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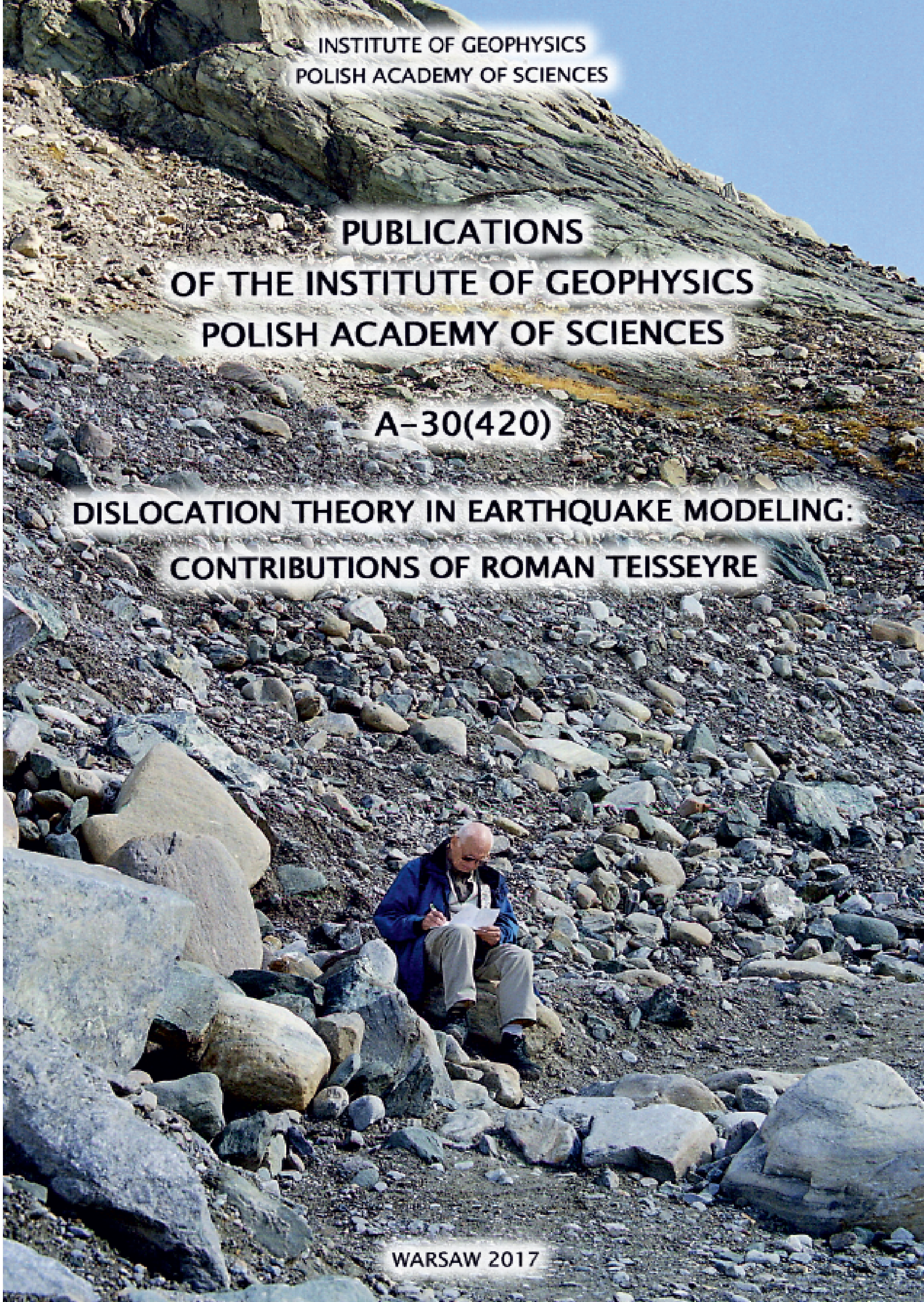
DISLOCATION THEORY IN EARTHQUAKE MODELING: CONTRIBUTIONS OF ROMAN TEISSEYRE



WARSAW 2017

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Dislocation Theory in Earthquake Modeling: Contributions of Roman Teisseyre

Editors: Zbigniew Czechowski and Anna Dziembowska

WARSAW 2017

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Contents

Editorial Note

Roman Teisseyre was one of the pioneers of applying the dislocation theory in geophysics. The present book recollects his major publications of the years 1961−1990, the milestones in the consecutive stages of the development of the Theory of Earthquake Premonitory and Fracture Processes. The collection reproduced here, showing the evolution of the Author's ideas, is sort of backup and supplement to monographic publications and gives the reader an easy insight into some top positions representing numerous papers scattered over various journals and books.

The idea of republishing some of Teisseyre's early publications, which exerted a lasting influence on seismic foci modeling and the theory of defects, came about when we realized that he had awarded the Title of Full Professor exactly half century ago, at the age of 38. To commemorate this 50-th anniversary, we decided to come back to the early years of his scientific work and emphasize his role in the development of modern theoretical geophysics at those times.

Teisseyre's scientific career, began at the Warsaw University, has been mainly associated with the Institute of Geophysics, Polish Academy of Sciences; he organized and led the modern center of theoretical earthquake research, and was the Institute's Director in 1970-1972 and Deputy Director in 1960-1970 and 1973-2001.

Teisseyre's achievements were widely recognized, already very early; he was nominated Member of Polish Academy of Sciences in 1969, and Foreign Member of the Finnish Academy of Science and Literature in 1975. He was Vicepresident of the European Seismological Commission in 1970-1976, and its President in 1976-1978. He was UNESCO Expert at the International Institute of Seismology and Earthquake Eng., Tokyo, Japan, in 1965-1966, and Visiting Professor at the University of Trieste, Italy, in 1979-1980, University of Strasbourg, France, in 1984, and Hokkaido University, Japan, in 1999. He was head of the Geophysical Expedition to Vietnam during the International Geophysical Year 1957-1960.

The outstanding accomplishments in global and mining seismology, with special emphasis on earthquake precursors, were the basis for granting him the *honoris causa* doctorate by the AGH University of Science and Technology in Cracow.

The present book contains also an introduction written by Roman Teisseyre, which outlines his newest, innovative ideas he is now working on. The problems concern an application of some elements of quantum theory, namely, the distribution of ideal black body radiation, to the description of energy release in some geophysical phenomena.

A very broad and complete bibliography of Teisseyre's publications gives evidence of a variety and diversity of scientific topics the Author dealt with, the innovative attitude to the studied problems, and his role in the scientific community.

Zbigniew Czechowski and Anna Dziembowska

Roman Teisseyre awarding the title of *Doctor Honoris Causa* from the AGH University of Science and Technology in 2004

Roman Teisseyre among his coworkers, friends and guests celebrating his 80. birthday at the Institute of Geophysics PAS in 2009

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Preface

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The classical theory of elasticity or plasticity is not able to describe processes of large deformation and destruction taking place over vast areas of very complex and inhomogeneous media, which are the object of geophysical research. It is necessary to introduce defects, cracks and dislocations, and rules of their evolution. First studies of dislocations (by V. Volterra and C. Somigliana) date back to the XIX century and were related to continuous media. The dislocation theory has experienced a very fast progress, owing to its applications in solid state physics. The importance of this generalized approach to the mechanics of continuous media consists in the introduction of a concept of inhomogeneous internal stresses.

In geophysics, the use of the theory of dislocations and cracks in the problems of elastic continuum evolution has its deep justification for description of seismic events. The observed tectonic dislocations may reach huge dimensions. The internal structure of the Earth's crust is a crucial element in the analysis of earthquake processes. The earthquake mechanisms can be divided into three groups: The first is the modeling by means of the system of body forces grouped in the source, the second one is focused on the dislocation processes (kinematic models), and the third deals with the evolution of cracks (dynamic models). The first and second group can be interrelated by the equivalence between the force distribution and the dislocation field, while the second and third group are linked by the possibility of description of cracks by means of a continuous dislocation field. Hence, the dislocation theory may offer some universal and sound description of real processes in earthquake sources.

Professor Roman Teisseyre was one of the pioneers of applying the dislocation theory in geophysics. The first attempts at incorporating this theory to geophysics were made in 1956 by A.V. Vvedenskaya, who considered the problem of abrupt formation of dislocations as a seismic source model. Research of J. A. Staketee (1958) was restricted to static problems. The author has shown how the Griffith crack can be modeled by means of dislocations. Already in the next year, there appeared the paper by Z. Droste and R. Teisseyre (1959), in which the authors emphasized a relation between the stress field and dislocation field in the context of spatial distribution of inhomogeneities in the Earth's crust and the location of seismic processes. The problems of dislocation motion, grouping and growth were treated as an important earthquake mechanism. This publication was the beginning of many-year involvement of Roman Teisseyre in dislocation models of seismic foci and the theory of defects in a continuous medium.

The present book recollects selected Teisseyre's publications, which can be considered the milestones in the consecutive stages of the development of the Theory of Earthquake Premonitory and Fracture Processes, published in old issues of journals which are now barely available, namely Acta Geophysica Polonica and Publications of the Institute of Geophysics, Polish Academy of Sciences. The papers demonstrate both the contemporary state-of-the-art relating to the earthquake mechanisms and the dislocation theory as well as creative endeavors of the researcher to combine the two branches of science and their joint development in the frame of the new theory just formulated.

In addition to reprints of eight publications, the book contains a full, very rich bibliography of Teisseyre's publications and a chapter outlining the problems on which the Author is currently working.

The first reprint is a comprehensive treatise of 1961 which, basing on the experience gained in preceding years, presents the rudiments of the Dislocation Theory of Earthquakes (DTE), and, in particular, the sources and mechanism of dislocation formation, seismic energy

The second paper, of 1964, is focused on the determination of the energy of earthquakes whose source is modeled by the contour dislocations. The formulae proposed follow from the calculation of energy concentrated in cylindrical vicinities of dislocation lines, and the numerical assessments agree with observational data.

A very interesting approach to the thermal stresses, associated, e.g., with convection in the Earth's interior, is presented in the paper of 1960 (third reprint). The use was made of the method of representation of thermal deformation by the equivalent distribution of dislocations.

A good model of the behavior of plastoelastic geological material is the glacier motion. A consecutive paper, of 1978 (fourth reprint), deals with this problem, presenting differential relations between the stress field for Maxwell's plastoelastic medium and the distribution of dislocations and dilatations in such a medium.

A process of creep-type displacement may be a cause of seismic zone migration. In the fifth paper, of 1980, the Author discusses a possibility of a movement of deformation zones as a result of dislocation motion, which convey local stress fields and may evoke changes in the material constants of the medium.

In the next paper (sixth reprint), the dislocation theory is used for describing the processes taking place in a medium prior to the earthquake. The paper presents a sequence of processes in which the dislocation distribution leads to the formation of shear cracks and tensile cracks,

The seventh reprint, of 1985, presents a mathematically refined theory of premonitory plastic processes in a medium before an earthquake, and a devastating energy release of the medium during the earthquake. The creation and propagation of cracks are described by the evolution of a respective dislocation field, but the rebound process during crack joining coalescence is described by a field of virtual cracks.

The last reprint in this book, being a synthesis of the former research, is the paper of 1990, which contains a summary, revision and some modification of the Earthquake Premonitory and Rebound Theory, developed by the Author, and its very important amendment by incorporating thermodynamical aspects.

It is to be emphasized that the theory was then widely described in a comprehensive, widely recognized monograph *Theory of Earthquake Premonitory and Fracture Processes* (Polish Scientific Publishers, 1995). However, unlike the monograph, the chronological and suitably selected set of reprints of Teisseyre's papers provides other, in my opinion very valuable outlook, such as a possibility of following the evolution of thoughts and concepts of the researcher in his consequent endeavour for developing a new theory, and a possibility of observing how his research techniques and tools have been evolving. These aspects are usually disregarded in scientific teaching, which is concerned with the current state-of-the-art alone.

The present book contains also a short introduction in which the Author outlines his newest ideas relating to a possibility of applying some elements of quantum theory, namely, the distribution of ideal black body radiation, to the description of energy release in some geophysical phenomena.

A very broad and complete bibliography of Teisseyre's publications gives evidence of a variety of scientific topics the Author dealt with, and innovative attitude to the studied problems.

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Dislocation Theory in Earthquake Modeling: Introduction to the Collection of Early Papers and Some New Ideas in Earthquake Theory

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The main aim of this book is to summarize the consecutive steps in the application of the dislocation theory in earthquake modeling. My colleagues asked me to re-publish some of my early papers on this topic. The reproduced papers were issued over the years 1961-1990 in *Acta Geophysica Polonica* and *Materiały i Prace* (*Publications of the Institute of Geophysics, Polish Academy of Sciences*) and are hardly available now.

My next theoretical results and formulation of the Asymmetric Continuum Theory have been comprehensively described in a series of monographs and papers, as indicated in the Bibliography prepared for this issue. These newer publications are widely accessible on line and in printed form.

I am currently working on further developments of the Asymmetric Continuum Theory with the shear and rotation strains and include the quantum processes. I am taking into account doublet continua with the elasticity and time rate plasticity, using a special definition of plasticity. I am also trying to include, as an important counterpart, the electric and magnetic fields.

It is assumed that the shear strain amplitudes prevail in an elastic continuum, while the rotation strains might be much smaller, even difficult to be observed. Reversely, the rotation strains can be more remarkable in the plastic part of the continuum. However, the space and time derivatives of the shear and rotation strains must always follow the release-rebound relations.

Finally, I am applying the synchronous quantum processes which appear due to the deformation fields related to the fracturing and other extreme processes at the Planck black body radiation. Moreover, in this approach any molecular motions can be related to the quantum synchronous processes.

In this way, it may be presented how some synchronous quantum processes could lead to the fracture events and, in a similar way, the lightning and aurora events related directly to the electron motions; moreover, the lava flows and the rotations in liquid Earth's core may be included too.

Of course, the synchronous quantum-related processes appear in all radiation processes; however, I will consider only those synchronous quantum processes which are related to the deformations, the shear and rotation strains, and lead to the Planck body radiation.

On this basis it is possible to assume that the strain energy can be comparable to the energy of the quantum synchronous processes with the black body radiation. It is to be noted that my considerations are confined to the processes under the thermodynamic equilibrium.

A new monograph is now in preparation. Its tentative title is: *Asymmetric Doublet Continua and Quantum Synchronous Processes*. These quantum processes relate, first of all, to the formation of the World (energy release and space/time formation). The present book concentrates on the fracture processes.

Dislocation Theory in Earthquake Modeling:

Selected Roman Teisseyre's Publications from the Years 1961-1990

A C T A G E O P H Y S I C A P O L O N I C A
Vol. VIII, no 1/2 1961

Roman TEISSEYRE

DYNAMIC AND TIME RELATIONS OF THE DISLOCATION THEORY OF EARTHQUAKES

Summary

Fundamentals of the dislocation theory of earthquakes are discussed, notably the sources and mechanisms of formation of dislocations, discharge of seismic energy, movement of dislocations and principles of the elementary theory of quake replicas.

1. APPLICATION OF THE PHYSICAL DISLOCATION TO THE THEORY OF EARTHQUAKES

The assumptions made in elaboration of the dislocation mechanism of earthquakes were given in papers [1] [2]. They referred mainly to the conditions of the formation of a dislocation in a shear stress field. The mechanism of earthquakes worked out on this basis [1] offers a fairly good explanation of the energetics aspect of the observed phenomena.

Application of the dislocation to description of geophysical processes and phenomena had been proposed by J. A. Steketee [3] at an earlier date, but it was used by him in considerations on a number of static problems only. In order to make a clear distinction between this mode and the application of physical dislocations in the theory of solid state, J. A. Steketee suggested the term „elastic theory of dislocation" (ETD), when applied to geophysical phenomena. Also A. V. Vviedenskaja [4], [5] introduced the physical dislocations as an essential element of the mechanisms of quakes and as basis for dynamic modelling of the foci. A. V. Vviedenskaja, however, confines herself to the process of the formation of the dislocation (notably of the finite disk type dislocation), regarding simultaneously this process as the basic quake mechanism.

The dynamic phenomena connected with the stresses in the crust and the upper parts of the earth have their specific characteristics. Application of the physical dislocations to the description of those phenomena is based on the following assumptions:

1*

1° The assumption that the dynamic processes in the earth's interior are in causal relation with the field of shear stresses and its changes. Hence, the character of the dynamic processes should correspond to that of the stress field. Dynamic processes, related e. g. with rapid transition of part of the material from one physical state to another, are therefore not taken into consideration. It is also being assumed that hydrostatic pressure does not play a direct role in the dynamic processes, but is only of indirect significance through its influence on the state of the matter, on the values of the elasticity constants, the strength of the material (the so called limiting pressures effect (6) etc. Consequently, only the non-hydrostatic part of the stress field is in principle taken here into consideration. This assumption is justified when the linear theory of elasticity is being used. The singular stresses around the dislocation line (dislocation front) are thus cut out, and the corresponding radius of the cylinder is defined as the radius of the dislocation [7]. The essential role of the shear stresses in the dynamic and deformation processes in the earth is pointed out by numerous authors [8] [9].

2° The assumption regarding the spatial distribution of inhomogeneities in the earth. This point has been discussed in detail in paper [1] in which the equal importance of the spatial distribution of the stress field and of the inhomogeneities for localization of seismic processes is being examined. Particularly high shear stresses in a given area are determinant for the dynamic processes and, simultaneously, the inhomogeneities of this region constitute *sui generis* attachment points for the former.

Seismological observations and material clearly indicate the existence of seismologically active areas in which dynamic phenomena and the accompanying earthquakes are concentrated. Those areas form frequently the surroundings of a certain plane, the so-called seismic foci plane or hypocentral plane. The data as well as the analysis of contemporaneous tectonic phenomena indicate that at least in the vicinity of such areas there are active shear stress fields [8] [9]. The above mentioned plane forms simultaneously the tectonic (dislocational) plane of the respective region [2].

In the following, the main part of the problems discussed will deal only with phenomena occurring along the given plane or its immediate vicinity. Along this plane, shear stresses are acting and there exists a certain field of inhomogeneities, the influence of which can in particular cases be considered also as a *sui generis* weakening of the material. The existence of such weakening follows, as was shown by D e N o y e r [10], from the general principles of R e i d's rebound theory.

In the cases analysed in the following, the plane of stress action and that of material weakening coincide. In general these planes may somewhat differ; the dynamic processes lead to the formation of zigzag type dislocation.

3° Relation between the shear stress field and the dislocation field, and the part of inhomogeneity in formation of the dislocation under the influence of the stress field [1]. The relation between the shear stress field and the dislocation field is of essential importance in our subsequent considerations. This relation may on one side explain the mechanism of transmission of stresses through a field of infinitely small dislocations, on the other side it throws light on the question of formation of separate physical dislocations.

The homogeneous stress field along the plane $x_2\ x_3$ can be expressed by means of a field of uniformly distributed small contour dislocations. Denoting the value of the vector of dislocation slip (B u r g e r s vector) by b, the radius of the contour dislocation by ϱ, and the number of dislocations per surface unit by n, we obtain in result of summing up the dislocation fields the following expression for the stresses p_{23} (which will be denoted by p):

$$p_{23} \overset{\text{def}}{=} p = \frac{\pi\mu}{2}\left(\frac{3}{2} - \frac{c^2}{a^2}\right) \lim (n \cdot b \cdot \varrho) \tag{1.1}$$

where: μ — modulus of rigidity; a, c — velocity of the waves P and S, respectively.

In paper [1] the respective formula did (by an oversight) not contain the factor $\pi\varrho^2$ — surface of the dislocation. The limit value $nb\varrho$, with $n \to \infty$ and $b \to 0$, $\varrho \to 0$, gives the field p. The postulate of finite value of the expression limb $(nb\varrho)$ can be replaced by the severer condition of constancy of the mean value of the product $nb\varrho$ along the surface:

$$nb\varrho = \text{const.} \tag{1.2}$$

This condition warrants on one side a constant mean value of the field p, on the other side it admits different values of vector b and radius ϱ, which allows to take account of the structure and inhomogeneities of the medium. We propose to return to this question in our considerations on the frequency of occurrence of shocks of different magnitude. Here it should only be mentioned that due to the existence of certain inhomogeneities (e. g. rigid intrusions) there may, in accordance with (1. 2), form in the medium greater dislocations in correspondingly smaller numbers. Also dislocations with different b-vector may be formed. Such dislocations, which will be termed hereafter elementary dislocations, do not in the beginning change the mean value of field p, but they produce local field anomalies which are potential centers for the formation of greater dislocation elements. Thus, the local field anomalies caused by inhomogeneities of the medium can be considered as sources of dynamic processes.

4° Equivalence of the crack field with the field of positive and negative dislocation series in the linear case [13], and its equivalence with a system of concentric contour dislocations in the case of a finite closed crack. Such equivalence is of fundamental importance as the crack is that form of a finite deformation inside a continuous elastic medium which comes probably closest to actual reality.

The theory of physical dislocations has developed through its application to solid state physics. The dislocation vector $\vec{b}$ in crystals is directly related to the constants of the crystal lattice. The dislocations are formed in the most simple case by a slip of a whole row of atoms to a distance equal to the interval between two adjacent rows. The stress field related with the dislocation in the crystal is formed in result of the forces of interaction between the crystal atoms. In the case of dislocation in a continuous medium, the formation of the dislocation and its field are connected with the external field of shear stresses [1]. The value of the slip vector is in principle limited only by the energy of the field which will be termed here as the external field. On the other hand, there arise here difficulties in explanation of the formation of particular values of the displacement vector $\vec{b}$. To apply in this case the crack theory, developed by A. Griffith for the problems of cracks in glass [14] [15], would avoid those difficulties. The crack is defined by the mutual displacement of the material along the surface of the crack, the displacement value being a function of its position, ranging from zero at the edge of the crack to a maximum value at its middle (fig. 1). The stress field of a linear crack is characterized by a function of type $\frac{1}{r^2}$ (the field of a single linear dislocation is proportional to $\frac{1}{r}$) and corresponds to the field of a dislocation pair with opposite signs. It is, of course, assumed that the distance between the edges of the crack or between dislocations of a pair is small in comparison with distance r. In paper [13] the equivalence of the crack field and the field of series of negative and positive dislocations has been demonstrated. This is illustrated by the consecutive

[1] An external field is here defined as the part of a field not related to the dislocation or dislocation system under consideration.

parts in Fig. 1. If, in relation to the distance, the dimensions of the crack are greater, the decisive role regarding the field value is played by the edge part only, in which the vector grows from zero to a certain mean value. The crack describes very well the deformation in amorphous bodies. It seems that in macroscopic description of phenomena the use of the theory of cracks for description of deformations and displacements in the earth's crust and mantle is fully justified. On the other hand, however, the edge part of a crack may (in accordance with the foregoing) be approximated by one, and — in further steps of approximation — by two or more dislocations. The whole crack may be described by a pair of dislocations or, better, by a series of positive and negative dislocations.

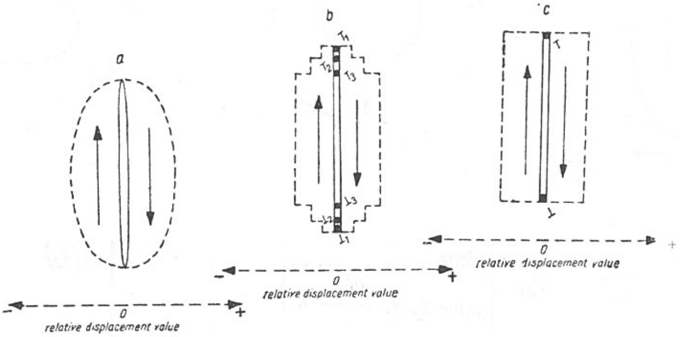

Fig. 1. a) Crack, b) Linear dislocation array or system of concentric loops, c) Two unlike dislocation or loop dislocation

The dislocations constitute here rather more idealized forms which are characterized by jump-wise change of the displacement vector $\vec{b}$, whereas in cracks the changes are continuous. Finally, the simpler form of mathematical interpretation and the possibility of grouping dislocations in various combinations closely approaching the real deformation and stress conditions in the medium, are also arguments in favour of using the dislocation in description of processes occurring in the earth. Similarities and differences between the crack and dislocation theory will be discussed in part 5 of this paper.

In the preceding part we have discussed the reasons for using the physical dislocation in the theory of earthquakes and the arguments justifying this procedure. In the last part of this paper we shall present the results obtained within the frame of the dislocation theory of earthquakes in the present study as well as in our preceding investigations [1], [2], [16], [17], [34].

2. DYNAMIC DISLOCATION SOURCES

The relations between the stress field and the inhomogeneities of the medium find their expression in the properties of the dislocation which describe the disturbances of the stress field. In paper [1] it was shown that the interaction between the dislocations and the action of field p lead to grouping (synthesis) and growth of these contour dislocations

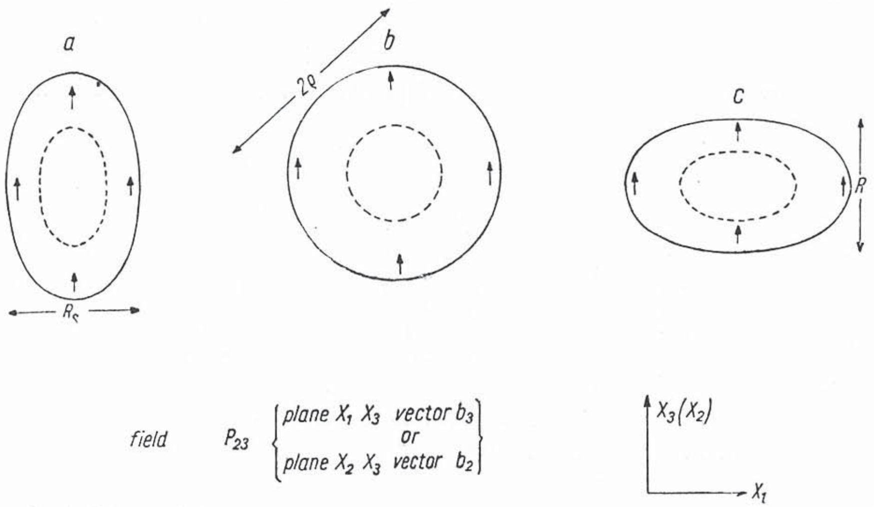

Fig. 2. a) Approach to apair of screw dislocations, b) Loop dislocation, c) Approach to apair of edge dislocations

whose orientation corresponds to field p. In dependence on the structure of the field and the medium, three extreme situations can be distinguished which result from the grouping and growth processes (fig. 2): (a) a pair of screw dislocations, (b) a contour dislocation, (c) a pair of edge dislocations. The cases (a) and (c) are discussed in detail in paper [1]. This discussion constituted the basis for formulating the conditions of the motion of dislocations belonging to one pair and, in further consequence, allowed formulation of the principles of the mechanism of earthquakes.

The basic condition for the development of dynamic processes is the postulate that the action of the external field exceeds the mutual attraction of the elements of a contour dislocation or a dislocation pair.

In the case of screw and edge dislocations the interaction of the dislocations amounts per unit of length, respectively, to

$$F = p_s b \quad \text{and} \quad F = p_e b \tag{2.1}$$

where: $p_s \equiv \dfrac{\mu b}{2\pi r_s}$ — screw dislocation field;

$p_e = \frac{\mu b}{2\pi(1-\sigma)r_e}$ — shear stresses field of the edge dislocation (σ — Poisson coefficient)

An analogous expression for the action of the external field $p: F = bp$ allows to express the conditions for the development of dynamic processes by means of the respective inequalities:

$$p > p_s \quad \text{or} \quad p > p_e$$

If a pair of screw or edge dislocations has formed through grouping of elementary contour dislocations, the external field can be expressed by the formulas (1.1), (1. 2), taking $n = \frac{1}{\pi\varrho_0^2}$ (condition of contact of the contour dislocations).

The abovementioned conditions for field magnitudes are then expressed for $\mu = \lambda \left(\sigma = 1/4, \frac{c^2}{a^2} = 1/3\right)$ by:

$$r_s > 0{,}135 \cdot 2\varrho_0 \quad \text{or} \quad r_e > 0{,}55 \cdot 2\varrho_0 . \tag{2.2}$$

These formulas indicate the lowest limit of initial approach of dislocations at which further development of dislocation processes becomes possible. These values are not dependent on the vector b, but only on the value of the diameter of the elementary dislocations $2\varrho_0$.

Evaluation of radius ϱ_0 can be based on formulas (1.1), (1.2) at $n = \frac{1}{\pi\varrho_0^2}$. Assuming that the shear stress field in the seismically active field is $p = 10^9$ and $\mu = \pi \cdot 10^{11} \left(\frac{\mu}{p} = \pi \cdot 10^2\right)$, we obtain (all values in the C.G.S. system [2]):

$$\frac{b}{2\varrho_0} \approx 8.5 \cdot 10^{-4} \tag{2.3}$$

This is an extreme value for the case when the elementary dislocations cover the whole surface.

Generally, the condition for the product $nb\varrho$ is expressed on basis of (1.1) and (1.2) by:

$$nb\varrho \approx 5.4 \cdot 10^{-3} \tag{2.4}$$

where: n is an arbitrary number; for high n we have a higher degree of

[2] The numerical values given here and in the following correspond approximately to the values obtained by verious authors. The specific values used for facilitating computation lie within the limit of the standard errors.

homogeneity of the field; inversely, for $n \ll 1$ the field is highly inhomogeneous.

In formation of greater dislocation elements, e. g. dislocation pairs fulfilling the inequalities (2.2), the field of a single dislocation can considerably exceed the value of field p, but the mean value computed according to (1.1), (1.2) will, at appropriately small n, be preserved. The considerations on the formation of dislocations of finite value b must be supplemented by considerations regarding the strength of the material. In the grouping and growth mechanism of dislocations it is usually assumed that these processes develop rather slowly. The formation of discontinuities is here connected with exceeding of the statical shearing strength. M. T. Huber [54] considered the strength definition in dependence on the stress field nature. The shearing strength of material is usually defined by the Mises function $S^2 = p'_{ik} p_{ik} = 2p^2_{23}$ (where: $p'_{ik} = p_{ik} - \frac{1}{3}\delta_{ik} p_{ss}$), sometimes also by the difference $|p_{22} - p_{33}| = \frac{1}{\sqrt{2}} p_{23}$ between the highest and the lowest normal stress. For our present considerations the choice of the function does not play any role. In the later part of this study we shall define the strength function in processes related with the dislocation movement. The numerical value of the strength of compact crystalline rocks is of the order 10^9 [53]. The static strength is lower than the dynamic strength. In paper [6] are given experimental results indicating clearly the increase of strength concomitant with the velocity rate of the external stress increase.

Assuming that the dynamic processes in the earth are related to mutual displacements of masses, which may be described by means of formation and motion of dislocations, we have the following situation. In an external field approaching static strength, we are dealing with a slow dislocation movement; the dislocation processes of grouping (synthesis) and growth of the dislocations develop gradually. In this way greater dislocations are formed.

It is only near the outer or inner discontinuity boundaries of the medium that more rapid course of the processes becomes possible. That is exactly what happens in investigation of limited samples. Whereas exceeding of the statical strength in a certain part of the medium's interior, lying far from the surface of discontinuity, leads to gradual changes which find their expression in the movement and formation of the dislocations.

The movement of the dislocation can be described by formula

$$m\dot{v} + \beta v + \delta = pb \tag{2.5}$$

where: pb — force acting on the dislocation in field p; m — mass of the dislocation, for screw dislocation equal to the ratio of the dislocation energy to the square of velocity of the waves S; β, δ — coefficients; v — velocity of dislocation movement.

If $\frac{\delta}{b}$ is interpreted as the static strength in the mechanism under discussion, we can obtain the dynamic strength from formula:

$$S = \frac{m\dot{v}}{b} + \frac{\beta v}{b} + \frac{\delta}{b}, \tag{2.6}$$

where: $\frac{\beta}{b}$ plays the role of the viscosity coefficient. The parametrical dependance of β and δ on the displacement vector b remains still unknown. The expressions $\frac{\beta}{b}$ and $\frac{\delta}{b}$ cannot be treated as explicite expressed functions. We shal return to this problem later on. At higher $\dot{v}$ and v the dynamic strength has a correspondingly higher value. Velocity v is here, of course, the velocity impressed by the external field.

From the above considerations it results that rapid formation of a crack or a contour dislocation or also a pair of dislocations requires a fairly strong external stress field. Such violent dynamic processes lead obviously to a shock and thus constitute one of the possible categories of earthquakes. This is a type of quakes corresponding to the models of V. I. Keylis-Borok in his representation of the so-called dynamic forces [18] [19], or to the models of A. V. Vviedenskaja [4] [5]. This, however, cannot be the basic mechanism of quakes. Disregarding the energetic aspect which will be discussed later on, we can at present state that neglect of the gradual building-up growth of the dislocation would presuppose a rapid rise of stresses in the interior of the earth, which seems rather doubtful. It is worth mentioning here that in the replica theory (discussed below) cases of rapid changes of the field are being considered, but only those occurring in result of discharge of internal energy in an earthquake. In case that in the given area the external field constantly exceeds the statical strength value, we must assume that a greater number of different dislocations exist in the medium. The interaction of those dislocations produces a field of internal strains approaching the equilibrum state, so that the dislocations are blocking each other and therefore can not shift. The strength of the material is thereby increased, similarly as in the hammering process. When in such a full dislocation system a change in the field occurs which is caused by release of the energy of one of the dislocations, e. g. at the medium boundary, displacement of the remaining dislocations and possibly further quakes, so called replicas, may be expected. This idea will be developed further on.

In analysing the formation of dislocations one has to consider the range of the displacement values b. Formula (2.3) determines the value of displacement b at a given ϱ_0, in the case when we consider only grouping processes of dislocations under tangency conditions (we have e. g. for $\varrho_0 = 1$ m, $b = 0.2$ cm). For isolated dislocations we have the condition (2.4). Generally, the value b has a lower limit given by the constants of the crystal lattice (of the order of 10^{-8} cm). The upper limit is difficult to establish, but already from the above mentioned relations it appears that b can not be very great.

On the basis of considerations on the velocity of fracturing and displacement formation, H. Jeffreys [20] defined the maximal value of the single displacement. The maximum value of b may reach 4 cm, the respective time of formation of a fracture 0.004 sec. H. Jeffreys takes account of the concomitant intense increase of temperature (of the order of 1000°) at the surface of the fracture. At such high temperatures one must, on the other hand, consider also the metamorphosing processes. These consist in violent heating and subsequent relatively quick cooling of the layer adjacent to the fracture, in result of which layers of vitreous character, the so called pseudotachylites, are formed. The thickness of the pseudotachylite layer is deduced by Jaffreys (for the standard case) from the value of the energy converted into heat [20]. The thickness of this layer is of the order of 16 cm.

Returning to the displacement value of a single dislocation it should be added that the restriction of the b value to the order of a few centimeters can very well be reconciled with the frequently observed great displacements of masses, by assuming the successive summing-up of a number of single displacements. Figs. 3a and 3b give a schematic presentation of two extreme cases of summation of dislocations which

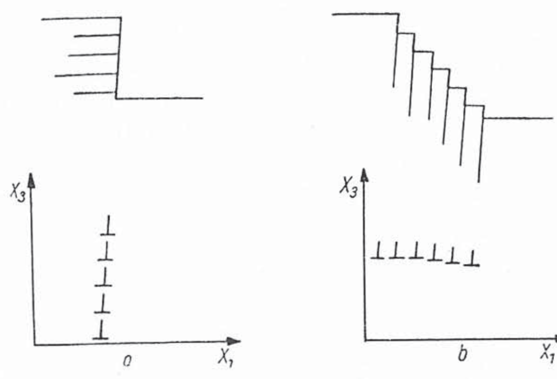

Fig. 3. Edge dislocations: a) time relation system, b) space relation system

we shall term hereafter the space and the time system. In the time system, the dislocations lie in the common dislocations plane, their arrival at the surface occurs successively in time.

In the space system, simultaneous discharge of the energy of the dislocation at the bounding surface is possible. The effect of the displacements at the surface is shown in the upper part of figs. 3a and 3b.

We shall now turn our attention to the properties of the fields of finite contour dislocations, primarily to the effect of the concentric dislocations, which will allow us to gain some insight into the deformative tendencies of the contour dislocations. In paper [1], the formation of edge or screw dislocation pairs, as the extremes of all possible cases, was studied in detail. The present case is more general, in the meaning, that deformations of contour dislocations may lead to formation of one of the abovementioned systems. Let us consider a circular dislocation lying in the plane x_1 x_3 and with displacement $b=b_3$. The field $dp=dp_{23}$ of the element of the dislocation line $(d\xi_1,\ d\xi_2)$ amounts to [12]:

$$dp=-\frac{mb}{4\pi}\cdot\frac{(x_3-\xi_3)\,d\xi_1}{R^3}+\frac{\mu b}{4\pi}\;\frac{(x_1-\xi_1)\,d\xi_3}{R^3} \tag{2.7}$$

where: $m=2\mu\dfrac{\lambda+\mu}{\lambda+\mu}$.

The full field p is correspondingly expressed by:

$$p=-\frac{mb\varrho}{4\pi}\left[-x_3\int_0^{2\pi}\frac{\sin\varphi d\varphi}{R^3}+\varrho\int_0^{2\pi}\frac{\sin^2\varphi d\varphi}{R^3}\right]-\frac{\mu b\varrho}{4\pi}\left[x_1\int_0^{2\pi}\frac{\cos\varphi d\varphi}{R^3}-\varrho\int_0^{2\pi}\frac{\cos^2\varphi d\varphi}{R^3}\right] \tag{2.8}$$

where: $R^2=\Gamma^2-\gamma^2\cos(\varphi-\varphi_0)$; $\Gamma^2=r^2+\varrho^2$; $\gamma^2=2r\varrho$; symbols as in fig. 4.

After computation we obtain the expression for the field p of a contour dislocation with radius ϱ

$$\begin{aligned}p=-\frac{\mu b}{2\pi}\Bigg[&-\left(1-\frac{2c^2}{a^2}\right)\frac{r+\varrho}{r^2}\,E\left(\frac{2\sqrt{r\varrho}}{r+\varrho}\right)-\frac{1}{r-\varrho}\,E\left(\frac{2\sqrt{r\varrho}}{r+\varrho}\right)+\\&+\left(1-\frac{2c^2}{a^2}\right)\frac{r^2+\varrho^2}{r^2\,(r+\varrho)}\,K\left(\frac{2\sqrt{r\varrho}}{r+\varrho}\right)+\frac{1}{r+\varrho}\,K\left(\frac{2\sqrt{r\varrho}}{r+\varrho}\right)+\\&+\left(1-\frac{2c^2}{a^2}\right)\frac{x_3^2\,(r^2-2\varrho^2)}{r^4\,(r-\varrho)}\,E\left(\frac{2\sqrt{r\varrho}}{r+\varrho}\right)-\left(1-\frac{2c^2}{a^2}\right)\frac{x_3^2\,(r^2+2\varrho^2)}{r^4\,(r+\varrho)}\,K\left(\frac{2\sqrt{r\varrho}}{r+\varrho}\right)\Bigg]\end{aligned} \tag{2.9}$$

where: E and K are complete elliptic integrals; $r^2=x_1^2+x_3^2$. With $\varrho\ll r$, i. e. a dislocation of small size, we will obtain the contour dislocation field given in paper [1]. The space-distribution of field p and related angular distribution influence the shape of the dislocation elements formed. If we assume that a certain area is the source of a dislocation series, we have to consider the action of concentrically placed disclocations. A complete dislocation system, i. e. one which in the external field approaches the state of equilibrium, is of special importance to us. The concentric dislocation system can in fact be just such a system. In the later discussion of the replica theory we shall analyze extreme cases of the system of linear dislocation series.

In the case of two concentric dislocations with uniform orientation, the repulsive force amounts per unit length of the external dislocation to:

$$F_1 = bpr \sin\psi d\psi\,, \qquad F_3 = bpr \cos\psi d\psi\,, \qquad F_r = bpr\, d\psi\,,$$

where p is given by formula (2.9).

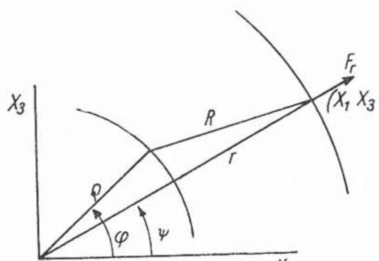

Fig. 4. Computation of the loop field and the interaction force of two loops

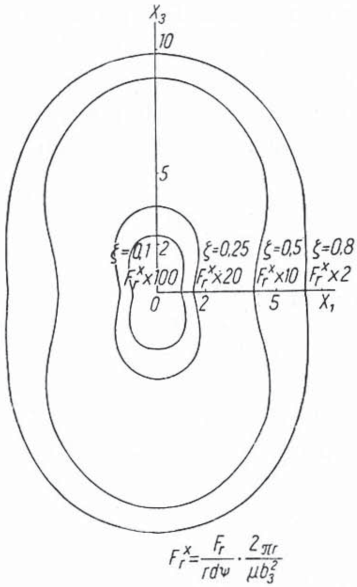

Fig. 5. Interaction force between two concentric loops

The resultant of forces F_1 and F_3 for the whole contour is equal to zero, which means that in a concentric system of dislocations their centers do not shift. The angular distribution of the radial component F_r per unit length indicates deformational tendencies in regard to the shape of the contour dislocation.

$$\frac{F_r}{rd\psi} = \frac{\mu b^2}{2\pi r}\left\{\left[0.333\,(1+\zeta) + \frac{1}{1-\zeta}\right] E\left(\frac{2\sqrt{\zeta}}{1+\zeta}\right) - \left[0.333\,\frac{1+\zeta^2}{1+\zeta} + \right.\right.$$
$$\left.\left. + \frac{1}{1+\zeta}\right] K\left(\frac{2\sqrt{\zeta}}{1+\zeta}\right) + 0.333\,\sin^2\psi\left[\frac{1+2\zeta^2}{1+\zeta} K\left(\frac{2\sqrt{\zeta}}{1+\zeta}\right) - \frac{1-2\zeta^2}{1-\zeta} E\left(\frac{2\sqrt{\zeta}}{1+\zeta}\right)\right]\right\} \tag{2.10}$$

where it was assumed that $\mu = \lambda$, whence $\frac{c^2}{a^2} = \frac{1}{3}$

$$\frac{\varrho}{r} = \zeta , \quad \text{whence} \quad 0 \leqslant \zeta < 1$$

The distribution is shown in fig. 5, where $F^* = \frac{F_r}{r d\psi} \cdot \frac{2\pi r}{\mu b^2}$.

The forces acting in the direction of axis x_3 (corresponding to the direction of displacement vector b) are approximately two times greater than the forces acting in a vertical direction, i. e. that of axis x_1. The extreme effect of the interactions of these dislocations would be a pair of screw dislocations, assuming of course, that the internal dislocation does not undergo opposite deformation. This assumption is justified for a greater number of concentric dislocations. In this way, the curves in fig. 5 illustrate the deformational tendencies of the external dislocation of a series. They have been computed for four values of parameter $\zeta = \frac{\varrho}{r}$: 0.8, 0.5, 0.25 and for 0.1.

3. STRUCTURAL SOURCES OF DISLOCATIONS

The preceding discussion on the formation mechanism of dislocations was based mainly on the action of the shear stress field. The inhomogeneities of the medium play also an important part as they determine the localization and constitute the necessary background of the dynamic processes.

At present we shall give more attention to the structure of the medium and those of its properties which — in the action of the stress field — determine the sources of dislocation. A problem of this type arises in the Frank-Read [21] mechanism of sources in crystals.

In the first place we shall examine the possibility of dislocation sources originating from the interior structure of contacts. When considering the actual contact between two media in the earth, one may imagine it as a set of a number of nearly parallel small layers representing transient states. This can be the result of mutual diffusion, intrusions of various kinds, or also of changes in the chemical composition or structure of the medium. Similarly, the cutting of the medium by a fault or dislocation plane has to be regarded as a set of a number of slip planes, forming together the fault zone in which the displacement occurrs.

Let us take a closer look at the situation which arises when the dislocation zone intersects the contact of two media (fig. 6). From the elementary properties of the stress field it follows that the shear stresses will favour formation of a dislocation in the contact zone as well as in

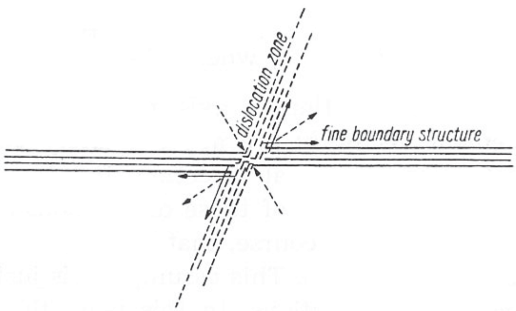

Fig. 6. Dislocation zone crossing fine boundary structure

the (vertical to the latter) displacement zone. In the intersection area of the two zones a fairly complicated interaction field of $\pm\frac{1}{r}$ type will arise, originating from the single dislocations. These dislocations can in certain cases form systems of internal stresses, in other cases they can become the source of secondary dislocations.

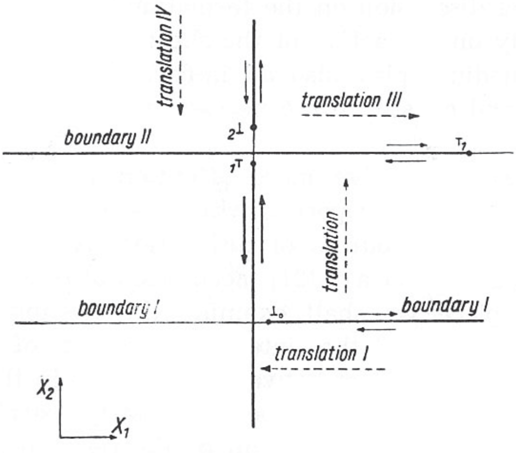

Fig. 7. Crossing mechanism

Fig. 7 presents one of the possible patterns of the processes in the intersection zone of the areas discussed. Let us imagine that under the influence of the stress field and in result of its interaction with the dislocations a displacement along the contact has occurred. The dislocation

$\perp_0$ thus formed creates an additional stress field. The following vertical displacement II is related to the existence of the thin contact layer II. The dislocation ${}_1\perp$ formed in this way has a Burgers vector b, equal to the distance between the layers. In the area above layer II the direction of displacement is inverse. Similar mass shifts occur in inverse direction to the left of dislocation ${}_1\top$ or ${}_2\perp$. Further factors supporting these processes are the interactions of the dislocation line with the boundary surfaces (by image process), and the interaction between the dislocations. Particularly, the attraction of the dislocation to the bounding surface can facilitate its movement, e. g. of the dislocation ${}_1\top$ in an upward direction. In the displacement marked IV, mutual attraction of the dislocations ${}_1\top$ and ${}_2\perp$ takes place. Mutual approach of these dislocations can cause their partial or full annihilation (at ${}_1b={}_2b$), accompanied by release of energy. In consequence, shocks may occur in the centre of the cross zone. The earthquake mechanism is discussed further on. Here, we have found one of the possible patterns of a mechanism which is in agreement with the general scheme of the junction of two dislocations with opposite sign [1], [16]. Returning to fig. 6, we observe that in the cross zone there occurs a sui generis contraction. The resulting concentration of stresses causes shocks, the mechanism of which was explained in the foregoing. We must now generalize the result of our considerations, illustrated in fig. 7, by assuming that the cross zones are not only sources of structural dislocations but also the place of possible shocks resulting from the energy discharge of dislocations with opposite sign. To complete these considerations, we may add that the forces of interaction between the dislocations lying along x_3—axis are [22]:

$$F_1 = b_i p_{2i}\,, \qquad F_2 = -b_i p_{1i} \tag{3.1}$$

The stress field of dislocation $\perp_n$ in its own coordinate system is expressed by [7]

$$\begin{aligned} p_{11} &= \frac{\mu b}{2\pi(1-\sigma)} \cdot \frac{x_2(3x_1^2+x_2^2)}{r^4} \\ p_{22} &= \frac{\mu b}{2\pi(1-\sigma)} \cdot \frac{x_2(x_1^2-x_2^2)}{r^1} \\ p_{23} &= \frac{\mu b}{2\pi(1-\sigma)} \cdot \frac{x_1(x_1^2-x_2^2)}{r^4} \end{aligned} \tag{3.2}$$

where: σ — Poisson module.

The field of dislocation ${}_n\perp$ is obtained by exchanging the indexes $1 \rightleftarrows 2$.

4. STATISTICS, MECHANISM AND ENERGY OF EARTHQUAKES

In the following it will be assumed — independently from the question of the mechanism of the sources — that there exists in every medium a certain dislocation density which depends from the degree of inhomogeneity, the history of the body and also from the value of the external stresses acting on the body. In the case of crystals, the dislocation density lies within the range 10^2—10^{12} [cm^{-2}] (from very pure crystals to strongly deformed bodies).

In the case of the earth's crust and mantle we shall assume the existence of a dislocation field with different displacements $\vec{b}$, and with a dislocation density depending, a. o., from the level of stresses in the medium. Putting in formulas (1.1), (1.2) the values: $\frac{c^2}{a^2}=\frac{1}{3}$; $\mu=\pi\cdot 10^{11}$ mean stress field in the medium $p=10^9$, we obtain approximately (all values in the C. G. S. system, as before)

$$nb\varrho \approx 5.4\cdot 10^{-3} \tag{4.1}$$

It is presumed here that the dislocations in the medium are to be considered as contour dislocations. The energy of the single contour dislocation can be calculated approximately by assuming that the mutual energy of two opposite elements of the dislocation amounts (per length unit) to $\frac{\mu b^2}{2\pi}\ln\frac{2\varrho}{r_0}$ [7]. We are hereby assuming that the energy of edge and screw dislocations can be expressed in approximation by the same formula. The total energy of a contour dislocation is thus equal to

$$E=\frac{\mu b^2\varrho}{2}\ln\frac{2\varrho}{r_0}, \tag{4.2}$$

where: r_0 — radius of the dislocation line. This is the radius of a cylinder cutting off the singularity of the dislocation. We assume that $\ln\frac{2\varrho}{r_0}$ equals 10; in the following it will be shown that this assumption is justified within the limits of the order of value. For the values taken above we obtain from (4.2)

$$E=b^2\varrho\cdot\frac{\pi}{2}\cdot 10^{12} \tag{4.3}$$

When introducing formula (4.1), it was tacitly understood that the mean value of the stress field in the medium is given by the sum of the dislocation fields of the number n per surface unit (the investigated area comprises a set of parallel planes, forming together the dislocation zone — for convenience one may take its thickness as unit).

The sum of dislocation energy per surface unit is $\varepsilon = nE$

$$\varepsilon = b \cdot 8.4 \cdot 10^9 \tag{4.4}$$

This expression cannot, however, be applied to computation of the b value from the mean field energy $\frac{1}{2}\frac{p^2}{\mu}$, because the field shows great local anomalies near the dislocation. By eliminating b from formulas (4.1) and (4.3) we obtain

$$n^2E = \frac{4.5 \cdot 10^7}{\varrho}. \tag{4.5}$$

The right side of formula (4.5) depends from ϱ — the radius of the contour dislocation. For a state nearing equilibrium, when the movement of the dislocations and their growth are stopped by the field of internal strains and, especially, by the dimensions of the structural systems characteristics for the given area, one may in rough approximation assume $\varrho = \text{const}$. From formula (4.1) results then the constancy of the product $n\,b$, and from formula (4.5) we obtain the constancy of the product n^2E. Without entering here upon a closer examination of the essential nature of the earthquake mechanism, we may assume that the number of earthquakes N within a given time is proportional to the value n. From this we obtain the constancy of the product N^2E. On the other hand, the research and observational data regarding energy E, magnitude M and earthquake frequency N show the following correlations [23], [24]:

$$\log E = a + bM \tag{4.6}$$
$$\log N = g - fM \tag{4.7}$$

The values for a and b obtained by different authors and different methods of computing M vary, b keeping within the limits 1.6 — 2.4. Value g depends on the seismic region under investigation and the depth of the observed quakes. Value f is nearly constant and lies within the range 0.8 — 1.2. Putting $\frac{b}{f} = 2$ we obtain from (4.6) and (4.7) the relation

$$\log N^2E = a + 2g \tag{4.8}$$

expressing the experimental law of the approximate constancy of product N^2E. This result is in accordance with the conclusion drawn from our preceding considerations on dislocations.

2*

We now propose to discuss shortly the mechanism and the energy of earthquakes. These questions have been studied in detail in papers [1] and [16]. The following categories of earthquakes can now be distinguished:

1. Quakes connected with violent formation or movement of dislocations; this mechanism corresponds in principle to the classic models of quakes [4], [18], [25]. In part II of the present paper we considered the question of these shocks under the aspect of the strength of the medium. In previous papers [1], [16] we have pointed out that this mechanism leads to only partial release of the internal energy, whereas its main part is being converted into energy of the dislocation formed.

2. Weak shocks accompanying the process of dislocation grouping; the adjacent elements of neighbouring dislocations undergo mutual annihilation.

3. Earthquakes connected with the approach of the dislocation to the earth's surface [1], [2], [16]. The energy of the dislocation is here converted into deformation work and wave radiation.

4. Earthquakes connected with the approach of the dislocation to the internal discontinuity surface with lower rigidity module μ [16]; a part of the dislocation energy, proportional to the jump of $\Delta\mu$, is released.

5. Quakes resulting from mutual annihilation of two dislocations with opposite sign at their junction [1].

6. Quakes forming in the cross zone, caused either by junction of two dislocations (as in 5) or by approach to one of the discontinuity surfaces (as in 4) constituting the contact of dislocation zone structure.

All of the enumerated categories of quakes can be represented by the mechanism of formation or vanishing of a contour dislocation or a pair of dislocations. This applies even to the movement of the dislocation wich can be represented as successive formation of dislocation pairs [26]. The same applies in the case of a dislocation approaching the discontinuity surface: the pair is here formed by the dislocation approaching the boundary surface and by the image dislocation [16]. The potential energy of a pair of dislocations situated at the distance L is [27], [7]

$$E=\frac{\mu b^2 l}{2\pi(1-\sigma)}\left(\ln\frac{L}{r_0}-\frac{1}{2}\right) \quad \text{(edge dislocation)} \qquad (4.8)$$

$$E=\frac{\mu b^2 l}{2\pi}\ln\frac{L}{r_0} \quad \text{(screw dislocation)} \qquad (4.9)$$

where: l — length of dislocation, r_0 — radius of dislocation line, b — value of displacement vector.

If two dislocations approach each other, then in consequence of their interaction and under the influence of the external field p, very rapid acceleration of the approach movement takes place at a certain mutual distance L and junction occurs, causing total or partial annihilation. The energy of the dislocations (4.8) and (4.9) is converted into deformation work in the medium and into kinetic energy of motion and energy of seismic waves emission. The energy (4.8) and (4.9) can be regarded as the total energy released in the quake in deformation work and radiation.

In the case of quakes of category 3 (taking $L=2H$, where H=distance of the dislocation from the earth's surface corresponding to the depth of the first impulse, and taking instead of μ the value $\frac{\mu}{2}$) we obtain the total dislocation energy release. Also in case 5 total annihilation can take place if the Burgers vectors of both dislocations are equal. In case 4 we have a partial release of the dislocation energy; we take here in the formulas (4.8) and (4.9) instead of μ, the difference $\Delta\mu$. Partial release of the energy is conditional on lower rigidity of the medium approached by the dislocation. Otherwise, the action of the surface of discontinuity will have repulsive character; an additional external energy is required for extension of the dislocation to the adjacent medium [16].

A field of screw dislocation near the boundary surface of two media, with the rigidity μ and μ' respectively, is expressed by the sum of the dislocation field and its image.

$$\text{Medium with rigidity } \mu\text{:}\quad u_x=\frac{b}{2\pi}\operatorname{arc\,tg}\frac{z-H}{y}+K_1\frac{b}{2\pi}\operatorname{arc\,tg}\frac{z+H}{y}. \tag{4.13}$$

$$\text{Medium with rigidity } \mu'\text{:}\quad u_x=K_2\frac{b}{2\pi}\operatorname{arc\,tg}\frac{z-H}{y} \tag{4.13a}$$

where: μ' is the rigidity of the adjacent medium: $K_1=\frac{\mu'-\mu}{\mu'+\mu}$, $K_2=\frac{2\mu}{\mu'+\mu}$, $1-K_1=K_2$. A field of edge dislocation (dislocation plane perpendicular to the medium's boundary) can be approximately expressed by similar formulas. On the earth's surface we obtain from (4.13) (putting $z=0$, $\mu'=0$, $K_1=-1$):

$$u_x^0=-\frac{b}{\pi}\operatorname{arc\,ctg}\frac{y}{H}. \tag{4.14}$$

We now shall pass to the examination of several questions which are of essential importance for better understanding of the dislocation processes.

The expression for the energy of a dislocation or a pair of dislocations contains the term r_0, i. e. the radius of the dislocation line. The continuous elastic medium is cylindrically hollowed along the dislocation line whereby the singularities are removed. The equilibrium radius r_0 of the cylinder can be found from the equivalence condition between the dislocation energy and the surface energy of the cylinder formed [7]. In crystals, owing to their inhomogeneous structure, we have a different situation; only in the case of high values of ther Burgers vector $b > 10^{-7}$ cm holes are formed in them. The corresponding values of the surface energy for crystals are of the order of 10^3 [erg cm^{-2}].

A. H. Cottrell gives a formula for the radius of the hole: r_0 [7]

$$r_0 = \frac{\mu b^2}{8\pi^2 \gamma}, \tag{4.15}$$

where: γ — surface energy of the hole.

In the case of a dislocation in the earth's interior, the formation of a hole (in the proper meaning of the word) is rather dubious in view of the high confining pressures. The center of the dislocation should be rather considered as a highly deformed cylindrical area; the bounding surface is presumably characterized by great values of the surface energy. The radius r_0 depends on the strength of the material through the amount of the surface energy (the latter being of another order than in crystals); the value γ should be very great, owing to the high confining pressures in the earth. For the sake of simplification let us consider a screw dislocation; its field is expressed by formula [7].

$$p = \frac{\mu b}{2\pi r}. \tag{4.16}$$

Let us assume that the distance r_0 from the center of the dislocation corresponds to the value p, equal to the shearing strength S. By eliminating from (4.15) and (4.16) the value b, and then r_0, we receive:

$$S = \sqrt{\frac{2\mu\gamma}{r_0}} = \frac{4\pi\gamma}{b}. \tag{4.17}$$

The relations (4.15) and (4.17) represent very important relations. Putting $S=10^9$ [28], $\mu=\pi\cdot 10^{11}$ we obtain from (4.16) and (4.17)

$$r_0 = 50\cdot b, \tag{4.16a}$$

$$\gamma = \frac{b}{4\pi}\cdot 10^9. \tag{4.17a}$$

Already for b of the order 1 cm we obtain high values of the surface energy $\gamma = 8\cdot 10^7$.

5. MOVEMENT OF DISLOCATIONS AND BASIC MECHANISM OF EARTHQUAKES

In our preceding survey of the categories of earthquakes we stated that the basic mechanism of earthquakes consists in mutual annihilation of a pair of dislocations or, inversely, in generation of a pair. Before entering upon a more detailed discussion of this mechanism, we shall now concern ourselves with the question of the movement of dislocations, notably with the process of the mutual approach of two dislocations.

The displacement of a dislocation is connected with the cracking of material at the dislocation front, whereupon occurs relative shifting along the surface of the crack, equal to vector $\vec{b}$ and, finally, juncture of the surface. It was here assumed by us that the material in the earth is fractured by a shearing process. A. Griffith assumes in his theory of cracks [14] [15] (which closely approaches our present considerations) that cracking of bodies is caused by exceeding of the tensile strength at the front of the crack, which thus is enlarged. This results from the characteristic field distribution of the stresses perpendicular to the crack surface. Also in the case of the edge dislocation we have at its front (i. e. just ahead of the dislocation line) a strong tensile force (fig. 8). But, in view of the great confining pressures in the earth's interior, one may rather presume that fracturing is the result of a shearing process, similarly as in Mohr's theory [30], [31]; this becomes apparent primarily from the increase of tensile strength at high confining pressures [6]. In the approach to the earth's surface the situation may, however, become reversed in favour of the tensile mechanism. In the case of a screw dislocation, the shearing character of the field is decisive for the extension of the dislocation.

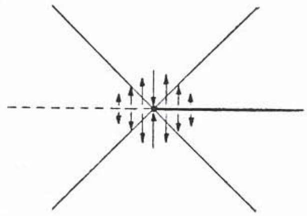

Fig. 8. Stresses normal to the plane of an edge dislocation

In the first part of this study we mentioned the equivalence of the series of negative and then the series of positive dislocations, with the crack. In considering now the movement and extension, of the deformation, we propose to make a short comparison between the dislocation theory and the crack theory. In Griffith's theory the cracks have an elliptic cross section. The equivalence demonstrated in paper [13], referred in the first place to infinitely narrow cracks (short axis of the ellipse equal to zero). This is a convenient assumption in view of the great confining pressures in the earth, but nearer the surface the situation may be somewhat different.

It is worth mentioning here that due to the medium's inner molecular structure one has to assume that the width of the crack has a lower limit. Also, the displacements along the crack do not begin from zero, but from a finite value. Hence the description of a crack by a series of dislocations.

The crack theory is especially suitable for describing the process of formation of inhomogeneities in the medium. Owing to the changes of the slip vector magnitudes, inner surfaces with surface energy are formed along the crack. A. T. Starr [32] gives the dependence of the critical field of the stresses S causing the crack on the surface energy γ and the length l_0. When the crack extends, the dislocational representation is more convenient. This is due to the fact that the middle part of the crack is characterized by a constant slip value b, and the dislocated material reaches there a state of rest. Thus, only the border part of the crack has an inner surface with the energy γ. In the dislocational description, these surfaces correspond to the joint surfaces surrounding the lines of the adjacent dislocations. The radii of those surfaces were given in the preceding paragraph. The surface of the crack edge, respectively the surface surrounding the dislocation line, contain the surface energy γ, wherefore we shall denote them in the following by the term „energetic surfaces". The edge of the crack can be described by one or by several closely adjacent dislocation lines [13]. At present, we have extended this description to the question of energetic surfaces.

The movement of the dislocation line (front) causing extension of the crack or — as assumed in the present paper — extension of the dislocation area, leads in consequence also to extension of the deformations, created by the high stresses within the energetic surface. It may be assumed that the material within these surface is being strongly deformed by extensive crushing and disintegration. The occurrence of changes in the structure of rock masses along dislocational displacements is being regularly observed. Such layers surrounding the plane of a dislocation are termed in geology mylonite or ultramylonite layers, in dependence on the degree of material disintegration. Thickness of these layers varies from a few centimeters to some meters or even more. Comparison of the latter data would however require more detailed analysis, taking into account also the possible occurrence of sets of parallel dislocational planes.

The conditions of the movement of dislocations are expressed by formula (2.5).

$$m\dot{v}+\beta v+\delta=pb. \tag{5.1}$$

The constant term $\frac{\delta}{b}$ was interpreted in the second part of this paper as the strength of the material, and $\frac{\beta}{b}$ as the coefficient related to viscosity. These values depend, of course, also on the magnitude of the confining pressures [31]. The left side of the equation as a whole represents (after dividing by b) the strength of the material, when the dislocation is moving at the velocity v. We shall define it as dynamic strength, even when we actually consider the static or quasi-static load $p > \frac{\delta}{b}$. At rapid changes of the external field, the term $\frac{m\dot{v}}{b}$ should be added to the strength. By interpreting $\frac{\beta}{b}v + \frac{\delta}{b}$ as shearing strength we are taking account of the characteristic distribution of the normal field (fig. 8), which reduces the influence of the confining pressures. This is, of course, the effect of the self-field of the dislocation; this effect manifests itself also in the proportionality of the force to the slip vector b. On the other hand, we are not yet able to define the parametric dependence of β and δ on the value of vector b. These relations will be discussed in detail at the end of this part. In estimating the influence of the factor b on the conditions of movement one should therefore not be misled by the expressions $\frac{\beta}{b}$ and $\frac{\delta}{b}$.

The strength problems which are being discussed here refer, of course, to specific processes connected with the movement of the dislocation. When speaking of the influence of the tensile stresses, it is worth mentioning that they are confirmed by observations of surface quakes. The rapid movement of the dislocation and the resulting release of dislocation energy at the earth's surface is of basically different character than the processes of dislocation movement in the interior of the earth. In the latter case, immediately after passing of the front (line), junction of the dislocated surfaces takes place under the influence of the confining pressures. With the approach of the dislocation to the earth's surface the confining pressures cease to play a major role, so that one observes a gap between the displaced parts of the crust. This pushing-apart, of the fracture sides may be ascribed to the influence of the tension forces at the front of the edge dislocation. Also the fracturing mechanism itself can here undergo a change in favour of predominance of the tensile stresses.

We shall now pass to a more detailed analysis of the basic mechanism of a quake caused by the approach and mutual annihilation of two dislocations. The generation of a pair is tantamount to the annihilation of a pair of dislocations of opposite sign, with accuracy up to the static part of the field (which does not interest us). In a given field p, the signs of the resulting displacements will in both processes be the same; in mathematical operations the change in sign must however be taken into account. The displacement field of a pair of edge or screw dislocations may be obtained by integrating the fields of contour dislocation series.

This method, given by Nabarro [26], was applied by him also to computation of the dislocation field in motion. To this end, Nabarro developed a formula for the displacement field of a contour dislocation created at the moment $t=\tau$ [26]

$$t-\tau<0: \qquad u_k=0 \tag{5.2a}$$

$$\frac{r}{a}\leqslant t-\tau\leqslant\frac{r}{c}: \quad u_k=bc^2\frac{\Delta S}{4\pi}\left\{\frac{x_k yz}{r^7}\left[\frac{3r^2}{a^2}-15(t-\tau)^2-2r^3\left(\frac{1}{a^3}\delta\left(t-\tau-\frac{r}{a}\right)-\frac{1}{c^3}\delta\left(t-\tau-\frac{r}{c}\right)\right)\right]+\frac{\partial(yz)}{r^5\partial x_k}\left[3(t-\tau)^2-\frac{r^2}{a^2}-\frac{r^3}{c^3}\delta\left(t-\tau-\frac{r}{c}\right)\right]\right\} \tag{5.2b}$$

$$\frac{r}{c}<t-\tau: \qquad u_k=bc^2\frac{\Delta S}{4\pi}\left[\frac{-3x_k yz}{r^5}\left(\frac{1}{c^2}-\frac{1}{a^2}\right)-\frac{1}{a^2r^3}\frac{\partial(yz)}{\partial x_k}\right], \tag{5.2c}$$

where: vector b is directed along axis x_3,

δ — the Dirac function,

ΔS — the dislocation area.

We shall now use the Nabarro formulas for computing the field of a pair of dislocations of the finite length l. The field of a screw dislocation pair is obtained by integrating (5.2) in respect to parameter ζ from $-\frac{l}{2}$ to $+\frac{l}{2}$ (in the formulas (5.2) we substitute $z-\zeta$ for the value $x_3=z$ and put $\Delta S=L\cdot d\zeta$). In the following it will be assumed that the length l of the dislocation is short in comparison with its distance R to field point x_k. We shall consider two cases $|z|>\frac{l}{2}$ and $|z|\leqslant\frac{l}{2}$ but in view of the postulated short length l of the dislocation we may in this case put $z=0$. With $|z|>\frac{l}{2}$, the distance ϱ of point x_k to the nearest dislocation element is $\varrho=\sqrt{x^2+y^2+\left(z-\frac{l}{2}\right)^2}$. Here as well as further on we will assume that the value $\frac{l}{2}$ changes its sign together with the coordinate of field z. The symbols are the same as in fig. 9. The integration method corresponds to that applied in paper [26]. In the interval $t-\tau<\frac{\varrho}{a}$ we

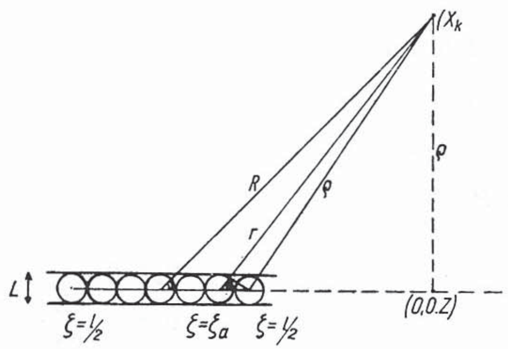

Fig. 9. Computation of the displacement field of a finite pair

have $u_k=0$ In the interval $\frac{\varrho}{a} \leqslant t-\tau < \frac{\varrho}{c}$ the displacements are given by the integral $\int\limits_{\zeta_a}^{l/2} d\zeta$ of the expression (5.2b). In the interval $\frac{\varrho}{c} \leqslant t-\tau$ the displacements are defined by the sum of the two integrals: $\int\limits_{\zeta_c}^{l/2} d\zeta$ of the expression (5.2c) and $\int\limits_{\zeta_a}^{\zeta_c} d\zeta$ of the expression (5.5b). The limits of integration ξ_a and ξ_c are defined here by the following relations

$$\varrho + \left(\frac{l}{2} - \zeta_a\right)\frac{Z}{R} = a\cdot(t-\tau), \quad \varrho + \left(\frac{l}{2} - \zeta_c\right)\frac{Z}{R} = c\cdot(t-\tau) \tag{5.3a}$$

The left side represents in approximation the distance between point x_k and point $(0,0,\zeta_a)$, $(0,0,\zeta_c)$; in view of the great (in comparison with l) distances R and ϱ, equality of the angles I and II in fig. 9 was assumed. For $|z| > \frac{l}{2}$ we obtain the following expressions for the field of screw dislocations of length l, being generated or undergoing annihilation at the moment τ (strictly speaking we are dealing here with a contour dislocation consisting of a pair of screw dislocations laterally bounded by a pair of edge dislocations of length L: we assume $L < l$):

$$\begin{array}{ll} \text{wave } P & \text{wave } S \\ u_x = -\frac{bc^2L}{2\pi a^2}\cdot\frac{xy(z-\zeta_a)}{R^3|z-\zeta_a|} & u_x = \frac{bL}{2\pi}\cdot\frac{xy(z-\zeta_c)}{R^3|z-\zeta_c|} \\ u_y = -\frac{bc^2L}{2\pi a^2}\cdot\frac{y^2(z-\zeta_a)}{R^3|z-\zeta_a|} & u_y = \frac{bL}{2\pi}\cdot\frac{(y^2-\frac{1}{2}R^2)(z-\zeta_c)}{R_3|z-\zeta_c|} \\ u_z = -\frac{bc^2L}{2\pi a^2}\cdot\frac{y(z-\zeta_a)^2}{R^3|z-\zeta_a|} & u_z = \frac{bL}{2\pi}\cdot\frac{y[(z-\zeta_c)^2-\frac{1}{2}R^2]}{R^3|z-\zeta_c|} \end{array} \tag{5.4a}$$

In view of the condition $l \ll R$, the expression ζ_a or ζ_c can, if convenient, be omitted in the numerator of these formulas.

For $z=0$ $\left(|z| \leqslant \frac{l}{2}\right)$ we obtain in an analogous way ($\varrho=R$ playing here the role of the nearest distance):

wave P wave S

$$u_k=0 \qquad \begin{aligned} u_x&=0\\ u_y&=0\\ u_z&=-\frac{bL}{2\pi}\cdot\frac{y}{R|\zeta_c|}\end{aligned} \tag{5.4b}$$

If we would (contrary to our assumption) put in formulas (5.4a) $z=0$ and would neglect the terms which are proportional to ζ_a or ζ_c, then the expressions obtained would agree with (5.4b), with an accuracy up to factor 2.

To obtain the field of the generating (disappearing) edge dislocation pair, we have to integrate the field of the contour dislocation fields, lying along the axis x_1, from $\xi=-\frac{l}{2}$ to $+\frac{l}{2}$ (in 5.2 we replace $x_1=x$ by the value $x-\xi$ and put $\Delta S=Ld\xi$). By introducing analogously to (5.3) the definitions for ξ_a and ξ_c the final result may be expressed as follows:

for $|x| \geqslant \frac{l}{2}$

wave P wave S

$$\begin{aligned} u_x&=-\frac{bc^2L}{2\pi a^2}\cdot\frac{(x-\xi_a)yz}{R^3|x-\xi_a|} & u_x&=\frac{bL}{2\pi}\cdot\frac{(x-\xi_c)yz}{R^3|x-\xi_c|}\\ u_y&=-\frac{bc^2L}{2\pi a^2}\cdot\frac{y^2z}{R^3|x-\xi_a|} & u_y&=\frac{bL}{2\pi}\cdot\frac{(y^2-\frac{1}{2}R^2)z}{R^3|x-\xi_c|}\\ u_z&=-\frac{bc^2L}{2\pi a^2}\cdot\frac{yz^2}{R^3|x-\xi_a|} & u_z&=\frac{bL}{2\pi}\cdot\frac{y(z^2-\frac{1}{2}R^2)}{R^3|x-\xi_c|}\end{aligned} \tag{5.5a}$$

and for $x=0$ $\left(|x| \leqslant \frac{l}{2}\right)$

wave P wave S

$$\begin{aligned} u_x&=0 & u_x&=0\\ u_y&=-\frac{bc^2L}{2\pi a^2}\cdot\frac{2y^2z}{R^3|\xi_a|} & u_y&=\frac{bL}{2\pi}\cdot\frac{2(y^2-\frac{1}{2}R^2)}{R^3|\xi_c|}\\ u_z&=-\frac{bc^2L}{2\pi a^2}\cdot\frac{2yz^2}{R^3|\xi_a|} & u_z&=\frac{bL}{2\pi}\cdot\frac{2y(z^2-\frac{1}{2}R^2)}{R^3|\xi_c|}\end{aligned} \tag{5.5b}$$

Also the formulas (5.5b) differ from the formulas (5.5a) at $x=0$ by the factor 2. The formulas (5.4) and (5.5) represent the fields of disappearing screw and edge dislocations (or of a generating pair with opposite sign). They represent the model of our mechanism, in which the process of approach and annihilation is reduced to an instantaneous phenomenon. The formulas obtained by us shall now be compared with the Keylis-Borok foci models [18], [19]. Nabarro [26] has demonstrated that a point model of two dipoles with moments corresponds to an infinitesimal contour dislocation. A. V. Vviedenskaja proved analogous correspondence for the finite contour dislocation [4], [5]. The Kejlis-Borok formulas for two dipoles with moments have the following form [18], [25]:

wave P / wave S

$$u_x = \frac{-\frac{\partial}{\partial t} K\left(t-\tau-\frac{R}{a}\right)\cdot l\cdot L}{4\pi\varrho a^3}\cdot\frac{xyz}{R^4} \qquad u_x = \frac{\frac{\partial}{\partial t} K\left(t-\tau-\frac{R}{c}\right)\cdot l\cdot L}{4\pi\varrho c^3}\cdot\frac{xyz}{R^4}$$

$$u_y = \frac{-\frac{\partial}{\partial t} K\left(t-\tau-\frac{R}{a}\right)\cdot l\cdot L}{4\pi\varrho a^3}\cdot\frac{y^2 z}{R^4} \qquad u_y = \frac{\frac{\partial}{\partial t} K\left(t-\tau-\frac{R}{c}\right)\cdot l\cdot L}{4\pi\varrho c^3}\cdot\frac{\left(y^2-\frac{1}{2}R^2\right)z}{R_4}$$

$$u_z = \frac{-\frac{\partial}{\partial t} K\left(t-\tau-\frac{R}{a}\right)\cdot l\cdot L}{4\pi\varrho a^3}\cdot\frac{yz^2}{R^4} \qquad u_z = \frac{\frac{\partial}{\partial t} K\left(t-\tau-\frac{R}{c}\right)\cdot l\cdot L}{4\pi\varrho c^3}\cdot\frac{y\left(z^2-\frac{1}{2}R^2\right)}{R^4} \tag{5.6}$$

where: $K(\tau)$ represents the time dependence of the forces acting in the focus.

These expressions correspond to the dipole system shown in figs. 10(a) and 11(a).

In formula (5.6) the force K is multiplied by $l \cdot L$; it becomes namely apparent that in synthesizing the dipoles along the axes z and x (similarly as was shown in regard to contour dislocations) the formulas for displacements at $l \ll R$ and $L < l$ remain unchanged; only K must be treated here as the force per unit of length l. Comparison of formulas (5.4) and (5.5) with the formula (5.6) indicates that, both in the case of screw dislocation and of edge dislocation pairs, we have a distribution of the nodal lines corresponding to that of a dipole pair with moments. Equivalent systems are represented by figs 10 and 11.

We now shall take account of the process of aproach of dislocations throughout the successive stages of their movement described by the series of generating dislocation pairs To this end, let us take a static

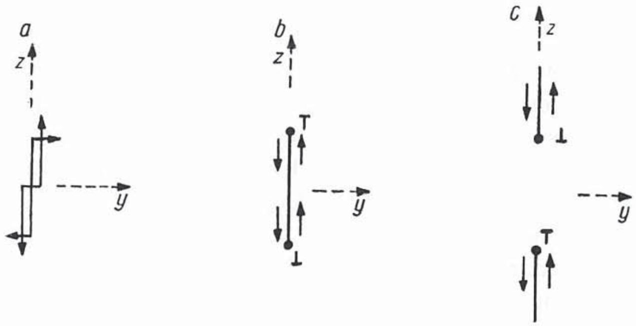

Fig. 10. Model equivalence for finite edge dislocations lying along x-axias: a) dynamic dipol pair, b) equivalent pair creation ⊤ ⊥ , c) equivalent pair annihilation ⊥ ⊤

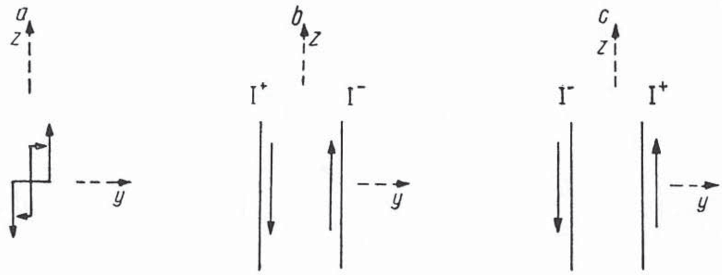

Fig. 11. Model equivalence for finite screw dislocations lying along x-axis: a) dynamic dipol pair, b) equivalent pair creation I^+ I^-, c) equivalent pair annihilation I^- I^+

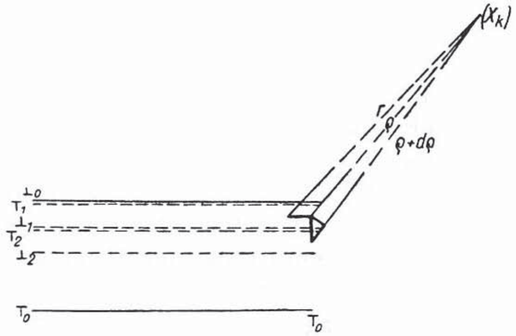

Fig. 12. Dislocation movement and pair annihilation

dislocation pair $\perp_0 \top_0$, as represented in fig. 12 by the thick lines. Let now at the moment $t=\tau$ be created a pair with the opposite signs $\top_1 \perp_1$. The outer dislocations annihilate one other, in result of which the new pair $\perp_1 \top_0$ has dislocations which are closer to each other. Then a new pair $\top_2 \perp_2$ is created at the moment $\tau+d\tau$, and thus, in further successive stages, the approach of the dislocations $\perp_i \top_0$ is being described. A similar method was used by Nabarro in computing the field of a moving dislocation. The above formulas developed for a pair of dislocations of finite length do not in principle change, provided that the values ζ_a, ζ_c, ξ_a, ξ_c appearing therein will depend on the self-time τ, and the displacement fields are integrated in respect to $d\tau$. In this way we obtain a field describing the process of approach and annihilation. Also the distance ϱ to the nearest dislocation element will be a function of τ. To substantiate this situation, let us take into consideration two pairs of screw dislocations. From fig. 12 results that the increment $d\varrho$ amounts to:

$$d\varrho = v \cdot d\tau \cdot \sqrt{1-\frac{z^2}{R^2}} \tag{5.7}$$

where: v — velocity of dislocation movement.
The function ζ_a (and the other functions analogously) is for the given time t and the formation self-time of the dislocation τ determined by the relation (5.3). Due regard has to be given to the fact that for the given time t also contributions of the field of the adjacent pair, which has formed at the moment $\tau+d\tau$, are added. For the distance of the first impulse from the adjacent pair one has to write:

$$\varrho + v \cdot d\tau \cdot \sqrt{1-\frac{z^2}{R^2}} + \left(\frac{l}{2} - \zeta_a(t-\tau-d\tau)\right)\frac{z}{R} = a \cdot (t-\tau-d\tau).$$

By subtracting (5.3) from the above relation we obtain:

$$\frac{d\zeta_a(t-\tau)}{d\tau} = \left(a + v \cdot \sqrt{1-\frac{z^2}{R^2}}\right)\frac{R}{z}$$

whence, by integrating from $\tau=0$ to τ (where $\tau=0$ denotes the time of the beginning of the quake), we obtain:

$$\zeta_a(t-\tau) = \zeta_a^0 + a\frac{R}{z}\tau + \frac{R}{z}\sqrt{1-\frac{z^2}{R^2}}\int_0^\tau v(\tau)d\tau \tag{5.8}$$

where: $\zeta_a^0 = \zeta_a(t)$.

In order to determine $v(\tau)$, we return to the equation of motion (5.1) in which we replace the field p by the field of interaction of the dislocations belonging to a pair (assuming that at the distance L of the dislocation, corresponding to the beginning of the quake, the field of mutual interaction exceeds considerably the external p):

$$m\dot{v}+\beta v+\delta=\frac{\mu b^2}{2\pi(L-\int_0^\tau v d\tau)} \tag{5.9}$$

where $\frac{\mu b^2}{2\pi(L-\int_0^\tau v d\tau)}$ is the force of interaction of two dislocations at the distance $L-\int_0^\tau v d\tau$, for edge dislocations one must multiply the denominator by the factor: $1-\sigma$.

The equation of motion takes now the form:

$$\frac{\dot{v}}{c^2}+\varphi v+\psi=\frac{1}{L-\int_0^\tau v d\tau} \tag{5.9a}$$

where: $\varphi=\frac{2\pi\beta}{\mu b^2}$; $\psi=\frac{2\pi\delta}{\mu b^2}$.

For $\tau=0$ we have $v^0=\frac{1}{\varphi L}$. Introducing v° to the integrand in the equation (5.9a), and then v^1, we successively obtain

$$v=\frac{1}{\varphi L}+\frac{\tau}{\varphi^2 L^3}+\frac{3}{2}\frac{\tau^2}{\varphi^3 L^5}+\ldots \tag{5.10}$$

We assume $v(\tau)$ in the form of a square function. From the following condition we obtain the duration time of an earthquake:

$$\int_0^{\tau^{\max}} v d\tau=L, \qquad \tau^{\max}\approx 0.65\varphi L^2 \tag{5.11}$$

Hence we have

$$v^{\max}\approx 2.30\frac{1}{\varphi L}, \qquad v^{\max}\tau^{\max}\approx 1.5L \tag{5.12}$$

Now we pass to the coordinate system related to the center between the approaching dislocations. In the former system, only the first dislocation was moving and approaching to the second dislocation of the pair. In the present coordinate system we assume that at the beginning the center is at the distance H from the dislocation $\perp, \top$. We shall replace in the formulas (5.11) and (5.12) the values τ and L by 2τ and $2H$. Hence we obtain

$$\tau^{\max}\approx 1.3\varphi H^2 \tag{5.10a}$$

$$v^{\max}\approx 1.15\frac{1}{\varphi H}, \qquad v^{\max}\tau^{\max}\approx 1.5H \tag{5.12a}$$

The last relation is very important. When a screw dislocation approaches the earth's surface, the displacement on the latter will be determined by the field of the moving dislocation. The field of moving screw dislocation is obtained from (4.13) by putting $z - v\tau$ instead of z. At the moment when a screw dislocation reaches the surface, we have from (5.12a) the following expression for the displacements:

$$u_x^0 = -\frac{b}{\pi} \operatorname{arc\,ctg} \frac{y}{1.5\,H}\,. \tag{5.13}$$

We return now to the problems of two finite dislocations, and to the former coordinate system. From (5.8) and (5.10) we obtain $\left(\text{for } v \approx \frac{1}{\varphi L}\right)$

$$z - \zeta_a = z - \zeta_a^0 - \frac{R}{z}\left(a + v\sqrt{1 - \frac{z^2}{R^2}}\right)\tau\,. \tag{5.14}$$

Similar formulas can be given for ζ_c, ξ_a ξ_c.

In order to obtain the field of displacement of approaching dislocations it is necessary to integrate the fields originating from the single dislocation pairs in respect to the changes in their mutual distances, expressed by the differential $v d\tau$. To this end we put the differential $dL = v d\tau$ in place of L. Neglecting the expressions proportional to value ζ_a^2 (and also to ζ_c^2, ξ_a^2, ξ_c^2), the calculation is reduced to computation of the integrals

$$\int_0^\tau |z - \zeta|^{-1} v d\tau\,, \qquad \int_0^\tau |z - \zeta|\, v d\tau\,, \qquad \int_0^\tau v d\tau\,.$$

From (5.14) we can obtain the approximate values of these integrals. We neglect here the ratio $\frac{v}{a}$, i. e. the ratio of the dislocation velocity to the P — wave velocity.

$$\int_0^\tau \frac{v d\tau}{|z - \xi_a|} \approx \frac{v\tau}{|z - \zeta_a^0|}\,, \qquad \int_0^\tau |z - \zeta_a|\, v d\tau \approx |z - \zeta_a^0|\, v\tau\,, \qquad \int_0^\tau v d\tau \approx v\tau \tag{5.15}$$

Similarly, for ζ_c, ξ_a, ξ_c.

It appears from these formulas that taking the process of dislocation approach into account does not basically change the formulas for field displacement (5.4) and (5.5), if instead of the expression $|z - \zeta|^{-1}$, $|z - \zeta|$ we insert the first two expressions (5.15) and, in other cases, put the third expression (5.15).

We now propose to return to the question of the equation of motion and that of strength. We shall determine the dependence of the parameters β and δ on the displacement b. As regards determination of the dependence $\delta(b)$, we have to remember that the order of static strength is similar in micro- and in macroscopic phenomena and therefore — putting in the equation of motion (5.1) $v=0$, and $p=S$ (S — strength of material) — have to assume $\delta=S\cdot b$. In this way the equation of motion takes the form (on the assumption that the mass of the dislocation per length unit is approximately equal to $\frac{\mu b^2}{2\pi c^2}\Big)$:

$$\frac{\mu b^2}{2\pi c^2}\,\dot{v}+\beta v+Sb=pb\,. \tag{5.16}$$

The right side of (5.16) is a force acting on the unit length of the dislocation line. We shall now pass to the stresses acting along the dislocation plane and to the real velocity of mass displacement caused by the dislocation movement. Let us take the length unit $\lambda_0=1$ in the direction of dislocation movement (i. e. in the direction perpendicular to the dislocation line). Then the stress acting on the dislocation plane just near its front would equal $\frac{pb}{\lambda_0}$. In order to determine volecity of a mass movement one must take into account that the dislocation movement is accompanied by the shift of the material $\vec{b}$ at its front. Hence, when a dislocation moves with velocity v, the corresponding displacement velocity equals $\frac{bv}{\lambda_0}$ (the quantity bv should have a dimension of velocity, therefore we write $\frac{bv}{\lambda_0}$ instead of bv). From the above consideration we obtain through division of (5.16) by λ_0:

$$\frac{\mu b\lambda_0}{2\pi c^2}\cdot\frac{b\dot{v}}{\lambda_0^2}+\frac{\beta\lambda_0}{b}\cdot\frac{bv}{\lambda_0^2}+S\,\frac{b}{\lambda_0}=\frac{pb}{\lambda_0}\,.$$

We define $\frac{b}{\lambda_0}=\varepsilon$ as a strain value; similarly we define $\frac{b\dot{v}}{\lambda_0^2}=\dot{\varepsilon}$, and $p_0=\frac{pb}{\lambda_0}$ as a value of shearing stress.

$$\frac{\mu b\lambda_0}{2\pi c^2}\,\ddot{\varepsilon}+\frac{\beta\lambda_0}{b}\,\dot{\varepsilon}+S\varepsilon=p_0 \tag{5.17}$$

By comparing of (5.17) (with small $\ddot{\varepsilon}$) with the strain — stress relation for viscous media we can interpret the coefficient at $\dot{\varepsilon}$ as the viscosity coefficient ν. In this manner we finally obtain the equation of motion

$$\frac{\mu b}{2\pi c^2}\cdot\dot{v}+\nu\cdot v+S=p \qquad \lambda_0=1 \tag{5.18}$$

and for small $\dot{v}$

$$\nu \cdot \dot{v} + S = p. \tag{5.18a}$$

In conclusion of this part of the paper we propose to return to some questions of energetics.

The total energy of a quake has been defined as the sum of the radiated energy (seismic energy) and the deformation energy of the medium (work done by the quake). It is given by the formulas (4.8) (4.9) of the dislocation theory of quakes. Byerly and DeNoyer have [10] presented a formula for the deformation work during an earthquake:

$$E_d = \frac{\mu H l b^2 a}{4\pi} \tag{5.19}$$

where in the present paper we write H, l, b instead of D, $2L$, $2M$ [10].

Byerly and DeNoyer's formula is based on the principles of the elastic rebound theory [11] which are generally accepted for dynamic processes in the earth. They are:

1. A fracture occurs in result of the elastic strain exceeding the strength of the material, whereby mutual displacement of the surrounding masses takes place.
2. Displacements do not originate suddenly and their velocity reaches a maximum in time.
3. Only the sudden elastic rebounds of the sides of the fracture towards the position of no elastic strain are the only movements of masses.
4. The dynamic processes start on a small area, which subsequently are being rapidly enlarged. Radiation of seismic energy occurs from the surface of the fracture.
5. The source of the released energy is the elastic strain energy of the rocks.

We return for a moment to the interpretation of the equation [5.17]. As the dislocation theory is a linear theory of elasticity, it follows from (5.17) that shearing strength S may be interpreted as rigidity module μ along the dislocation plane. We come back here to the well-known difference between the numerical values S and μ, beeause of the following conclusion in Byerly and DeNoyer's paper.

In order to satisfy the postulates of the rebound theory, Byerly and DeNoyer had to assume in their calculations of the deformation work that the rigidity module μ has a lower value in the quake area than in its farther environs. This means introducing a *sui generis* inhomogeneities field, equivalent to some extent to the role of the inhomogeneities in the dislocation theory of earthquakes.

3*

Formula (5.19) contains the value a, which is the parameter in the $u = -\frac{b}{\pi}$ arc ctg (ya) function, chosen empirically to the geodetically measured horizontal displacements in the function of their distance from the fracture plane. Now it is just this empirically selected arcctg function which corresponds exactly to the field of the displacement of a screw dislocation reaching earth's surface (5.13). This is a very significant confirmation of the dislocation theory of earthquakes [17]. One has to take here into account that the field of displacement of a screw dislocation near the earth's surface is given by the sum of the dislocation field and its image.

Comparison of Byerly and DeNoyer's empiric formulas with the displacement field of a pair of screw dislocations, corresponding to the depth of the first impulse H, leads to the equality $a = \frac{1}{1.5H}$. Whence a direct method of computing the depth of quakes from the geodetic data. The values thus obtained for H are slightly lower than the depths estimated by Byerly and DeNoyer. Byerly and De Noyer's formula for deformation work is now simplified to the expression:

$$E_d = \frac{\mu b^2 l}{6\pi} \tag{5.20}$$

We shall now examine the problem of radiation energy.

S. Droste computed the energy flow in a time unit through a spheric surface from a source defined by the formulas (5.4) and (5.5). By subsequent integration in respect to selftime τ from 0, i. e. from the beginning of the violent dislocation movement to the moment of junction, the total amount of radiated energy was obtained [17].

We can, however, segregate approximately the part representing work from that representing radiation in the formulas for total energy of an earthquake (4.8) and (4.9). Let us imagine that a violent movement of the dislocations $\perp$ and $\top$ begins at the distance L. The main part of their mutual energy goes at the beginning into deformation work, but with rising velocity of the movement the radiation losses increase. Now, by neglecting the radiation generated by the movement of the dislocation, we can make the following estimation. In view of the presence of energetic surfaces around the dislocation lines $\perp$ and $\top$, contact between the dislocations will not occur at a distance equal to zero, but at $2r_0$. The values of the mutual energy at a distance of $2r_0$ can, as a first approximation, be considered as the main part of the radiation energy, as this part is emitted in the annihilation process. The remaining part of the energy has been transformed into deformation work on the way from distance L to $2r_0$. The radiation losses during the movement are here neglected, as was mentioned above.

Using the formulas (4.8) and (4.9) we obtain expressions for the radiation energy: $E_s = \frac{\mu b^2 l}{2\pi(1-\sigma)}\left(\ln 2 - \frac{1}{2}\right)$ (edge dislocation) (5.24)

$$E_s = \frac{\mu b^2 l}{2\pi} \ln 2 \quad \text{(scerw dislocation)} \qquad (5.25)$$

and also formulas the deformation work: $E_d = E - E_s$:

$$E_d = \frac{\mu b^2 l}{2\pi(1-\sigma)}\left(\ln \frac{L}{r_0} - \ln 2\right) \quad \text{(edge dislocation)} \qquad (5.26)$$

$$E_d = \frac{\mu b_2 l}{2\pi(1-\sigma)}\left(\ln \frac{L}{r_0} - \ln 2\right) \quad \text{(screw dislocation)} \qquad (5.27)$$

The values in the formulas (5.24) — (5.27) are of approximately similar order and also similar in regard to the energy values (5.20) and (4.8), (4.9). Consequently, comparisons with the observational data [1], [2] may be considered as fully satisfactory also for this situation. In the case of screw dislocations, the above formulas can be compared with the previously mentioned formulas of Byerly and DeNoyer and S. Droste. In particular, comparison of (5.27) and (5.20) leads to very close correspondence (in the formula (5.27) we put $\frac{\mu}{2}$ and 2H instead of μ and L, as we are dealing here with a surface earthquake).

6. THE ELEMENTARY REPLICA THEORY

In the second part of the present paper it was mentioned that for areas with high shearing stress values (seismically active areas) it is necessary to assume the existence of an internal strain field, created by the interaction of a number of dislocations. Shift of one dislocation of the system changes the state of equilibrium and thus causes also changes in the position of the other dislocations. This question is a rather complicated one, for which reason we shall restrict our discussion to the consideration of a system of dislocations lying in a common plane. This restriction could, of course, be partly evaded by introducing such substitutive distances and values b for the displacements by which the interaction field with the nearest dislocations does not undergo a change. In the case of an edge type dislocation this method would be restricted to dislocations lying in a time or space system. By "time system" we understand here a system of dislocations lying within a cone inclined under an angle of $\frac{\pi}{4}$ in respect to the dislocation plane.

The problem of a system of n linear dislocations lying in a common plane was solved by I. D. Eshelby, E. C. Frank and F. R. N. Nabarro [13] for the following special conditions: the dislocation lines are parallel to each other, the dislocations have the same vector b values and are in equilibrium. The equilibrium state in a constant stress field is possible only then when at least one of the external dislocations of the system has a locked position, checking the movement of other dislocations which are under the influence of the external field and the field of interactions. This is called a locked dislocation. This case represents a static approximation to the problem under discussion, i. e. the problem of interaction of dislocations, provided their b- vectors are equal. Prior to further discussion of the more general case, we propose to utilize some results from paper [13], by adapting them to the needs of the present study and of further analysis. Let us take the series ($n \geqslant 2$) of the dislocation $\perp_1, \perp_2, \ldots \perp_n$ in the case of screw dislocations the series $|_1, |_2, \ldots |_n$ respectively). For convenience, the same symbol $\perp_i$ will be used for both kinds of linear dislocations; the coordinates of the dislocation lines in the plane perpendicular to the dislocation surface, will correspondingly be indicated by $z_1, z_2, \ldots z_n$. We shall consider the case of dislocations with equal sign, whose interaction has repulsive character. The constant external field pushes the dislocations in the direction of the locked dislocations, in consequence of which a certain state of equilibrium in the system of interior stresses is formed. In result, a very strong internal field acts on the locked dislocation. The equilibrium conditions for the dislocation are as follows:

$$\sum_{i=1}^{n} \frac{A_i^{(s)}}{z_s - z_i} - p = 0\,, \tag{6.1}$$

where: $A_i^{(s)} = A_i$ for $i \neq s$ and $A_s^{(s)} = 0$; $A_i = \frac{\mu b i}{2\pi}$ for a screw type dislocation; $A_i = \frac{\mu b i}{2\pi(1-\sigma)}$ for an edge type dislocation; $b_s \frac{A_i^{(s)}}{z_s - z_i}$ is the interaction force of dislocation $\perp_s$ and $\perp_i$; $b_s p$ is the force exercised by the field p on $\perp_s$; in the case discussed here $b_i = b$ and $A_i = A$. The approximate positions for great n, corresponding to equilibrium conditions, are expressed by relation [13]

$$z_i = \frac{j_i^2 \cdot A}{8\pi n p} \tag{6.2}$$

at the position of the locked dislocation $\perp_1 : z_1=0$, j_i signifies here the i-th root of the Bessel function J_1.

Also for great n, the following relations were obtained in paper [13]

$$L=2n\frac{A}{p}, \quad n_z=\frac{2}{\pi}\sqrt{\frac{2npz}{A}}, \quad d=1.84\frac{A}{np} \tag{6.3}$$

where: L — length of area occupied by the dislocations; n — number of dislocations in interval $(0, z)$; $d=z_2-z_1$ distance between dislocations $\perp_2$ and $\perp_1$. On the locked dislocation acts the multiplied field amounting to np. Cottrell obtained the same result, using the virtual work arguments [7].

From (6.3) the dislocation density can be computed:

$$\varrho(z)=\frac{dn_z}{dz}=\frac{1}{\pi}\left(\frac{2np}{zA}\right)^{1/2}$$

This is obviously a smoothed curve. Similarly, one may compute the discontinuity curve, expressing the relative displacements along the dislocation surface. Instead of a stepped curve, the following smoothed curve was obtained [13]:

$$\Delta(z)=\frac{2bp}{\pi A}\sqrt{Lz}+b$$

Dislocation systems of this type, bounded by a locked dislocation, were used in paper [13] for description of the crack edge. In the present considerations we shall, however, treat the single dislocations as separate dynamic units. The relations given above under [13] can be easily generalized for the case that the first locked dislocation has a Burgers vector $b_1=kb$. To this end it suffices to substitute in the formulas the value KA for value A, and in the free term of the last formula to replace b by Kb.

Let us now consider the example of the system of ten dislocations-one locked and nine free dislocations — having the values A equal to $\pi\cdot 10^{11}$ ($b=2\pi$ at $\mu=\pi\cdot 10^{11}$ for screw and $b=2\pi(1-\sigma)$ for edge dislocations). We will assume for the external field a value $p=10^9$. From formula (6.2) we obtain the equilibrium states defined by the relation $z=1.25\,j_i^2$. Fig. 13 shows the distribution of the first 6 dislocations of these series, illustrating the action of field p, which pushes the dislocations in the direction of the locked dislocation $\perp_1$. The length of the whole system is according to (6.3) 20 m. As was previously mentioned, the results of paper [13] can be generalized by putting for the first dislocation the displacement $b_1=Kb$, and for the value A_1 the value kA. In this case, the coordinates of the dislocation positions in fig. 13 must be multiplied by the factor K. The distance between the first and the second dislocation is in this more general case $d = 1.84 \frac{KA}{np}$. This distance depends on the number n of dislocations of the series, and on the parameter K,

Fig. 13. First six dislocations in the array of the ten dislocations

characterizing the first dislocation. The distance d, in dependence on n — number of dislocations, has been plotted in fig. 14 for the parameter values k=0.025, 0.063, 0.16, 0.4, 1, 2.5, 6.3, 16, 40. The approximation formula

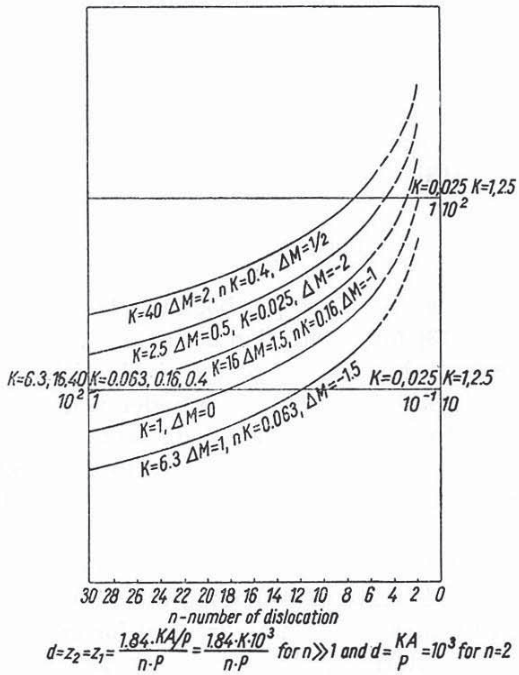

Fig. 14. $d = z_2 - z_1$, a function of the dislocation number in array

can not be used for small n. In the extreme case $n = 2$, the equilibrium states can be easily calculated from (6.1) $d = \frac{KA}{p}$; this was taken into account in plotting the curves in fig. 14.

We now pass to formulation of the elementary theory of quake replicas. We shall assume for this purpose that the locked dislocation lies near the discontinuity surface of the medium, e. g. near the earth's surface. A very strong field *np*, acting on this dislocation, may cause its shift in the direction of the surface and, in consequence, discharge of its energy at the boundary surface. The magnitude of the respective energy is given

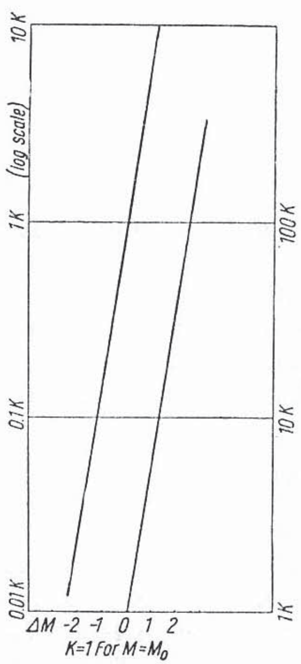

Fig. 15. K as a function of $\Delta M = M - M_0$

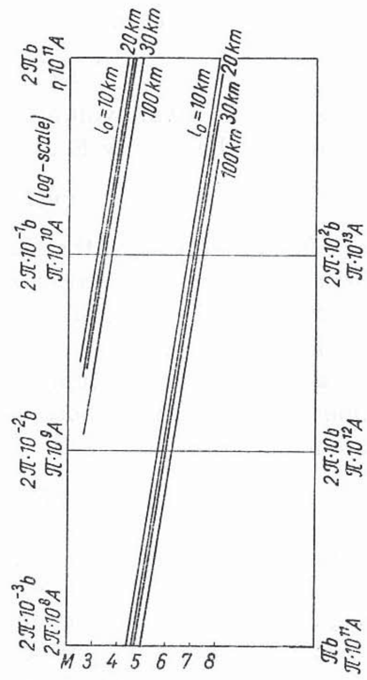

Fig. 16. Functions $A(M)$ and $b(M)$ for $l = 10, 20, 30, 100$ km

by formulas (4.8) and (4.9) respectively, in which we put $L = 2H$ and, instead of the value μ, the value $\frac{\mu}{2}$ or $\Delta\mu$, in dependence on whether we are dealing with the surface of the earth or with an interior discontinuity surface with the jump $\Delta\mu$. Taking approximately $ln\frac{2H}{r_0} = 10$, we will assume the value of the energy released at the earth's surface to be equal for edge and for screw dislocations, and to amount to

$$E = 10 A^2 l \frac{\pi}{\mu}. \tag{6.4}$$

The differences between the case of the edge and that of the screw dislocation can be neglected (if for no other reason) with regard to the approximate estimate $\ln \frac{2H}{r_0}$. We shall now introduce the standard value of the ratio $\frac{A}{p} : \frac{A_0}{p} = \pi \cdot 10^2$ (at a field value of 10^9, which corresponds to the standard value $A_0 = \pi \cdot 10^{11}$). For correlation of the value A with the computed magnitude values we shall use the formula [23]

$$\log E = 11 + 1.6M \tag{6.5}$$

For quakes of a given value $A = kA_0$ we obtain by utilizing the proportionality of the energy E to the square A

$$\log K = 0.8 \Delta M \tag{6.6}$$

where: $\Delta M = M - M_0$; M_0 — the standard value of the magnitude. The relation (6.6), allowing computation of the factor k for a quake of the given magnitude M, is shown in fig. 15. By eliminating from the formulas (6.4) and (6.5) the energy E, we obtain the relation between value A and magnitude M for various lengths of the dislocation l. Putting $\mu = \pi \cdot 10^{11}$ (a value approximating those occurring near the earth's surface), we obtain the relation

$$\log A = 10.5 - 0.5 \log l + 0.8M \tag{6.7}$$

which in fig. 16 is presented graphically for $l = 10$ km, 20 km, 30 km and 100 km. This allows computation of the value A from the given value of the magnitude M. Taking the standard value $A_0 = \pi \cdot 10^{11}$, we shall obtain the standard value of magnitude $M_0 = 5$ for the length $l = 10^6$ (10 km). The corresponding energy of the quake is according to (6.4) approximately 10^{19} erg. It is worth noting that the values of the parameters in fig. 14 correspond to the magnitude values 3, 3.5, 4, 4.5, 5, 5.5, 6, 6.5, 7.

As was previously mentioned, the multiplied field acting on $\perp_1$ can cause a movement of this dislocation, and subsequently the release of its energy at the earth's surface. In this case, the role of leading dislocation is taken by the dislocation $\perp_2$, whose movement will be determined by the new distribution of the stress field. This field can, by shifting the dislocation $\perp_2$ to the boundary surface, cause the release of its energy. In this way occurs the secondary quake, called replica. Subsequently, a similar process may cause a quake due to the $\perp_3$ dislocation reaching the surface.

Let the investigated series $\perp_i$ have the values $A_i = K_i A$, where A refers to the standard value. The position of the dislocation will be marked by z_i, the corresponding nondimensional values defined by $x_i = \frac{p}{A} z_i$. To the values A_i are assigned the displacement vectors $b_i = K_i A$. Let us first calculate the field acting on the locked dislocation $\perp_1$. To this end we shall use the virtual work arguments, similarly as in Cottrell's [7] computations at b=const. Let us consider the virtual work, taking a displacement δz of the dislocation $\perp_1$ in a total stress field S_1. The displacement of the dislocation causes equal displacements of the entire dislocation system, the whole system remaining thus in a state of equilibrium. The displacement work will be equal to the work of displacement of the leading dislocation $\perp_1$ in field S_1 on one side, and the work of displacement of the dislocations $\perp_1, \perp_2, \ldots \perp_n$ in the external field p (respectively the work done by this field) on the other side

$$\delta z S_1 b_1 = \delta z p \sum_{i=1}^{n} b_i ,$$

hence

$$S_1 = p\sigma_1 , \qquad \sigma_1 = \frac{1}{b_1} \sum_{i=1}^{n} b_i = \frac{1}{K_1} \sum_{i=1}^{n} K_i \tag{6.8}$$

With $b_i = \text{const.}$, i.e. $k_i = 1$, we obtain $S_1 = np$, which result has been cited before [7], [13].

The dislocation $\perp_2$ is in a state of equilibrium; on one side acts here the repulsive field of $\perp_1$, on the other side the field S_2^0, equal to the field of dislocations $\perp_3, \perp_4, \ldots \perp_n$ and the field p. To compute field S_2^0, we effect a virtual displacement δz_2 of the dislocation $\perp_2$. At locked position of $\perp_1$, this displacement will cause certain displacements δz of the dislocations $\perp_3, \perp_4, \ldots \perp_n$; the value of these displacements should be here of such an order that in the new system the resultant force acting on $\perp_3, \perp_4, \ldots \perp_n$ of the dislocations $\perp_2$ and $\perp_1$ does not undergo a change: $|\delta F_{1i}| \approx |\delta F_{2i}|$:

$$\frac{K_1 \delta z}{(r+d)^2} \approx \frac{K_2(\delta z_2 - \delta z)}{r^2} ,$$

where: δz — displacement of the dislocation $\perp_i$ $(i \geqslant 3)$;
d — distance between $\perp_1$ and $\perp_2$;
r — distance between $\perp_2$ and $\perp_i$.

Assuming $d < r$ (comp. fig. 13) we cen write in approximation

$$\delta z \approx \delta z_2 \frac{K_2}{K_1 + K_2} \tag{6.9}$$

The virtual work of the displacement of $\perp_2$ will be equal to the work of the field S_2^0 done against the repulsing field of the dislocation $\perp_1$

$$\delta z_2 S_2^0 K_2 b = \delta z_2 \frac{K_1 A}{d} \cdot K_2 b . \tag{6.10}$$

The virtual work of displacement of dislocation $\perp_2$ by δz_2 and $\perp_i (i \geqslant 3)$ by δz is, on the other hand, equal to the work field p (assuming here that they all are near equilibrium position, which is partly secured by relation (6.9))

$$\delta z_2 S_2^0 K_2 b = \delta z_2 p K_2 b + \delta z p \sum_{i=3}^{n} K_i b \tag{6.11}$$

whence follows from (6.9)

$$S_2^0 = p\sigma_2^0; \quad \sigma_2^0 = \frac{1}{K_1+K_2} \sum_{i=1}^{n} K_i . \tag{6.12}$$

By comparing (6.10) with (6.12) we can calculate the distance $d = z_2 - z_1$ in an arbitrary dislocation system $\perp_i$.

Putting $z_1 = o$ we obtain

$$z_2 = \frac{A}{p} x_2; \quad x_2 = \frac{K_1(K_1+K_2)}{\sum\limits_{i=1}^{n} K_i} = \frac{K_1}{\sigma_2^0} \tag{6.13}$$

Taking $K_1 = 1$ we obtain the approximate value $d = \frac{2A}{np}$, which at $n = 2$ is equal to the real value d, and at great n forms a good approximation of formula (6.3).

A strong field acting on $\perp_1$ can, if it is situated in the vicinity of the discontinuity surface, cause a rapid movement of the dislocation toward the surface, where its discharge occurs. The position of the dislocation $\perp_1$ at the moment of the beginning of its accelerated movement towards the surface is defined in our system by $z_1 = 0$. This depth corresponds to the depth H of the first impulse of the seismic shock. In this system the earth's surface is therefore given by $z = -H$. After discharge of the energy of dislocation $\perp_1$ there remains the series of dislocations $\perp_2, \perp_3, \ldots \perp_n$. The dislocations in these series are now obviously not in a state of equilibrium. Under the influence of field p and also of the dislocation field, there occurs a slow movement of the dislocation $\perp_2$ approaching the position $z = 0$. In the proximity of this position a new shock will take its beginning. Simultaneously with the movement $\perp_2$ there occur displacements of the remaining dislocations. In this way, the dislocations could occupy in regard to one other positions corresponding to mutual equilibrium. We shall assume that these two processes occur simultaneously and hat both, the arrival of the dislocation $\perp_2$ at point $z = 0$ and the realization of mutual equilibrium positions, happen at approximately the same time. In the final stage, analogously to (6.8), on the dislocation $\perp_2$ will act the field:

$$S_2 = p\sigma_2, \qquad \sigma_2 = \frac{1}{K_2} \sum_{i=2}^{n} K_i. \tag{6.14}$$

In accordance with the above we shall assume that during the time, when the dislocation moves from $x = x_2$ to $x = 0$, the field undergoes linear change from value $p\sigma_2^0$ to value $p\sigma_2$

$$\sigma_2^0 < \sigma_2; \qquad \bar{\sigma}_2 = \sigma_2 + \frac{x}{x_2}(\sigma_2^0 - \sigma_2) \tag{6.15}$$

where: $z_2 = \frac{A}{p} x_2$ is the coordinate defining its position. In the position $x = 0$ of the dislocation $\perp_2$ can now arise conditions similar to those which were created by the violent displacement and the subsequent energy discharge of dislocation $\perp_1$. Now, there remains the dislocation series, and this process continues in a similar way. For the r-th shock (i.e. the $(r—1)$—th replica) we will have the following generalized relations:

$$\sigma_r^0 = \frac{1}{K_{r-1} + K_r} \sum_{i=r-1}^{n} K_i; \qquad \sigma_r = \frac{1}{K_r} \sum_{i=r}^{n} K_i; \qquad \bar{\sigma}_r = \sigma_r + \frac{x}{x_r}(\sigma_r^0 - \sigma_r), \tag{6.16}$$

where: x_r denotes the position of the $\perp_r$ when it is an a state of equilibrium in the dislocation series $\perp_{r-1}, \perp_r, \perp_{r+1}, \ldots \perp_n$. Analogously to formula (6.13) we get for x_r:

$$x_r = \frac{K_{r-1}(K_{r-1} + K_r)}{\sum\limits_{i=r-1}^{n} K_i} = \frac{K_{r-1}}{\sigma_r^0}. \tag{6.17}$$

We shall now go over to determination of the time required for the passing of the dislocation from the position $x = x_r$ to the point $x = 0$. This time is equal to the difference between the moments of the r—th and $(r—1)$ th shock.

To this end we return to the equation of motion of the dislocation (5.17), substituting for p the value of the field amplified by the dislocation system: $\bar{\sigma}_r p$

$$\frac{\nu}{p} \cdot \frac{A}{p} \cdot \frac{dx_r}{dt} + \frac{S}{p} = \bar{\sigma}_r \tag{6.18}$$

whence:

$$T_r = \frac{\nu}{p} \frac{A}{p} \frac{x_r}{(\sigma_r - \sigma_r^0)} \int_{x_r}^{0} \frac{dx}{x - \dfrac{x_r}{\sigma_r^0 - \sigma_r}(\sigma_r - \gamma)}.$$

Finally, with regard to (6.17), we have:

$$T_r = a \frac{k_{r-1}}{\sigma_r^0(\sigma_r - \sigma_r^0)} \ln \frac{\sigma_r - \gamma}{\sigma_r^0 - \gamma} \tag{6.19}$$

where: $\gamma = \frac{S}{p}$ is the ratio of static shearing strength to the value of the field of shearing stresses (the movement is conditional on $\gamma < \sigma_r^0$);

$$a = \frac{\nu}{p} \cdot \frac{A}{p}.$$

The relation (6.19). has two coefficients a, γ, which have to be determined from the observational data. The experimental verifications of the relations obtained consists thus on the one hand in determining the values γ and a, lying within the permissible limits, and on the other hand (with a greater number of replica observations) in the conformity of the general form of the relation (6.19) with the curve (T_r, K_r) for the given series of replicas. Practically, however, the situation looks different. The fargoing simplification of the theory, together with the complexity of the problem, cause wide scattering of the observational values and, in consequence, difficulties in determining accurately the values a and γ. For these reasons we will assume in this analysis $\gamma=1$ ($p=S$). A further difficulty in computation is caused by the fact that we do not know the full dislocation series but only those dislocations which have become apparent in the earthquake. We shall assume, as before, the standard value $A_0=\pi \cdot 10^{11}$, which does not affect the general character of our considerations. The standard value of the magnitude will be $M_0=5$ at $l_0=10$ km. For μ we will take, as previously, $\pi \cdot 10^{11}$. The other values, including that of field p, will not yet be determined at this moment. Before discussing numerical examples, we shall determine from equation (6.18) the initial v_r^0 and the final v_r value of the dislocation's velocity in the interval (z_r, 0):

$$v_r^0 = \frac{P}{\gamma}(\sigma_r^0 - \gamma), \qquad v_r = \frac{P}{\gamma}(\sigma_r - \gamma), \qquad v_r - v_r^0 = \frac{P}{\gamma}(\sigma_r - \sigma_r^0). \tag{6.20}$$

In the analysis of numerical examples we shall again return to these values, since in the equation of motion the accelarations were neglected on the assumption of only small changes in velocity. The formulas (6.20) define the velocities prior to the onset of the violent movement accompanying a quake (5.10). The numerical examples will be based on data from series of replicas with defined magnitude values. As replicas shall be regarded shocks with the closest possible coordinates.

The numerical analysis can be performed most conveniently by certain transformations of formula (6.19).

Utilizing formula (6.16) we receive:

$$T_r = aK_r \frac{(K_{r-1}+K_r)^2}{\sum\limits_{i=r-1}^{n} K_i \sum\limits_{i=r+1}^{n} K_i} \ln \frac{K_{r-1} \sum\limits_{i=r}^{n} K_i + K_r \left[\sum\limits_{i=r}^{n} K_i - (K_r + K_{r-1})\gamma \right]}{K_{r-1} K_r + K_r \left[\sum\limits_{i=r}^{n} K_i - (K_r - K_{r-1})\gamma \right]}. \tag{6.21}$$

Introducing now the definition $\varkappa_{\alpha,\beta} = \frac{K_\alpha}{K_\beta}$ $(\varkappa_{\alpha,\beta} = \varkappa_{\alpha,\beta}^{-1})$ we obtain

$$T_r = aK_r \frac{(1+\varkappa_{r,r-1})^2}{\left[\sum\limits_{i=r+1}^{n} \varkappa_{i,r-1} - (1+\varkappa_{r,r-1}) \sum\limits_{i=r+1}^{n} \varkappa_{i,r-1} \right]} \cdot$$
$$\ln \frac{(1+\varkappa_{r,r-1}) \sum\limits_{i=r+1}^{n} \varkappa_{i,r-1} + \varkappa_{r,r-1}(1+\varkappa_{r,r-1})(1-\gamma)}{\varkappa_{r,r-1} \sum\limits_{i=r+1}^{n} \varkappa_{i,r-1} + \varkappa_{r,r-1}(1+\varkappa_{r,r-1})(1-\gamma)}. \tag{6.22}$$

This formula is convenient in application; regarding the value T_{r+1} (difference between the $(r+1)$–th and r–th shock) one has to substitute $\sum\limits_{i=r+2}^{n} \varkappa_{i,r}$ for $\sum\limits_{i=r+1}^{n} \varkappa_{i,r-1}$ and $\varkappa_{r+1,r}$ for $\varkappa_{r,r-1}$. . To this end we utilize the obvious relation

$$\sum_{i=r+2}^{n} \varkappa_{i,r} = \varkappa_{r-1,r} \sum_{i=r+1}^{n} \varkappa_{i,r-1} - \varkappa_{r+1,r}. \tag{6.23}$$

Introducing the expression $p_r = \sum\limits_{i=r+1}^{n} \varkappa_{i,\varkappa-1}$ and $q_r = \varkappa_{r,r-1}$ we obtain the simple formulas:

$$\sigma_r^0 = \frac{1+q_r+p_r}{1+q_r}, \quad \sigma_r = \frac{q_r+p_r}{q_r}, \quad \sigma_r - \sigma_r^0 = \frac{p_r}{q_r(1+q_r)} \tag{6.16a}$$

$$\frac{1}{aK_r} T_r = \frac{(1+q_r)^2}{p_r(1+q_r+p_r)} \ln \frac{(1+q_r)p_r + q_r(1+q_r)(1-\gamma)}{q_r p_r + q_r(1+q_r)(1-\gamma)}. \tag{6.22a}$$

$$p_{r+1} = p_r q_r^{-1} - q_{r+1} \tag{6.23a}$$

The graphic representation of this relation for $\gamma = 1$ is shown in fig. 17. The values p_r are treated as parameters and the value q_r appears as a variable.

Corresponding diagrams for the values $\gamma = 0.1$, 0.5, 0.9 are given in fig. 18, 19, 20. The enclosed tables contain the initial values for the series of investigated replicas, and also the values of the parametres K_r, q_r, p_r and the values σ_r^0 and σ_r, required for analysis of a series of shocks.

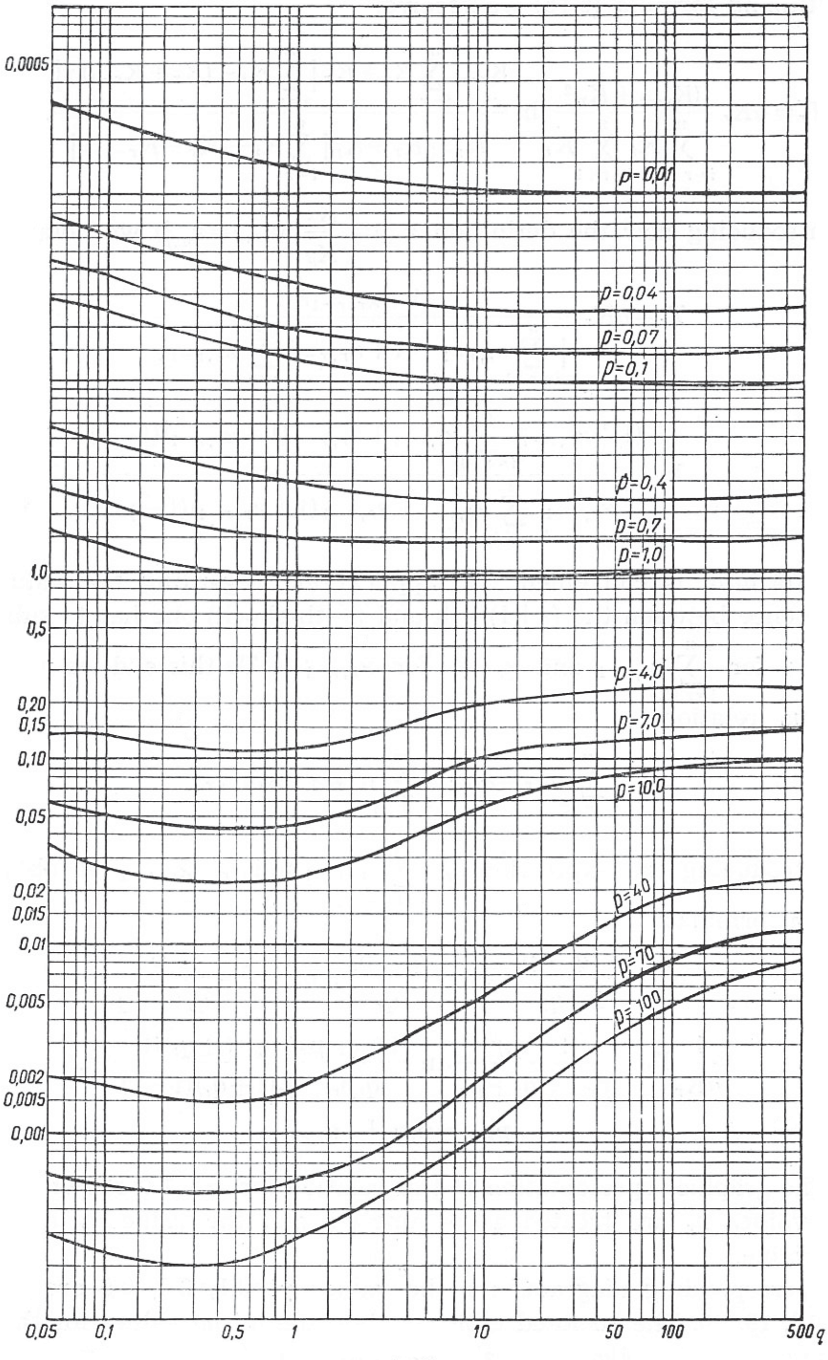

Fig. 17. Relations $\frac{1}{a} \cdot \frac{T_r}{K_r} = f(q, p)$, for $\gamma = 1$

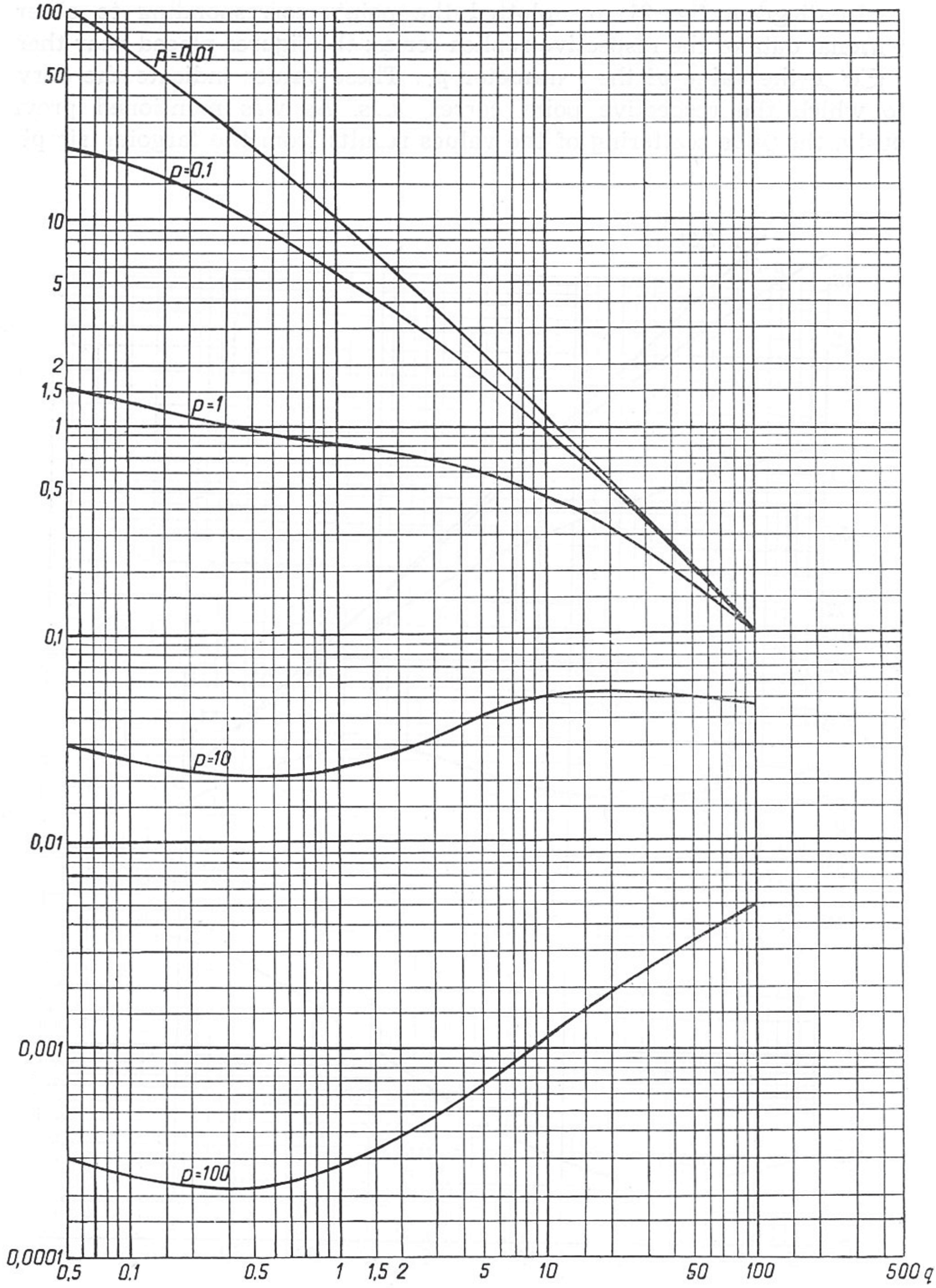

Fig. 18. Relations $\frac{1}{a} \cdot \frac{T_r}{K_r} = f(q, p)$, for $\gamma = 0,9$

In diagram fig. 21 are plotted the points corresponding to observational data of the respective replica series; the figures placed near them indicate the value of the parameter p_r. These values indicate the curve to which the respective point corresponds. As was mentioned previously, the wide scattering of the values results from the fargoing simpli-

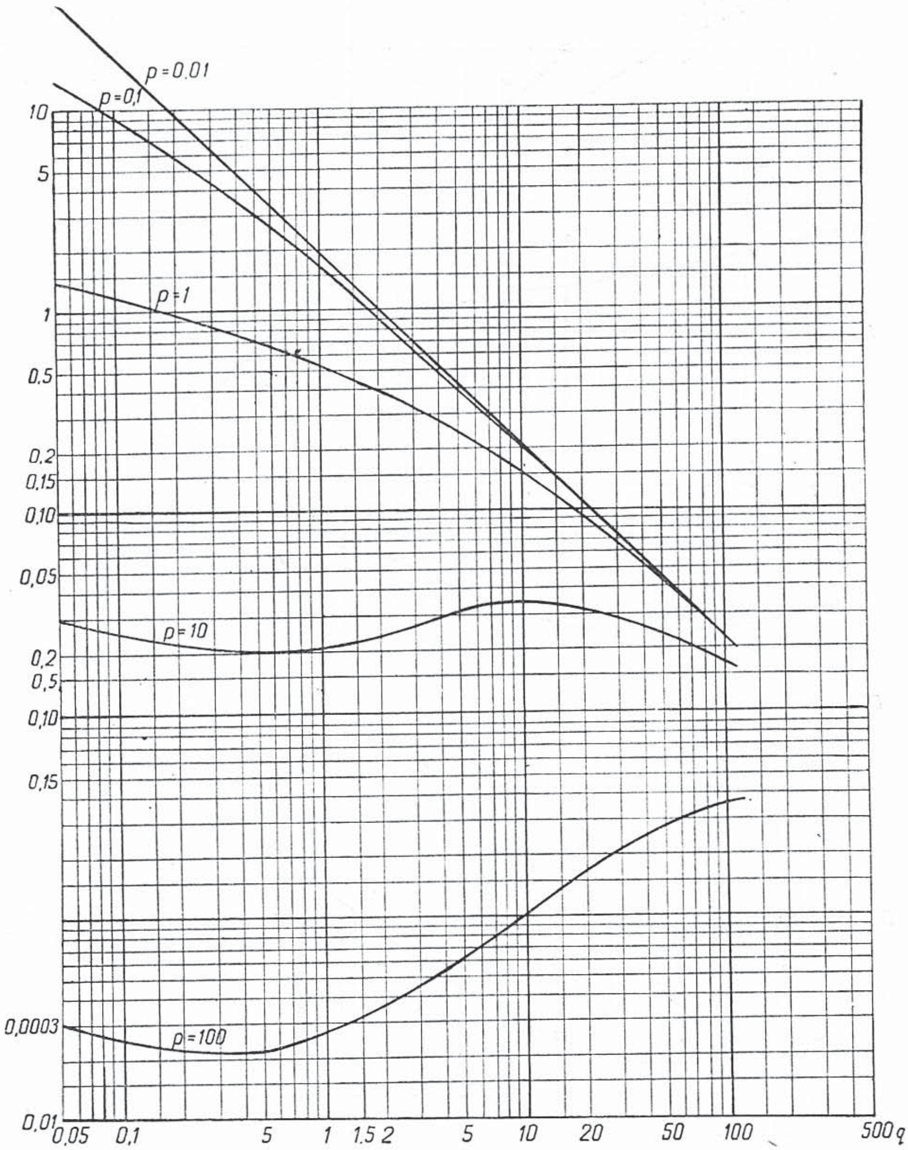

Fig. 19. Relations $\frac{1}{\alpha}\cdot\frac{T_r}{K_r}=f(q, p)$, for $\gamma=0,5$

fication of our assumptions, as compared with the actual complicated phenomenon of replica creation. In the case of the replicas A an effort was made to secure better agreement with theory by assuming an additional sum to the values K_i of those deeper dislocation which were not released by the shocks, equal to ten ($\sum_{i=5}^{n} K_i = 10$). The correspondingly amended values are marked by (p_r). From the shift of the vertical scales

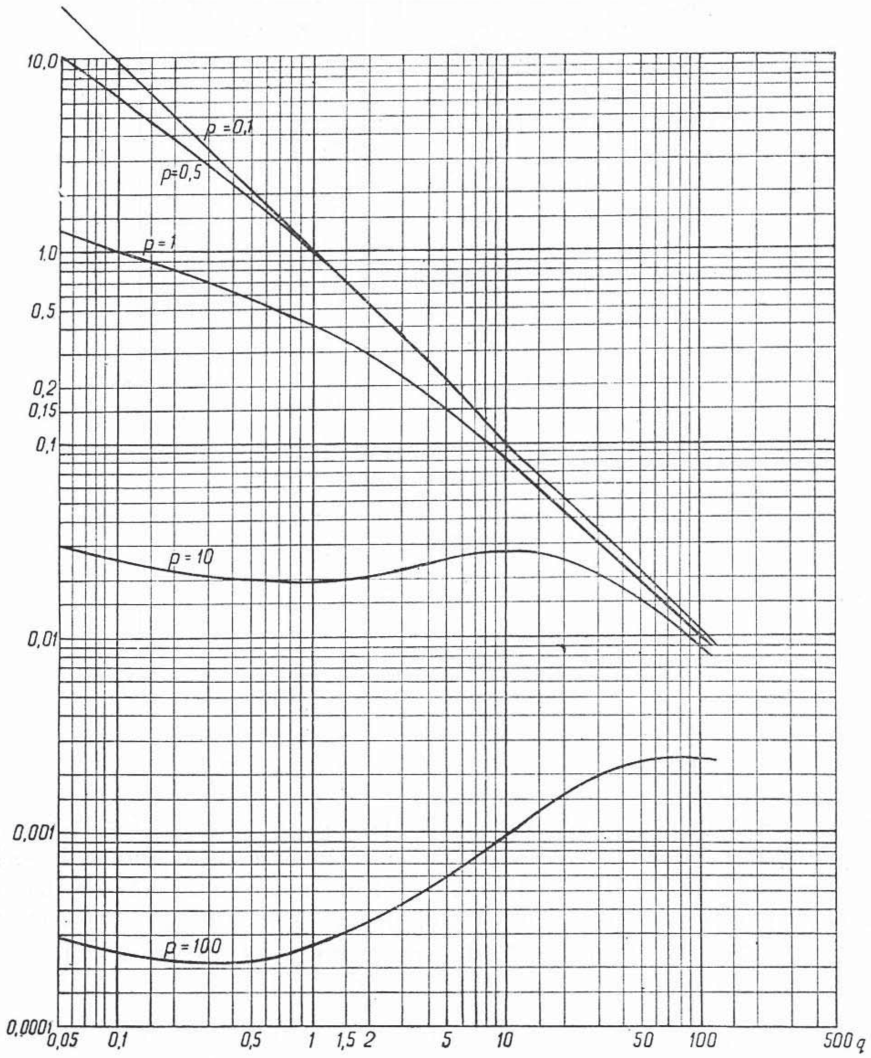

Fig. 20. Relations $\frac{1}{\alpha} \cdot \frac{T_r}{K_r} f(q, p)$, for $\gamma = 0,1$

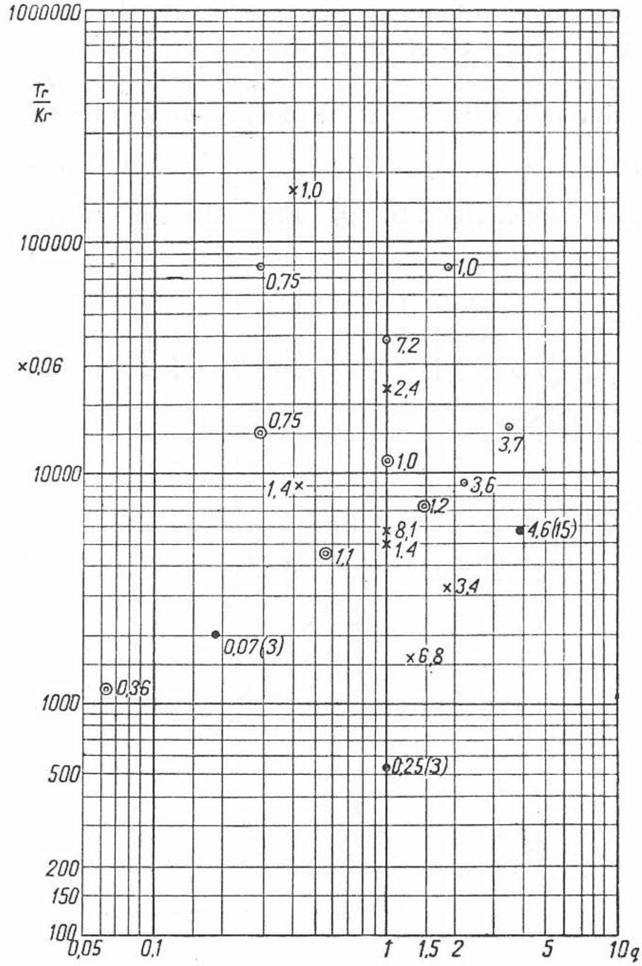

Fig. 21. Observational date: $\frac{T_r}{K_r}(q, p)$
Point series A, B, C, D denoted respectively by ● ⊙ ◎ ×

of the theoretical curve in respect to the values resulting for the quake replicas, the following values for the coefficient α were obtained: series A: $3.5 \cdot 10^4$ ($2.5 \cdot 10^5$), 10^2 ($2 \cdot 10^3$), 70 ($8 \cdot 10^3$), mean value $1.5 \cdot 10^4$ ($8 \cdot 10^4$); series B: $9 \cdot 10^5$, $9 \cdot 10^4$, $5 \cdot 10^4$, $8 \cdot 10^4$, mean value $2.8 \cdot 10^5$; series C: 15, $5 \cdot 10^4$, $5 \cdot 10^3$, $1.2 \cdot 10^4$, $9 \cdot 10^3$, $9 \cdot 10^3$, mean value $1.4 \cdot 10^4$; series D: $4 \cdot 10^2$, $1.5 \cdot 10^5$, $3 \cdot 10^4$, $2 \cdot 10^4$, $1.2 \cdot 10^4$, $7 \cdot 10^4$, $8 \cdot 10^3$, $1.6 \cdot 10^5$, mean value $6 \cdot 10^4$.

Assuming a mean value $\alpha \approx 10^5$, we obtain $\nu = \alpha \frac{P}{A} p \approx 3 \cdot 10^{12}$ (we assume here a shearing strength 10^9, whence, with regard to $p = S$, we have $p = 10^9$).

The obtained value of the viscosity coefficient ν lies within the limits of the lower values for solid bodies.

In conclusion, we give also the estimated velocity of the dislocation (6.20) prior to the violent movement in an earthquake.

From the value $\frac{p}{\gamma}$ for the series A, B, C, D we obtain from (6.20):

A: $v_r^0 = 2\cdot 10^{-2}\sigma_r^0$, $v_r = 2\cdot 10^{-2}\sigma_r$ B: $v_r^0 = 10^{-3}\sigma_r^0$, $v_r = 10^{-3}\sigma_r$

C: $v_r^0 = 2\cdot 10^{-2}\sigma_r^0$, $v_r = 2\cdot 10^{-2}\sigma_r$ D: $v_r^0 = 5\cdot 10^{-3}\sigma_r^0$, $v_r = 5\cdot 10^{-3}\sigma_r$

For the greatest values σ_r and σ_0^r in table I, we obtain the highest dislocation velocities v_r and v_r^0: 0.2 cm/sec, 0,05 cm/sec. These values and their changes (assuming a time duration of the order given in table I) are very small. The small velocities and accelerations justify our previous assumptions.

The numerical analysis indicates that for the first or the last shock we often obtain a great difference between the corresponding ν — value and the obtained mean values of viscosity. This difference may result from the fact, that we did not take into account small and very small quakes.

7. CONCLUSIONS

This part gives a survey of the major results obtained sofar on the basis of the dislocation theory of earthquakes (D.T.E.). Beside the findings of the present paper, also those of papers [1], [2], [16], [17], [34] are here taken in consideration.

I. The basic earthquake model of the D.T.E. explains the release mechanism of the internal strain energy of the medium. In other theories this question was either not discussed at all or the essential mechanism of energy release was not explained. The Keylis—Borok models of dynamic forces systems do not indicate the sources nor the mechanism of formation of those forces. On the other hand, in quakes caused by the creation of a dislocational element. e. g. those discussed by Vviedenskaja, or in the quakes described in part 4 point 1 of the present paper, only part of the internal energy is released, whereas the other part is transformed into energy of the created dislocation.

II. The influence of the medium's inhomogeneities on the generation of the dislocation, and the part of the microdislocation in the mechanism of stress transfer are explained. The correlations between the stress field and the inhomogeneity field are determined [1].

III. The influence of the discontinuity surface in the process of seismic energy release is determined and the corresponding formulas are given. On this basis, the ratio of the mean energy of shallow, intermediate and deep quakes for an equal number of quakes is explained in paper [16]. For elucidation of the value of the energy of intermediate quakes, a jump of the rigidity module $\Delta\mu$ on the discontinuity surface of the order 0.1μ is sufficient, for deep quakes one of the order 0.01μ.

IV. On the basis of the D.T.E. formula for the total energy of a quake good agreement with the observational data [1], [2] was obtained. The respective formulas for radiation energy and deformation work give values of similar order.

V. Highly accurate agreement between the displacements caused by the quakes with the expression for displacements of a pair of screw dislocations [17], [10].

VI. Estimation of the depth of the quakes from the surface displacements by means of the D.T.E. formulas. This was made possible by statement V.

VII. Extensive interpretation of the equivalence of the crack with the dislocation system — notably in regard to energetic surfaces — allowed better understanding of the essential features of internal deformations in the earth. The mylonite layers observed around the dislocation confirm the accepted interpretation of far-advanced disintegration of the material within the energetic surface.

VIII. Approximate elucidation of the observed statistic laws regarding the occurrence of earthquakes. Whereas the empirical relations for magnitude and number of earthquakes lead to approximate N^2E constancy, the D.T.E. adds to it the dependence on the radius (length) ϱ of the dislocation.

IX. Theoretical estimation of the values of the coefficients in the equation of motion of the dislocation.

X. Formulation of a new conception of the strength problems connected with the movement of the dislocation. Determination of the conditions of dynamic and static strength.

XI. Numeral assay of the viscosity coefficient in the dislocation movement.

XII. Development of a number of theoretical formulas for the contour dislocation field, the field of approaching dislocation pairs etc.

XIII. Development of relations for the velocity of motion of the dislocation in the quake, and for the time duration of the quake.

XIV. Formulation of an elementary theory of replicas, and determination of the relation between the time of replica occurrence and the

Table I

Sh. num.	Magn. M	M	K_r	q_r	P_r	(P_r)	T_r — time between the sucssesive shocks	$\frac{T_r}{K_r}$	σ_r	r
A. Earthquake series: White Wolf Fault 23. VII. 1952, 10^h54^m GMT, 35°15'N, 118°30'W										
1	5.0	0.0	1	—	—	—	—	—	—	9.30
2	5.7	0.7	3.7	3.7	4.61	15	21 780 sec	5 850	1.98	2.24
3	5.7	0.7	3.7	1	0.25	3	1 980	535	1.12	1.24
4	4.8	−0.2	0.68	0.18	0.07	3	1 380	2 020	1.05	1.33
5	4.2	−0.8	0.225	0.33		at $\sum_{i=5}^{n} K_i = 10$				
B. Earthquake series: White Wolf Fault, 21. VII. 1952, 08^h21^m GMT, 35°N, 119°W										
1	4.1	−0.9	0.19	—	—	—	—	—	—	10.25
2	4.1	−0.9	0.19	1.0	7.25		7 140 sec	37 700	4.6	8.25
3	4.8	−0.8	0.68	3.58	3.69		11 520	15 900	1.8	2
4	4.1	−0.9	0.19	0.28	0.75		15 660	82 500	2	3.7
5	4.4	−0.6	0.32	1.78	1.0		24 600	77 000	1.37	1 59
6	4.1	−0.9	0.19	0.59						
C. Earthquake series: White Wolf Fault, 21. VII. 1952, $23^h0.4^m$ GMT, 35°25'N, 118°35'W										
1	6.1	1.1	7.5	—	—	—	—	—	—	1.42
2	4.6	−0.4	0.46	0.062	0.36		540 sec	1 170	1.34	6.87
3	5.0	0.0	1.0	2.12	3.62		9 060	9 060	2.16	2.70
4	4.7	−0.3	0.56	0.56	1.10		2 580	4 600	1.73	3.04
5	4.7	−0.3	0.56	1.0	1.04		6 240	11 200	1.52	2.04
6	4.0	−1.0	0.16	0.29	0.75		2 400	15 000	1.58	3.62
7	4.2	−0.8	0.23	1.44	1.19		1 680	7 300	1.49	1.83
8	4.1	−0.9	0.19	0.83						
D. Series of the mongolian earthquake: 4. XII. 1957, 03^h37^m GMT, 45°N, 100°E										
1	7.9	2.9	1.80	—	—	—	—	—	—	1.05
2	5.0	0.0	1.0	0.0055	0 055	—	29 850 sec	29 850	5.55	10.1
3	? (5)	(0)	(1)	1	8.1	—	5 670	5 670	5.05	9.1
4	5.2	0.2	1.3	1.3	6.8	—	2 210	1 620	3.9	6.2
5	5.5	0.5	2.4	1.84	3.4	—	7 240	3 030	2.3	2.8
6	? (5)	(0)	(1)	0.42	1.4	—	8 880	8 880	2.7	4.4
7	? (5)	(0)	(1)	1	2.4	—	23 340	23 340	2.2	3.4
8	5.0	0.0	1.0	1	1.4	—	5 100	5 100	1.7	2.4
9	4.5	−0.5	0.4	0.4	1.0	—	66 450	168 000	1.7	3.5
10	5.0	0.0	1.0	2.5						

Remark. The value (5) is assumed for earthquakes of an unknown magnitude.

magnitudes of the dislocation series. This allowed preliminary comparison of theory with observation data.

XV. Estimate of the velocity of the dislocation movement preceding the quake.

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ZALEŻNOŚCI DYNAMICZNE I CZASOWE DYSLOKACYJNEJ TEORII TRZESIEŃ

Streszczenie

W pracy przedyskutowano podstawy dyslokacyjnej teorii trzęsień Ziemi (D.T.T.), a w szczególności źródła i mechanizm tworzenia się dyslokacji, wyładowanie energii sejsmicznej, ruch dyslokacji oraz zasady elementarnej teorii replik.

Zasadniczy model trzęsienia Ziemi według D. T. T. wyjaśnia mechanizm wyzwalania się sprężystej energii wewnętrznej ośrodka. W mechanizmie tym uwzględniony został wpływ niejednorodności ośrodka na tworzenie się dyslokacji i udział mikrodyslokacji w mechanizmie przenoszenia napięć. W szczególności przedyskutowany został wpływ powierzchni nieciągłości w procesie wyzwalania się energii sejsmicznej. Dla przypadków tych podano wielkość energii sejsmicznej wyzwalanej w trzęsieniach i wielkość pracy deformacji.

W niniejszej pracy ponadto przeanalizowano wielkości przesunięć wywołanych trzęsieniami powierzchniowymi i wyniki porównano z danymi obserwacyjnymi [10].

W sposób przybliżony wyjaśniono obserwowane prawa statyczne dotyczące trzęsień Ziemi. O ile empiryczne związki prowadzą do przybliżonej stałości N^2E, to w D. T. T. dochodzi jeszcze zależność od promienia (długości) dyslokacji. Rozszerzenie równoważności pęknięcia wewnętrznego z układem dyslokacji, w szczególności w zakresie tzw. powierzchni energetycznych, pozwoliło lepiej zorientować się w istocie wewnętrznych deformacji w Ziemi. Obserwowane wokół dyslokacji strefy mylonityczne potwierdzają przyjętą interpretację daleko posuniętego rozbicia materiału wewnątrz powierzchni energetycznych.

Obszernej analizie poddane zostało zagadnienie ruchu dyslokacji. Pozwoliło to na sformułowanie elementarnej teorii replik i ustalenie związku między czasem wystąpienia repliki a magnitudami ciągu dyslokacji.

Orientacyjne porównanie teorii w tym zakresie z danymi obserwacyjnymi prowadzi do dużych rozrzutów otrzymanych wielkości, spowodowanych prawdopodobnie nieuwzględnieniem słabych i bardzo słabych wstrząsów w serii replik.

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SOME REMARKS TO THE DISLOCATIONAL MODEL OF ENERGY RELEASE IN THE EARTHQUAKES

When discussing the dislocation processes we should pay attention to the difference in signs of the particular dislocations.

The unique mode of signs determination shall assure the clarity of the theory and permits to avoid misunderstandings in application. Therefore we want to adjust the sign convention and to present it for the case of continuous medium.

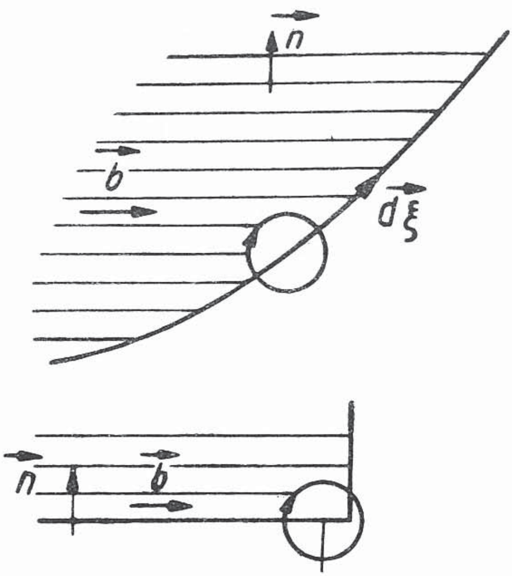

Fig. 1

An element of dislocation is fully determined by three vectors: $\vec{b}$ — displacement vector, $\vec{d\xi}$ — vector of an element of dislocation line, $\vec{n}$ — vector normal to dislocation plane (fig. 1).

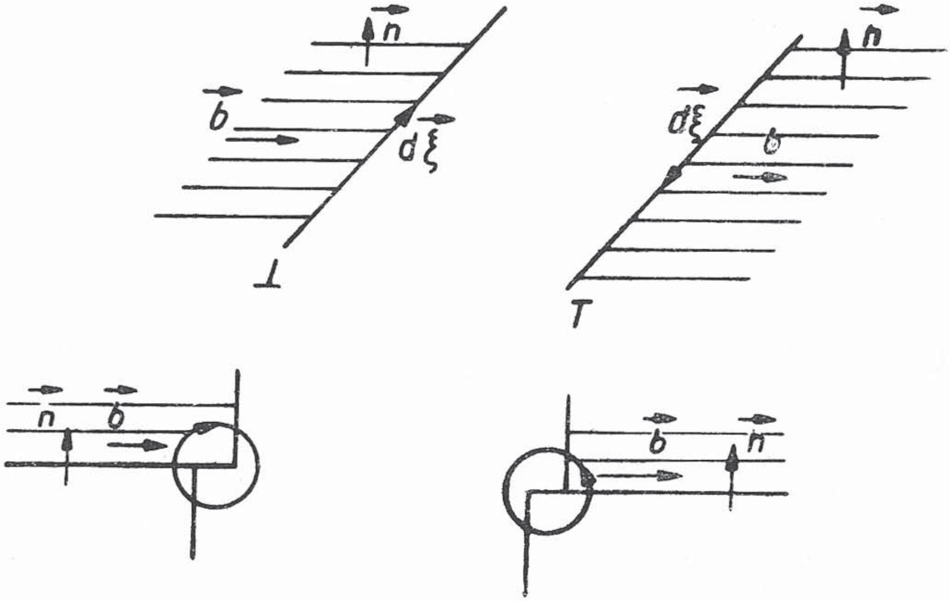

Fig. 2

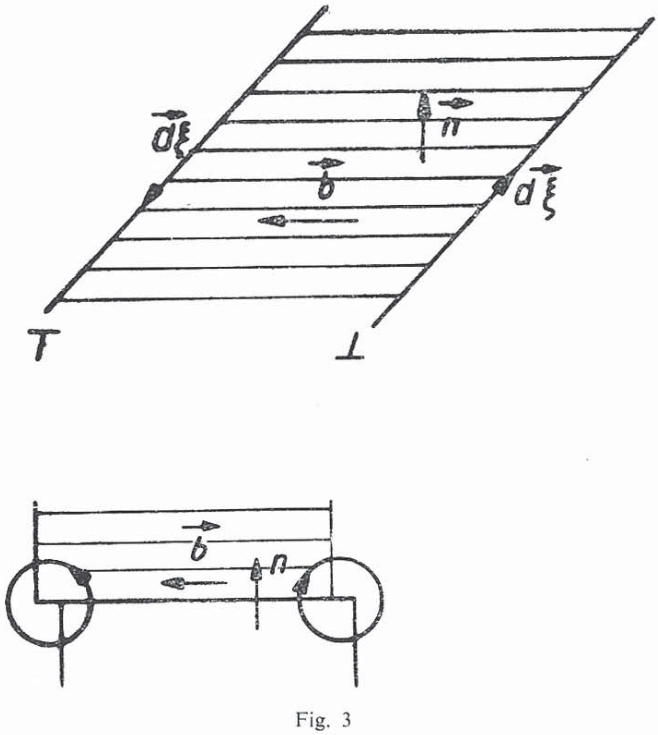

Fig. 3

After [1] we assume that the positive sense of normal vector is directed from the undisturbed medium to the its part submitted to displacement. A dislocation line confines the dislocation area; the small contour surrounding this line has a positive circulation if it coincides on the dislocation area with the positive sense of the normal vector [1]. The sense of a vector of line element $\overleftarrow{d\xi}$ follows now from the right-screw principle (fig. 1).

At these conventions we are able to define a sign of dislocation. Let us take the case of edge dislocation. Right-screw system of vectors $(\vec{b}, \vec{d\xi}, \vec{n})$ defines positive edge dislocation $\perp$. In the opposite case we have a negative dislocation $\top$.

The case of a pair — $(\perp, \top)$ is shown in fig. 2, this pair is mathematically equivalent to the case demonstrated in fig. 3.

In the case of screw dislocations the vectors $\vec{b}$ and $\vec{d\xi}$ are parallel (positive dislocation I^+), or antiparallel (negative dislocation I^-). In fig. 4 and 5 are presented the equivalent cases of the pair (I^+, I^-).

The basic element of seismic models is a dislocation rectangle formed by edge and screw dislocation pairs, as presented in fig. 6. In dependence on the geometry of the system, we shall consider in approximation a pair of edge dislocations $(\perp, \top)$ or a pair of screw dislocations (I^+, I^-).

In the dislocation theory of earthquakes the pair annihilation (creation) presents a basic model of earthquake [3], [4], [5]. From the dynamic point of view the annihilation process is equivalent to creation of an opposite pair.

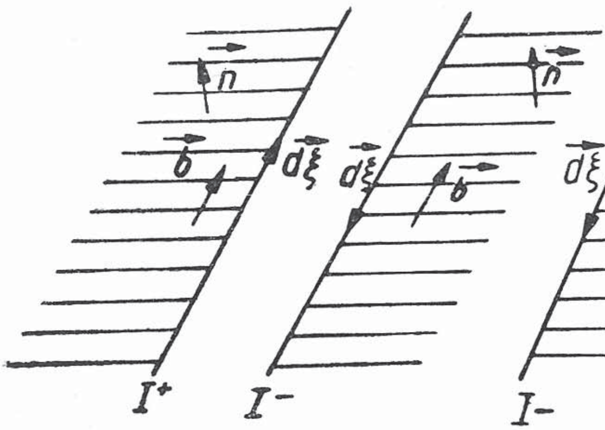

Fig. 4

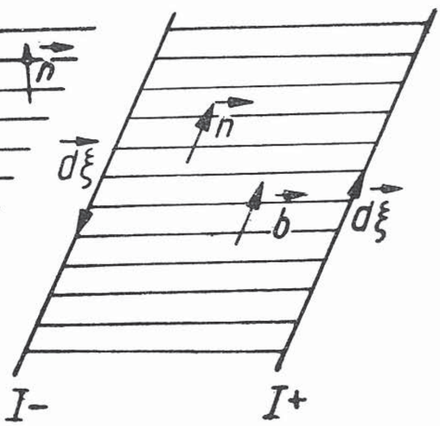

Fig. 5

The physical counterpart of this mathematical formulation may be related to any change in the dislocation area (which is limited by the dislocation line) [3], to the approach of the dislocation to the inner or outer boundary of the medium (interaction with the image dislocation leading to mutual annihilation at the boundary)

[3, 4], and to the processes of the thermal stress field [5]. In special cases the latter have dislocation-stress character; these thermal stresses may be released by annihilation of such quasi-dislocation field through a real dislocation.

The model of dynamic forces can readily be computed by means of Voltera's formula:

$$u^k(x)=\frac{1}{8\pi\mu}\iint\limits_{\Sigma} \Delta u_i \tau_{ij}^k n_j \, ds .$$

The dislocation field u^k in the point x^m is determined by the values of field τ_{ij}^k on the dislocation plane Σ.

The field τ_{ij}^k from the other side we take as equating the stress field of the point force F_k, as it would be situated in the point x^m. If distance R from focus to

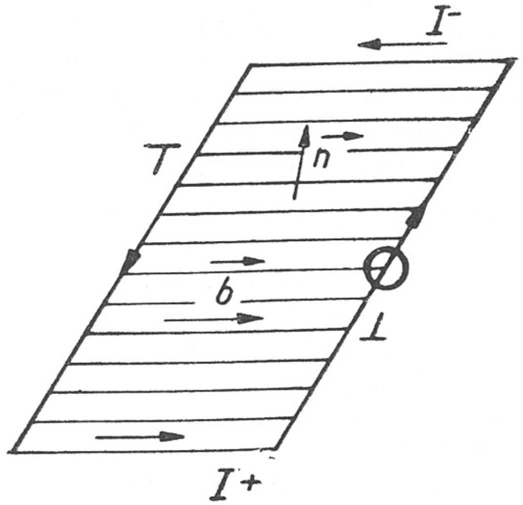

Fig. 6

observation point is considerable compared with focus dimension (length of the dislocation pair l, playing here therefore the primary role), we can consider the model of this pair as defined with good approximation by formula:

$$u_{ij}^k=\frac{\partial u_i^k}{\partial x_j}+\frac{\partial u_j^k}{\partial x_i},$$

where: i, j — are the indices of vectors b_i, n_j $(\vec{b}\perp\vec{n})$, while index k denotes the displacement component, u_i^k — displacement field of point force, index i denotes the force component.

This is evidently a sum corresponding to two dipoles of forces with moment.

Considerations on the dislocation mechanism of earthquake formation have yielded formulae for the total energy of the earthquake and an approximation mode for dividing the latter in that part corresponding to deformation work and that corresponding to radiated (seismic) energy [3, 4].

Deformation work —

$$\text{edge dislocation:} \quad E_d = \frac{\mu b^2 l}{2\pi(1-\sigma)}\left(\ln\frac{L}{r_0} - \ln 2\right),$$

$$\text{screw dislocation:} \quad E_d = \frac{\mu b^2 l}{2\pi}\left(\ln\frac{L}{r_0} - \ln 2\right). \qquad (1)$$

Radiation energy —

$$\text{edge dislocation:} \quad E_s = \frac{\mu b^2 l}{2\pi(1-\sigma)}\left(\ln 2 - \frac{1}{2}\right),$$

$$\text{screw dislocation:} \quad E_s = \frac{\mu b^2 l}{2\pi}\ln 2 . \qquad (2)$$

The formula for deformation work given by Byerly and De Noyer [6] is for the value of the α parameter $\alpha = H$ comparable with E_d.

To determine the values of term $\ln\frac{H}{r_0}$ we should turn to the question of dislocation energy and more especially to the problem of stress concentration in the vicinity of the dislocation lines, i. e. in the vinicity of the boundaries of the dislocation area.

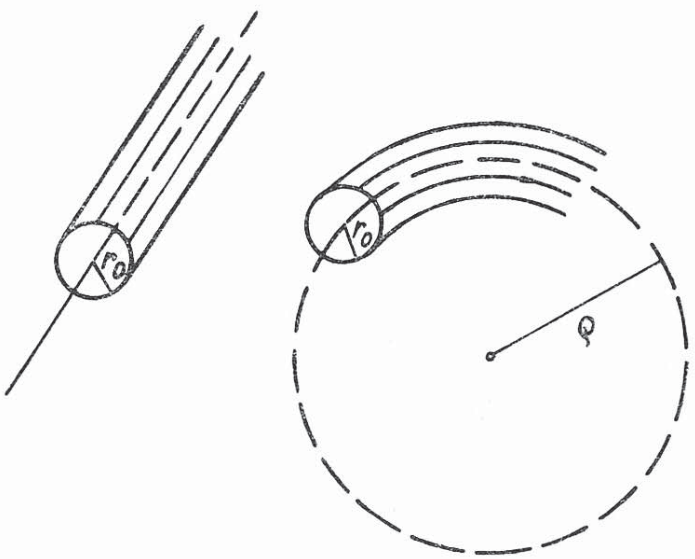

Fig. 7

Irrespective of the kind of dislocation, the dislocation energy per length unit can (disregarding factor $1 - \sigma$ in edge dislocation) be expressed by formula [2]:

$$e = \frac{\mu b^2}{4\pi} \ln \frac{L}{r_0} . \tag{3}$$

We assume that this energy is concentrated on the surface of a cylinder with radius r_0. Total energy concentrated on a lenght unit of the cylinder amounts to $2\pi r_0 \gamma$, where γ is the surface energy per surface unit. The cylinder has full physical meaning; the material in its interior has become disintegrated, while its external part forms a medium not affected by disintegration. Quantity γ can be computed by comparing surface energy with the energy given by formula (3) for the case of a contour dislocation with diameter 2ρ (we put $L=\rho$):

$$2\pi r_0 \gamma = \frac{\mu b^2}{4\pi} \ln \frac{\rho}{r_0}$$

hence

$$\gamma = \frac{\mu b^2}{8\pi^2 r_0} \ln \frac{\rho}{r_0} .$$

Putting $\ln \frac{\rho}{r_0} = 5$, as follows from further considerations, we obtain:

$$\gamma = 0.06 \frac{\mu b^2}{r} . \tag{4}$$

The own stress field of the dislocation is given by the expression (disregarding factor $1 - \sigma$ in edge dislocation):

$$p = \frac{\mu b}{2\pi r} .$$

As was previously shown [4] this field at $r = r_0$ is of the order of the shearing strength (S) of he material. Thus we have

$$S = \frac{\mu b}{2\pi r_0} . \tag{5}$$

Substituting in this expression r_0 computed from (4), we obtain the relationship between material strength, surface energy and the Burgers vector:

$$S = \frac{\gamma}{0.38 b} .$$

Putting for strength the value $S = 10^9$, we get

$$\gamma = 3.8 \cdot 10^8 b .$$

Putting also $\frac{S}{\mu}=3\cdot10^{-3}$ ($S=10^9$, $\mu=3\cdot3\cdot10^{11}$) we obtain from (5):

$$\frac{b}{r_0}=2\cdot10^{-2}.$$

Dislocation movement is conditioned by the shearing strength of the material. Along the path on which the dislocation is moving forms in consequence of the displacement of the dislocation line the so called mylonitic zone, characterized by intense crushing of the rock material.

In the case of a contour dislocation we may assume that shearing strength and therefore resistance to the dislocation movement has in all directions approximately equal value, wherefore we may in first approximation put $L\approx l$ in formulae (1), (2). We obtain furthermore an estimate for $\ln\frac{L}{r_0}$ from formula (5), namely

$$\ln\frac{L}{r_0}\approx\ln\frac{l}{r_0}\approx\ln\frac{2\pi Sl}{\mu b} \tag{6}$$

and for $\frac{S}{\mu}\approx3\cdot10^{-3}$ we get correspondingly:

$$\ln\frac{L}{r_0}\approx\ln 2\cdot10^{-2}\frac{l}{b} \quad \text{for a screw dislocation} \tag{7}$$

and

$$\ln\frac{L}{r_0}\approx\ln 1.5\cdot10^{-2}\frac{l}{b} \quad \text{for an edge dislocation.}$$

The formulae for seismic energy (1) (2) can in this way be expressed by two parameters: l — length of dislocation, b — value of displacement (shift value). In addition we have here (as appears from our previous considerations) the inequality $l>r_0>b$.

In tab. I are given the values $\eta=\frac{\rho}{r_0}=2\cdot10^{-2}\frac{l}{b}$ and the values $\ln\eta$, from which results that for approximate evaluation one may take $\eta=150$, $\ln\eta=5$. Thus we obtain from (3) an estimate for the energy of a contour dislocation.

$$E=2\pi\rho e=\frac{\mu b^2\rho}{2}\ln\frac{L}{r_0}=2.5\mu b^2\rho\,. \tag{8}$$

Using then formula (5), we have for $\frac{\rho}{r_0}=150$

$$b=2\pi\frac{S}{\mu}r_0=0.042\rho\frac{S}{\mu}, \tag{9}$$

and particulary for $\frac{S}{\mu}=3\cdot 10^{-3}$:

$$\rho=8\cdot 10^3 b\,.$$

From formula (9) results for contour-dislocation energy

$$E=60\cdot\frac{\mu^2}{S}b^3 \tag{10}$$

and particularly for $\mu=3.3\cdot 10^{11}$, $\frac{S}{\mu}=3\cdot 10^{-3}$, we have

$$E=6.6\cdot 10^{15}b^3\,. \tag{11}$$

This is the estimated value of contour-dislocation energy. Putting e. g. $b=10^2$ cm we obtain

$$E=6.6\cdot 10^{21}\ \text{erg}$$

and for $b=10^3$ cm we get

$$E=6.6\cdot 10^{24}\ \text{erg}\,.$$

In the following we propose to reexamine the question of numerical evaluation of energy in a number of strong surface earthquakes [4] (tabl. 1).

From formulae (7) and (1) we obtain for the deformation energy ($\mu=3.3\cdot 10^{11}$):

$$\begin{aligned} E_d &\approx 7\cdot 10^{10}b^2 l\left[\ln\left(0.015\frac{l}{b}\right)-\ln 2\right] \quad \text{— edge dislocation,}\\ E_d &\approx 5\cdot 10^{10}b^2 l\left[\ln\left(0.02\ \frac{l}{b}\right)-\ln 2\right] \quad \text{— screw dislocation.}\end{aligned} \tag{12}$$

For the seismic energy we get from (2):

$$\begin{aligned} E_s &=1.3\cdot 10^{10}b^2 l \quad \text{— edge dislocation,}\\ E_s &=3.6\cdot 10^{10}b^2 l \quad \text{— screw dislocation.}\end{aligned} \tag{13}$$

If no distinction between dislocation types is required we shall be using for comparative purposes the formulae:

$$E_d\approx 6\cdot 10^{10}b^2 l\left(\ln 0.018\,\frac{l}{b}-0.7\right), \tag{14}$$

$$E_d\approx 2.5\cdot 10^{11}b^2 l\left(\text{at } \ln\frac{2H}{r_0}=\ln\eta=5\right), \tag{15}$$

$$E_s\approx 2.5\cdot 10^{10}b^2 l\,. \tag{16}$$

Table I

Lp.	Earthquake	km	b m	η	$\ln\eta$	M	E_s acc. to magnitude	E_s theoret. (16)	E_d theoret. (15)	E_d theoret. (14)	E_d acc. to (17)
1	California 1906	450	3.05	$3\cdot10^3$	8.0	$8\frac{1}{4}$	$1.6\cdot10^{24}$	$1.0\cdot10^{23}$	$1.0\cdot10^{24}$	$1.8\cdot10^{24}$	$9.0\cdot10^{22}$
2	Nevada 1915	30	5	$1.2\cdot10^2$	4.8	$7\frac{3}{4}$	$2.1.10^{23}$	$1.9\cdot10^{22}$	$1.9\cdot10^{23}$	$1.9\cdot10^{23}$	$4.1\cdot10^{23}$
3	Mino-Owari 1891	65—120	7	$2.4\cdot10^2$	5.5	$7\frac{1}{2}$	$1.0\cdot10^{23}$	$1.1\cdot10^{23}$	$1.1\cdot10^{24}$	$1.4\cdot10^{24}$	$1.2\cdot10^{24}$
4	Assam 1897	20	12	$3.4\cdot10$	3.5	$8\frac{1}{2}$	$4.0\cdot10^{24}$	$7.2\cdot10^{22}$	$7.2\cdot10^{23}$	$4.8\cdot10^{23}$	$5.5\cdot10^{24}$
5	Nevada 1954	80	1.85	$9.2\cdot10^2$	6.8	$7\frac{1}{4}$	$4.0\cdot10^{22}$	$6.7\cdot10^{21}$	$6.7\cdot10^{22}$	$9.8\cdot10^{22}$	$2.0\cdot10^{22}$
6	Tango 1927	30	1.5	$4.0\cdot10^2$	6.0	7.4	$6.9\cdot10^{22}$	$1.7\cdot10^{21}$	$1.7\cdot10^{22}$	$2.2\cdot10^{22}$	$1.2\cdot10^{22}$
7	North Idu 1930	15	2.5	$1.2\cdot10^2$	4.8	7	$1.7\cdot10^{22}$	$2.4\cdot10^{21}$	$2.4\cdot10^{22}$	$2.4\cdot10^{22}$	$5.0\cdot10^{22}$
8	Mongolia 1957	300	3	$2.0\cdot10^3$	7.6	7.9	$4.3\cdot10^{23}$	$6.7\cdot10^{22}$	$6.7\cdot10^{23}$	$1.1\cdot10^{24}$	$9.0\cdot10^{22}$

For earthquakes with undefined length, we can use the estimate for contour dislocation energy. In this case the dislocation forms part of the contour, the latter being closed by dislocation image in Earth's surface. The value of energy is taken now from formula (11) with factor 1/2:

$$E \approx 3.3 \cdot 10^{15} b^3 . \tag{17}$$

By means of the above formulae the value of energy E_d and E_s was computed for a number of examples, taking as total energy the sum $E_d + E_s$ and giving also the value of total energy computed with formula (17). The computation results presented in tab. I are compared with the values for E_s computed from the earthquake magnitudes M.

Attention deserves the generally good agreement of the energy data computed with the simple formula (17) (except in the Californian earthquake). In comparison of data we have also to remember that no deeper critical analysis was attempted here of the values of dislocation length and the values of the Burgers vector, which were taken from literature. It is evident that the data for such analysis should represent mean values (or preferably mean quadratic values) of the Burgers vector. Accurate computations can be made by adding the sum $\Sigma\, b_i^2\, l_i$ on sectors where shift-value is approximately constant.

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UWAGI O DYSLOKACYJNYM MODELU TRZĘSIENIA ZIEMI

Streszczenie

W pracy przedyskutowane jest zagadnienie energii trzęsień Ziemi, wraz z przybliżoną oceną wielkości energii deformacji i energii sejsmicznej. Ocena oparta jest na analizie energii skoncentrowanej wokół linii dyslokacyjnej (front obszaru dyslokacji). Wyniki podane są w tablicy I.

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THERMAL STRESSES AND THE EQUIVALENT DISLOCATION FIELDS

Relations between thermal and dislocation stresses are discussed for plane problems and the general spatial problem. The interpretation on ground of differential geometry follows Kröner's, Bilby's and Kondo's papers.

Application to the case of thermal convection and a linear heat source is discussed in some detail and there are drawn some remarks for investigation of such processes in the Earth's interior.

The new trends in the physics of continuous media are focussed on the problems of incompatibility, which occur both in the case of a dislocation density field and of thermal deformation. The method proposed in the former papers (T e i s s e y r e, 1963, 1969a) describes thermal stresses in Earth structures by an equivalent dislocation distribution (dislocation density). The stress equivalence between thermal convection and dislocation density is illustrated in Fig. 1. This dislocational representation of a thermal state has at least two aspects:

1) a real dislocation can compensate, that is remove, thermal stresses,

2) processes between two convection cells can be investigated in terms of dislocation dynamics.

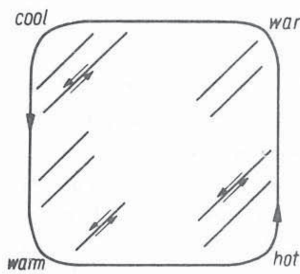

Fig. 1
Equivalece of stresses between thermal convection and dislocation density

The first point can be related to a mass shift in the convection cell's environment, while the second could explain the well known rupture processes in the region between convection cells. This is shown in Fig. 2. Two convection cells with opposite circulation are given and the corresponding dislocation distribution is presented. The dislocation pairs BA and A′B′ of neighbouring cells have opposite character. Hence the dislocations A and A′ have the same sign and repel each other mutually. This blocking action stops the outward spreading tendency (T e i s s e y r e, 1969b) represented by those dislocations. The dynamic development will thus favor the decomposition of the dislocations A and A′ into vertical and horizontal components. The horizontal displacements cd, cd, ..., bring by compensation zero (Fig. 3), whereas the vertical dislocations will join in common planes. Energy release is also to be expected in

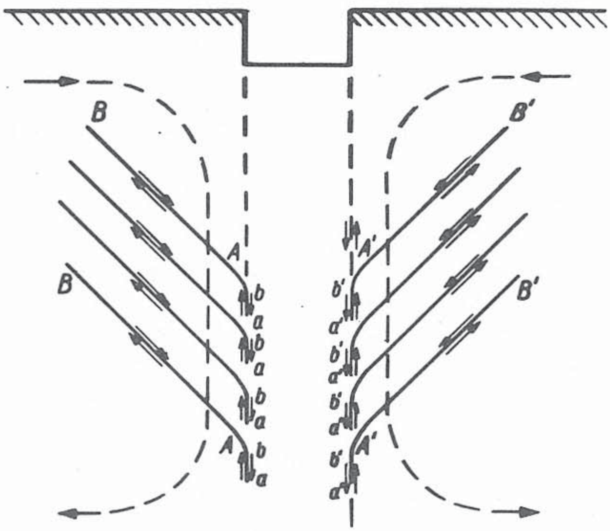

Fig. 2
Region between two convection cells

those annihilation processes in which the dislocation a and b (or a′ and b′) of neighbouring pairs join into one element – in result of which a shift of masses occurs in the vertical planes adjacent to both convection cells, resulting in a typical trench section (Fig. 2).

A general relation between thermal and dislocation fields has been sought in some papers (Kröner, 1958, Kondo, 1963; Stojanovitch, Djuritch, Vujoshevitch, 1964). Such general relation shall be discussed here too and some applications to the Earth's interior be proposed. Therefore we propose to discuss here a general approach to the problem of thermal stresses. Thermal stresses have incompatible character, analogous to dislocational stresses. Kröner (1958), Kondo (1962), Stojanovitch, Djuritch, Vujoshevitch (1964) presented general considerations on the thermal field and its image in a geometry of deformation.

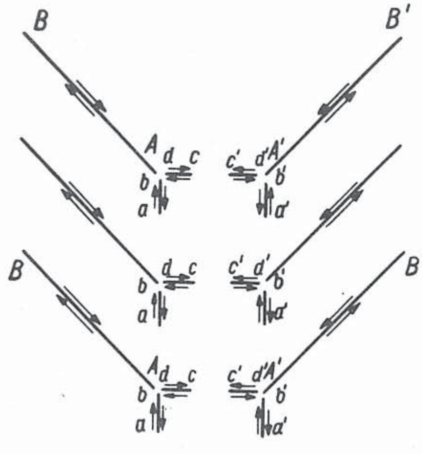

Fig. 3.
Decomposition of dislocation vectors

The approach proposed by Stojanovitch, Djuritch, Vujoshevitch (1964) consists in the following. Temperature field deformations which can be expressed by anholonomic transformation lead from the Euclidean into non-Riemannian space. As the second step we perform the next transformation in such a manner, as to set a body again in the Euclidean space – physically this means the introduction of thermal stresses.

In our further considerations we propose to adopt another approach, which seems more direct and allows the immediate computation of stresses and the equivalent dislocation densities. We start with a real medium in a certain state of thermal stress. An anholonomic transformation connected with distortions u^{*}_{ik} could transform the real medium to the stressless state, but its geometry would then become non-Euclidean. The distortions u^{*}_{ik} are defined by the transformations expressing a line r expansion:

$$dX_k = dx_k + u^{*}_{ik}\, dx_i , \quad u_{ik} = \alpha\, \delta_{ik} (T - T_0) , \tag{1}$$

here: α – coefficient of linear expansion.

The stresses related to this state shall vanish, thus the equivalent dislocation field is related to distortions

$$u_{ik} = - u^{*}_{ik} . \tag{2}$$

In linear theory we can put after Kröner (1958)

$$\alpha_{mn} = \varepsilon_{nab}\, u_{am,b} \tag{3}$$

$$\eta_{tn} = \varepsilon_{tab}\, \varepsilon_{nsr}\, u_{br,as} \tag{4}$$

where: α_{mn} – the dislocation density of Burgers – like dislocation density;
η_{tn} – the density of rotational dislocations.

Hence an apparent dislocation density in an isothermal case, equivalent to the thermal field of the original problem, shall be defined according to equation (1) as follows:

$$\alpha_{xz} = -\alpha\, \Theta \frac{\partial}{\partial y} T, \quad \alpha_{yz} = \alpha\, \Theta \frac{\partial}{\partial x} T, \tag{5}$$

with $\Theta = 1$ for the three dimensions and

$$\Theta = \frac{3\lambda + 2\mu}{2\lambda + 2\mu}$$

in the twodimensional case (Teisseyre, 1969 b).

By arguments similar to those discussed before, thermal stresses can be removed by an appropriate distribution of real dislocations density. For the rotational dislocation density we get according to (4)

$$\eta_{zz} = 2\alpha\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)T, \tag{6}$$

but this vanishes for the stationary plane case $\Delta T = 0$.

We find thus that the dislocation density related to distortions (1) forms the counterpart of a thermal state. For the displacement vector related to total distortion along a closed contour we get according to (1) and (2)

$$\Delta u_x = \oint u_{xx}\,dx, \quad \Delta u_y = \oint u_{yy}\,dy, \tag{7}$$

$$\Delta u_x = \alpha\Theta \oint T\,dx, \quad \Delta u_y = \alpha\Theta \oint T\,dy. \tag{8}$$

Defining the analytic function $F = T + iE$ by the condition $\mathrm{Re}\,F = T$, we obtain

$$\Delta u_x = \alpha\Theta\,\mathrm{Re} \oint F\,dz, \quad \Delta u_y = \alpha\Theta\,\mathrm{Im} \oint F\,dz$$

or, putting $\Delta u = \Delta u_x + i\Delta u_y$, we have

$$\Delta u = \alpha\Theta \oint F\,dz, \tag{9}$$

where dislocational displacement Δu can be expressed by Burgers vector and rotation vector:

$$\Delta u_i = b_i + \varepsilon_{iks}\,\omega_k x_s. \tag{10}$$

The relation (9) corresponds directly to formula derived by Muskhelishvili (1953) in which one determines the total vector of discontinuity for a given contour or surface element bounded by it. The general relations derived above allow to calculate a dislocation density tensor at each point. Muskhelishvili' method is thus related to an average behaviour, while the present approach brings exact values of the equivalent dislocation distribution.

Now let us return to plane cases of the temperature field.

For a line temperature source we have $T = -\gamma \ln r$ and $F = -\gamma \ln z$. Then the formula (5) yields for the equivalent dis ocation density:

$$\alpha_{xz} = \alpha\Theta\frac{y}{r^2}, \quad \alpha_{yz} = -\alpha\Theta\frac{x}{r^2}. \tag{11}$$

For the average displacement discontinuity we get after formula (9) and (10)

$$\omega_z = - \; 2\pi\,\alpha\,\Theta\,\gamma\,. \tag{12}$$

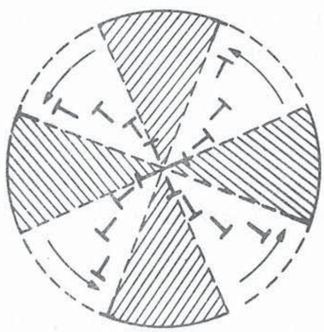

Fig. 4
Equivalence of dislocation density with rotational dislocation

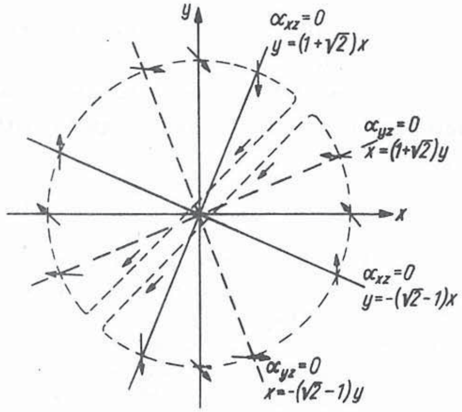

Fig. 5
Dislocation density in the case of dipole source

Thus the stress field of dislocation density (11) shall be equivalent to rotational dislocation (12); this is shown on Fig. 4. For a dipole type source $T = \gamma \dfrac{x - y}{r^2}$ we get correspondingly

$$b_x = 2\pi\,\alpha\,\Theta\,\gamma\,, \quad b_y = 2\pi\,\alpha\,\Theta\,\gamma\,. \tag{12}$$

The Burgers vector is therefore constant, but the dislocation density (5) has a more complex microstructure ($\delta = \gamma\, d\sigma^{-1}$)

$$\alpha_{xz} = -\,\alpha\,\Theta\,\delta\,\frac{y^2 - x^2 - 2xy}{r^4}\,,$$

$$\alpha_{yz} = -\,\alpha\,\Theta\,\delta\,\frac{x^2 - y^2 - 2xy}{r^4}\,. \tag{13}$$

This is shown in Fig. 5, where the arrows indicate the directions of the vector $(\alpha_{xz}, \alpha_{yz})$ and the continuous lines are nodals of α_{xz} while the dotted ones are nodals of α_{yz}.

For the cases discussed above we can construct the field due to a given distribution of temperature sources:

$$T = \iiint T\,(x - x_0,\, y - y_0,\, z - z_0)\, dx_0\, dy_0\, dz_0\,,$$

getting for the equivalent dislocation density the values according to the equation (5).

This dislocational interpretation enables us to gain a clearer image of the interaction pattern between regions with different temperatures.

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RELATION BETWEEN THE DEFECT DISTRIBUTION AND STRESSES. THE GLACIER MOTION

Abstract

Differential relations between the distribution of defects (dislocations and dilatations) and the stress field for Maxwell's plasto-elastic medium are given. Applications to the glacier motion problem, treated as phenomenon determined by plastic flow conditions, are discussed.

1. Introduction. The problem of relationship between the stress field and defects in the medium is trivial for a single object. By linear superposition one can obtain the stress field for a series of discrete defects. The situation becomes more complicated for a continuous distribution. Therefore, in this paper we look for direct differential relationships between the distribution of defects and the stress field. Applications to the problem of a glacier motion – treated as phenomenon determined by the plastic flow – are also discussed.

2. Relation between the defect density field and stress field. The distribution of defects can be treated as a source field determining the stresses in a medium. It is of importance to find the equations which would directly connect these quantities, in particular in the case of a continuous distribution of dislocations. The following formulae, linking the incompatibility tensor and the dislocation tensor, result from general relations of the differential geometry:

$$\eta_{tl} = \epsilon_{tsk}\,\alpha_{kl,\,s} = \epsilon_{tsk}\,\epsilon_{lmn}\,e^{(pl)}_{km,\,ns}\,,$$
$$\epsilon_{tsk}\,\epsilon_{lmn}(e^{(el)}_{km,\,ns} + e^{(pl)}_{km,\,ns}) = 0\,, \tag{1}$$

where $e^{(el)}_{ik} + e^{(pl)}_{ik} = e_{ik}$ is the full deformation tensor (Maxwell's medium), consisting of an elastic and plastic part; of course, field e_{ik} satisfies the compatibility conditions. If $e^{(el)}_{ik} = U_{(i,k)}$, then obviously $\eta_{tl}=0$. For Maxwell's medium stresses are equal $t^{(el)}_{ik} = t^{(pl)}_{ik} = t_{ik}$, so that we can introduce into relations (1) the stress field defined by the relation for an elastic body,

$$e^{(el)}_{km} = \frac{1}{2\mu}\,t_{km} - \frac{\lambda}{2\mu(3\lambda+2\mu)}\,t\delta_{km}\,. \tag{2}$$

2*

Thus, we obtain the equation

$$\epsilon_{tsk}\,\epsilon_{lmn}\,t_{km,\,ns}+\frac{\lambda}{3\lambda+2\mu}\left[t_{,tl}-\delta_{tl}\,t_{,ss}\right]=2\mu\epsilon_{tsk}\,\alpha_{kl,\,s}\,. \tag{3}$$

Assuming the static equilibrium case $t_{is,s}=0$, we can introduce the potential stress field defined through the Airy function. In the two-dimensional case this function is defined by the relation

$$t_{\alpha\beta}=\epsilon_{\alpha\gamma}\,\epsilon_{\beta\delta}\,U_{,\gamma\delta}\qquad(\alpha\,,\beta\,,\ldots=1\,,2)\,.$$

It follows from the equations of motion and the relation between the stress field and displacements that both the stress field components $t_{\alpha\beta}$ and the Airy function itself should satisfy the biharmonical equation $\Delta\Delta U=0$.

Let us introduce now a generalization of the Airy function for a three-dimensional case.

$$t_{is}=\epsilon_{asb}\,\epsilon_{aid}\,U_{,bd}=U_{,ll}\,\delta_{is}-U_{,is}\,. \tag{4}$$

Substituting relation (4) into equation (3) describing the stress field when the source field α_{ks} is specified, we obtain

$$\frac{\lambda+\mu}{3\lambda+2\mu}(\delta_{tl}\,U_{,ssii}-U_{,sstl})=\mu\epsilon_{tsk}\,\alpha_{kl,\,s}\,. \tag{5}$$

In the case of purely elastic deformations, the right-hand side of equation (5) vanishes and in accordance with compatibility conditions the Airy function for three-dimensional fields should satisfy the harmonical equation $\Delta U=0$. In a more general case of plastic and elastic deformations considered here, relation (5) is a differential equation for the Airy function with a given source field α_{kl}. From equations (4) one can then determine the stress field.

Many authors define the dislocation tensor by the relation with distortion field u_{km} determined from the anholonomic transformation (Kröner and Seeger, 1959)

$$\alpha_{kl}=\epsilon_{lmn}\,u_{km,\,n}\,. \tag{6}$$

The relations between distortion and quantities of torsion and curvature in geometrical representation of dislocation fields have already been given. Let us consider now a particular case of deformations connected with thermal stress field θ

$$t^{(t)}_{km}=-(3\lambda+2\mu)\,\alpha\theta\delta_{km}\,, \tag{7}$$

where α is the coefficient of linear expansion.

The corresponding distortion and dislocation density fields are:

$$u^{(t)}_{km}=\alpha\theta\delta_{km}\,,\qquad \alpha^{(t)}_{kl}=\alpha\epsilon_{lkn}\,\theta_{,n}\,. \tag{8}$$

Thus, the thermal stress field is given by the relation

$$\epsilon_{lmn}\,t^{(t)}_{km,n}=-(3\lambda+2\mu)\alpha^{(t)}_{kl}\,. \tag{9}$$

For the Airy function we have

$$\epsilon_{lkn} U^{(t)}_{,ssn} = -(3\lambda+2\mu)\alpha^{(t)}_{kl}. \tag{10}$$

This equation allows us to calculate the Airy stress function for a given thermal dislocation density distribution. Equation (10) will also be satisfied if the following relation resulting from equation (8) is true

$$U^{(t)}_{,ss} = -(3\lambda+2\mu)\alpha\theta. \tag{11}$$

For a micromorphic medium, the measures of deformations connected with the deformation of the medium as a whole and that of its internal structure elements are given by the deformation and microdeformation tensors of the second and third order

$$e_{ik} = u_{(i,k)}, \qquad \varepsilon_{ik} = u_{k,i} + \varphi_{ik}, \qquad \gamma_{ins} = -\varphi_{ik,s}, \tag{12}$$

where φ_{ik} is the microdisplacement tensor.

It follows from definition (12) that the deformation fields should satisfy certain compatibility relations

$$\begin{gathered} \epsilon_{kmp}\epsilon_{lnq} e_{mn,pq} = 0, \\ \epsilon_{kmn}\varepsilon_{ml,n} + \epsilon_{kmn}\gamma_{mln} = 0, \\ {}_{kpq}\gamma_{lmp,q} = 0. \end{gathered} \tag{13}$$

The microdislocation tensor is defined here by the following relation

$$\alpha^{(m)}_{kl} = \epsilon_{lmn}\epsilon_{km,n}, \qquad \epsilon_{lmn}\varphi_{km,n} = -\epsilon_{lmn}\gamma_{kmn}. \tag{14}$$

In the symmetric theory of a micromorphic medium, the constitutive relations for the stress tensor, microstress tensor and the stress moment tensor are as follows (Teisseyre, 1973)

$$\begin{aligned} t_{kl} &= \lambda\mu_{i,i}\delta_{kl} + 2\bar{\mu}u_{(k,l)} + 2\gamma\varphi_{(k,l)}, \\ s_{kl} &= \lambda\mu_{i,i}\delta_{kl} + 2(\bar{\mu}+\nu)u_{(k,l)} + 2(\bar{\nu}+\nu)\varphi_{(k,l)}, \\ \Lambda_{klm} &= 0. \end{aligned} \tag{15}$$

Denoting by $s^{(m)}_{kl}$ the part of the stress tensor which is connected with microdisplacement-type deformations $\varphi_{(kl)}$ we can, using equation (14), determine the relation linking this part of the tensor with the dislocation density field $\alpha^{(m)}_{kl}$:

$$\alpha^{(m)}_{kl} = \frac{1}{4(\bar{\nu}+\nu)}\epsilon_{lmn} s^{(m)}_{km,n} + \tfrac{1}{2}\epsilon_{lmn}\varphi_{[km],n}. \tag{16}$$

In the symmetric micromorphic theory the antisymmetric field $\varphi_{[km]}$ does not cause the stress field directly through the constitutive relations. However, $\varphi_{[km]}$ is related to rotations resulting from differences between the relevant diagonal components of the microinertia tensor, i.e. from the inertial properties of the elements composing the internal structure of the medium. According to the formulae given by Teisseyre (1973), we have

$$\varphi_{[km]} = \frac{1}{2I_k} \varphi_{km}(I_k - I_m), \tag{17}$$

where indices k, m are not summed.

Hence, we obtain

$$\epsilon_{lmn} s^{(m)}_{km,n} = 4(\bar{v} + v)\,\alpha^{(m)}_{kl} + 2(\bar{v} + v)\,\Psi_{l,k}, \tag{18}$$

where $\varphi_{[km]} = \epsilon_{ikm} \Psi_i$, $\quad \Psi_{i,i} = 0$.

Both the dislocation field and the rotation field Ψ_l (connected with the distribution of the microinertia tensor, i.e. with the nature of internal structure of the medium) are considered here as known quantities. In equation (18) they are treated as sources of stress field $s^{(m)}_{km}$. For the stress field $s^{(m)}_{km}$ we can introduce the relevant Airy function $U^{(m)}$, defined in the same manner as it was done in the case of equation (4). We obtain

$$\epsilon_{lkn} U^{(m)}_{,ssn} = 4(\bar{v} + v)\,\alpha^{(m)}_{kl} + 2(\bar{v} + v)\,\Psi_{l,k}. \tag{19}$$

For other types of the micromorphic medium one can find similar relations between the dislocation field and the stress field.

Now we will consider the distribution of dilatations. In a similar manner as it was done above, nonelastic volumetric deformations can be linked by direct relations with stresses.

As before we will consider Maxwell's plastic medium. It is more convenient to rewrite relation (3) applying the stress deviator; using relations (1) we obtain relation analogous to (3) but in a more general form, valid for any deformation field $e^{(pl)}_{km}$.

$$\frac{1}{2\mu} \epsilon_{tsk} \epsilon_{lmn} \hat{t}_{km,ns} + \frac{1}{3(3\lambda + 2\mu)} (t_{,tl} - \delta_{tl} t_{,nn}) = \epsilon_{tsk} \epsilon_{lmn} e^{(pl)}_{km,ns}. \tag{20}$$

Moreover, this relation remains valid for $\mu = 0$, when the first term on the left-hand side is rejected.

For dilatation $\gamma = e^{(pl)}_{nn}$, substituting $e^{(pl)}_{nm} = \frac{1}{3}\delta_{nm}\gamma$ into (20), we obtain:

$$\frac{1}{3\lambda + 2\mu} (t_{,tl} - \delta_{tl} t_{,nn}) = \gamma_{,tl} - \delta_{tl} \gamma_{,ss}. \tag{21}$$

The obtained differential relation is consistent with the constitutive equation for dilatations proposed by Nur (1975) in the form

$$\gamma = \delta t^n, \tag{22}$$

for $n = 1$ and $\delta = 1/(3\lambda + 2\mu)$.

Let us notice that the dilatation for the micromorphic medium can also be connected with the field of microdisplacements φ_{in} and $\varphi = \varphi_{nn}$.

3. The glacier motion. Now we will discuss some applications of the obtained relations between the stress field and defect field in the analysis of processes accompanying plastic flow of a glacier.

Basic equation (3), describing the relation between the stress and dislocation fields, can be used the other way round: we can determine the distribution of dislocations if we know the stress field for a certain plasticity problem. Let us take as an example the glacier motion described by the stress field according to Nye (1957)

$$\begin{aligned} \sigma_{xx} &= -\rho\gamma y\cos\alpha \pm 2\sqrt{\tau^2-(\rho\gamma y\sin\alpha)^2}\,, \\ \sigma_{yy} &= -\rho\gamma y\cos\alpha\,, \\ \tau_{xy} &= -\rho\gamma y\sin\alpha\,, \end{aligned} \tag{23}$$

and

$$\sigma_{zz}=\frac{\lambda}{2(\lambda+\mu)}(\sigma_{xx}+\sigma_{yy})\,,$$

provided that deformation $e_{zz}=0$. It is easy to calculate for this field the left-hand side of equation (3). Its only non-vanishing components lead to the formula (Teisseyre, 1977):

$$\begin{aligned} \frac{\partial}{\partial y}\alpha_{13} &= \mp\frac{\lambda+2\mu}{4\mu(\lambda+\mu)}\rho^2\gamma^2\sin^2\alpha\frac{\partial}{\partial y}\left(\frac{y}{\sqrt{\tau^2-(\rho\gamma\sin\alpha)^2}}\right), \\ \frac{\partial}{\partial y}\alpha_{23} &= 0\,. \end{aligned} \tag{24}$$

Thus, for the dislocation density field we can write

$$\begin{aligned} \alpha_{13} &= \mp\frac{\lambda+2\mu}{4\mu(\lambda+\mu)}\rho^2\gamma^2\sin^2\alpha\frac{y}{\sqrt{\tau^2-(\rho\gamma y\sin\alpha)^2}}\pm\beta x+\eta\,, \\ \alpha_{23} &= \pm\delta x+\varepsilon\,, \end{aligned} \tag{25}$$

where the integration constants β, η, δ, ε and their signs should be chosen taking into account the character of the glacier motion (extensive or compressive).

However, to have a complete picture of the relationship between the stresses and dislocations, we should include the equations describing the dynamics of dislocations. Therefore, we will now consider the problem of motion of dislocations, and a model of a medium in which the changes in the defect distribution affect the migration of regional deformation and stress fields.

The dilatation processes are also of great importance in the glacier motion and the formation of cracks, in particular in the region of open cracks. Interpreting the glacier motion as a plastic process connected with the medium dilatation and using equation (21), we obtain from stress field (23) the following formula for dilatations:

$$\gamma=\frac{1}{2(\lambda+\mu)}[-2\rho g y\cos\alpha\pm2\sqrt{\tau^2-(\rho g y\sin\alpha)^2}]\mp\alpha y\pm\beta x+\eta\,, \tag{26}$$

where α, β, η are the integration constants (the upper and lower signs refer to extensive and compressive motions, respectively). Taking into account (22) we could neglect the integration constants, but it is more convenient to preserve a possible dependence upon variable x.

In the real glacier motion both the dislocation and dilatation processes participate most probably in the proportion corresponding to the type of the motion. Phenomenologically, this is expressed by the dependence of stresses on the deformation rate for diffusion and dislocation processes. The participation of these processes depends upon the conditions of motion: pressure and temperature. In the problem under consideration, however, we do not deal with the process of dilatation diffusion. The dilatation processes should be understood here as a kind of deformation appearing in the plastic flow region and cooperating with the dislocation processes in the formation of open cracks.

Starting with the formula

$$e_{is}^{(pl)} = \tfrac{1}{3}\gamma\delta_{is} + e_{is}^{(dys)}, \tag{27}$$

where $e_{is}^{(dys)}$ denotes the plastic part of deformation connected with the dislocation processes, we can now define the following invariants:

$$2\epsilon^2 = e_{is}^{(pl)}\, e_{is}^{(pl)} = \tfrac{1}{3}\gamma^2 + 2\bar{e}^{(dys)^2}, \tag{28}$$

where $2\bar{e}^{(dys)^2} = e_{is}^{(dys)}\, e_{is}^{(dys)}$.

In accordance with (28) we will now introduce a certain function $\theta(x, y)$ describing the type of glacier motion by the following relations

$$\tfrac{1}{3}\gamma^2 = 2\epsilon^2\theta, \qquad 2\bar{e}^{(dys)^2} = 2\epsilon^2(\theta - 1), \tag{29}$$

under the condition $0 \leqslant \theta \leqslant 1$. At the glacier surface, $y=0$, in the region Ω in which open cracks are absent we can put $\theta(x_0, 0)=0$, where $x_0 \in \Omega$. The glacier motion in this region depends upon the dislocation processes. As already mentioned, the opposite case $\theta=1$, in which the motion would depend exclusively on the dilatation processes, does not seem real. Finally, let us note that of great importance in the glacier motion under consideration is water and ice thawing in the regions of increased pressure, e.g. in the vicinity of defects. One can assume that dilatation is accompanied by the increased amount of interstitial water; this can be expressed by the proportionality of dilatations and porosity q of the medium filled with liquid:

$$\gamma = \alpha q. \tag{30}$$

However, in the vicinity of the glacier surface the cracks are filled with air and the role of liquid is secondary.

We can now introduce a more general relation between the deformation field and dilatation. Let ν_n be the normal to the crack. Let the positive value of the increment during dilatation $\dot{\gamma}$ mean the opening of cracks. Cherry et al. (1975) put

$$e_{ns}^{(pl)} = \nu_n \nu_s \gamma. \tag{31}$$

For the case under consideration, $\nu_n = (1, 0, 0)$, the dilatation cracks are perpendicular to the x-axis direction, coinciding with the glacier motion; their opening is also consistent with this direction. As we already mentioned, the integration constants ε, β and η can be neglected. In this case, taking into account the condition $\gamma \geqslant 0$, we can easily determine from (26) the depth range of cracks as a function of the type of glacier motion. For the extensive motion (the upper sign in (26)), we have

$$y_d = \frac{\tau}{\rho q}\,.$$

For the compressive motion, both terms in (26) are negative and the cracks are not formed.

At the end let us return to the general formulae for dilatation in nonlinear deformation processes. We will use the differential geometry concepts, which we already quoted earlier in this paper. The dilatation connected with plastic distortion $u_{\alpha\beta}$ is described by the formula

$$\gamma = u_{\alpha\alpha}\,.$$

In linear approximation the torsion tensor and spatial curvature (in an imaginary state with no stresses) can be expressed by distortion

$$S_{\mu\gamma\alpha} = 2u_{\alpha\,[\mu,\,\gamma]}\,, \qquad R^x = 4S_{\alpha\lambda\alpha,\,\lambda} = 4(u_{\alpha\alpha,\,\gamma\gamma} - u_{\gamma\alpha,\,\gamma\alpha})\,,$$

where R^x is understood to mean this part of the curvature (obtained through contraction of the relevant tensor) which depends exclusively on distortion $u_{\alpha\beta}$.

Putting $u_{\gamma\alpha} = \frac{1}{3}\delta_{\gamma\alpha}\gamma$ we obtain

$$R^x = \tfrac{8}{3}\gamma_{,\gamma\gamma}\,. \tag{32}$$

From this formula we can see that quantity $(3/32\pi)\cdot R^x$ describes the dilatation source field. One can notice here a distant analogy to the equations of general theory of relativity.

The quantities appearing in the above formula can also be linked with the distribution of dislocations, in particular rotational dislocations – disclinations. We obtain from this formula joining incompatibility with curvature (comp. (1)):

$$\eta = \eta_{\alpha\alpha} = \tfrac{1}{2}R^x\,,$$

and

$$\eta = \tfrac{4}{3}\gamma_{,nn}\,. \tag{33}$$

In particular, for the distortion field connected with thermal stresses

$$u_{\alpha\nu} = \alpha\delta_{\alpha\nu}(T - T_0)\,,$$

we have

$$R^x = \gamma\alpha(T - T_0)_{,\gamma\gamma}\,. \tag{34}$$

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ZWIĄZEK ROZKŁADU DEFEKTÓW Z POLEM NAPRĘŻEŃ. RUCH LODOWCA

Streszczenie

W pracy podano związki różniczkowe między rozkładem defektów (dyslokacje i dylatacje) a polem naprężeń dla ośrodka plastyczno-sprężystego Maxwella. Przedstawiono ponadto zastosowania dla problemu ruchu lodowca jako zjawiska określonego przez warunki plastycznego płynięcia.

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MIGRATION OF SEISMIC BELTS. MOTION OF DEFECTS

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A b s t r a c t

A possible displacements of deformation zones resulting from the motion of defects is considered. The defects penetrating the medium bring local stress fields and produce changes in the material constants of the medium. Considerations on the laws of motion of the defects, in particular of dislocations, enable us to introduce the notion of migration of deformation zones.

1. Introduction

Teisseyre et al. (1974) have introduced the concept of a seismic belt which refers to the region of active stress concentration; this region is associated with the processes of elastic energy release in earthquakes. However, considerable stresses produce durable material changes; this may result in a displacement of seismically active belts to adjacent regions, which are more susceptible to deformations, being still untouched by destructive action of strong stresses. In the above mentioned paper, the seismic zone consists of a series of subregions defined as seismic belts; rheological processes can produce secular changes in their spatial configuration. The appendix of the cited paper gives a simple model for calculating the displacement of elastic energy concentration as a result of the assumed rigidity changes μ, provided that the stress field remains constant.

In the present paper we make an attempt to determine the migration of deformation zones resulting from the motion of defects. Thus, the changes in the material constants are assumed to be connected with the presence of defects penetrating the medium. In the first part of the paper, laws of motion of the defects are considered.

2. Equation of motion of dislocation fields

Starting from the equation for a force acting upon a dislocation line element ξ_k:

$$F_s = \epsilon_{skn} \Delta u_i \sigma_{in} \xi_k, \tag{1}$$

we can formally write the equation of motion of this element as follows (the inertial forces connected with the definition of ''mass'' of a dislocation element are neglected):

$$\nu \frac{\xi_k v_s}{\xi v} \dot{b} \xi_k + \epsilon_{nsk} b_i S_{in} \xi_k = \epsilon_{nsk} b_i \sigma_{in} \xi_k \tag{2}$$

where $b^2 = b_s b_s$.

The first term, having the same direction as the force vector, represents the viscous friction connected with the dislocation displacement. The other one, which has a structure of the expression for force (right-hand side), corresponds to the resistance determined by static strength S_{ij}. The effective viscosity coefficient ν can, in general, depend upon stress field σ_{in}. The Burgers vector $\Delta u_i = b_i$ is understood here to be a continuous representation with the derivatives; in accordance with the law of conservation we have

$$\dot{b} = - v \,\mathrm{grad}\, b$$

where v is the velocity of dislocation motion. Consequently, we obtain

$$- \nu \frac{\xi_k v_n v_s}{\xi v} b_{,n} \xi_k + \epsilon_{nsk} b_i S_{in} \xi_k = \epsilon_{nsk} b_i \sigma_{in} \xi_k. \tag{3}$$

As can be seen, the first term was chosen so as to represent the proportionality of friction to velocity v and gradient b. The sense of this choice can also be shown by comparing the dislocation motion phenomena with the description of these phenomena in a macroscopic approach to creep in the viscoelastic medium. To this end, let us introduce certain vector l_p lying in the dislocation plane and having the same direction as the dislocation motion. Stresses on an element of the line in the vicinity of the dislocation front can be obtained upon dividing the force (right-hand side of equation (1)) by a surface element lying in the dislocation plane $\epsilon_{nkp} \xi_k l_p$ (k - constant). We obtain here an equation of the following type

$$\nu\left(\frac{\dot{b}}{l}\right) + \bar{s}\left(\frac{b}{l}\right) = \bar{\sigma}$$

Identifying the expressions in parentheses as deformation rate $\dot{\bar{\varepsilon}}$ and deformation $\bar{\varepsilon}$, respectively, we can compare this equation with the constitutive relation

$$\nu\dot{\bar{\varepsilon}} + \mu\bar{\varepsilon} = \bar{\sigma}.$$

Let us introduce now the dislocation density tensor

$$\alpha_{ik} = \frac{\xi_k \sum b_i}{\xi \Delta S} = \frac{\xi_k \; n \; b_i}{\xi \Delta S} . \tag{4}$$

In this formula we treat ξ_k/ξ as an unit vector of the dislocation line; ΔS is the surface element perpendicular to it; $\sum b_i$ or nb_i is the number of dislocation lines crossing this surface element.

The equation of motion for a set of dislocations represented by tensor α_{ik} takes the following form (we divide (1) by volume element $(\xi\Delta S)$):

$$\nu \frac{v_s \; \alpha_{ik}}{v\alpha} \dot{\alpha}_{ik} + \epsilon_{nsk} \; \alpha_{ik} \; s_{in} = \epsilon_{nsk} \; \alpha_{ik} \; \sigma_{in} \tag{5}$$

where $\alpha^2 = \alpha_{ik} \; \alpha_{ik}$.

Making use of the law of conservation we get in accordance with (3):

$$-\nu \frac{\alpha_{ik} \; v_s \; v_n}{\alpha v} \alpha_{ik,n} + \epsilon_{nsk} \; \alpha_{ik} \; s_{in} = \epsilon_{nsk} \; \alpha_{ik} \; \sigma_{in}. \tag{5a}$$

Introducing now the dislocation current density tensor (Holländer, 1960),

$$\frac{1}{c} I_{ikn} = \alpha_{ik} \; v_n$$

where c is the transversal wave velocity, we obtain, provided that $v_{n,n} = 0$, the following relation:

$$-\frac{\nu v_s \; \alpha_{ik}}{c \; v\alpha} I_{ikn,n} + \epsilon_{nsk} \; \alpha_{ik} s_{in} = \epsilon_{nsk} \; \alpha_{ik} \; \sigma_{in} \tag{6}$$

or

$$-\frac{\nu I_{iks}}{c \; I} I_{ikn,n} + \epsilon_{nsk} \; \alpha_{ik} \; s_{in} = \epsilon_{nsk} \; \alpha_{ik} \; \sigma_{in} \tag{6a}$$

where $I^2 = I_{abc}I_{abc}$.

Neglecting the resistance term S_{in} and making use of the relation between the dislocation current density tensor and distortion u_{ip} (Teisseyre, 1967), we have

$$\frac{1}{c} I_{ikm} = \epsilon_{kmp} \dot{u}_{ip}.$$

Whence we obtain also the equation for the distortion field changes:

$$- \nu \frac{v_s \alpha_{ik}}{v\alpha} \dot{u}_{is,n} = \alpha_{ik} \sigma_{in}.$$

Let us return now to equation (6) for a particular case of screw dislocation $b \parallel \xi$, $\xi = (0, \xi, 0)$; we obtain:

$$\frac{\nu}{c\alpha} = I_{221,1} + S = \sigma_{23},$$
$$-\frac{\nu}{c\alpha} I_{223,3} + S = \sigma_{21}, \qquad (7)$$

for motion in the x_1 and x_3 directions, respectively.

Similarly for edge dislocations $b \perp \xi$ we have

$$\frac{\nu}{c\alpha} I_{121,1} + S = \sigma_{13},$$
$$-\frac{\nu}{c\alpha} I_{323,3} + S = \sigma_{13}. \qquad (8)$$

The ratio of the corresponding components of the current density tensor determines the slope of the plane of motion in the (x_1, x_3) cross-section; for screw and edge dislocations we have, respectively:

$$I_{223}/I_{221} = \operatorname{tg} \alpha, \quad I_{123}/I_{121} = \operatorname{tg} \alpha. \qquad (9)$$

From the law of dislocation density conservation follows the relation:

$$\int \dot{\alpha}_{pn} \, dV = - \frac{1}{c} \int I_{pns} n_s d\sigma,$$

which on the boundary of two media leads to the following boundary condition (the normal to the boundary between the two media has the x_3-axis direction):

$$\dot{\beta}_{pn} = - \left[\left(\frac{1}{c} I_{pn3} \right)^{II} - \left(\frac{1}{c} I_{pn3} \right)^{I} \right], \qquad (10)$$

where β_{pn} is the surface density of the dislocation tensor. Apart from conditions (9) and (10), the remaining conditions on the boundary of the two media can be obtained from relations (7) or (8).

Neglecting resistance S we obtain:

$$\left(\frac{\nu}{c\alpha} I_{221}\right)^{II} = \left(\frac{\nu}{c\alpha} I_{221}\right)^{I}$$

and

$$\left(\frac{\nu}{c\alpha} I_{121}\right)^{II} = \left(\frac{\nu}{c\alpha} I_{121}\right)^{I},$$

$$\left(\frac{\nu}{c\alpha} I_{323,3}\right)^{II} = \left(\frac{\nu}{c\alpha} I_{323,3}\right)^{I}.$$

3. The migration of deformation fields

Dynamic processes in the Earth's interior can be divided into fast changes manifesting themselves in tectonic movements and recorded as earthquakes, and changes taking place slowly in time. The mechanism of these slow displacements, connected with the material creep, is explained either by the motion of dislocations or by the diffusion of dilatations. Gordon (1965) has drawn the attention to the fact that for high temperatures - corresponding to the conditions within the Earth's mantle - the diffusive creep is in the main part responsible for the displacement processes and that these processes can be described by the effective viscosity coefficient

$$\hat{\sigma} = \nu \dot{\hat{e}} \tag{11}$$

where the circumflex denotes the deviator of the relevant stress and deformation tensor.

It seems nevertheless that in seismic region strong nonhydrostatic stresses may produce the motion of dislocations, which may play a considerable role in the processes of deformation and migration of displacement fields. It is now estimated that considerable part of global displacements and motions in the Earth's mantle is indeed realized by the slow, creep-type displacements. ''Silent'' earthquakes in the ultralow frequency region could be intermediate form between these motions and the real earthquakes. Both the creep processes and other movements manifested in the form of violent displacements and earthquakes are connected with the motion of a defects.

In our considerations, the objects responsible for the creep mechanisms, i.e. dilatations and dislocations, will be treated as objects penetrating the medium. Their density is denoted by ϱ_d, the density of the medium with no defects being ϱ_m. Thus, the partial densities ϱ' and ϱ'' are, respectively:

$$\varrho' = (1 - q)\varrho_m, \quad \varrho'' = q\,\varrho_d, \quad \varrho = \varrho' + \varrho''$$

where q is the ''porosity'' coefficient determining the concentration of defects.

By analogy to the porous media we will now introduce the dilatation flow equation (which may be responsible for the dilatation diffusion process):

$$\text{grad } p = - D(\dot{u}'' - \dot{u}') \tag{12}$$

where u' is the partial displacement in part of the medium with no defects, u'' is the displacement of defects, $D = \nu \varrho q^2/k^2$, and k is the ''permeability'' coefficient. Let us note that in accordance with the constitutive relation for dilatations (Nur, 1975), we have

$$\gamma = \delta\, p^n$$

where $\gamma = u''_{s,s}$.

Using further the porous medium formalism we can write the following partial equations of motion:

$$\begin{aligned} &- \varrho' \ddot{u}'_i + (\lambda + \mu) u'_{s,si} + \mu u'_{i,ss} + D(\dot{u}''_i - \dot{u}'_i) = 0, \\ &- \varrho'' \ddot{u}''_i + \varkappa u''_{s,si} + \frac{\nu}{3} \dot{u}''_{s,si} + \frac{\nu}{2} \dot{u}''_{i,ss} - D(\dot{u}''_i - \dot{u}'_i) = 0 \end{aligned} \tag{13}$$

where the constitutive equations of a viscous, compressible medium are adopted for the field of defects; in particular, they comprise the constitutive equation for dilatations in the case of n = 1.

Introducing for u'_i and u''_i scalar and vector potentials φ, ψ_1 and Φ, Ψ_1, respectively, we obtain, ignoring the terms of inertia,

$$\begin{aligned} &- D\dot{\varphi} + (\lambda + 2\mu)\Delta\varphi + D\dot{\Phi} = 0, \\ &- D\dot{\Phi} + \varkappa\Delta\Phi + \frac{5}{6}\ \nu\Delta\dot{\Phi} + D\dot{\varphi} = 0. \end{aligned} \tag{14}$$

According to (12), $D(\dot{u}'' - \dot{u}')$ is given through gradient of a certain quantity; it follows from this fact that $D(\dot{\Psi} - \dot{\psi}) = 0$. In this manner we obtain for vector potentials the noncoupled equations:

$$\mu \Delta \psi_1 = 0,$$
$$\frac{\nu}{2} \Delta \dot{\Psi}_2 = 0. \qquad (15)$$

Changes connected with slow creep are described by the field u'', i.e. by potentials Φ and Ψ_1.

Considering the displacement of dislocation field we should introduce, in place of equation (12), the equations of motion based on the formula for forces acting upon dislocations (1). The dislocation density α_{ik} can be expressed by the number of dislocation lines crossing a unit surface (4). Hence, the force acting on a volume unit $\Delta V = \xi \Delta S$ containing the dislocation field is

$$f_s = \frac{nF_s}{\Delta V}, \quad f_s = \epsilon_{skn}\, \sigma_{in}\, \alpha_{ik}.$$

In accordance with the equation of dislocation motion (5a) we obtain, neglecting the resistance term:

$$f_s = \nu \left(\frac{v_s\, \alpha_{ik}}{v\alpha}\right) \dot{\alpha}_{ik} = -\nu \left(\frac{v_s\, \alpha_{ik}}{v\alpha}\right) \alpha_{ik,n} v_n$$

where ν is the effective coefficient of viscosity, and v_s is the mean velocity of dislocation motion.

Consequently, by analogy to (12), we obtain the equation

$$f_s = \epsilon_{skn}\, \sigma_{in}\, \alpha_{ik} = \bar{D} v_s = \bar{D}(\dot{u}''_s - \dot{u}'_s) \qquad (16)$$

where $\bar{D} = -\nu \frac{\alpha_{ik}\, v_n}{\alpha v}\, \alpha_{ik,n}$.

Introducing now potentials into equations (13) and making use of the fact that quantity $\bar{D}(\dot{u}'' - \dot{u}')$ is given through rotation (16) - we obtain the following, noncoupled equations for the scalar part

$$(\lambda + 2\mu)\Delta\varphi = 0,$$
$$\varkappa \Delta \Phi + \frac{5}{6} \nu \Delta \dot{\Phi} = 0 \qquad (17)$$

and the coupled equations for the vector potentials:

$$-\bar{D}\psi_1 + \mu\Delta\psi_1 + \bar{D}\dot{\Psi}_1 = 0,$$
$$-\bar{D}\dot{\Psi}_1 + \frac{\nu}{2}\Delta\dot{\Psi}_1 + \bar{D}\dot{\psi}_1 = 0. \qquad (18)$$

As before, for slow changes due to creep processes we neglected the terms with time derivatives of the second order.

Moreover, we assumed that quantity $\bar{D}$ is approximately constant, at least for the considered range of dislocation density. Otherwise, the form of equation of motion (16) should be more complicated because of quantity $v_s = \dot{u}''_s - \dot{u}'_s$, and the coupling forces contained in the last terms of the equation of motion (13) should be changed correspondingly. The viscosity coefficient ν, which also appears in $\bar{D}$, cannot be treated always as a constant parameter for dislocation processes. This results from the relation between the deformation rate and stresses for dislocation creep. Thus, the complicated form of coefficient $\bar{D}$ itself brings on serious doubts as to the validity and range of the assumptions made.

Let us return now to the first case described by slow deformations connected with diffusive creep processes. Assume that the pressure gradient is constant, thus due to (12), we can put in first approximation:

$$\dot{\Phi} = \varepsilon \dot{\varphi} \quad \text{where } \varepsilon < 1. \tag{19}$$

In this case, the first one of equations (14) leads to the diffusion equation

$$\dot{\varphi} - n^2 \Delta \varphi = 0 \tag{20}$$

where $n^2 = \dfrac{\lambda + 2\mu}{D(1 - \varepsilon)}$.

This equation describe changes in the stress field due to the creep processes. Of course, field u'' when related to a volume unit is here much smaller than field u'; this is so on account of negligible density of defects ϱ'' as compared to ϱ', rather than on account of relation $\dot{u}'' = \varepsilon \dot{u}'$. Even if the velocity of motion of individual defects highly exceeds the mean velocity u of the medium, the mean value of u'' per volume unit will always be smaller.

The second one of equations (14) takes the form

$$D\left(\frac{1}{\varepsilon} - 1\right)\dot{\Phi} + \varkappa \Delta \Phi + \frac{5}{6}\nu \Delta \dot{\Phi} = 0.$$

In the case of dislocation creep, we can treat in a similar manner system (18). Putting in first approximation:

$$\dot{\Psi}_1 = \gamma \dot{\phi}_1, \tag{21}$$

we obtain the diffusion equation for field ψ_1:

$$\dot{\psi}_1 - m^2 \Delta \psi_1 = 0 \tag{22}$$

where $m^2 = \frac{\mu}{\bar{D}(1-\gamma)}$,

and for Ψ_1 the equation:

$$\bar{D}\left(\frac{1}{\gamma} - 1\right)\dot{\Psi}_1 + \frac{\nu}{2}\Delta\dot{\Psi}_1 = 0.$$

Thus, similarly as before when the coupling of fields φ and Φ yielded the conclusion that for diffusive creep (dilatation motion) the potential field φ is subject to diffusion laws, also here, for the creep connected with dislocation motion, we arrive at the conclusion that the vector field ψ coupled with Ψ is governed by diffusion.

In real cases, the systems of equations (14) and (18) should be actually solved without additional assumptions (19) and (21). In particular, the coupling of these equations through factors D and $\bar{D}$ enables us to apply the method of consecutive approximations.

The derived diffusion equations (20) and (22), on the other hand, have here a demonstrative sense, explaining the changes in stresses related to field u', which take place due to rheological changes in the medium. In other words, the deformation of the medium connected with this field is subject to diffusion; the migration of defects, affecting the properties of the medium, produces changes in the distribution of deformation belts. It seems that this reasoning can explain the secular and spatial changes in seismic systems of various regions. The displacement field u' of the medium is coupled with the field of defects; their motion affects the changes in configuration of deformation belts in the medium.

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MIGRACJA STREF SEJSMICZNYCH. RUCH DEFEKTÓW

S t r e s z c z e n i e

W pracy rozważana jest możliwość przesuwania się stref odkształceń na skutek ruchu defektów. Defekty przenikające ośrodek niosą ze sobą pola lokalnych naprężeń i powodują zmiany stałych materiałowych ośrodka. Rozważania nad prawami ruchu defektów, a w szczególności dyslokacji, umożliwiają wprowadzenie pojęcia migracji odkształceń.

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A THEORETICAL APPROACH TO MODEL THE SEQUENCE OF PREMONITORY STAGES BEFORE AN EARTHQUAKE

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A b s t r a c t

The paper contains a theoretical approach for describing the development of premonitory phenomena before an earthquake. The processes ''dislocations to crack'' explain very early stages of the sequence. Microcracks and joints contribute to a dilation stage, while during the last stage the reverse process of convergency and collective crack grouping leads to material fracturing. Phenomenological laws for each stage are discussed and a theoretical approach based on a continuum model is presented.

For better understanding of earthquake process and its complex sequence of premonitory phenomena it is desirable to include these phenomena in a model of a continuum or at least in a sequence of such models.

We will consider here a Maxwell body which undergoes some changes caused by the development of defects and by the changes of stresses confining the body. A sequence of premonitory stages, which describe behaviour of the body, will be defined by the sequence of some limit conditions and phenomenological laws governing plastic strains.

We start with an elastic medium, later including plastic deformations caused by the dislocation growth and interactions, while microfracture mechanics deals already with crack processes. Here the total deformation tensor ε is always regarded as a sum composed of the elastic $\mathbf{e}$ and plastic deformation ϵ:

$$\varepsilon = e + \epsilon . \qquad (1)$$

The plastic part refers both to dislocation and crack processes.

The compatibility condition requires that

$$\text{rot rot } \mathcal{E} = \text{rot rot } \mathbf{e} + \text{rot rot } \epsilon = 0. \tag{2}$$

Hence we get the following relations, in which the incompatibility tensor η appears by definition (T e i s s e y r e, 1975):

$$\eta = - \text{rot } \alpha = \text{rot rot } \mathbf{e} = - \text{rot rot } \epsilon, \tag{3}$$

where α is the dislocation density tensor.

The requirement defining the beginning of elasto-plastic behaviour would be given by a certain limit condition for the stresses τ. It is usually expressed by a relation of the following form

$$f(\tau) = 0, \tag{4}$$

for the stress invariant

$$2\tau^2 = \tau\tau^T.$$

Condition (4) is not understood here in a sense of the ideal plasticity condition. The plastic behaviour is related to stress excèss and its appearence should also influence the state of elastic deformation. This probably may be achieved by some additional compability condition for stresses and will be considered later. The stresses in our Maxwell body are subject to the elastic stress-strain relation

$$\mathbf{e} = \frac{1}{2\mu}\tau - \frac{1}{2\mu(3\lambda + 2\mu)} \mathbf{1} \tau^0, \tag{5}$$

where the upper index zero denotes the trace operator

$$\text{tr } \tau = \tau^0 \tag{6}$$

and $\mathbf{1}$ denotes the unit tensor.

From compatibility condition (2) and incompatibility definition (3) the following relations for stresses (5) are obtained:

$$\eta = \frac{1}{2\mu} \text{rot rot } \tau - \frac{\lambda}{2\mu(3\lambda + 2\mu)} \left(\mathbf{1} \Delta \tau^0 - \text{grad grad } \tau^0\right), \tag{7}$$

$$\eta = \frac{1}{2\mu} \text{rot rot } \hat{\tau} - \frac{1}{3(3\lambda + 2\mu)} \left(\mathbf{1} \Delta \tau^0 - \text{grad grad } \tau^0\right), \tag{8}$$

$$\eta = - \text{rot rot } \hat{\epsilon} - \frac{1}{3} \left(\mathbf{1} \Delta \epsilon^0 - \text{grad grad } \epsilon^0\right), \tag{9}$$

where the ''circumflex'' refers to the deviatoric part of the tensor under consideration, e.g.:

$$\hat{\tau} = \tau - \frac{1}{3} \mathbf{1} \tau^0. \tag{10}$$

The dislocation phase of the plastic behaviour is assumed to be governed by the Glen power law:

$$\dot{\varepsilon} = A\,\tau^{n}, \qquad (11)$$

where the invariant t is given by relation (5) and similarly we have here

$$2\,\dot{\varepsilon}^{2} = \dot{\varepsilon}\dot{\varepsilon}^{T}. \qquad (12)$$

Assuming the validity of relation (9) we must be aware, however, that the plastic strains are already bounded to stresses by the compatibility relations, namely from (8) and (9) some compatibility equation for stresses may follow unless the strain rate $\dot{\varepsilon}$ is considered as independent of the plastic strain tensor $\dot{\varepsilon}$.

The dislocation density tensor is related to the shear stress field by the differential equation which follows from (3) and (7) or (3) and (8):

$$\mathrm{rot}\,\alpha = -\frac{1}{2\mu}\,\mathrm{rot}\ \mathrm{rot}\,\hat{\tau} + \frac{1}{3(3\lambda + 2\mu)}\left(1\,\Delta\,\tau^{0} - \mathrm{grad}\ \mathrm{grad}\ \tau^{0}\right). \qquad (13)$$

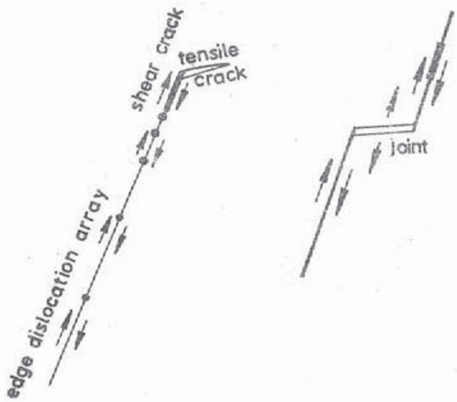

Fig. 1. The examples of formations of an open crack and a joint

Thus, for a given problem of plastic deformation the stress field determines the field of dislocation density. Dislocation grouping and concentration leads to the next stage, in which the microcracks appear. The transition process from a dislocation system to a microcrack formation was considered by S t r o h (1954). The stress concentration factor reveals the effect of dislocation array.

Screw dislocations may contribute to the formation of transversal cracks, while edge dislocations contribute both to shear and tensile cracking. Further development of microshear cracks and their propagation leads to the formation of tensile open cracks as well. The above-mentioned processes are schematically presented in Fig. 1, where the formation of a joint is also taken into account. The joint is equivalent to a system of two cracks.

The sequence: edge dislocations (shear microcracks) ⟶ tensile cracks and joints ⟶ medium dilation explains part of the premonitory sequence before an earthquake.

As it was noted, the formation of microcracks and joints leads to dilatancy. Medium dilation may be considered as the next stage of body behaviour in the sequence of phenomenological continuum models. N u r (1975) assumes that the dilatancy ϑ can approximately be described by a constitutive law of the power type:

$$\vartheta = B\,\tau^{n}, \quad \vartheta = \frac{1}{3}\,\epsilon^{0}, \tag{14}$$

where τ refers to the shear stress and can be expressed by invariant (5), while ϑ relates to the nonelastic volume increase. A constant n is close to 2 for microcrack dilatancy, while at approaches 1 for joints.

The dilation stage starts at a certain stress level under the condition that dislocation density is high enough in the medium. A threshold can thus by expressed by a limit conditon somewhat different from that given by (4):

$$g(\hat{\tau},\alpha,p) = 0, \tag{15}$$

where the stresses are separated into the deviatoric part $2\,\hat{\tau}^{2} = \hat{\tau}\,\hat{\tau}^{T}$ and the confining pressure $p = \frac{1}{3}\,\tau^{0}$ indicates the role of pressure for dilatancy. The density of dislocations is also included $2\,\alpha^{2} = \alpha\,\alpha^{T}$.

Now we can examine the consistency of dilatancy law (14) with compatibility equations (8) and (9). Putting $\hat{\epsilon} = 0$ and $\vartheta = \frac{1}{3}\;\epsilon^{0}$, according to (14) we get

$$\frac{1}{2\mu}\,\mathrm{rot\,rot}\,\hat{\tau} + \frac{1}{3(3\lambda+2\mu)}\left(\mathbf{1}\Delta\tau^{0} - \mathrm{grad\,grad}\,\tau^{0}\right) =$$

$$= -B(\mathbf{1}\Delta\,\tau^{n} - \mathrm{grad\,grad}\,\tau^{n}).$$

This equation of consistency can also be presented as follows

$$\mathrm{rot\,rot}\left(\hat{\tau} + \frac{2\mu}{3(3\lambda+2\mu)}\mathbf{1}\,\tau^{0} + 2\mu\,B\,\mathbf{1}\,\tau^{n}\right) = 0. \tag{16}$$

The last equation could also be recognized as the following stress compatibility equation

$$\text{rot rot}\ \tau^* = 0, \tag{17}$$

where $\tau^* = \hat{\tau} + \frac{1}{3}\mathbf{1}\left(\frac{2\mu}{3\lambda+2\mu}\tau^0 + 6\mu B\tau^n\right)$ constitutes certain equivalent stress field with its hydrostatic part modified by the existence of medium dilatancies.

We recognized that condition (4) expresses the beginning of plastic flow phenomena, and condition (15) describes microfracturing and dilatancy.

A typical process of microfracturing and dilatancy is presented already in Fig. 1, in which the final configuration of microfractures is shown. No attention is so far paid here to the propagation pattern and time sequence of microfracturing. We will consider this problem later.

The next stage of the material behaviour is usually related to grouping of cracks and formation of fracture. However, this stage could be preceded by the convergency stage. We consider that the body is under constant or increasing shearing load.

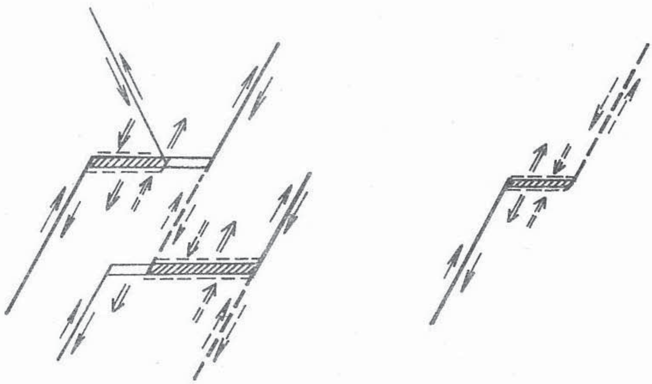

Fig. 2. Convergency phase based on preexisting dilatancy fracturing

The existing shear cracks may further be extended while the open tensile cracks and joints might be closed by the reverse propagation pattern under some shear load. This is explained in Fig. 2: the new shear cracks cause closing of openings - the convergency stage is related entirely to the existing dilatancies. The solid lines in Fig. 2 show shear cracking and formation of open cracks and joints as a result of tensile traction at the edges of shear cracks.

The increased shear cracking and the changes in its geometry distribution lead to the convergency stage marked by the dotted lines in Fig. 2.

We should note here that the sense of propagation of the defects discussed could be changed during the convergency stage in respect to that in the dilatancy stage. One of possible schemes is given in Fig. 3, where the arrows indicate the propagation path during dilation (along the solid lines) and during convergency (along the dotted lines). The reverse motion in the sense of displacements occurs only on the dilatancy objects, while shearing displacement sense remains unchanged (Fig. 2). The convergency phase can start when certain limit condition is fulfiled:

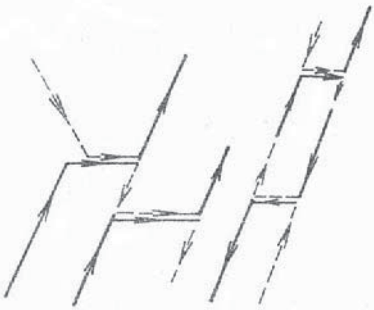

Fig. 3. A possible scheme of defect propagation in the dilatancy stage and in the convergency stage: same shear load

$$h(\hat{\tau}, \gamma, p) = 0, \qquad (18)$$

where γ describes now the dilatancy limit under the given field $\hat{\tau} = \hat{\tau}\hat{\tau}^T$, p.

This stage might be followed immediately by the formation of fracture and its propagation. It is assummed here that the fracture condition depends on the ratio $\gamma/\bar{\gamma}$, where $\bar{\gamma}$ denotes the part of dilatancies closed by the convergency process:

$$\bar{h}(\hat{\tau}, \gamma/\bar{\gamma}, p) = 0. \qquad (19)$$

T e i s s e y r e (1978–1979) assumed that the law of fracture propagation is of the form:

$$vb = C(\tau - \tau_F)^n \qquad (20)$$

where v is the defect propagation velocity, b is the local value of fracture displacement, τ is related to the shearing field, while τ_F is the friction stress.

Now we will look for a theoretical background of this law for $n = 1$ and $\tau_F = 0$.

We start with the continuity relation linking the rate of dislocation density with the dislocation flow tensor I:

$$\frac{1}{c} \mathbf{I} = \alpha \cdot \nu \qquad \text{(tensor product)},$$
$$c\dot{\alpha} + \operatorname{div} \dot{\mathbf{I}} = 0, \tag{21}$$

where c is the shear wave velocity.

According to compatibility equation (2) we have

$$-\frac{1}{c} \operatorname{rot} \operatorname{div} \mathbf{I} = \operatorname{rot} \dot{\alpha} = \operatorname{rot} \operatorname{rot} \dot{\varepsilon}. \tag{23}$$

Taking now the simplified version of the Glen law in the form describing viscous flow, $\dot{\varepsilon} = A\,\tau$, we have from (21) and (23):

$$\frac{1}{c} \operatorname{div} \mathbf{I} = \operatorname{div}(\alpha \cdot \nu) = (\nu \operatorname{grad})\alpha, \tag{24}$$

with condition div $\nu = 0$, and further on we have

$$-\frac{1}{c} \operatorname{rot} \left[(\nu \operatorname{grad})\alpha\right] = A \operatorname{rot} \operatorname{rot} \tau. \tag{25}$$

The last equation is fulfiled when the following relations are valid:

$$-\frac{1}{c} (\nu \operatorname{grad})\alpha = A \operatorname{rot} \tau,$$

or

$$\frac{1}{c} \nu \cdot \alpha = \mathbf{A}\,\tau \tag{26}$$

where the tensor **A** is given by the following formula in the index notation

$$A_{skn} = -A\,\epsilon_{skn}.$$

Equation (26) expresses the proportionality of the product $\nu\alpha$ (defect propagation velocity times defect intensity) to the shear field τ. This is the same as required in the postulated empirical law (20) for n = 1, $\tau_F = 0$. Another approach to the defect propagation law was also made by T e i s s e y r e (1979), and similar results were obtained.

We will now look for some experimental data justifying relation (20). There are some experimental data which can be used to derive the relation between the propagation velocity and the stress load. Figure 4, taken from W i e d e r h o r n (1967) and R i c e (1978), gives the velocity

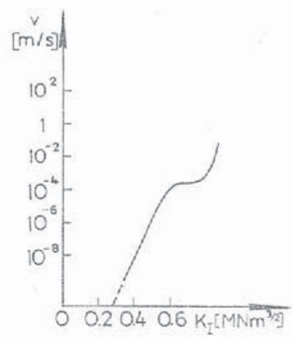

Fig. 4. Velocity of micro-crack propagation as a function of the intensity factor (W i e d e r h o r n, 1967)

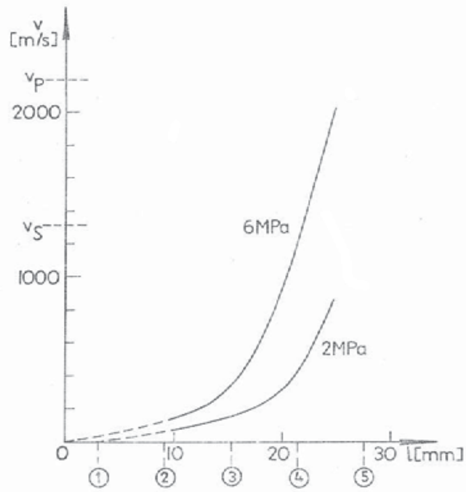

Fig. 5. Crack velocity along its path; curves for different stress loads (S h a m i n a and P a v l o v, 1979)

of microcrack propagation as a function of the intensity factor. This factor depends, of course, on the stress load. According to R i c e and S i m o n s (1976) the intensity factor with retarding friction stress amounts to $K = 1.6(\tau - \tau_F)\sqrt{l}$, where l is a crack length.

S h a m i n a and P a v l o v (1979) made several experimental tests, which can be very useful in our considerations here. Some results are given in Fig. 5, which presents the original results of the observed velocity along a crack path. The observations were made in the points marked by number 1, 2, ... 5 (the whole crack length: L = 30 mm). The crack velocity along a pre-existing cut increases from its starting point and even overpasses for some stress load the shear wave velocity, but the mean crack velocity remains always below it.

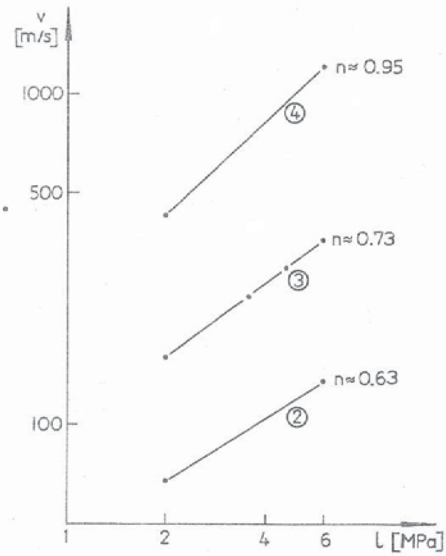

Fig. 6. The velocity of crack propagation as a function of stress load. Curves for different points along the crack path

These experimental data make it possible to construct the diagram presented in Fig. 6. It shows the crack velocity as a function of the stress load which is presented in the double logarithmic scale.

The different curves are related consecutively to the points near the crack start (1), up to the point near the crack end (5). The velocity relation is different for different points. The experimental values are marked on the curves. The first curve, for point (2), near the place where the crack starts to move, represents slow crack propagation. One can roughly assume that we deal here with a quasi-static case. This propagation curve can be approximated by formula (20) with $n \approx 0.03$. We put also $\tau_F = 0$ as the experiments are related to the preexisting cut.

Line (3) already shows the effect of crack acceleration, while line (4) refers evidently to the dynamic case. We get here $n \approx 0.73$ and $n \approx 0.95$, respectively.

The assumed relation for a rupture velocity (20) becomes much more complicated when considering stress drop and friction changes during a fracture process. Friction stress or coefficient $\mu_F = \tau_F/N$ (N is a normal load) dependes on a contact time or for a state of motion on sliding velocity (D i e t e r i c h, 1978):

$$\mu_F = \mu_{F\infty} + A \log\left(\frac{B}{v} + 1\right), \tag{27}$$

where A, B are constants, B depends on surface roughness. The velocity correction is, however, very small.

For a breakdown zone model, R i c e and S i m o n s (1976) have assumed a friction decrease with an amount of slip b. Such relation corresponds to a friction coefficient decrease for dynamic process.

For a realistic earthquake model one shall admitt also a decrease of loading stress due to internal energy release during the fracture process.

According to B u r r i d g e and K n o p o f f (1966) the energy release for a strike slip fault at a border of a half-space amounts to

$$\Delta E = \frac{\pi}{8}\,\mu l b^2\,\frac{\bar{\tau}}{\Delta\tau}, \tag{28}$$

where $\frac{\Delta\tau}{\bar{\tau}}$ is a relative stress drop, $\bar{\tau}$ is the average of stresses before and after an earthquake, and μ, l, b are rigidity, fault lenght, and slip value, respectively. Comparing the energy release value with the work done along a fault, K n o p o f f (1958) got also the following relation:

$$\frac{\Delta\tau}{\mu} = \frac{b}{d}, \tag{29}$$

where d is a fault depth. This formula is sometimes also written as follows

$$\Delta\tau = \frac{M_0}{ld^2}, \quad M_0 = \mu bS$$

where S is a fault surface.

The last formula expresses the proportionality of stress drop to slip amount. During the fracture process itself the stress drop according to J o h n s o n (1978) seems to be proportional to a particle velocity at sliding surfaces (here $\dot{b}$) and almost independent of rupture velocity (Fig. 7)

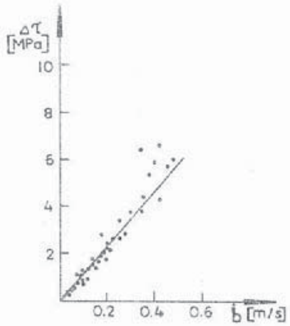

Fig. 7. Stress drop and particle velocity for stick slip (J o h n s o n, 1978)

$$\Delta\tau \sim \dot{b}. \tag{30}$$

J o h n s o n (1978) confirmed his experimental results by simple harmonic oscillator theory with constant static and dynamic friction. Average value of $\dot{b}$ is here proportional to total slip amount b, which agress with (29).

We turn now to the left side of relation (20). A more comprehensive formula shall include here also $\dot{b}$ and the inertia term $m\dot{v}$ with some effective mass of propagating defect. We assume here a more complex law of fracturing ($v = \dot{l}$):

$$m\ddot{l} + k(b\dot{l} + l\dot{b}) = C(\tau - \tau_F)^n,$$

where τ depends also on $\dot{b}$ due to a stress drop and τ_F on $\dot{l}$ due to a friction process. For a stopping phase $\tau \to \tau_F$, $\dot{l} \to 0$, $\ddot{l} < 0$ we get

$$k\dot{b}l = -m\ddot{l},$$

hence we still have a significant or even increasing particle velocity $\dot{b}$ near the fracture end.

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TEORETYCZNY MODEL SEKWENCJI PROCESÓW PRZED TRZĘSIENIEM

S t r e s z c z e n i e

W pracy przedstawiono opis stanów ośrodka przed trzęsieniem. Uwzględniono modele ośrodka ciągłego z procesami plastycznymi, dylatacją, stanem kompresji i tworzeniem się uskoku. Jakościowe zmiany charakteru procesów są określone przez pewne warunki graniczne. Możliwość definicji tych warunków zaproponowano na podstawie praw empirycznych.

A C T A G E O P H Y S I C A P O L O N I C A
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CREEP-FLOW AND EARTHQUAKE REBOUND: SYSTEM OF THE INTERNAL STRESS EVOLUTION

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Abstract

The paper presents the theory of premonitory mechanical processes and energy release during the earthquake rebound. The adopted model assumes that the medium is permeated by the continuum field of defects and that the flow of defects describes an advanced stage of deformation. The equation of internal stress evolution is derived; the energy criterium supplements the system of equations.

1. INTRODUCTION

The theory of premonitory mechanical processes and energy release during the earthquake rebound process is presented. The theory deals with the continuum field of defects (cracks) and is based on the evolution equation of internal stresses. The theory is self-consistent and its presentation does not necessarily require to study all given references; however, many quoted references explain the gradual development of this approach to the precursory mechanics and earthquake processes. Two main assumptions govern the adopted model. First, we assume that a medium is permeated by the continuum field of defects, described by the defect density field — the tensor field $\boldsymbol{\alpha}$ (α_{ik} — the first index refers to the local value of Burgers vector, the second to the element of dislocation line). Secondly, we assume that in an advanced precursory stage there is the flow process over the whole considered region, which accounts for the defect evolution (crack movements and grouping). The defect field is related to internal stresses, as follows from defect self-energies. The equation of stress evolution derived here governs the whole process: preparation of an earthquake, energy release and stress diffusion.

2. STRESS EVOLUTION AND DEFECT FLOW

The theory of evolution of internal stresses has been presented in several papers (Teisseyre, 1980; Teisseyre and Kijko, 1985). A non-linear theory of the evolution of crack population was presented by Newman and Knopoff (1982, 1983).

In our theory we assume that the continuum field of defects (cracks) is described by the density function and that the defects permeate the body structure. To account for the body response, starting first with elastic strains and stresses, we introduce consecutively the plastic and visco-elastic strains and correspondingly we introduce — to the initial regional stresses — additional stress fields, called the internal stresses. This approach corresponds to the alternatively applied Maxwell and Voigt-Kelvin models for the body response in a more and more advanced stage of deformation. However, once the equations governing the internal stresses and defect distribution are determined, we are not restricted to recall this procedure again.

The first equation of the system, which contributes to the theory of evolution of internal stresses, constitutes the relation between the defect density and its stress field (the internal stresses defined here are in general non-symmetric; they design the fracture plane): this is a kind of the constitutive law. The next equation of our system, considered further on, refers to the defect motion. The last equation is just an energy balance equation.

The stress-defect relation is assumed in the form:

$$\boldsymbol{\alpha} = A \operatorname{curl}_{(2)} \boldsymbol{\tau}, \tag{1}$$

where subscript (2) refers the curl operator to the second tensor index of $\boldsymbol{\tau}$. This form of relation is suggested by the particular solution of the compatibility condition expressed by the defect density (as equivalent to the plastic strain $\boldsymbol{\varepsilon}$) and by the Maxwell stresses (as equivalent to the elastic strain $\mathbf{e}$):

$$\operatorname{curl}_{(1)} \operatorname{curl}_{(2)} (\mathbf{e} + \boldsymbol{\varepsilon}) = 0 \tag{2}$$

with

$$\operatorname{curl}_{(2)} \boldsymbol{\varepsilon} = \boldsymbol{\alpha} \tag{3}$$

and with the Maxwell stresses given by

$$\hat{\mathbf{T}} = 2\mu \hat{\mathbf{e}}, \tag{4}$$

where $\mathbf{E} = \mathbf{e} + \boldsymbol{\varepsilon}$ is the total strain tensor; $\hat{\mathbf{e}}$, $\hat{\mathbf{T}}$ are the deviatoric parts of elastic strains and stresses, while

$$\frac{1}{2\mu} \dot{\hat{\mathbf{T}}} + \frac{1}{2\nu} \hat{\mathbf{T}} = \dot{\hat{\mathbf{E}}} \tag{5}$$

defines the visco-elastic Maxwell body response.

The flow of defects including both stick slip mechanism (discrete motion) and stable slidings (bulk motion) has been considered already (Teisseyre, 1978, 1980). The following elements help to formulate the law governing the defect flow:

— the experiments of Wiederhorn (1967); the crack velocity is found to be proportional to the intensity factor K. On the other hand, Rice and Simons (1976) have established that $K \simeq 1.6\,(T - \tau_F)\sqrt{l}$, where T is the external stress, τ_F is the friction stress and l is the crack length. Hence we have the following proportionality:

$$v \propto (T - \tau_F), \tag{6}$$

– the considerations of creep by Garofalo (1966); the creep rate can be expressed by the relation

$$\dot{\varepsilon}=Nvb\,, \tag{7}$$

where N is the number of dislocations moving with the velocity v; b is a Burgers vector;

– the experimental results of Shamina and Pavlov (1979); these experiments indicate that the crack velocity (in pre-cut experiments) should follow the relation (Teisseyre, 1980):

$$v \propto \sigma^{n}\,, \tag{8}$$

where σ is the uniaxial stress load and n is about 1.7.

The above results can be generalized by assuming the law of defect flow in the form

$$v\alpha=B(T+\tau-\tau_F)^{n}\,, \tag{9}$$

where on the left side we inserted instead of v the product $v\alpha$, which α being the mean value of defect density; $v\alpha=Nvb$ accounts for the creep rate (7) and also for the velocity differences between the crack tip v_0 and the propagation of maximal displacement b_m ($v_m b_m = v_0 b_0$); such differences $v_m \ll v_0$ (because $b_0 \ll b_m$) have been observed experimentally; on the right side of relation (9) we put the total stress field $T+\tau$ (external plus internal) minus the shear friction τ_F – according to relations (6) and (8). If the external field is nearly equal to the frictional stress or to the creep fracture strength, we can put

$$v\alpha=B\tau^{n}\,. \tag{10}$$

We will consider now this problem from a theoretical point of view. Returning to the compatibility condition (3) we notice that we can rewrite it in the following form

$$\mathrm{curl}_{(2)}\,\dot{\boldsymbol{\varepsilon}}-\dot{\boldsymbol{\alpha}}=0\,. \tag{11}$$

The plastic strain rate $\dot{\boldsymbol{\varepsilon}}$ can be now used to introduce the stress field which according to relation (5) can be taken as

$$\hat{\mathbf{T}}=2\nu\dot{\boldsymbol{\varepsilon}} \tag{12}$$

or

$$\frac{1}{2\nu}\mathrm{curl}_{(2)}\,\hat{\mathbf{T}}-\dot{\boldsymbol{\alpha}}=0\,, \tag{13}$$

where $\hat{\mathbf{T}}$ represents the total stress field $\hat{\mathbf{T}}+\boldsymbol{\tau}$ (external plus internal). Further on we will also use, instead of relation (12), the power law (the Glen law):

$$\dot{\varepsilon}=BT^{n}\,. \tag{14}$$

In equation (13) we can take advantage of the condition governing the defect flow (Holländer, 1960; Teisseyre, 1980):

$$\frac{\partial}{\partial t}\alpha_{kl}=\frac{\partial}{\partial x_n}(\alpha_{kn}v_l-\alpha_{kl}v_n)\,. \tag{15}$$

From relations (13) and (15) we arrive at the following equations (in tensor index notation):

$$\frac{\partial}{\partial x_n}[B\epsilon_{lnp}\hat{T}_{kp}-\alpha_{kn}v_l+\alpha_{kl}v_n]=0, \tag{16}$$

where B is a material constant related to a given form of flow. Using relation (1) and (16) we obtain the evolution equation of internal stresses.

Omitting the differential operator on the left-hand side of equation (16) we arrive at the proper system of equations. We take the plane problem (x, y), with functions not dependent on z, and with the defect density lines (dislocation lines) parallel to z. We obtain:

$$B(T_{xy}+\tau_{xy})=-\alpha_{xz}v_x=Av_x\left(\frac{\partial}{\partial x}\tau_{xy}-\frac{\partial}{\partial y}\tau_{xx}\right), \tag{17}$$

$$B(\hat{T}_{yy}+\tau_{yy})=-\alpha_{yz}v_x=Av_x\left(\frac{\partial}{\partial x}\tau_{yy}-\frac{\partial}{\partial y}\tau_{yx}\right), \tag{18}$$

$$B(T_{zy}+\tau_{zy})=-\alpha_{zz}v_x=Av_x\left(\frac{\partial}{\partial x}\tau_{zy}-\frac{\partial}{\partial y}\tau_{zx}\right), \tag{19}$$

$$B(T_{xx}+\tau_{xx})=\alpha_{xz}v_y=Av_y\left(\frac{\partial}{\partial y}\tau_{xx}-\frac{\partial}{\partial x}\tau_{xy}\right), \tag{20}$$

$$B(T_{yx}+\tau_{yx})=\alpha_{yz}v_y=Av_y\left(\frac{\partial}{\partial y}\tau_{yx}-\frac{\partial}{\partial x}\tau_{yy}\right), \tag{21}$$

$$B(T_{zx}+\tau_{zx})=\alpha_{zz}v_y=Av_y\left(\frac{\partial}{\partial y}\tau_{zx}-\frac{\partial}{\partial x}\tau_{zy}\right). \tag{22}$$

The form of the obtained set of equations agrees with the previously deduced equation for the defect flow (9) or (10).

The introduced internal stresses are in general non-symmetric as a result of a non-symmetric distribution of defect surfaces (which specifies the future fracture plane).

In the case of antiplane shearing the equations are reduced to

$$C(T+\tau)=v\frac{\partial}{\partial x}\tau, \tag{23}$$

$$\left(T=T_{zy}, \quad \tau=\tau_{zy}, \quad v=v_x, \quad C=\frac{B}{A}\right),$$

while for the in-plane case the shear and tension components are bounded together:

$$\begin{aligned} C(T+\tau)&=v\left(\frac{\partial}{\partial x}\tau-\frac{\partial}{\partial y}\sigma\right),\\ C(S+\sigma)&=w\left(\frac{\partial}{\partial y}\sigma-\frac{\partial}{\partial x}\tau\right), \end{aligned} \tag{24}$$

$$(T=T_{xy}, \quad \tau=\tau_{xy}, \quad S=\hat{T}_{xx}, \quad \sigma=\tau_{xx}, \quad v=v_x, \quad w=v_y).$$

For the power flow law (14) the form of the above equations changes to

$$C(T+\tau)^3 = v\frac{\partial}{\partial x}\tau \quad \text{(antiplane case, } n=3) \tag{25}$$

and similarly for the in-plane case.

The derived equations (general system (17) – (22), antiplane case (23) or (25), and in-plane case (24)) are called the evolution equations of internal stresses (Teisseyre, 1980). To solve the above systems an additional condition is required to determine the flow velocity. We will accept here the energy balance criterion (Kostrov et al., 1969; see also Aki and Richards, 1980).

3. THE [$\alpha\beta$] PROCESS – A FUNCTION OF DEFECT CREATION

In our model we assumed a priori that there exists a certain defect distribution, described by the α density. The conservation law (15) does not account for the possibility of creation (or annihilation by joining process) of new defects. We may assume that α describes positive defects, while the other density function β represents negative defects – both defined by the same rules as positive and negative dislocations. An elementary crack is thus described by a coupled set of positive and negative defects distributed along the surface of crack (Fig. 1). The creation process of such a crack will be denoted by [$\alpha\beta$]. The [$\alpha\beta$] defect

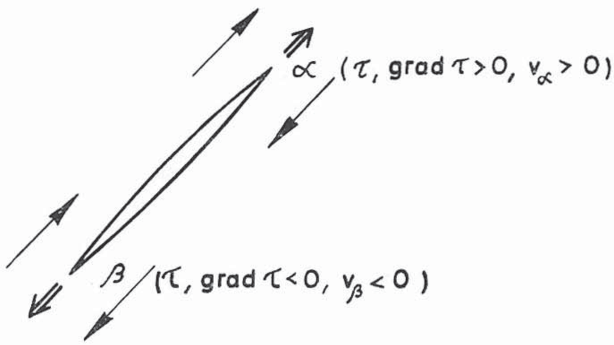

Fig. 1. The [$\alpha\beta$] operator related to the creation of an elementary crack

distribution rate described the α defect density concentrated at one end of a crack and the β defect density on the other; both are associated with the same internal field τ but with opposite stress gradients. The stress field acting on both ends of the crack, that is at the α and β densities, tends to spread the crack ends in opposite directions (Fig. 1 – double arrows). We can write

$$\frac{\partial \alpha_{kl}}{\partial t} - \frac{\partial}{\partial x_n}(\alpha_{kn} v_l - \alpha_{kl} v_n) = \sum[\alpha\beta] - \sum[\beta\alpha], \tag{26}$$

where the symbol $[\beta\alpha]$ labells the opposite process — annihilation of defects; the process is equivalent to that of joining of two neighbouring cracks (Fig. 2).

For the small distance l between the crack tips we can define the density function of $[\alpha\beta]$ process for a unit length along dislocation lines:

$$s=\lim_{l\to 0}\frac{[\alpha\beta]}{l}. \tag{27}$$

Its energy density can be compared to energies of two elementary dislocations at the

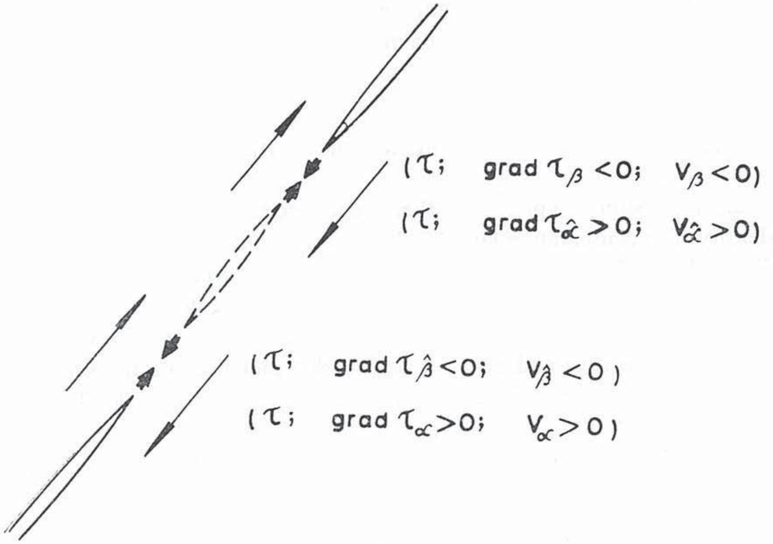

Fig. 2. The $[\alpha\beta]$ operator and joining process of two cracks: creation of virtual crack $[\hat\alpha\hat\beta]$

distance $l=2r_0$, where r_0 is the radius of dislocation line cutting off the stress singularity (Teisseyre, 1961):

$$\frac{E^{[\alpha\beta]}}{L}=\frac{\mu b^2}{4\pi}\ln 2, \tag{28}$$

with a Burger's vector b expressed by the average of defect density over the surface $\Delta s=\pi r_0^2$:

$$b^2=\alpha\alpha(\pi r_0^2)^2.$$

Further we obtain for a given surface element:

$$\frac{d}{dt}b^2=2\alpha\dot\alpha\pi^2 r_0^4=2\alpha s\pi^2 r_0^4 l,$$

where we have put $\dot\alpha=sl$ according to the preceding definitions. For the energy density rate we have

$$\frac{\dot E^{[\alpha\beta]}}{Llh}=\mu r_0^3\alpha s\frac{\pi}{4}\ln 2 \tag{29}$$

for $l=2r_0$ and $h=2r_0$ (Fig. 3).

To visualize that the crack creation process is discrete we can multiply the energy density rate defined above by the non-local Dirac function $\delta(x;\varepsilon)$, where $\delta(x;\varepsilon)\to\delta(x)$ for $\varepsilon\to 0$:

$$\dot{e}^{[\alpha\beta]}=\frac{\dot{E}^{[\alpha\beta]}}{V}\delta\left[(x-x_i)-v_i(t-t_i);\,t_{i0}\right], \tag{30}$$

where (x_i, t_i) are the coordinates of an elementary event, t_{i0} is its duration and v_i is the velocity of mutual spreading of crack tips.

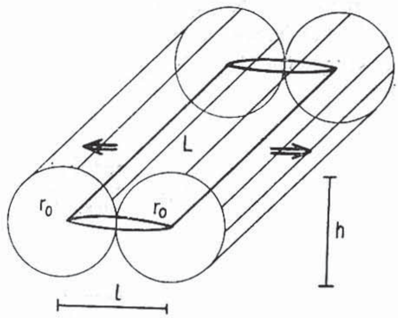

Fig. 3. Explanation to the energy rate calculation

Equation (1) states that the internal stresses are related to defects; formally we can obtain from it the following relation:

$$\tau=\tau(\alpha)+\tau^*(t)+\operatorname{grad}\tau^\circ(x,t).$$

Hence we can put $(\tau^*+\operatorname{grad}\tau^\circ)$ equal to zero or associate this terms with the external field. Thus for the internal field we have from the preceding formulas the following relation:

$$\frac{d\tau}{dt}=\frac{d\tau}{d\alpha}\dot{\alpha}. \tag{31}$$

On the other hand, starting from the time rate of internal stresses, we can write for processes related to the creation of new defects:

$$\dot{e}=\frac{1}{2\mu}\tau\dot{\tau}=\frac{1}{2\mu}\tau\frac{d\tau}{d\alpha}[\alpha\beta]=\frac{r_0}{2\mu}s\frac{d\tau^2}{d\alpha}. \tag{32}$$

Comparing this relation with equation (29) we obtain for the differentials:

$$d(\tau^2)=\mu^2 r_0^2\frac{\pi}{4}\ln 2d(\alpha^2), \tag{33}$$

which describes the change of the total internal field in respect to the change of defect density and which completes relation (1) for the case of discrete processes.

4. THE ENERGY BALANCE CRITERION

Increments in the total crack surface contribute to the increment of the internal energy stored: the part of the work done by the external field is converted to the kinetic energy of crack motion and to the seismic radiation and friction heat; the later is here neglected.

The time rate of total strain energy is compared here to the rate of increment of the total crack surface related to the crack flow $\alpha \mathbf{v}$:

$$\frac{1}{4\mu}(\mathrm{T}+\tau)(\dot{\mathrm{T}}+\dot{\tau})=\alpha \mathbf{v} F(v). \tag{34}$$

We take here a quasi-static case and also neglect a kinetic energy rate.

For $\mathbf{v}F(v)$ we can take the energy criterion for the creation of unit surface of crack moving with the velocity v (Kostrov et al., 1969):

$$\mathbf{v}F(v)=\sum_i vF_{(i)}(v), \tag{35}$$

$$F_{(1)}=\frac{\pi v^2 k_1^2 r_p}{2\mu V_s^2 \Delta}, \quad F_{(2)}=\frac{\pi v^2 k_2^2 r_s}{2\mu V_s^2 \Delta}, \quad F_{(3)}=\frac{\pi k_3^2}{2\mu r_s}, \tag{36}$$

where

$$r_p=\sqrt{1-\left(\frac{v}{V_p}\right)^2}, \quad r_s=\sqrt{1-\left(\frac{v}{V_s}\right)^2},$$

$$\Delta=4r_p r_s-\left[2-\left(\frac{v}{V_s}\right)^2\right]^2.$$

Formula (35) simplifies for a given type of crack: k_1 – for an open crack, k_2 – for a shear crack, k_3 – for an antiplane (transversal) crack.

5. EVOLUTION OF STRESSES AND STRESS DROP

5.1. The antiplane case. The governing equations here are equations (23) and (34) with the boundary conditions determining on $x-Vt=0$ $(0\leqslant t\leqslant t_0)$ the fracture velocity $v=V$ (assuming that always $v\leqslant V$) and the stress drop $\Delta\tau$. Assuming that T is nearly constant we can consider τ as a total field under the condition that at infinity $\tau=T$. We can assume that the search functions $\tau(x, y, t)$ and $v(x, y, t)$ for a two-dimensional case can be treated as functions of $\xi=x-vt$ and y as a parameter. According to relation (23) we can write (see Fig. 4)

$$C\tau=v\frac{\partial}{\partial\xi}\tau, \tag{37}$$

and according to relations (34), (35) (with $k_1=k_2=0$, $F=F_3$) and (1) we have

$$A\frac{\partial\tau}{\partial\xi}vF_{(3)}=\frac{1}{4\mu}\tau\dot{\tau}. \tag{38}$$

To solve this system we should make an assumption regarding the external field T and its derivative $\dot{T}$: a slowly varying function can be preferably chosen.

According to equation (37) the quantitative behaviour of τ and v can be represented by the curves which are given in Fig. 4. In the right-hand figure a source with the fracture propagation $v=V$ and the surrounding defect flow are marked on the (x, t) diagram; the left-hand diagram shows the stress increase, for $v>0$, after partial small releases, τ tends to increase further on; and only for $v<0$ (change of the sign of flow velocity) we get the stress dissipation after the energy release (the sign are chosen conventionally). The domain $v<0$ is called the rebound motion; it starts before the main event at the moment when stresses reach their maximum and the stress gradient becomes singular $\partial\tau/\partial\xi=\pm\infty$. A plausible explanation of the behaviour of stress gradient is discussed in the last section. The stress drop at the main event may lead to small positive (curve 1) or small negative (curve 2) internal stresses which further on approach zero as a result of diffusion processes.

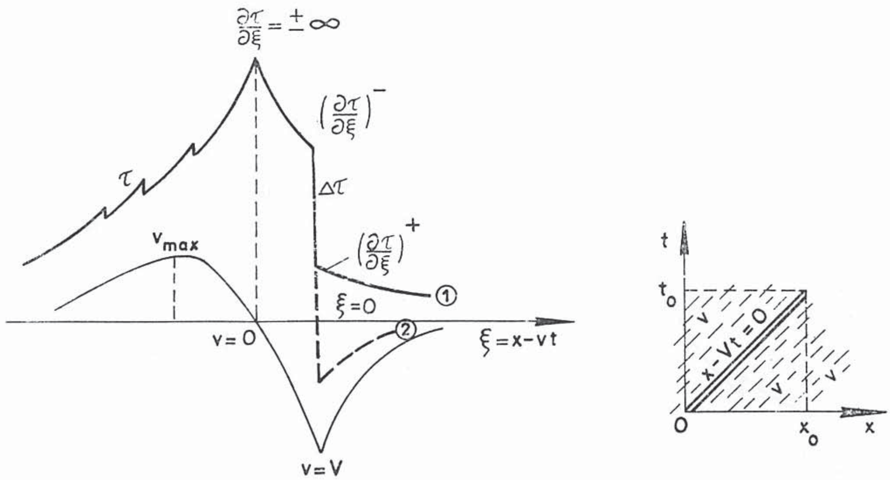

Fig. 4. Stress evolution and rebound motion for the antiplane case

From equation (37) it follows that for a given stress drop we have:

$$\Delta\tau=\frac{1}{C}V\left[\frac{\partial\tau}{\partial\xi}\right]_{-}^{+},$$

hence for $v<0$ and for $\partial\tau/\partial\xi<0$ (Fig. 4) we get

$$\left|\frac{\partial\tau^{-}}{\partial\xi}\right|>\left|\frac{\partial\tau^{+}}{\partial\xi}\right|. \tag{39}$$

The absolute value of the stress gradient after the earthquake becomes smaller in respect to that just before the event.

5.2. The in-plane case. Almost the same discussion can be applied to the in-plane case of development and motion of cracks.

Fig. 5 presents the behaviour of the τ and σ stresses and the respective flow velocities v and w. The signs are again chosen conventionally. The basic system of equations (24) and

(34) determine τ, σ, v, w for a given external field T, S and the boundary condition $\Delta\tau$, $\Delta\sigma$, $v=V$, $w=W$ on the crack planes $\xi=x-vt$ for $0\leqslant t\leqslant t_0$ and $\eta=y-wt$ for $t_0\leqslant t\leqslant t_1$. Equation (24) can be rewritten in the following form:

$$C\tau(\xi, y)=v\left(\frac{\partial\tau}{\partial\xi}-\frac{\partial\sigma}{\partial\eta}\right), \quad C\sigma(\eta, x)=w\left(\frac{\partial\sigma}{\partial\eta}-\frac{\partial\tau}{\partial\xi}\right), \tag{40}$$

while equation (36) for $t\neq 0$, $t\neq t_{i0}$ becomes

$$A\left(\frac{\partial\tau}{\partial\xi}-\frac{\partial\sigma}{\partial\eta}\right)(vF_2+wF_1)=\frac{1}{4\mu}(\tau\dot{\tau}+\sigma\dot{\sigma}). \tag{41}$$

The fracturing is assumed to take place consecutively along the (xz) plane (shear crack) and along the (yz) plane (open crack). We can easily prove that those cracks cannot develop simultaneously starting from the same point. Indeed, from relations (40) we have

$$\frac{\tau}{\sigma}=-\frac{v}{w}; \tag{42}$$

hence taking $\sigma>0$, $\tau>0$ we admit a simultaneous motion on the positively defined elements of the x and y axes, but from relation (42) we have then $v/w<0$ which contradicts our assumption. Thus, according to the scheme in the right part of Fig. 5, we are forced to assume that shear and open cracking takes place consecutively one after the other.

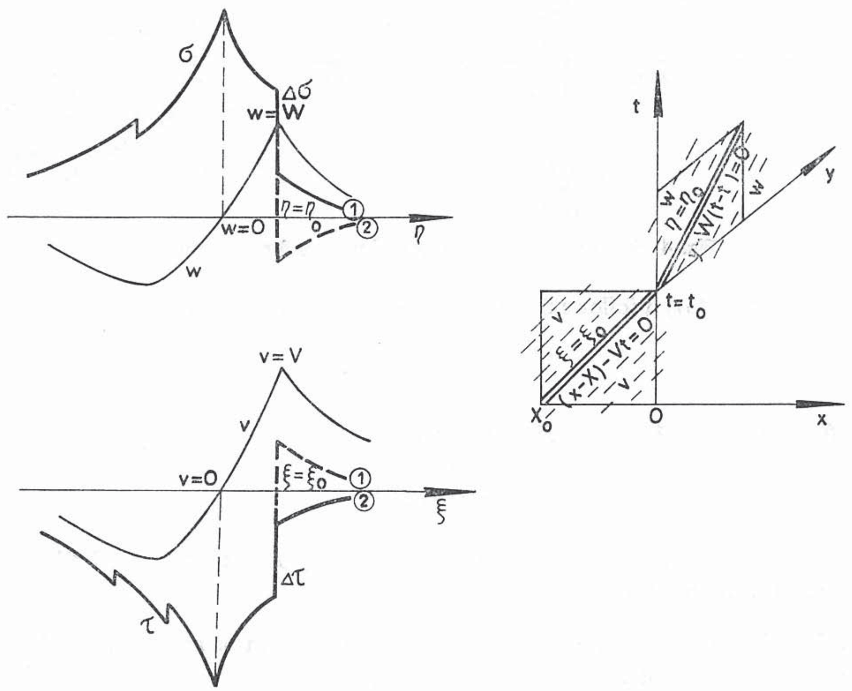

Fig. 5. Stress evolution and rebound process for the in-plane case

The right parts of Fig. 5 present the possible behaviours of evolution of the τ and σ internal stresses. The rebound motion starts again before the main fracture and at this moment the gradients become singular: $(\partial\tau/\partial\xi - \partial\sigma/\partial\eta) = \pm\infty$. This also proves that a change in the direction of bulk velocities of the v and w crack motion takes place at the same moment. Other peculiarities of stress evolution are just the same as in the antiplane case; the possible choice of branches (1) and (2) due to the assumed stress drops is independent for τ and σ.

6. STRESS GRADIENT AND VIRTUAL CRACKS

According to equation (23) the stress gradient becomes infinite when the bulk of flow velocity changes its sign, that is for $v=0$. However, for $v=0$ we have here grad $\tau=\pm\infty$. To explain the gradient problem we have to remember and consider the following:

– in the used theory defects are associated with stress singularities,

– up to now we considered only a flow of the α defect (defect of one sign); let us label that flow by v_α. In reality we have the both α and β defects with v_β opposite to v_α: $v_\beta = -v_\alpha$. If positions of the β defects are treated as reference then for the relative velocity we have : $v = v_\alpha - |v_\beta| = 2v_\alpha$,

– when internal stresses increase we can assume that there is also an increase of the $[\alpha\beta]$ processes which increase both the α and β density and produce higher stress gradients,

– the α density is associated with positive gradients (sign assumed conventionally), while the β density is related to negative gradients (Fig. 1):

$$\operatorname{grad}\tau_\alpha = -\operatorname{grad}\tau_\beta\,,$$

– starting with the α density and introducing the $[\alpha\beta]$ processes to our model we assume that the number of elementary defects n_α and n_β increases and that $n_\alpha - n_\beta > 0$ and thus $v_\alpha - v_\beta > 0$; when n_α, n_β tend to ∞ we reach the saturated stage, thus approaching with the gradient of total internal stresses to infinity:

$$\operatorname{grad}(\tau_\alpha + \tau_\beta) \to +\infty\,,$$

– considering Fig. 2 we may assume that the rebound process would take place just starting from the saturated stage. We may also introduce here a notion of virtual defects: because of extremally dense packing of defects we can associated with an α defects the virtual defects $\hat{\beta}$ whose motion, in opposite direction to that of α, produces the same changes in body structure (Fig. 2). Thus the rebound process refers to the motion of virtual defects; we have $n_{\hat{\beta}} = n_\alpha$, $n_{\hat{\alpha}} = n_\beta$, $n_{\hat{\alpha}} - n_{\hat{\beta}} = -(n_\alpha - n_\beta) < 0$, and $v_{\hat{\beta}} = -v_\alpha$.Thus we get $v = v_{\hat{\beta}} - v_{\hat{\alpha}} < 0$: a bulk motion takes place in an opposite direction to that before the saturated stage. Also we understand that the gradients become negative as grad $\tau_{\hat{\beta}} = -$grad τ_α and grad $(\tau_{\hat{\beta}} + \tau_{\hat{\alpha}}) < 0$. This also explains the singular behaviour of grad τ at the moment of defect saturation: grad $\tau = \pm\infty$. Passing the saturated stage is equivalent to replacing the α, β densities by $\hat{\beta}$, $\hat{\alpha}$ ones. The notion of virtual defects might seem to be artificial, but it explains the preparation phase and rebound response of highly cracked zone leading to bulk fracture processes which constitute an earthquake.

The appearance of virtual crack might be physically understood considering a crack under a strong influence of stresses due to neighbouring cracks. Let us imagine a stress concentration at the crack tips: under the influence of other cracks the own stress concentration regions become (when passing the saturated stage) just those which would be proper for the stress concentration of the virtual crack.

The same reasoning applies to system (24) and to the gradient of τ and σ, which according to relation (40) becomes singular for $v=0$ and $w=0$.

7. A SPECIAL CASE

We consider here a special case of the in-plane cracking, defined by the following boundary conditions at infinity (external fields): $\tau_{xy}=T=0$, $\sigma_{xx}=\sigma_{yy}=S$. This case describes equal loading for a two-dimensional case.

System of equations (40) and (41) describes the stress evolution, in which an internal field τ can be formed, but there are no constraints determining its sign. At high confining load no tensile crack can be formed and we put $\sigma=$const.

The remaining equations describe the possible shear cracking:

$$C\tau=v\frac{\partial\tau}{\partial\xi}, \quad A\frac{\partial\tau}{\partial\xi}vF_2=\frac{1}{4\mu}\tau\dot{\tau}.$$

Let us assume that firstly a number of shear cracks develops, forming a certain internal field $\tau>0$, while we can also assume conventionally $v>0$ for $\partial\tau/\partial\xi>0$. An increase of the τ

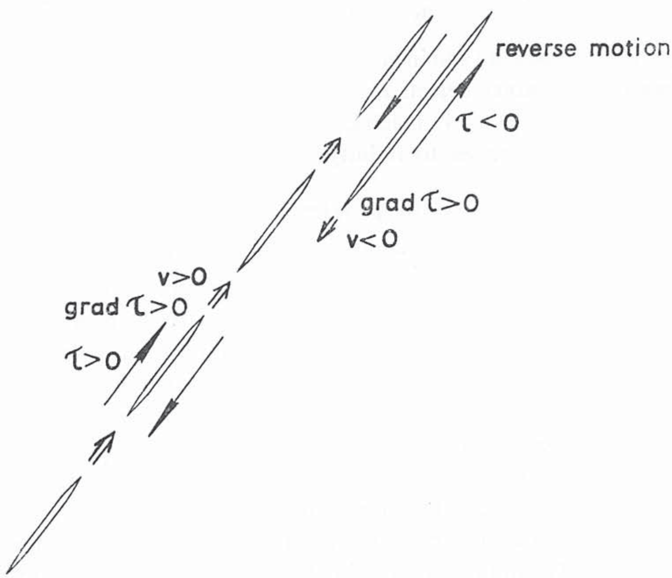

Fig. 6. Rebound process for the equal stress loading

field, however, will be stopped at a certain place because $\tau \to 0$ near the boundaries. In that place the cracks with the opposite orientated self-stresses $\tau < 0$ will be formed; their development being described by the condition $v\, \partial\tau/\partial\xi < 0$. This means that now a reverse motion starts form the considered place back along the almost same path (Fig. 6). Thus, the rebound process leads to the compensation of the transient shear fields.

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PROCESY PLASTYCZNEGO PŁYNIĘCIA PRZED TRZĘSIENIEM ZIEMI I ODPRĘŻENIA OŚRODKA: SYSTEM EWOLUCJI NAPRĘŻEŃ WEWNĘTRZNYCH

Streszczenie

Praca przedstawia teorię procesów przed trzęsieniem ziemi i wyzwolenia energii w niszczącym odprężeniu ośrodka. Przyjęty model zakłada, że ośrodek jest wypełniony polem gęstości szczelin i że ruch szczelin opisuje zaawansowyny stan deformacji: wyprowadzono równania ewolucji naprężeń wewnętrznych; kryterium energetyczne uzupełnia system równań.

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EARTHQUAKE PREMONITORY AND REBOUND THEORY: SYNTHESIS AND REVISION OF PRINCIPLES

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Abstract

Some principles and assumptions of the Earthquake Premonitory and Rebound Theory are presented, including also their modifications and corrections. Special attention is paid to thermodynamical implications of the Theory.

1. INTRODUCTION

New Rebound Theory has been formulated by Teisseyre in 1985; it describes premonitory and rebound processes including an earthquake event. Since that time, new elements and numerous modifications have been introduced (compare: Teisseyre, 1985a, b, 1986, 1987a, b, 1988, 1990; Teisseyre and Stankiewicz, 1987; Droste and Teisseyre, 1988). In its recent form, the theory is known as the Earthquake Premonitory and Rebound Theory (EP&RT); we try to explain with it the physics of fracturing in terms of the continuum approach.

In this paper we review some principles and modifications (including corrections) introduced into the Theory. Special attention is paid to its thermodynamical implications.

2. COMPATIBILITY

For a Maxwell body with the total deformation given by a sum of elastic and non--elastic parts we can write the compatibility condition in the following form:

$$\varepsilon_{tsk}\,\varepsilon_{lmn}\frac{\partial}{\partial x_s}\frac{\partial}{\partial x_m}(e_{kn}+\epsilon_{kn})=0\,. \tag{1}$$

Recalling the Kröner relation for the dislocation density and the plastic density $\beta^P = \epsilon + \omega^P$ (see remark at the end of this Chapter)

$$\alpha_{kl}=\varepsilon_{lmn}\frac{\partial}{\partial x_m}\beta^P_{kn} \tag{2}$$

we get that for a Maxwell body (using the relation of an elastic type between stresses and the elastic part of strains) the compatibility relation (1) is satisfied when we have

$$\alpha_{kl}-\alpha^{\circ}_{kl}=-\frac{1}{2\mu}\varepsilon_{lmn}\frac{\partial}{\partial x_m}\left(\tau_{kn}-\frac{1}{3}\delta_{kn}\tau^{\circ}_{ss}\right)+\frac{\lambda}{2\mu(3\lambda+2\mu)}\delta_{kn}\varepsilon_{lmk}\frac{\partial}{\partial x_m}(\tau_{ss}-\tau^{\circ}_{ss}),$$

where τ_{ik} are the stresses, α°_{kl} is a constant reference density of dislocations and $-1/3$ value of τ°_{ss} is the corresponding reference pressure; further on we omitt both terms. With $\lambda=\mu=1$ and $A=-1/2\mu$ we can write

$$\alpha_{kl}=A\varepsilon_{lmn}\frac{\partial}{\partial x_m}\left(\tau_{kn}-\frac{1}{5}\delta_{kn}\tau_{ss}\right), \tag{3}$$

where A is a material constant. This is the assumed relation between stresses and dislocation density, first formulated by Teisseyre (1980a, b). A similar relation has been derived by Bilby et al. (1958).

Remark. The Kröner relation (2) in fact joins the dislocation density and plastic distortion, which includes both the plastic strain and the local rotation $\beta^P=\epsilon+\omega^P$. Kröner (1981) requires that rotation of total distortion (elastic and plastic) equal zero, $\mathrm{curl}(\beta+\beta^P)=0$; this is the first integrability condition necessary for the existence of a vectorial displacement field. Then in equation (3) we shall put instead of α the contortion tensor k:

$$k_{ij}=\alpha_{ji}-\tfrac{1}{2}\alpha_{ss}\delta_{ij} \quad \text{(Nye relation)}.$$

This procedure makes is sure that strains and stresses remain symmetric. However, introducing the incompatibilities we can require that condition (1) hold for the sum of distortion (elastic and plastic), that is, curl curl $(\beta+\beta^P)=0$, while curl $(\beta+\beta^P)$ may differ from zero (anholonomic deformation). Admitting just that condition (1) relates to distortions (e.g. elastic deformation) we keep the above derivations without a change. We shall note, however, that stresses in equation (3) may be asymmetric. For further applications there is no essential difference between the components of α_{ij} and k_{ji}.

3. CONTINUITY RELATION AND SOURCE/SINK DISLOCATION FUNCTION

The integral form of the dislocation density conservation law can be expressed as follows:

$$\frac{d}{dt}\iint\alpha_{mn}\,dS_n=-\oint\varepsilon_{nsk}\alpha_{mn}V_s\,dl_k+F\oint\varepsilon_{nsk}\alpha_{mn}V_s\,dl_k. \tag{4}$$

Circuit integrals mark here an outflow/inflow of dislocations, the second term with a certain coefficient F represents a source/sink function for dislocation density. The source/sink function is assumed to be proportional to the number of dislocations outflowing/inflowing to a surface element bounded by that circuit. Of course, this integral can be transformed to a surface integral representing the density of dislocation source/sink. It represents changes in the number of dislocations: either an increase, when new dislocations are formed, or a decrease, when dislocations join and group (by the mechanism of annihilation of the dislocation lines separating two neighbouring dislocated surfaces).

The differential form does not follow from relation (4) immediately, because dislocation density is related to a surface element which undergoes changes as well. The procedure to be applied is quite similar to that for a mass density balance. We start with a conservation of the total number of dislocations:

$$\frac{d}{dt}(\alpha_{mn}\Delta S_n)=0.$$

We get further

$$\alpha_{mn}\frac{d}{dt}\Delta S_n=\alpha_{nm}\Delta S_n\frac{\partial}{\partial x_s}V_s-\alpha_{ms}\Delta S_n\frac{\partial}{\partial x_s}V_n,$$

where we have taken into account changes in the numbers of dislocations crossing a surface element due to the surface velocity gradients (third term); the normal velocity gradient does not enter here (it is mutually cancelled by the second and third terms).

Finally, the continuity equation leads to the formula:

$$\frac{\partial}{\partial t}\alpha_{mn}+(1-F)\frac{\partial}{\partial x_s}(\alpha_{mn}V_s-\alpha_{ms}V_n)=0. \tag{5}$$

Formula (5) generalizes the conservation for the case which includes the source/sink function.

With the Kröner relation between a non-elastic part of deformation and a dislocation density (2) we get from relation (5):

$$\varepsilon_{nsb}\frac{\partial}{\partial t}\frac{\partial}{\partial x_s}\beta_{mb}+(1-F)\frac{\partial}{\partial x_s}(\alpha_{mn}V_s-\alpha_{ms}V_n)=0. \tag{6}$$

Finally, we get for the substantial derivative:

$$2\frac{d}{dt}\beta_{mt}-\varepsilon_{nst}[F\alpha_{mn}V_s+(1-F)\alpha_{ms}V_n]=0. \tag{7}$$

To get strain rate we shall make symmetrization.

4. THE EVOLUTION EQUATIONS

The non-linear response of materials in the state of an advanced deformation under high loading stresses can be phenomenologically expressed by the power creep/flow law. In our model it corresponds to a bulk development and motion of defects (dislocations and cracks). We will write this law in the following form:

$$\frac{d}{dt}\epsilon_{ik}=B(\tau_{ns}\tau_{ns})^{(n-1)/2}\tau_{ik},\quad \frac{d}{dt}\epsilon=B\tau^n, \tag{8}$$

where n is a value of exponent, often estimated between 1 and 3. Droste and Teisseyre (1988) indicated that the material rheology could be described assuming that n depends on stresses or/and on time (under a constant load). A transition from elasticity to visco-plastic flow starts with n increasing from zero; the time duration of different phases (time scales) depends functionally on $n(t)$.

Further on we put $n=3$:

$$\frac{d}{dt}\,\epsilon_{ik}=B\tau_{ik}\,\tau^2, \tag{9}$$

where $\tau^2=\tau_{ns}\tau_{ns}$. For assymmetric stresses we shall put hereabove distortion rate.

With relation (3) between stresses and dislocation density we get now from e quations (7) and (9) the following evolution equations (in which the dislocation densiti es might be eliminated):

The antiplane case (transversal shearing):

$$-2B\tau^3=(1-2F)\,V\alpha=(1-2F)\,AV\frac{\partial}{\partial x}\tau, \tag{10}$$

where $\tau=\tau_{32}$, $V=V_1$, $\alpha=\alpha_{33}$; dislocation lines extend along the x_3 axis and move in the x_1 direction.

The in-plane case (in-plane shearing and tension):

$$\begin{aligned}
-2B(\sigma^2+\tau^2+\hat{\sigma}^2+\hat{\tau}^2)\tau&=(1-2F)\,V\alpha=(1-2F)\,AV\left[\frac{\partial}{\partial x_1}\tau-\frac{\partial}{\partial x_2}\left(\frac{4}{5}\sigma-\frac{1}{5}\hat{\sigma}\right)\right],\\
2B(\sigma^2+\tau^2+\hat{\sigma}^2+\hat{\tau}^2)\sigma&=(1-2F)\,W\alpha=(1-2F)\,AW\left[\frac{\partial}{\partial x_1}\tau-\frac{\partial}{\partial x_2}\left(\frac{4}{5}\sigma-\frac{1}{5}\hat{\sigma}\right)\right],\\
-2B(\sigma^2+\tau^2+\hat{\sigma}^2+\hat{\tau}^2)\hat{\tau}&=(1-2F)\,W\hat{\alpha}=(1-2F)AW\left[\frac{\partial}{\partial x_2}\hat{\tau}-\frac{\partial}{\partial x_1}\left(\frac{4}{5}\hat{\sigma}-\frac{1}{5}\sigma\right)\right],\\
2B(\sigma^2+\tau^2+\hat{\sigma}^2+\hat{\tau}^2)\hat{\sigma}&=(1-2F)\,V\hat{\alpha}=(1-2F)\,AV\left[\frac{\partial}{\partial x_2}\hat{\tau}-\frac{\partial}{\partial x_1}\left(\frac{4}{5}\hat{\sigma}-\frac{1}{5}\sigma\right)\right],
\end{aligned} \tag{11}$$

where $\tau=\tau_{12}$, $\sigma=\tau_{11}$, $\hat{\tau}=\tau_{21}$, $\hat{\sigma}=\tau_{22}$, $V=V_1$, $W=W_2$, $\alpha=\alpha_{13}$, $\hat{\alpha}=\alpha_{23}$; the dislocation lines extend along the x_3 axis and move in the (x_1x_2) plane. When only the stress components τ and σ differ from zero (the case studied by Teisseyre, 1988) the system of equations simplifies considerably.

5. REBOUND MOTION

The conservation law for dislocation density can be written separately for each of the two types of dislocations (differing by their sign: α and β), provided that an appropriate source/sink function includes the processes of formation and annihilation of the pairs (α, β). We can assume that the source/sink events are in their number proportional to an amount of the outflowing/inflowing dislocations into a given surface element and this can be expressed by the integral containing a flux of the considered dislocation types with a certain proportionality coefficient. With such an assumption, the conservation law can be maintained separately for each type of dislocation, so of course it remains valid also for their sum.

Up to now we considered only a flow of dislocations of one sign α; let us label that flow by V_α. In reality we shall include also a motion of dislocations of the other sign, β, denoting it by V_β. According to (7) the non-elastic strain rate is proportional to the product of dislocation density and its velocity, hence we can write:

$$\dot{\epsilon}=\dot{\epsilon}_\alpha-\dot{\epsilon}_\beta\cong\alpha V_\alpha-\beta V_\beta .$$

We can define a relative velocity as

$$V=\frac{\alpha V_\alpha+\beta V_\beta}{\alpha+\beta}.$$

It is easy to proof that all evolution equations remain invariant when one substitutes a sum of densities $\alpha+\beta$ for the dislocation density and the above defined relative velocity for the dislocation density (Droste and Teisseyre, 1988). As discussed in the previous papers, we can always define the relative velocity so as to have $V>0$ for the premonitory processes; when V changes its sign we enter into the rebound domain in which the crack grouping and dislocation joining prevail (dislocation pair annihilation processes). Hence the velocity $V<0$ is also called a rebound velocity.

The dilemma: how is it possible to consider both α and β densities in relation to one point — it can be solved assuming that we deal here with the microvolumes condensated in a limit to a point (similar assumptions are used in the micropolar and micromorphic elastic theories).

6. ENERGY BALANCE

A balance of energy rates includes changes in potential and kinetic energies on the one side and on the other side — the rates of friction work and work needed for creation of a unit of crack surface, both multiplied by a crack density (Teisseyre, 1988).

The energies released in the pair annihilation processes (α, β) shall be included also in the balance of energy rates, similarly as it has been already taken into account in the conservat on law.

A probab lity, that the annihilation of two dislocation lines (pair annihilation process) will occur, depends evidently on the dislocation density. If we denote by πr_0^2 (r_0 is a dislocation radius) an active cross-section for a pair annihilation process, we can estimate the probability that two dislocation lines annihilate by a square of ratio $\pi r_0^2/\Delta s_0$ where Δs_0 is a value of surface intersected, on the average, by one dislocation line (Δs_0 is related to dislocation density as follows: $\alpha=nb/\Delta s=nb/\Delta s_0$, $\Delta s/\Delta s_0=n$, where n is the number of dislocations crossing a surface element Δs, b is a Burgers vector). Hence the estimate of energy release due to pair annihilation is

$$dE(\alpha, \beta)=\left(\frac{\pi r_0^2}{\Delta s_0}\right)^2 dE_0 ,$$

where dE_0 is the energy release value due to elementary process of pair annihilation.

However, at high dislocation density we shall take into account the interaction forces between dislocations. This gives a correction to the estimate of energy release by increase of active cross-section by a factor proportional to the stress concentration.

We get that energy release $dE(\alpha, \beta)$ is proportional to the product $\alpha d\alpha$ (Teisseyre, 1985b):

$$dE(\alpha, \beta)=2\tau d\tau=\tfrac{1}{8}\mu^2\pi r_0^2(\ln 2)\alpha d\alpha, \tag{12}$$

where r_0 is a dislocation radius, $\mu=1$ in our units.

Hence, after this correction the balance of energy rate becomes:

$$\frac{d}{dt}E_K+\frac{d}{dt}E_P+L_F+L_C+\frac{d}{dt}E(\alpha, \beta)=0 \tag{13}$$

(the corresponding equations in the cited paper – Teisseyre, 1988 – include a printing error in derivative symbols).

The last term in equation (13) is especially important for $V<0$.

The energy balance condition holds separately for the α and β densities; the term $dE(\alpha, \beta)$ remains common in both equations. As stated before, the stress evolution equations (10) and (11) are invariant when introducing $\alpha+\beta$ instead of α and the rebound velocity instead of velocity related only to α. The full system of equations (10) or (11) and (13) can be thus solved either for $\alpha \geqslant |\beta|$ ($V>0$) or for $|\beta| \geqslant \alpha$ ($V<0$).

7. THERMODYNAMICAL APPROACH

From thermodynamical considerations it follows that a body containing a certain number of dislocations cannot be in a state of equilibrium; there is no minimum of the Gibbs function. For a dense distribution of dislocations we can assume, however, that there exists a certain superlattice composed of dislocations which interact between themselves. We refer here, of course, to a random distribution of dislocations, taking the mean value of distances or using a notion of dislocation density ($\alpha=mb/\Delta s$, where b is the Burgers displacement vector and m is the number of dislocations crossing a surface element Δs). More precisely a superlattice could be defined as follows: take a real number of dislocations m in a body and then add to it (in the appropriate positions) a certain number of vacancies $\hat{m}$; a value of $\hat{m}$ might be found by condition that a total $M=m+\hat{m}$ of defects (real+vacancies) fit in the best way to a regular superlattice.

By analogy with thermodynamics of point defects we can find now an equilibrium value related to the line vacancies that appear in such a way when comparing it with a superlattice. It is given by the following formula:

$$\hat{m}=M\exp\left(\frac{-\hat{g}^f}{kT}\right) \quad \text{or} \quad \hat{\alpha}=\frac{b^1}{\Lambda^2}\exp\left(\frac{-\hat{g}^f}{kT}\right), \tag{14}$$

where $\hat{m}$ is the equilibrium number of line vacancies; $3M$ is the number of dislocations in a body (M is a number of dislocations per surface); $\hat{g}^f$ is the formation energy for a line vacancy (that contributes to the Gibbs energy function); k is the Boltzmann constant.

For a regular superlattice with constant Λ the density of dislocations is evidently given by $\alpha^\circ = b/\Lambda^2$. Hence an equilibrium density of dislocations becomes

$$\alpha = \alpha^\circ - \hat{\alpha} = \frac{b}{\Lambda^2}\left[1 - \exp\left(\frac{-\hat{g}^f}{kT}\right)\right]. \tag{15}$$

This equilibrium density may be useful for us when looking for the most probable density value of defects after an energy release in a fracturing process. Here a density α° may be identified with a reference density (equation (3)).

The seismic moment is

$$\mathcal{M} = \mu b \Delta s = \mu b \Lambda^2 M .$$

We can express it by an equilibrium value $\hat{m}$ (equation (14)), which determines a value of a density drop (comp. (15)):

$$\mathcal{M} = \mathcal{M}^\circ \hat{m} \exp\left(\frac{\hat{g}^f}{kT}\right),$$

where $\mathcal{M}^\circ = \mu b \Lambda^2$ is an elementary value of seismic moment for a given structure.

We can assume that before an earthquake a superlattice is almost completely fulfilled by dislocations ($m \cong M$ and $\hat{m} \cong 0$). Hence using the expression for a change of the free energy values we put $G = G^\circ + \hat{m}kT$. Now we can write the seismic moment for a given energy release (putting $\Delta E = G - G^\circ$):

$$\mathcal{M} = \mathcal{M}^\circ \Delta E \exp\left(\frac{\hat{g}^f}{kT}\right)\Big/ kT . \tag{16}$$

This formula gives an important relation between the energy release and seismic moment, e.g. for given ΔE a seismic moment decreases with temperature. A free energy related to defect formation $\hat{g}^f$ is proportional to $\mu b \Lambda^2$, being constant for a given structure and a given superlattice constant; with greater value of Λ the seismic moment becomes greater.

We shall add here few words on possible global density changes in an earthquake preparation zone. The formation of open cracks in a dilatancy phase leads to volume changes: hence, starting with the equation of motion in the form

$$\frac{d}{dt}(\rho V_i) = \frac{\partial}{\partial x_i} \tau_{si}$$

and neglecting the acceleration term and velocity product we get the equation:

$$V_i \frac{\partial}{\partial t} \rho = \frac{\partial}{\partial x_s} \tau_{is} .$$

This equation is obtained under the special assumptions: we take into account possible change of a total rock mass in a given volume, or a change of rock volume with a given mass (even for locally incompressible medium); these changes are associated to defects, e.g open cracks. Using some simple transformations (Teisseyre, 1987a, b) we get with the help of equation (3) the basic equation describing density changes in the Rebound

Theory:

$$V_i \frac{\partial}{\partial t} \rho = \frac{3}{5} \frac{\partial}{\partial x_i} \tau_{ss} - A^{-1} \varepsilon_{irs} \alpha_{rs} \tag{17}$$

provided that stresses entering in equation (3) are symmetric.

8. SEISMIC EVENT, STRESS DROP AND ENTROPY CHANGE

As discussed in the previous papers an additional assumption is required to introduce a seismic event into the solution of the EP&RT equations. It concerns a definition of a moment of seismic event and of a value of stress drop. In most of the cited papers the assumption has been adopted that a stress drop occurs at the moment when the rebound velocity ($V<0$) reaches its extremum. Another possibility has been tested by Droste and Teisseyre (1988), namely that the stress drop takes place when a rebound velocity overpasses certain threshold. Such threshold might be equal to the velocity value separating the quasi-static and dynamic modes of crack motion.

The criterion of the extremum velocity has an advantage because it relates the fracture velocity to a stable value.

Teisseyre (1986) determines the value of stress drop from the principle in which the time duration of a rebound domain ($V<0$) is demanded to be minimum: $\int dt = \text{minimum}$ for $V<0$.

Another approach is proposed by Teisseyre in his paper of 1990; according to relation (12) he assumes that during a rebound time domain ($V<0$) the annihilation processes of dislocation pairs cause infinitesimal stress drops $d\tau$ due to drops of defect densities $d\alpha$ – we have here a kind of continuous creep. For the discrete event (e.g. at the moment of rebound velocity extremum) taking a certain value $\Delta\tau$ we can find the corresponding value of a change $\Delta\alpha$ using a relation for finite differentials – analogous to (12). We find that after this change a new value of density becomes

$$\alpha' = \frac{C\alpha^2 - \tau\Delta\tau}{C\alpha}, \tag{18}$$

where $C=(1/8)\pi r_0^2 \ln 2$ (as previously, we put $\mu=1$).

A new bulk crack velocity after a seismic event can be now found from equations (11) in the in-plane case, or from equation (10) in the antiplane case. The unknown value of a stress drop can be found either demanding that a new value of density α' becomes as close to zero as possible (providing that a new value of velocity remains reasonable, $|V'|<1$), or assuming that a new value of density (relation (18)) is equal to a thermodynamical equilibrium value (equation (15)).

For entropy we can write (neglecting the term $\hat{s}^f = -\frac{\partial}{\partial T}\hat{g}^f\Big|_\tau$) after Varotsos and Alexopoulos (1986):

$$S = S^\circ + \hat{m}k\left(1 + \frac{\tau b \Lambda^2}{kT}\right)$$

putting for a formation free energy of line vacancy $\hat{g}^f = \tau b \Lambda^2$ (formation energy of a dislocation is $-\tau b \Lambda^2$; comparing Kocks et al., 1975). Hence we get for the entropy change:

$$\delta S = k \hat{\delta} m - \frac{\hat{m} \tau b \Lambda^2}{TM} \delta M$$

(because $\Delta s / M = \Lambda^2$, where Δs is a surface element and $\delta M = -2M \delta \Lambda / \Lambda$).

For premonitory processes we propose to write the entropy change jointly for internal and external regions of earthquake preparation:

$$\delta S = \delta S_i + \delta S_e \geqslant 0 .$$

For the inside region we assume that the number of dislocation increases, $\delta M > 0$, and the number of vacancies decreases, $\delta \hat{m} < 0$ (due to overflow processes of defects from one region to another), and hence $\delta S_i < 0$, while for the outside region we shall assume a reverse compensation process, with $\delta M < 0$ and $\delta \hat{m} > 0$. Finally we approach in a region „i" to the saturated values corresponding to $\hat{m} \cong 0$ and $m \cong M$. For rebound processes (including an earthquake event) we can assume that the number of dislocations rapidly decreases (due to processes of pair annihilations). Hence we have an increase of vacancies as an imminent process:

$$\Delta S = k \Delta \hat{m} = k \hat{m} > 0 ,$$

where $\hat{m}$ is an equilibrium value (14). Referring to the relation $\Delta E = \hat{m} k T$ we put

$$\Delta S = \frac{\Delta E}{T} ; \tag{19}$$

for a given energy release, a value of an entropy jump decreases with temperature.

9. ELASTIC COUNTERPART – THE EDDINGTON SOLUTION

The incompatibility tensor is defined by the following relation:

$$I_{ij} = -\varepsilon_{ikm} \varepsilon_{jln} \frac{\partial}{\partial x_m} \frac{\partial}{\partial x_n} e_{kl} .$$

Using relation (2) we get

$$I_{ij} = \varepsilon_{ikm} \frac{\partial}{\partial x_m} \alpha_{kj} \tag{20}$$

(after Kröner, 1981, we shall put here a contortion tensor k instead of α, or we shall introduce symmetrization of curl α – see the remark in the first Chapter). The incompatibilities are related to defects and can be treated as sources of elastic strains. With the boundary condition on a surface of a body $I_{ij} n_j = 0$ we get the following solution (Eddington, 1923) for a finite region (Eshelby, 1956):

$$e_{ij}(\mathbf{r}) = \frac{1}{4\pi} \iiint \frac{I_{ij}(\mathbf{r}') - \delta_{ij} I_{ss}(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|} dv , \tag{21}$$

which is closely related to Poisson's solution.

Considering any problem of defect distribution (dislocations, disclinations) we can find the associated elastic strain field. Thus we obtain a full pattern of elastic and non--elastic strains.

In many considerations related to earthquake processes we have confined ourselves to non-elastic strains as directly related to the defect distribution. The Eddington solution permitts us to get its elastic counterpart. The Eddington solution can be used for problems in which a domain of incompatibility is finite.

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SEJSMICZNA TEORIA PRZYGOTOWANIA I ODPRĘŻENIA: SYNTEZA I MODYFIKACJA ZASAD

Streszczenie

W pracy przedstawiono pewne zasady i założenia sejsmicznej teorii przygotowania i odprężenia, wraz z ich modyfikacjami i zmianami. Szczególną uwagę zwrócono na termodynamiczne implikacje tej teorii.

The eight papers of Roman Teisseyre reprinted here were chosen from his publications over the 30-year period 1961-1990 to demonstrate the consecutive steps in the development of the Theory of Earthquake Premonitory and Fracture Processes.

The comprehensive bibliography that follows portrays further achievements of the author and his activity in a variety of fields.

Roman Teisseyre's Bibliography over the Years 1953-2016

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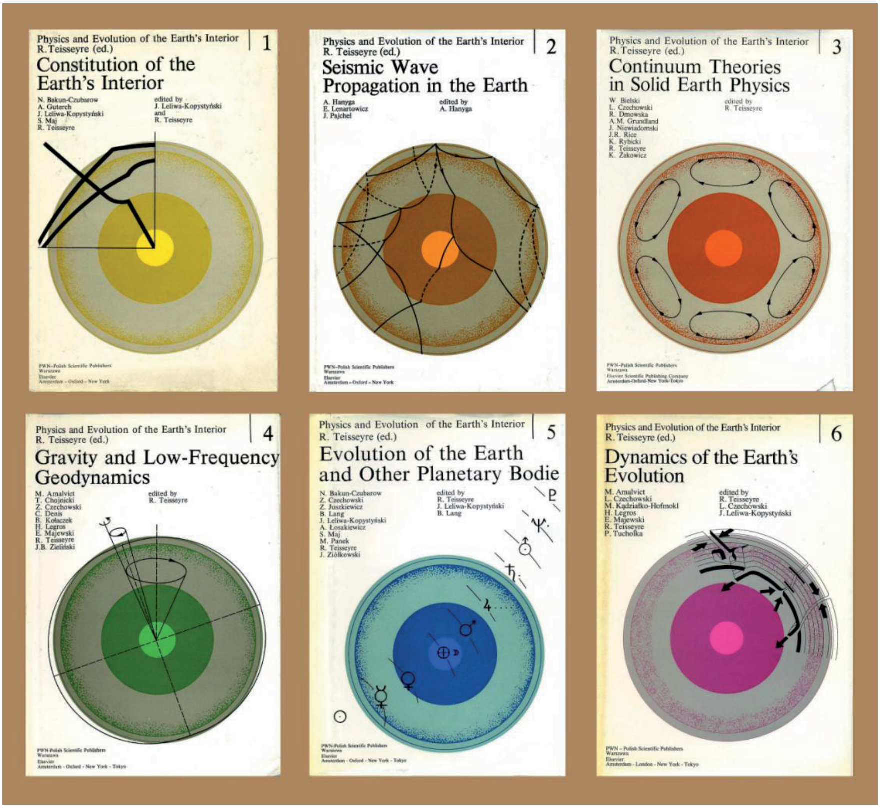
We present here the bibliography of Professor Roman Teisseyre, key person in the whole publishing activity of the Institute of Geophysics, Polish Academy of Sciences. His full scientific career has been associated with the Institute; he organized and led the modern center of theoretical earthquake research, and was the Institute's Director in 1970-1972 and Deputy Director in 1960-1970 and 1973-2001.

Teisseyre belonged to the group of first editors of *Acta Geophysica Polonica* (now *Acta Geophysica*) since the very beginning, being the Editor-in-Chief in 1995-2005. The bibliography quotes his article in Volume 1, issued in 1953. He was also one of creators and Head of Editorial Board of *Materiały i Prace Zakładu Geofizyki PAN* (1963-1976), later transformed into the series *Publications of the Institute of Geophysics, Polish Academy of Sciences.* He was also very strongly involved in creating, in cooperation with Springer Verlag, the book series *GeoPlanet: Earth and Planetary Sciences Series,* being member of its editorial board and frequent author.



We made every possible effort to retrieve the whole, extremely rich collection of Teisseyre's publications, including not only the strictly scientific ones. The entries are grouped in years. Each year, they are listed, roughly speaking, in the following order: The list begins with books/monographs, he wrote or edited, followed by scientific papers, short communications, popular science articles and obituaries. Of great help were the bibliographies compiled by Dr. Kazimiera Warzechowa, issued in *Publications of the Institute of Geophysics, Polish Academy of Sciences.*

Worth emphasizing are the numerous comprehensive monographs, giving the state-of-the-art of earthquake physics over the years. The books include the monumental 6-volume monograph *Physics and Evolution of the Earth's Interior*, issued by Polish Scientific Publishers PWN, and more recent ones, issued by Springer Verlag.

Warsaw, January 2017

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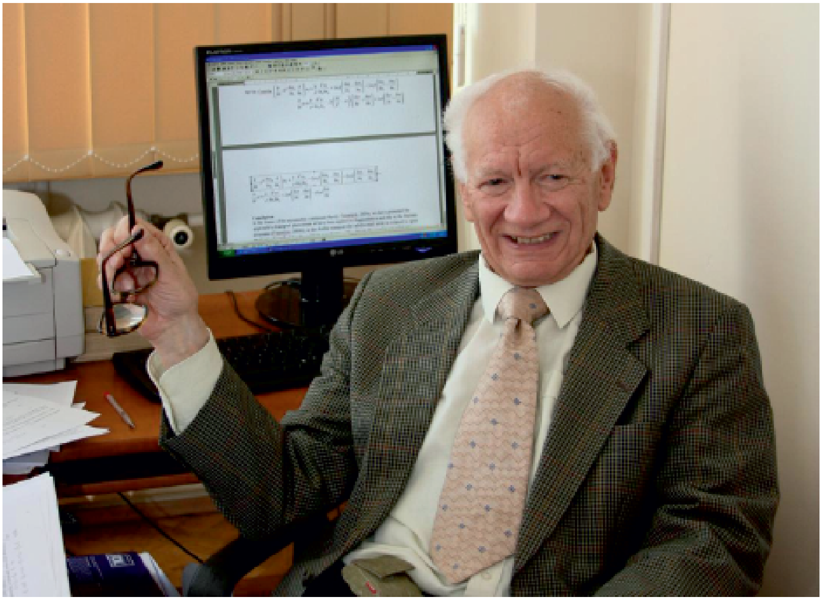

Professor Roman Teisseyre is one of the pioneers of applying the dislocation theory in geophysics. The editors of Publications of the Institute of Geophysics, Polish Academy of Sciences, found it very useful and interesting to republish some of his papers of the years 1961−1990, the milestones in the consecutive stages of the development of the Theory of Earthquake Premonitory and Fracture Processes. The collection reproduced here, showing the evolution of the Author's ideas, is sort of backup and supplement to his renowned monographs.

The direct occasion for publishing this book was the fact that Roman Teisseyre received the Title of Full Professor in 1967, i.e., exactly half a century ago. The book contains also a comprehensive bibliography of Teisseyre's publications, giving evidence of a variety and diversity of scientific topics he dealt with, his innovative attitude to the studied problems, and his role in the scientific community.

In a short introduction the Author outlines his newest ideas he is now working on.