1.1 EARTHQUAKE MECHANISM: PREPARATORY PHASE AND RUPTURE

by

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SYNOPSIS

The wave radiation resulting from earthquake ruptures is described successfully by modern source models. Source parameters (moment, length, stress drop) are estimated with errors of factors between 1.2 and 4 (10 in the worst case), however, rheological processes along the fault plane during rupture are not yet understood. Physical parameters of the earth's crust change before some shallow earthquakes. Some of the most easily and most economically observable premonitory parameters are seismicity, vertical displacements, P-travel time, magnetic field and ground water chemistry or level. As in developing countries most of the population will continue to live in the present old and unsafe buildings, it is especially important for these countries to establish an earthquake prediction capability. The combined observations of the above parameters may furnish such a capability in the near future.

INTRODUCTION

The earthquake mechanism may be divided into three phases: the preparatory processes, rupture, and post failure adjustments. The rupture processes and post failure phenomena have received most attention in the past, whereas the preparatory phase has only recently been studied intensively. Consequently, the preparatory processes leading to failure of the earth's lithosphere are the least known and the least understood, even though the understanding of preparatory processes is the most important, because it holds the key to the possibility of earthquake prediction.

Workers studying the earthquake rupture mechanism generally agree that some of the present simplified source models do describe the earthquake failure approximately correctly, and that source parameters such as dimension, dislocation, and stress-drop can be derived with reasonable confidence. A new generation of more sophisticated models is now being proposed to explain details of the earthquake rupture. However, the rheological processes of failure are still not understood for both shallow and deep earthquakes.

Recent studies have shown beyond a doubt that physical changes take place in the earth's crust before at least some shallow earthquakes. If these premonitory physical changes can be measured and understood, earthquake prediction may become possible. For this reason, premonitory processes leading to rupture are now energetically studied in the field and the laboratory. Unfortunately, they are still poorly known and poorly understood. As a consequence, the proposed models may still be subject to major revision. Because earthquake prediction is of

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economical importance to man, I will emphasize the discussion of processes premonitory to failure.

EARTHQUAKE SOURCE MECHANISM

First motions of P-waves from shallow and deep earthquakes always indicate that the source of energy is best described as failure along a plane. For shallow and deep earthquakes, aftershocks locate mostly onto a plane, which also indicates that the main rupture occurred in a plane. Regardless of the unknown rheological details of the rupture processes, seismologists have proposed approximate models for the earthquake source, which describe quite well the far- and near-field waves generated by earthquakes (e.g., Madariaga, 1976; Haskell, 1964; Archambeau, 1968; Brune, 1970; Molnar et al., 1973; Sato and Hirasawa, 1973). The general shape of the body wave amplitude spectra is agreed to be as follows: constant amplitude spectral density at low frequencies, with a ω^{-2} or ω^{-3} fall off at high frequencies, ω. The frequency at which the two types of behavior meet is a critical frequency, ω_o, which is related to the source dimensions, r, by an equation of the form

$$r = c \frac{v_R}{\omega_o} \tag{1}$$

where v_R is the rupture velocity, and c is a constant.

Because the value of c is debated, we have attempted to calibrate equation (1) for earthquakes where r and v_R are known (Hanks and Wyss, 1972; Wyss and Shamey, 1975). The dimensions r can be estimated from aftershock distributions, but v_R is almost never known. The stress-drop, $\Delta\sigma$, is calculated from M_o and r by

$$\Delta\sigma = k \frac{M_o}{r^3} \tag{2}$$

If rupture velocities are unknown and vary between $.4\beta$ and β(shear velocity) the dimensions are poorly estimated by (1), and the error is compounded by (2) for the stress-drop determination. Table 1 summarizes the errors with which source parameters may be derived from teleseismic signals. The first column is for the fortunate case where the rupture velocity is known to within a factor of 1.2, the second column is for the general case where v_R is unknown and assumed to be 0.63β. The parameters derived from spectral values directly are the most accurately known, (M_o), and for the parameters which are calculated from equations (1) and (2) errors will be larger. The approximate factors in Table 1 by which a particular earthquake parameter may be in error are derived under the assumption that part of errors in M_o and r will cancel in the average for the stress drop determination.

The ground acceleration near an earthquake will depend linearly on the stress drop. If our ability to measure $\Delta\sigma$ is affected by errors of a factor of 2 to 4, so will be the prediction of ground acceleration near faults. The average stress drops of earthquakes larger than magnitude 5 are usually a few tens of bars, never much more than 100 bars. Therefore, acceleration of 1 g may generally be expected near these earthquakes (Brune, 1970). However, it has been shown that many intermediate and large earthquakes are multiple events, which means that stress drop varies along the rupture plane. For multiple events like the Alaska (Wyss and Brune, 1977) and the San Fernando earthquakes, stress drops are about 10 times larger on portions of the fault plane (Hanks, 1973; Alewine and Jungles, 1976). In the immediate vicinity of these high stress portions of the source area, one may expect very high accelerations.

PREPARATORY PROCESSES OF THE EARTHQUAKE MECHANISM

Recent observations show that at least some shallow earthquakes are preceded by a preparatory phase before rupture (Scholz et al., 1973). During this preparatory phase physical properties of the earth's crust change. The characteristic pattern of these changes can be observed and earthquakes may be predicted (Aggarwal et al., 1975). The Haicheng, China, earthquake of February 1975, was the first large earthquake to be predicted (Anonymous, 1975). More than one million people were evacuated. There is no doubt that a large number of lives and much property was saved by this prediction.

It is clear that the Chinese have decided that the most effective means to minimize losses due to earthquakes is earthquake prediction. The Chinese realize that the majority of their population will continue to occupy existing buildings for many decades. They further realize that most new buildings constructed in the next few decades will not be sufficiently earthquake resistent to protect the inhabitants. The money and building material needed is simply not available. Virtually all developing nations in seismic areas face the same situation as China: the overwhelming majority of their population will continue for decades to live in unsafe buildings. For this reason it is of interest here to ask what type of observations could help developing nations to assess the earthquake risk in their countries.

The most commonly observed precursory phenomena have been summarized elsewhere, and models for the preparatory phase have been proposed (Nur, 1972; Scholz et al., 1973; Whitcomb et al., 1973; Stuart, 1975; Mjachkin et al., 1975; Brady, 1975). Most models for precursory phenomena agree on the following points: (1) Many independently measurable physical parameters of the earth's crust change before some shallow earthquakes. (2) The duration of the precursory changes is proportional to the size of the impending earthquake. (3) Dilatancy during the preparatory phase is probably the cause of many of the precursory changes (dilatancy is the volume expansion of rock under deviatoric stresses). (4) Before large earthquakes the preparatory phase lasts for years and it often culminates in accelerated activity (short term precursors) before the mainshock. Some important points of disagreement between the models are: (1) The mechanism of rupture initiation. (2) The role of pore fluids during preparatory phase. (3) The detailed nature and role of dilatancy. Obviously, we do not understand the physics of the preparatory phase of the earthquake mechanism yet, but we agree that some shallow earthquakes can be predicted by specifying location, size and time on the basis of measurements in the source area.

For nations with limited scientific resources, it is important to know which precursory parameters may be measured economically and yet allow the identification of crustal volumes in the preparatory phase.

I believe that some important indicators of the seismic risk which can be measured relatively cheaply are: (1) seismicity patterns; (2) local uplift as revealed by sea level subsidence; (3) P-wave travel time delays as indicated by increased residuals; (4) local changes in the earth's magnetic field; and (5) changes of ground water characteristics. The causes and the detailed patterns of these changes are still a matter of debate. The following is a description of the changes one may expect during the preparatory phase.

(1) Seismicity patterns. There are two types of seismicity observations which are helpful for seismic risk evaluation: defining seismic gaps, and plotting background seismicity as a function of time. The seismic gap idea is based on the fact that earthquakes occur along extended continuous fault systems, especially along plate boundaries. If portions of a plate boundary have ruptured in historic time, then unbroken portions of the same boundary between the breaks are called gaps, and judged to be areas of increased seismic risk, because they will have to break next. Several workers (e.g., Mogi, 1969; Fedotov, 1969; Kelleher et al., 1973) have mapped ruptures of large earthquakes by plotting their aftershocks. With the gap method, the location and maximum size can es estimated, but not the time. Several seismic gaps have been filled in by earthquakes, after the gap was identified. One example is the Sikta, Alaska, earthquake of 1972 (Sykes, 1970).

The seismic background activity as a function of time sometimes shows a marked low activity period before an impending earthquake. This may be due to dilatancy hardening. Before the quiet period, unusually high activity could be demonstrated in some cases (Nersesov, 1972). Figure 1 shows schematically the change of seismicity and other parameters as a function of time before earthquakes. Not all of these fluctuations are well established. The most uncertain ones are shown by dashed curves. Foreshocks were the decisive factor that led to the successful evacuation before the Haicheng earthquake (Anonymous, 1975). Jones and Molnar (1976) showed that many large earthquakes are preceded by foreshocks. The difficulty lies in the identification of foreshocks as different from the background activity.

(2) Vertical displacements are expected to precede rupture in tectonic regimes of thrusting if dilatancy occurs. Thrusting occurs where tectonic plates converge, that is, along most boundaries of the Pacific Ocean. Geodetic measurements are expensive and time consuming. However, nations with shoreline maintain tide gauge networks. By observing the relative mean annual (or monthly) sea levels recorded at a number of stations along a coast, local areas of crustal uplift of subsidence may be identified (Omori, 1913). Sea level data from Japan and South America show that pre-, co-, and post-seismic local sea level changes must have been due to crustal movements and not due to shifting tides (Tsumura, 1972; Wyss, 1976). For a detailed and careful continuous monitoring of coastal movements tide gauge networks of 100 to 50 km density are needed.

(3) Travel time delays for seismic waves have been the direct source for our hope to be able to predict earthquakes. An increase in travel time is followed by a return to normal, which is followed by an earthquake (Figure 1). If this pattern is observed, the location, size and occurrence time of an earthquake may be predicted. Most of the best data on

seismic velocity changes was obtained in the form of velocity ratios (P-wave divided by S-wave velocity) and from measurements recorded by very dense local station networks. Unfortunately, these operations are expensive. For this reason, it is of interest to determine whether teleseismic P-waves recorded at a single station, or at a loose network, may show a delay during a preparatory phase near one recording station. This method needs refinement, like all other methods, but I believe that the answer is, yes, P-wave delays can be detected before thrust earthquakes, if a station is close enough to the epicentral area, and especially if reference stations within a couple hundred km are available (e.g., Wyss and Johnston, 1973; Wyss, 1975; Engdahl, 1975; Evison, 1975). A further condition is, of course, that the time keeping of the stations is of good quality.

(4) Magnetic field changes during the preparatory phase are not well-documented yet (e.g., Fujita, 1965; Tazima, 1966; Rikitake, 1967; Nagata, 1970). However, from laboratory results it is expected that stress changes should cause magnetotectonic effects (Shamsi and Stacey, 1969) and that tectonic creep should be accompanied by large magnetic field changes (Martin and Wyss, 1975). If magnetic field changes can be demonstrated to occur before earthquakes, it would be possible to implement the method of relative field change observations used by Smith and Johnston (1976).

(5) Ground water chemistry and ground water level in wells are reported to change before earthquakes. The best known case is the increase in Radon content reported by Ulomov (1970). Reports from China (Anonymous, 1976) indicate that the water level of shallow wells changes also. The chemical analysis of ground water requires detailed and careful study; the measurement of well levels, on the other hand, would be very easy, if water level can be shown to be related to approaching earthquakes and not only to local precipitation.

The above parameters and their uses are summarized in Table 2. The last column indicates the predictive capability: L = location; S = size, and T = time of occurrence may be predicted.

DISCUSSION AND CONCLUSION

Seismic disturbances are known to be failures along planes. Even simplified models describe the radiated wave spectra rather well. More complex models are now being developed. The rheological processes during rupture are still unknown. Seismic moment and source dimension can be estimated in the best cases to 20% accuracy, the stress drop within a factor of 2 to 10 depending on the circumstances.

I submit that at present the most pressing problem is to understand the preparatory phase of the earthquake mechanism, because such understanding will most likely furnish an earthquake prediction capability. Recent results indicate that at least some shallow earthquakes are preceded by a preparatory phase before rupture, and some physical properties of the earth's crust change during this preparatory phase. For nations with limited scientific resources, it is important to know which precursory parameters may be measured economically and yet allow the identification of crustal volume in the preparatory phase. I believe that some important indicators of the seismic risk which can be measured relatively cheaply are: (1) Seismic gaps develop. (2) Local uplift of several centimeters before large coastal earthquakes can be demonstrated using mean annual sea level if one or more tide gauge stations are available as reference stations along the same coastline. (3) At existing seismic stations in tectonically active areas it is possible to resolve locally caused travel time delays if they exceed 0.3 sec or 0.15 sec if reference stations are available. It appears that in the preparatory phase of even moderate earthquakes delays of 0.4 sec occur. (4) Laboratory tests show that the magnetic remanence of rock samples can change by about 1% under constant pressure if creep occurs. This may be a part of the explanation for the magnetic anomalies of several to 30 gammas observed to indicate the preparatory phase of some earthquakes. (5) The chemical content of wells has been shown to change substantially and possibly well levels may change also.

If several of the changes discussed above are observed simultaneously, an earthquake prediction may be issued with considerable confidence. We hope that during the next few years we will move closer to the realization of this goal, and that we will be able to furnish governments with information detailed enough to allow them to effectively implement disaster reducing measures.

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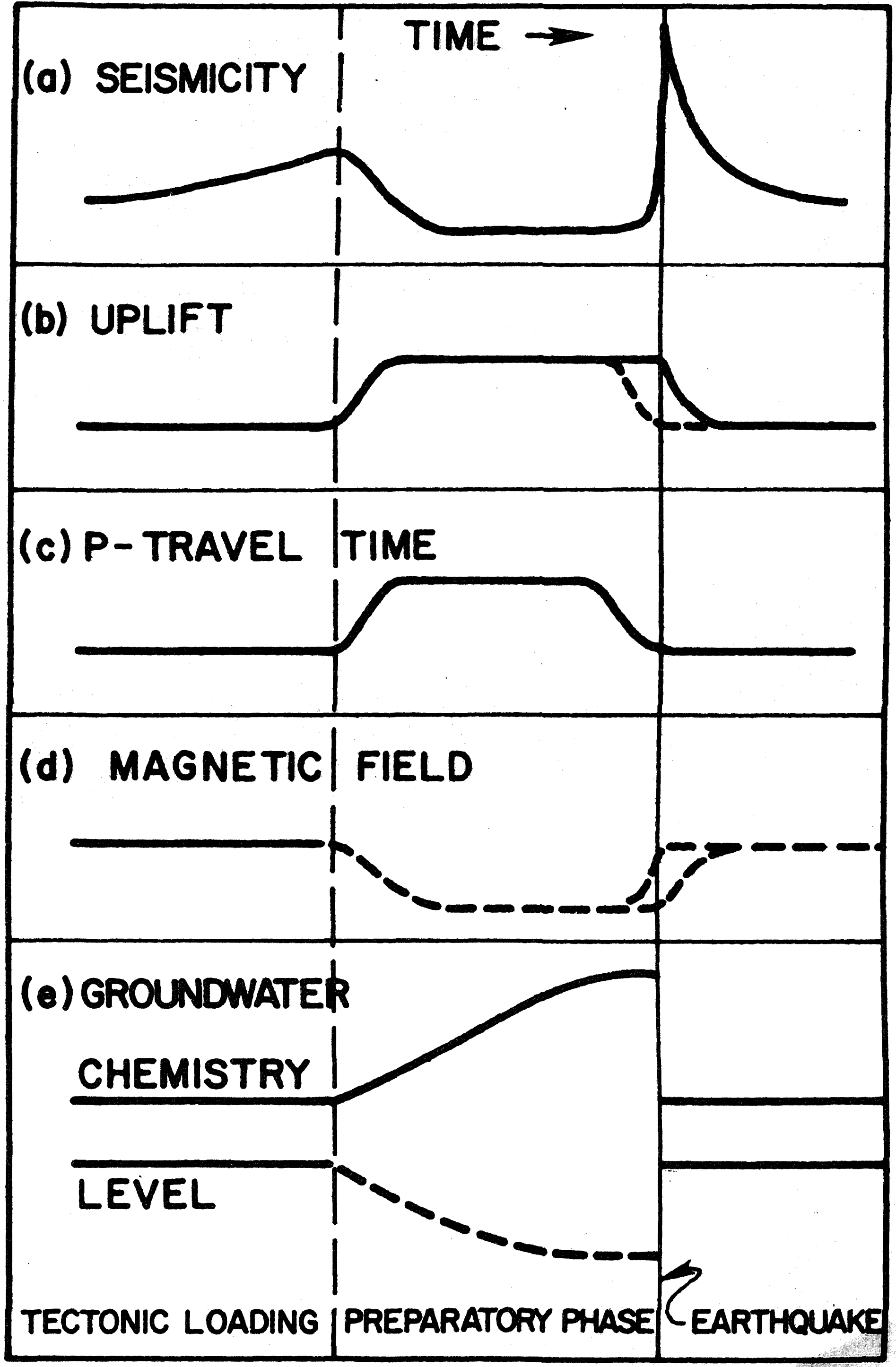

Figure 1: Schematic pre-earthquake changes of parameters which may be measured economically, as a function of time.

Table 1: Approximate errors of seismic source parameters estimated from teleseismic body waves

	Factor by which the value may be multiplied or divided	
	v = known	v = unknown
Moment $M_o = \mu DA$	1.2	1.2
Dimension $r = (\frac{A}{\pi})^{1/2}$	1.2	1.6
Rupture velocity v	1.2	1.6
Dislocation D	1.4	2.5
Stress drop $\Delta\sigma$	1.8	4.0

Table 2: Some economically observable earthquake precursory parameters

Parameter		Idea	Method and Measurement	Prediction Capability
Seismicity	(a)	Gaps in continuous fault zones	Plotting map of epicenters	L, (S), -
	(b)	Numbers of local earthquakes reflect changing strength	Counting numbers in local volume	L, S, -
	(c)	Foreshocks, initiation of rupture	Counting numbers, identification?	T
Uplift		Dilatancy	Land uplift compared to sea level or geodetic leveling	L, (S), -
P-travel time		New cracks decrease velocity	Accurate or average arrival times of local or teleseismic waves	L, S, T
Magnetic field		Magnetotectonic effects due to accelerated deformation	Local field changes relative to net work	L, (S), ((T))
Ground water	(a)	Increasing crack surface	Chemical composition	L, S, ((T))
	(b)	Changing crack volume and stresses	Level position in wells	L, S, ((T))