Earthquake Source Physics

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A review of the physics of processes originating in an earthquake source ought to contain an explanation of the nature of these processes and of the mechanism of seismic energy radiation from the source. However this is not feasible in the present state of knowledge and instead, the principal problems of seismic source physics currently under study will be examined.

As early as 1911, Reid formulated his elastic rebound theory, which is still accepted as a classic canon describing the process of earthquake energy release : slow long-term deformations cause the accumulation of stress, and when the stress exceeds the strength of material, a fracturing and displacement of rock mass occurs, and the medium becomes relaxed.

Earthquake Source Models

The basic information about earthquakes and source processes is carried by seismic waves : the longitudinal waves (P), shear waves (S : SV, SH) and surface waves -Love (L), Rayleigh (R), Stoneley, channel waves. In an epicentral area, close to the focus, permanent deformations of the Earth's surface can also be observed. Besides these, a whole spectrum of effects are registered near to and far from an earthquake area, but even a short description of these phenomena would require a separate review.

Observations of the first motion of direct longitudinal waves (P), recorded at various seismic stations located on the Earth's surface, revealed a specific radiation pattern, azimuth dependent, of the seismic energy released from a given source. A classical solution for the displacement field originated by a point force had been worked out by Love (1927) and it was found that source models based on point volume forces could describe this observed pattern. Complex models are usually obtained by a superposition of simple forces, and with point source models this leads to systems of force dipoles and multipoles.

The existence of strong shear stress fields provides the starting point for the majority of seismological analyses, the source model corresponding to a pure field being composed of two dipoles - the double couple model. Very close to the Earth's surface, tensile mechanisms are also possible, but at depth, because of confining pressure, only a shear mechanism need in practice be considered. The range over which tensile processes can still be significant is strongly influenced by the extent to which fluids penetrate the rock mass, so that an important role might be played by rock melting resulting from friction. To what degree this does affect the earthquake process is not yet sufficiently clear, although it is known that it has a considerable impact upon the course of large earthquakes, which are characterized by substantial relative displacements of rock mass (from 0.1 to 10 m) in the source area. The presence of metamorphic layers several centimetres thick, adherent to a dislocation surface is, moreover, testified by geological observations.

Large displacements of rock mass are accompanied by changes in the rock structure: a certain type of phase transformation, raising the question whether phase transformations - from a state of lower to higher density - could possibly explain the mechanism of the origin of deep earthquakes. Petrological and thermodynamic considerations indicate such a possibility.

To explain the dynamic properties of the observed seismic field, it has been necessary to replace the models based on point forces acting at a specified position, by models of a propagating seismic source, i.e. by models of propagating single point forces or force systems. Observations indicate that the amplitudes of the displacement field (for body and surface waves) differ, depending on the direction of source propagation. A simple theoretical solution, introducing the additional factor Y for the effect of source propagation, gives a satisfactory approximation for the displacement field at distances large in comparison with the source size (Ben-Menahem, 1962) where :

$$Y = e^{iX}(\sin X)/X \quad , \quad X = r\omega'/2v$$

and r is the focus radius, v is the fracture velocity, $\omega' = \omega[1-(v/V_F)\cos\Phi]$ is the Doppler frequency, V_F is the phase velocity for surface waves or apparent volume wave velocity $V/\sin i$, Φ the angle between fracture propagation and observed wave direction.

In most considerations of the source models or seismic radiation patterns, an approximation for the displacement field at distances large in comparison with the wave length or source size is made, and linear elastic theory is used, which is valid for small displacements. In the source area and near the source, these assumptions are not valid.

Restricting ourselves, however, to the linear theory, let us consider physical models of the source processes. Stress fields in the Earth's interior, in areas of a relatively homogeneous rock medium, are distributed roughly homogeneously, changing slowly in space and time. To account for the local stress fields it has been necessary to introduce material inhomogeneities, or more specifically material defects and for this, elastic theory methods and techniques were available for use by seismologists. Dislocation theory is usually associated with solid state physics and with the concept of crystallography nets. In reality, however, early dislocation theory grew from the continuum theory elaborated at the end of the last and at the beginning of the present century. A special term "elastic dislocation theory", as opposed to dislocation theory in crystals, was introduced in 1958 by Stekeetee who was one of the first to apply dislocation theory to seismology. Dislocation displacement - the Burgers vector - observed along faults at the Earth's surface can attain a dimension of up to 10 m, and although large displacements normally result from the total effect of several parallel dislocations, single distinct rock displacements of several meters are observed along well defined slip surfaces.

The thermal stress field is of special interest in the consideration of dislocation source models as it was shown by Muskhelishvili (1953) that a stationary thermal field originates stresses equivalent to a dislocation field. Conversely as Teisseyre (1963) pointed out, real dislocation displacements can occur whereby their stresses annihilate the thermal stress field.

Dislocation models describe with adequate accuracy the deformation field at the Earth's surface when dislocations corresponding to earthquakes reach the surface or are very shallow. The most classic example for this situation is the dependence of displacement values upon distance from the fault line, i.e. from the trace of the dislocation surface (Fig. 1).

The concept of dislocation, however, still requires continuity in the material, whereas in reality, geological dislocations have a defined slip surface which becomes a permanent tectonic feature. The models presenting the formation or propagation of cracks are, therefore, better approximations to real earthquake sources.

The process of transition from a dislocation system to crack formation is of special interest for seismological applications. Stroh (1954) explained the formation of a crack in terms of plastic deformations accompanied by dislocations. The dislocations → crack process can describe the development of defects, their qualitative change, and explain the radiation mechanism of part of the internal energy. Dislocations move in a specified direction under the effect of the stress field and the leading dislocation is stopped, e.g. by meeting a barrier along its path; the remaining dislocations approach and concentrate around the blocking dislocation and can finally merge into a crack. This process is shown in Fig. 2, where a series of edge dislocations forms a tensile crack.

Dislocation processes can be considered as relatively slow defor-

Fig. 2 — Process dislocations → crack.

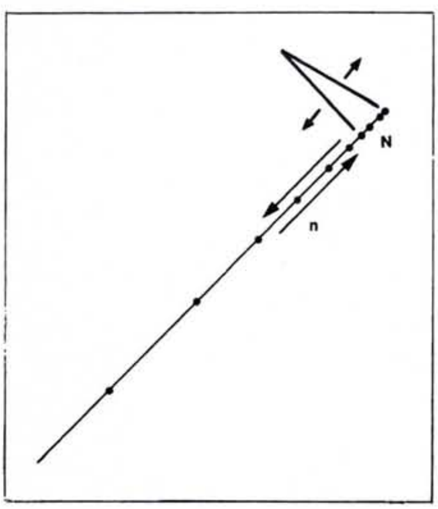
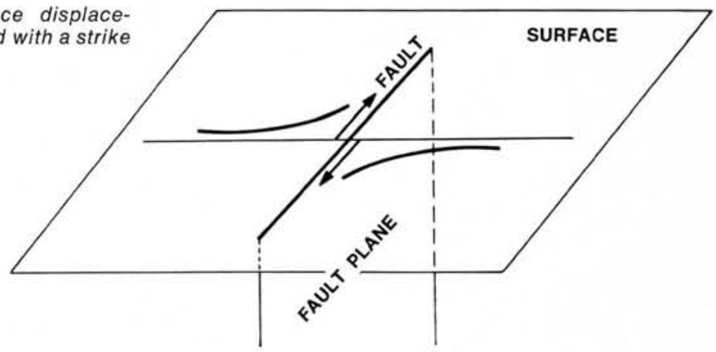


Fig. 1 — Surface displacements associated with a strike slip fault.



mations, as a rock creep of the geological medium. Only considerable stress accumulation connected with the concentration of dislocations leads to the fracturing and destruction of material expressed by crack formation.

For earthquakes that are not too deep, the following process: edge dislocations → tensile cracks → medium dilatation, describes a typical sequence of the premonitory phenomena. Joint action of dislocation systems and barriers leads to a crack field and a grouping of cracks is followed by the formation of a large fault; slow movements give rise to a sudden process of displacements at the focus.

Models of Premonitory Processes

In the first instance we are concerned with the source of motor forces provoking the accumulation of internal energy in the Earth's interior. This problem is related to the general dynamics and evolution of our globe, i.e. to that is now known as plate tectonics (which has replaced the Wegener theory of continental drift) and to the driving forces of global tectonics, which most likely are convection and gravity differentiation and the accompanying phase transformations.

The second aspect concerns the reaction of the medium to the stress field, a problem closely related to the premonitory processes and therefore essential for prediction methods. At present, two models describing the premonitory processes and their development up to the occurrence of an earthquake are accepted.

They are dilatancy models of the processes occurring in the earthquake source area. The theory of rock dilatation, occurring before the formation of a fracture, is essential for the understanding of several phenomena premonitory to an earthquake. The dilatation is an increase of rock volume as a result of deformations, originated by stress increase and by the formation of open cracks. The cracks open - the beginning of dilatation - when the stress values reach $1/2$-$1/3$ of the strength values of the material.

Model D - dilatancy - was elaborated by Soviet seismologists Myachkin *et al.* (1972), and model DD - dilatancy diffusion - by the Americans Nur (1972), Scholz *et al.* (1973). Both models are based upon the processes of microcrack development, but in model DD an essential role is played by interstitial fluid.

The essence of model D is explained by consecutive stages of crack formation. During phase I, elastic deformations grow and almost uniformly distributed cracks are formed. During phase II, the cracks interact between themselves and their development is accelerated while changes in the physical parameters of the medium become observable. In phase III an unstable development of cracks occurs, followed by their concentration in a narrow zone of the coming main fracture, larger parallel cracks are formed, succeeded by some relaxation of the medium outside the crack area, followed by a general stress drop and by a stopping of the crack development process. In a narrow zone the unstable process persists and the main fault is formed (Fig. 3).

In model DD, the participation of interstitial fluid and its translocations during consecutive phases before an earthquake is an essential factor controlling the process. During phase I, deformations grow, during dilatancy phase II an increase in the number of cracks follows and open cracks orientated perpendicularly to the direction of minimum compression stresses are formed. The cracks are not yet saturated by fluid, giving rise to an outflow of fluid from the area as seen by an increase of water level. During the further phase III however the fluid is pushed into the cracks, accelerating the fracture process and decreasing friction, and then an earthquake occurs. An important factor in the process is the simultaneous increase of material porosity. Other physical properties are also changed, but during phase III some of them return almost to their previous values.

According to model D, an earthquake occurs when stress is already diminished, and the crack orientation is parallel to the main fault, which is usually connected with a specified tectonic direction. In model DD an earthquake occurs when stresses reach maximum values, and the forming cracks are perpendicular to the direction of minimum compression stresses.

It is difficult from existing observations to choose between the models as, in principle they both explain in different ways the same changes of physical parameters observed prior to earthquakes. Geodetic measurements in an epicentral area might solve the problem in view of the fact that the dilatancy diffuse model, DD, predicts the maximum uplift of the Earth's surface, caused by dilatation, when the earthquake originates, while the non-diffusive model, D, predicts that after the uplift of the surface, subsidence should occur before the earthquake. Unfortunately, such measurements have not yet been made.

Changes of some of the parameters predicted by the dilatancy theories have been observed during various seismic events of very different scale: during laboratory microfracturing of rock samples and during rock bursts in underground mines for example, as well as during earthquakes.

Cherry *et al.* (1975) have considered a medium with non-elastic deformations. Taking into account non-elastic volume deformations and the stress limits for the start of dilatation processes and for the material strength, they estimated the velocity changes of P and S waves as a function of a certain dimensionless parameter describing the "imminence" of stress state against the material fracturing. The results obtained indicate the presence of anisotropy of the velocity changes in relation to the direction of principal stresses.

Nur (1975) assumes that medium dilatation can be approximately described by an exponential constitutive equation: $\gamma = \delta\tau^n$ where γ is the volume deformation or dilatation, τ the shear stress, and n a constant. In the case of crack dilatation a value of $n \cong 2$ can be accepted while in a material with joints $n \cong 1$, and in a grained material $n \cong 1/2$. Nur has also considered the pattern of vertical deformations before the earthquake for those three types of dilatation. The size of the dilatation area, however, also depends upon the processes of stable rock creep before the earthquake, and as a result the size can change considerably with time and differently for different types of medium. These results imply that different reactions of the medium prior to earthquakes should be expected.

The process of dislocations → crack → dilatancy described previously, could explain some elements of the theories mentioned. In DCD processes, an essential role is played by the pre-existing planes or boundaries along which cracks are formed. The transition process from dislocations to cracks could well be a real description of the changes in medium structures, representing at the same time the transition from slow plastic deformations to sudden fractures of the medium. Specified pre-existing slip planes or block boundaries in the medium can originate the concentration of these processes along them and their merger, leading to dynamic events on a large scale.

Earthquake premonitory processes and related phenomena now form a large subject within earthquake science, a subject of great importance for earthquake prediction, but a separate review would be needed to describe its scope in detail.

Search for Generalizations

Studies of dislocation distributions and their dynamics cannot be restricted to the problem of crack development only. A more advanced description of deformations in the continuum media can be achieved by the introduction of a dislocation density field containing any space distributions. This applies to a medium exhibiting considerable heterogeneities with a stochastic distribution.

It has already been noted that the dislocation density field can describe plastic processes and may also be connected with thermal stresses. The rock medium, where premonitory processes and earthquakes take place, is very complex. Originating stresses and deformation processes are imposed there upon a field of numerous existing defects and heterogeneities. This medium and its state can be described by the term "geological space". To describe dynamic processes occuring there, far-reaching approximations are needed.

Examples of descriptions, explaining certain characteristics of seismic phenomena, should be mentioned here. These descriptions use complex theories of the continua, in which defects and structural features are considered as continuous quantities, distributed with some density over the entire space. A medium with a continuous dislocation distribution can be described by the continuum properties in non-Riemannian space with torsion and curvature. In this way an explanation of certain plastic and thermoplastic processes is obtained.

A geometrical interpretation of these considerations leads to a description of the deformation problems in terms of differential geometry. The relation between geometry and physics is here, however, of a rather mathematical formal character and does not go so far as describing the nature of phenomena as did for example the general theory of relativity for gravity. Defects of the dislocation type can be described by the properties of the lines which formed a continuous closed contour before deformation, and were broken and displaced after the introduction of a dislocation. For the case of discrete dislocation distribution, the appropriate two-dimensional graphical representation is given by a line with several breaks and

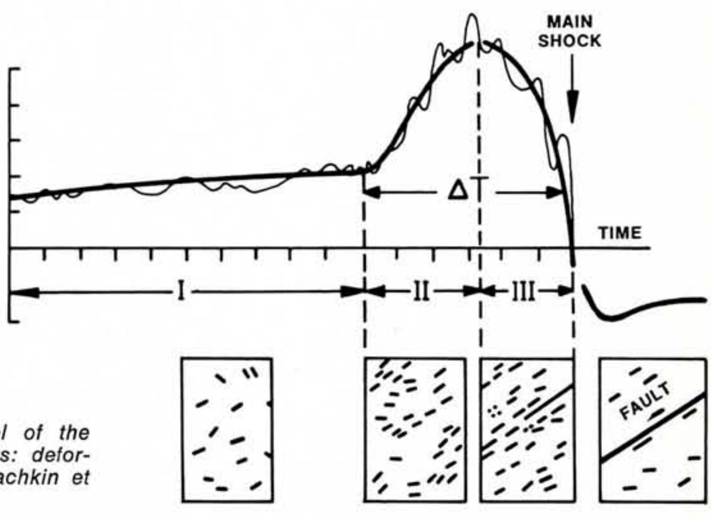


Fig. 3 — Model of the precursory events: deformation rate (Myachkin et al., 1975).

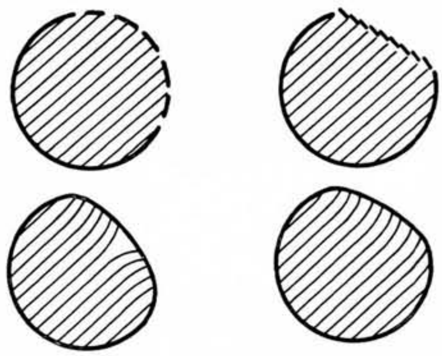


Fig. 4 — Two dimensional representation of continuous defect distribution and curvature of surface.

displacements (Fig. 4, upper diagrams). The lines under consideration, so far situated on a plane, can be brought back to continuous contours without any change of the surface size but by its curvature in space. Thus the size of the curvature would be a measure of the dislocation content. Such an operation starting from spatial elements would of course be physically impossible, since in general it would lead to curvature in non-Euclidean space. This simple consideration shows that transition from an ideal medium without stress to a real medium with defects, or the converse, is not possible, at least for a continuous holonomic transformation.

Although differential geometry methods are very convenient in the study of complex stress states when defects are present, they should be supplemented by dynamic considerations. In these field descriptions the problems of crack formation are, of course, not present. The process mentioned earlier, would correspond to a transition from continuous description — dislocations — to a discrete description — cracks.

The influence of internal structure and the heterogeneity field in the source area should also be taken into account in the formalism of the theory.

The Cosserats medium, micropolar and micromorphic media and non-local media form a group of theories permitting a more general approach to dynamics and deformation problems. Deformation history is covered by ascribing to the medium memory, or fading memory. Similarly, in non-local theories the stress state is dependent on the situation in a neighbouring area. Previously presented methods of description of deformation and stress states are related to classical media; they are not concerned with the theory of a medium with internal structure. Of course, discrete structures, e.g. block structures, could be described within a frame-work of the classical theory, using sufficiently complex mathematical apparatus, but when the size of structure distortions — blocks, grains, intrusions — is small compared with the wave length, it is possible to use the theory with a continuous description of the internal structure field.

The basic concept of the theory of so-called micromorphic media is the introduction of a wider range of point deformations related to additional degrees of freedom describing oscillations and deformations of elements forming the structure. The seismological applications are concerned with fields near the source, leading to a complex model of earthquake mechanism.

Earthquake processes are caused by instability. Mechanical instability in solid bodies which is the subject of numerous laboratory and theoretical studies, in general results from a situation in which the resistance of the material — in the sense of either mechanical strength or phase transformations or any other — decreases with the developing process of deformation. Several mechanical processes can satisfy this criterion and at greater depths phase transformations could also be sufficiently violent to originate shock waves and therefore the radiation of seismic waves as well.

Instabilities related to brittle fracturing of the material in shear processes, and sudden but restricted displacements of the stick-slip type, connected with fault planes, defects or other discontinuities existing in the material, are of special importance. Development of such instability depends on several factors, Brace (1972). As a rule, when effective pressure is low, porosity is high, low strength minerals are present, and temperature and partial pressure of interstitial water are high, the rock material undergoes a continuous deformation process approaching stable creep. Under contrary conditions, sudden instabilities expressed by a series of stick-slips would occur. The mechanism of stick-slip resembles the dislocations $\rightarrow$ crack process, in which plastic deformations are concentrated and then released by displacements along existing structural elements in the medium (discontinuities, slip planes).

It has been noted already that from considerations of the stress concentration process it follows that the earthquake should be considered as an element of a whole series of processes undergone by the medium. This is a series of transitions in which the last conclusive stage — the earthquake — is a discontinuous transition on a macroscopic scale; earlier formations of small cracks in the DCD process are also discontinuous transitions but on a smaller scale.

From this point of view, an earthquake can also be considered as a movement of the boundary describing generalized phase transformations in the medium. Using this approach earthquake processes were studied by Archambeau and Minster (1977) and Hanyga (1973). Hanyga studied generalized shock waves — the waves of reaction — which are connected with phase changes in the medium. He also showed that shear shock waves are possible. Before an earthquake, the medium can gradually pass into a metastable state, and the final stage is the consecutive phase transition from the metastable state — a process which occurs suddenly.

By such approaches, a rather general description of earthquake processes could be obtained, and taking into account non-linear phenomena and the formation of shock waves, further approximations to the physical processes in an earthquake source should be sought.

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