

Recent Research on the Physical Aspects of Earthquakes

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ABSTRACT

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Recent developments in the field of physical aspects of earthquakes, which encompasses in present-day terminology the analysis of focal dynamics and of catastrophic effects of earthquakes, are reviewed. In particular individual sections of this review deal with the earthquake source, effects of earthquakes on the ground, the geographic and temporal distribution of earthquakes, the characterization of seismic risk, earthquake prediction and with the artificial release of earthquakes. In this instance, the review supplements earlier information by the author (1975) by new data published mainly between 1975 and 1984.

1. INTRODUCTION

Seismology as a science is concerned with two fundamentally different aspects of the effects of earthquakes: first, with the analysis of the mechanics of the focus and the catastrophic effects thereof in the vicinity of the epicenter; second, with the problem of wave transmission through the Earth and the results concerning the structure of our planet that can be obtained therefrom.

This paper is concerned only with the first of the aspects mentioned above; we refer to this part of seismology as “seismicity studies”. Inasmuch as such studies are basic to the understanding of the catastrophic effects of earthquakes, the writer has summarized the state of the art up to about 1974 in his book on natural catastrophes (Scheidegger, 1975). In the decade

*¹ For a short biography of the author the reader is referred to *Earth - Science Reviews*, 21(4), p. 226.

elapsed since then, much work has been reported on focal models, seismic statistics and on earthquake prediction, although the central problem of forecasting the occurrence of an earthquake with regard to its exact location, time of occurrence and magnitude is still far from a possible solution.

It is the intention in this paper to review the most important research that has been achieved during the last decade in the subject of the physical aspects of earthquakes.

2. THE EARTHQUAKE SOURCE

2.1. Phenomenological description

As is well known, earthquakes commonly appear as “shocks” which can cause considerable damage to structures and great numbers of casualties. Because of this, field studies have been made of many earthquakes that have occurred, which are, however, too numerous to be mentioned here individually. Let it suffice to refer to the new catalogue of Gause and Nelson (1982) in which all significant earthquakes from 2000 B.C. to 1979 A.D., including quantitative figures on casualties and damage, have been listed.

Regarding the general phenomenology of surface effects of earthquakes, a new classification based on strong motion characteristics has been proposed by Rustanovich (1977). Furthermore, attendant effects, such as “earthquake lights”, have been described by Derr (1977), who also speculated upon the possible causes of such lights (violent low-level air oscillations; piezoelectric effect in quartz-bearing rock) the existence of which he considers as established.

2.2 Causes of earthquakes

Plate-tectonic activity has now been firmly established as the underlying cause of the occurrence of most earthquakes. For the specific mechanism of stress build-up there are, however, still many possible models. Thus, Thatcher and Rundle (1979) propose a model for earthquake cycles in underthrust zones, Chapple and Forsyth (1979) connect earthquake build-up with the bending of trenches, and Sykes (1980) proposes a mechanism of reactivation of preexisting zones of weakness.

Models for rather special cases were also proposed. Thus, Goodacre and Hasegawa (1980) envisaged gravitational stress-build-up mechanisms along the edge of a rift, thinking particularly of the Ottawa–St. Lawrence graben. Similarly, the gravitational potential was envisaged by Barrows and Langer (1981) as a source of earthquake energy. Regarding the many earlier claims that gravitational tides could trigger earthquakes, Heaton (1982) failed to

find a correlation between the origin times of shallow dip-slip earthquakes and solid-earth tides.

Finally non-tectonic causes of earthquakes were also considered. For instance, a source mechanism was proposed by Hedervari (1975) and by Ferrick et al. (1982) for volcanic tremors; it is based on the assumption of unsteady flow in volcanic conduits. Of the more “unusual” theories, those ascribing the occurrence of earthquakes to atmospheric loading (Caloi and Migani, 1975) and to the release of (amongst others) hydrocarbon gases from the deep interior of the Earth (Gold and Soter, 1980) are worthy of mention.

2.3. *Source model*

2.3.1. *General remarks*

An “earthquake” can usually be considered to originate from a “focus” which is definite with regard to its location and activity-time. In fact, a focus is, of course, extended in space as well as with regard to the time-span of activity, but it is usually sufficient to consider it in a first approximation as occupying a specific point in space and time. Later, adjustments for its volume and activity-time can be made.

The problem is, then, to envisage specific (idealized) models for explaining the observed effects. As the latter, the most important are the far-field displacements that are registered by seismographs. The basic problems involved have recently been discussed by Ben-Menahem and Singh (1981), by Kasahara (1981) and by Boatwright (1982). The possibilities for these models are: a rigid fault with stick-slip, a stress- or strain-singularity in an elastic medium, or some complicated fracture process. We shall proceed to consider these possibilities individually.

2.3.2. *Rigid fault model (with stick-slip)*

This is probably the oldest model of the earthquake process: A fault exists in the Earth, along which the two halves slide intermittently.

Further mathematical calculations for such a simple model have been made by Scholz (1982a) who derived scaling laws for earthquakes from it. Direct mechanical experiments based on this model have been reported with a foam rubber model (Hartzell and Archuleta, 1979) and with a triaxial compression machine (Shimamoto et al., 1980).

The most severe problem with models assuming a simple fault is the well-known fact (cf. e.g. Scheidegger, 1975) that the “ordinary” (frictional) sliding process would require shear stresses at the focal depths which are much greater than the shear-strength of the material concerned. The required lowering of the coefficient of friction can only be obtained if the presence and involvement of a pore fluid is invoked (Barley, 1978; Rudnicki, 1979).

Such a pore fluid could perhaps also be responsible for local melting of the material, but its existence is, of course, highly hypothetical.

2.3.3. Stress and strain singularities

The next possibility of constructing focal models has been by the assumption of the sudden origination of singularities in an elastic medium.

The most widely used of these has been the sudden introduction of a dipole with a moment in the stress or strain field, but it leads to the difficulty that the region cannot be in mechanical equilibrium before and after the "earthquake", unless far-field external mechanical forces are also introduced. Nevertheless, dipole-type models in the stress field have generally yielded acceptable far-field solutions for the radiated elastic waves. A recent treatment of the problem is due to Gever and Hasegawa (1981). Rundle (1980) has included self-gravitational effects. The corresponding singularities in the strain field (dislocations) have recently been discussed by Melosh (1983).

The difficulty with the equilibrium conditions is avoided if multipole rather than dipole singularities are considered; these solutions have also been known for a long time. A further development is the introduction of a moment-density tensor. (Strelitz, 1978; Rudnicki and Freund, 1981). From such models far-field solutions and radiation energy estimates have been deduced.

2.3.4. Fracture models

Finally, a proper model of the earthquake source must evidently be based on an over-idealized mathematical scheme. In this vein, there have been a number of investigations into the possibility of using realistic fracture models for the explanation of seismic phenomena.

All these models are based upon some view of the formation and propagation of a crack. In essence, there are two types of approaches that can be taken: first, various types of assumptions can be made regarding the mechanics of the developing fractures; second, mathematical "far-field solutions" for various types of developing cracks, and finally, geological consequences of these models can be considered.

Turning first to the basic fracture process, we note that Chang et al. (1975) have considered processes that occur in rock fracture experiments as representative of earthquake mechanisms. Similar investigations were also made by Stiller and Wagner (1978). In the same vein, Yamashita (1982) has studied the (in)stability conditions for shear cracks. Finally, Newman and Knopoff (1982) advocated a crack-fusion mechanism as basic for large earthquakes.

As was noted earlier by this writer (Scheidegger, 1982), the most success-

ful fracture-type model for earthquake mechanisms is that of a dynamic shear crack which is produced by a mechanical instability in the material. Further far-field solutions (in addition to those listed in Scheidegger, 1982) of models of this type have been reported by Ben-Menahem (1976), Miyatake (1980), Das (1981), Madariaga (1983) and by Beck and Ruff (1984).

The various mechanical models of the earthquake source process can be used to make interpretations of tectonic processes. Thus, Bankwitz (1980) has deduced that the energy of earthquakes is radiated to a significant part from relatively small, numerous fault planes and not from large single faults. Boatwright (1981) has been able to explain the accelerogram of a specific earthquake in California by a fracture-source model, and Das and Scholz (1983) have been able to explain some general features of seismicity, viz. the reason why large earthquakes do not nucleate at shallow depths: ruptures nucleating at shallow depths are inhibited for propagating because of the low stress drops, whereas ruptures at great depth (large potential stress drops) can easily propagate over an entire fault plane.

2.4. Source parameters

2.4.1. General remarks

The earthquake source and the various models of it that have been proposed can be characterized by a variety of parameters.

The most important of these are the origin-place and -time. We shall, however, not be too concerned with the location of earthquakes, but rather with the mechanical aspects of the source. Nevertheless, let it be stated that the localization of earthquakes has been the subject of many investigations. In this connection, a quite general statement can be made which is connected with the fact that seismic observations can principally only be obtained on the *surface* of the Earth. This has the consequence that it is possible to determine the epicenter with increasing precision as the number of surface measurements increases (to infinity), but that the depth of the source cannot be determined in this fashion: its estimation depends critically on auxiliary assumptions concerning the Earth's structure (Lomnitz, 1982a).

Apart from this general observation on the place and time of an earthquake source, we shall now turn to a discussion of mechanical parameters.

2.4.2. Magnitude

The magnitude-parameter is an old one. It is based on the logarithm of the maximum amplitude produced by an earthquake at a standard distance on a (then) standard seismograph. The problem, now, has been that of determining magnitudes from observations on non-standard seismographs, at non-standard distances; i.e., the maximum amplitude observed on such

instruments and distances must somehow be “reduced” to the standard instrument and distance.

The problem appears to be insoluble. There is no proportional relation between maximum amplitudes on different instruments, and no simple relation between the amplitude and the distance. Thus the magnitude scale obtained using some logarithmic relation is particular to the instrument used. Scales obtained from different instruments can be matched at some magnitude-level, but they will then diverge at other levels. Thus, a series of magnitude (local magnitude M_L , volume-wave magnitude M_B , seismic moment magnitude M_W , surface wave magnitude M_S , teleseismic magnitude M_D) scales have come into existence, and a voluminous discussion has arisen regarding conversion procedures (Aki and Duda, 1978; Båth, 1977, 1981; Herrmann and Nuttli, 1982; Kanamori, 1983; Wahlström and Strauch, 1984). Some investigations propose relations valid only for “large” earthquakes (Purcaru and Berckhemer, 1978; Wyss and Habermann, 1982), others only for specific regions (Chung and Bernreuter, 1981 for the U.S., Wahlström and Ahjos, 1982 for the Baltic Shield). A general conversion table cannot be constructed (cf. Fig. 1).

2.4.3. Energy

The hope, of course, is to determine the seismic wave energy release from the seismographic station records. In this fashion, a true physical parameter would be obtained.

The general procedure for doing this is based on an estimate of the energy flux per unit area around the seismograph station from the seismograph record (by integrating the trace after converting to an elastic strain energy

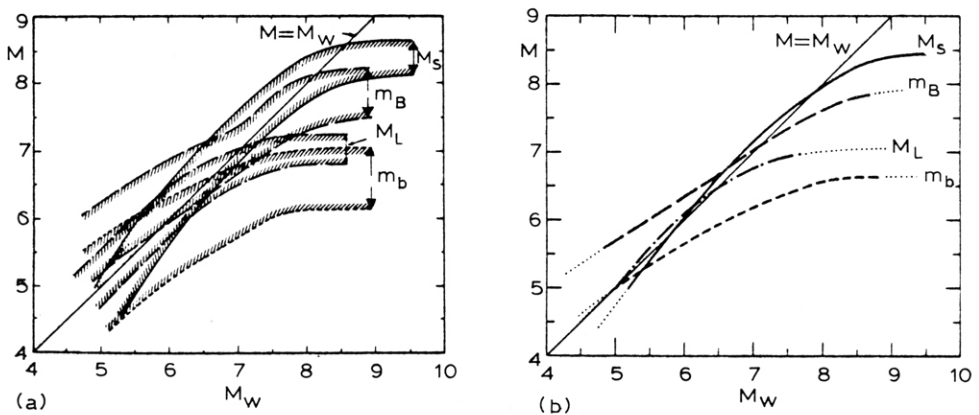


Fig. 1. Relation between various magnitude scales (after Kanamori 1983.) Explanation of symbols see text; (a) gives ranges, (b) mid-points of the ranges of the “correlations”.

curve) and then extrapolating to the radiation of the entire focus by assuming some type of radiation pattern. The model of a rigid fault allows one to proceed to the introduction of a further energy parameter: the seismic efficiency: the proportion of elastic energy released at the source which is radiated as seismic waves. The term was actually used long ago by Richter (1958); recent studies on it have been reported by Sibson (1978). In order to set up unambiguous correlations between the energy released and seismic records, it is necessary that the former is independently known. This is sometimes the case in atomic explosions for which Yacoub (1981) has made seismic yield estimates from Rayleigh wave records which he compared with the announced yields based on the amount of fissionable material used. He was able to achieve an accuracy of 2–6%.

2.4.4. Earthquake volume and other kinematic parameters

Earthquake volume can be estimated from the region “occupied” by the aftershocks (cf. the reviews by Scheidegger, 1975, 1982). This has been the standard practice. It has recently been applied also to the series of earthquakes in Friuli (Duma, 1981), and to the Oroville earthquake (Boatwright 1984a).

Other “geometrical” parameters relating to the earthquake focus are the fault parameters: length, width and area. Generally, one assumes linear relationships between the logarithm of these quantities and magnitude. The inevitable scatter inherent in such relations has been ascribed by Anderson (1979) to saturation effects, these, however, not being the only reason.

Finally, a new kinematic parameter has been introduced by Furumoto (1979) in the form of “duration time”. It can be determined from long-period surface waves. Source times for various types of earthquakes, such as low-angle thrust shocks in deep sea trenches and intraplate shocks, have been determined by Furumoto and Nakanishi (1983): the source times for the former types of earthquakes tend to be longer than those for the latter.

2.4.5. Focal strain and stress

In a strained elastic body, the strain is proportional to the square root of the energy stored per unit volume. It is therefore possible to calculate the earthquake strain from its energy and ultimately from its magnitude. It turns out that the strain is independent of magnitude: this appears to represent the “critical” strain which the material can support before it breaks.

When an earthquake occurs, the stress drops at the (hypothetical) focal fault plane; this stress drop corresponds to the shearing strength. Stress drops can be estimated from the critical strain estimates mentioned above. Values lie between 1 and 10 MPa. Stress drops can also be obtained by looking at far-field velocity pulses (Boatwright, 1980, 1984b; Mori, 1983). A

computation method was devised by Mavko (1982) based on two-dimensional models of heterogeneous stress drop. Estimates of stress drops for small earthquakes have been reported by Snoke et al. (1983); these are based on a relation (Madariaga, 1979) between the stress drop $\Delta\tau$ and the seismic moment M_o (see 2.4.6. below):

$$\Delta\tau = CM_o/a^3$$

where a is a characteristic dimension of the earthquake fault zone and C some dimensionless parameter.

Regarding the variation of stress drops with region, Richardson and Solomon (1977) found no systematic variations with location of an earthquake relative to plate boundaries (interior, margin), but Scholz (1982b) noted a systematic variation from 0.75 to 1.2 to 6 MPa for intraplate strike-slip thrust and Japanese intraplate earthquakes, respectively. Caputo (1980) found a statistical frequency distribution of stress drops $\Delta\tau$ in aftershock series which is proportional to $\Delta\tau^{-n}$ with $1 < n < 2$.

2.4.6. Other fundamental parameters

Concerning other parameters, we have already referred to the “seismic moment” M_o introduced by Aki (1966). This is the mechanical moment of the point source equivalent to the faulting motion:

$$M_o = \mu \bar{D}S$$

where \bar{D} is the average slip on the fault, S the total area and μ the rigidity. Thus defined, the seismic moment is a scalar, but since it depends on the orientation of the fault as well, it should actually be defined as a tensor (Backus and Mulcany, 1976a, b).

The determination of the seismic moment is effected directly from very-long-period seismograms of body and surface waves (Aki and Patton, 1978; Aki, 1982). Many individual determinations are now available (catalog by Purcaru and Berckhemer, 1982a). The relationship of the seismic moment with other focal parameters (stress, volume, energy) has been investigated by Olsson (1980) and by Purcaru and Berckhemer (1982b).

3. EFFECTS ON THE GROUND

3.1. Phenomenological description

Earthquakes can cause disastrous effects on the ground. Many descriptions of recent catastrophic earthquakes have appeared in the literature, which will not be reviewed here individually. Of interest are the *principal* investigations into the phenomenological surface effects of earthquakes.

Thus, the principal concern has been the *causes* of the hazard presented by earthquakes: these have generally been ascribed to the surface faultings that occur in earthquakes. Kobayashi (1976) has summarized the morphology of the hazards due to the offsets of ground, graben, tension cracks, gentle flexure and wavy swellings of the land surface. Similarly, horizontal displacements caused by an earthquake have been described by Clark et al. (1976), vertical ones by Kisslinger (1975) and by Melosh (1983).

The particular mechanism by which damage to houses is caused has been studied by Tchalenko and Ambraseys (1973), and the specific causes of fatalities were investigated by Kobayashi (1981).

Further accompanying effects of earthquakes are tsunamis (Nishenko and McCann, 1979), and earthquake lights (Derr, 1977). Lockner et al. (1983) have proposed a possible mechanism for the generation of such lights based on a concentration of charge densities in a conductive earth caused by frictional heating of the fault.

3.2. Intensity scales and isoseismals

As is well known, the ground effects of earthquakes are measured by a phenomenological intensity scale which is indicative of the type of damage that has been caused by an earthquake at a particular spot. For the intensity-tables, some modified form of the Mercalli scale is used; these are all very similar. The differences between the modified Mercalli scale used preferentially in America and the Medvedev–Sponheuer–Karnik-scale preferentially used in Europe (Drimmel, 1985) are most notable in the range of intensities from 5 to 9 (Cosentino and Lombardo, 1980). Nevertheless, the “intensity” observed depends very much on the dynamic parameters of the buildings (Fig. 2).

The actual establishment of isoseismal maps from field data has now successfully been computerized (Riznichenko et al., 1977; Mayer-Rosa, 1981). The alteration of the intensity with epicentral distance has been studied by Gupta and Nuttli (1976) and by Karnik et al. (1978). Studies of the maximum intensity I_0 in dependence of magnitude M and focal depth H (km) have been reported by Franke and Gutdeutsch (1974). The latest relation proposed is (M means here Karnik-magnitude):

$$M = 0.54I_0 + 0.50 \log H + 0.67$$

As a macroseismic parameter additional to the intensity, the “felt area” f has been introduced (Nutti and Zollweg, 1974). The supposed relationship between $f(\text{km}^2)$ and the body-wave magnitude M is:

$$M = 2.65 + 0.098 f + 0.054 f^2$$

at least in the Central United States of America.

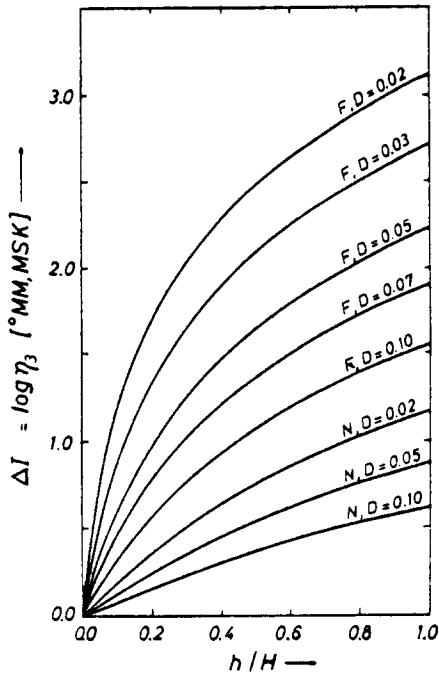


Fig. 2. Intensity decrease (I) caused by the various dynamic responses of buildings due to different internal dampings (D) in the near-field (N) and far-field (F) of strong earthquakes, as a function of the relative height (h/H) of the storeys. After Drimmel, 1984.

3.3. Displacement, velocity, acceleration and spectra

3.3.1. General remarks

This section is, in fact, concerned with the *quantification* of the intensity concept which is, after all, very phenomenological, based on the subjective assessment of damage. The problem is that of introducing some *physical* parameters which underlie the damage effects. In contrast to the suppositions in section 2, these parameters do not refer to the focus of an earthquake, but to the “observation point” at which the damage is experienced.

3.3.2. The ground motion

The primary information on earthquake motion are data on the movement of the ground. From seismograms, it is possible to deduce the displacements, the velocities and the accelerations at a site as a function of time. In fact, if one of these quantities is known, the others can be deduced therefrom by simple differentiation (or integration).

The “raw” data, thus, are e.g. accelerograms. Naturally, these are not

“raw” in the sense that simply the trace of a seismic record could be used directly; rather, making allowance for the characteristics of the seismograph, one has to compute the ground acceleration (or velocity, displacement) by means of the seismograph equation. Nevertheless, the whole procedure has been automatized to such an extent that it is possible to obtain “accelerograms” (or “velocity-grams”, “displacement-grams”) in the epicentral area. A typical catalog of accelerograms has been published for the Friuli earthquake of 1976 and its aftershocks (Commissione CNEN-ENEL, 1976).

3.3.3. Peak values

The raw accelerograms have very little direct bearing upon the appearance of ground effects. Thus, the attention has been directed towards particular features of such records.

The first interesting quantities are the peak values, notably those of the acceleration inasmuch as the latter is thought to be directly responsible for the occurring damage, at least under certain conditions.

If an accelerogram is available, the peak value is easy to identify. Such peak values have been used to establish relations to the intensity level. This has been done by Schnabel and Seed (1972) for the western United States. The same authors have also established (a direct determination of) the dropoff of peak acceleration with epicentral distance. A similar study has been published by Ambraseys (1974b) by calculating the regression between peak acceleration a and local intensity I on a world-wide basis; the relations are different for the horizontal (a_H) and vertical (a_V) peak accelerations (units of acceleration: % g)

$$\log a_H = 0.09 + 0.30 I$$

$$\log a_V = 0.32 + 0.31 I$$

The scatter is considerable (standard deviation is 70% of the mean). It is even greater if peak velocity instead of peak acceleration is considered; the data are then barely sufficient to define a trend.

Because of the large scatter, other authors have come up with different relations between a and I . These have been collected and compared by Trifunac and Brady (1975a) and by Boore and Joyner (1982). The result is a rather broad band (for the correlations) in a plot of $\log a$ vs. I .

From all this, the following statements can be made as a conclusion:

(1) Peak horizontal accelerations are from 1.5 to 2.5 times larger than peak vertical accelerations.

(2) For peak velocities, the data are insufficient to give a trend; they do, however, suggest that, on the average, the peak vertical velocity is about 60% of the peak horizontal velocity.

(3) The scatter of the data is large; hence the correlations should not really be used for design purposes.

Finally, an attempt can be made to define a “duration” of the peak (or strong) motion. Trifunac and Brady (1975b) have based this “duration” on the mean-square integral of the velocity of the ground motion and have also correlated it with the intensity. The dimension of the thus-defined “duration”, however, is not simply “time”. Trifunac and Brady found a (more or less) linear correlation between the logarithm of (their) “duration” and the intensity.

3.3.4. *Spectral analysis*

The raw accelerograms can be further analysed by spectral methods (for a general background on this, see Båth, 1974). Generally, a “response” spectrum is calculated, based upon a single-degree-of-freedom viscously damped oscillator, to forced oscillations for given, observed accelerograms. Usually, the complete accelerogram is used but Khalturin and Rautiani (1978) used the coda only.

The response spectra are quite individualistic. Therefore, it is important to collect characteristic type-cases. Generally, a statistical characterization of response spectra is attempted (Udwadia and Trifunac, 1974; Kaul, 1978). Lyakhter and Frolova (1977) classified the spectral properties according to the macroseismic intensity. Båth et al. (1976) made an analysis of spectra found and expectable in Sweden. Furthermore, the characteristics of spectra of nuclear explosions were discussed by McCreery and Walker (1983). Finally, studies of the mechanical provenance of the various modes encountered in the spectra were made by Hasegawa (1974a) and by Muramatu and Irikura (1982).

3.3.5. *Models and forecasts*

The last studies already lead to the problem of setting up models for the generation of spectra and the forecasting of response spectra of future earthquakes at a given site.

Quite generally, it can be stated that one cannot scale easily from small earthquakes to large ones. Predictions have been based on models for the expected source (nuclear explosions: Johnson, 1973; strike-slip and dip-slip fault: Bouchon, 1980). More complicated models for the deduction of scaling relations have been advocated by Scholz (1982b), Irikura (1983), Aki (1984) and Joyner (1984). The problem is evidently very dependent on the model chosen, and does not become much more definite if only *peak* values are to be scaled (Hadley et al., 1982).

3.4. *The effect of topography and geology*

3.4.1. *General remarks*

The ground motions are locally greatly affected by the topography and the

geology prevailing in the vicinity. The geometrical configuration of regions with varying seismic transmission properties (air, friable material, hard rock) can cause local concentrations of the wave-energy density; thus, regions of great damage may alternate with regions of little damage.

3.4.2. The effect of topography

The classic case where the effects of local topography was noted is the Pacoima Dam site in the San Fernando Valley of California, which had already been reviewed in the writer's book (Scheidegger, 1975). An additional study of this site was made by Boore (1973) who concluded that the rugged topography of the area tends to enhance the higher ground-motion frequencies. A physical model-study of the same site was reported by Rogers et al. (1974) which confirmed the frequency dependence of the motions. A numerical model study of the topographic effect at mountain sites was made by Castellani et al. (1978), who showed that in the presence of valleys or mountains a variety of reflections and refractions occur which amplify the intensity of the ground motion. The theoretical results were compared and checked with recordings from the Friuli earthquakes of 1976. Topography can also have an effect on the frequency of earthquake occurrence (Mino, 1984) because of the formation of tectonic stress concentrations.

3.4.3. Effect of geology

The effect of geology is mainly caused by the seismic wave transmission properties of the layers in question. It is well known that, the softer the ground, the more severe are the damage effects. This general observation has been confirmed again and again, such as in studies by Kobayashi (1974, 1976), Mohraz (1976), Drimmel (1980, 1984), Cohn et al. (1982) and Mochizuki et al. (1982).

However, not only the *kind* of material is of importance, but also the *structures* obtaining in the various layers. This is an effect similar to that of topography, but in three dimensions. It may show itself in the general intensity-variations of earthquake shocks over a whole range like "the Alps" (Drimmel et al., 1973), or a "subduction zone" (Melosh and Raefsky, 1983) or in the ground motion over a single structure (Kasuga and Irikura, 1982): an amplification occurs with an abrupt change of sedimentary layer thickness on the side of the greater thickness.

3.5. Engineering aspects

3.5.1. General remarks

We are now turning our attention to the problem of protecting structures against hazards that might be presented by future earthquakes. Variouslly,

the damage caused by earthquakes has been ascribed to the accelerations or to the velocities of the ground motion to which the buildings (structures) are subject, or even to the displacements. Thus, the hazards from (long-term) faulting have been described by Kobayashi (1976). However, the latter case is rather unusual, and most of the effort has been directed to determining the “response” of the structures to the expected (“design”-) earthquake. The general problems involved in this approach have been described, for instance, by Ambraseys (1974a, b) d’Albe (1974), and by Bolt (1976).

3.5.2. The design-quake

In order to design a structure, an assumption has to be made regarding the character of the earthquake against which the design has to protect the structure. This is the “design-quake”.

The choice of a design-quake depends on general considerations of seismic risk which will be treated later on in this paper. At this juncture, we only discuss the types of parameters that are involved in the “design-quake”. These parameters are taken from strong-motion seismograms of earthquakes in the area. For this purpose, accelerograms are collected and adjusted for attenuation from active faults etc. The procedure has been illustrated by Furuzawa (1976) for Japan and by Selnes (1978) for Scandinavia. A review of the methods applicable elsewhere has been given by Studer and Ziegler (1983). In the work cited last, characteristic design spectra are given.

3.5.3. General response methods

As noted above, the general method for the calculation of a response of a structure to a design-earthquake consists in representing the structure by an oscillator and feeding the data for the design-earthquake into terms representing the external input. A flexible computer program to effect this calculation has been devised by Bathe et al. (1974).

The general procedure is evidently quite involved. Thus, rules for special cases have been developed, such as for systems with natural frequencies close to one another (Villaverde, 1984). The problem has also been studied by means of scale-model experiments (Fumagalli and Casirati, 1978).

A special case of seismic “response” consists in a change of the rheological equation of state of the material affected. Generally, this is a liquefaction of soil layers. On slopes, this leads to a triggering of landslides and has been treated in a review of mass movements (Scheidegger, 1984). However, the liquefaction can also occur on level ground; in this context its mechanism has been treated by Prater (1977). Laboratory tests for the determination of the liquefaction-potential of soils have been reported by Trommer (1977).

3.5.4. *Specific site-types*

Finally, the general theory discussed above has been applied to specific sites. The applications to individual structures are, naturally, very numerous and are often contained in the classified files of construction firms and consultants. However, discussions of some types of sites are of more general interest.

Thus, the problems connected with housing units have been investigated by Castoldi and Casirati (1978a). Special problems are presented by nuclear power plants, to which a textbook (Hansen, 1972) and other works (e.g. Castoldi and Casirati, 1978b) have been devoted.

Much work has been devoted to the stability of dams. The classic case is the Pacoima Dam (Perez, 1973), others concern the Guri Dam (Fiedler, 1977) and the Abiesta Dam (Castoldi, 1978). Studer (1977) presents general design considerations on the subject matter of dams. In this connection it should be noted that dams present an additional problem with regard to earthquakes: the water build-up behind a dam can trigger seismic activity. This problem will be treated in Section 6 of this paper.

Finally the resistance of a pipeline network to earthquake motions has been investigated in connection with Arctic conditions, where a break could lead to an ecological disaster (Hasegawa, 1974b).

4. THE GEOGRAPHIC DISTRIBUTION OF EARTHQUAKES

4.1. *General remarks*

It is a well-known observation that the occurrence of earthquakes is more frequent in some areas than in others. In order to determine the regions of high earthquake frequency, the focal coordinates are determined and plotted. It is obvious that these hypocenters refer to a certain time interval, so that their density also represents in some way the *temporal* frequency of the shocks. However, specific questions regarding the temporal sequence of the shocks will be relegated to Section 5 of this review.

Here, we shall assume that a large enough time interval has been chosen for temporal stability of the averages to be assured; then, the geographic patterns of the earthquake occurrences will be of concern: first, on a large scale, and second as regards to specific regions.

4.2. *World seismicity*

All studies have yielded the result that there is a strong correlation of earthquake frequency with other geodynamic phenomena: the zones of high seismicity quite generally coincide with the tectonic plate boundaries. This

has been an old observation which has been confirmed again and again, for instance by a study of historical seismicity (Ambraseys, 1983) or in a catalogue of significant earthquakes that occurred between 2000 B.C. and 1979 A.D. (Ganse and Nelson, 1982). Specifically, the seismic potential for the world's major plate boundaries was investigated by Nishenko and McCann (1981), the correlation with volcanism by Acharya (1981).

Finally, some general relations regarding the spatial distribution of hypocenters have been deduced from a correlation study between pairs of foci: The number of events per unit volume always decreases hyperbolically with distance, independently of magnitude and dimensions of the region (Kagan and Knopoff, 1980).

4.3. *Type regions*

4.3.1. *General remarks*

According to the plate tectonic models, "type regions" for seismicity are represented by the various "types" of plate margins; and, last but not least, by the plate interiors as a "type".

4.3.2. *Consuming plate margins*

The first types of regions which we shall consider are the "consuming" plate margins. These are the regions where plates collide; depending on the nature of the local structure (continental, oceanic), high mountain ranges or deep sea trenches may be present. These types of plate margins are connected with the regions of the Earth that show the highest possible seismicity: The Alpine–Himalayan and the circum-Pacific belts.

Local seismicity studies for these regions are legion; they will not be listed here individually. Of interest, however, are some studies of the *general* conditions existing in such areas. Amongst these, we may mention a paper by Lomnitz (1982b) on Mexico, by Hatzfeld and Frogneux (1981), Bath (1979b) and Ritsema (1979) on the Mediterranean, and by Sykes et al. (1980) on Alaska. These papers attempt to describe the general mechanical conditions in the corresponding regions.

4.3.3. *Accreting plate margins*

The accreting plate margins are the opposite to the consuming ones: morphologically they are characterized by rift valleys, often atop a ridge. The typical case occurs in midocean ridge areas, such as the western edge of the European plate (Limond and Recq, 1981). Similar conditions, however, may also be encountered in rift valleys which have been considered as possible incipient breakups at which an oceanic crust may be formed. The best known case of this type refers to the East African rift valleys; local studies

on them are numerous and will not be listed here. Another case is the Rhine graben in Germany (Schneider, 1979).

4.3.4. Intraplate seismicity

The regions in the interior of the tectonic plates are, on the whole, the most aseismic ones of the world. This concerns the abyssal oceanic plains and the ancient continental shields.

However, there are intraplate areas which do show considerable earthquake activity in spite of the general remark made above.

A notable case is represented by the Scandinavian Shield, where the seismic activity is normally ascribed to the isostatic rebound in consequence of the melting of the ice load after the end of the last ice age (Båth, 1978a, 1979a; Caputo et al., 1985).

However, an alternative interpretation has recently been proposed, notably by Båth (1984): an evident correlation between regional and global seismicity seems to indicate that the Scandinavian seismicity is independent of isostatic effects, and that, in actuality, its origin lies in globally active phenomena (Fig. 3).

A similar condition may apply in the Mississippi valley in the middle of North America (Johnston, 1982). In some fashion, the intraplate seismicity must be connected with the rheology of the lithosphere (Kunze, 1982).

A study of oceanic intraplate seismicity has been made by Wiens and Stein (1984). The main result was that this seismicity is extremely uneven and is most probably caused by local (thermal ?) heterogeneities.

Inasmuch as the intraplate seismicity is most important in the Chinese craton, a whole symposium has been devoted to the subject in Beijing (Gu

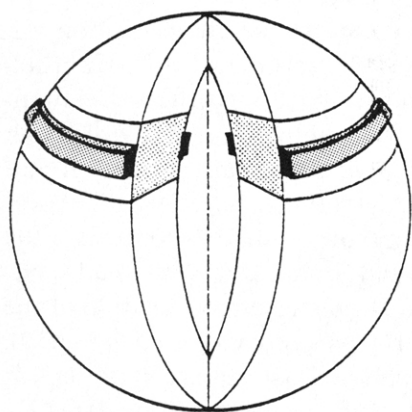


Fig. 3. Global seismicity due to mountain range loading: dotted areas indicate the section with maximum shear stress. After Caputo et al., 1985.

and Ma, 1984). Again, it is not possible to communicate generally valid “conclusions” regarding the origin of intraplate seismicity. Its origin is evidently different in different regions and very much tied to the prevailing local conditions.

5. TEMPORAL DISTRIBUTION OF EARTHQUAKES

5.1. Introduction

In addition to the geographic distribution of earthquakes, the temporal one is of great importance. In this section, we refer to such problems. Frequency, rates of occurrence etc. will be considered. In this, we are solely concerned here with *focal* parameters; problems regarding *phenomenological* parameters, such as intensity, belong to questions of seismic *risk*, to which the last section of this review will be devoted.

5.2. Magnitude–frequency relations

The fundamental relation between magnitude and frequency has been set up long ago by Gutenberg and Richter; it is of the form:

$$\log N(M) = a - bM$$

where N is the frequency (referred to a given time-interval, e.g. a year or a decade) and M the magnitude; a and b are constants.

Inasmuch as the basic equation of Gutenberg and Richter has been well confirmed, recent studies are mainly concerned with detailing it further. One of the principal problems is the determination of the constants a and b for various time intervals, regions and magnitude scales (Båth, 1978b; Weichert, 1980; Knopoff et al., 1982; Schenk, 1982; Wesnousky et al., 1983).

Modifications, in minor details, of the Gutenberg-Richter relationship have also been suggested. Thus, Howell (1981) postulates a “saturation effect”, i.e. an upper limit to the magnitudes for which the original relationship would be valid. A similar limitation is also implicit in a study of Singh et al. (1983) where the statistics of small and large earthquakes are not found to be the same. Caputo (1976), Wesnousky et al. (1983), Seggern (1980) and Kiremidjan and Anagnos (1984) published mechanical models to explain the magnitude–frequency law; Lomnitz-Adler and Lomnitz (1979) made stochastic models of the earthquake process and suggested a modification of the original relationship which is attained only asymptotically. Dong et al. (1984) used a maximum entropy rather than a least square relation for establishing correlations between magnitude and frequency from data. Finally, Main and Burton (1984) have attempted to connect magnitude–frequency relations with information theory.

5.3. *Aftershock sequences*

The pattern of aftershock statistics has also been established for a long time (cf. e.g. Richter, 1958; Scheidegger, 1975); it is determined by three laws: that of Gutenberg-Richter (frequency versus magnitude follows the same basic relation as earthquakes generally), that of Omori (frequency decays hyperbolically with time) and that of Lomnitz (average magnitude is constant).

Many aftershock sequences have been analysed in the light of the laws mentioned above. Of some of the more recent studies the following may be mentioned: aftershocks of the earthquakes near Lompoc in California of 1927 (Hanks, 1979); near Parkfield in California of 1966 (Bakun and McEvilly, 1984); near Borgatfjörður in Iceland of 1974 (Einarsson et al., 1977); in Friuli of 1976 (Cagnetti and Console, 1977); and in the Azores of 1980 (Hirn et al., 1980).

More interesting are studies of the more fundamental statistical patterns of the aftershocks (Prozorov and Dziewonski, 1982) and the mechanics of the creation of these patterns (Bonafede et al., 1980; Cohen, 1981; Olsson, 1981; Das and Scholz, 1981). This also leads to rather interesting investigations into the general conditions that lead to the creation of aftershock sequences (Olsson, 1979): after all, not every earthquake is followed by aftershocks!

5.4. *Earthquakes as time series*

The number of earthquakes per time unit in an area represents a "time series", whose stochastic properties have been studied for a long time.

In general, it has been surmised that the above time series is that of a stationary stochastic process, at least if the obvious "clusters" due to aftershocks are taken out. However, the question as to whether this process is really stationary has by no means been finally settled as of yet. A discussion of this problem has, for instance, been given by Vere-Jones and Smith (1981). These and other authors admit large-scale fluctuations in "seismicity", but these could be obtained also in an appropriate stationary model. A well-known seismicity peak is supposed to have occurred around the turn of the century, but Kanamori and Abe (1979) show that this "peak" could be due to a misinterpretation of old instrumental records and might thus not have been real at all.

Clusters are removed by assuming that each earthquake generates additional shocks with a probability that decays with time (Kagan and Knopoff, 1981). Conversely, shocks that fit this pattern can be taken as related and counted as one.

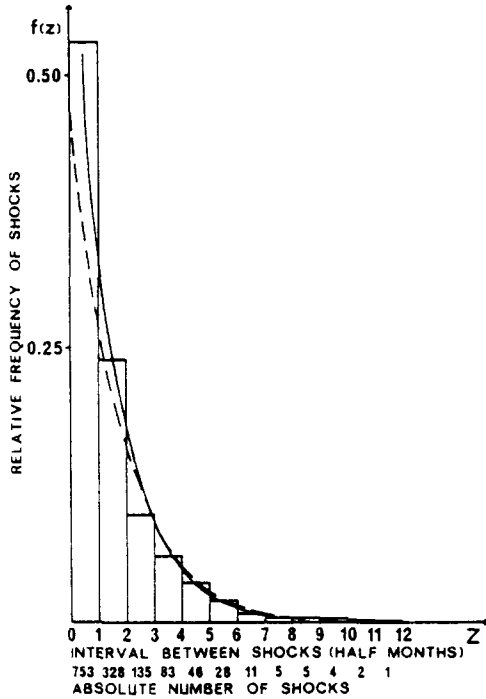


Fig. 4. The relative frequency of earthquakes as a function of the time lapse between consecutive shocks (1897–1977, $M \geq 7.0$): (a) theoretical function (solid line) $f(z) = 0.67 \exp(-0.67z)$; (b) least-squares solution (dashed line) $f(z) = 0.48 \exp(-0.58z)$. After Olsson, 1982.

When the clusters are removed, the time series that remains has usually been taken as that corresponding to a Poisson process. Recent studies have now introduced different views; thus Knopoff and Kagan (1977) have used the well-known extreme-value statistics of Gumbel. Anderson (1981) and Campbell (1982) have extended the extreme-value approach by introducing a Bayesian model. Finally, Basili et al. (1977) have used a negative binomial distribution with which to compare earthquake events, rather than a Poisson or Bayesian statistic.

However, as noted above, the assumption that earthquakes correspond to a stationary random process has been challenged. Olsson (1982) finds that the comparatively small shocks are not independent (Fig. 4). From time to time, the world-wide seismic activity accelerates; it is thus not stationary. The present is a highly active time (Mogi, 1979; Fig. 5).

The apparent variations of seismicity have prompted the search for “periodicities”. Thus, Dubourdieu (1980, 1983) believes in seismicity cycles of 4 and 88 years, Sano and Nakajima (1982) in a cycle of 6 years. None of

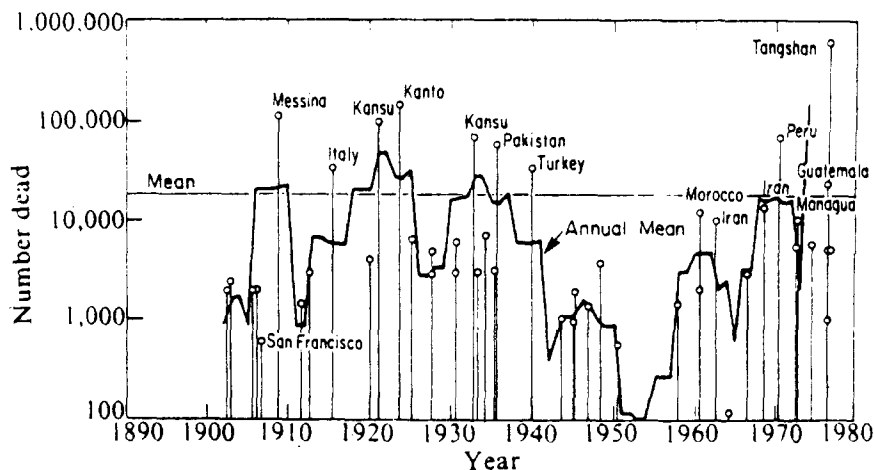


Fig. 5. Loss of life caused by large earthquakes. The vertical bars are for the individual earthquakes and the solid curve shows the annual average obtained by taking an unlagged 5-year running average. From Mogi, 1979.

these cycles, however, are very well established. The last authors, as well as also McClellan (1984) believe in a correlation of earthquakes with seasons, and Anghel (1978) even assumes a correlation with solar activity (which should take place via the telluric currents induced by perturbations in the ionosphere caused by solar flares). Physically more likely would be triggering effects by the tidal stresses. The search for the evidence of such effects had also been going on for a long time; recent attempts have been made by McNutt and Beavan (1981) and by Kilston and Knopoff (1983). Although statistically significant correlations appear to have been established in certain cases, these would not appear to be sufficient for establishing a certain cause-and-effect relationship.

This leaves only the general observation (Ito, 1980) that the earthquake activity exhibits nonperiodic, “chaotic” ups and downs that do not seem to follow any pattern which could be deduced from a stationary stochastic process.

This leaves one with the task of explaining the “chaotic” behavior of the seismicity.

Most common models for providing such an explanation are based on some unstable faulting (or rupture) mechanism (stick-slip, barriers) that does not correspond to a stationary stochastic process. Such models have been proposed by Stuart (1979), Bonafede et al. (1982), Lomnitz-Adler (1983), Newman and Knopoff (1983) and by Mendoza and Dewey (1984). Alternatively, Kanamori (1977) has sought an influence of the variation of the rotation rate and of the Chandler wobble on seismicity. Finally, large-scale

non-random geodynamic processes (slab subduction) have been invoked by Melosh and Fleitout (1982) as being at the root of the chaotic time-behaviour of seismicity.

5.5. Energy and strain release

The magnitude of an earthquake can be related to the energy released by the focus (cf. Sect. 2.4.3 of this review). Therefore, from lists of earthquakes and their magnitudes, the rate of seismic energy released can be obtained for a region or for the globe as a whole. Furthermore, the square root of the energy radiated in an earthquake is proportional to the strain released in that earthquake. Therefore, energy release rates can be converted into strain release rates.

The above procedure is an old and well known one; it goes back to Benioff in the 1950's. A new study of the subject based on new and improved global data was made by Kanamori (1977). The unexplained chaotic secular variation in seismicity naturally is also reflected in the variation of the energy (and strain) release rates. In a renewed study of the problem, Vassiliou and Kanamori (1982) used an improved, sounder magnitude–energy relation and arrived at the conclusion that a stationary or static stochastic model could not be excluded after all.

The energy and strain release in aftershocks is better understood. Evidently, some sort of “rebound” takes place with decreasing rate (Olsson, 1973; Cohen, 1981). There is, however, still considerable uncertainty regarding the type of rheology which is involved in this rebound.

6. SEISMIC RISK

6.1. Introduction

The final section of this review is concerned with questions of risk, earthquake prediction and artificial release.

The problem has been investigated quite generally in some reports and textbooks, such as that by Lomnitz (1974), St. Amand et al. (1975) or that by Lomnitz and Rosenblueth (1976). Accounts of insurance problems connected with earthquake risk have been published by Kulhanek and Båth (1976, 1978), Müller (1978) and by Petak and Atkisson (1982).

The problem, however, has to be treated in its detailed aspects in order to get at quantitative risk estimates.

6.2. Characterization of seismic risk

6.2.1. General requirements

For the characterization of the risk with regard to any natural hazard it is

required to give the probability for an event of given “strength” (or above) to occur at a specific locality. The statistical problems of characterizing earthquake hazards have been described recently by Bolt (1976, 1978), by Shapira (1983) and by Keilis-Borok et al. (1984).

In seismicity studies, the “strength” of the event is usually represented by the intensity-level I , and the probability of occurrence can be represented by the annual recurrence rate $B(I)$ or by the recurrence interval $T(I) = 1/B(I)$. These quantities can be determined for the past, and are then taken as representative for the future. In the light of the recognition of “chaotic” secular changes in earthquake activity, the above procedure is, of course, a bit problematical. It is also evident that the relationship of B or T versus I has some upper limit. Thus, one has introduced the notion of “maximum possible earthquake”.

Recent studies of these problems will be reviewed in the section following.

6.2.2. *Recurrence times*

The determination of recurrence times T versus intensity I proceeds in a straight-forward manner from earthquake damage catalogues. An interesting study has been reported by Sims (1975) who based estimates of such recurrence times on structures in young lacustrine sediments. Weichert (1980) has attempted to estimate recurrence parameters for unequal observation periods. A seismicity study for particular geodynamic conditions was made for the subduction zones by Rikitake (1976) and for the Alps by Botti et al. (1980). The last authors attempted a matching with Gumbel-type statistics for the estimation of seismic risk.

Finally, Caputo (1981a) used maximum acceleration rather than intensity for specifying the “strength” level of the seismic events. This, of course, is possible in view of the general relationship existing between maximum acceleration and intensity.

6.2.3. *The maximum possible earthquake*

As noted above, there are indications that earthquakes cannot become arbitrarily “large”: there appears to be a maximum possible earthquake, maybe a different one for each specific region considered.

In connection with risk studies, the maximum possible *intensity* is of interest. However, it is not known in an earthquake area where the next earthquake is going to occur and hence the maximum possible intensity I_0 is directly related to the maximum possible magnitude by means of the general relationships between I_0 and M (cf. Sect. 3.2). Thus, the procedure has been to estimate the maximum possible *magnitude* in an area: this then allows one to estimate the maximum possible *intensity* which may be expected anywhere in an earthquake region where the epicenter might occur. Upon a

statistical analysis of data from the past, Yegulalp and Kuo (1974), Caputo (1978), and Howell (1979) have followed this procedure.

It should be noted that the above statistical procedures are generally based on the statistics of extreme values (Gumbel-statistics). Other models have been based on Bayesian statistics (Mortgat and Shah, 1979) and truncated exponential models (Cosentino and Luzio, 1977).

6.2.4. Geodynamic considerations

The procedures outlined above are based purely on the statistics of past seismicity. One can also try to set up more causative models.

Thus, the likelihood of the occurrence of earthquakes is inferred from geodynamic studies of active faults etc., and the resulting ground effects from an integration over the possible sources. This approach has been taken by Mark (1977), by Wyss (1979a), and by Sykes and Quittmeyer (1981).

6.3. Site investigations

6.3.1. General zoning

According to the general remarks on the characterization of seismic risk, the assessment of a site requires an estimate of the recurrence times of earthquakes of different intensities and an estimate of the maximum possible earthquake at the site. Thus, general zoning maps can be made of a country or region where iso-lines of intensities can be given for a series of chosen recurrence intervals; or conversely, isolines can be given for the recurrence times for chosen intensities.

On the above basis, conditions have been analysed in many countries (e.g. Norway: Selnes et al., 1980, Fennoscandia: Båth, 1979a, c; Germany: Ahorner et al., 1976; Switzerland: Pavoni, 1977, Pavoni and Mayer-Rosa, 1978; Austria: Drimmel and Trapp, 1982; Italy: Iaccarino, 1973, Siro, 1984; Israel: Shapira, 1983; East Africa: Unesco, 1980; Pakistan: Quittmeyer and Jacob, 1979; Japan: Seno, 1979, Wesnousky et al., 1984; Australia: McEwin et al., 1976; United States: Algermissen and Perkins, 1976, 1977, McGuire, 1977; Saskatchewan: Horner and Hasegawa, 1978; Cuba: Alvarez and Bune, 1977; amongst others).

Maps based on *acceleration* rather than on intensity have been proposed by Ahorner and Rosenhauer (1975) for Europe and by Algermissen and Perkins (1976) for the United States. An example of a study for Israel is shown in Fig. 6.

6.3.2. Specific types of structures

Many studies have been made for ascertaining the safety of specific types of structures. Thus, of much concern have been nuclear power plants

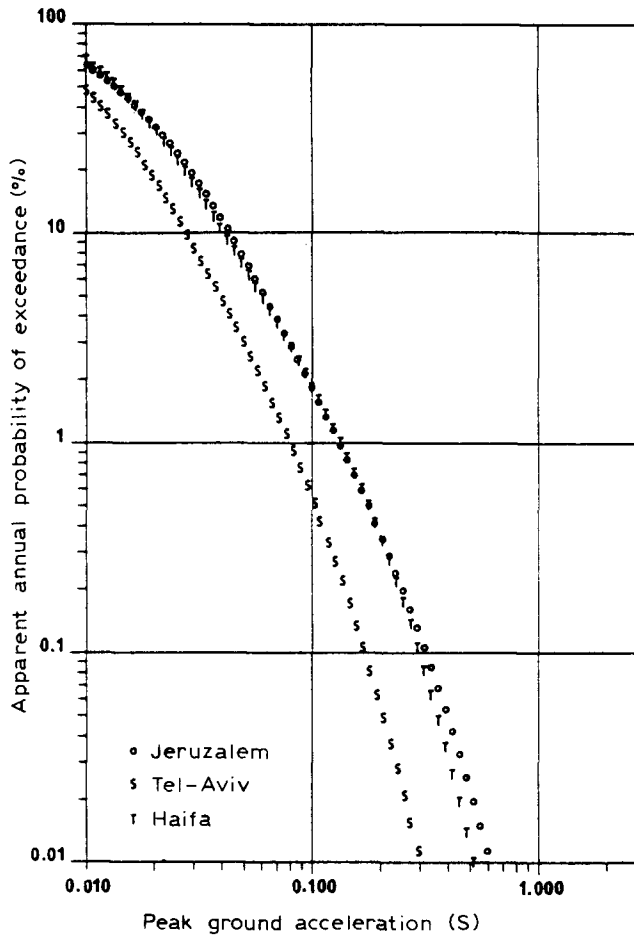


Fig. 6. Curves of the apparent annual probability of exceeding peak ground accelerations in Israel. From Shapira, 1983.

(Newmark, 1972; Symposium, 1975; Taleb-Agha and Whitman, 1977; Aggarwal and Sykes, 1978), dams and reservoirs (Fiedler, 1977; Castle et al., 1980; Baecher et al., 1980) and pipelines (Stevens and Milne, 1974; Taleb-Agha, 1977).

6.4. Earthquake prediction

6.4.1. General remarks

During the last decade, a vast effort has been undertaken in order to predict earthquakes: one would like to know the time, the place and the magnitude of an impending earthquake. It can, however, be safely stated that at this time a reliable prediction of earthquakes is not yet possible.

There have, in fact, been spectacular “successes” (the earthquake of 4 February 1975 near Haicheng) but also some spectacular “failures” (the earthquake of 28 July 1976 near Tangshan). A whole new journal (*Earthquake Prediction Research*, Dordrecht, vol. 1 in 1982) has been devoted to the subject.

The approach to earthquake prediction can principally be taken along two paths: (i) by a statistical study of the past performance of the seismicity; and (ii) by the search for specific “forerunners” (precursors) which would “announce” the earthquake. As the latter, a variety of phenomena has been considered which will be discussed in detail; general reviews of the problems involved have been given by Meissner (1979), Kisslinger and Suzuki (1978), Landsberg (1978), Isikara et al. (1980), Rikitake (1980, 1982), Simpson and Richards (1981), Vogel (1981), Raleigh (1982), Allen (1982), Mogi (1984), Evernden (1982), Utsu (1983), and Wyss (1983).

6.4.2. *Prediction statistics*

In line with the usual risk estimates, the probability of earthquake-occurrence is deduced from past “performance”. However, now one tries to extract a time-dependent probability of earthquake occurrence from the time-series represented by past earthquakes. This is a well-known procedure in connection with volcanic eruptions where the (daily) probability of the next eruption was found to increase with the duration of the time interval since the last eruption. This type of approach has been used by Matsuda (1977); also by Matsuda et al. (1978), by Liu (1984), by Thatcher (1984a, b), and by Jacob (1984) in connection with earthquakes.

6.4.3. *Direct precursors*

More important than general prediction statistics would be the recognition of specific precursors that would herald an earthquake. Many precursors have been suggested. The general requirement is not only that the “precursor” would indicate the imminence of an earthquake with a certain (high) probability, but also that the absence of the precursor would indicate a “safe” time interval: only then are the precursors “significant” for the public policy issues connected with earthquake forecasts (Allen, 1976; Usami, 1977; Paté and Shah, 1979; Evison, 1982a, b). Not only is it desirable to warn people before an earthquake, but it is also important not to give any “false” alarms.

The main problem, thus, is one of recognizing *patterns* (in whatever phenomena) that might be indicative of an earthquake (Wyss, 1983). The possible precursors have been divided into several classes (Rikitake, 1975a, 1978b, 1979) and the next problem is to make inferences from “unreliable” indicators. For this purpose, some sophisticated statistics is employed (Col-

lins, 1977; Guagenti and Scirocco, 1980; Anderson, 1981, 1982; Campbell, 1982; Hamada, 1983; Ferraes, 1985; Niazi, 1984). The problems of this approach, however, have been shown by Lomnitz (1984).

After the above general remarks, we shall now turn to *specific* precursors that have been considered.

6.4.4. Seismicity patterns

It is hoped that patterns of seismicity exist which are characteristic of impending earthquakes (Wyss, 1979b; McNally, 1982; Keilis-Borok, 1982).

One hopeful parameter is the quantity b in the frequency–magnitude relationship ($\log N(M) = a - bM$); this has been described by Caputo (1981b) Reyners (1981), Seggern (1981), and Smith (1981).

Furthermore, it has been noted that changes in micro-earthquake activity precedes some earthquakes, usually expressing itself as “foreshocks”, as “precursory swarms” (Avachyan et al., 1976; Evison, 1977, 1982b; Caputo et al., 1977; Dieterich, 1978; Brune, 1979; Blot, 1979; Bakun and McEvilly, 1979; Keilis-Borok et al., 1980a, b; Teisseyre, 1980, 1983; Alessio et al., 1981; Seggern et al., 1981; Frankel, 1982; Raleigh et al., 1982; Jones et al., 1982; Schenkova et al., 1982; Adams, 1982).

A more sophisticated approach to the “foreshock problem” is by searches of patterns in the space–time distribution of earthquake activity (not necessarily “foreshocks”) which are associated with a future large earthquake. These patterns are of three basic types: activation, quiescence and migration of epicenters. The idea of *activation* is identical to that of foreshocks and has been dealt with above.

The idea of *quiescence* corresponds to expecting “quiet before the storm”. If a Benioff diagram of energy is drawn for a region, one often observes a “plateau” before a large increment. Qualitatively, this is also evident in a curve representing the cumulative number of earthquakes in an area. (Fig. 7) On this basis, a major earthquake has been predicted by Wyss and Baer (1981) for the western part of the Hellenic arc.

The idea of *migration of epicenters* may also be expressed as that of “seismic gap”: in a seismically active region, the concentration of epicenters is by no means uniform over short periods. Over long periods of time, it must be expected that the whole area is covered uniformly by epicenters. Thus, if there is for some time a “seismic gap” in part of the area, then an earthquake may be expected to fall into this “gap” in the near future. This idea has been confirmed on several occasions. (Kelleher and Savin, 1975; Gupta, 1975; Wesson et al., 1977; Yamashina and Inoue, 1979; Acharya, 1979; Singh et al., 1980, 1981; Kristy and Simpson, 1980; House et al., 1981; Papazachos et al., 1982; Purcaru and Berckhemer, 1982b; Seeber et al., 1982; Habermann and Wyss, 1984; Anagnos and Kiremidjian 1984; Kiremidjian

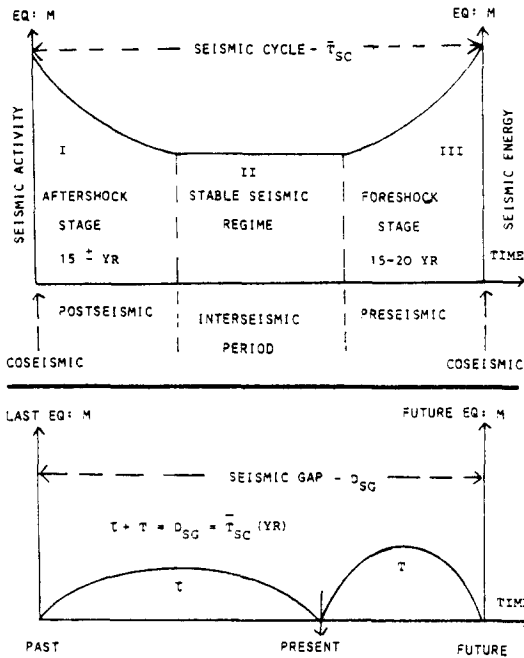


Fig. 7. The relationship between the “seismic cycle” and a (suspected) “seismic gap”. From Purcaru and Berckhemer, 1982b.

and Anagnos, 1984; Hasegawa et al., 1985). However, Lomnitz (1982c; also Lomnitz and Nava, 1983) has pointed out that a “gap” need not be a significant feature in the seismicity at all; it could be caused purely by a stochastic random process. Only if a particular mechanical model for the earthquake preparation process is envisaged does the gap have a predictive significance. Such possible mechanical models based on failure or rupture processes have been proposed by Blacic and Malone (1977), Brady (1977; also Brady and Leighton, 1977), Sobolev et al. (1978), Rice (1979), Kostrov and Das (1982), and Jones (1982), the last author taking strain-softening into account as well.

6.4.5. Geomechanical forerunners

Of the specific effects that have been used as potential earthquake forerunners, geomechanical changes in the groundwater chemistry have been considered. Mainly, one was concerned with the gases dissolved in the water; however, studies have also been made on other isotopes.

The general problems involved in monitoring geomechanical changes have been discussed in symposiums arranged by King (1980, 1981). As noted, isotopes of various solid elements can be used (Chalov et al., 1977; Shi and

Cai, 1980) but mostly the monitoring was done with gases such as helium (Reimer, 1981) and particularly, radon. The two symposiums arranged by King (1980, 1981) mentioned above are dealing mainly with radon. In addition, the methodology for making the measurements has been dealt with by Noguchi and Wakita (1977), Friedmann and Hernegger (1978), and by Klusman and Webster (1981); results have been reported by King (1978) and by Teng (1984) on the San Andreas Fault, by Wang et al. (1980) in China, by Wakita et al., (1980) in Japan and by Hauksson (1981) in Iceland. In such studies it appeared that, while no clear pattern of correlation between the short term local fluctuations and the occurrence of small earthquakes was observed, it was clear that the spacially coherent episodic radon increases coincided with the occurrence of several larger earthquakes.

Possible mechanisms for the release of gases prior to earthquakes were proposed by Giardini et al. (1976), Jiang and Li (1981) and by Fleischer (1981). Generally, some strain-effect prior to fracture is invoked for the release of the gases.

6.4.6. Electrical and magnetic effects

The next possibility that comes to one's mind is a change in electrical effects. Electrical properties of water-saturated rocks change if the rocks are strained; thus a change of resistivity may be expected when the rock is being stressed to the breaking point. However, field tests have yielded only very small changes of the order of mV/km (e.g. Varotsos and Alexopoulos, 1984). Thus, it has been noted that the changes in resistivity with stress that accompany sliding on a fault are insignificant (Brace and Orange, 1968; Rikitake and Yamazaki, 1976, 1979). Other possible earthquake indicators might be electrokinetic phenomena caused by diffusion of underground fluids into a stressed focal region (Mizutani et al., 1976). This might affect the self-potential as well (Corwin and Morrison, 1977) and possibly atmospheric electricity (Pierce, 1976; note also the question of earthquake lights: Noszticzius, 1979, Lockner et al., 1983). The latter might in effect also be influenced by the increased radon flux (ionizing radiation) and cause strange behavior of animals. Reports mainly from China seem to support such observations (Tributsch, 1978; Rikitake, 1978a, Kerr, 1980; Buskirk et al. 1981, Lowry, 1982). Unfortunately the results of serious studies are, at best, inconclusive.

The same may be said regarding the so-called "seismomagnetic" effect: a change in the magnetic field just before or during the occurrence of an earthquake. The reason for suspecting a seismomagnetic effect lies in the observation that the magnetic susceptibility changes if material is stressed. Thus, a change in the magnetic field may accompany a dangerous stress-build up (Fig. 8, Nagata, 1972; Mizutani and Ishido, 1976; Fitterman, 1978;

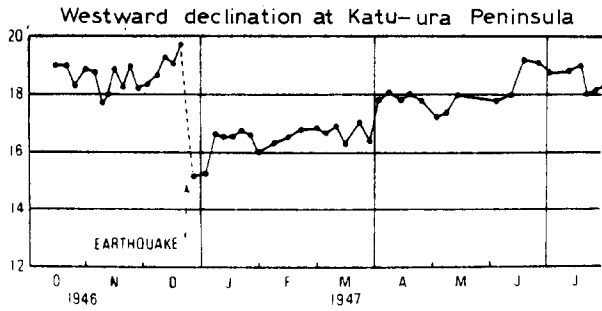


Fig. 8. Co-earthquake change in the westward geomagnetic declination observed at Katu-ura on the Kii Peninsula, near Kusimoto in connection with the Nankaido earthquake of 1946. From Nagata, 1972.

Bonafede and Sabadini, 1980; Johnston et al., 1981; Hao et al., 1982). However, the results were again inconclusive.

6.4.7. Earth strain

More hopeful than the above phenomena are observations of strain build-up in the ground prior to earthquakes. Thus, anomalous deformations prior (hours or days) to large earthquakes have been reported on several occasions. They may be detected as changes of water level in wells (Johnson et al., 1973; Merifield and Lamar, 1981; Leary and Malin, 1984) changes of sea level (Wyss, 1975) or as horizontal or vertical shifts revealed by accurate surveys (Fig. 9; Scholz, 1972, 1974; Castle et al., 1975; Stuart and Johnston, 1975; Fuji, 1976; Reilinger et al., 1977; Savage et al., 1977; Stein and Thatcher, 1981; Rikitake, 1984). Such shifts may be caused by an acceleration of creep phenonema leading to the earthquake (Liu and Livanos, 1976). Actual observations have been made in connection with studies of the Long Beach (1933), the Hyuganada (Japan, 1961 and 1968) and the Perú (1966

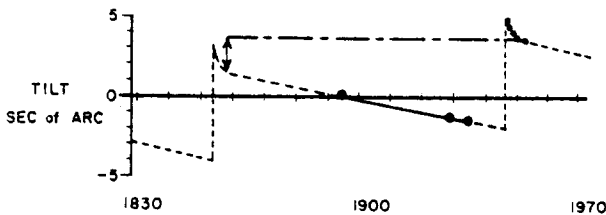


Fig. 9. The sequence of tilting at Muroto Point, southwest Japan, in a direction SSW (NNE positive). Solid circles are measured values, dashed curves are extrapolated from other information. Offsets in the curves were at the time of the 1854 and 1946 earthquakes and the double ended arrow gives the permanent tilt produced by this earthquake cycle. From Scholz, 1972.

and 1970) earthquakes (Wyss, 1977). Although there was a definite connection between geodetic changes and the earthquakes *in these cases*, the unequivocal premonitory significance of such changes is by no means certain yet (Bilham, 1981; King et al., 1981b). The geodetic measurements can also refer to Earth's tilts (Gerard, 1978; Beavon et al., 1983) or to differential strain rates (Rikitake, 1974, 1975b; Bischke, 1976), again with uncertain premonitory significance.

6.4.8. Earth stress

Instead of strain, one might attempt to monitor the stress-changes in the Earth's crust, inasmuch as it would appear as reasonable to suppose that the stress must increase before the occurrence of an earthquake.

Direct stress monitoring has been attempted by Clark (1981) and by Zobak and Zobak (1981). Long-term stresses are notoriously difficult to measure in situ, but an increase prior to the 1979 Lyle Creek earthquake was noted in California.

The stress build-up may express itself also in a change of mechanical rock properties, manifested in a change of wave propagation velocity, particularly evident in the ratio of pressure to shear wave velocity. This, in effect, proved to be the most certain diagnostic feature thus far pointing towards the impending occurrence of an earthquake. Thus, it was observed that the ratio v_p/v_s of the velocities of P to S waves has a characteristic course before the onset of a major earthquake. Then the time evolution of the ratio v_p/v_s is found to have a characteristic bayshape: it decreases at first, then mounts rapidly back to its original value, rises substantially above it until the earthquake occurs, and drops finally back to its "normal" value. Depending on the magnitude of the major earthquake, the "bay" may last some days, months or years. The pattern of "bays" appears to occur consistently as a precursory event before thrust-type earthquakes with a focal depth of not more than 10 km. It can be hoped, therefore, that these types of earthquakes can be predicted if the characteristic "bay" is observed. Observations and monitoring of the "bay-phenomenon" have been variously reported (Gupta, 1974; Kisslinger and Engdahl, 1974; Anderson and Whitcomb, 1975; VanWorner et al., 1975; Medzhitova, 1977; Sobolev and Slavina, 1977; Fedotov et al., 1977; Hedayati et al., 1978, cf. Fig. 10; Talwani, 1979; Feng and Gu, 1981; Wyss et al., 1981).

Regarding a physical explanation of the (suspected) bay-phenomenon, attempts have gone in two directions. First, it has been thought that there could be effects of the increasing stresses prior to an earthquake on cracks in rock (Feves and Simmons, 1976; Stiller et al., 1977; Stiller and Wagner, 1979; Wagner and Engler, 1980; Wagner, 1981) which would affect the wave velocities. Second, the explanation has been sought in a "dilatancy"-phe-

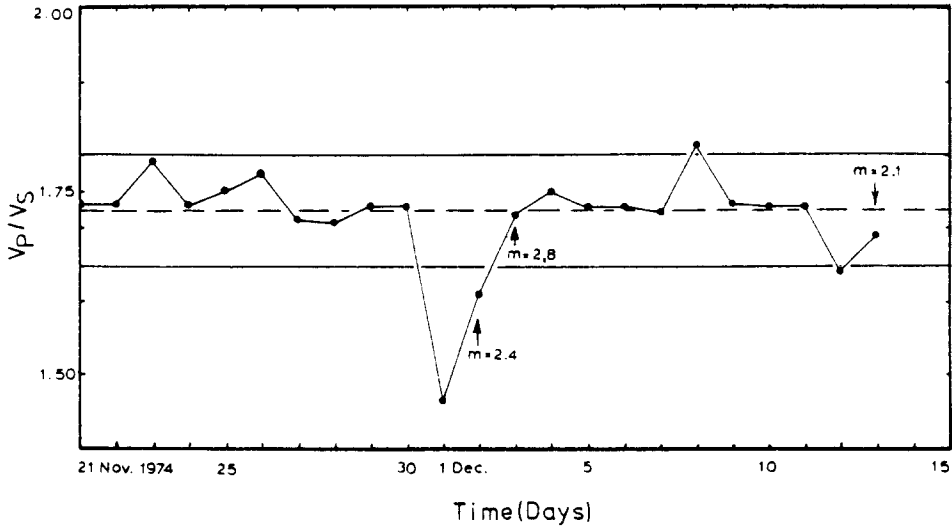


Fig. 10. The values of mean crustal velocity ratio before earthquakes in Iran. After Hedayati et al., 1978.

nomenon: Nur (1972, 1974) has noted that generally the wave velocity is affected by porosity and saturation. Crustal rock, even granite, is slightly porous; in the “normal” state it is fully saturated with pore fluid (water). Just before fracture, the porosity increases (phenomenon of “stress dilatancy”). During the occurrence of dilatancy the rock becomes undersaturated since, because of the low permeability, it will take some time until the full saturation state is again reached. When this occurs, the rock may finally fracture and lead to an earthquake. In this fashion, the bay-phenomenon can be explained. The dilatancy hypothesis has been studied and restudied by many authors (Scholz et al., 1973; Bonner, 1974; Hanks, 1974; Stuart, 1974; Rice, 1975; Hadley, 1976; White, 1976; Holcomb, 1978; Rice et al., 1978; Scholz, 1978; Rice and Rudnicki, 1979; Teufel, 1980; Crampin et al., 1980). The result of these studies is that a dilatancy phenomenon can evidently exist as a physical reality. However, its occurrence before *every* earthquake is by no means assured.

6.4.8. Assessment of predictability of earthquakes

In summary, it may be said that the problem of the prediction of an earthquake is still far from solved. The various indicators mentioned may or may not be significant. The most celebrated case of a successful prediction is that of the 1975 Haicheng earthquake in which a variety of the indicators mentioned above gave premonitions of the earthquake. However, Scholz (1977) pointed out that this was perhaps an exceptional case: the earthquake

may have been triggered by a deformation front moving steadily and thus implicitly predictably through northeast China at a velocity of about 110 km/year. In other disastrous earthquakes conditions are evidently not predictable.

6.5. *Artificial release of earthquakes*

6.5.1. *General remarks*

Once we have studied the problem of the focal mechanisms of an earthquake, the next problem is that of the triggering of the mechanism. If the material in the focal region is close to the breaking point, then it may be expected that relatively minor causes could “trigger” earthquakes. We have seen that the time-sequence of energy release of earthquakes does not appear to contain any periodicities; thus periodically acting effects, such as the tides of the solid Earth, must be excluded as possible earthquake triggers, and the search for possible agents must be confined to aperiodic phenomena.

One of the possible triggering mechanisms is represented by the activities of man. These consist of three types in connection with the induction of seismicity: mining activities, fluid injection, and the filling up of artificial reservoirs. The entire problem was discussed in a symposium in Banff, Canada (Milne, 1976) and in a review by Gough (1978).

6.5.2. *Mining activity*

It is well known that straightforward mining (by excavation) always causes a stress- redistribution which may induce seismic events. By miners these are usually referred to as “rock-bursts”. Whilst rock bursts may pose a serious problem in mining operations, they are, seen from the standpoint of seismologists, rather insignificant. They are properly dealt with in mining engineering publications and have been reviewed recently by Kohlbeck and Scheidegger (1984).

In rare occasions, underground mining or tunneling operations can also trigger “proper” earthquakes. Cases have been reported from the deep mines in South Africa (Cook, 1976), from tunnels in Switzerland (Schneider, 1975) and mines in Canada (Gendzwill et al., 1982). Earthquakes have also been triggered by surface mining (Pomeroy et al., 1976): for example on June 7, 1974, an earthquake of magnitude $M = 3.3$ occurred at Wappinger Falls, N.Y.; the maximum intensity was level 5 with a radius of perceptibility of 10 km. The focal mechanism solution fits together well with the NNE-trending maximum compressive stress determined otherwise for the area. The available evidence, including previous seismic history, locations and the fault-plane solution, indicates that this earthquake has been triggered by unloading associated with quarrying operations in the presence of high horizontal

compressive stress. Estimates of the stress relief caused by the quarrying support this hypothesis.

6.5.3. Fluid injection

Most interesting are cases of earthquake triggering when injection and flow of pore fluids are involved. Thus, hydraulic mining in western New York State seems to have triggered a series of earthquakes. Although the seismic events were small, as many as 80 occurred per day, and many were felt locally. The mining procedure employs hydraulic fracturing in injection wells, and tectonic strains present in nearby faults seem to have been released to cause earthquakes (Fletcher and Sykes, 1977).

Fluid injection in connection with oil well fracturing operations seems to have triggered seismic activity in Lacq, France (Rothé, 1977). The most celebrated case of triggering of earthquakes by pore pressure changes in rocks has occurred near Denver, Colorado (Raleigh et al., 1976; Herrmann et al., 1981; Hsieh and Bredehoeft, 1981). The theory of this phenomenon (Martin, 1975; Weertman and Chang, 1977; Lockner et al., 1982) has to be sought in the well-known Terzaghi relation, according to which an increase in pore water pressure may cause a material to fail. The Terzaghi principle states that the deformation of a porous medium is the same as that of a continuous medium, if the total stress σ_t is replaced by the effective stress σ_e given by:

$$(\sigma_e)_{ik} = (\sigma_t)_{ik} - p\delta_{ik}$$

where p is the pore pressure. This relation has as a consequence that a stress state may become a failure state if the pore pressure increases. This can be most easily demonstrated by using a Mohr diagram for the representation of a stress state: the effective pressure is *less* than the total pressure, hence the center of the Mohr circle is shifted towards lower values and, thus, may exceed the failure-enveloppes. Thus, the injection of fluid into the ground may be expected to cause failure under certain circumstances. Indeed, near Denver, the earthquake activity was directly related to the rate of injection of fluids into the formation. The above mechanism has also been used for attempts at “controlling” earthquakes: if the prevailing stresses could be relieved by the artificial triggering of small earthquakes, the build-up of a large earthquake might possibly be prevented (loc. cit. above). However, this idea has not yet reached the stage of practicality.

6.5.4. Earthquakes and artificial lakes

The final section of this paper is concerned with the possibility that the impounding of an artificial reservoir might trigger earthquakes.

One of the most notorious cases of this type was the earthquake of December 10, 1967, which was triggered by the impounding of a reservoir

near Koyna in Maharashtra State in India: two hundred lives were lost, 1500 people were injured and much damage was caused to houses (Guha et al., 1970; 1974; Kaila et al., 1981a, b; Sharma and Murty, 1982; Gupta and Iyer, 1984).

Other notable cases include Lake Kariba in Africa (Gough and Gough, 1970 a, b; 1976), the Nurek reservoir in the USSR (Leith et al., 1981; Simpson and Negmatullaev, 1981; Keith et al., 1982) and Lake Orville in California (Clark et al., 1976; Beck, 1976; Bell and Nur, 1978; Peppin and Bufe, 1980). Minor events were recently described from North America (Monticello Reservoir, South Carolina: Rastogi and Talwani, 1977; Zoback and Hickman, 1982; Secor et al., 1982, Fletcher, 1982; – Manic Reservoir Quebec: Leblanc and Anglin, 1978; – Geysers, California: Allis, 1982; Denlinger and Bufe, 1982) and from Europe (Spain: Buforn and Udías, 1979; – Punt da Gall, Italy: Deichmann and Bonhage, 1982; – Schlegeis, Austria: Blum and Fuchs, 1974; Blum et al., 1977; – Switzerland: Mayer-Rosa and Deichmann, 1979; – Alps–Carpathians: Merkle et al., 1981).

The above instances represent only some of the observed or suspected cases; there have been many others. It may be of historical interest that the very first case where reservoir-induced seismicity was suspected was Lake Mead (Carder, 1945). On a world-wide basis, Simpson (1976), Nikolayev (1976), Gupta and Rastogi (1976), Gough (1977) and Baecher and Keeney (1982) have given reviews of cases where earthquakes were induced in this fashion. Accordingly, earthquakes with magnitudes from 5.0 to 6.5 on the Richter scale were induced by 5 artificial reservoirs, in 12 cases the induced earthquakes had magnitudes between 3.5 and 5. However not all artificial reservoirs have induced earthquakes, of the 5 largest reservoirs on Earth, only 1 (Kariba Lake in Africa) created earthquakes. Thus, it is a minority (10%) of reservoirs that cause seismicity. Whether this happens or not evidently depends on the tectonic stress state and the water depth that is present in the area.

Studies of the mechanism that triggers the earthquakes have focussed on two possibilities: by increasing the surface load owing to the accumulation of water, and by increasing the pore water pressure in the formation. The most direct triggering mechanism is caused by the additional load of the water. The stresses induced in a layered-elastic half-space by a nonhomogeneous load from above (corresponding to a lake) have been calculated by Lee (1972). It was found that the stress induced by a water volume of the order of 10^{10}m^3 are noticeable as far down as the Mohorovičić discontinuity.

The above triggering mechanism, based on the addition of small incremental stresses to the tectonic stresses which are already present, acts without delay. However, delay-times of 0 to 5 years between the filling of the reservoir and the occurrence of the induced earthquakes have been found;

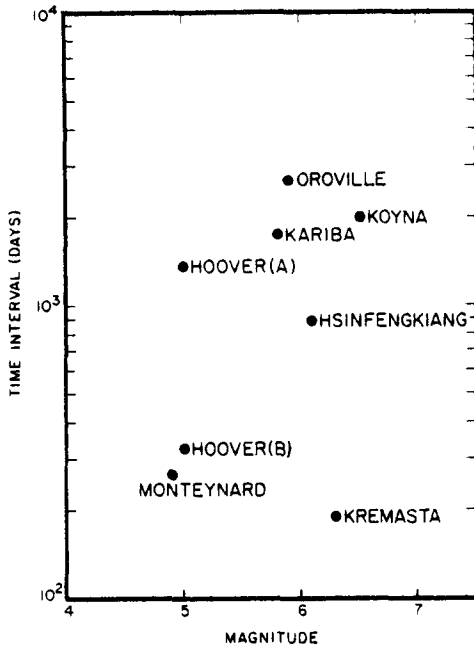


Fig. 11. Time delays observed in some reservoir-induced earthquakes, plotted against their magnitude. After Simpson, 1976.

similarly Beck (1976) has shown at least in one instance (Lake Oroville, California) that weight-induced stresses are too small to trigger the observed earthquakes. Thus, another mechanism must, on occasion, be involved: this is the action via the pore pressure. As noted already in sect. 6.5.3. an increase in pore pressure may cause a material to fail. It is thought that this is, in effect, the mechanism by which many reservoirs trigger earthquakes. It explains the long time delays of up to 5 years between the filling of a reservoir and the occurrence of earthquakes which are occasionally observed: the pore pressure increase is not communicated immediately to the strata which are prone to earthquake activity, but only after a long time delay (Withers and Nyland, 1978; Simpson, 1976; Guha et al., 1981; cf. Fig. 11). An additional triggering effect may be represented by the action of marine tides (Klein, 1976).

The crucial question, of course, is that of whether a contemplated reservoir will or will not induce seismic activity in the area. Unfortunately, one is still very far from a solution of this problem, although it has been discussed at length during a conference held in London in 1980 (Conference, 1981). First of all, one may note that there seems to be no correlation between reservoir-induced seismicity and the natural seismicity of a region. Thus, the Koyna reservoir is located in an aseismic region of India. On the

other hand, one may argue that high background seismicity may constantly relieve the ambient stresses so that the additional load or pore water pressure caused by an artificial lake makes very little difference in the regime. Next, it has been observed that lakes impounded in flexible terrains (friable sandstones and clays) are generally aseismic. On the other hand, the competent basalt layers around Koyna seem to have enhanced the danger of that reservoir: large stresses can be stored in such rocks. It is, thus, probably the presence of critical tectonic stresses which cause the seismicity to be enhanced by the triggering effect due to the impounding of a large lake. Any indications pointing toward the presence of such stresses should be taken as a danger signal (Guha et al., 1981). Large horizontal stress differences may be of prime importance. These could be deduced e.g. from fault plane solutions of earthquakes and joint orientation measurements. Apart from general tectonic risk studies, attempts at the prediction of an impending severe earthquake can be made by the same means as generally in earthquake prediction (cf. Sect. 6.4.). Specifically for the cases of the Koyna and Kremasta reservoirs, Papazachos (1973) has tried to investigate the significance of the time distribution of the foreshocks.

7. REFERENCES

- Acharya, H., 1979. A method to determine the duration of quiescence in a seismic gap. *Geophys. Res. Lett.*, 6(9): 681–684.
- Acharya, H., 1981. Volcanism and aseismic slip in subduction zones. *J. Geophys. Res.*, 86(B1): 335–344.
- Adams, R.D., 1982. Detailed studies of seismicity as an indication of focal processes. *Earthquake Prediction Res.*, 1: 209–222.
- Aggarwal, Y.P. and Sykes, L.R., 1978. Earthquakes, faults, and nuclear power plants in Southern New York and Northern New Jersey. *Science*, 200: 425–429.
- Ahorner, L. and Rosenhauer, W., 1975. Probability distribution of earthquake accelerations with applications to sites in the northern Rhine area, central Europe. *J. Geophys.*, 41: 581–594.
- Ahorner, L., Flick, J.A., Van Gils, J.M., Houtgast, G. and Ritsema, A.R., 1976. First draft of an earthquake zoning map of northwest Germany, Belgium, Luxemburg and the Netherlands. In: *On earthquake risk for nuclear power plants*, Proc. European Seismological Commission Symposium Luxemburg, 20–22 October, 1975. Royal Netherlands Meteorological Inst., KNMI, 153: 39–41.
- Aki, K., 1966. Generation and propagation of G waves from the Niigata earthquake of June 16, 1964, 2: Estimation of earthquake moment, released energy, and stress-strain drop from G-wave spectrum. *Bull. Earthquake Res. Inst. Tokyo Univ.*, 44: 73–88.
- Aki, K., 1982. Progress report on the determination of seismic moment tensor from long-period surface waves. *Tectonophysics*, 8: 1–2.
- Aki, K., 1984. Asperities barriers, characteristic earthquakes and strong motion prediction. *J. Geophys. Res.*, 89(B7): 5867–5872.
- Aki, K. and Duda, S.J. (Editors), 1978. Quantification of earthquakes. *Tectonophysics*, 49 (3/4): 119–272.

- Aki, K. and Patton, H., 1978. Determination of seismic moment tensor using surface waves. *Tectonophysics*, 49: 213–222.
- Alessio, M. et al., 1981. Study of some precursory phenomena for the Umbria earthquake of September 19, 1979. *Nuovo Cim.*, 3C(6): 589–600.
- Algermissen, S.T. and Perkins, D.M., 1976. A probabilistic estimate of acceleration in rock in the contiguous United States. U.S. Geol. Surv. Open File. Rept. 76–416, 45 pp.
- Algermissen, S.T. and Perkins, D.M., 1977. Earthquake hazard map of the United States. *Earthquake Inf. Bull.*, 9(1): 20–21.
- Allen, C.R., 1976. Responsibilities in earthquake prediction. *Bull. Geol. Soc. Am.*, 66 (6): 2069–2074.
- Allen, C.R., 1982. Earthquake prediction—1982 overview. *Bull. Seismol. Soc. Am.*, 72(6): 331–335.
- Allis, R.G., 1982. Mechanism of induced seismicity at the Geysers geothermal reservoir, California. *Geophys. Res., Lett.*, 9(6): 629–632.
- Alvarez, L. and Bune, V.I., 1977. Seismic risk estimation of southeast Cuba. *Bull. (Izv.) Acad. Sci. USSR, Earth Phys.*, 13: 54–67.
- Ambraseys, N.N., 1974a. Recent advances in engineering seismology. *Proc. Symp. Europ. Seismol. Conf. Trieste*.
- Ambraseys, N.N., 1974b. The correlation of intensity with ground motion. *Prepr., 14th Conf. Europ. Seismol. Comm., Trieste*, 12 pp.
- Ambraseys, N., 1983. Notes on historical seismicity. *Bull. Seismol. Soc. Am.*, 73(6): 1917–1920.
- Anagnos, T. and Kiremidjian, A.S., 1984. Stochastic time-predictable model for earthquake occurrences. *Bull. Seismol. Soc. Am.*, 74(6): 2593–2611.
- Anderson, D.L. and Whitcomb, J.H., 1975. Time-dependent seismology. *J. Geophys. Res.*, 80 (11): 1497–1503.
- Anderson, J.G., 1979. A comment on the relationship between earthquake magnitude and rupture length. *Earthquake Notes*, 50(2): 3–8.
- Anderson, J.G., 1981. A simple way to look at a Bayesian model for the statistics of earthquake prediction. *Bull. Seismol. Soc. Am.*, 71(6): 1929–1931.
- Anderson, J.G., 1982. Revised estimates for the probabilistic of earthquakes following observation of unreliable precursors. *Bull. Seismol. Soc. Am.*, 72(3): 879–888.
- Anghel, M., 1978. A new physical model for earthquake triggering effect of solar activity and application to the Vrancea zone. *Proc. 10th Symp. Appl. Geophys Earth Phys., Bucharest*, Nov. 28–30, 12 pp.
- Avachyan, G.M., Belyaevskiy, N.A. and Polshkov, M.K., 1976. A single mechanism for the generation of shallow earthquakes and their precursors. *Bull. (Izv.) Acad. Sci. USSR, Earth Phys.*, 12(12): 38–48.
- Backus, G. and Mulcahy, M., 1976a. Moment tensors and other phenomenological descriptions of seismic sources, I. Continuous displacements. *Geophys. J. R. Astron. Soc.*, 46: 341–361.
- Backus, G. and Mulcahy, M., 1976b. Moment tensors and other phenomenological descriptions of seismic sources, II. Discontinuous displacements. *Geophys. J. R. Astron. Soc.*, 47: 301–329.
- Baecher, G.B. and Keeney, R.L., 1982. Statistical examination of reservoir-induced seismicity. *Bull. Seismol. Soc. Am.*, 72(1): 553–569.
- Baecher, G.B., Paté, M.E. and de Neufville, R., 1980. Risk of dam failure in benefit-cost analysis. *Water Resour. Res.*, 16(3): 449–456.
- Bakun, W.H. and McEvelly, T.V., 1979. Are foreshocks distinctive? *Bull. Seismol. Soc. Am.*, 69(4): 1027–1038.

- Bakun, W.H. and McEvilly, T.V., 1984. Recurrence models and Parkfield, California earthquakes. *J. Geophys. Res.*, 89(B5): 3051–3058.
- Bankwitz, P., 1980. Zum Bewegungsablauf an Bruchstörungen mit seismotektonischer Aktivität. *Z. Geol. Wiss. (Berlin)*, 8(3): 353–362.
- Barley, G.J., 1978. Brittle fracture, pore fluids and Q. *Tectonophysics*, 51: T9–T13.
- Barrows, L. and Langer, C.J., 1981. Gravitational potential as a source of earthquake energy. *Tectonophysics*, 76: 237–255.
- Basili, A. et al., 1977. Earthquake occurrence as a stochastic event: theoretical models. *Boll. Geofis. Teor. Appl.*, 20 (74/74): 3–10.
- Båth, M., 1974. *Spectral Analysis in Geophysics*. Elsevier, Amsterdam, 563 pp.
- Båth, M., 1977. Telesismic magnitude relations. *Ann. Geofis. (Roma)* 30(3/4): 299–327.
- Båth, M., 1978a. The seismicity of Sweden. *Geol. Fören.*, 100(3): 295–299.
- Båth, M., 1978b. A note on recurrence relations of earthquakes. *Tectonophysics*, 51: T23–T30.
- Båth, M., 1979a. Seismic risk in Fennoscandia. *Tectonophysics*, 57: 285–295.
- Båth, M., 1979b. A Mediterranean earthquake project. *Tectonophysics*, 58: T17–T21.
- Båth, M., 1979c. Earthquakes in Sweden. *Sver. Geol. Unders., Årsb.*, 72(12): 1–79.
- Båth, M., 1981. Earthquake magnitude—recent research and current trends. *Earth. Sci. Rev.*, 17(4): 315–398.
- Båth, M., 1984. Correlation between regional and global seismic activity. *Tectonophysics*, 104: 187–194.
- Båth, M., Kulhanek, O., Van Eck, T., and Wahlström, R., 1976. Engineering analysis of ground motion in Sweden. *Rept. Seismol. Inst., Uppsala*, 5-76, 59 pp.
- Bathe, K.J., Wilson, E.L. and Peterson, F.E., 1974. SAPN, a structural analysis program for static and dynamic response of linear systems. *Rept. Earthquake, Eng. Res. Center, Univ. Calif., Berkeley*, No. 3–11, 168 pp.
- Batti, L.G., Pasquale, V. and Anghinolfi, M., 1980. A new general frequency–magnitude relationship. *Pure Appl. Geophys.*, 119(1): 196–206.
- Beavan, J., Hauksson, E., McNutt, S.R., Bilham, R. and Jacob, K.H., 1983. Tilt and seismicity changes in the Shumagin seismic gap. *Science*, 222: 322–325.
- Beck, J.L., 1976. Weight-induced stresses and the recent seismicity at Lake Oroville, California. *Bull. Seismol. Soc. Am.*, 66(4): 1121–1131.
- Beck, S.L. and Ruff, L.J., 1984. The rupture process of the great 1979 Colombia earthquake: evidence for the asperity model. *J. Geophys. Res.*, 89 (B11): 9281–9291.
- Bell, M.L. and Nur, A., 1978. Strength-changes due to reservoir-induced pore pressure and stresses and application to Lake Oroville. *J. Geophys. Res.*, 83 (B9): 4469–4483.
- Ben-Menahem, A., 1976. The role of the shear Mach number in earthquake source dynamics. *Bull. Seismol. Soc. Am.*, 66 (6): 1787–1800.
- Ben-Menahem, A. and Singh, S.J., 1981. *Seismic Waves and Sources*. Springer, Berlin, 1108 pp.
- Bilham, R., 1981. Delays in the onset times of near-surface strain and tilt precursors to earthquakes. *Earthquake Prediction—AGU*, pp. 411–421.
- Bischke, R.E., 1976. Secular horizontal displacements: a method for predicting great thrust earthquakes and for assessing earthquake risk. *J. Geophys. Res.*, 81 (14): 2511–2516.
- Blacic, J.D. and Malone, S.D., 1977. Preliminary analysis of microacoustic signals associated with rock fracture. *Geophys. Res. Lett.*, 4(10): 477–480.
- Blot, C., 1979. Deep earthquakes that were precursors of the eruption of Ruapehu, New Zealand. *N.Z. J. Geol. Geophys.*, 22(3): 413–414.
- Blum, R. and Fuchs, K., 1974. Observation of low-magnitude seismicity at a reservoir in the Eastern Alps. *Eng. Geol.*, 8: 99–106.

- Blum, R. et al., 1977. Correlation between micro-activity and variation of water level at the Schlegeis reservoir. *J. Geophys.* 43: 561–567.
- Boatwright, J., 1980. A spectral theory for circular seismic sources; estimates of source dimension, dynamic stress drop and radiated seismic energy. *Bull. Seismol. Soc. Am.*, 70(1): 1–28.
- Boatwright, J., 1981. Quasi-dynamic models of simple earthquakes: Application to an aftershock of the 1975 Oroville, California, earthquake. *Bull. Seismol. Soc. Am.*, 71(1): 69–94.
- Boatwright, J., 1982. A dynamic model for far-field acceleration. *Bull. Seismol. Soc. Am.*, 72(4): 1049–1068.
- Boatwright, J., 1984a. The effect of rupture complexity on estimates of source size. *J. Geophys. Res.*, 89(B2): 1132–1146.
- Boatwright, J., 1984b. Seismic estimates of stress release. *J. Geophys. Res.*, 89(B8): 6961–6968.
- Bolt, B.A., 1976. Hazards from earthquakes. *Naturwissenschaften*, 63: 356–363.
- Bolt, B.A., 1978. Earthquake hazards. *EOS*, 59(11): 946–962.
- Bonafede, M. and Sabadini, R., 1980. A theoretical approach to the seismomagnetic effect. *Boll. Geofis. Teor. Appl.*, 22 (86): 105–116.
- Bonafede, M., Boschi, K. and Dragoni, M., 1982. On the recurrence time of great earthquakes on a long transform fault. *J. Geophys. Res.*, 87(B13): 10551–10556.
- Bonafede, M., Mulargia, F. and Boschi, E., 1980. Implications of the dilatancy fluid diffusion theory. *Nuovo Cim., Ser. 1*, 3C: 180–190.
- Bonner, B.P., 1974. Shear wave birefringence in dilating granite. *Geophys. Res. Lett.*, 1(5): 217–220.
- Boore, D.M., 1973. The effect of simple topography on seismic waves: implications for the acceleration recorded at Pacoima Dam, San Fernando Valley, California. *Bull. Seismol. Soc. Am.*, 63 (5): 1603–1609.
- Boore, D.M. and Joyner, W.B., 1982. The empirical prediction of ground motion. *Bull. Seismol. Soc. Am.*, 72(6): 43–60.
- Botti, L.G., Pasquale, V. and Anghinolfi, M., 1980. A new general frequency–magnitude relationship. *Pure Appl. Geophys.*, 119 (1): 196–206.
- Bouchon, M., 1980. The motion of the ground during an earthquake. *J. Geophys. Res.*, 85(B1): 356–375.
- Brace, W.F. and Orange, A.S., 1968. Further studies of the effects of pressure on electrical resistivity of rocks. *J. Geophys. Res.*, 73(16): 5407–5420.
- Brady, B.T., 1977. An investigation of the scale-invariant properties of failure. *Int. J. Rock Mech. Min. Sci.*, 14(3): 121–126.
- Brady, B.T. and Leighton, F.W., 1977. Seismicity anomaly prior to a moderate rock burst. *Int. J. Rock Mech. Min. Sci.*, 14(3): 127–132.
- Brune, J.N., 1979. Implications of earthquake triggering and rupture propagation for earthquake prediction based on premonitory phenomena. *J. Geophys. Res.*, 84(B5): 2195–2198.
- Bufo, E. and Udias, A., 1979. A note on induced seismicity in dams and reservoirs in Spain. *Bull. Seismol. Soc. Am.*, 69(5): 1629–1632.
- Buskirk, R.E., Frohlich, C. and Latham, G., 1981. Unusual animal behavior before earthquakes: a review of possible sensory mechanisms. *Rev. Geophys. Space Phys.*, 19(2): 247–270.
- Cagnetti, V. and Console, R., 1977. Space–time distribution of the Friuli (1976) earthquakes. *Ann. Geofis. (Roma)*, 30(1/2): 107–183.
- Caloi, P. and Migani, M., 1975. Micromovimenti nella Centrale di Somplago, presso la faglia del Lago di Cavazzo, I. Micromovimenti comunque legati all'attività della Centrale, alla pressione atmosferica o d'origine astronomica. *Rend. Cl. Sci. Fis., Mat. e Nat., Accad. Naz. dei Lincei*, (8) 58(6): 911–918.

- Campbell, K.W., 1982. Bayesian analysis of extreme earthquake occurrences, I. Probabilistic hazard model. *Bull. Seismol. Soc. Am.*, 72(5): 1689–1705.
- Caputo, M., 1976. Properties of earthquake statistics. *Ann. Matemat. Pura Appl.*, (4)111: 185–193.
- Caputo, M., 1978. The distribution of the faults and the maximum magnitude of a seismic region. *Proc. Spec. Mtg. 1976 Friuli Earthquake*, CNEN, Roma, pp. 709–735.
- Caputo, M., 1980. Analysis of statistical distribution of stress drops occurring during earthquakes. *Tectonophysics*, 69: T9–T13.
- Caputo, M., 1981a. Earthquake-induced ground acceleration. *Nature* 291: 51–53.
- Caputo, M., 1981b. A note on random stress model for seismicity statistics and earthquake prediction. *Geophys. Res. Lett.*, 8(5): 485–488.
- Caputo, M. et al., 1977. Earthquake swarms as forerunners of strong earthquakes. *Ann. Geofis. (Roma)*, 30 (3/4): 269–283.
- Caputo, M., Manzetti, V. and Nicelli, R., 1985. Topography and its isostatic compensation as a cause of seismicity; a revision. *Tectonophysics*, 111: 25–39.
- Carder, D.S., 1945. Seismic investigations in the Boulder Dam area 1940–1944 and the influence of reservoir loading on earthquake activity. *Bull. Seismol. Soc. Am.*, 35: 175–192.
- Castellani, A., Riccioni, R. and Robusti, G., 1978. Surface effects on seismic waves. *ISMES (Bergamo) Repts.*, 106(3): 91–103.
- Castle, R.O., Church, J.P., Elliott, M.R. and Morrison, N.L., 1975. Vertical crustal movements preceding the San Fernando earthquake of February 9, 1971: A summary. *Tectonophysics*, 29: 127–140.
- Castle, R.O., Clark, M.M., Grantz, A. and Savage, J.C., 1980. Tectonic state: its significance and characterization in the assessment of seismic effects associated with reservoir impounding. *Eng. Geol.*, 15 (1–2): 53–99.
- Castoldi, A., 1978. Contribution of the surveillance to the evaluation of the seismic efficiency of dams. Example of the Ambiesta Dam. *Repts. ISMES (Bergamo)*, 112(4): 107–118.
- Castoldi, A. and Casirati, M., 1978a. Forced vibration tests on a single family prefabricated housing unit. *Repts. ISMES (Bergamo)* 97: 1–16.
- Castoldi, A. and Casirati, M., 1978b. In situ dynamic tests and seismic records on the RHR System building ENEL IV nuclear plant/Caorso (Italy). *Nucl. Eng. Des.*, 45: 497–505.
- Chalov, P.I., Tuzova, T.V. and Alekhina, V.M., 1977. Forecasting of earthquakes from the changes in the radioisotopic parameters of fracture water of the earth's crust. *Bull. (Izv.) Acad. Sci. USSR, Earth Phys.*, 13(8): 563–566.
- Chang, W.Y., Chung, C.Y., Yeh, H. and Cong, B.L., 1975. Preliminary note of the origin and development of rock-fracture and its bearing on earthquakes. *Acta Geol. Sinica*, 1975: 17–27.
- Chapple, W.M. and Forsyth, D.W., 1979. Earthquakes and bending of plates of trenches. *J. Geophys. Res.*, 84(B2): 6729–6749.
- Chung, D.H. and Bernreuter, D.L., 1981. Regional relationships among earthquake magnitude scales. *Rev. Geophys. Space Phys.*, 19(4): 649–663.
- Clark, B.R., 1981. Stress anomaly accompanying the 1979 Lyle Creek earthquake: implications for earthquake prediction. *Science*, 211: 51–53.
- Clark, M.M., Sharp, R.V., Castle, R.O. and Harsh, P.W., 1976. Surface faulting near Lake Oroville, California in August 1975. *Bull. Seismol. Soc. Am.*, 66(4): 1101–1110.
- Cohen, S.C., 1981. Postseismic rebound due to creep of the lower lithosphere and asthenosphere. *Geophys. Res. Lett.*, 8(5): 493–496.
- Cohn, S.N., Hong, T.-L. and Helmlinger, D.V., 1982. The Oroville earthquake—A study of source characteristics and site effects. *J. Geophys. Res.*, 87(B6): 4585–4594.

- Cook, N.G.W., 1976. Seismicity associated with mining. *Eng. Geol.*, 10: 99–122.
- Collins, J.D., 1977. The probabilistic significance of earthquake prediction. *Bull. Seismol. Soc. Am.*, 67(1): 243–244.
- Commissione CNEN-ENEL, 1976. Strong motion earthquake accelerograms, digitized and plotted data: Uncorrected accelerograms. CNEN Roma, 218 pp.
- Conference, 1981. Dams and earthquake: Proceedings of a conference held at the Institution of Civil Engineers, London, on 1–2 October, 1980, Institution of Civil Engineers, Thomas Telford Ltd., London, 313 pp.
- Corwin, R.F. and Morrison, H.F., 1977. Self-potential variations preceding earthquakes in central California. *Geophys. Res. Lett.*, 4(4): 171–174.
- Cosentino, P. and Luzio, C., 1977. Earthquake risk and connected statistical parameters in the truncated exponential model. *Riv. Ital. Geofis. Sci. Aff.*, 4(3): 119–121.
- Cosentino, M. and Lombardo, G., 1980. Correlation between the modified Mercalli seismic scale and the Medvedev–Sponheuer–Karnik scale for the earthquakes of Sicily and Calabria. *Boll. Geofis. Teor. Appl.*, 22(85): 29–37.
- Crampin, S. et al., 1980. Observations of dilatancy-induced polarization anomalies and earthquake prediction. *Nature*, 286: 874–877.
- D'Albe, F., 1974. Environmental Seismology. *Proc. Symp. Europ. Seismol. Comm., Trieste*.
- Das, S., 1981. Three-dimensional spontaneous rupture propagation and implications for the earthquake source mechanism. *Geophys. J.R. Astron. Soc.*, 67: 375–393.
- Das, S. and Scholz, C.H., 1981. Off-fault aftershock clusters caused by shear-stress increase? *Bull. Seismol. Soc. Am.*, 71(5): 1669–1675.
- Das, S. and Scholz, C.H., 1983. Why large earthquakes do not nucleate at shallow depths. *Nature*, 305: 621–623.
- Deichmann, N. and Bonhabe, R., 1982. Frost-induced seismic events: investigations at the Punt dal Gall arch dam. *Proc. 14th Congr. Grands Barrages, Rio de Janeiro*, pp. 1077–1091.
- Denlinger, R.P. and Bufe, C.G., 1982. Reservoir conditions related to induced seismicity at the Geysers steam reservoir, Northern California. *Bull. Seismol. Soc. Am.*, 72(4): 1317–1327.
- Derr, J.S., 1977. Earthquake lights. *Earthquake Inf. Bull.*, 9(3): 18–21.
- Dieterich, J.H., 1978. Preseismic fault slip and earthquake prediction. *J. Geophys. Res.*, 83(B8): 3940–3948.
- Dong, W.M., Bao, A.B. and Sham, N.C., 1984. Use of maximum entropy principle in earthquake recurrence relationships. *Bull. Seismol. Soc. Am.*, 74(2): 725–737.
- Drimmel, J., 1980. On the resonance effects of strong earthquakes and their consideration in the intensity scales. *Arch. Meteorol., Geophys. Bioklimatol.*, A29(3): 327–332.
- Drimmel, J., 1984. A theoretical basis for macroseismic scales and some implications for practical work. *Eng. Geol.*, 20: 99–104.
- Drimmel, J., 1985. Seismische Intensitätsskala 1985 (SIS-85). *Arb. Zentr. Anst. Meteorol. Geodyn.*, 62: 1–28.
- Drimmel, J. and Trapp, E., 1982. Die Erdbeben Österreichs 1971–1980. *S.-Ber. Österr. Akad. Wiss., Math.-Naturw. Kl., Abt. I*, 191(3): 73–102.
- Drimmel, J., Gangl, G., Gutdeutsch, R., Koenig, M. and Trapp, E., 1973. Modellseismische Experimente zur Interpretation makroseismischer Daten aus dem Bereich der Ostalpen. *Z. Geophys.*, 39: 21–39.
- Dubourdieu, G., 1980. Mise en évidence de la période sismique de 4 ans au 19me siècle. *Collège de France, Paris*, 43 pp.
- Dubourdieu, G., 1983. Quelques indices d'un cycle sismique de 88 ans. *Presse-Diffusion, Paris*, 47 pp.

- Duma, G., 1981. Ein Beitrag zur praktischen Abschätzung der Ausdehnung von Erdbebenherden. *Arch. Meteorol., Geophys. Bioklimatol.*, A30: 391–398.
- Einarsson, P., Klein, F.W. and Björnsson, S., 1977. The Borgarfjörður earthquakes of 1974 in West Iceland. *Bull. Seismol. Soc. Am.*, 67(1): 187–208.
- Evernden, J.G., 1982. Earthquake prediction: what we have learned and what we should do now. *Bull. Seismol. Soc. Am.*, 72(6): 5343–5349.
- Evison, F.F., 1977. The precursory earthquake swarm. *Phys. Earth Planet. Int.*, 15(4): 19–23.
- Evison, F.F., 1982a. Earthquake forecasting and countermeasures planning. *Earthquake Prediction Res.*, 1: 115–124.
- Evison, F.F., 1982b. Generalized precursory swarm hypothesis. *J. Phys. Earth*, 30(2): 155–170.
- Fedotov, S.A. et al., 1977. Long- and short-term earthquake prediction in Kamchatka. *Tectonophysics*, 37: 305–321.
- Feng, D.Y. and Gu, J.P., 1981. Temporal and spatial characteristics of the variations of seismic velocity ratio anomalies. *Earthquake Prediction*, AGU, pp. 357–366.
- Ferraes, S.C., 1985. The Bayesian probabilistic prediction of strong earthquakes in the Hellenic arc. *Tectonophysics*, 111: 339–354.
- Ferrick, M.G., Qamar, A. and St. Lawrence, W.F., 1982. Source mechanism of volcanic tremor. *J. Geophys. Res.*, 87(B11): 8675–8683.
- Feves, M. and Simmons, G., 1976. Effects of stress on Westerly Granite. *Bull. Seismol. Soc. Am.*, 66(5): 1755–1765.
- Fiedler, G., 1977. Forced oscillations of the Guri Dam in Venezuela. *Bol. IMME*, 15(57): 127–143.
- Fitterman, D.V., 1978. Electrokinetic and magnetic anomalies associated with dilatant regions in a layered earth. *J. Geophys. Res.*, 83(B12): 5923–5938.
- Fleischer, R.L., 1981. Dislocation model for radon response to distant earthquakes. *Geophys. Res. Lett.*, 8(5): 477–480.
- Fletcher, J.B., 1982. A comparison between tectonic stress measured in situ and stress parameters from induced seismicity at Monticello Reservoir, South Carolina. *J. Geophys. Res.*, 87(B8): 6931–6944.
- Fletcher, J.B. and Sykes, L.R., 1977. Earthquakes related to hydraulic mining and natural seismic activity in Western New York State. *J. Geophys. Res.*, 82(26): 3767–3780.
- Franke, A. and Gutdeutsch, R., 1974. Makroseismische Abschätzungen von Herdparametern österreichischer Erdbeben aus den Jahren 1905–1973. *J. Geophys.*, 40: 173–188.
- Frankel, A., 1982. Precursors to a magnitude 4.9 earthquake in the Virgin Islands. *Bull. Seismol. Soc. Am.*, 72(4): 1277–1294.
- Friedmann, H. and Hergnegger, F., 1978. A method for continuous measurement of radon in water of springs for earthquake prediction. *Geophys. Res. Lett.*, 5(7): 565–568.
- Fuji, Y., 1976. Vertical crustal movement and dilatancy associated with the Ito earthquake swarm in 1930. *J. Geodet. Soc. Jpn.*, 22(3): 139–148.
- Fumagalli, E. and Casirati, M., 1978. Essais dynamics sur modèles réduits. *Repts. ISMES (Bergamo)*, 96: 1–15.
- Furumoto, M., 1979. Initial phase analysis of R waves from great earthquakes. *J. Geophys. Res.*, 88(B3): 2191–2198.
- Furumoto, M. and Nakanishi, I., 1983. Source times and scaling relations of large earthquakes. *J. Geophys. Res.*, 88(B3): 2191–2198.
- Furuzawa, T., 1976. Some problems of seismic data processing, 3. Particle motion analysis of local earthquake waves and the underground structure beneath recording sites. *Bull. Disas. Prev. Res. Inst., Kyoto Univ.*, 26(1): 1–15.
- Ganse, R.A. and Nelson, J.B., 1982. Catalog of significant earthquakes 2000 B.C. to 1979, including quantitative casualties and damage. *Bull. Seismol. Soc. Am.*, 72(3): 873–877.

- Gendzwill, D.J., Horner, R.B. and Hasegawa, H.S., 1982. Induced earthquakes at a potash mine near Saskatoon, Canada. *Can. J. Earth Sci.*, 19(3): 466–475.
- Gerard, V.B., 1978. Earthquake precursors from Earth tilt observations corrected for rainfall. *Nature*, 276: 169–170.
- Gever, J.W. and Hasegawa, H.S., 1981. A model for P-wave nodal solutions. *Can. J. Earth Sci.*, 18(4): 818–823.
- Giardini, A.A., Subbarayudu, G.V. and Melton, C.E., 1976. The emission of occluded gas from rocks as a function of stress: its possible use as a tool for predicting earthquakes. *Geophys. Res. Lett.*, 3(6): 355–358.
- Gold, T. and Soter, S., 1980. The deep-earth gas hypothesis. *Sci. Am.*, 242(6): 154–161.
- Goodacre, A.K. and Hasegawa, H.S., 1980. Gravitationally induced stresses at structural boundaries, *Can. J. Earth Sci.*, 17(9): 1286–1291.
- Gough, D.I., 1977. Induced seismicity. Preprint FUNVISIS Symposium July, 1977, Caracas, 20 pp.
- Gough, D.I., 1978. Induced seismicity. In: *Assessment and Mitigation of Earthquake Risk*, Unesco, Paris pp. 91–117.
- Gough, D.I. and Gough, W.I., 1970a. Stress and deflection in the lithosphere near Lake Kariba, I. *Geophys. J.R., Astron., Soc.*, 21: 65–78.
- Gough, D.I. and Gough, W.I., 1970b. Local-induced earthquakes at Lake Kariba, II. *Geophys. J.R. Astron. Soc.*, 21: 79–101.
- Gough, D.I. and Gough, W.I., 1976. Time dependence and trigger mechanism for the Kariba (Rhodesia) earthquakes. *Tectonophysics*, 10: 211–217.
- Gu, G.-X. and Ma, X.-Y. (Editors), 1984. A collection of papers of an international symposium on continental seismicity and earthquake prediction. Beijing, Seismological Press, 867 pp.
- Guagenti, E.G. and Scirocco, F., 1980. A discussion of seismic risk including precursors. *Bull. Seismol. Soc. Am.*, 70(6): 2245–2251.
- Guha, S.K. et al., 1970. Recent seismic disturbances in the Shivajisagare-lake area of the Koyna hydroelectric projekt, Maharashtra, India. Comprehensive report up to 1969. Central Water Power Res. Sta., Poona.
- Guha, S.K. et al., 1974. Koyna earthquakes October 1963 to December 1973. Central Water Power Res. St., Poona.
- Guha, S.K., Padale, J.G. and Gosavi, P.D., 1981. Probable risk estimation due to reservoir-induced seismicity. *Proc. Dams and Earthquake Conference*, Institution of Civil Engineers, London. Thomas Telford, London, pp. 297–312.
- Gupta, H.K. and Iyer, H.M., 1984. Are Reservoir-induced earthquakes of magnitude = 5.0 at Koyna, India, preceded by pairs of earthquakes of magnitude = 4.0? *Bull. Seismol. Soc. Am.*, 74(3): 863–873.
- Gupta, H.K. and Rastogi, B.K., 1976. *Dams and Earthquakes*. Elsevier, Amsterdam, 229 pp.
- Gupta, I.N., 1974. Dilatancy and spatial distribution of aftershocks. *Bull. Seismol. Soc. Am.*, 64(6): 1707–1713.
- Gupta, I.N., 1975. Precursory reorientation of stress axes due to vertical migration of seismic activity. *J. Geophys. Res.*, 80(2): 272–273.
- Gupta, I.N. and Nuttli, O.W., 1976. Spatial attenuation of intensities for Central U.S. earthquakes. *Bull. Seismol. Soc. Am.*, 66(3): 743–751.
- Habermann, R.E. and Wyss, M., 1984. Earthquake triggering during preparation for great earthquakes. *Geophys. Res. Lett.*, 11(4): 291–294.
- Hadley, K., 1976. The effect of cyclic stress on dilatancy: another look. *J. Geophys. Res.*, 81(4): 2471–2474.

- Hadley, D.M., Helmberger, D.V. and Orcutt, J.A., 1982. Peak acceleration scaling studies. *Bull. Seismol. Soc. Am.*, 72(3): 959–979.
- Hamada, K. 1983. A probability model for earthquake prediction. *Earthquake Prediction Res.*, 2: 227–234.
- Hanks, T.C., 1974. Constraints on the dilatancy–diffusion model of the earthquake mechanism. *J. Geophys. Res.*, 79(20): 3023–3025.
- Hanks, T.C., 1979. The Lompoc California earthquake (November 4, 1927; $M = 7.3$) and its aftershocks. *Bull. Seismol. Soc. Am.*, 69(2): 451–462.
- Hansen, R.J., 1972. *Seismic Design for Nuclear Power Plants*. General Publ. Co. Ltd., Canada, 298 pp.
- Hao, J.Q., Hastie, L.M. and Satcey, F.D., 1982. Theory of the seismomagnetic effect: a reassessment. *Phys. Earth Planet. Int.*, 28(2): 129–140.
- Hartzell, S.H. and Archuleta, R.J., 1979. Rupture propagation and focusing of energy in a foam rubber model of a stick-slip earthquake. *J. Geophys. Res.*, 84(B7): 3623–3636.
- Hasegawa, H.S., 1974a. Theoretical synthesis and analysis of strong motion spectra of earthquakes. *Can. Geotech. J.*, 11(2): 278–297.
- Hasegawa, H.S., 1974b. A theoretical evaluation of design ground seismic motions for pipelines in the Yukon Territory and Mackenzie Valley. *Publ. Earth. Phys. Branch, Ottawa*, 44(12): 261–271.
- Hasegawa, H.S., Adams, J. and Yamazaki, K., 1985. Upper crustal stresses and vertical stress migration in eastern Canada. *J. Geophys. Res.*, 90(B5): 3637–3648.
- Hatzfeld, D. and Frogneux, M., 1981. Intermediate depth seismicity in the western Mediterranean unrelated to subduction of oceanic lithosphere. *Nature*, 292: 443–445.
- Hauksson, E., 1981. Radon content of groundwater as an earthquake precursor: evaluation of worldwide data and physical basis. *J. Geophys. Res.*, 86(B10): 9397–9410.
- Heaton, T.H., 1982. Tidal triggering of earthquakes. *Bull. Seismol. Soc. Am.*, 72(6): 2181–2200.
- Hedayati, A., Brandner, J.L. and Mason, R.G., 1978. Instances of premonitory crustal velocity ratio changes in Iran. *Tectonophysics*, 44(1–4): T1–T6.
- Hedervari, P., 1975. On the possible relationship between the Matushiro earthquake swarm and the inactivity of Asama-yama Volcano. *Ann. Geofis. (Roma)*, 28(4): 345–364.
- Herrmann, R.B. and Nuttli, O.W., 1982. Magnitude: The relation of M_L to M_{BLG} . *Bull. Seismol. Soc. Am.*, 72(2): 389–397.
- Herrmann, R.B., Park, S.K. and Wang, C.Y., 1981. The Denver earthquakes of 1967–1968. *Bull. Seismol. Soc. Am.*, 71(3): 731–745.
- Hirn, A., Haessler, H., Trong, P.H., Wittlinger, G. and Victor, L.A.M., 1980. Aftershock sequence of the January 1st earthquake and present-day tectonics in the Azores. *Geophys. Res. Lett.*, 7(7): 501–504.
- Holcomb, D.J., 1978. A quantitative model of dilatancy in dry rock and its application to westerly granite. *J. Geophys. Res.*, 83(B10): 4941–4950.
- Horner, R.B. and Hasegawa, H.S., 1978. The seismotectonics of southern Saskatchewan. *Can. J. Earth Sci.*, 15(8): 1341–1355.
- Howell, B.F., 1979. The largest possible earthquake. Preprint I.U.G.G. Meeting Canberra, 25 pp.
- Howell, B.F. Jr., 1981. On the saturation of earthquake magnitudes. *Bull. Seismol. Soc. Am.*, 71(5): 1401–1422.
- House, L.S., Sykes, L.R., Davies, J.N. and Jacob, K.H., 1981. Identification of a possible seismic gap near Unalaska Island, Eastern Aleutians, Alaska. *Earthquake Prediction AGU*, pp. 81–92.
- Hsieh, P.A. and Bredehoeft, J.D., 1981. A reservoir analysis of the Denver earthquakes: a case of induced seismicity. *J. Geophys. Res.*, 86(B2): 903–920 (1981).

- Iaccarino, E., 1973. Probabilità della scossa di IX grado in Italia (map). Com. Naz. Energ. Nucl., Roma.
- Irikura, K., 1983. Semi-empirical estimation of strong ground motions during large earthquakes. *Bull. Disas. Prev. Res. Inst., Kyoto Univ.*, 33(2): 63–104.
- Isikara, A.M., Vogel, A. and Soysal, H. (Editors), 1980. *Multidisciplinary Approach to Earthquake Prediction*. Vieweg, Braunschweig, 700 pp.
- Ito, K., 1980. Periodicity and chaos in great earthquake occurrence. *J. Geophys. Res.*, 85(B3): 1399–1408.
- Jacob, K.H., 1984. Estimates of long-term probabilities for future great earthquakes in the Aleutians. *Geophys. Res. Lett.*, 11(4): 295–298.
- Jiang, F.L. and Li, G.R., 1981. Experimental studies of the mechanisms of seismo-geochemical precursors. *Geophys. Res. Lett.*, 8(5): 473–476.
- Johnson, A.G., Kovach, R.L. and Nur, A., 1973. Pore pressure changes during creep events on the San Andreas fault. *J. Geophys. Res.*, 78(5): 851–857.
- Johnson, R.A., 1973. An earthquake spectrum prediction technique. *Bull. Seismol. Soc. Am.*, 63(4): 1255–1274.
- Johnston, A.C., 1982. A major earthquake zone on the Mississippi. *Sci. Am.*, 246(4): 60–68.
- Johnston, M.J.S., Mueller, R.J. and Keller, V., 1981. Preseismic and coseismic magnetic field measurements near the Coyote Lake, California, earthquake of August 6, 1979. *J. Geophys. Res.*, 86(B2): 921–926.
- Jones, L.M., Wang, B.Q., Su, S.X. and Fitch, T.J., 1982. The foreshock sequence of the February 4, 1975, Haicheng earthquake. *J. Geophys. Res.*, 87(B6): 4575–4584.
- Jones, T.D., 1982. Strain softening of faults and earthquake precursors. *Tectonophysics*, 88 (1–2): 161–174.
- Joyner, W.B., 1984. A scaling law for the spectra of large earthquakes. *Bull. Seismol. Soc. Am.*, 74(4): 1177–1188.
- Kagan, Y.Y. and Knopoff, L., 1980. Spatial distribution of earthquakes: the two-point correlation function. *Geophys. J. R. Astron. Soc.*, 62(2): 303–320.
- Kagan, Y.Y. and Knopoff, L., 1981. Stochastic synthesis of earthquake catalogs. *J. Geophys. Res.*, 86(B4): 2853–2862.
- Kaila, K.L., Murty, P.R.K., Rao, V.K. and Kharechko, G.E., 1981a. Crustal structure from deep seismic soundings along the Koyna II (Kelsi–Loni) profile in the Deccan Trap area, India. *Tectonophysics*, 73: 365–384.
- Kaila, K.L., Reddy, P.R., Dixit, N.M. and Lazarenko, M.A., 1981b. Deep crustal structure at Koyna, Maharashtra, indicated by deep seismic soundings. *J. Geol. Soc. India*, 22(1): 1–16.
- Kanamori, H., 1977. The energy release in great earthquakes. *J. Geophys. Res.*, 82(20): 2981–2988.
- Kanamori, H., 1983. Magnitude scale and quantification of earthquakes. *Tectonophysics*, 93: 185–199.
- Kanamori, H. and Abe, K., 1979. Reevaluation of the turn-of-the-century seismicity peak. *J. Geophys. Res.*, 85(B11): 6131–6139.
- Karnik, V. et al., 1978. Map of isoseismals of the main Friuli earthquake. *Pure Appl. Geophys.*, 116: 1307–1313.
- Kasahara, K., 1981. *Earthquake Mechanics*. Cambridge University Press, Cambridge, 248 pp.
- Kasuga, S. and Irikura, K., 1982. Earthquake ground motions influenced by horizontally discontinuous structures. *Bull. Disas. Prev. Res. Inst., Kyoto Univ.*, 32(2): 97–114.
- Kaul, M.K., 1978. Stochastic characterization of earthquakes through their response spectrum. *Earthquake Eng. Struct. Dyn.*, 6(5): 497–509.

- Keilis-Borok, V.I., 1982. A world-wide test of three long term premonitory seismicity patterns — a review. *Tectonophysics*, 85: 47–60.
- Keilis-Borok, V.I., Knopoff, L. and Rotvain, I.M., 1980a. Bursts of aftershocks long-term precursors of strong earthquakes. *J. Geophys. Res.*, 85(B2): 803–812.
- Keilis-Borok, V.I., Knopoff, L. and Allen, C.R., 1980b. Long-term seismicity patterns in Tibet and Himalayas. *J. Geophys. Res.*, 85(B2): 813–820.
- Keilis-Borok, V.I., Kronrod, T.L. and Molchan, G.M., 1984. Seismical hazard for the largest cities of the world. Repts. 27th Int. Geol. Congr., Moscow, C06: 12–34.
- Keith, C.M., Simpson, D.W. and Soboleva, O.V., 1982. Induced seismicity and style of deformation at Nurek reservoir, Tadjikistan, USSR. *J. Geophys. Res.*, 87(B6): 4609–4624.
- Kelleher, J. and Savino, J., 1975. Distribution of seismicity before large strike slip and thrust type earthquakes. *J. Geophys. Res.*, 80(2): 260–271.
- Kerr, R.A., 1980. Quake prediction by animals gaining respect. *Science*, 208: 695–696.
- Khalturin, V.I. and Rautiani, T.G., 1978. The use of the coda for determination of the earthquake source spectrum. *Bull. Seismol. Soc. Am.*, 68(4): 923–948.
- Kilston, S. and Knopoff, L., 1983. Lunar–solar periodicities of large earthquakes in southern California. *Nature*, 303: 21–25.
- King, C.Y., 1978. Radon emanation on San Andreas Fault. *Nature*, 271: 516–519.
- King, C.Y. (Editor), 1980. Geochemical measurements pertinent to earthquake prediction. *J. Geophys. Res.*, 85(B6): 3051–3121.
- King, C.Y. (Editor), 1981. A special collection of reports on earthquake prediction: hydrologic and geochemical studies. *Geophys. Res. Lett.*, 8(5): 421–424.
- King, N.E., Savage, J.C., Lisowsky, M. and Prescott, W.N., 1981b. Preseismic deformation associated with the Coyote Lake, California, earthquake. *J. Geophys. Res.*, 86(B2): 892–898.
- Kiremidjian, A.S. and Anagos, T., 1984. Stochastic-predictable model for earthquake occurrences. *Bull. Seismol. Soc. Am.*, 74(2): 739–755.
- Kisslinger, C., 1975. Processes during the Matushiro, Japan, earthquake swarm as revealed by leveling, gravity and spring-flow observations. *Geology*, 3(2): 57–62.
- Kisslinger, C. and Engdahl, E.R., 1974. A test of the Semyenov prediction technique in the central Aleutian Islands. *Tectonophysics*, 23: 237–246.
- Kisslinger, C. and Suzuki, Z. (Editors), 1978. *Earthquake Precursors*. Academic Publ. Japan, Tokyo, 304 pp.
- Klein, F.W., 1976. Tidal triggering of reservoir-associated earthquakes. *Eng. Geol.*, 10: 197–210.
- Klusman, R.W. and Webster, J.D., 1981. Preliminary analysis of meteorological and seasonal influences on crustal gas emission relevant to earthquake prediction. *Bull. Seismol. Soc. Am.*, 71(1): 211–222.
- Knopoff, L. and Kagan, Y., 1977. Analysis of the theory of extremes as applied to the earthquake process. *J. Geophys. Res.*, 82(36): 5647–5657.
- Knopoff, L., Kagan, Y.Y. and Knopoff, R., 1982. b-values for foreshocks and aftershocks in real and simulated earthquake sequences. *Bull. Seismol. Soc. Am.*, 72(5): 1663–1676.
- Kobayashi, Y., 1974. Some problems related to engineering geology in earthquake hazard assessment and prediction. *Proc. 2nd Int. Congr. Int. Assoc. Eng. Geol.*, Sao Paolo, 15(4): 20–29.
- Kobayashi, Y., 1976. Hazards from surface faulting in earthquakes. *Bull. Disas. Prev. Res. Inst., Kyoto Univ.*, 26(4): 213–240.
- Kobayashi, Y., 1981. Causes of fatalities in recent earthquakes in Japan. *J. Disas. Sci.*, 3(2): 15–22.

- Kohlbeck, F. and Scheidegger, A.E., 1984. Gebirgsspannung und Bergschläge. Proc. 4. Bergbehördliches Kolloquium über Geotectonik und Sicherheit, BM Handel & G. Wien.
- Kostrov, B.V. and Das, S., 1982. Idealized models of fault behavior prior to dynamic rupture. *Bull. Seismol. Soc. Am.*, 82(3): 679–703.
- Kristy, M.J. and Simpson, D.W., 1980. Seismicity changes preceding two recent central Asian earthquakes. *J. Geophys. Res.*, 85(B9): 4829–4837.
- Kulhanek, O. and Båth, M., 1976. Earthquake insurance coefficients with application to some south-central American capitals. *Rept. Seismol. Inst. Uppsala*, 8–76: 1–57.
- Kulhanek, O. and Båth, M., 1978. Seismic risk and earthquake insurance in South and Central America. *Geol. Mijnb.*, 57(2): 251–253.
- Kunze, A.W.G., 1982. Some aspects of viscous stress relaxation and intraplate seismicity. *Tectonophysics*, 82: T1–T9.
- Landsberg, H.E., 1978. Geophysical predictions. Overview and recommendations. *EOS*, 59(7): 710–718.
- Leary, P.C. and Malin, P.E., 1984. Ground deformation events preceding the Homestead Valley earthquakes. *Bull. Seismol. Soc. Am.*, 74(5): 1799–1817.
- Leblanc, G. and Anglin, F., 1978. Induced seismicity at the Manic-3 reservoir, Quebec. *Bull. Seismol. Soc. Am.*, 68(5): 1469–1485.
- Lee, T., 1972. A method for computing the deformation of the crust caused by the filling of large lakes. *Bull. Seismol. Soc. Am.*, 62: 1597–1610.
- Leith, W., Simpson, D.W. and Alvarez, W., 1981. Structure and permeability: Geologic controls of induced seismicity at Nurek reservoir, Tadjikistan, USSR. *Geology*, 9(10): 440–444.
- Limond, W.Q. and Recq, M., 1981. Possible earthquake migration along the western European plate boundary. *J. Geophys. Res.*, 86(B12): 11623–11629.
- Liu, H.P. and Livanos, A.C.R., 1976. Dilatancy and precursory bulging along incipient fracture zones in uniaxially compressed westerly granite. *J. Geophys. Res.*, 81(20): 3495–3510.
- Liu, Z.R., 1984. Earthquake frequency and prediction. *Bull. Seismol. Soc. Am.*, 74(1): 255–265.
- Lockner, D.A., Okubo, P.G. and Dieterich, J.H., 1982. Containment of stick-slip failures on a simulated fault by fluid injection. *Geophys. Res. Lett.*, 9(8): 801–804.
- Lockner, D.A., Johnston, M.J.S. and Byerlee, J.D., 1983. A mechanism to explain the generation of earthquake lights. *Nature*, 302: 28–33.
- Lomnitz, C., 1974. *Global Tectonics and Earthquake Risk*. Elsevier, Amsterdam. 320 pp.
- Lomnitz, C., 1982a. An uncertainty principle of earthquake locations. *Bull. Seismol. Soc. Am.*, 72(2): 669–670.
- Lomnitz, C., 1982b. Seismology in Mexico. *Earthquake Inform. Bull. (UGBS)*, 14(1): 30–32.
- Lomnitz, C., 1982c. What is a gap? *Bull. Seismol. Soc. Am.*, 72(4): 1411–1413.
- Lomnitz, C., 1984. The physics and metaphysics of earthquake prediction. *Proc. Symp. Continental Seismicity Peking 1982*, pp. 688–693.
- Lomnitz, C. and Nava, F.A., 1983. The predictive value of seismic gaps. *Bull. Seismol. Soc. Am.*, 73 (A6): 1815–1824.
- Lomnitz, C. and Rosenblueth, E., 1976. *Seismic Risk and Engineering Decisions*. Elsevier, Amsterdam, 425 pp.
- Lomnitz-Adler, J., 1983. A statistical model of the earthquake process. *Bull. Seismol. Soc. Am.*, 73(3): 853–862.
- Lomnitz-Adler, J. and Lomnitz, C., 1979. A modified form of the Gutenberg-Richter magnitude–frequency relation. *Bull. Seismol. Soc. Am.*, 69(4): 1209–1214.

- Lowry, M.A., 1982. Can animals help earthquake predictors? *N.Z. Vet. J.*, 31: 35–39.
- Lyakhter, V.M. and Frolova, N.I., 1977. Statistical calculations of the spectra of seismic effects. *Bull. (Izv.) Akad. Sci. USSR., Earth Phys.*, 13(8): 25–40.
- Madariaga, R., 1979. On the relation between seismic moment and stress drop in the presence of stress and strength heterogeneity. *J. Geophys. Res.*, 84(B5): 2243–2250.
- Madariaga, R., 1983. High frequency radiation from dynamic earthquake fault models. *Ann. Geophys.* 1(1): 17–23.
- Main, I.G. and Burton, P.W., 1984. Information theory and the earthquake frequency–magnitude distribution. *Bull. Seismol. Soc. Am.*, 74(4): 1409–1426.
- Mark, R.K., 1977. Application of linear statistical models of earthquake magnitude versus fault length in estimating maximum expectable earthquakes. *Geology*, 5(8): 461–463.
- Martin, J.C., 1975. The effect of fluid pressure on effective stresses and induced faulting. *J. Geophys. Res.*, 80(26): 3783–3785.
- Matsuda, T., 1977. Estimation of future destructive earthquakes from active faults on land in Japan. *J. Phys. Earth*, 25 Suppl.: 251–260.
- Matsuda, T., Ota, Y., Ando, M. and Yonekura, N., 1978. Fault mechanism and recurrence time of major earthquakes in Southern Kanto district, Japan, as deduced from coastal terrace data. *Bull. Geol. Soc. Am.*, 89: 1610–1618.
- Mavko, G.M., 1982. Easy computation of static stress drop, slip, and moment on two-dimensional heterogeneous faults. *Bull. Seismol. Soc. Am.*, 72(5): 1499–1508.
- Mayer-Rosa, D., 1981. A computerized method for the evaluation of seismic intensity data: Experiences and results for earthquakes in Switzerland. *Gerl. Beitr. Geophys.*, 90(3): 231–240.
- Mayer-Rosa, D. and Deichmann, N., 1979. Observations of reservoir-related seismicity in Switzerland. *Proc. Int. Res. Conf. Intra-Continental Earthquakes*, Okrid, Sept. 17–21, 1979, 278: 1–14.
- McClellan, D.H., 1984. Earthquake seasonality before the 1906 San Francisco earthquake. *Nature*, 307: 153–156.
- McCreery, C. and Walter, D., 1983. Spectra of nuclear explosions, earthquakes and noise from Wake Island bottom hydrophones. *Geophys. Res. Lett.*, 10(1): 59–52.
- McEwin, A., Underwood, R. and Denham, D., 1976. Earthquake risk in Australia. *Bur. Mines J. Austral. Geol. Geophys.*, 1(1): 15–21.
- McGuire, R.K., 1977. Effects of uncertainty in seismicity on estimates of seismic hazard for the coast of the United States. *Bull. Seismol. Soc. Am.*, 67(3): 827–848.
- McNally, K., 1982. Variations in seismicity as a fundamental tool in earthquake prediction. *Bull. Seismol. Soc. Am.*, 72(6): 5351–5366.
- McNutt, S.R. and Beavan, L., 1981. Volcanic activity at Pavlof volcano correlated with the solid earth tide. *Nature*, 294: 615–618.
- Medzhitova, Z.A., 1977. Study of the space–time distributions of the velocity ratio v_p/v_s in the Chukchi depression and the mountain framework. *Bull. (Izv.) Acad. Sci. USSR, Earth Phys.*, 13(10): 74–77.
- Meissner, R., 1979. Introduction to the problem of predicting earthquakes. *Proc. ESA-Council of Europe Seminar on Earthquake Prediction*, Strasbourg, pp. 3–6.
- Melosh, H.J., 1983. Vertical movements following a dip-slip earthquake. *Geophys. Res. Lett.*, 10 (1): 47–50.
- Melosh, H.J. and Fleitout, L., 1982. The earthquake cycle in subduction zones. *Geophys. Res. Lett.*, 9(1): 21–24.
- Melosh, H.J. and Raefsky, A., 1983. Anelastic response of the earth to a dip slip earthquake. *J. Geophys. Res.*, 88(B1): 515–526.

- Mendoza, C. and Dewey, J.W., 1984. Seismicity associated with the great Colombia-Ecuador earthquakes of 1942, 1958 and 1979: Implications for barrier models of earthquake rupture. *Bull. Seismol. Soc. Am.*, 74(2): 577-593.
- Merifield, P.M. and Lamar, D.L., 1981. Anomalous water-level changes and possible relation with earthquakes. *Geophys. Res. Lett.*, 8(5): 437-440.
- Merkler, G., Bock, G. and Fuchs, K., 1981. Correlation between microactivity, temperature and subsidence of water level at reservoirs. *J. Geophys. Res.*, 49: 198-206.
- Milne, W.G. (Editor), 1976. Induced seismicity. *Eng. Geol.*, 10(2-4): 83-388.
- Mino, K., 1984. On a formation mechanism of topography and its relation to earthquake occurrence in Southwest Japan. *Bull. Disas. Prev. Res. Inst., Kyoto, Univ.* 34(3): 129-167.
- Miyatake, T., 1980. Numerical simulation of earthquake source process by a three-dimensional crack model. *J. Phys. Earth*, 28(6): 565-598.
- Mizutani, H. and Ishido, T., 1976. A new interpretation of magnetic field variation associated with the Matushiro earthquakes. *J. Geomag. Geoelect.*, 28: 179-188.
- Mizutani, H., Ishido, T., Yokokura, T. and Oknishi, S., 1976. Electrokinetic phenomena associated with earthquakes. *Geophys. Res. Lett.*, 3(7): 365-368.
- Mochizuki, T., Miyon, M. and Tajime, T., 1982. Relationships among hypocentral distances, radiation patterns, landforms and seismic intensities estimated from toppled tombstones and damage to wooden buildings in the great Kanto earthquake of 1923. *Nat. Disas. Sci.*, 4(1): 31-49.
- Mogi, K., 1979. Global variation of seismic activity. *Tectonophysics*, 57: T43-T50.
- Mogi, K., 1984. Fundamental studies on earthquake prediction. In: *Proc. Symp. Continental Seismicity, Peking, 1982*, pp. 619-652.
- Mohraz, B., 1976. A study of earthquake response spectra for different geological conditions. *Bull. Seismol. Soc. Am.*, 66(3): 915-935.
- Mori, J., 1983. Dynamic stress drops of moderate earthquakes of the Eastern Aleutians and their relation to a great earthquake. *Bull. Seismol. Soc. Am.*, 73 (4): 1077-1097.
- Mortgat, C.P. and Shah, H.C., 1979. A Bayesian model for seismic hazard mapping. *Bull. Seismol. Soc. Am.*, 69(4): 1237-1251.
- Müller, S., 1978. *Erdbeben. Schweiz. Ing. und Arch.-Ver., Zürich*, 24 pp.
- Muramatu, I. and Irikura, K., 1982. Synthesis of strong earthquake motions over a wide frequency range. *Nat. Disas. Sci.*, 4(2): 55-78.
- Nagata, T., 1972. Application of tectonomagnetism to earthquake phenomena. *Tectonophysics*, 14 (3-4): 263-271.
- Newman, W.I. and Knopoff, L., 1982. Crack fusion dynamics: a model for large earthquakes. *Geophys. Res. Lett.*, 9(7): 735-738.
- Newman, W.I. and Knopoff, L., 1983. A model for repetitive cycles of large earthquakes. *Geophys. Res. Lett.*, 10(4): 305-308.
- Newmark, N.M. (Editor), 1972. *Earthquake Guidelines for Reactor Siting*. Int. Atomic Energy Agency, Vienna, Rept. 139, 26 pp.
- Niazi, M., 1984. Application of logistic models to earthquake forecasting. *Earthquake Prediction Res.*, 2(3): 221-225.
- Nikolayev, N.I., 1976. Tectonic and tectonophysical conditions for the occurrence of earthquakes connected with the engineering activities of man. *Bull. (Izv.) Acad. Sci. USSR, Earth Phys.*, 12(10): 33-47.
- Nishenko, S. and McCann, W., 1979. Large thrust earthquakes and tsunamis: implications for the development of fore-arc basins. *J. Geophys. Res.*, 84(B2): 573-584.
- Nishenko, S.P. and McCann, W.R., 1981. Seismic potential for the world's major plate boundaries. *Earthquake Prediction (AGU)*, 4: 20-28.

- Noguchi, M. and Wakita, H., 1977. A method for continuous measurements of radon in groundwater for earthquake prediction. *J. Geophys. Res.*, 82(8): 1353–1357.
- Noszticzius, Z., 1979. A possible explanation for the origin of earthquake lights. *Bull. Seismol. Soc. Am.*, 69(5) 1627.
- Nur, A., 1972. Dilatancy pore fluids and premonitory variations of t_s/t_p travel times. *Bull. Seismol. Soc. Am.*, 62(5): 1217–1222.
- Nur, A., 1974. Matsushiro, Japan, Earthquake swarm: Confirmation of the dilatancy fluid diffusion model. *Geology*, 2(5): 217–222.
- Nuttli, O.W. and Zollweg, J.E., 1974. The relation between felt area and magnitude for central United States earthquakes. *Bull. Seismol. Soc. Am.*, 64(1): 73–85.
- Olsson, R., 1973. Strain energy release, deformation energy release and related problems. *Riv. Ital. Geofis.*, 23 (5/6): 341–352.
- Olsson, R., 1979. On the occurrence of aftershock sequences. *Rept. Seismol. Inst., Uppsala*, 4–79: 1–27.
- Olsson, R., 1980. Some aspects on stress, seismic moment, energy and earthquake volume. *Seismol. Sec. Rept.* 4–80, Uppsala 26 pp.
- Olsson, R., 1981. Models and analogies in geophysics, earthquake behavior and time studies of aftershocks. *Acta Univ. Uppsala*, 586: 2–9.
- Olsson, R., 1982. The randomness of major global earthquakes. *Tectonophysics*, 82: T11–T15.
- Papazachos, B.C., 1973. The time distribution of the reservoir-associated foreshocks and its importance to the prediction of principal shocks. *Bull. Seismol. Soc. Am.*, 63(6): 1973–1978.
- Papazachos, B.C., Tsapanos, T.M. and Panagiotopoulos, D.G., 1982. A premonitory pattern of earthquakes in Northern Greece. *Nature*, 296: 232–235.
- Paté, M.E. and Shah, H., 1979. Public policy issues: earthquake prediction. *Bull. Seismol. Soc. Am.*, 69(5): 1533–1547.
- Pavoni, N., 1977. Zur Seismizität der Erde und der Schweiz. *Mitt. Schweiz. Ges. Boden- und Felsmech.*, 97: 1–3.
- Pavoni, N. and Mayer-Rosa, D., 1978. Seismotektonische Karte der Schweiz, 1:750000. *Eclogae Geol. Helv.*, 71(2): 293–295.
- Peppin, W.A. and Bufe, C.G., 1980. Induced versus natural earthquakes: Search for a seismic discriminant. *Bull. Seismol. Soc. Am.*, 70(1): 269–281.
- Perez, V., 1973. Velocity response envelope spectrum as a function of time, for the Pacoima Dam, San Fernando earthquake, February 9th, 1971. *Bull. Seismol. Soc. Am.*, 63(1): 299–313.
- Petak, W.J. and Atkisson, A.A., 1982. *Natural Hazard Risk Assessment and Public Policy*. Springer, Berlin, 489 pp.
- Pierce, E.T., 1976. Atmospheric electricity and earthquake prediction. *Geophys. Res. Lett.*, 3(3): 185–188.
- Pomeroy, P.W., Simpson, D.W. and Sbar, M.L., 1976. Earthquakes triggered by surface quarrying—the Wappinger Falls, New York Sequence of June, 1974. *Bull. Seismol. Soc. Am.*, 66(3): 685–700.
- Prater, E.G., 1977. Verflüssigung von Bodenschichten infolge Erdbeben. *Mitt. Inst. Grundbau Bodenmech. ETH-Zürich*, 110(2): 1–8.
- Prozorov, A.G. and Dziewonski, A.M., 1982. A method of studying variations in the clustering property of earthquakes: application to the analysis of global seismicity. *J. Geophys. Res.*, 87(84): 2829–2839.
- Purcaru, G. and Berckhemer, H., 1978. A magnitude scale for very large earthquakes. *Tectonophysics*, 49: 189–198.
- Purcaru, G. and Berckhemer, H., 1982a. Quantitative relations of seismic source parameters and a classification of earthquakes. *Tectonophysics*, 84: 57–128.

- Purcaru, G. and Berckhemer, H., 1982b. Regularity patterns and zones of seismic potential for future large earthquakes in the Mediterranean region. *Tectonophysics*, 85 (1/2): 1–30.
- Quittmeyer, R.C. and Jacob, K.H., 1979. Historical and modern seismicity of Pakistan, Afghanistan, Northwestern India and Southeastern Iran. *Bull. Seismol. Soc. Am.*, 69(3): 773–823.
- Raleigh, B.R., 1982. A strategy for short-term prediction of earthquakes. *Bull. Seismol. Soc. Am.*, 72(6): 337–342.
- Raleigh, C.B., Helay, J.H. and Bredehoeft, J.D., 1976. An experiment in earthquake control of Rangely Colorado. *Science*, 191: 1230–1237.
- Raleigh, C.B., Sieh, K., Sykes, L.R. and Anderson, D.L., 1982. Forecasting southern California earthquakes. *Science*, 217: 1097–1104.
- Rastogi, B.K. and Talwani, P., 1977. Spatial and temporal variation in t_s/t_p at Monticello reservoir, South Carolina. *Geophys. Res. Lett.*, 7(10): 781–784.
- Reilinger, R.E., Citron, G.P. and Brown, L.D., 1977. Recent vertical movements from precise levelling data in southwestern Montana, western Yellowstone National Park and the Snake River plain. *J. Geophys. Res.*, 82(33): 5349–5359.
- Reimer, G.M., 1981. Helium soil-gas variations associated with recent central California earthquakes: Precursor or coincidence? *Geophys. Res. Lett.*, 8(5): 433–435.
- Reyners, M., 1981. Long and intermediate term seismic precursors to earthquakes—state of the art. *Earthquake Prediction AGU*, pp. 333–347.
- Rice, J.R., 1975. On the stability of dilatant hardening for saturated rock mass. *J. Geophys. Res.*, 80(11): 1531–1536.
- Rice, J.R., 1979. Theory of precursory processes in the inception of earthquake rupture. *Gerl. Beitr. Geophys.*, 88(2): 91–127.
- Rice, J.R. and Rudnicki, J.W., 1979. Earthquake precursory effects due to pore fluid stabilization of a weakening fault zone. *J. Geophys. Res.*, 84(B5): 2177–2193.
- Rice, J.R., Rudnicki, J.W. and Simons, D.A., 1978. Deformation of spherical cavities and inclusions in fluid-infiltrated elastic materials. *Int. J. Solids Struct.*, 14: 289–303.
- Richardson, R.M. and Solomon, S.C., 1977. Apparent stress and stress drop for intraplate earthquakes and tectonic stress in the plates. *Pure Appl. Geophys.*, 115: 317–331.
- Richter, C.F., 1958. *Elementary Seismology*. Freeman, San Francisco, Calif.
- Rikitake, T., 1974. Probability of earthquake occurrence as estimated from crustal strain. *Tectonophysics*, 23: 299–312.
- Rikitake, T., 1975a. Earthquake precursors. *Bull. Seismol. Soc. Am.*, 65(5): 1133–1162.
- Rikitake, T., 1975b. Statistics of ultimate strain of the earth's crust and probability of earthquake occurrence. *Tectonophysics*, 26: 1–21.
- Rikitake, T., 1976. Recurrence of great earthquakes at subduction zones. *Tectonophysics*, 35(4): 335–362.
- Rikitake, T., 1978a. Biosystem behaviour as an earthquake precursor. *Tectonophysics*, 51: 1–20.
- Rikitake, T., 1978b. Classification of earthquake prediction information for practical use. *Tectonophysics*, 46: 175–185.
- Rikitake, T., 1979. Classification of earthquake precursors. *Tectonophysics*, 54: 293–309.
- Rikitake, T. (Editor), 1980. *Current Research in Earthquake Prediction*. Reidel, Dordrecht, 400 pp.
- Rikitake, T., 1982. *Earthquake Forecasting and Warning*. Reidel, Dordrecht, 400 pp.
- Rikitake, T., 1984. Strain rate of active fault and earthquake risk. *Earthquake Prediction Res.*, 2: 277–303.
- Rikitake, T. and Yamazaki, Y., 1976. Resistivity changes as a precursor of earthquake. *J. Geomag. Geoelectr.*, 28(6): 497–506.

- Rikitake, T. and Yamazaki, Y., 1979. A resistivity precursor of the 1974 Izu-Hanto-ki earthquake. *J. Phys. Earth*, 27(1): 1–6.
- Ritsema, A.R., 1979. Active or passive subduction at the Calabrian arc. *Geol. Mijnbouw*, 58(2): 127–134.
- Riznichenko, Yu.V., Seyduzova, S.S. and Matasova, L.M., 1977. Macro seismic program. *Bull. (Izv.) Acad. Sci. USSR, Earth Phys.*, 13(3): 8–20.
- Rogers, A.M., Katz, L.J. and Bennett, T.J., 1974. Topographic effects on ground motion for incident P waves: A model study. *Bull. Seismol. Soc. Am.*, 64(2): 437–456.
- Rothé, J.R., 1977. Séismes artificiels et exploitations pétrolières: l'exemple de Lacq (France). *Ann. Geofis.*, 30(3–4): 369–383.
- Rudnicki, J.W., 1979. The stabilization of slip on a narrow weakening fault zone by coupled deformation pore fluid diffusion. *Bull. Seismol. Soc. Am.*, 69(4): 1011–1026.
- Rudnicki, J.W. and Freund, L.B., 1981. On energy radiation from seismic sources. *Bull. Seismol. Soc. Am.*, 71(3): 583–595.
- Rundle, J.B., 1980. Static elastic-gravitational deformation of a layered half space by point couple sources. *J. Geophys. Res.*, 85(B10): 5335–5363.
- Rustanovich, D.N., 1977. Earthquake classification. *Bull. (Izv.) Acad. Sci. USSR, Earth Phys.*, 13(10): 48–53.
- Sano, Y. and Nakajima, S., 1982. Secular and seasonal variations of transfer functions at Kakioken from Mar. 1977 to Apr. 1981. *Mém. Kakioka Obs.*, 19(2): 31–51.
- Savage, J.C., Lisowski, M., Prescott, W.H. and Church, J.P., 1977. Geodetic measurements of deformation associated with the Oroville, California, earthquake. *J. Geophys. Res.*, 82(11), 1667–1671.
- Scheidegger, A.E., 1975. *Physical Aspects of Natural Catastrophes*. Elsevier, Amsterdam, 284 pp.
- Scheidegger, A.E., 1982. *Principles of Geodynamics*. Springer, Berlin, 3rd ed., 395 pp.
- Scheidegger, A.E., 1984. A review of recent work on mass movements and on rock falls. *Earth-Sci. Rev.*, 21: 225–249.
- Schenk, V., 1982. On the problem of standardization of the magnitude–frequency relation. *Stud. Geophys. Geodaet.*, 26(4): 398–400.
- Schenkova, Z., Schenk, V. and Karnik, V., 1982. Foreshocks and aftershocks in recent earthquakes. *Earthquake Prediction Res.*, 1(14): 287–318.
- Schnabel, P.B. and Seed, H.B., 1972. Accelerograms in rock for earthquakes in the western United States. Rept. No. EERC 72-2, Coll. Eng., Univ. Calif., Berkeley, 15 pp.
- Schneider, G., 1975. Man-made earthquakes oder die Beeinflussung der Erdbebenätigkeit durch den Menschen. *Jahrb. Ges. Naturkd. Württemberg*, 130: 36–53.
- Schneider, G., 1979. Seismotectonic movements inside the southern German triangle. *Allg. Vermess.-Nachr.*, 92(10): 379–382.
- Scholz, C.H., 1972. Crustal movements in tectonic areas. *Tectonophysics*, 14 (3/4): 201–217.
- Scholz, C.H., 1974. Post-earthquake dilatancy recovery. *Geology*, 2(11): 551–554.
- Scholz, C.H., 1977. A physical interpretation of the Haicheng earthquake prediction. *Nature*, 267: 121–124.
- Scholz, C.H., 1978. Velocity anomalies in dilatant rock. *Science*, 201: 441–442.
- Scholz, C.H., 1982a. Scaling laws for large earthquakes: consequences for physical models. *Bull. Seismol. Soc. Am.*, 72(1): 1–14.
- Scholz, C.H., 1982b. Scaling relations for strong ground motion in large earthquakes. *Bull. Seismol. Soc., Am.*, 72(6): 1903–1909.
- Scholz, C.H., Sykes, L.R., Aggarwal, Y.P., 1973. Earthquake prediction: a physical basis. *Science*, 181: 803–810.

- Secor, D.T. et al., 1982. Geology of the area of induced seismic activity at Monticello reservoir, South Carolina. *J. Geophys. Res.*, 87(B8): 6945–6957.
- Seeber, L., Armbruster, J.G. and Bollinger, G.A., 1982. Large-scale patterns of seismicity before and after the 1886 South Carolina earthquake. *Geology*, 10(7): 382–386.
- Seggern, D.V., 1980. A random model for seismicity statistics and earthquake prediction. *Geophys. Res. Lett.*, 7(9): 637–640.
- Seggern, D.V., Alexander, S.S. and Baag, C.E., 1981. Seismicity parameters preceding moderate to major earthquakes. *J. Geophys. Res.*, 86(B10): 9325–9351.
- Selnes, P.B., 1978. Earthquake parameters for use in engineering design in Scandinavia. *Geol. Fören.*, 100(3): 301–305.
- Selnes, P.B., Ringdal, F., Jensen, D. and Hove, K., 1980. Earthquake risk on the Norwegian continental shelf. *Norw. Marit. Res.*, 8(1): 13–25.
- Seno, T., 1979. Pattern of intraplate seismicity in southwest Japan before and after great intraplate earthquakes. *Tectonophysics*, 57: 267–283.
- Shapira, A., 1983. A probabilistic approach for evaluating earthquake risks. *Tectonophysics*, 91: 321–334.
- Sharma, H.S.S. and Murty, G.S., 1982. Pattern of seismic energy release from Koyna as seen at Gauribidanur. *Tectonophysics*, 82(3/4): T5–T7.
- Shi, H.X. and Cai, Z.H., 1980. Anomalous migration of shallow groundwater and gases in the Beijing region and the 1976 Tangshan earthquake. *Acta Seismol. Sin.*, 2: 64.
- Shimamoto, T., Handin, J. and Logan, J.M., 1980. Specimen–apparatus interaction during stick-slip in a triaxial compression machine: a decoupled two-degree-of-freedom model. *Tectonophysics*, 67: 175–205.
- Sibson, R.H., 1978. Radiant flux as a guide to relative seismic efficiency, *Tectonophysics*, 51: T39–T46.
- Singh, S.K. and 5 others, 1980. Seismic gap of Michoacán, México. *Geophys. Res. Lett.*, 7(1): 69–72.
- Singh, S.K., Astiz, L. and Havskov, J., 1981. Seismic gaps and recurrence periods of large earthquakes along the Mexican subduction zone: a reexamination. *Bull. Seismol. Soc. Am.*, 71(3): 827–843.
- Singh, S.K., Rodriguez, M. and Esteva, L., 1983. Statistics of small earthquakes and frequency of occurrence of large earthquakes along the Mexican subduction zone. *Bull. Seismol. Soc. Am.*, 73(6): 1779–1796.
- Simpson, D.W., 1976. Seismicity changes associated with reservoir loading. *Eng. Geol.*, 10: 123–150.
- Simpson, D.W. and Negmatullaev, S.K., 1981. Induced seismicity at Nurek reservoir, Tadzhikistan, USSR. *Bull. Seismol. Soc. Am.*, 71(5): 1561–1586.
- Simpson, D.W. and Richards, P.G. (Editors), 1981. *Earthquake Prediction: An International Review*. AGU, Washington, 680 pp.
- Sims, J.D., 1975. Determining earthquake recurrence intervals from deformational structures in young lacustrine sediments. *Tectonophysics*, 29: 141–152.
- Siro, L., 1984. Alcuni metodi e limiti della microzonazione sismica. *Ric. Studi Formez RS*, 37: 297–362.
- Smith, W.D., 1981. The *b*-value as an earthquake precursor. *Nature*, 289: 136–139.
- Snoke, J.A., Linde, A.T. and Sacks, I.S., 1983. Apparent stress: an estimate of the stress drop. *Bull. Seismol. Soc. Am.*, 73(2): 339–348.
- Sobolev, G.A. and Slavina, L.B., 1977. Spatial and temporal variations of v_p/v_s prior to strong earthquakes in Kamchatka. *Bull. (Izv.) Acad. Sci. USSR, Earth Phys.*, 13(7): 91–98.
- Sobolev, G., Spetzler, H. and Salov, B., 1978. Precursors to failure in rocks while undergoing anelastic deformations. *J. Geophys. Res.*, 83(B4): 1775–1784.

- St. Amand, P., Engel, R., Park, W.H. and Williams, B.F., 1975. *Geology and Earthquake Hazards*. Kern Country Council, Bakersfield, Calif., 216 pp.
- Stein, R.S. and Thatcher, W., 1981. Seismic and aseismic deformation associated with the 1952 Kern County California earthquake and relationship to the Quaternary history of the White Wolf Fault. *J. Geophys. Res.*, 86(B6): 4913–4928.
- Stevens, A.E. and Milne, W.G., 1974. A study of seismic risk near pipeline corridors in northwestern Canada and eastern Alaska. *Can. J. Earth Sci.*, 11(1): 147–164.
- Stiller, H. and Wagner, F.C., 1978. Physikalische Prozesse in Erdbebengebieten. *Z. Angew. Geol.*, 24(11): 456–464.
- Stiller, H. and Wagner, F.C., 1979. Elastic wave velocities in rocks under pressure and cracking phenomena. *Gerl. Beitr. Geophys.*, 88(2): 128–139.
- Stiller, H., Wagner, F.C. and Vollstädt, H., 1977. A two-phase model for the description of the influence of cracks on the P- and S-wave velocities in dry and saturated rock samples. *Tectonophysics*, 43: 181–197.
- Strelitz, R.A., 1978. Moment tensor inversions and source models. *Geophys. J.R. Astron. Soc.*, 52(2): 359–364.
- Stuart, W.D., 1974. Diffusionless dilatancy model for earthquake precursors. *Geophys. Res. Lett.*, 1(6): 261–264.
- Stuart, W.D., 1979. Quasi-static earthquake mechanics. *Rev. Geophys. Space Phys.*, 17(6): 1115–1120.
- Stuart, W.D. and Johnston, M.J.S., 1975. Intrusive origin of the Matsushiro earthquake swarm. *Geology*, 2(2): 63–67.
- Studer, J., 1977. Dimensionierung von Staudämmen gegen Erdbebenwirkung. *Mitt. Inst. Grundbau Bodenmech. ETH Zürich*, 110(1): 1–7.
- Studer, J. and Ziegler, A., 1983. Grundlagen zur Berechnung von Bemessungserdbeben. *Mitt. Inst. Grundbau Bodenmech. ETH Zürich*, 122: 1–100.
- Sykes, L.R., 1980. Earthquakes and other processes within lithospheric plates and the reactivation of the pre-existing zones of weakness. *Geol. Assoc. Can. Spec. Pap.*, 20: 215–237.
- Sykes, L.R., Kisslinger, J.B., House, L., Davies, J.N. and Jacob, K.N., 1980. Rupture zones of great earthquakes in the Alaska–Aleutian arc, 1784 to 1980. *Science*, 210: 1343–1345.
- Sykes, L.R. and Quittmeyer, R.C., 1981. Repeat times of great earthquakes along simple plate boundaries. *Earthquake Prediction (AGU)*, pp. 217–247.
- Symposium, 1975. *Symposium on Earthquake Risk for Nuclear Power Plants*. Europ. Seismol. Com., Luxemburg.
- Taleb-Agha, G., 1977. Seismic risk analysis of lifeline networks. *Bull. Seismol. Soc. Am.*, 67(6): 1625–1645.
- Taleb-Agha, G. and Whitman, R.V., 1977. Seismic risk analysis of discrete systems of sites. *Earthquake Eng. Struct. Dyn.*, 5: 293–304.
- Talwani, P., 1979. An empirical earthquake prediction model. *Phys. Earth Planet. Int.*, 18(4): 288–302.
- Tchalenko, J.S. and Ambraseys, N.N., 1973. Earthquake destruction of adobe villages in Iran. *Ann. Geofis. Roma*, 26(2): 357–389.
- Teisseyre, R., 1980. Earthquake premonitory sequence-dislocation processes and fracturing. *Boll. Geofis. Teor. Appl.*, 22(88): 245–254.
- Teisseyre, R., 1983. The theory of earthquake premonitory phenomena. *Earthquake Prediction Res.*, 2(1): 69–74.
- Teng, T.L., 1984. Some development on earthquake precursor monitoring in Southern California. *Proc. Symp. on Continental Seismicity*, Peking, 1982. Seismological Press, Beijing, pp. 462–479.

- Teufel, L.W., 1980. Precursive pore pressure changes associated with premonitory slip during stick-slip sliding. *Tectonophysics*, 69: 189–199.
- Thatcher, W., 1984a. The earthquake deformation cycle at the Nankai Trough, Southwest Japan. *J. Geophys. Res.*, 89(B5): 3087–3101.
- Thatcher, W., 1984b. The earthquake deformation cycle recurrence and the time-predictable model. *J. Geophys. Res.*, 89(B7): 5674–5680.
- Thatcher, W. and Rundle, J.B., 1979. A model for the earthquake cycle in underthrust zones. *J. Geophys. Res.*, 84(B10): 5540–5556.
- Tributsch, H., 1978. Do aerosol anomalies precede earthquakes? *Nature*, 276: 606–607.
- Trifunac, M.D. and Brady, A.G., 1975a. On the correlation of seismic intensity scales with the peaks of recorded strong ground motion. *Bull. Seismol. Soc. Am.*, 65(1): 139–162.
- Trifunac, M.D. and Brady, A.G., 1975b. A study on the duration of strong earthquake ground motion. *Bull. Seismol. Soc. Am.*, 65(3): 581–626.
- Trommer, B., 1977. Labormethoden zur Untersuchung des Verflüssigungspotentiales von kohäsionslosen Böden. *Mitt. Inst. Grundbau Bodenmech. ETH Zürich*, 110(3): 1–5.
- Udwadia, F.E. and Trifunac, M.D., 1974. Characterization of response spectra through the statistics of oscillator response. *Bull. Seismol. Soc. Am.*, 64(11): 205–219.
- Unesco, 1980. Report on Unesco Regional Seminar on Seismic Risks in Countries Associated with the East African Rift System. Unesco, Nairobi, 76 pp.
- Usami, T., 1977. Earthquake prediction studies in Japan. *Endeavour*, N.S., 1(3, 4): 92–96.
- Utsu, T., 1983. Probabilities associated with earthquake prediction and their relationships. *Earthquake Prediction Res.*, 2: 105–114.
- VanWorner, J.D., Gedney, L.D., Davies, J.N. and Condal, N., 1975. V_p/V_s and b -values: A test of the dilatancy model for earthquake precursors. *Geophys. Res. Lett.*, 2(11): 514–516.
- Varotsos, P. and Alexopoulos, K., 1984. Physical properties of the variations of the electric field of the Earth preceding earthquakes I and II. *Tectonophysics* 110: 73–125.
- Vassiliou, M.S. and Kanamori, H., 1982. The energy release in earthquakes. *Bull. Seismol. Soc. Am.*, 72(2): 371–387.
- Vere-Jones, D. and Smith, E.G.C., 1981. Statistics in seismology. *Commun. Statist. – Theor. Meth.*, A10(15): 1539–1585.
- Villaverde, R., 1984. On Rosenblueth's rule to combine the modes of systems with closely spaced natural frequencies. *Bull. Seismol. Soc. Am.*, 74(1): 325–338.
- Vogel, A., 1981. Contribution of space technology to earthquake prediction research. *Adv. Earth Orient. Appl. Space Tech.*, 1: 1–17.
- Wagner, F.C., 1981. Ein Modell des Einflusses der Anisotropie von Klüften und Spalten der Gesteine auf die Geschwindigkeiten elastischer Wellen in Erdbebengebieten. *Neue Bergbautech.*, 11(12): 679–683.
- Wagner, F.C. and Engler, R., 1980. Fractured rock models of the elastic wave velocities in earthquake areas. *Gerl. Beitr. Geophys.*, 89(3/4): 311–318.
- Wahlström, R. and Ahjos, T., 1982. Determination of local magnitude and calibration of magnitude scales for earthquakes in the Baltic Shield. *Seismol. Dept. Univ., Rept. No. 1–82*, Uppsala, 39 pp.
- Wahlström, R. and Strauch, W., 1984. A regional magnitude scale for central Europe based on crustal wave attenuation. *Centr. Inst. Phys. Earth, DDR Acad. Sci., Publ., No. 1379*, 16 pp.
- Wakita, H., et al., 1980. Radon anomaly: a possible precursor of the 1978 Izu-Oshima-Kinkai earthquake. *Science*, 207: 882–883.
- Wang, C.L., Yao, Q.C. and Long, M., 1980. On the abnormal characteristics of radon contents in the spring waters north of the epicentral area of the Sungpan-Pingwu earthquake before its occurrence and their cause. *Acta Seismol. Sin.*, 2: 83.

- Weertman, J. and Chang, S.P., 1977. Fluid flow through a large vertical crack in the Earth's crust. *J. Geophys. Res.*, 82(5): 929–932.
- Weichert, D.H., 1980. Estimation of the earthquake recurrence parameters for unequal observation periods for different magnitude. *Bull. Seismol. Soc. Am.*, 70(4): 1337–1346.
- Wesnousky, S.G., Scholz, C.H., Shimazaki, K. and Matsuda, T., 1983. Earthquake frequency distribution and the mechanics of faulting. *J. Geophys. Res.*, 88(B11): 9331–9340.
- Wesnousky, S.G., Scholz, C.H., Shimazaki, K. and Matsuda, T., 1984. Integration of geological and seismological data for the analysis of seismic hazard: A case study of Japan. *Bull. Seismol. Soc. Am.*, 74(2): 687–708.
- Wesson, R.L. et al., 1977. Search for seismic forerunners to earthquakes in Central California. *Tectonophysics*. 42: 111–126.
- White, J.E., 1976. Elastic dilatancy fluid saturation and earthquake dynamics. *Geophys. Res. Lett.*, 3(12): 747–750.
- Wiens, D.A. and Stein, S., 1984. Intraplate seismicity and stresses in young oceanic lithosphere. *J. Geophys. Res.*, 89(B13): 11442–11464.
- Withers, J. and Nyland, E., 1978. Time-evolution of stress under an artificial lake and its implication for induced seismicity. *Can. J. Earth Sci.*, 15(9): 1526–1534.
- Wyss, M., 1975. Mean sea level before and after some great strike-slip earthquakes. *Pure Appl. Geophys.*, 113: 107–118.
- Wyss, M., 1977. The appearance rate of premonitory uplift. *Bull. Seismol. Soc. Am.*, 67(4): 1091–1098.
- Wyss, M., 1979a. Estimating maximum expectable magnitude of earthquakes from fault dimension. *Geology*, 7(7): 336–340.
- Wyss, M. (Editor), 1979b. *Earthquake Prediction and Seismicity Patterns*. Birkhäuser, Basel, 238 pp.
- Wyss, M., 1983. Earthquake prediction. *Rev. Geophys. Space Phys.*, 21(6): 1291–1298.
- Wyss, M. and Baer, M., 1981. Seismic quiescence in the Western Hellenic Arc may foreshadow large earthquakes. *Nature*, 289: 785–787.
- Wyss, M. and Habermann, R.E., 1982. Conversion of m_p to M_s for estimating the recurrence time of large earthquakes. *Bull. Seismol. Soc. Am.*, 72(5): 1651–1662.
- Wyss, M., Johnston, A.C. and Klein, F.W., 1981. Multiple asperity model for earthquake prediction. *Nature*, 289: 231–234.
- Yacoub, N., 1981. Seismic yield estimates from Rayleigh-wave source radiation pattern. *Bull. Seismol. Soc. Am.*, 71(4): 1269–1286.
- Yamashina, K. and Inoue, Y., 1979. A doughnut-shaped pattern of seismic activity preceding the Shimane earthquake 1978. *Nature*, 278: 48–50.
- Yamashita, T., 1982. Stability and instability of interactive shear cracks generating mechanism for slow earthquakes and fault creeps. *J. Phys. Earth*, 30(2): 131–154.
- Yegulalp, T.M. and Kuo, J.T., 1974. Statistical prediction of the occurrence of maximum magnitude earthquakes. *Bull. Seismol. Soc. Am.*, 64(2): 393–414.
- Zoback, M.D. and Hickman, S., 1982. In situ study of the physical mechanisms controlling induced seismicity at Monticello Reservoir, South Carolina. *J. Geophys. Res.*, 87(B8): 6959–6974.
- Zoback, M.D. and Zoback, M.L., 1981. State of stress and intraplate earthquakes in the United States. *Science*, 213: 96–104.

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