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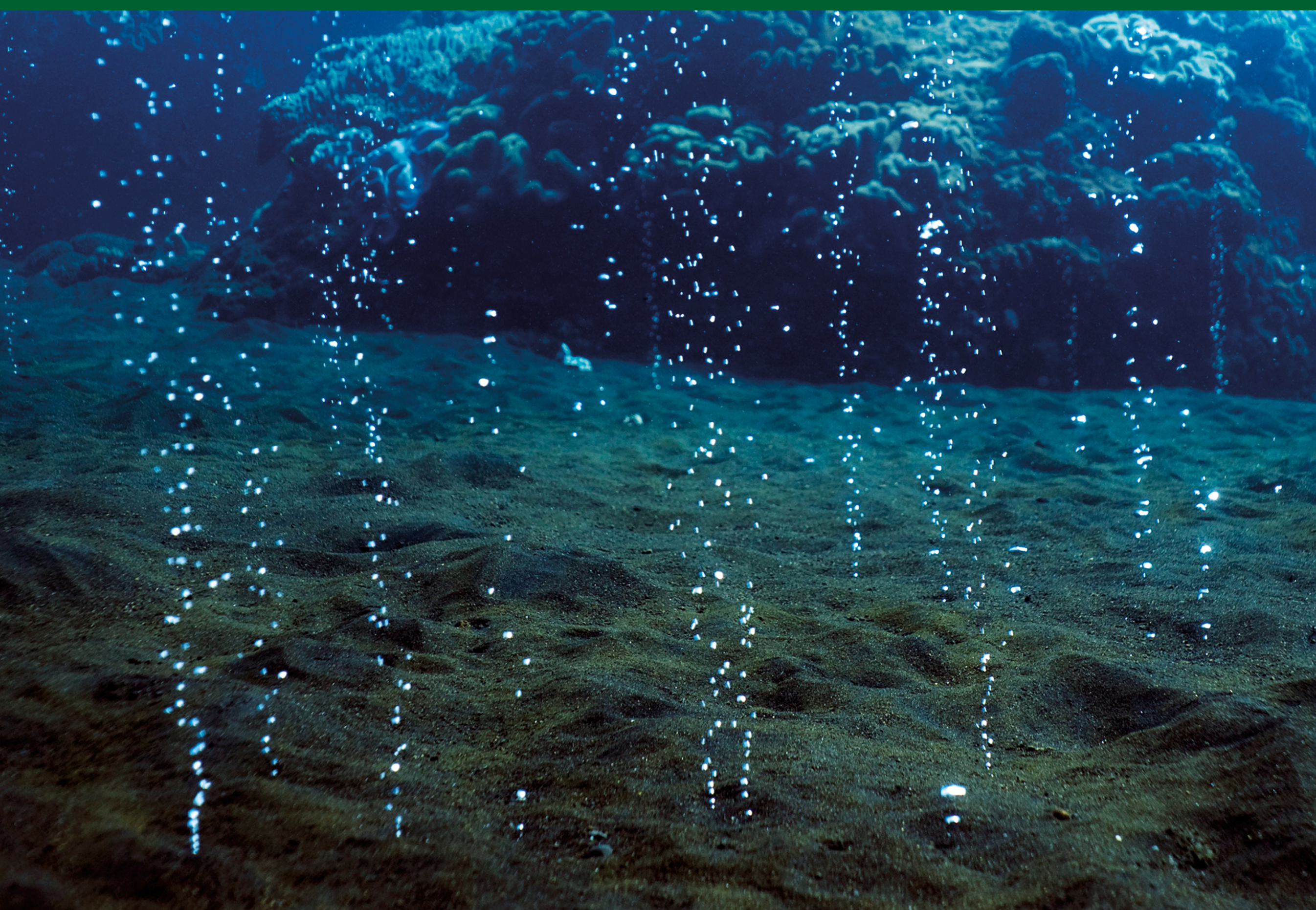
The Possibility of Earthquake Forecasting

Learning from nature

Sergey Pulinets
Dimitar Ouzounov



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Thanks to our lovely wives, without their faith and support this book was never been finished

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Preface

> "Some things are not understandable to us not because our concepts are weak, but because these things are not included in the range of our concepts."
>
> *Koz'ma Prutkov*

In 1997, some scientists issued their final and non-appealable judgment: earthquakes cannot be predicted—and this is the last word on the matter (Geller *et al* 1997). This verdict became a road block for many researchers who wanted to focus their efforts on the study of earthquake precursors. Even now, at least, in professional journals on seismology it is difficult to find an article devoted to the problem of short-term earthquake forecast. However, in the scientific literature on the problems of atmosphere and space geophysics, the number of papers discussing the short-term precursors of earthquakes increases exponentially. How does one explain this contradiction?

It is reasonable to state that science is not subject to decree: what yesterday seemed to be fiction (even science fiction), is becoming a matter of routine today. It is enough to look at the history of some inventions. In 1895, Lord Kelvin said: 'The creation of a flying machine heavier than air is impossible.' He was seconded (also in 1895) by one of the most famous inventors in history, Thomas Edison: 'It is apparent to me that the possibilities of the aeroplane...have been exhausted, and that we must turn elsewhere.' In addition, interestingly, is that in 1901 Wilbur Wright wrote a letter to his brother Orville Wright stating: 'A man will not be able to fly in the next 50 years!'

And in 1903 the Wright brothers took to the air in a plane of their own invention!

One can cite many examples of this kind, but I will mention only one. Even in the 1970s, the diagnosis 'cancer' sounded like a death sentence. Today, at least some types of cancer can be cured completely, and there are hundreds of thousands, if not millions of known cases of a complete cure of this terrible disease. Try to imagine what would have happened if at that time there was a group of doctors, similar to Geller's group in seismology, who issued a decree: 'cancer is not curable'—and stopped further study in this direction?

This book is a story, which is offering hope for a possible solution to one of the major problems of humanity—protection against destructive earthquakes—by early warning (for several days) of an impending catastrophic event. Established in the last few years, a complex model of geo-effective phenomena coupling the lithosphere, atmosphere, and ionosphere (Lithosphere–Atmosphere–Ionosphere Coupling Model—LAIC) provides a tool of meaningful and purposeful monitoring of pre-earthquake anomalies at the Earth's surface, in the atmosphere and ionosphere that reliably indicate the approach of an earthquake. Most importantly, it is not just theoretical developments, but also a verifiable technique of forecasting, which gives promising results. The multi-parameter approach using the data of ground-based and satellite remote sensing monitoring techniques opens the way for a reliable short-term earthquake forecast.

So, on this optimistic note, we invite readers to learn some of the results of the activities of a group of scientists, colleagues and those to whose results we refer. The book is written in accessible language, so it is easy to read, and is not only for professional researchers but also for undergraduate students.

Any theory has different stages and algorithms of its development. This new approach is based on nature-driven observations. Considering different solid and well-documented pre-earthquake anomalies, we are looking for the possible mechanisms able to generate them, and for interconnection or interrelation between the observed anomalies. With this approach we found the real chains of physical (and chemical) processes where one is the source for the next one, where these time and causal relations demonstrate the general process directivity on the way to the moment when an earthquake happens. This is what we call 'learning from Nature.'

This project was part of two international projects on 'Validation of Lithosphere–Atmosphere–Ionosphere–Magnetosphere Coupling (LAIMC)' supported by the International Space Science Institute in Bern and Beijing.

Introduction

Earthquakes, which annually take thousands of lives and cause billions of dollars in financial costs to recuperate the affected regions, continue to be one of the most pressing problems of humanity. One can find many examples of the disastrous effects of strong earthquakes, successful and failed predictions, but in the purposes of not overburdening this monograph, we refer the reader to numerous publications, where the history of earthquake forecasting is described in detail (Rikitake 1976, Mogi 1985, Sobolev 1993, Lomnits 1994).

Traditional ground-based equipment used for earthquake forecasting does not provide fully reliable short-term predictions and in the past has not always forecasted devastating earthquakes (Mexico, Iran, Greece, Taiwan, Turkey, India, Pakistan, Indonesia, Japan), so there is talk of the need for substantial progress in solving the problem and finding additional signs to predict earthquakes. The latest advances in geospace and remote sensing technologies provided scientist's with new tools and opportunities for testing the short-term forecasting of major earthquakes and other natural and anthropogenic disasters, by integrating with traditional ground-based techniques for monitoring. This complex approach for ground and space monitoring based on new scientific and technological developments will be described below. This approach is able to monitor earthquake precursors at different levels, ranging from the Earth's surface, the atmosphere, ionosphere, and magnetosphere, and provides a short-term forecast of earthquakes using information on detected precursors and developed prediction algorithms. The possibility of such methods of earthquake forecasting has been confirmed by numerous experimental and theoretical investigations indicating the coupling of physical processes in the lithosphere, atmosphere, and the ionosphere during the preparatory phase of earthquakes. Discoveries in circum-terrestrial space on the eve of strong earthquakes of anomalous physical phenomena has brought confidence in the possibility of predicting threatening seismic disasters using remote sensing technologies and prompted a wide range of experiments devoted to their study.

Very often a new technology measurement of various processes leads not just to improve the quality of data collected but also to radical changes in the understanding of processes, an understanding of the mechanisms of their generation, and the overall relationship of phenomena at different levels of their manifestation. This is what happened with the development of methods for satellite monitoring of natural and anthropogenic disasters. Let us consider, as an example, the thermal anomalies observed in the seismoactive areas before earthquakes. The emergence of infrared radiometers on satellites and measurements over seismically active areas (Gornyi *et al* 1988) were initially regarded as confirmation of the known existence of thermal (or meteorological) anomalies detected by ground-based measurements (Mil'kis 1986). However, the improvement of technologies can reveal a revolution in our understanding of the process of the preparation of earthquakes and geotectonics. First, it confirms the fact mentioned in the literature that gas discharges from the Earth's crust play an important role in the preparatory process of the earthquake (Khilyuk *et al* 2000). The migration of geogas in the Earth's crust, such as helium, hydrogen, carbon dioxide, and methane, causes changes in its mechanical properties (Soter 1999). The inert and radioactive gas radon, as soon as it has been released on the surface, triggers a chain of processes in the atmosphere, responsible for generating various types of short-term precursors. Latest technological progress in the observation of geogas initiated the historical comeback of radon being studied in association with major seismicity, as was shown in the occurrence of the April 2009 $M6.3$ in L'Aquila, Italy. The physical theory proposed in this book deals with complex relationships in the system of the Lithosphere–Atmosphere–Ionosphere–Magnetosphere, and radon plays a very important, leading role. We will start by describing this role; its connection with the theoretical concept and with the proposed methods of satellite and ground based monitoring of earthquake precursors. The intensive release of radon from active tectonic faults ultimately leads to the generation of thermal anomalies detected by satellites, as well as a modification of the global electrical circuit leading to the formation of large-scale irregularities in the ionosphere over the zone of a strong earthquake's preparation. A set of short-term precursors of earthquakes used in the new methodology is described in the first chapter. The second chapter describes the complex itself as an association model geo-effective phenomena in the lithosphere, atmosphere and ionosphere (Lithosphere–Atmosphere–Ionosphere–Magnetosphere Coupling Model—LAIMC). In the third chapter we discuss the final stage of the preparation of strong earthquakes and the appearance of a variety of physical precursors. In the fourth chapter we look at the system of interaction of geospheres from the point of view of synergetics as an integrated open system with dissipation during approach of the critical state—the seismic event. The fifth chapter describes the methodology of monitoring short-term precursors such as integrated monitoring, interpretation of data, and principles of automatic identification of precursors of different types, which results in the imposition of an expert opinion on the possibility of earthquakes in the area studied. External factors playing the role of triggers or retarders of seismic events, and leading to forecasting faults are also considered.

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Author biographies

Sergey Pulinets

Sergey Pulinets graduated from the Physical Department of Lomonosov Moscow State University. He obtained his PhD and Habilitation at Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radiowave Propagation of the Russian Academy of Sciences (IZMIRAN) where he worked for 30 years. His last position was Deputy Director of the Institute. He led the Departments of Space Electrodynamics and Physics of Ionosphere, and was PI of many experiments onboard Soviet and Russian satellites. From the beginning of the 1990s his scientific interests turned to the studies of the physical precursors of earthquakes, and the mechanisms of their generation. As Senior Scientist of the Institue of Geophysics of UNAM he spent several years in Mexico studying these phenomena in seismically active regions of Mexico and published, together with Dr Boyarchuk, the Springer monograph 'Ionospheric precursors of earthquakes' in 2004. Approximately at this time he started to collaborate with Dr Ouzounov, who developed the technology of operative monitoring of thermal anomalies before strong earthquakes. The fruitful discussions with Dr Ouzounov initiated the development of the complex theory of Lithosphere–Atmosphere–Ionosphere Coupling (LAIC). After his return to Russia, Dr Pulinets worked as the Head of Laboratory at Fiodorov Institute of Applied Geophysics. In 2009 he was invited by the Director of the Space Research Institute of the Russian Academy of Sciences (IKI) Acad., Lev Zelenyj, to head the development of the topside sounder for the Russian satellite constellation 'IONOSOND'. Since 2009, Dr Pulinets has been working at IKI as a Principal Research Scientist. During the last six years Dr Pulinets participated as Co-PI or Head of several International Projects directed to the studies of pre-earthquake processes, development and validation of the Lithosphere–Atmosphere–Ionosphere Coupling model: European FP-7 project PRE-EARTHQUAKES, ISSI project 'Multi-instrument Space-Borne Observations and Validation of the Physical Model of the Lithosphere–Atmosphere–Ionosphere–Magnetosphere Coupling', ESA project INSPIRE (Ionospheric Sounding for Identification of Pre-Seismic Activity), He is member of the Scientific Council of the China Seismo-Electromagnetic Satellite (SCES). As an invited professor or lecturer he conducted his research and lecture courses in Taiwan, Japan, Pakistan, and the USA. Dr Pulinets is an Individual member of the International Union of Radio Sciences (URSI), and a full member of the Russian Academy of Natural Sciences.

Dimitar Ouzounov

Dimitar Ouzounov received his PhD in Geophysics in 1990 at the Schmidt Institute of Physics of the Earth, Russian Academy of Sciences, Moscow. After a period as a Researcher at the Academy of Science in Bulgaria, in 1999 he became a Research Scientist at NASA Godard Space Flight Center, Greenbelt, USA. As a member of the NASA Goddard SFC Geodynamics team he developed an original methodology for studying thermal transient radiation in the atmosphere in relation to earthquakes and geodynamics processes from space. Since October 2009 he has been an Associate Professor in Geophysics at the Center of Excellence in Earth Systems Modeling & Observations, Chapman University, Orange, CA, USA. Dimitar became a guest-investigator for two satellite missions to study electromagnetic signals from space in relation to earthquake and volcanoes—the French DEMETER (2004) and the Chines CSES1 (2017). In 2004 he began collaborating with Dr Pulinets studying the processes of the Earth's lithosphere–atmosphere–ionosphere coupling in order to obtain a new understanding of the geospheres' interactions associated with lithosphere processes, pre-earthquake phenomena, and other major natural hazards. In geophysics, he is recognized for applying an interdisciplinary sensor-web methodology for time-dependent assessment of earthquake hazards and short-term warnings. In the field of Earth Science research he contributed in the development of a new paradigm of satellite monitoring of Earth's radioactivity processes for Disaster applications. He is the author of about two hundred papers and conference proceedings. He has also co-authored with Dr Pulinets on two other books—*AGU Geophysical* and *Springer-Nature monograph* series on Pre-Earthquake processes and on Earthquake precursors in the Atmosphere and Ionosphere.

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Chapter 1

What is the meaning of a short-term earthquake forecast?

1.1 Basic concepts of seismology

An earthquake is a discontinued shift along weak zones, which are faults in the Earth's crust. According to (Reid 1910), an earthquake is the result of elastic recoil. Elastic deformation of stretching or compression of the crust occurs due to the slow flow of substances, caused by thermal and gravitational convection in the mantle (Yanovskaya 2008). There are several types of crustal blocks' relative movement in the moment of an earthquake (called the focal mechanism). For example, when blocks move from each other in a horizontal direction this is called a strike-slip, in the case of one block going down over another one, it is called normal faulting, when a block is moving up it is called reverse faulting or thrust. The oblique slip (combination of mechanisms) could take place as well. The type of slip is determined semi-automatically from the seismic waveforms, and expressed mathematically in the form of the seismic moment tensor. Visual representation of the focal mechanism uses the so-called beachball diagram. Different areas of our globe have typical focal mechanisms to that demonstrated in figure 1.1 (Kagan and Jackson 2014).

An earthquake is the source of a huge amount of energy release that goes into thermal energy, energy of plastic deformation and energy of seismic waves, while just the seismic waves are used to estimate earthquake energy. For the convenience of earthquake energy assessment, the magnitude concept was introduced.

Magnitude—is the decimal logarithm of the maximum amplitude, measured in microns, recorded by a standard Wood–Anderson seismograph at a distance of 100 km from the epicenter. This definition is called local magnitude M_L and can be calculated as shown (1.1) (Shearer 2009):

$$M_L = \log_{10} A + 2.56 \log_{10} \Delta - 1.67, \tag{1.1}$$

where A [μm] is the waveform amplitude; Δ [km] is the distance from the seismograph to the epicenter. The formula is valid for values of $10 < \Delta < 600$ km.

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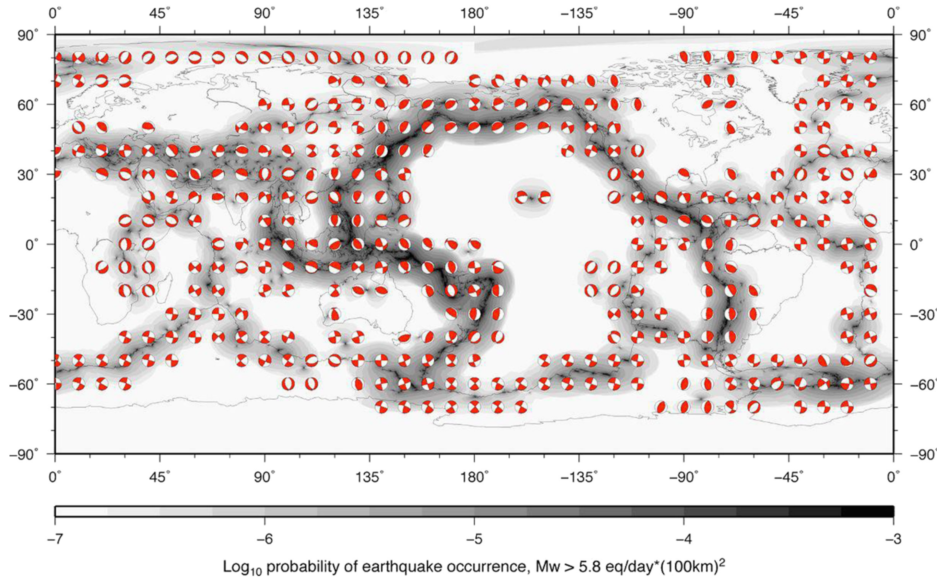

Figure 1.1. Global earthquake long-term focal mechanism forecast based on smoothed seismicity, latitude range [90° S–90° N]. After Kagan and Jackson (2014).

As a result of the Earth's crust rupture during an earthquake, different types of seismic waves are generated: volumetric (longitudinal P-waves of compression and lateral shear S-waves), and surface waves (Rayleigh wave polarized in the plane of incidence and Love waves polarized perpendicular to the plane of incidence) (Yanovskaya 2008).

The energy of each wave is different and is some part of the total energy of the earthquake, therefore the magnitude determined on the basis of seismic waves will vary, depending on what kind of wave is used (formulas (1.2)–(1.4) and table 1.1) (Shearer 2009).

The determination of magnitude based on body waves' registration is expressed by the formula (1.2) (Shearer 2009):

$$m_b = \log_{10}(A/T) + Q(h, \Delta) \tag{1.2}$$

where A [μm] is the amplitude; T, [s] is the wave period; Δ [km] is the distance from the seismograph to the epicenter; the calibration function is $Q(h, \Delta)$, depending on the depth of the earthquake h, [km] and distance Δ take into account the geometric waves' divergence and attenuation due to absorption.

To assess the magnitude of an earthquake by surface waves formula (1.3) is used (Shearer 2009):

$$M_S = \log_{10}(A/T) + 1.66\log_{10}\Delta + 3.3. \tag{1.3}$$

Magnitude M_S is determined within the period of 20 s. Magnitude m_b is determined within the period of 0.3–3 s (or an average within a period equal to 1 s).

Table 1.1. Differences in the scales of magnitude (Shearer 2009).

Date	Region	m_b	M_S	M_W	M_O
22.05.1960	Chile	–	8.3	9.5	2000
28.03.1964	Alaska	–	8.4	9.2	820
26.12.2004	Sumatra-Andaman	6.2.	8.5	9.1.	680
09.03.1957	Aleutian Islands	–	8.2	9.1.	585
04.02.1965	Aleutian Islands	–	–	8.7	140
28.03.2005	Sumatra	7.2	8.4	8.6	105
19.08.1977	Indonesia	7.0	7.9	8.3	36
25.09.2003	Hokkaido, Japan	6.9	8.1	8.3	31
04.10.1994	Shikotan, Kurile Islands	7.4	8.1	8.2	30
09.06.1994	Bolivia	6.9	–	8.2	26
23.12.2004	Macquarie Ridge	6.5	7.7	8.1	16

Magnitude scales m_b and M_S for strong earthquakes give lower values for magnitude. This phenomenon is called the saturation of magnitude scales. In order to avoid errors in assessing the strength of an earthquake, Kanamori proposed to determine the magnitude through the seismic moment M_0, [Nm], (Kanamori 1977). The magnitude is called the moment magnitude. Instantaneous magnitude is indicated by M_W and determined by formula (1.4):

$$M_W = 2/3\log_{10}M_0 - 10.7, \tag{1.4}$$

here $M_0 = \mu DA$, where μ is the shear modulus of rocks (about 30 HPa); D is the mean displacement within the fault; A is the area of the fault.

The magnitude of the seismic moment, presented in table 1.2 is in 10^{20} [Nm]

Strong earthquakes occur much less frequently than weak ones (see table 1.2). The number of strong earthquakes associated with weak events could be expressed by the Gutenberg–Richter law or Frequency–Magnitude Relation (FMR) (Gutenberg and Richter 1944):

$$\log_{10}N(M) = a - bM \tag{1.5}$$

where N is the number of earthquakes with magnitude $\geqslant M$, a and b are local constants, meanwhile b can vary depending on the phase of the earthquake cycle from 0.5 to 2, with a mean value close to 1.

The energy of strong earthquakes far exceeds the total energy of many weak earthquakes. For example, the energy of one powerful earthquake with a magnitude of 9.0 is comparable to the energy emitted as a result of 1 million earthquakes with a magnitude of 5.0, or energy equal to 32 000 earthquakes with a magnitude of 6.0.

The average number of earthquakes per year, according to the statistics of the United States Geological Survey's National Earthquake Information Center (USGS NEIC) [http://earthquake.USGS.gov/regional/neic/] 1900–2012: $M \geqslant 8.0$ is one

Table 1.2. The number of earthquakes per year with a magnitude (M) ⩾ 5.0, according to statistics of the USGS NEIC [https://earthquake.usgs.gov/earthquakes/browse/stats.php].

(M)	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2012	2016
8–9.9	1	1	0	1	2	1	2	4	0	1	1	1	2	2	1
7–7.9	14	15	13	14	14	10	9	14	12	16	23	19	12	17	11
6–6.9	146	121	127	140	141	140	142	178	168	144	150	185	108	123	143
5–5.9	1344	1224	1201	1203	1515	1693	1712	2074	1768	1896	2209	2276	1401	1453	1574

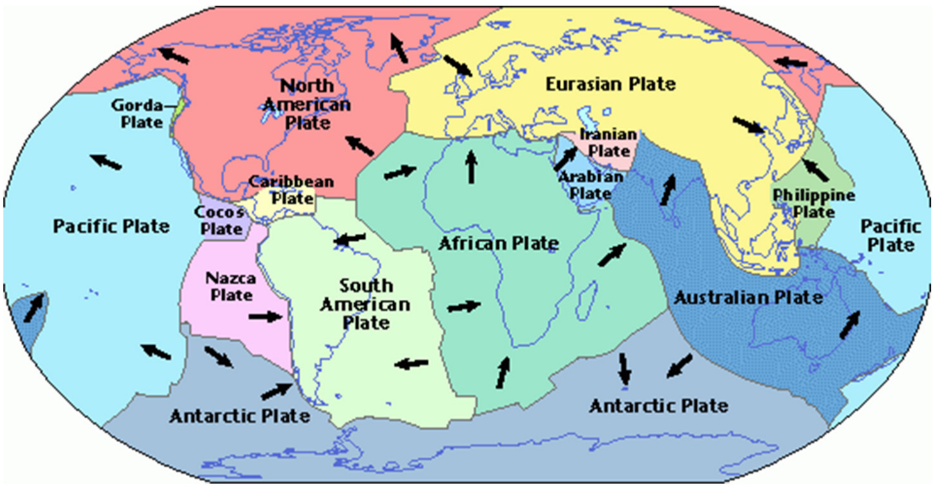

Figure 1.2. Major lithospheric plates and the movement at their borders.

earthquake; 7.0 ⩽ M ⩽ 7.9–15 earthquakes; 6.0 ⩽ M ⩽ 6.9–134 earthquakes; 5.0 ⩽ M ⩽ 5.9–1319 earthquake.

Alfred Wegener's idea of continental drift was supported by progress in marine geology, which by the end of the 1950s to the beginning of the 1960s led to the foundation of the plate tectonic hypothesis, which subsequently formed the basis of the modern theory of geotectonic plates. To date, it is known that the lithosphere consists of rigid plates (Antarctic, Africa, Eurasian, Indian (or Indo-Australian), Pacific; the American plate is divided into two—the North and South American, Arabian, as well the Caribbean, Nazca, Cocos, Philippine, Juan de Fuca, Scotia) that are in relative motion. Figure 1.2 from the website of Bucknell University [http://www.bucknell.edu/x17758.xml] demonstrates the major lithospheric plates and the movement at their borders.

The movement of plates occurs due to thermal convection in the mantle. Each major tectonic plate moves over the asthenosphere. In areas stretching constantly, the new plots of lithospheric plates are created with a type of oceanic crust. In zones of compression, where lithospheric plates collide, one lithospheric plate dives under another plate, and eventually the subducting slab material turns into the material of the mantle (Yanovskaya 2008).

The boundaries between plates are divided into stretching borders, where a new crust is created (constructive borders), compression borders where the crust dies (destructive borders); horizontal shifts, including transform faults along which the plates move in different directions horizontally, and the crust is not formed and not destroyed.

At the present time, due to the active development of Global Navigational Satellite Systems (GNSS), as well as networks of ground-based navigational receivers, receiving signals from various regions of the Earth, the direction of motion of each plate is determined with a precision of fractions of millimeters. The speed and the absolute offset of the tectonic plates are also determined. The necessary information can be found freely available on the Internet, for example, on the official website of Scripps orbit and permanent and array center (SOPAC) [http://sopac.UCSD.edu/].

The concept of the earthquake preparation zone has been developed by different authors: Dobrovolsky and co-authors (Dobrovolsky *et al* 1979, Dobrovolsky 2009), Keilis-Borok and Kossobokov (Keilis-Borok and Kossobokov 1990), Bowman and co-authors (Bowman *et al* 1998). An earthquake preparation zone is an area where the local deformation, associated with the source of earthquakes, takes place. Deformations are implied as changes in the properties of the Earth's crust that can be detected by different methods.

According to the dilatancy–diffusion model (Scholz *et al* 1973, Mjachkin *et al* 1975), at various stages of an earthquake's cycle within the earthquake preparation zone different changes of geophysical parameters can be observed (Kasahara 1983). Among them, the seismic velocity (change in the relation of longitudinal and transverse waves velocities V_P/V_S), the ratio of strong and weak aftershocks (change of the earthquake's occurrence slope), the resistivity of the Earth's crust, as well as geochemical precursors (radon emanation, etc) can be seen. Data about these changes create a physical basis for predicting future earthquakes (Rikitake 1976, Mogi 1985, Sobolev 1993). The effects of both versions of the dilatancy model are presented in figure 1.3.

Changes of chemical, physical and other properties of materials composing the crust, caused by the accumulation of stress in it, lead to the generation of different kinds of anomalies within the earthquake preparation zone; these changes are called the precursors of earthquakes, they are studied by seismologists, and serve as a basis for earthquake forecasting.

To determine the size of the earthquake, the preparation zone is used for both the seismic precursors such as foreshocks or deformation distribution and a whole complex of geophysical parameters is measured in the area of earthquake preparation.

The common understanding of the Earthquake preparation zone is that it is a specific area on the Earth's surface, where the signs of earthquake precursors may be registered. It does not mean that all of the area will be occupied by geophysical anomalies associated with the earthquake preparation. Due to Earth's crust's heterogeneity the concentration of registered anomalies will be different for different parts of the zone, they can move within the area while the earthquake is approaching. So, anomalies can appear in any area of the preparation zone, and the radius of this zone determines the maximal distance from the epicenter of an impending earthquake where they could be registered.

To determine the radius of the earthquake preparation zone, Dobrovolsky *et al* (1979) used two factors: empirical spatial distribution of different physical precursors as a function of magnitude and projection of deformation inclusion within the crust on the ground surface using an ellipsoid with different levels of elastic deformation. This approach revealed the distribution of the most distant precursors (in relation to the epicenter's position) along the line depicting the area with the level of elastic deformation equal to 10^{-8} at its outer edge (see figure 1.4). It gives the radius of the earthquake preparation zone (in km) as (figure 1.4):

$$\rho_1 = 10^{0.43M}. \tag{1.6}$$

Here M is the earthquake's magnitude.

To get an idea of how large the size of this zone could be, we present the radius value for different magnitudes in table 1.3.

Bowman *et al* (1998) considered the critical earthquake concept to obtain the best fit for the zone of activation, mentioning that for large earthquakes it coincides with Dobrovolsky's determination while they have a slightly larger exponent:

$$\rho_2 = 10^{0.44M} \tag{1.7}$$

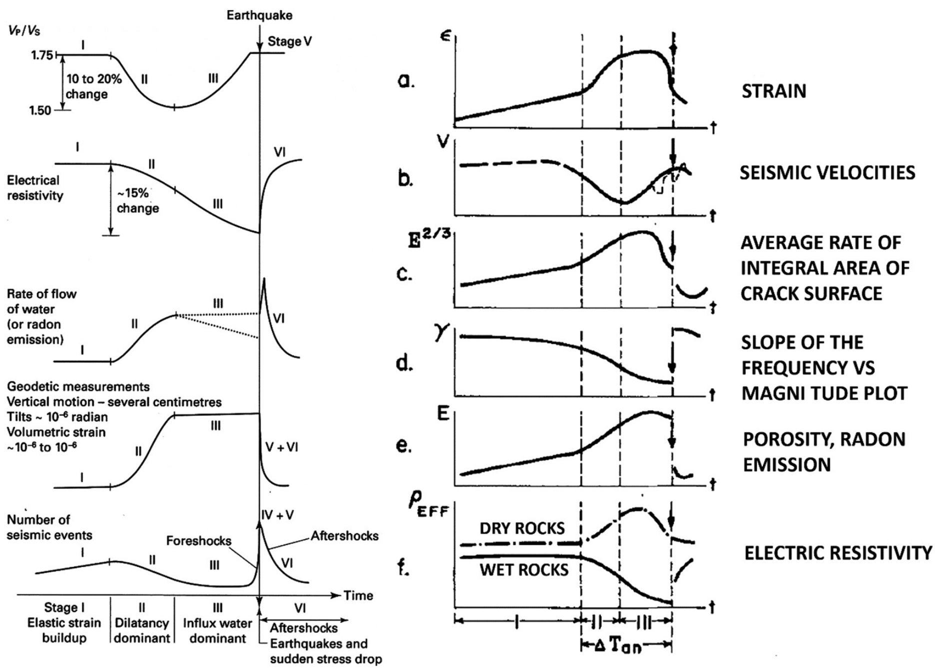

Figure 1.3. Left panel: variation of the physical parameters in the dilatancy–diffusion model (Scholz *et al* 1973). Right panel: the same from the Schmidt Institute of Physics of the Earth dilatancy model (Mjachkin *et al* 1975).

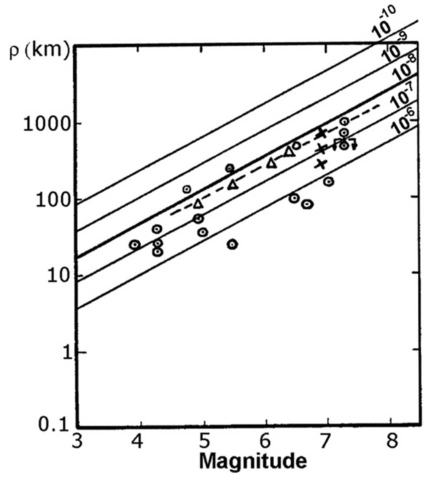

Figure 1.4. Radius of the earthquake preparation zone versus an earthquake's magnitude. Different signs denote the different anomalies registered within the earthquake preparation zone.

Table 1.3. Earthquake preparation zone radius as a function of magnitude.

Magnitude	3	4	5	6	7	8	9
Earthquake preparation zone radius ρ (km)	**19.5**	**52.5**	**141**	**380**	**1022**	**2754**	**7413**

where ρ_1, ρ_2, [km] is the radius of the earthquake preparation zone, respectively, according to (Dobrovolsky *et al* 1979) and according to (Bowman *et al* 1998), M is the earthquake's magnitude.

Keilis-Borok and Kossobokov (1990) obtained an expression for the diameter of the earthquake preparation zone expressed in degrees:

$$l(M_0) = \exp(M_0 - c) + 2\varepsilon \tag{1.8}$$

where M_0 is the seismic moment of the earthquake, ε is the possible error of 0.5°, and c is calculated from the data fitted to the magnitude 8 event $l(8) = 12°$. This estimation is in good agreement with formula (1.7).

Looking at the problem of earthquake forecasting it is worth noting that today we can still observe conflict between the two approaches. The first one, which prevails in seismology now, is based on a concept that started to be used in seismology in the 1990s and is called self-organized criticality (Bak 1996). According to the theory of self-organized criticality, the final stage of earthquake preparation is the transition of the system from the chaotic state to a self-organization earthquake when the system reaches its critical state. This theory is able to explain why a very small impact on the system may lead to a catastrophic change (in our case, an earthquake), and periodic larger impacts do not lead to essential effects in the system state. It is practically impossible, knowing the initial state of the system, to calculate its final state, which may have an infinite number of meanings. In its temporal behavior the chaotic dynamical system exhibits trajectories that converge to a strange attractor. The fractal dimension of this attractor characterizes how close the system is to its critical state. It revealed the different values of the fractal dimension D of hypocenters in a locked and creeping segment of the San Andreas fault, and its connection with the b-parameter in the FMR relationship (Wyss *et al* 2004). Schorlemmer *et al* (2004) claim 'lower than average b-values characterize locked patches of faults (asperities), from which future mainshocks are more likely to be generated.' This is a direct indication of the physical interpretation of the FMR. More convincing results were obtained by Bayrak and Bayrak (2012) studying regional variations and correlations of Gutenberg–Richter parameters and the fractal dimension for different seismogenic zones in Western Anatolia. This relation looks like:

$$D_C = 1.17 + 0.14a/b \tag{1.9}$$

where a and b are the coefficients of the FMR (figure 1.5).

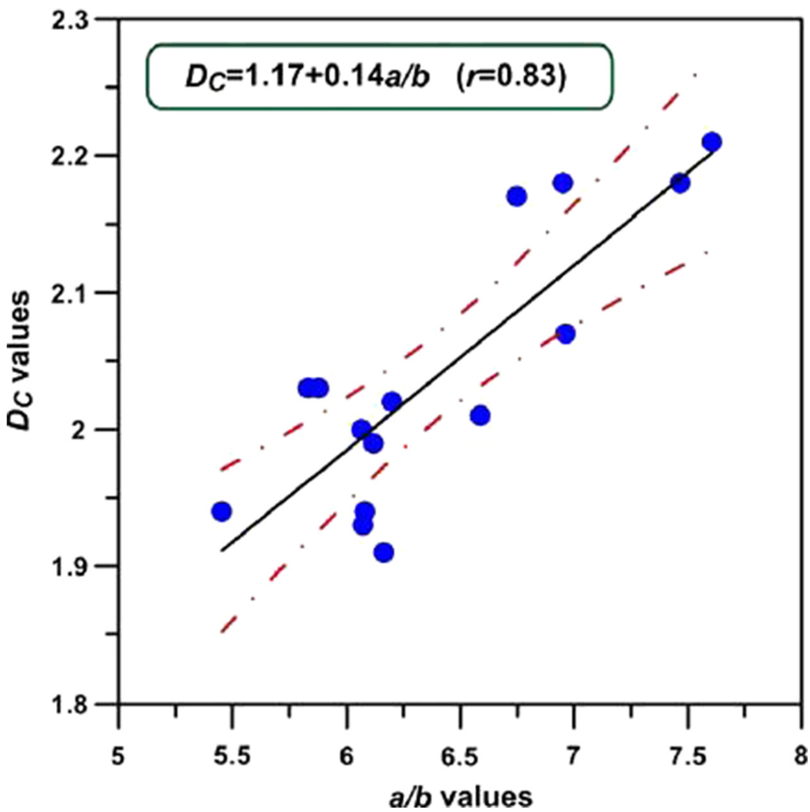

Figure 1.5. Relationship between a/b and DC values for 15 different seismogenic zones in Western Anatolia. The straight line is the linear regression and the dashed lines are 95% confidence limits and r is the correlation coefficient (after Bayrak and Bayrak (2012)).

Concluding this introduction, we can summarize that regardless of the chaotic behavior of the seismically active regions there exist some measurable indicators of the system approaching a critical state. As we have seen from figure 1.3 these indicators are not from seismometers but from measurements of different physical parameters. In the literature they have been called 'earthquake precursors,' which will be discussed in more detail in chapter 2.

Moreover, we use the physical principle as the basic criteria for our research of the problem of earthquake forecasting. It means that if a causal link is established, and it is based on fundamental physical laws, Nature will keep and execute it in all cases in similar situations of earthquake preparation because of the universality of physical laws (meaning that the laws of physics, for example, Newton's laws, are executed in the same way everywhere regardless of whether it is Japan or Venezuela).

1.2 What other measurements are available to complement seismological observations?

The twentieth century was a whirlwind of technological innovations, and some inventions qualitatively changed our life beyond recognition. Red telephone boxes in London became archeological artifacts following the invention of mobile phones. The Russian Sputnik in 1957 started the Space Era and now we can stop discussing whether continents move or not because with the help of GNSS systems we can observe their movement in real time with extremely high precision. Remote sensing brought completely unexpected results to the observation of earthquake precursors. Instead of collecting point-by-point ground-based measurements to obtain the spatial distribution of precursors for the determination of the earthquake preparation zone, we can simply visualize it using the IR images of the ground surface thermal anomalies as demonstrated in figure 1.6 (Pulinets *et al* 2013).

The more that people started working in remote sensing and space plasma physics, analyzing the results of satellite measurements over the earthquake

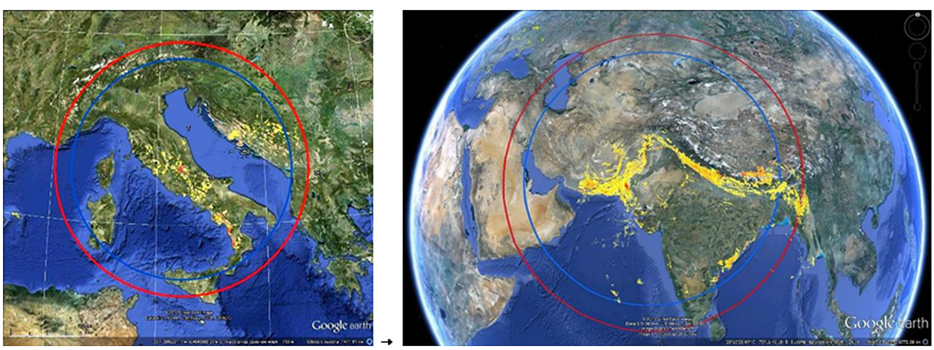

Figure 1.6. Left panel: the surface thermal infrared (TIR) anomaly before L'Aquila (Italy) *M*6.3 earthquake on April 6, 2009 (yellow and red). Right panel: the TIR anomaly before Gujarat (India) *M*7.7 earthquake on January 26, 2001. In both cases, the epicenter of the earthquake is located in the center of the circle. Blue circle: Dobrovolsky zone (1.6), red circle: Bowman zone (1.7).

preparation zone, the more that different kinds of pre-seismic anomalies were revealed. Practically any type of satellite payload is able to register some kind of pre-earthquake anomaly. Infrared spectrometers within the specific spectral bands of the IR (0.75–15 μm) spectrum can register thermal anomalies at different levels starting from the ground surface, through the troposphere up to the top of clouds in the form of outgoing longwave radiation. Microwave sounders and Fourier spectrometers register anomalies in the vertical and spatial distribution of air temperature and humidity, visual cameras together with infrared imagers can register the formation of anomalous cloud structures formed over the earthquake preparation zone, lidars and spectra radiometers permit one to retrieve the aerosol content, including the seismically induced aerosol. Presently, one of the most explored precursors are the ionospheric anomalies registered before earthquakes, which were successfully registered by all of the available ionospheric techniques including the local plasma probes, topside sounding, Global Position System (GPS) Total Electron Contents, GPS occultation measurements, and ionospheric tomography. Finally, we should mention the measurements of electromagnetic fields and emissions from quasi-stationary up to very high frequency (VHF) bands.

This satellite fleet should be supported by new types of ground-based measurements starting from traditional instruments used in seismology in the 1970s and 1980s such as ground conductivity, geomagnetics, water levels, geochemical monitoring, to completely new fields such as sub-ionospheric propagation of VLF waves, over-horizon propagation of VHF waves, vertical and oblique ionospheric sounding, atmospheric electric field and conductivity, ion content, and updates of traditional measurements such as radon monitoring by gamma-spectrometry.

Even pure enumeration of the different anomalies associated with earthquake preparation gives us an idea of how widely all geospheres are involved in the complex unstable system of earthquake preparation. All of them should be carefully studied from the point of view of their physical nature (which will be described in the following chapters). However, from the point of view of the precursors' confirmations, we could envision the strong potential support of the seismology community, which could make a difference in providing new technologies for the precursors' monitoring and their assessments.

1.3 Brief summary on earthquake prediction/forecasting

For the last 50 years many attempts been made to achieve reliable, short-term earthquake prediction in the USA, Russia (Soviet Union), Japan, and China. Despite all of the successes and failures, today there is no operational methodology to predict/forecast a few days or hours in advance of the major ($M > 6$) earthquakes worldwide. In fact, there was no internationally accepted successful prediction by any national earthquake prediction projects. Not only scientific and social communities, but also governments, became totally pessimistic and this pessimism has essentially lasted until today (Evernden 1982, Uyeda 2013).

Earthquake prediction/forecast means advance assessment of the number of parameters characterizing a seismic event, answering three basic questions: when (time), where (location) and how strong (the magnitude). The common understanding of the type of earthquake prediction/forecast is classified by a time scale into long-term (decades), medium-term (years) and short-term (month to weeks, hours). There are two different approaches in the assessment of earthquake risk in advance.

(a) Probabilistic estimate—usually the forecast is expressed in probability, or the increase of probability of earthquakes. This approach requires one to study the historical seismicity of the area, and to characterize the geological-tectonics factors in the local or regional scales (Gelfand *et al* 1972, Keilis-Borok 1990).
(b) Deterministic approach—the 'prediction' is in most cases expressed by alarms and is based on the assessment of precursors. This approach is based on established physical laws, which relate to precursors and the actual occurrence of seismic events (Martinelli 1998).

People have been trying to forecast earthquakes through the interpretation of precursory phenomena from early historical times. The first scientifically described earthquake precursors were in Ancient Greece. The Greek philosophers described earthquakes defined by meteorological factors. Aristotle (384–322 BC) in *Meteorologica* described for first time the possible origin of earthquakes generated by underground forces (winds—'pneuma'). It was described in the history books that Anaximandros, in 550 BC in Sparta, warned the inhabitants of the city of an upcoming powerful earthquake, and since they stayed up all night outside their homes, they saw their city being completely destroyed. Other historical reports mention the case of Pherecydes of Syros (the famous teacher of Pythagoras) who successfully predicted that in three days there would be an earthquake by examining water from a well. Pausanias also mentions the existence of precursor phenomena. Extended summaries of the history of earthquake prediction/forecasting can be found in the following excellent reviews (Kalenda and Neumann 2010, Martinelli 1998, Hough 2016, Huang *et al* 2017).

In figure 1.7 the Prediction/Forecast paradigm has been explained in relation to Shannon information (Tom Jordan, SCEC 2011). For operational use, deterministic prediction is useful in the high probability score ($P > 0.8$), in contrast to the probabilistic approach, which can be useful only in a low probability environment ($P < 0.2$).

In the mid-1990s many methods were developed in Russia (former Soviet Union) based on the statistical assessment of seismicity (algorithms 'M8', 'CN', 'SSE', 'RTP') (Keilis-Borok and Kossobokov 1990, Keilis-Borok and Rotwain 1990, Keilis-Borok *et al* 2002).

At the same time, prediction techniques were examined during an experiment in Parkfield, California, USA, when an earthquake with $M \approx 6$ magnitude within a period of 22 years (Bakun and Lindh 1985) was expected (Kalenda and Neumann 2010). The National Earthquake Prediction Evaluation Council Program (NEPEC) (Bakun *et al* 1987) was created to maintain the necessary measurements prior to, during, and after the anticipated earthquake. The Parkfield experiment failed for the most part. On September 28, 2004, an $M6$ was observed, 11 years after the forecasted time window. After an assessment of all the methods deployed in

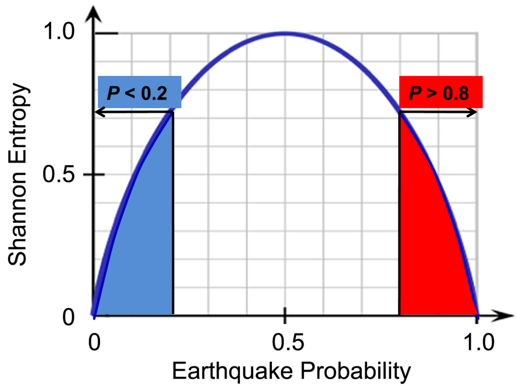

Figure 1.7. Prediction versus forecasting. Deterministic prediction (red) and probabilistic forecasting (blue) (Jordan 2011).

Parkfield, geophysicists reported that even in 2004, their data had not identified any reliable precursors (Harris and Arrowsmith 2006, Bakun *et al* 2005.

In 1991, the Southern California Earthquake Center (SCEC) was founded with joint funding by the National Science Foundation (NSF) and the U. S. Geological Survey (USGS). The main goal of the SCEC was to advance earthquake system science by gathering information from seismic and geodetic sensors, geologic field observations, and laboratory experiments; synthesizing knowledge of earthquake phenomena and seismic hazards to reduce earthquake risk. The SCEC promoted the Uniform California Earthquake Rupture Forecast Model, Version 3 (UCERF3) as a comprehensive model of earthquake occurrence for California. It represents the best estimates of the magnitude, location, and likelihood of potentially damaging earthquakes in California. Currently, there is the Collaboratory for the Study of Earthquake Predictability (CSEP) testing Center at the Southern California Earthquake Center (SCEC) and four more worldwide. The CSEP Project has developed procedures for registering prediction experiments and to allow researchers to participate in prediction experiments and update their procedures as results become available [http://www.cseptesting.org/].

During the 1980s, the Japanese earthquake prediction program became focused on predicting an $M8$ earthquake in a highly populated Tokai region, an area west of Tokyo. On January 17, 1995, a powerful earthquake with a magnitude of 7.3 hit Kobe, Japan, near Osaka, far from the Tokyo area. Nearly 4600 people were killed and more than 200 000 were made homeless (Martinelli 1998, Kalenda and Neumann 2010). The 1995 Kobe earthquake pointed to an unbalanced approach in the Japanese prediction program. Later, it was found that the Kobe earthquake's main shock had been preceded by a variety of precursors (Silver and Wakita 1996). The 2011 $M9$ Tohoku-Oki earthquake was not predicted, despite the fact that it occurred during 35 years of a continuous funded prediction research program. Immediately after the 2011 earthquake, seismological communities in Japan stopped official funding for short-term earthquake prediction research (Uyeda 2013). The latest unsuccessful attempts to predict/forecast major earthquakes in the USA and Japan resulted in the development of wide skepticism among scientific communities and government organizations: that short-term earthquake prediction may soon not be feasible.

China has carried out research programs on earthquake prediction and mitigation of earthquake disasters and their program was developed slightly differently to other countries. In addition to the standard terminology for earthquake forecast and prediction (long-middle-short), China used 'imminent' types (days, even hours). The successful prediction/forecast of the February 4, 1975, Haicheng *Ms*7.3 earthquake was mainly based on foreshocks (figure 1.8) and other geophysical precursors (radon, electrical signals, animal behavior, weather, etc) as well as on the macro-anomalies reported to seismological agencies from local residents.

Despite intiating an evacuation in advance of the earthquake, 1328 people died. In 1976, based on almost exactly the same method (and philosophy), Chinese seismologists failed to forecast the tragic Tangshan *Ms*7.8 earthquake where the number of deaths initially reported by the Chinese government was 655 000. The failure to predict the Tangshan earthquake was not because of a lack of warning signals. A recent example is an account from an eyewitness to the catastrophic Tangshan earthquake of July 1976. The account's author and his companions were all intellectuals in a 're-education program' at a state-owned farm outside Tangshan (Gold 1998).

The time of the strange animal behavior was around midnight, some four hours before the earthquake: '*We were telling stories in the dormitory when out of the large dorm opposite ours burst hundreds of rats. Back and forth they swarmed, many scrambling five or six feet up the walls until they lost hold. … As we pondered this in amazement, the sound of thousands of excited hens and roosters reached our ears.*

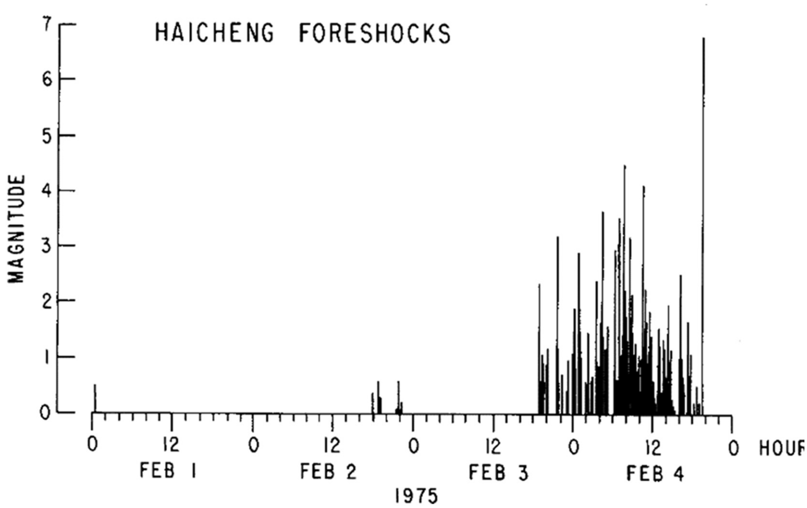

Figure 1.8. A plot of magnitude versus time of occurrence of the larger foreshocks of the Haicheng earthquake sequence, February 1–4, 1975. (EOS 1977) used primarily to issue an evacuation.

There was poultry nearby, but nobody had recalled ever hearing the roosters' crow at night' (Li 1980). Though filled with amazement—the Tangshan witnesses were not familiar with the strange animal behavior before earthquakes. They went to bed, and in a few hours some of them were killed when their dormitory collapsed. The failure of the Tangshan earthquake prediction invoked doubt about the reality of earthquake prediction in China (Huang *et al* 2017).

In 2008, the Great Wenchuan earthquake was not noticed in advance by Chinese seismologists. The Wenchuan earthquake had a great impact on the Chinese science community, which started embracing the importance of an international discussion on the seismology, geology, and geodynamics of strong-to-great earthquakes, their predictability, and how to make full use of the present knowledge and techniques to reduce earthquake disasters (Huang *et al* 2017).

Earthquake prediction is complicated and errors are very likely. John Filson (currently a geologist emeritus at USGS in Reston, VA, USA) describes his firsthand experience of the well-known case of a non-successful forecast (Johnston 2009). In 1980, a scientist at the U.S. Bureau of Mines (USA) announced that a major quake would strike Lima, Peru, around June 28, 1981. The NEPEC (National Earthquake Prediction Evaluation Council, USA) analyzed the data and concluded that a quake is less likely to occur during the proposed four-day window around the date. Filson went to Peru, where he tried to calm citizens via television and newspaper interviews. NEPEC was right, no earthquake hit Peru during the predicted time window. At a dinner at the U.S. embassy, he saw the ambassador and his wife served tuna sandwiches, and he thought that this was an attempt to save taxpayers' money. Then the ambassador's wife revealed that all of the staff at the embassy, including the cooks, had left Lima for their hometowns to die with their families (Johnston 2009). No one died, obviously, but the question remains about the correctness of earthquake prediction, their validation, and how this information should be disseminated to the public. The new scientific developments regarding the physical processes associated with pre-earthquakes described in this book provides hope that short-term forecasting could be feasible.

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