NOTES

THE NATURE OF SEISMIC SOURCES AND THE PREDICTION OF EARTHQUAKES

Introduction

This note attempts to summarise the salient aspects of the special issue of Tectonophysics (v.338, 2001) edited by H. Gupta, P.K. Chadha and D. Srinagesh, which is entirely devoted to the topic of sesimic sources and the prediction of earthquakes.

This volume incorporates the proceedings of the International Symposium on " The Nature of Seismic Sources and the Prediction of Earthquakes" organised by the International Association of Seismology and Physics of the Earth's Interior (IASPEI) during the XXII General Assembly of the International Union of Geodesy and Geophysics (IUGG) at Birmingham, UK during July 1999. The volume contains 14 papers; first three deal with the problems and approaches for possible prediction of earthquakes, the next four deal with the testing of forecast hypothesis, while the remaining seven are case histories.

Hypothesis and Problems

In the first paper, Prof. F.F. Evison argues that earthquakes, though obeying physics of failure processes, cannot be simply predicted by application of laws of physics, as an electric current in a resistive circuit can be predicted by Ohm's law. He further argues that the discovery of "plate tectonics" though supports the concept of 'seismic cycle', a corollary of 'seismic gap' hypothesis, evidence for the seismic cycle is in any case difficult to obtain because of the very long periods of time between successive large earthquakes. The more recent discovery of 'deterministic chaos' has challenged the 'seismic gap' hypothesis, but the seismogenic medium is in a state of "self organised criticality", a type of deterministic chaos. This opens up the prospect of long range synoptic forecasting based on precursory phenomena, as in Meteorology. According to him, the seismicity precursors are much easier to study because of the wealth of observatory data and the efficacy of modern seismograph networks. The comparative lack of data in other types of precursors like seismic velocity change, electrical resistivity, radon emission, water level change and geochemical indications makes their empirical study more difficult. He believes that empirical seismicity studies may be successful for 'synoptic earthquake forecasting' despite the recent emergence of a view that earthquake prediction is unattainable.

In the second paper, Prof. MaxWyss has been equally candid. He says that the statement of Geller et al. (1997) that "earthquakes are not predictable" is misleading. The problem of earthquake physics is difficult because the source in deep earth is not directly accessible for experiment, and because the state of stress cannot be directly observed. Further, seismology is extraordinarily young science. The causes of earthquakes are known only after the discovery of plate tectonic theory in 1960s, and technological advances for superior earthquake catalogues started in the 1980s. This means that for a study of seismicity patterns of smaller earthquakes, we have not quite two decades of data, yet return periods of large earthquakes typically extend over 100 years. It was Geller's (1997) incorrect statement that "earthquake prediction research has been conducted over 100 years with no obvious success". He further added that the very recent Global Positioning System (GPS) and Synthetic Aperture Radar Interferometry (InSAR) techniques are spectacularly successful methods to measure and monitor crustal deformation at the sub-centimetre level. These are suitably deployed in Japan and are responsible for significant advances in the understanding of the rupture initiation process. The level of funding in US and in other countries has been far below the level to make any significant advances in this difficult problem.

It is expected that major ruptures of Earth's crust are associated with 'transients'; transient means local temporary change in some physical parameters. Thus our job should be how best we measure carefully and quantitatively the properties of transients in Earth's crust, how to construct models to understand them, and how to test hypothesis. This is not an easy job, because we must expect substantial differences in behaviour of the crust in different tectonic settings, thrust environments and normal faulting regimes having opposite orientations and different levels of stress tensor, are not likely to produce the same phenomena. He concludes that the earthquake prediction is difficult, but not impossible. Therefore, the question is not whether or not we can predict earthquakes; rather it is how well we can predict them. Although claims of successful predictions are often not justified, a few correct predictions have been made. Leadership is necessary to raise the funding to an adequate level and to involve the best minds in this promising, potentially extremely rewarding, but controversial research topic.

Prof. P. Bernard, in the third paper, emphasises that the 'crustal transients' are much more diagnostic than 'precursors' to understand earthquake processes. Many observations on precursory (like geochemistry, temperature) phenomena are reported during the last decade, but the reliability of their physical correlation to the subsequent earthquake is often debatable and very little can be inferred concerning the underlying coupling processes. Study of 'crustal transients' (like earthquake swarms, quiescent, fluid instabilities, episodic fault creep, ...) should be our targets, but it is an extremely difficult problem. He suggests multi-parameter measurements in deep boreholes, in particular fault zones at seismogenic depths, differential tomography of the elastic and electric properties of the crust. Deep borehole drilling projects with permanent downhole observatories, consisting major faults at seismogenic depths, are starting in California, Japan and Europe. He believes that the ability to detect transients and to model the 'transient-to-earthquake' triggering process will be the key for assessing the predictability of earthquakes in future.

Some Experimental Results

In the next section, some experimental results of testing of hypothesis are discussed. Stuart Crampin suggests that study of 'shear-wave splitting' which is sensitive to microcrack geometry can monitor build-up of stress before large earthquakes. He terms this experiment as 'stress forecast' and successfully estimated time and magnitude of an M=5 earthquake in Iceland . He suggested that in the absence of local seismicity, or optimum recording geometry, the time and magnitude of future earthquakes can be estimated by analysing shear-wave splitting in controlled-source cross-well seismology between three boreholes. In northern Iceland, a preliminary stress monitoring site is being set up.

In their paper, Keilis Borok et al. sum up the 'holistic' approach in earthquake prediction. This approach is part of a much broader range of studies in non-linear dynamics of the lithosphere including chaos, self organised criticality and scale invariance. A large scale experiment in advance prediction of large earthquakes worldwide has been launched to test the prediction algorithm. The test is unprecedented in rigor and coverage, but the major drawback is the rate of false alarms. A possibility is outlined to develop new generation prediction-methods with five fold increase in accuracy.

R. Console outlines the methodological aspects of the statistical evaluation of earthquake forecasting hypothesis. The concept of likelihood allows the comparison between different forecasting hypothesis. He suggests that time dependent clustering model performs better than Poisson time-independent model with a likelihood ratio of 5×10^{36}. The test of earthquake forecasting models requires suitable data base for a reliable statistical analysis, and the database should be independent of that used in the formation of the hypothesis. Unfortunately, for earthquake forecasting hypotheses involving large recurrence times, a real time test on new observations could take an exceedingly long time to be practically feasible.

Gennady Sobolev tests the RTL algorithm, which includes three functions : r_i = epicentral distance, t_i = times of past events and l_i = source size of seismic event, using the seismological catalogues of Kamchatka and Japan. The reduction of the RTL parameter, as product of R, T and L, from the zero level of perennial background corresponds to the stage of 'seismic quiescence', while subsequent reestablishment to zero level characterises the stage of foreshock activation. The author observes that a seismic quiescence had taken place before the three Kamchatka earthquakes M>7.0, and the large 1995 Kobe earthquake in Japan, M=7.2, which was followed by foreshock activation. Although the RTL results were encouraging and in the recent past a real time prediction was made based on seismic quiescence and foreshock activation before the December 5, 1997 earthquake (M 7.7) in Italy, the author suggests that further investigation should be combined to understand physics of the earthquake source for reliable predictions.

Case Histories of Earthquake Forecasts

Harsh K. Gupta reports that Gupta and Singh (1986) made a medium-term forecast of an earthquake M=8.0±0.5+ depth 100 ± 40 km in NE India region, in an area between 21-25.5° N and 93-96°E, within a time-span 1986-1990. The forecast came true with the occurrence of the M=7.3 earthquake on August 6, 1988 with the specified spatial, depth and temporal parameters. The forecast was based on the concept of precursory swarms and quiescence preceding the main shocks.

Masajiro Imoto applies the stress release (SR) model to Nankai earthquakes in Japan. The SR model is based on the concept of elastic rebound theory. The author studied eight most recent earthquake sequences, and observed that this region is a typical example of repetition of stress accumulation and its release. He suggests that long term probabilities in the Nankai area based on this model would be worth evaluating as a better option, than simple Poisson model. He has also argued the superiority of the SR model to renewal models of earlier researchers.

Enescu and Ito report detailed analysis of seismic activity between 1996 and 1998 in a broad area surrounding the 1995 Kobe earthquake. Various precursory changes, such as quiescence followed by increased seismicity, b-value and fractal dimension, were reported before the occurrence of the main shock.

Arabelos et al. report underground water level and temperature changes with respect to earthquakes occurring during 1988-1989 in a seismically active area close to Thessaloniki, Greece. The magnitude of the underground water level change varies from 3 to 10 cm and that of temperature from 0.3 to 0.8°C. They applied a graphical method in order to detect observations that may unduly influence the sample autocorrelation coefficients. They observed a correlation between magnitude of earthquake and the magnitude of changes (level or temperature) of the underground water.

Popescu and Radulian report the source characteristics of two seismic areas in the eastern Carpathians foredeep region, Romania. The application of empirical Green's function deconvolution is proved to be highly efficient, and the recent broad band networks offer good opportunities for better constraints of the seismic source of future sequences in the region.

Giovambattista and Tyupkin report the relation of the time-to-failure model to the hypothesis of fractal structure of seismicity. The results of application of the long-periodic time-to-failure model to the analysis of the process of acceleration of seismic energy emission in the laboratory experiments on rock destruction and before strong earthquakes on Kamchatka and in Italy are also presented.

In the last paper, Gupta advocates intense monitoring of precursors in Koyna-Warna region in western India. This he feels, is an ideal site where earthquakes occur in a small area of 30 km x 15 km. Some precursory changes in b-value, fractal dimension, swarms are observed before moderate magnitude events in this area.

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METALLOGENY OF THE BARBERTON GREENSTONE BELT

A summary of the "Metallogeny of the Barberton Greenstone Belt, South Africa and Swaziland" by J.H.W. Ward, published by the Geological Survey of South Africa in 1999 is presented in the following.

The Barberton Greenstone Belt is internationally renowned for its antiquity, preservation, exposures, lithologies, early life forms, structure and mineralisation. The Council of Geoscience has undertaken a metallogenic assessment of the region by a compilation of the mapping and other information on record, made available in various publications and otherwise by mining houses, research institutes, individual researchers and others, to produce a metallogenic map of the greenstone belt on 1: 100,000 scale. The process of compilation has facilitated a synoptical appreciation of the geology, structure, tectonogenesis and mineralisation of the region and has resulted in the publication of this memoir. To keep up the continuity of information over the entire greenstone belt extent, the South African Geological Survey has made a very commendable effort in incorporating the data from the adjacent kingdom of Swaziland over which the belt also extends.

Over the past century, more than 320 tons of gold have been won from mine workings on disseminated and lode gold deposits in the early Archaean Barberton Greenstone Belt. Additionally, some 28 Mt of high grade haematite ore, 5 Mt of chrysotile asbesots fibre, 500 000 t of magnesite ore, 1 25 000 t of talc and 56 000 t of crude barytes have been produced from the opencast and underground mines in the belt. Minor amounts of stibnite, cinnabar, cassiterite, and verdite have been recovered from prospects in the area. Extensive exploration for the ultramafic-mafic greenstones for nickel-copper sulphide ore bodies has located only one minor strata-bound deposit, while one small zinc-silver massive sulphide ore body has been discovered in the felsic volcanic rocks.

An overall account is given of the regional geology, as well as a more detailed description of the geology and mineralisation of the significant ore bodies, together with an appraisal of their metallogenesis. The book comprises chapters on antimony, barytes, chrysotile, gold, iron, magnesite, mercury, nickel-copper, talc, tin, verdite and 'buddstone', and zinc arranged in an alphabetical order,

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