Transactions on Science and Technology Vol. 3, No. 3, 507-516, 2016

TRANSACTIONS ON SCIENCE AND TECHNOLOGY

Earthquake Prediction

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ABSTRACT: This paper aims at the types, methods, and four basic factors of earthquake prediction: model and mechanism, single or multiple observation method, the accuracy of predicting, and testing space and time. They are used to examine and clarify the content and condition of earthquake prediction. Earthquake prediction first stresses on setting up physical model. To conform with tectonic structure and the earth surface fault system distribution, multiple observation methods are used to examine different seismogenic processes of temporal unusual precursors. Scientists have the opportunity to measure the unusual precursor data of the physical model, and further reach the prediction goal of earthquakes. This paper discusses the six great potential kinds of earthquake prediction methods, where half of the methods belong to the electromagnetic precursor anomalies. By establishing the mechanism of the LAI coupling, earthquake prediction is expected to have further break-through in the near future.

KEYWORDS: Earthquake prediction; EQ precursors anomalies; Electromagnetic anomalies; LAI coupling

Received 7 March 2016 **Revised** 22 September 2016 **Accepted** 9 December 2016 **Online** 20 December 2016

INTRODUCTION

In general, there are four kinds of earthquake prediction: (1) estimate of time-independent hazards, (2) estimate of time-dependent hazards, (3) earthquake forecasting (Seismic potential evaluation), and (4) deterministic prediction. Earthquakes are inherently predictable. We can certainly know in advance their location (latitude, longitude and depth), magnitude, and time of quakes, all within narrow limits (again above the level of chance) so that evacuation can take place (Main, 1999). The fourth kind is called earthquake prediction in this article.

Earthquake prediction is important for planning and preparing for disaster management (Cheng, 2016a). It is a prediction analysis of multiple goals, it must meet the needs of the following three factors: (1) magnitude (2) epicenter and (3) time, and it must comply with certain precise requirements of the three prediction goals at the same time. In addition, the methods of earthquake prediction must be examined through the precision of time and space. That means the same prediction method (or the same type of earthquake prediction) must apply to different area, time, and environment. In addition, we need to look at the historical earthquake catalogues in different areas to see whether there is no precursor (this area needs to have built the earthquake precursor observation system beforehand), but having earthquake “fail to report”, or if there is an observation of earthquake precursor but without any earthquake taking place like a “false report” (See Table 1). These are the two precision tests that all earthquake prediction methods have to face, and they are also the basic requirement of earthquake prediction.

Table 1. Earthquake precursor observation system

Precursor	If Quake	If No Quake
Yes	Good	**False report**
No	**Fail to report**	Sure

The only two successful earthquake prediction events based on the historical review of earthquake prediction were the 0204 M7 Haicheng earthquake of China in 1975, and the 0712 M7 earthquake occurred in Menlian city of Yunnan in China in 1995. Other released events of earthquake prediction are considered doubtful or failing prediction events.

EARTHQUAKE PREDICTION MODEL

There are numerous earthquake prediction methods. This paper focuses on six aspects of these predictions: (1) category (2) method (3) model and mechanism (4) single or multiple observation method (5) accuracy of prediction, and (6) space-time inspection. The following is the basic classification of earthquake prediction. There are six major kinds of earthquake prediction includes (1) characteristic of seismic activity, (2) crustal deformation, (3) gravity and terrestrial magnetism, (4) electromagnetic, (5) groundwater chemistry and water level, and (6) others including satellite infrared and telemeter measurement etc. This paper chooses six major kinds of earthquake prediction methods with clear physical model and tectonic structure, including VAN method, M8 method, pattern dynamics method, electromagnetic anomalies (EK) & (AE), ionospheric total electron content method (TEC), and flow mechanochemistry model.

On the aspect of category, it can be divided into statistics model, statistics-physical model, and physical model. The general physical model includes two kinds: long-immediate precursors and short-term precursors. On the mechanism aspect, it can be divided into three kinds such as the fault system, tectonic structure, LAI coupling and others. Here LAI coupling refers to Lithosphere-Atmosphere-Ionosphere coupling. For single or multiple observation method, the prediction of the location of epicenter is considered the most difficult among the three goals of earthquake prediction. The single method is often difficult to meet three prediction goals that have the precision requirement at the same time. For the observation method of single precursor, the magnitude and time appear to be easier to observe from general single earthquake precursor; however, there is a lack of certain precise earthquake prediction method on the epicenter of quake. The tectonic structure and the earth's fault system must telescope in order to predict possible epicenter position. The observation method of multiple precursors is a complementary method which combines the three goals of earthquake prediction.

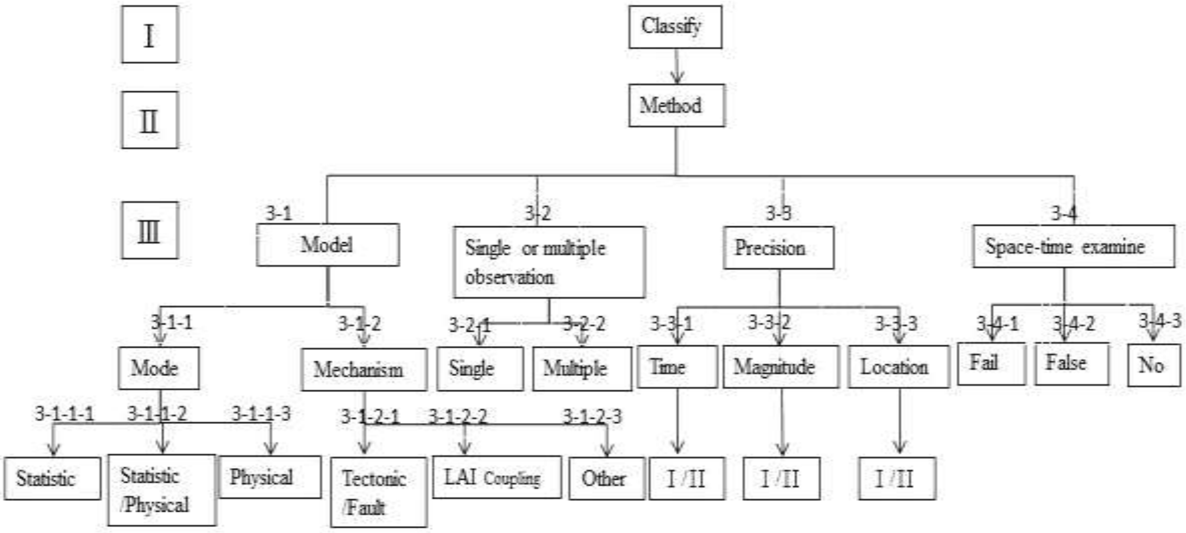


Figure 1. Earthquake prediction: The model, method and test relation diagram (Cheng, 2016).

On the aspect of accuracy of prediction, it typically fails to reach Level I (magnitude: M±0.5, location: ±30km, time: ±3 days), but it reaches the prediction accuracy at least with Level II (magnitude: M±0.7, location: ±100km, time: ±22 days). The last aspect is space-time inspection: It is the main method that examines model accuracy. If the model reports "Fail to report", it is having no precursor but earthquake incidents appear, and "False report" for having precursor but no earthquake incident appear. From the six kinds of basic classification mentioned above, we can get the following related diagram represent Earthquake Prediction (Figure 1).

EARTHQUAKE PREDICTION METHOD

The historical development of earthquake prediction emphasizes on the seismology prediction method in early days such as seismic precursor activity, the change precursors of seismic activity parameter, the Vp/Vs focal mechanism, and the precursor of parameter changes. The two examples of statistic models are GM (1,1) model and GM (1,1) Verhulst model that are used in Cheng (2016b) for predicting the seismic activities in Sabah. They are under the Grey Forecasting theory in Grey System Theory. They are used to evaluate seismic potential zones of future earthquakes. The ground motion is often the highly centralized concentration area. The control of the physical mechanism of crustal deformation can usually identify potential ground motion areas. Gravity, magnetic changes, the ground water chemistry, and the rising and lowering of groundwater level before the earthquake are all common precursors of traditional earthquake prediction. Typically, through the continuous observation system, if the observation position or the observation wells are appropriately selected in the fault distribution, there are better prediction results in magnitude and earthquake occurrence time if the noise from the environment is filtered out.

Lithosphere electromagnetic anomaly is an earthquake prediction method that has the most potential to fit the tectonic structure and fault distribution. Since one can measure data with physical models, it can further predict earthquakes. It is deductive in nature. This kind of earthquake prediction method is currently the most effective one. The researches of earthquake precursors during the past decades have collected many results, but the materials must pass testable tests to be published. Although general statistical earthquake prediction method can be used to examine the reliability of the data, and to further sum up the relationship, there is less ability to predict. We can further predict earthquakes only on the basis of the physical model to examine data. This is the first and the decisive element of the four primary conditions of earthquake prediction (model, single or multiple precursor observation method, accuracy of prediction, and space-time inspection).

In this paper, the six kinds of earthquake prediction methods described in the next section all belong to physical model. Among those methods, three of them belong to electromagnetic precursor anomaly, one belongs to seismicity model, another as ultrasonic thermodynamic model, and the other as the dynamic mechanism. Figure 2 shows the possible observation method for earthquake precursors, whereas Figure 3 shows the relation between the time of earthquake precursor and magnitude. The best choice of earthquake prediction is to use a variety of observation methods to determine the location of the epicenter.

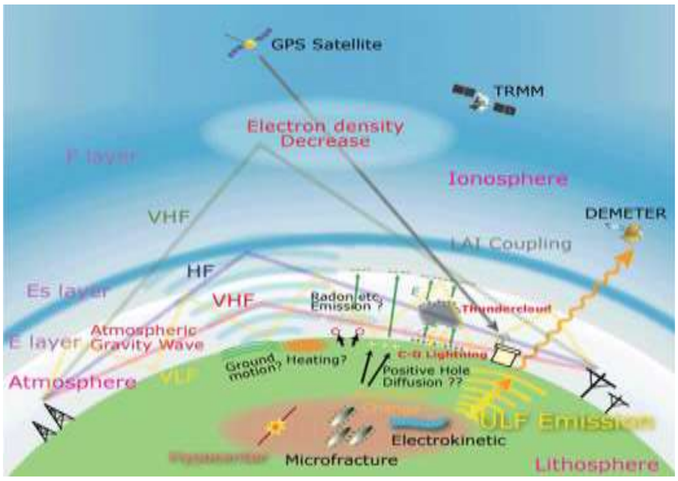


Figure 2. Cycle and layer couple of earthquake precursor and electromagnetic anomaly precursor (Liu *et al.*, 2002).

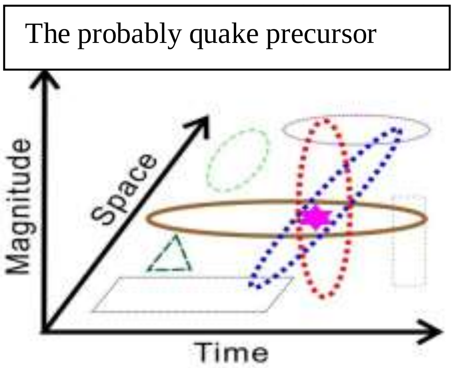
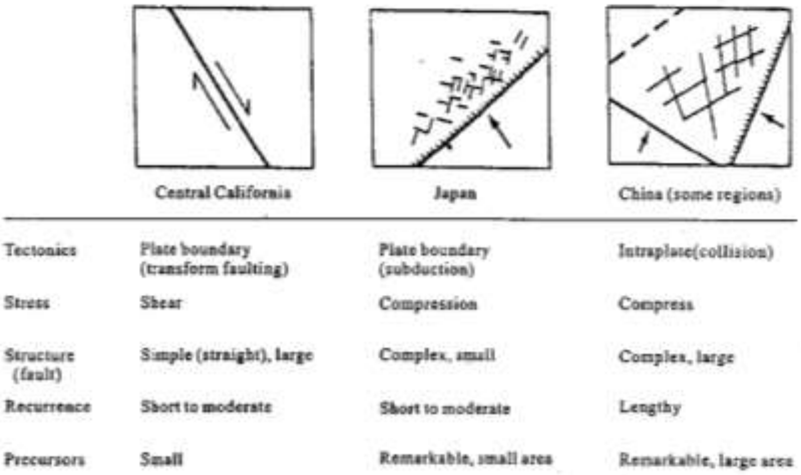


Figure 3. Time, magnitude and location relation of the earthquake precursors

Mogi (1985) proposed the relationship of different tectonic structures in the area and earthquake precursors more than 30 years ago. Figure 4 shows the diagram of earthquake precursor characteristics of different tectonic structures area. From the development of these physical models, multiple observation approaches, and the construction of tectonic mechanism, to the LAI coupling which yield brilliant results in recent years, a multiple electromagnetic observation method combined with a multi-physical model is developed (see Figure 2). It is the most breakthrough physical model which is precise and is able to pass the space-time inspection.



	Central California	Japan	China (some regions)
Tectonics	Plate boundary (transform faulting)	Plate boundary (subduction)	Intraplate(collision)
Stress	Shear	Compression	Compress
Structure (fault)	Simple (straight), large	Complex, small	Complex, large
Recurrence	Short to moderate	Short to moderate	Lengthy
Precursors	Small	Remarkable, small area	Remarkable, large area

Figure 4. Earthquake precursor characteristics of different tectonic structures area (Mogi, 1981).

THE SIX MAIN KINDS OF EARTHQUAKE PREDICTION METHODS

VAN method (Electromagnetic, Single method, Level II, Space-time testable)

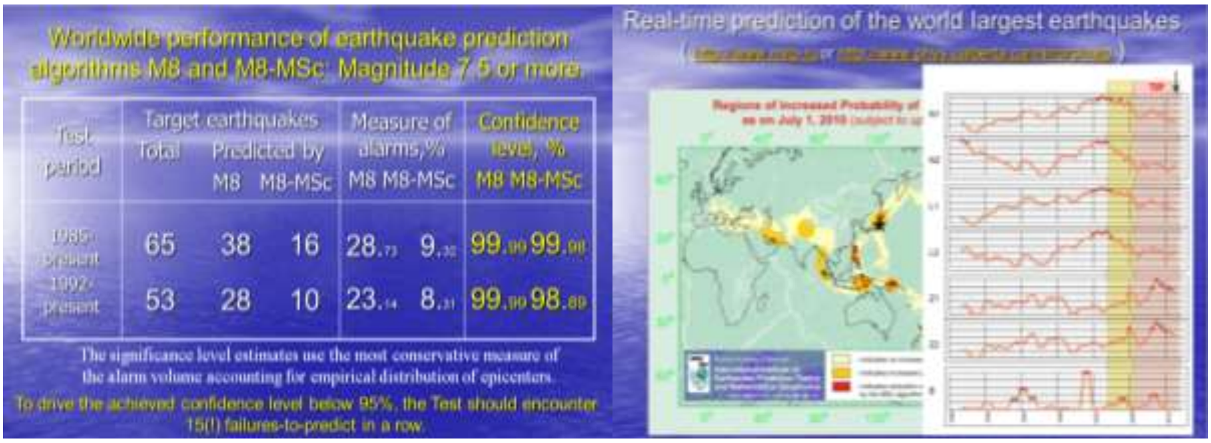
Professors Varotsos, Alexopoulos and Nomicos (Lazaridou-Varotsos, 2013) -“ known as the VAN”- claimed in a 1981 paper an ability to predict M ≥ 2.6 earthquakes within 80 km of their observatory in Greece approximately seven hours beforehand, by measurements of “seismic electric signals”. In 1996 Varotsos and other colleagues claimed to have predicted impending earthquakes within windows of several weeks, 100–120 km, and ±0.7 of the magnitude.

The VAN predictions have been criticized on various grounds, including being geophysically implausible, being “vague and ambiguous”, failing to satisfy prediction criteria, and retroactive adjustment of parameters. Among a critical review of 14 cases where VAN claimed, only an earthquake occurred within the prediction parameters in one case. The VAN predictions not only fail to do better than chance, but show “a much better association with the events which occurred before them”, according to Mulargia and Gasperini. In addition, VAN’s publications do not identify and eliminate possible sources of electromagnetic interference (EMI). Taken as a whole, the VAN method has been criticized as lacking consistency in the statistical testing of the validity of their hypotheses. In particular, there has been some contention over which catalog of seismic events to use in vetting predictions. This catalog switching can be used to conclude that, for example, of 22 claims of successful prediction by VAN, 74% were false, 9% correlated at random and for 14% the correlation was uncertain. In 1996 the journal Geophysical Research Letters presented a debate on the statistical significance of the VAN method; the majority of reviewers found the methods of VAN to be flawed, and the claims of successful predictions statistically insignificant. In 2001, the VAN method was modified to include time series analysis, and Springer published an overview in 2011.

M8 method (Seismicity pattern, Single method, Space-time testable)

This algorithm was designed by retrospective analysis of seismicity preceding the greatest (M ≥ 8) earthquakes worldwide, as its name. Its prototype (Keilis-Borok & Kossobokov, 1984) and the original version (Keilis-Borok & Kossobokov, 1987) were tested retroactively at 143 points, of which 132 are recorded epicenters of earthquakes of magnitude 8.0 or greater from 1857-1983 (see Figure 5). The M8 algorithm uses traditional description of a dynamical system adding to a common phase space of rate (N) and rate differential (L) dimensionless concentration (Z) and a characteristic measure of clustering (B).

The algorithm to reduce the area of alarm was designed by retroactive analysis of the detailed regional seismic catalog (Kossobokov, Keilis-Borok & Smith, 1990) prior to the Eureka earthquake (1980, M=7.2) near Cape Mendocino in California, hence its name was abbreviated to MSc. Qualitatively, the MSc algorithm outlines an area of the territory of alarm where the activity, from the beginning of seismic inverse cascade recognized by the first approximation prediction algorithm (e.g. by M8), is continuously high and infrequently drops for a short time. Such an alternation of activity must have a sufficient temporal and/or spatial span. The phenomenon, which is used in the MSc algorithm, might reflect the second (possibly, shorter-term and, definitely, narrow-range) stage of the premonitory rise of seismic activity near the incipient source of main shock. The M8 algorithm is applied first, then, if the data permits, the algorithm MSc provides a reduction of the TIPs’ spatial uncertainty (although at the cost of additional failures-to-predict).



Worldwide performance of earthquake prediction algorithms M8 and M8-MSc: Magnitude 7.5 or more

Test period	Target earthquakes Total	Predicted by M8	Predicted by M8-MSc	Measure of alarms, % M8	Measure of alarms, % M8-MSc	Confidence level, % M8	Confidence level, % M8-MSc
1985-present	65	38	16	28.73	9.30	99.99	99.98
1992-present	53	28	10	23.14	8.31	99.99	98.89

The significance level estimates use the most conservative measure of the alarm volume accounting for empirical distribution of epicenters.

To drive the achieved confidence level below 95%, the Test should encounter 15(!) failures-to-predict in a row.

Figure 5. M8 prediction accuracy test and M8 method (Kossobokov, 2011).

Pattern Dynamics method (Fault system, Single method, Space-time testable)

Earthquake faults occur in topologically complex, multiscale networks or systems that are driven to failure by external forces arising from plate tectonics. The faults occurred interaction over a wide range of spatial and temporal scales. The basic problem is that the details of the true space-time, force-displacement dynamics are unobservable. In order to completely specify the problem, the true dynamics would have to be observable for all space and at all times. In fault systems these unobservable dynamics are usually encoded in the time evolution of the Coulomb failure function as:

$$CFF(x, t): CFF(x, t)=\tau(x, t) -\mu_s\sigma_N(x, t) \quad (1)$$

where $\tau(\mathbf{x}, t)$ is shear stress at point $\mathbf{x}$ and time t, μ_s is the coefficient of static friction, and $\sigma_N(\mathbf{x}, t)$ is normal stress. However, the space-time patterns associated with the time, location, and magnitude of the sudden events (earthquakes) are observable, leading to a focus on understanding their observable, multiscale, apparent dynamics (Rundle *et al.*, 2000; 2003).

The second problem, equally serious, is that the nonlinear earthquake dynamics is strongly coupled across a vast range of space and timescales that are much larger than “human” dimensions. Complex nonlinear threshold systems frequently show space-time behavior that is difficult to interpret. It describes a technique based upon a Karhunen-Loeve expansion that allows dynamical patterns to be understood as eigenstates of suitably constructed correlation operators. The evolution of space-time patterns can then be viewed in terms of a “pattern dynamics” that can be obtained directly from observable data.

Electromagnetic anomalies (EK) & (AE) (Electromagnetic, Single method)

Electromagnetic anomalies (Hayakawa & Fujinawa, 1994; Hayakawa, 1999) cover a wide range of frequencies from ultra-low frequency (ULF), very low frequency (VLF) up to very high frequency (VHF) that have been observed before earthquakes. However, the ULF range emissions provide a greater source of information regarding the earthquake precursor. One of the main techniques of investigating such a precursor is by using a magnetic sensor. The magnetic field, generated by the electrokinetic (EK) (Majaeva *et al.*, 1997) effect is calculated for a spherical, time-varying pressure source in a layered half-space chosen due to its exact solvability. Therefore, in the general case, if the electrokinetic effect occurs in a water filled fault, the transient magnetic field can appear at the surface as an ULF pulse. It could be found enhancement in ULF magnetic field intensity 3 to 5 days before the main shock as usual. Micro-cracking in the earthquake preparation zone is accompanied by the generation of acoustic emission (AE) (Fedorov & Pilipenko, 2014). Even low-intensity AE can essentially modify the underground fluid dynamics owing to the influence of high-frequency acoustic field on filtration process. The occurrence in the crust under pressure of a region with distinct hydrodynamic and electrokinetic parameters will result in an appearance of anomalous telluric and magnetic fields on the surface above. The suggested hypothesis about possible coupling between AE and geoelectrical anomalies need observational verification.

Ionospheric Total Electron Content method (TEC) (Electromagnetic, Ionospher LAI coupling, Multiple method, Level I, Space-time testable)

Prior to a loud earthquake, various unusual precursor anomalies such as sound, light, electricity, magnetism for a long time by mankind can be observed. Researchers working in U.S.A., Russia, Japan and China etc., have already invested the earthquake observation and prediction for many years. After the heavy earthquake of Kobe in 1995, Japan invested a large number of manpower and funds to study the electromagnetic precursor anomaly of the earthquake, and has issued nearly one thousand academic periodical theses and has already made considerable progress.

The global positioning system (GPS) has broadened applications in geosciences. It could study variations of the ionospheric total electron content (TEC) to search anomalies associated with strong earthquakes. This paper aims to (1) deduce ionospheric TEC from measurements of the CWB GPS (from Taiwan) receiver network, (2) construct a reference for identifying anomalies of the GPS TEC, (3) examine the relationship between ionospheric anomalies and strong earthquakes, and (4) develop a statistical model to identify and monitor temporal and spatial anomalies of the ionospheric GPS TEC in Taiwan (Liu *et al.*, 2002; 2006; 2008; 2009). The working items have been cross-compared with various pre-earthquake anomalies of the ionospheric GPS TEC and the other measurements, such as the geomagnetic field, land deformation, geography, well water level etc. to search for the forthcoming epicenter. Meanwhile, data from the CWB GPS network will be used to construct the ionospheric TEC maps to monitor pre-earthquake anomalies and also to foresee the epicenter (see Figure 6).

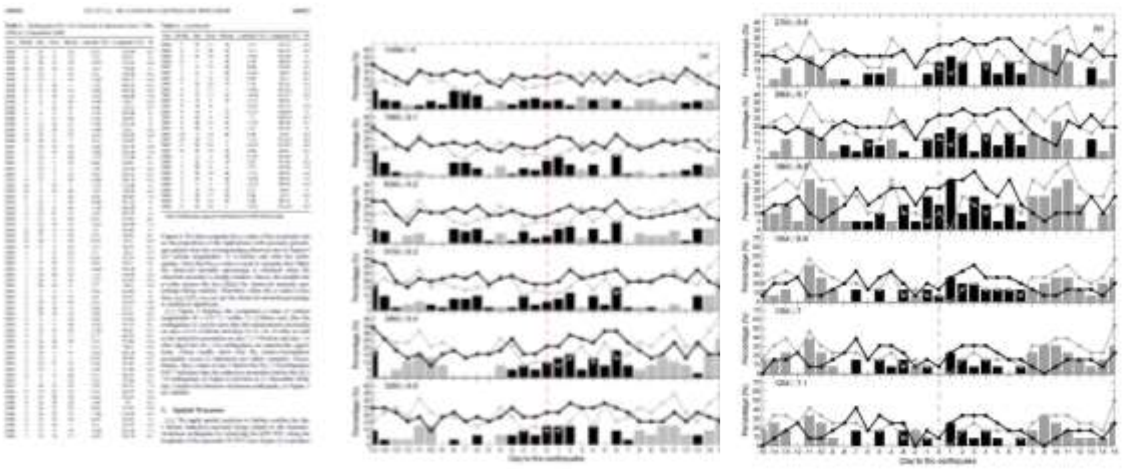


Figure 6. TEC prediction accuracy test (Liu *et al.*, 2010).

Flow Mechanochemistry Model (Fault theory, Single method)

It is proposed that tectonic instability leads to an explosive transformation, creating a slightly supersonic shock wave propagating along the altered fault core, leaving a wake of shaking fragments. As long as the resulting high-frequency acoustic waves remain of sufficient amplitude to lead to a fluidization of the fault core, the fault is unlocked and free to slip under the effect of the tectonic stress, thus releasing the elastic part of the stored energy. Figure 7 shows the crust control of the chemical transformations. Strain, stress and heat flow paradoxes: there is no need for elastic strain concentration over a scale of about 10 km (which, as we have reviewed, is usually not 16 observed) and very localized plastic-ductile strains are expected. There is no need for large stress to unlock the fault and the low friction is generated dynamically, preventing heat generation and providing a solution to the heat flow paradox.

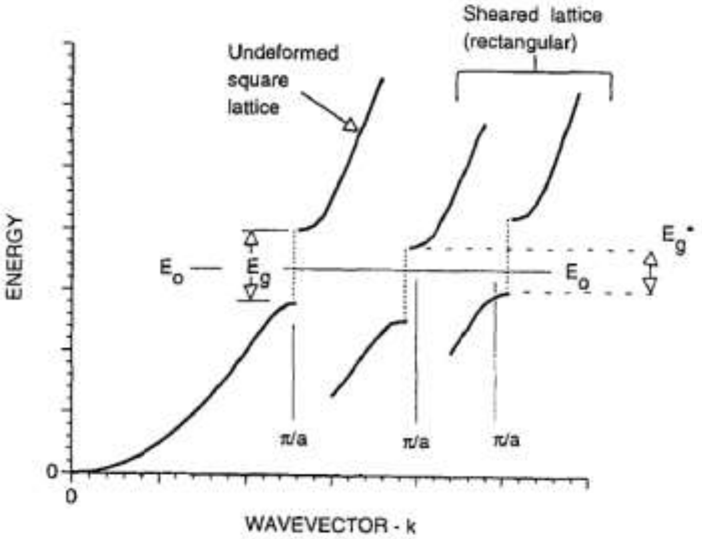


Figure 7. Crust control of the chemical transformations (Sornette, 2008).

CONCLUSION

Earthquake prediction is the ultimate goal of earthquake science. If the lithosphere and the regional fault system of the earth's surface is a non-linear system, earthquake can be predicted. In other words, based on the accumulation of seismic strain energy and reaching critical state, the trigger mechanism, the focus area rupture, the instant strain energy release, and the fault plane dislocation, they can induce the quake groups and aftershocks. Passing through these procedures, in the space-time domain, with physical model, scientists will look over various earthquake precursors step by step to assess how long after and where magnitude earthquakes will take place.

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