warning has yet been issued since this system was established, so it is difficult to discuss its practical usefulness. Still, we are delighted to have reached this stage. Earthquake prediction is now being developed in many countries according to the characteristic seismic activity of these regions. Naturally, it is desirable that this work be advanced further by close international cooperation.

Now I wish to take up a problem concerning the prediction of volcanic eruptions. Needless to say, Japan has suffered incessantly from disasters caused by volcanic eruptions. The disasters caused by recent activity of the Mount St. Helens and Nevado del Ruiz volcanoes are well known. In Japan, fairly strong eruptions have occurred recently on the islands of Miyake and Ohsima, causing lava flows and considerable damage. For some active volcanoes we have geophysical observing stations for monitoring volcanic activity. In some cases these are near the crater, but it is still hard to understand precisely volcanic movements and to issue a warning of an outburst of the volcanic activity. Recently, however, research on volcanic prediction has been strengthened, and it is expected to make great progress, along with that on earthquakes.

In our country, and also in some other countries of the world, volcanic areas are in most cases densely populated or crowded by sightseers. Protection against volcanic disasters has become an urgent problem. There are two types of volcanic activity: one for which active movement is frequent and provides eruptions now and then, and the other kind that produces great sudden eruptions. These eruptions occur after a long silence. Because of this difference, the sociological consequences of a formal warning will also be different, and it seems to me that further studies are required by both natural and social scientists.

Although the relationship between the occurrence of earthquake and volcanic activity has been discussed for a long time, still more precise research on this problem is needed, as well as on the relationship between the eruptions of two volcanoes located near one another.

5. TSUNAMI AND STORM SURGES

Since ancient times, Japan has suffered frequently from disasters caused by "tsunamis." In particular, great earthquakes that occur off the Pacific coast of the Japanese Islands usually cause very heavy damage to the coastal areas, even though the shocks are not always as violent there.

The Sanriku coast, which faces the Pacific, is well known by the tragic damage caused there twice, by earthquakes on June 15, 1896, and March 3, 1933. Along this coast of Liassic topography, there occurred various types of tsunamis in its different bays and harbors. In the former case, the wave height of the tsunami was 38.2 m in Ryori-Bay and 24.4 m in Yoshihama-Bay, and the number of deaths totalled about 22,000. In the latter case, the scale of the tsunami was nearly the same, but the disaster caused was not so heavy because of the advanced development of countermeasures.

Considerable tsunami damage has also been produced along the Pacific coast of Japan by large earthquakes originating at far remote places in the Pacific Ocean. For example, those coastal areas were attacked by tsunami waves on May 23, 1960, caused by the great earthquake of magnitude 8.5 that occurred off the coast of Chile. The tsunami propagated across the Pacific Ocean and arrived at the Japanese coast with long waves of 3–6 m height, and 140 lives were lost. After this event the Pacific Tsunami Warning System was established with its center in Hawaii and with the cooperation of the countries concerned. It is one example of an international system for prevention of natural disasters, and consideration is now being given to consolidate it with a similar system to monitor other global phenomena, such as air and marine pollution.

In Japan, storm surges caused by typhoons are very important natural phenomena, and we frequently suffer from these abnormally high tides. Typhoons usually give rise to heavy disasters by strong wind and rain, but the largest disasters sometimes are caused by the storm surges. The two typhoons of Muroto and Isewan raised terrible storm surges in Osaka Bay on September 21, 1934, and in Ise Bay on September 26, 1959, respectively. The height of sea level caused by these typhoons was 3 m or more and caused heavy damage to the cities of Osaka and Nagoya and their surroundings. In the latter case, about 5000 lives were lost by this typhoon, mostly due to the storm surge.

The causes and mechanisms of tsunamis and storm surges are different from each other, but the means for prevention of disasters due to these phenomena seem to be very similar. In Japan, cities are mostly located on low land, sometimes lower than the mean sea level, along the coast or inside bays. So it is a very serious problem to defend the coast against the attack of these phenomena, and therefore to issue the tsunami warning immediately after the occurrence of big earthquakes or to forecast accurately the passage of a typhoon.

6. DEVELOPMENT OF A SCIENCE FOR DISASTER PREVENTION

In view of the heavy damage caused by the Muroto typhoon, a new research institute for disaster prevention was established in Osaka in 1937, and I worked there for five years. At first, I did research on typhoons and earthquakes, but my main research made there was concerned with the phenomena of ground subsidence and air pollution.

The disaster of the lowlands of West Osaka was, of course, caused by the high storm surge of the Muroto typhoon, but the reason its damage was so heavy was ground subsidence that had been already occurring there for many years.

Ground subsidence had already been observed in the lowlands of Tokyo, where it reached even 20 cm yr^{-1} at some places. It was considered that this might have some relation to the occurrence of great earthquakes, and this made people feel uneasy.

There were many discussions about the cause of ground subsidence but no theory was established in scientific circles. In Osaka, I first tried to make a special instrument to record the daily vertical movement of the ground and also that of the underground water level, and I started observing at a suitable place in the subsiding area.

By investigating ground subsidence and underground water level data, I concluded that subsidence is caused by the marked lowering of underground water level—that is, a decrease of underground water pressure. Also, it was found that this subsidence was nothing but a contraction effect of the surface soft layer. The amount of subsidence correlated closely with the decrease of underground water pressure. It was concluded that this remarkable decrease of underground water pressure was caused by too much use of the groundwater, primarily by manufacturing plants. Accordingly, it can be regarded as a phenomenon caused by human activity and consequently quite different from the crustal movement related to the occurrence of earthquakes.

My papers on this problem were published in 1939–42, but in those days when the war was close at hand, my suggestions about the control of the use of underground water were not listened to by the authorities. But after more than 10 years, these arguments were generally accepted because the ground subsidence stopped during and after the war, since almost no pumping of the underground water had been made owing to the annihilation of industrial activities.

Special waterworks for industrial use were established in Osaka in 1951 and successively in Tokyo and in other cities. Now such marked ground subsidence in big cities and other districts has nearly stopped.

By the way, some years ago there occurred remarkable ground subsidence in the plain of Niigata. It resulted from heavy pumping of deep underground water for the purpose of obtaining natural gas. In this case underground water contains dissolved natural gas, and the ratio of water to gas is nearly 1 : 1. The depth of the underground water is about 600 m, and it caused remarkable ground subsidence around there that amounted to even more than 40 cm yr^{-1}. The mechanism of this phenomenon is regarded to be similar to that of the ground subsidence generally experienced in Tokyo and other places, although the depth of underground water was different.

The other main subject I studied in Osaka concerned the air pollution in this area. Before, Osaka was sometimes called the "Manchester of the Orient," and the citizens were proud of this name as a symbol of the flourishing industry. But actually they knew its harmful influence on health. I thought this air pollution over a great city should be scientifically studied as an important environmental problem, and I made routine observations and research on the phenomenon, particularly on the nature of floating particles.

In the course of this study, I was most impressed that the cause of the large-scale stoppage of electric service that occasionally occurred in the morning was found to be a harmful effect of the dirty dense fog that covered this area before dawn on the transmission lines.

Looking back upon my work in the Research Institute of Osaka, I see that I started to study disasters caused by natural phenomena, but as time went by I turned to research primarily on disasters brought about by human activities. Certainly, disasters occurring nowadays are caused by the combined effects of natural and artificial causes. The latter have come to play a dominant role.

When I worked in those days in Osaka, I believed that my duty was to investigate natural disasters, and so to my regret I did not carry out research on disasters caused mainly by human activities as fully as I might have. My full recognition of the importance of environmental problems came only later.

7. PROGRESS OF GEOSCIENCES AND THE CREATION OF AN IDEAL EARTH

I was appointed Director of the Central Meteorological Observatory of Japan in 1947 and worked to establish a new organization for meteorological service as well as investigations in oceanography, seismology, geomagnetism, and to promote scientific research in Earth sciences. In 1950, I had an opportunity to travel to the United States and Canada for three months to study the weather services and geophysical research carried out in governmental agencies, institutes, and universities.

This was my first travel abroad, and I was deeply impressed by seeing with my own eyes the splendid advancement of research in various fields of geophysics, and particularly by the newly developed instruments for geophysical observations. Thereafter, I attended various kinds of international geophysical meetings and had a good opportunity to become personally acquainted with the geophysicists of the world.

It is unnecessary to say that recently remarkable progress is being made in various fields of geophysics and geochemistry, such as environmental problems, plate tectonics, prediction of earthquakes and volcanic eruptions, and observations by satellites. These are now mostly made on a global and planetary scale. Recent geophysical research is being advanced by the international cooperation of many branches of science and by consideration of effects and variations of phenomena far distant in space and time. On the other hand, practical applications sometimes require that investigations be made on a very local scale.

In 1974–75, at the age of 72, I joined the Japanese Antarctic Research Expedition Team and experienced for the first time the glorious world of snow and ice of the South Pole region. I was deeply impressed by the beauty of nature and thought of my good fortune that I was born in a country of earthquakes and could study geophysics.

I am now mainly working on the prevention of natural disasters and environmental problems. The environment surrounding us is of both natural and artificial origin, and these are intertwined in a complicated way. Recently the artificial side has become predominant, particularly in densely populated districts. It is not an exaggeration that the Earth is changing its original state, and nature will be destroyed if things go as they are going now. Actually, it may be impossible to stop this present trend of gradual worsening of environmental conditions. But we must at least endeavor to create a new ideal Earth, searching for the best way to human happiness today and in the future. In the quest for this goal, research in geophysics will naturally play an important part, and its advancement is strongly anticipated.

Lastly, I think that we should be always be modest while carrying out this serious task, as our knowledge about the Earth is not yet enough.