Review

On Earthquake Prediction in Japan

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(Contributed by Seiya UYEDA, M.J.A.)

Abstract: Japan's National Project for Earthquake Prediction has been conducted since 1965 without success. An earthquake prediction should be a short-term prediction based on observable physical phenomena or precursors. The main reason of no success is the failure to capture precursors. Most of the financial resources and manpower of the National Project have been devoted to strengthening the seismographs networks, which are not generally effective for detecting precursors since many of precursors are non-seismic. The precursor research has never been supported appropriately because the project has always been run by a group of seismologists who, in the present author's view, are mainly interested in securing funds for seismology — on pretense of prediction. After the 1995 Kobe disaster, the project decided to give up short-term prediction and this decision has been further fortified by the 2011 M9 Tohoku Mega-quake. On top of the National Project, there are other government projects, not formally but vaguely related to earthquake prediction, that consume many orders of magnitude more funds. They are also un-interested in short-term prediction. Financially, they are giants and the National Project is a dwarf. Thus, in Japan now, there is practically no support for short-term prediction research. Recently, however, substantial progress has been made in real short-term prediction by scientists of diverse disciplines. Some promising signs are also arising even from cooperation with private sectors.

Keywords: earthquake prediction, short-term prediction, Mega-quake, seismology, private sector, government support

Introduction

Earthquake (EQ hereinafter) prediction must specify the time, epicenter, and size of impending EQ with useful accuracy. Among the long-, intermediate- and short-term predictions, only the short-term prediction is meaningful for directly protecting human lives and social infrastructures. The other two are mainly mere statistic forecasts based on past experiences and should not even be called prediction, although the intermediate-term forecast has entered into a new stage thanks to the GPS measurements, *e.g.*, Ruegg *et al.*, (2009).[1)]

Seismology has two major aspects, *e.g.*, Shearer (1999).[2)] One is to investigate the internal structure of the earth by seismic waves recorded by seismometers. It was first developed in Europe, *e.g.*, Oldham (1906),[3)] Wiechert (1910).[4)] The other is to study the EQs themselves and is called EQ seismology. Naturally, seismologists in EQ prone regions are keener about it. In fact, the modern EQ seismology may be said to have started in California, after the 1906 M8.3 San Francisco EQ. To explain the observed displacement of the ground surface around the San Andreas Fault, the elastic rebound theory by Reid (1910)[5)] was presented. The theory says that as rocks on opposite sides of a fault are subjected to shear stress they slowly deform until their internal strength is exceeded producing an EQ. Stress is accumulated taking many years and released instantly. This idea has since been the theoretical guideline for EQ generation. However, in the following several decades, there has practically been no serious scientific attempt at prediction. Knowledgeable experts knew it was not possible.[6)]

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Optimism in the early 1970's, soon followed by pessimism

It was in the 1960's that national projects for EQ prediction started in several countries including Japan, USSR, China and USA. The reason why it happened more or less simultaneously is not quite clear. Perhaps it was because scientific activity was recovered from the World War II at about that time with EQ seismology in the forefront, aided by the World-wide Standardized Seismograph Network (WWSSN) for nuclear blast detection.[7)]

Optimism prevailed globally in the early 1970's due, for instance, to the advent of the dilatancy-diffusion model by Sholtz *et al.* (1973),[8)] which appeared to explain almost all the reported precursory phenomena like crustal uplift, 10–20% change in Vp/Vs (the ratio of the velocity of p and s seismic waves), radon emission, electrical conductivity variation etc. The success of long, intermediate and short term prediction of the 1975 M7.3 Haisheng EQ highlighted the optimism, *e.g.*, Press (1975).[9)]

However, this optimism was ephemeral. Putting details aside, 10–20% change in Vp/Vs was denied by later work[10)] and the Chinese failed to predict 1975 M7.8 Tangshan EQ.[11)] In the USA, the Parkfield EQ predicted to occur before 1993 did not come until 2004.[12),13)] In fact, there was not a single successful prediction by EQ prediction projects of any country. The whole community became pessimistic, *e.g.*, Evernden (1982).[14)] This pessimism has persisted until now, except among some mostly non-mainstream researchers.

History of EQ Prediction in Japan — before 1995

The world's first seismological society, the Seismological Society of Japan (SSJ) was borne in 1880 through the efforts of foreign visiting scientists hired by the Meiji government, like John Milne (1850–1913). It is remarkable that in his lecture entitled "Seismic Science in Japan",[15)] delivered in the SSJ's 2nd general assembly, he said that one of the main purposes of seismologists was to discover the way to foretell the occurrence of EQs. He actually gave many examples of possible precursory phenomena.

Aikitu Tanakadate (1856–1952) started geomagnetic field measurements after the occurrence of the M8.0 Nobi EQ (1891) in the epicentral area. He also discovered the famous Neodani Fault. For him, it was only three months after returning home from a UK study. Motivated by the Nobi EQ, the Meiji government swiftly established the Imperial Earthquake Investigation Committee in 1892. These were even before the San Francisco EQ (1906) and may well be considered as the dawn of EQ research in Japan. However, despite the high-spirited far-sights of these Meiji scientists, EQ prediction became almost a taboo and remained so in the following decades because it was regarded as not a productive science.

Although perhaps not well known in the contemporary community, issues on EQ prediction were taken up as early as in 1946, the next year after the end of World War II, between US and Japanese seismologists through orders of the General Headquarters (GHQ) of the US occupation forces. The background information on these affairs is found in Rikitake, 2001.[16)] Apparently, the US side intended to probe if Japan was more advanced in this respect since the interest in EQ prediction in the US at that time was almost none. The real Japanese situation was not much different. Actually, in his report of visiting Japan, not disclosed to Japanese at that time but reproduced in Rikitake 2001,[16)] Beno Gutenberg was critical of the un-cooperative relations between the Japan Meteorological Agency (JMA) and the Earthquake Research Institute (ERI), University of Tokyo. But these affairs motivated the Japanese community to become gradually interested in EQ prediction. Then in 1962 an overall plan, generally called the "Blueprint" (Tsuboi, Wadati, and Hagiwara (1962),[17)] was formulated. This document, originally in Japanese, made considerable global impacts after translated into English, also included in ref. 16), by the present author, then a young research assistant to Rikitake at ERI.

Actual National EQ Prediction Project funding, which could be used by university researchers, 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 on crustal movements, tides, seismicity, seismic wave velocity, active faults, geomagnetism and geoelectric currents etc. It was proposed to promote monitoring of all of them. This was a reasonable start. It may well be a reasonable set of plans even today, because the full plans have never been conducted as recommended.

To begin the National Project, the government consulted seismologists to formulate a practical program. This was also reasonable because there was no other organized group of relevant scientists. The project started with considerable funding. Ever since, however, not a single successful short-term prediction has been made. No false prediction either, because no prediction has been issued. This is a natural consequence because short-term prediction has never been a serious target of the project. One of the main purposes of this paper is to present the author's view on how this strange situation was brought about. Naturally, most of what happened was not scientific matters, so that there are only a few scientific publications to be referred to in the following.

For the first five year, the project was named "EQ Prediction Research Project", and seismologists proposed to strengthen their seismic network. This was also a reasonable start and ample funds were allotted. Because of the ample funds secured for multiple years, however, strengthening the seismic network became an endless enterprise that has kept monopolizing most of the funds and staff all through the subsequent consecutive five year projects.

Motivated by the occurrences of EQs like 1968 M7.9 Tokachi-oki EQ, the government decided a larger effort may be made for practical EQ prediction, so that from the second five year plan, dropping the word Research, the name of the project was changed to "EQ Prediction Project" as if the research stage was over. Naturally, funding was substantially increased.

Of course, it goes without saying that short-term EQ prediction absolutely needs precursors. There have been reports of many kinds of EQ precursors since ancient Greek time until today, *e.g.*, Uyeda, Nagao and Kamogawa (2011).[18] They can be geodetic signals like 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 behaviors. Seismological events like foreshocks and pre-seismic quiescence can also be precursors. However, the majority of the reported EQ precursors are non-seismological. Therefore, the need for non-seismological measurements has been and remains obvious. But, these were never seriously supported by the project. So, no prediction was made and the five year reviews (always internal) therefore always left the impression that short-term EQ prediction was unrealistic, while the project itself prospered after each disastrous event.

One thing that has to be emphatically mentioned here is that in the early 1970's many government agencies began to jump on the EQ prediction bandwagon. Many projects, formally unrelated to EQ prediction but related 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 must 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 structure of the Big Projects is complicated and their budgets are nebulous. The only budget known to the author is that of the Headquarters for Earthquake Research Promotion, MEXT, which I might call "Big MEXT Project". (MEXT stands for the Ministry of Education, Culture, Sports, Science and Technology, Japan.) The 2012 annual budget of the Big MEXT Project was ~11 billion yen. This is big enough but, in fact, it is only a small fraction of Big Projects of other agencies. The 2012 budget of the National Project for EQ Prediction, available for 14 universities was a mere ~0.4 billion yen. Out of ~0.4 billion, ~0.02 billion can be used for short-term prediction research. What can we do?

History of EQ Prediction in Japan —after 1995 to 2011

The 1995 M7.3 Kobe EQ occurred without prediction, during the seventh five year plan (Fig. 1). Approximately 6,450 people lost their lives. This was Japan's worst EQ in the 20th century after the 1923 M7.9 Great Kanto EQ. The National Project for EQ Prediction, which never made any prediction, became a target of severe criticism. After prolonged deliberations at various levels, including genuinely external review held for the first time, a conclusion was reached that short-term prediction should be given up formally and efforts should concentrate on the "fundamental research", which was actually seismology in the author's view. Although they say their statement did not explicitly declare to abandon prediction, any reader can see it (see Nature News.[19),20)])

"Fundamental research" sounded sweet to the bureaucrats so that the project not only survived the criticism but funding was even increased. Thanks to this success, high-power seismic and GPS networks

Fig. 1. A high rise after a few weeks of the Kobe EQ. Photo taken by the author.

Fig. 2. After a few weeks of 3.11 Tsunami. Picture taken by the author.

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 scientists' hard work, precursors were too difficult to catch. But, this was untrue. Those who were involved with the National Project had not made a serious effort to research precursors because they knew seismometers would not help much. Practically no reports on precursors were presented at the meetings of the Coordinating Committee for Earthquake Prediction (CCEP) held every three months. When such reports were made rarely, they were received as laughable rumor. However, since they had been enjoying ample funding (although it was a dwarf amount in comparison with that of the Big Projects) for many years under the pretext of "EQ prediction", even the outside reviewers could not challenge the established vested interests of the powerful seismologists. After this, in the seismology community, negative perception toward short-term prediction was escalated to deny even the existence of precursors and to regard the research on them as not science.

After the Kobe disaster, there was a dramatic infrastructural change in the EQ related administration. The task of monitoring seismic activity was totally transferred from the National Project to the Headquarters for EQ Research Promotion of the Big MEXT Project, which is not interested in EQ prediction (in particular short-term prediction). Since the National Project was freed from seismic monitoring and long-term forecasting jobs by this change, it could concentrate on short-term prediction. But things went in a wrong direction.

EQ Prediction in Japan —after 2011 Tohoku EQ to present

On 11 March 2011, M9.0 Tohoku EQ hit Japan (Fig. 2). This EQ produced a huge tsunami, resulting in devastation of the Pacific side of the entire northeastern Japan. Damage included the loss of over 20,000 lives, and explosions and melt down at Fukushima No. 1 Nuclear Plant, *e.g.*, Tanaka, (2012).[21] The whole nation was thrown into crisis almost instantly.

Thanks to the National Project and Big Projects, Japan is where one of the world's best seismic as well as geodetic observation networks are installed. The mechanism of generation of this type of EQs is well explained by plate tectonics. They are sudden fault motions as a result of subduction of the Pacific plate (Fig. 3). The way EQs occur was believed to have been well understood by the so called asperity model (Fig. 4). 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, whereas outside the asperities, plates are less strongly coupled so that they can slip without EQs. From the 400 year history of old documents and modern seismometry, seismologists believed that the conceivable maximum EQ in this region could not exceed M8 class. However, the 2011 event demonstrated that 400 years was too short a period for evaluating the regional seismicity. In fact, geologic

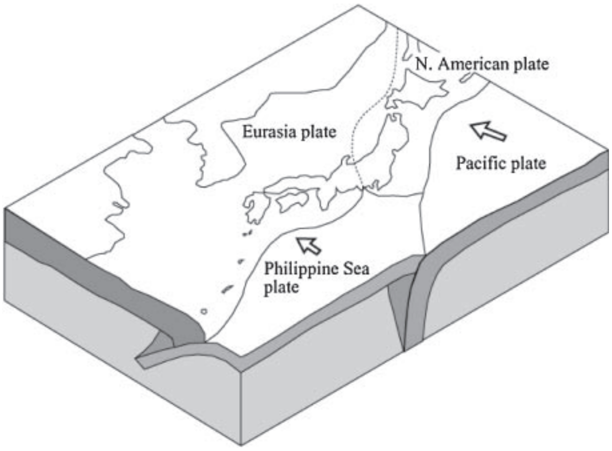


Fig. 3. Plate configuration around Japan.

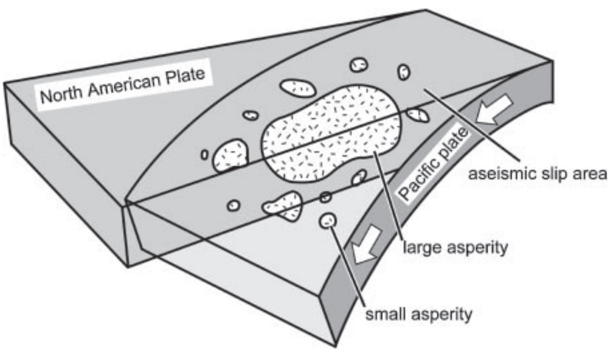


Fig. 4. Asperity model.

records of tsunami sediments were indicating that the AD 869 Jogan EQ could have been a M9 class event.[22] But such geologic information was not taken seriously.

After the 2011 event, some seismologists claimed that their misjudgment was, at least partially, due to the influence of "comparative subductology" which the present author and Kanamori developed some 4 decades ago.[23] We proposed that the subduction zones can be classified into Chilean and Marianas types by various contrasting features as illustrated in Figs. 5a and 5b. For example, the landward side of the Chilean subduction zone is the actively rising lofty Andean Cordilleras, whereas that of the Marianas is the actively spreading Philippine Sea, and very large EQs occur in Chile but not in the Marianas. We still hold this view since these are well observed facts. Some seismologists might have thought that the Japan subduction zone belonged to the Marianas type. In our view, however, the Japanese subduction zones are intermediate type in the sense that they are Marianas type topographically but Chilean type in the present day activity. The Japan Sea ceased opening millions of years ago and the Japanese Alpine mountains have been rising ever since. Perhaps, we should have emphasized more clearly that subduction type depends on time.

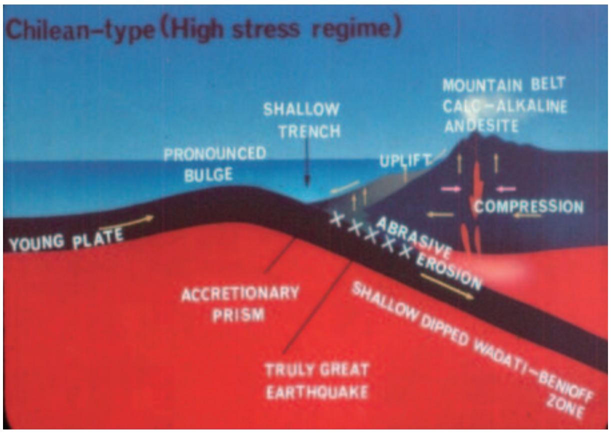
Regrettably, the general situation surrounding the EQ prediction remains essentially the same as before or is even worse after the 2011 Mega-quake. Seismologists lost confidence in general, so that their "Impossibility Myth" has become more "legitimate". They want to promulgate the impossibility of EQ prediction and even talk about disbanding the Working Group for EQ Prediction of the Seismological Society of Japan (SSJ).

On November 28, 2012, a proposal was made to renew the National Project which after the Kobe EQ had the name "Observation Research Project for Prediction of EQ and Volcanic Eruptions", which was essentially a simple coalition of the old EQ National Project and Volcanic Eruption National Project. The Science and Technology Council, MEXT came up with the interim outline of the renewed plan on September 4, 2013 inviting public opinions. 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 but completely free from prediction. They can keep receiving research contracts from the Big Projects as before.

Outlook for the future

Thus, the future of short-term prediction is bleaker. However, we have a different view. Since EQs are natural phenomena, they should be predicted by scientific endeavors. Indeed, we already have undeniable accomplishments. There have been numerous reports on electromagnetic and geochemical precursors after the 1995 Kobe EQ.[24)–27)] 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)[28] showed by rigorous statistics that their correlation with nearby EQs was clearly beyond chance (Fig. 6a, Fig. 6b). Also in the Izu island region, anomalous changes in the ultra-low frequency

(a)



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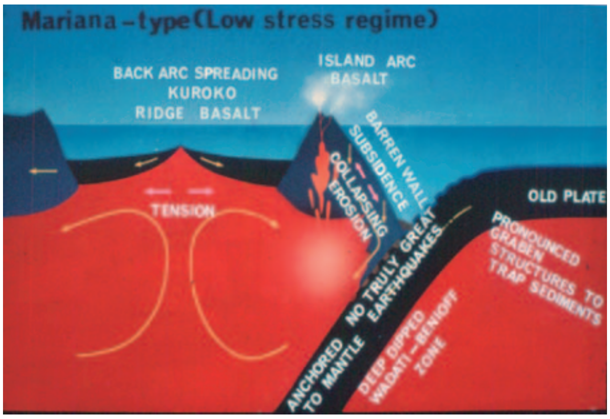

Fig. 5. (a) Chilean-type subduction. (b) Marianas-type subduction.

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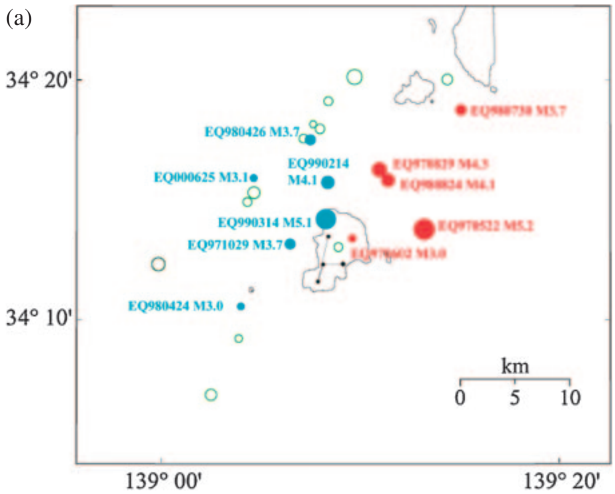

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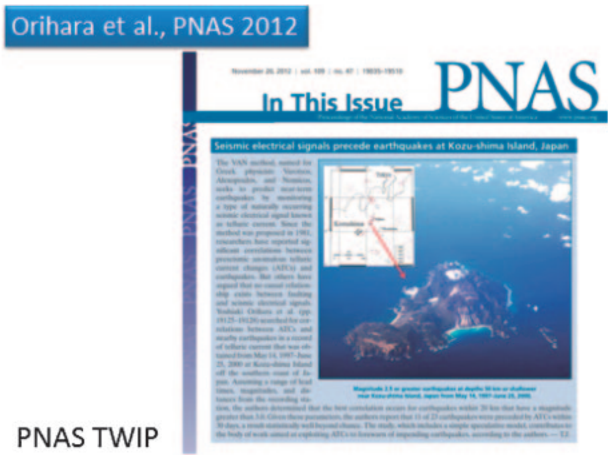

Fig. 6. (a) Geoelectric signals and nearby EQs around Kozu-shima Island. From May 14, 1997 to June 25, 2000. Red and blue circles are EQs with positive and negative signals. Broken line indicates the orientation of the Zenisu-ridge. For details, see Orihara *et al.*, (2012).[28] (b) Orihara *et al.*, (2012)[28] was selected for Highlights of PNAS Nov. 20, 2012 issue.

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 (Fig. 7).[29]

What about the Tohoku Mega-quake? There were in fact precursors, although most of them were recognized afterwards. There are also encouraging signs for the 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[30] for using satellites may come true soon.

There are reports on pre-seismic electromagnetic changes. One is on a pre-seismic reception anomaly of VLF and LF waves[31] and the other is on the variations of the geomagnetic field approximately 2 months prior to the main shock.[32] An issue of hot debate is the pre-seismic variation of the ionospheric electron content.[33)–35] One of the highly promising new developments is the detection of pre-seismic land movements using GPS data, which finally became tractable in 2013 by more than one group, including private sectors. Some unpublished sources claim GPS precursors to the Mega-quake were actually identified and the news was informed to a government agency before the main shock but was ignored as a rumor. Although still at preparation stage now, publications on these matters are expected in the very near future.

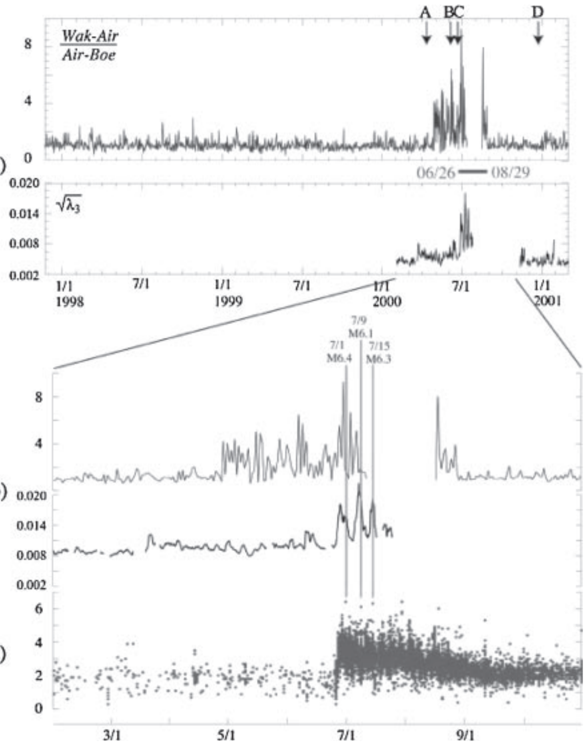

Fig. 7. Change of 0.01 Hz spectral intensity ratio of geoelectric potential difference at Wak–Air and Boe–Air dipoles, Niijima Island, and that of the third principal component at 0.01 Hz of the geomagnetic field at Izu Peninsula array station. (a) For 3-year period. A, D are signal-free, and B, C contain signals. (b) January through October, 2000. Three M6 EQs in July are indicated by vertical lines. (c) Seismicity of the Izu Island region. For details see Uyeda *et al.*, 2002.[29)]

Encouraging is that reports on promising pre-seismic phenomena are starting to come out even from the seismological data analysis.[36)–39)] Apparently, the longstanding "unproductive" National Project for EQ Prediction has finally been upgraded to a "productive" one. Sarlis *et al.* (2013),[40)] based on the basic concept that EQs are critical phenomena,[41),42)] examined the seismicity of Japan and found fluctuation of some parameter revealed a deep minimum a few months before the Mega-quake while all the other $M > 7.6$ main shocks in 1993–2011 also showed similar but shallower minimum.

The rapidly rising activity of the private sector is also encouraging. The reason for the rise is obvious. This is because the government will never make short-term predictions. If a government agency makes a false safety declaration, the result will be like the L'Aquila case.[43)] Inversely, if the prime minister declares an M8 Tokai EQ would come in three days and nothing happens, what would be the result? The "Large-scale earthquake countermeasures act" (English version is included in Rikitake (2001)[16)]) depicts the most unrealistic scenario. The government obviously is not an appropriate body for issuing short-term predictions. However, the demands for short-term prediction are acute from industries, hospitals, schools, local governments, and individuals, who realize that the National Project cannot be counted on and are willing to pay charges for useful information. In fact, there are several private companies who took up short-term prediction for their own business in cooperation with interested scientists. That in turn will be a source of research money for involved scientists. This will be a useful and flourishing information industry.

With all these new developments, we now are optimistic about the future of short-term prediction. We feel we are on the right track this time and our goal is in sight. But our optimism is not shared by seismologists at large for several reasons. One reason is their prejudice, namely the impossibility Myth. Another more understandable reason is that many, if not all, precursors are mere by-products of the EQ preparation processes and play no causative roles in EQ generation. Anomalous geoelectric currents may appear before an EQ, but they will not generate EQs. It is quite natural that seismologists are not interested in these precursors. Thus, the precursor research cannot be the main target of seismology.

This leads us to the very essence of the argument of this paper. Namely, seismology and the science of short-term EQ prediction are related but different scientific disciplines. I presume their difference is clear to the readers by now. In absence of a proper term for the variety of EQ prediction research, let us tentatively call this discipline "Predictology". At universities, there are courses on seismology, but not on "Predictology". This science has been pursued, without its name, mostly by physicists, radio engineers, chemists and even biologists, with no or little support. Now is the time when a university "Predictology" course should be established.

Conclusion

The National Project for Earthquake Prediction has been in operation with ample financial support in Japan since 1965, but no prediction has ever been made. It goes without saying that short-term prediction is the only meaningful prediction and precursors are absolutely needed for it. The majority of precursors are non-seismic. The main reason of no success so far is that the National Project has failed in harnessing any reliable precursors because most of the efforts have been devoted to merely strengthening the seismometer network, which is not best suited for precursor search. This wrong strategy has not been changed because the project has been run by a group of seismologists.

After the unpredicted Kobe earthquake in 1995, the National Project officially gave up short-term prediction and decided to concentrate on basic seismology, namely installing more seismic stations. At about the same time, there was a big infrastructural change in the national earthquake related administration. By this change, monitoring of seismic activities was totally transferred from the 0.4 billion yen National Project to the 11 billion yen Headquarters for Earthquake Research Promotion, MEXT, which is not interested in EQ prediction. They are interested only in long-term assessment.

After the Tohoku Mega-quake, there has been considerable confusion among seismologists, and now the National Project carries an arcane title "Earthquake and Volcano Observation Research Project to contribute to Disaster Mitigation", completely dropping the word Prediction.

Recently, however, significant progress is being made in real short-term prediction by scientists of diverse disciplines including even seismologists and some promising signs are arising from private sectors. It is the time that we should realize that short-term prediction is the job of neither the National Project nor the national government. Precursor research will be done by interested scientists and actual prediction alerts will be done by private sectors or by local authorities of high EQ/tsunami risk areas. We look forward to a big-bang in the new era of earthquake prediction. EQ prediction will be the best international contribution that Japanese science and technology can make to the circum-Pacific and other earthquake countries.

The National Project should be criticized for not making efforts for short-term prediction. But much more outrageous is the Big Projects. Their programs are not all meaningless. In fact, some are useful. What is almost criminal is that the Big Projects secured and still secure their large funds in ambiguous pretext of EQ prediction.

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Profile

Seiya Uyeda was born in 1929 in Tokyo. He graduated from the University of Tokyo and served the Geophysical Institute and Earthquake Research Institute of the same university until 1990. His research may be roughly divided into three. One is rock-magnetism in his graduate student days (1950–1957) under T. Nagata. He discovered the Reverse Thermo-Remanent Magnetism on which he wrote his thesis for Doctor of Science. For this work, he was invited to Cambridge and Oxford Universities in 1958–59 as British Council Scholar where he further learned about geophysics from Sir Edward Bullard. The second research in the following 30 years was general solid geophysics, including land and marine terrestrial heat flow measurements with K. Horai at University of Tokyo and with R. von Herzen at Scripps Institution of Oceanography, the driving mechanism of plate tectonics at MIT and Lamont-Doherty Earth Observatory with D. Forsyth, tectonics of island arcs and subduction zones with A. Sugimura, A. Miyashiro and many others at Tokyo, with H. Kanamori at Caltech and with T. Hilde at Texas A&M University. The last and the present research after ∼1990 is the short-term earthquake prediction at Tokai University, Riken and Japan Academy. On top of the Japanese colleagues (T. Nagao, M. Kamogawa and others), the group under P. Varotsos from Greece, J-Y Liu and C-S Lee from Taiwan, Q. Huang from China are close colleagues in research. He is a member of the Japan Academy and foreign associate of the National Academy of Sciences, USA, foreign member of the Russian Academy of Sciences and the American Academy of Arts and Sciences.