1

Earthquakes and EQ Prediction

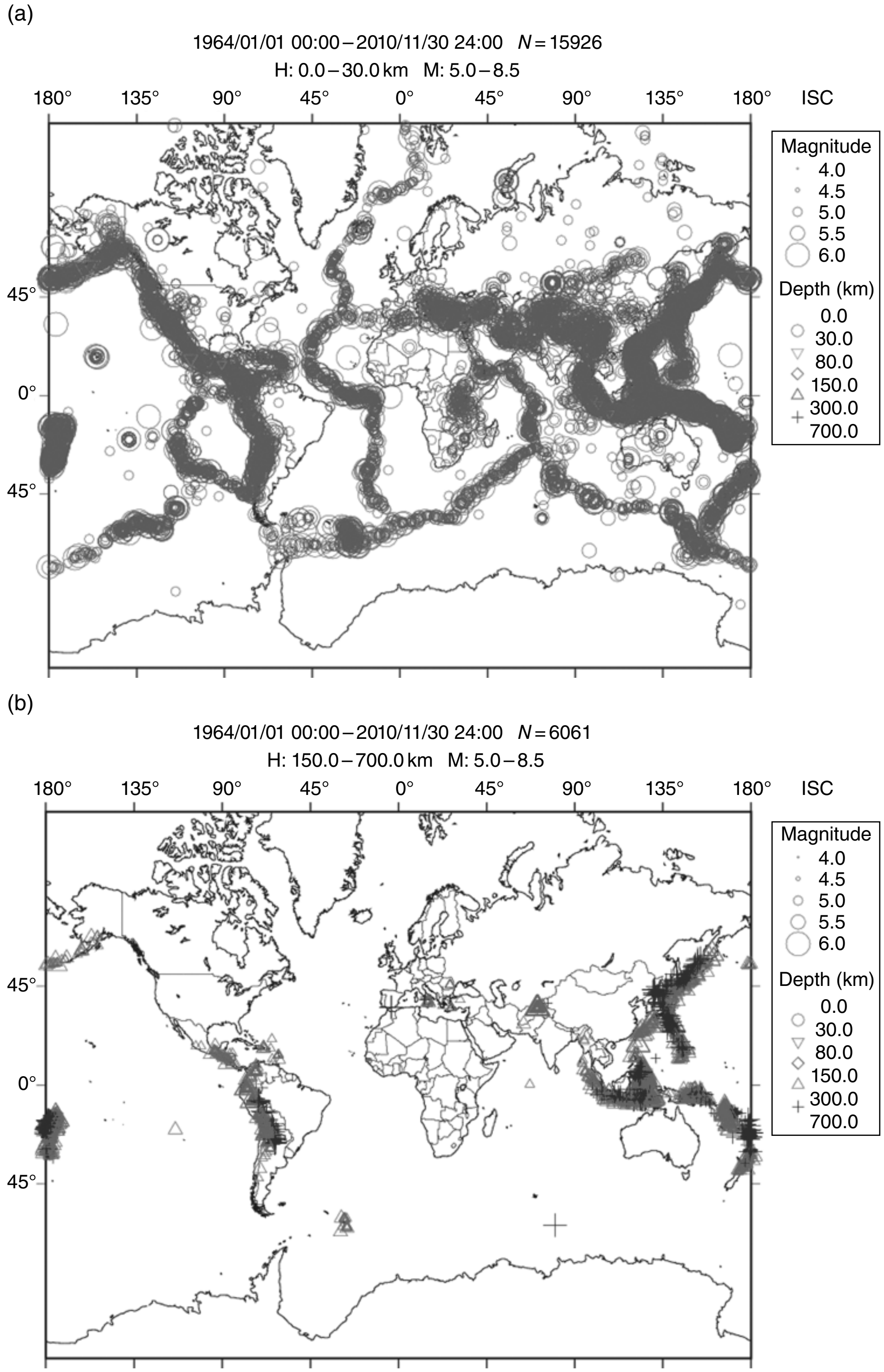
1.1 Fundamentals of Earthquakes

There have been published many books on seismology and earthquakes (EQs), including Richter (1958), Scholtz (1990), Shearer (1999), Uzu (2001), and Rikitake (2001a), so we advise interested readers to consult these books for further details. The information on EQs in Wikipedia (on EQs) was also helpful and useful in writing this chapter.

An EQ is the result of a sudden release of energy in the Earth's crust that generates seismic waves. At the Earth's surface, EQs manifest themselves by shaking and sometimes displacement of the ground as in the case of the 1995 Kobe EQ. When the epicenter of a large EQ is located offshore, the seabed may be displaced sufficiently to cause a tsunami. A typical example of this EQ type is the recent 2011 Tohoku EQ. EQs can also trigger landslides and occasionally volcanic activity.

In its most general sense, the word EQ is used to describe any seismic event that gives rise to seismic waves. The point of initial rupture of an EQ is called its focus or hypocenter, and epicenter is defined as the point at ground level directly above the hypocenter. Figure 1.1a and b illustrates the worldwide spatial distributions of EQs with magnitude larger than 5.0 during a period from January 1964 till the end of November 2010. Figure 1.1a refers to shallow EQs (with depth <30 km), while Figure 1.1b refers to deep EQs (with depth >150 km). It is found from these figures that EQs tend to take place in the following major regions: (i) Pacific region; (ii) Southeast Asia, Middle Asia, the Middle East, and South Europe; and (iii) Mid-rim Atlantic ridge and Indian Ocean ridge.

Earthquake Prediction with Radio Techniques, First Edition. Masashi Hayakawa.



(a)

1964/01/01 00:00 – 2010/11/30 24:00 *N* = 15926
H: 0.0 – 30.0 km M: 5.0 – 8.5

(b)

1964/01/01 00:00 – 2010/11/30 24:00 *N* = 6061
H: 150.0 – 700.0 km M: 5.0 – 8.5

Figure 1.1 Global distribution of EQs (a) shallow (depth ≤30 km) and (b) deep (depth ≥150 km) during the period of 1964–2010. Reproduced with permission from https://wwweic.eri.u-tokyo.ac.jp/db/isc/index.html, International Seismological Centre

1.1.1 Naturally Occurring EQs

Tectonic EQs can occur anywhere on the Earth where there is sufficient stored elastic strain energy to drive fracture propagation along a fault plane. The sides of a fault move past each other smoothly and seismically only if there are no irregularities or asperities along the fault surface that increase frictional resistance. Most fault surfaces do have such asperities, and this leads to a form of stick–slip behavior. Once the fault has locked, continued relative motion between the plates leads to increasing stress and therefore stored strain energy in the volume around the fault surface. This continues until the stress has risen sufficiently to break through the asperity, suddenly allowing sliding over the locked portion of the fault and releasing the stored energy. This energy is released as a combination of radiated elastic strain seismic waves, frictional heating of the fault surface, and cracking of the rock, thus causing an EQ. This process of gradual buildup of strain and stress punctuated by occasional sudden EQ failure is referred to as the elastic-rebound theory. It is estimated that only 10% or less of the total energy of an EQ is radiated as seismic energy. Most of the EQ energy is used to power the EQ fracture growth or is converted into heat generated by friction. Therefore, EQs lower the Earth's available elastic potential energy and raise its temperature, though these changes are negligible compared to the conductive and convective flow of heat from the Earth's deep interior.

1.1.2 EQ Fault Types

There are three main types of fault, all of which may cause an EQ: (i) normal, (ii) reverse (thrust), and (iii) strike slip as shown in Figure 1.2. Normal and reverse faulting are examples of dip slip, where the displacement along the fault is in the direction of dip and movement on them accompanies a vertical component. Normal faults occur mainly in areas where the crust is being extended, such as a divergent boundary. Reverse faults occur in areas where the crust

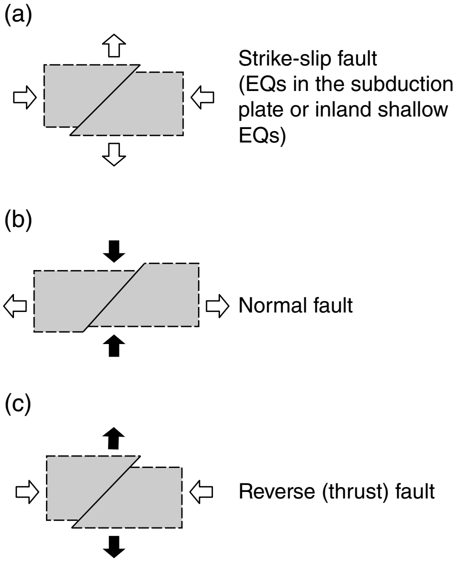


Figure 1.2 Three different kinds of fault types (a) strike-slip fault, (b) normal fault, and (c) reverse (thrust) fault

is being shortened, such as at a convergent boundary. Strike-slip faults are steep structures where the two sides of the fault slip horizontally past each other: Transform boundaries are a particular type of strike-slip fault. Many EQs are caused by movement on faults that have components of both dip slip and strike slip; this is known as oblique slip.

Reverse faults, particularly those along convergent plate boundaries, are associated with the most powerful EQs, including almost all of those with magnitude 8 or more. Strike-slip faults, particularly continental transforms, can produce major EQs up to about magnitude 8. EQs associated with normal faults are generally less than magnitude 7.

This is so because the energy released in an EQ, and thus its magnitude, is proportional to the area of the fault that ruptures and the stress drop. Therefore, the longer the length and the wider the width of the fault area, the larger the resulting magnitude. The topmost, brittle part of the Earth's crust and the cool slabs of the tectonic plates that are descending into the hot mantle are the only parts of our planet which can store elastic energy and release it in fault ruptures. Rocks hotter than about 300°C flow in response to stress; they do not rupture in EQs. The maximum observed lengths of ruptures and mapped faults are approximately 1000 km. Examples are the EQs in Alaska, 1957; Chile, 1960; Sumatra, 2004; and Japan, 2011, all in subduction zones. The longest EQ ruptures on strike-slip faults, like the San Andreas Fault (1857, 1906), the North Anatolian Fault in Turkey (1939), and the Denali Fault in Alaska (2002), are about half to one-third as long as the lengths along subducting plate margins, and those along normal faults are even shorter.

The most important parameter controlling the maximum EQ magnitude on a fault is, however, not the maximum available length, but the available width, since the latter varies by a factor of 20. Along converging plate margins, the dip angle of the rupture plane is very shallow, typically about 10°. Thus, the width of the plane within the top brittle crust of the Earth can be as much as 50–100 km (Japan, 2011; Alaska, 1964), making the most powerful EQs possible.

Strike-slip faults tend to be oriented vertically, resulting in an approximate width of 10 km within the brittle crust, so EQs with magnitudes much larger than 8 are not possible. Maximum magnitudes along many normal faults are even more limited because many of them are located along spreading centers, where the thickness of the brittle layer is only about 6 km.

In addition, there exists a hierarchy of stress level in the three fault types. Thrust faults are generated by the highest, strike slip by intermediate, and normal faults by the lowest stress levels. This can easily be understood by considering the direction of the greatest principal stress, the direction of the force that pushes the rock mass during the faulting. In the case of normal faults, the rock mass is pushed down in a vertical direction as in Figure 1.2a, where the pushing force (greatest principal stress) equals the weight of the rock mass itself. In the case of thrusting, the rock mass escapes in the direction of the least principal stress, that is, upward, lifting the rock mass up as in Figure 1.2b, and the overburden equals the least principal stress. Strike-slip faulting is intermediate between the other two types described earlier as in Figure 1.2c. This difference in stress regime in the three faulting environments contributes to differences in stress drop during faulting, which contributes to differences in the radiated energy, regardless of fault dimensions.

1.1.3 EQs Away from Plate Boundaries (Interplate EQs)

Where plate boundaries occur within continental lithosphere, deformation is spread over a much larger area than the plate boundary itself. In the case of the San Andreas Fault continental transform, many EQs occur away from the plate boundary and are related to strains developed within the broader zone of deformation caused by major irregularities in the fault trace. The Northridge EQ was associated with movement on a blind thrust within such a zone.

All tectonic plates have internal stress fields caused by their interactions with neighboring plates and sedimentary loading or unloading. These stresses may be sufficient to cause failure along existing fault planes, giving rise to intraplate EQs.

1.1.4 Shallow-Focus and Deep-Focus EQs

The majority of tectonic EQs originate at the ring of fire in depths not exceeding tens of kilometers. EQs occurring at a depth of less than 70 km are tentatively classified as “shallow-focus” EQs, while those with a focal depth between 70 and 300 km are commonly termed “midfocus” or “intermediate-depth” EQs. In subduction zones, where an older and colder oceanic crust descends beneath another tectonic plate, deep-focus EQs may occur at much greater depths (ranging from 300 up to 700 km). These seismically active areas of subduction are known as Wadati–Benioff zones. Deep-focus EQs occur at a depth where the subducted lithosphere is no longer brittle, due to the high temperature and pressure. A possible mechanism for the generation of deep-focus EQs is faulting caused by olivine undergoing a phase transition into a spinel structure.

1.1.5 Frequency of EQ Occurrence

It is estimated that about 500 000 EQs occur each year, detectable with current instrumentation, and about 100 000 of these can be felt by humans. Minor EQs occur nearly constantly around the world in places like California and Alaska in the United States, as well as in Mexico, Guatemala, Chile, Peru, Indonesia, Iran, Pakistan, the Azores in Portugal, Turkey, New Zealand, Greece, Italy, India, and Japan, but EQs can occur almost anywhere, including Tokyo, New York City, London, and Australia. Larger EQs occur less frequently, the relationship being exponential: for example, roughly ten times as many EQs larger than magnitude 4 occur in a particular time period than EQs larger than magnitude 5. In the (low seismicity) United Kingdom, for example, it has been calculated that the average recurrences are an EQ of 3.7–4.6 every year, an EQ of 4.7–5.5 every 10 years, and an EQ of 5.6 or larger every 100 years. This is an example of the Gutenberg–Richter law (Richter, 1958; Scholtz, 1990; Molchanov and Hayakawa, 2008).

1.2 Conventional EQ Prediction by Seismic Measurements

1.2.1 Historical Background

We pay particular attention to EQ prediction studies in Japan. Rikitake (2001b) has made a review of EQ prediction studies till just after the 1995 Kobe EQ, and there have recently been published two excellent review papers by Uyeda (2012, 2013) updating the former review by Rikitake (2001b). The following description is mainly based on the reviews by Uyeda.

It was in the 1960s that national projects for EQ prediction started in several countries including Japan, the USSR, China, and the United States. The reason why it happened so simultaneously is not clear, but it was partly because scientific activity recovered from World War II about that time and EQ seismology was in the forefront, aided by the Worldwide Standardized Seismograph Network (WWSSN) for nuclear blast detection (e.g., Bolt, 1976).

Optimism prevailed globally in the early 1970s due, for example, to the advent of the dilatancy–diffusion model (Scholz *et al.*, 1973), which appeared to explain almost all the reported precursory phenomena like crustal uplift, 10–20% change in V_p/V_s (the ratio of the velocity of P and S seismic waves), radon emission, electrical conductivity variation, and so on. The success of long-, intermediate-, and short-term prediction of 1975 $M7.3$ Haisheng EQ highlighted this optimism (e.g., Press, 1975).

However, this optimism was ephemeral. Putting details aside, a 10–20% change in V_p/V_s was denied by later works (e.g., McEvilly and Johnson, 1974), and further Chinese failed in predicting the 1975 $M7.8$ Tangshan EQ (Chen *et al.*, 1988). And in the United States, the Parkfield EQ predicted to occur before 1993 did not come until 2004 (e.g., Bakun and Lindh, 1985; Langbein *et al.*, 2005). In fact, there was not a single successful prediction by EQ prediction projects in any countries, so the whole prediction community became pessimistic (e.g., Evernden, 1982). This pessimism has persisted until now, except among nonmainstream researchers like us.

Although perhaps not well known in the contemporary community, as early as in the late 1940s, issues on EQ prediction were taken up between US and Japanese seismologists through orders of the General Headquarters (GHQ) of the US occupation forces. Apparently, the United States suspected that Japan was more advanced in this respect since the interest in EQ prediction in the United States at that time was almost zero, but the real Japanese situation was not much different. Actually, in his report of visiting Japan, Gutenberg was said to be bitterly critical of the uncooperative relations between Japan Meteorological Agency (JMA) and Earthquake Research Institute, University of Tokyo, but these affairs motivated the Japanese community to become more interested in EQ prediction. Then in 1962, a national project, generally called the "Blueprint," was formulated (Tsuboi *et al.*, 1962).

National EQ prediction project funding came in 1965 based on the "Blueprint" and has continued until now through consecutive five-year plans. The contents of the "Blueprint" were essentially empirical, referring to previous works carried out by various organizations without much coordination, such as crustal movements, tides, seismicity, seismic wave velocity, active faults, geomagnetism, and geoelectric currents. It was proposed to promote monitoring of all of these, and this was a reasonable start. It may be worth noting that this is a reasonable set of plans even today because the full plans have never been conducted as recommended.

To begin the project, the Japanese government consulted seismologists to formulate a practical program. It was also reasonable because there was no other organized group of relevant scientists, and the project started with considerable funding. Ever since, however, not a single successful prediction has been made and no false prediction either, because no predictions have been issued. This is a natural consequence because short-term EQ prediction has never been a serious target of the national project. The main cause for this strange situation is that the national project has always been dictated by only seismologists. It may sound strange, and later, we will try to clarify how this situation came about.

For the first five-year project, named "EQ Prediction Research Project," seismologists proposed to strengthen their seismic network. It was also reasonable as a first step and ample funds were allotted. Because of the ample funds, however, strengthening the seismic network became an endless enterprise that has kept monopolizing most of the funds and staff all through consecutive five-year projects. From the second five-year plan, dropping the word research, the name was changed to "EQ Prediction Project" as if the research stage was over. Naturally, funding substantially increased.

One thing that has to be emphatically mentioned here is that in the early 1970s many government agencies began to jump on the EQ prediction bandwagon. Many projects, formally unrelated to EQ prediction but associated with EQ research, were devised by clever bureaucrats one after another. Their budgets were many orders of magnitude larger than the national project. Let us call them collectively "big projects" for convenience. It should be noted that in each Big Project, the same seismologists, who were running the national project, were involved either as committee members or consultants. As a result, they profoundly benefitted by obtaining extramural contracts from the big projects.

The *M*7.3 Kobe EQ occurred on January 17, 1995, without prediction, during the seventh five-year plan. Approximately 6450 people lost their lives, and this was Japan's worst EQ in the twentieth century after the 1923 Great Kanto EQ in the Tokyo district. The national program, which never made any prediction, became a target of severe criticism. After prolonged deliberation at various levels, including genuinely external review held for the first time, the conclusion was reached that short-term EQ prediction should be given up formally and efforts should concentrate on "fundamental research," which was actually seismology. "Fundamental research" sounded sweet to the bureaucrats, so that the project not only survived the criticism but funding even increased. Thanks to this success, high-power seismic and Global Positioning Satellite (GPS) networks were installed to cover the whole country, and seismology has made great progress. But, of course, hardly any precursory information was obtained.

The justification for this "no short-term prediction policy" was that, despite their hard work, precursors were too difficult to observe, which was untrue. Those involved with the national project had never made serious efforts to search for precursors because they knew seismometers would not help much. Practically no reports on precursors were presented at the meetings of the Coordinating Committee for EQ Prediction held every 3 months. When such reports were rarely made, they were received as laughable rumors. However, since they had been enjoying ample funding for many years under the pretext of "EQ prediction," even the outside reviewers did not challenge the vested interests of the powerful seismologists.

After this, the policy of no short-term EQ prediction was escalated to "decide" that precursors do not exist and research on them is not science. Thus, there is practically no government support for research on EQ precursors now, while the national project enjoys ever increasing funds. Is this an acceptable situation?

On March 11, 2011, *M*9.0 Tohoku-Oki EQ hit Japan. This EQ produced a huge tsunami, resulting in devastation of the Pacific side of almost all northeastern Japan. Damage included the loss of over 20 000 lives, and explosions and a melt down at Fukushima No.1 Nuclear Plant (e.g., Tanaka, 2012). The whole nation was thrown into crisis almost instantly.

Thanks to the national project, Japan is a place where one of the world's best seismic and geodetic observation networks have been installed. The mechanism of generation of this type of EQs is well explained by plate tectonics discussed in the previous subsections. They are sudden fault motions as a result of accumulation of mechanical stress by the subduction of the Pacific plate. In fact, the ways EQs occur were believed to have been well understood by the so-called asperity model. According to this model, there are several seismogenic areas, called asperities, along the interface between the subducting Pacific plate and the overlying North American plate.

The two plates are strongly stuck at asperities, so that the upper plate is dragged down by the subducting plate and mechanical stress develops until rupture, while outside the asperities, plates are less strongly coupled so that they can slip without EQs. Based on the 400 year history of old documents and modern seismometry, seismologists believed that the conceivable maximum EQ in this area cannot exceed *M*8 class. However, the 2011 Tohoku EQ event demonstrated that 400 years was too short a period for evaluating regional seismicity. In fact, geologic records of tsunami sediments indicated that the AD 869 Jogan EQ could have been an *M*9 class event (e.g., Sawai *et al.*, 2008). But such geologic information was not taken seriously.

Regrettably, the general situation surrounding the EQ prediction has remained essentially the same or even worse since the 2011 megaquake (e.g., Geller, 2011). Seismologists lost confidence in general, so that their "Impossibility Myth" has become more prevalent. They now want to promulgate the impossibility of EQ prediction and even talk about disbanding the Working Group for EQ Prediction of the Seismological Society of Japan.

On November 28, 2012, a proposal was made to renew the national project which, after the Kobe EQ, was given the name "Observation Research Project for Prediction of EQ and Volcanic Eruptions" and which was essentially a simple coalition of the old EQ National Project and Volcanic Eruption National Project. The Science and Technology Council of the Ministry of Education, Culture, Sports, Science and Technology (MEXT) came up with an interim outline of the renewed plan on September 4, 2013, inviting public opinion. Now, the title has been further changed to "Promotion of EQ and Volcano Observation Research Project to Contribute to Disaster Mitigation," finally dropping the word prediction. The document is wordy and long, and even though it certainly emphasizes disaster mitigation aspects, it still preserves practically every issue of the old EQ and Volcanic Eruption Prediction National Projects. In short, the future 0.4 billion national project will be as before, without funds for prediction. They will keep receiving research contracts from the big projects as before.

1.2.2 Measurement of EQs and Crustal Movement

The conventional EQ prediction study performed during the last several decades as mentioned in the previous subsection is fundamentally based on the mechanical method, that is, the measurement of crustal movements by means of seismometers.

EQs can be recorded by seismometers up to great distances because seismic waves travel through the whole Earth's interior. The absolute magnitude of an EQ is conventionally reported by numbers on the moment magnitude scale (formerly Richter scale, magnitude 7 causing serious damage over large areas), whereas the felt magnitude is reported using the modified Mercalli intensity scale (intensities II–XII).

Every tremor produces different types of seismic waves, which travel through the Earth's crust with different velocities (Scholtz, 1990):

- Longitudinal primary (P) waves (shock or pressure waves)
- Transverse secondary (S) waves (body waves)
- Surface waves (Rayleigh and Love waves)

Propagation velocity of the seismic waves ranges from approximate 3 up to 13 km/s, depending on the density and elasticity of the medium. In the Earth's interior, the *P* waves travel much faster than the *S* waves (~1.7–1). The differences in travel time from the epicenter to the observatory are a measure of the distance (which is currently utilized as an early EQ warning system) and can be used to image both sources of EQs and structures within the Earth. Also, the depth of the hypocenter can be computed roughly.

In solid rock, *P* waves travel at about 6–7 km/s; the velocity increases within the deep mantle to approximately 13 km/s. The velocity of *S* waves ranges from 2 to 3 km/s in light sediments and 4–5 km/s in the Earth's crust up to 7 km/s in the deep mantle. As a consequence, the first waves of a distant EQ arrive at an observatory through the Earth's mantle.

Standard reporting of EQs includes its magnitude, date and time of occurrence, geographic coordinates of its epicenter, depth of the hypocenter, geographical region, distances to population centers, location uncertainty, a number of parameters that are included in the US Geological Survey (USGS) EQ reports (number of stations reporting, number of observations, etc.), and a unique event ID.

In addition to seismometers, different measurement techniques have been developed: tilt meter, strainmeters, and so on. Recently, you are aware of GPS measurement of surface movement, which is purely a radio technique that will be discussed later in this book, but is fundamentally the measurement of crustal movement in seismology.

1.2.3 Long-Term, Medium-Term, and Short-Term EQ Prediction

When we speak of the terminology of EQ prediction, different people use the same EQ prediction in totally different ways, which is one of the reasons for confusion. The EQ prediction can be classified into the following three types depending on its time scale. We will make a brief description of each prediction one by one:

a. Long-Term Prediction
   The time scale of this EQ prediction is of the order of a few hundred years or so. This kind of analysis is based on plate tectonics, activity of EQs, anecdotal records, fault records, archeological survey, and so on. This kind of information would be of great use in the long-term disaster prevention program or civil engineering, but it is nearly useless in saving human lives.
b. Medium-Term Prediction
   The time scale of this medium-term EQ prediction is from a few decades to a few years, which is based on the data bases of seismicity and crustal movement. Mainly based on the long-term EQ catalogue, it is possible to evaluate the probability of a large EQ in a certain area during a prescribed period. For example, the people in Tokyo are informed that the occurrence probability of EQs with magnitude greater than 7 in the coming 30 years is about 70% in the Tokyo region, which is a typical example of medium-term EQ prediction. The medium-term information will be of essential importance in future city planning and educational purposes.
c. Short-Term EQ Prediction
   The time scale of this short-term EQ prediction is from a few days to a few weeks (at maximum 1 month). We believe that this short-term prediction would be the most important among the predictions of three different time scales. It will save human lives, and it is a topic of the greatest concern for human beings. As mentioned in the previous subsection, this

short-term EQ prediction is essentially different from the aforementioned two long-term and medium-term predictions and cannot be investigated by seismological methods such as seismometers. However, it has recently been confirmed that short-term EQ prediction can be studied by nonseismic methods (the main method is electromagnetic effect by radio techniques as treated in this book), so that this short-term information would be quite useful for disaster prevention, mitigation of human lives, or so.

1.3 Nonconventional (Nonseismic) EQ Prediction with Radio Technique

1.3.1 Historical Introduction of EQ Prediction

We begin with the story of why this author started the study of electromagnetic phenomena associated with EQs. I am not a seismologist, but a radio scientist. When I was working in Nagoya University, I was working on space plasma physics and atmospheric science, including electromagnetic waves in the upper atmosphere (ionosphere/magnetosphere) and wave–particle interactions and also lightning discharges and associated phenomena. When I moved to a different university, the University of Electro-Communications in Tokyo in 1991, I was asked by its president to change or widen my field so as to include practical or engineering subjects because the university is engineering oriented. I immediately agreed to extend my former research (mainly academic topics), to a great extent, by expanding my field by including a few new topics; one is electromagnetic compatibility (EMC), and another is electromagnetic phenomena associated with EQs.

In the years just around 1990, I was thinking that electromagnetic phenomena in possible association with EQs were a very attractive topic, even though there was no consensus even on the presence of such precursory seismoelectromagnetic phenomena at that time. Before that time, there had been very few reports on the presence of precursory seismogenic phenomena in the USSR, Greece, or elsewhere. After moving to Tokyo, we worked, for the first time, with Russian colleagues on the analysis of satellite very-low-frequency (VLF) electromagnetic emission data looking for any seismogenic emissions. According to this analysis, I personally felt that something may exist, but not really clear. However, when we encountered a huge EQ, Kobe EQ in 1995 with many casualties, we happened to find very clear evidence of ionospheric perturbations of the EQ by means of my previous space physics techniques. The most important point was that ionospheric anomaly as a result of subionospheric VLF signal data appeared only as a precursor to the EQ (Hayakawa *et al.*, 1996). This evident signature of the EQ effect was a great surprise not only for us but also for the seismo-electromagnetic community, and also, this is a time when we thought that the seismogenic effects really exist. So I had some confidence that these seismogenic phenomena might be utilized for short-term EQ prediction and that this seismogenic effect would be an extremely important new science field, though it is a very difficult discipline.

As already described in the previous subsection, our short-term EQ prediction is totally different from the long- and medium-term predictions. We will show here how the former long- and medium-term predictions worked or, to be more exact, how useless these predictions turned out to be. Figure 1.3 illustrates the map of the occurrence probability during the coming 30 years published by the Seismology Research Promotion Headquarter of MEXT (2010), in which higher occurrence rate is indicated by more darkness. In this figure, recent large EQs are plotted as well for the sake of comparison. A comparison of this medium-term prediction with

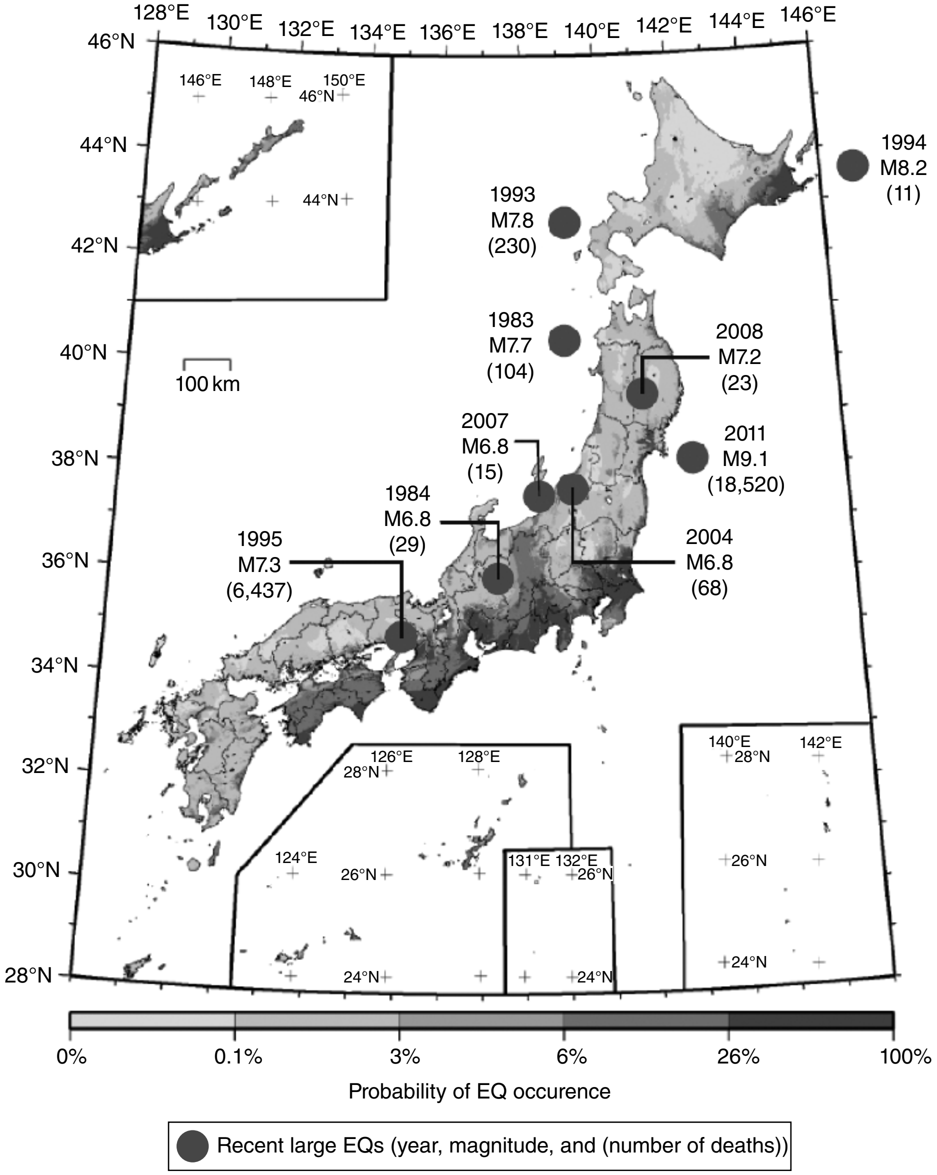


Figure 1.3 A map of the EQ occurrence probability during the coming 30 years, on which recent large EQs are plotted, including the 1995 Kobe EQ and the 2011 Tohoku EQ. Reproduced with permission from Uyeda (2012). © 2012, Nihon-Senmontosho-Shuppan

actual EQs may indicate that a majority of large EQs happened in an area with lower probabilistic EQ occurrence. This means that medium-term EQ prediction is nearly of no use in saving human lives, and this is the very reason why we pay more attention to short-term EQ prediction.

1.3.2 Nonseismic (Mainly Electromagnetic) Short-Term Precursors

Due to enormous advance in seismology, geodesy, and so on, we find significant developments both in the (i) long-term and (ii) medium-term predictions of EQs. Short-term EQ prediction is recognized as being the most important for human beings, but it is far from realization. Even though different kinds of observational networks (seismometers, crustal movements, GPS, etc.) have been extensively established in Japan, there have been no examples of success of short-term EQ prediction in Japan, for example, the unsuccessful examples of our disastrous 2011 Japan EQ. At present, a very pessimistic opinion on the possibility of short-term EQ prediction is prevailing, especially among scientists of seismology. Seismo-electromagnetic methods can be roughly classified into two categories: The first one is changes in lithospheric parameters, and the second is electromagnetic signals (which is the topic of this book and will be discussed extensively in this book). The first category can be investigated with measurements of magnetic or electric fields due to the electrical conductivity change. These properties are important and should be pursued from the academic sense, but many problems remain to be solved for short-term EQ prediction. This kind of lithospheric change is known to belong to the medium-term temporal scale.

Of course, it goes without saying that short-term EQ prediction absolutely needs precursors. There have been reports of many kinds of EQ precursors from ancient Greek time until today (e.g., Rikitake, 2001a; Molchanov and Hayakawa, 2008; Uyeda *et al.*, 2008; Hayakawa and Hobara, 2010). They can be geodetic signals such as tilt; GPS data; hydrological data like level, temperature, and chemistry of underground water; electromagnetic fluctuations in various frequencies; emission of radon and other gases; and anomalous animal behavior (Rikitake, 2001a). Seismological events like foreshocks and preseismic quiescence can also be precursors. However, the majority of the reported EQ precursors found during the last few decades have been proven to be nonseismological, and such nonseismological continuous measurements have been performed mainly after the 1995 Kobe EQ (Hayakawa, 1999, 2009, 2012, 2013; Hayakawa and Molchanov, 2002; Pulinets and Boyarchuck, 2004; Molchanov and Hayakawa, 2008). But these were never seriously supported by the Japanese project.

In the following chapters (Chapters 3–8), we will try to provide you with some detailed description of the observational facts and the corresponding generation mechanism of generation lithospheric, atmospheric, and ionospheric precursors, with some mathematics. However, here we try to give you a comprehensive idea on how the electromagnetic phenomena appear prior to an EQ, before going into details in the following chapters.

We are pleased to provide the most fundamental concept of electromagnetic phenomena in possible association with an EQ. Figure 1.4 illustrates the general concept of seismo-electromagnetic phenomena. One thinks of the situation taking place just at or around the EQ hypocenter under continued stress accumulation. In order to simulate this situation, let us consider that we hold an old plastic plate and bend it slowly. At the final stage of stress accumulation, we will have rupture, which corresponds to the occurrence of an EQ. Always before this rupture, there occurs the generation of cracks (we call it “microfracture”). This process is simply a mechanical effect, so we would be happy to detect those microfractures by means of subsurface seismometers. However, this is not the case due to their insufficient sensitivity. The most fortunate thing for us is that when we have cracks, there exist a few processes leading to the generation of electrical charges (plus and minus) (or electrification), due to, for example, triboelectricity, piezoelectricity, or so. This process is poorly understood at

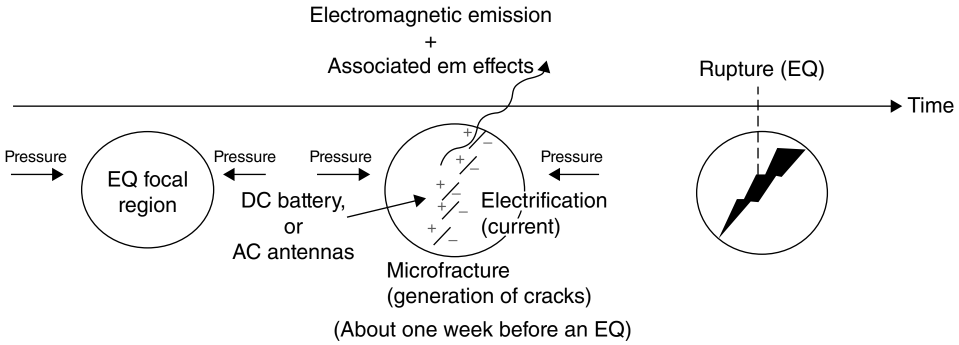


Figure 1.4 Schematic illustration of the temporal evolution of stress accumulation near the EQ hypocenter. When we observe the generation of microcracks (microfracturing), electric charges (positive and negative) appear on the walls of cracks around the hypocenter

the moment, and this is an important topic to be investigated in the future. Once electric charges are generated (electrification), there would occur different kinds of subsequent electromagnetic effects. In other words, we can imagine that a DC battery is generated around the EQ hypocenter in the ground or a lot of small antennas, as a source of oscillating charges, are generated in the ground. Fortunately, as will be shown later, these electromagnetic processes are found to take place about 1 week before an EQ, and we think that this is a most important gift from God. Also, when we think of extremely low-frequency waves (ELF)/ultra low-frequency (ULF) waves, they can propagate over a distance of approximately 100 km in the ground without any problems, so long-distance propagation is feasible. These two essential properties (precursory nature and long-distance propagation) are considered to be the quarterback, which cannot be realized by means of mechanical methods.

Figure 1.5 is a conceptual picture of different seismo-electromagnetic phenomena measured by different radio techniques. Though you are going to enjoy the details of seismogenic effects in the following chapters, Figure 1.6 summarizes a brief history of seismo-electromagnetic studies performed all over the world. The first two observational items in Figure 1.6 refer to the lithospheric effect, or the direct effect of the lithospheric pre-EQ phenomena. The third item is the seismo-atmospheric effect, and the last three items all refer to the ionospheric effect. The first two effects are very easy to imagine because they are the direct consequence of lithospheric pre-EQ fracture effects. On the other hand, other seismo-atmospheric and seismo-ionospheric effects are much more complicated than the former two items, because these are indirect effects in the sense that there appear some perturbations either in the atmosphere or in the ionosphere due to same pre-EQ effect. The first geoelectric current measurement has the longest history, and we will show, in Chapter 3, recent achievements of the Greek VAN method. The second, ULF electromagnetic emissions started with the Spitak EQ, and they are of extreme importance in short-term EQ prediction studies. However, the number of events is still not so sufficient. Seismo-atmospheric perturbation, the third item in Figure 1.6, was discovered for the 1995 Kobe EQ (Kushida and Kushida, 2002), which has been studied mainly in Japan. The last item of ionospheric perturbation has a relatively short history. Since convincing evidence of ionospheric perturbation for the 1995 Kobe EQ was found with the use of subionospheric VLF propagation (Hayakawa *et al.*, 1996), there has been widespread use of VLF/LF network

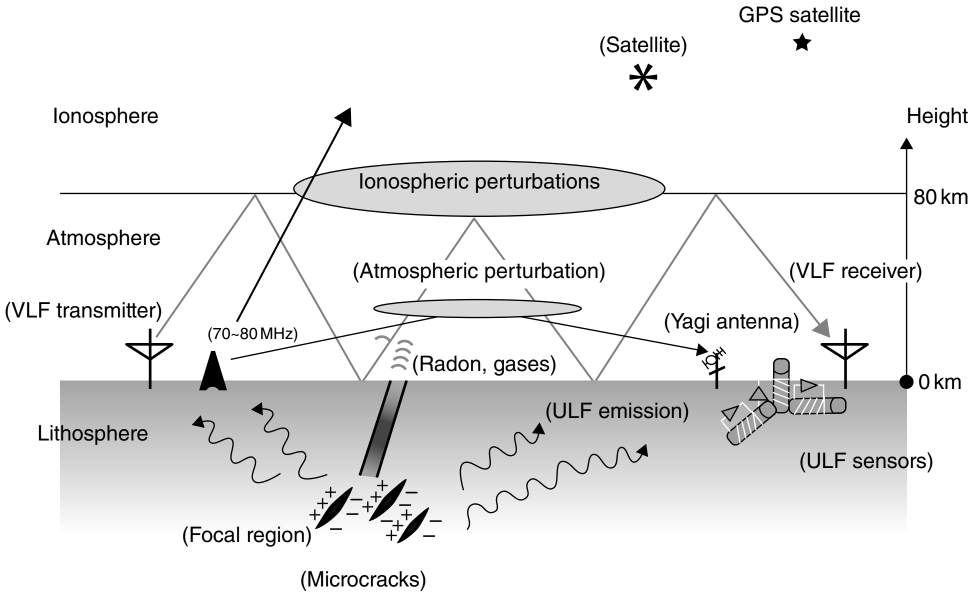


Figure 1.5 Conceptual general view of electromagnetic phenomena in possible association with EQs and different radio techniques to measure those electromagnetic effects

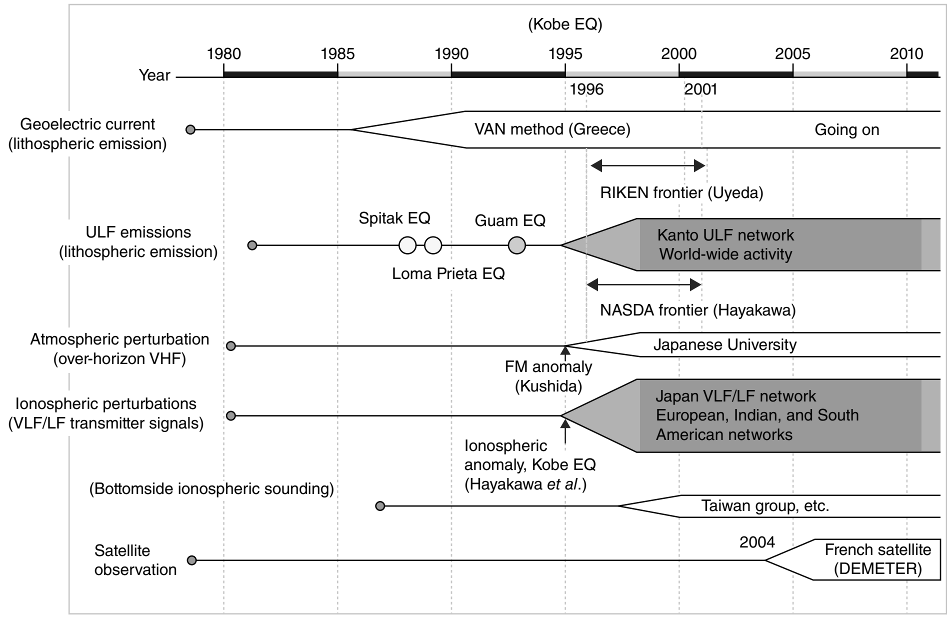


Figure 1.6 History of seismoelectromagnetic studies (including lithospheric effects, atmospheric effects, and ionospheric signatures)

all over the world, including Europe, India, and South America. Being stimulated by the discovery of ionospheric perturbations for the Kobe EQ, many scientists gave new attention to the upper ionosphere (like F region) (Pulinets and Boyarchuk, 2004) because VLF/LF waves can monitor only the lowest part of the ionosphere. There have recently been established statistical correlations between the ionospheric perturbations (either in the lower and upper ionosphere) (Liu, 2009; Hayakawa *et al.*, 2010), which means that we will be able to make an attempt to forecast any EQ as a practical subject. The French satellite DEMETER, dedicated to the study of seismo-electromagnetics, was launched in 2004, and a lot of scientific success has been achieved of the study on how the ionosphere is disturbed due to the lithospheric pre-EQ effect (Parrot, 2012, 2013). One more important point as related to Figure 1.6 is that we, the seismo-electromagnetic group in Japan, were funded only once just after the 1995 Kobe EQ. Two institutions were asked to do a feasibility study of electromagnetic effects in short-term EQ prediction during 5 years (1996–2001): (i) Institute of Physical and Chemical Research (RIKEN) and (ii) former National Space Development Agency of Japan (NASDA, presently JAXA) in the framework of Earthquake Integrated Frontier by the former Science and Technology Agency (now MEXT). The RIKEN frontier project was led by Prof. S. Uyeda and the latter, NASDA’s frontier project, by the author of this book. The RIKEN group had a lot of interests in installing geoelectric measurements in Japan, together with the measurement of ULF electromagnetic emissions, while we, the NASDA team, tried to expand the observation area as much as possible by including the ULF electromagnetic waves in the lithosphere, atmospheric effect, and also ionospheric signatures with ground- and satellite-based observations. Of course, our main concern has been the use of subionospheric VLF/LF signals. The success of these Japanese frontier projects has stimulated a lot of interest in other countries.

Finally, we mention the outlook for the future as closely related to this book. Since EQs are natural phenomena, they can be predicted by scientific endeavor. Indeed, we already have undeniable accomplishments, as will be presented in this book. There were numerous reports on electromagnetic and geochemical precursors after the 1995 Kobe EQ. For instance, 19 anomalous changes in the telluric current were identified during monitoring conducted on Kozu-shima Island about 170 km south of Tokyo from May 14, 1997, to June 25, 2000. Orihara *et al.* (2012) showed by rigorous statistics that correlation with nearby EQs was clearly beyond chance. Also in the Izu island region, anomalous changes in the ULF range (0.01 Hz), starting from a few months before the 2000 major volcano–seismic swarm activity, were observed in both geoelectric and geomagnetic fields. The changes culminated immediately before nearby $M6$ class EQs (Uyeda *et al.*, 2002).

What about the Tohoku megaquake? There were in fact precursors, although most of them were only recognized afterward. There are also encouraging signs for future developments in short-term prediction, some of them being so new that presenting evidence needs to be excused. For instance, there is good news from different sources that the long-cherished desires for using satellites may come true soon.

There are reports on preseismic electromagnetic changes. One is on a preseismic reception anomaly of VLF and LF waves (Hayakawa *et al.*, 2012), and the other is on variations in the geomagnetic field approximately 2 months prior to the main shock (Xu *et al.*, 2013). One issue of hot debate is the preseismic variation of the ionospheric electron content (Heki, 2011; Kamogawa and Kakinami, 2013). One of the highly promising new developments is the detection of preseismic land movements using GPS data, which finally appeared in 2013 by more than one group, including private sectors. Some other new findings for the 2011 Japan EQ will also be presented in this book.

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