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THE HORIZONTAL SPREAD OF CRATONIC EARTHQUAKES AND THE CORRESPONDING BLOCK MOVEMENTS

by

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Abstract

The cratonic earthquakes are considered to result from movements of crustal blocks. A theory of the horizontal propagation of stress fields with resulting disturbances in the block structure is introduced. The theory is compared with the time-space distribution of Finnish earthquakes, and good agreement seems to exist.

1. *Introduction*

The study of earthquakes has been concentrated mainly on the earthquakes occurring in the recently active belts, while less attention has been paid to the earthquakes of the stable areas, such as the Precambrian shields or cratons. It would seem, however, that the shield earthquakes are of considerable importance as a source of information not only on the recent structure and movements of the shields but also on the ancient history of the earth's crust. Moreover, they are suitable for studying the horizontal propagation of stress fields and the resulting mass displacements in the earth's crust. In respect of the origin and mechanism of earthquakes, this kind of investigation might even yield important information which would not be obtained from more complicated systems.

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The present paper relates to the earthquakes recorded in Finland since 1930. Although the country occupies only a small fraction of the shield areas of the earth, its earthquakes may be considered characteristic of any shield area. On the other hand, the recent uplift of Fennoscandia has intensified the tectonic processes and the activity of earthquakes in the area.

The recent deformations of the shields or, to use a more general term, cratons, take place mainly in the form of block movements. Therefore the shields or cratons can be considered to be stable areas subjected mainly to block movements. In the deformation of the shields the movements are concentrated to the block boundaries where the earthquakes also originate.

The problem is how extensive the relationships are between the dynamic processes that occur along the block boundaries and how the block structure affects the space pattern of displacements and the energy releases. Can a block be considered so rigid that a displacement at some point along its boundary will cause consecutive displacements at distant points? Conditions should exist for both slow creep along the boundaries and rapid displacements, the latter being manifested by earthquakes.

The following approach to the problem is based on seismological and geological data as well as on theoretical aspects of block dynamics.

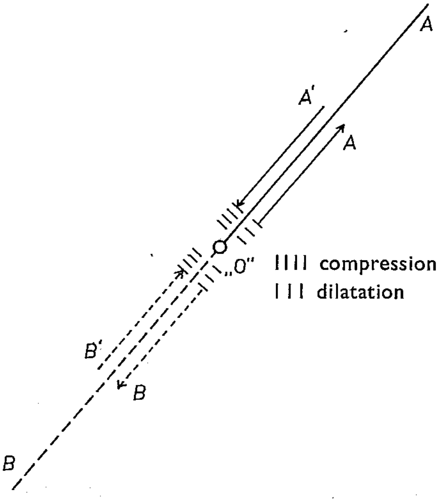


Fig. 1. Equivalent displacement systems: A, A', and B, B', producing the same stress field around „O".

2. *Displacements along block boundaries*

Assume that the earth's crust has a block structure in the sense that the internal stresses are released in a relative displacement of masses along the boundary of the adjacent blocks. Let us first give a more precise description of the displacements that occur along a limited part of a boundary plane of a block. Fig. 1 shows the trace of a plane along which a relative displacement is supposed to take place. The circle indicates the line (perpendicular to the drawing) at which displacement stops (or begins). The process can be described by a step function — in this case we are dealing with a dislocation. When the displacement along the dislocation plane is not constant, *i.e.*, described by a continuous function, we are dealing with a crack. Here, however, it is not necessary to state the character of the deformation precisely.

2.1 Horizontal mass displacement

In Fig. 1 the different mass shifts are indicated by the arrows A, A' and B, B' in respect to the limiting line ,,O'' (perpendicular to the drawing) and the sides of the dislocation plane. The stresses produced by the shifts indicated around ,,O'' are exactly the same and therefore the shifts are equivalent. The opposite case is presented in Fig. 2, where the stress field caused by displacement A differs in sign from the stress field caused by displacement B or B'. So, when the lines ,,O'' and ,,$\bar{O}$''

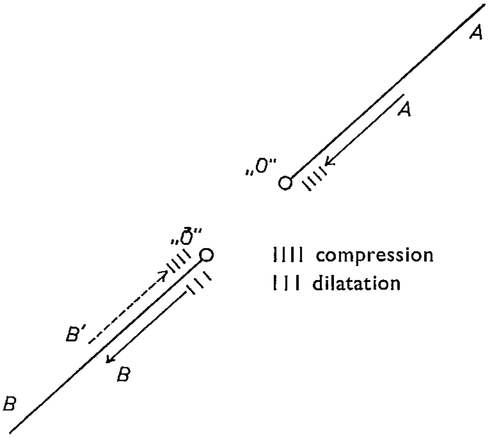


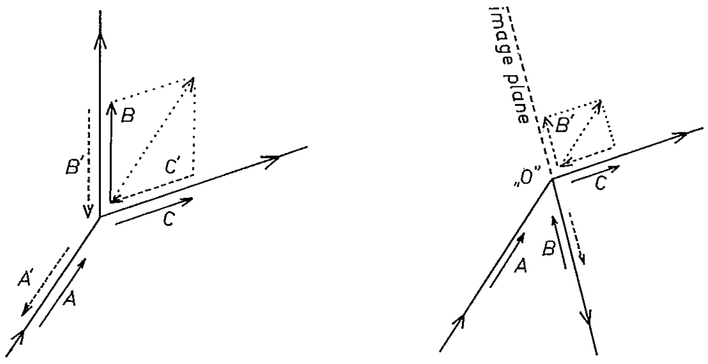
Fig. 2. Opposite displacement systems: A and B, or A and B'. Stresses release when the distance ,,O''—,,$\bar{O}$'' decreases to zero.

are brought to coincide the respective stresses are compensated. The resulting situation corresponds to a no-stress system. Joining two dislocated areas by mutual approach of the lines ,,O'' and ,,$\bar{O}$'' can be regarded as one of the possible mechanisms leading to the release of internal stress.

Now consider some of the basic rules governing the displacement vector that represents a mass shift along a block boundary. As mentioned above, these considerations are valid not only for dislocations but also for a more general type of deformation. For the sake of simplicity, however, the term dislocation will be used.

Let us assume that the block boundaries represent the lines of possible successive movements of dislocations. This is to be understood in the following sense. The total stress field pushes the limit line of the dislocation to extend the dislocation area toward the adjacent parts. As a result, a consecutive shifting of masses takes place along the boundary plane. This can be interpreted as some kind of propagation of the dislocational deformation along the block boundary. The propagation could take place by creep, but in certain conditions a more rapid process can be expected. In this respect special attention should be paid to processes connected with a great release of the internal strain energy.

Fig. 3 represents a simple splitting of the dislocation vector when the advance of mass displacement reaches the boundary intersection. As was shown in Fig. 1, the equivalent displacements can be considered independently: A equivalent to A', B to B' and C to C'. It is not necessary to discuss all possible combinations of the equivalent displacements. The rule of vector splitting in respect to boundary planes shows that



a) b)

Fig. 3. Splitting of dislocation vector at boundary junction.

simple vector analysis holds in different regions because the components B and C are connected with different blocks. But if we consider the components B and C' which are related to the same block, the simple vector rules do not hold.

For better understanding of the possible directions of a successive advance of dislocational deformations, these directions are indicated by arrows at the boundary lines seen in the different figures.

Fig. 3b represents a similar vector splitting. The image boundary plane is constructed to show the full equivalence with the case represented on Fig. 3a as the displacements B and B' are exactly equivalent in

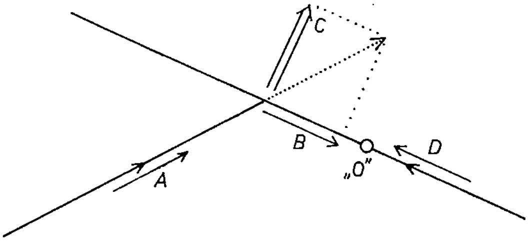


Fig. 4. Energy release at closing of a block contour by two dislocations B and D in the case of a wide angle between boundaries. The diagram corresponds to block rotation. Residual dislocation C marked by double line.

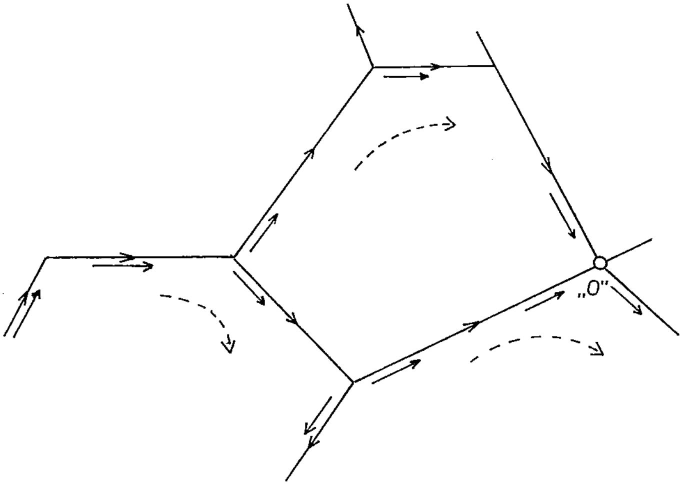


Fig. 5. Block diagram representing the case of block rotation. Energy release when a disturbance comes to close a contour at „O".

respect to the line ,,*O*''. Another case with a wide angle between the boundaries is given in Fig. 4. The residual dislocation *C* is marked.

Fig. 5 is a block diagram. It shows firstly that for a closed contour the dislocations that propagate along opposite boundaries of a block will meet somewhere and their stresses will be released by mutual compensation. Secondly, this diagram shows that the neighboring blocks rotate in the same direction.

The cases considered on Figs. 6 and 7 represent a more complex pattern. Two dislocations attached to the neighboring boundaries, which join at the line ,,*O*'', interact mutually. For small angles they are attracting to the line ,,*O*''. The parallel components of the original dislocations *A* and *D* will be compensated and their stresses released. The mechanism is very similar to crack formation at triple points (WILLIAMS, [4]). The energy release may have a rapid enough character to be classified as an earthquake.

Now let us assume that at the line ,,*O*'' two other block boundaries *B* and *C* meet. The above vector splitting evidently shows the part of components that are mutually compensated. The residual parts of the components are indicated by double lines. In the assumed case the residual dislocations will move further along these two boundaries *B*

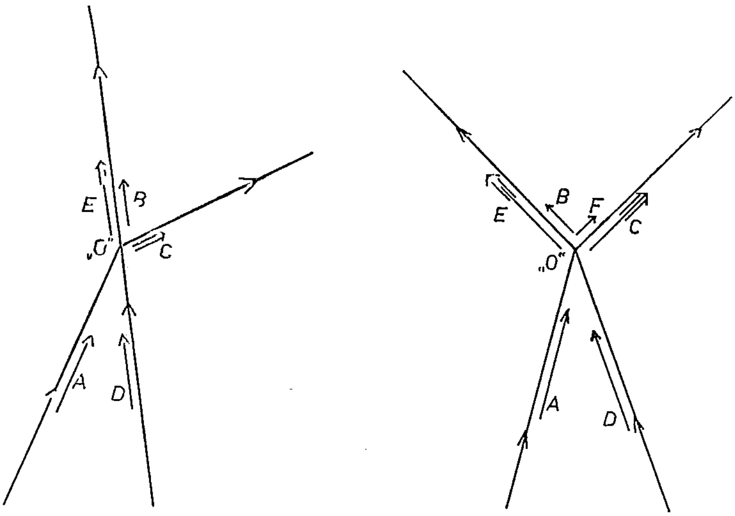


Fig. 6. Partial energy release when two dislocations *A* and *D* arrive to close a contour at „*O*" in the case of a small angle between boundaries. The diagram represents block pushing. Residual dislocations area shown by double lines.

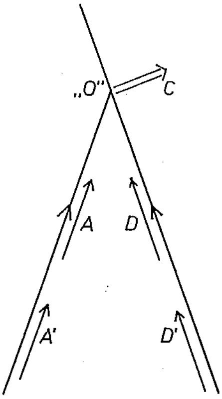


Fig. 7. Cottrell barrier. Residual dislocation C forms stress barrier stopping next dislocations A', D', . . .

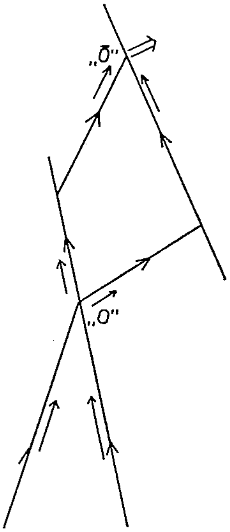


Fig. 8. Block pushing. Energy release at „O" and „$\bar{O}$". Stress barrier formation at „$\bar{O}$".

and C. In the case shown in Fig. 7, where only one, or even no, additional boundary exists, there remains at the line „O" a dislocation that forms a kind of stress barrier (Cottrell, [1]). To overcome such a barrier a greater stress concentration is needed. The barriers can thus stop further dislocations until these become more numerous and condensed to overcome the repelling stress of the barrier. It can be shown that to overcome these stress barriers the next dislocations A' and D' must have respectively greater displacement vectors. The release of energy that will take place again at „O" as a result of the mutual compensation of the parallel components A' and D' will be much greater. Furthermore, the previously created residual dislocation C can be pushed away to form a new tectonic plane.

Fig. 8 shows the situation when two nearly parallel dislocations push a block, as in the cases considered in Fig. 6 and 7. Here the dislocations considered propagate along the boundaries of the same block towards the line „O". Even if the residual dislocations can propagate further along other boundaries, the analogous situation will occur at the next closing point „$\bar{O}$". A part of the dislocation energy is released and the residual dislocation will form a stress barrier, as shown before.

2.2 Vertical mass displacement

In vertical mass displacement the polygons that form the block boundaries are characterized by a vertical movement of block masses. In this case the mechanism is simpler, as the dislocation vectors remain in the same direction, *i.e.*, vertical. The dislocational disturbances are assumed to propagate horizontally along block boundaries. These advances can be treated to some extent as creep phenomena. In other cases, especially when dislocational disturbances approach to close the contour of a block or when two dislocations meet at a boundary junction (Fig. 10), a rapid process and an appropriate energy release are expected.

Fig. 9 explains the splitting of a vertical vector at a boundary intersection. The direction of propagation is indicated by arrows. Symbols (+) and (—) mean displacement vectors directed upwards and downwards, respectively. However, as we deal with stresses in the gravitational field, the relative sense of the movement must be treated with caution.

Fig. 10 shows the mechanism of energy release when two dislocations in the same direction with respect to a given block reach the junction of two boundaries. This can be the case when the dislocational disturbance closes the contour around a block. For equal value of dislocation vectors, the stresses will be fully compensated and a corresponding energy release will take place. No residual dislocation will remain at the junction.

The mechanism of a stress barrier discussed above for horizontal displacements does not apply to the vertical movements. We stated

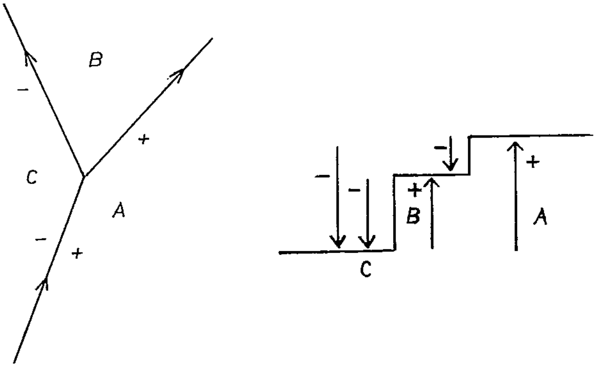


Fig. 9. Splitting of a vertical vector of dislocation at boundary junction.

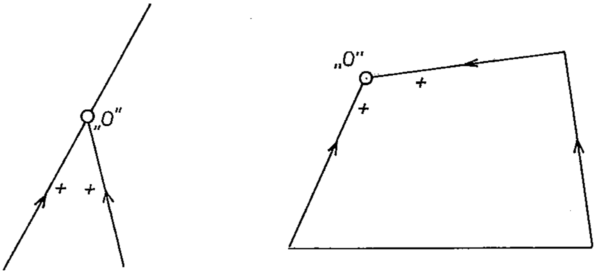


Fig. 10. Energy release when two dislocations arrive at junction „*O*".

above that the stress barriers formed at the boundary junction need a greater local stress concentration to overcome the barrier. This would probably explain the occurrence of strong earthquakes. In the present case of the block structure and the vertical mass shifts no stress barriers are expected. As the energy release can take place without stress barriers there will be more or less even portions of released energy of dislocations. Thus in the structure discussed no strong earthquakes are expected for vertical movements.

Fig. 11 represents a block diagram. Possible directions of disturbance propagation are indicated. The signs of vectors (+) and (—) are to be understood relatively. The central block in this diagram can be treated either as partly upheaved or as completely stable, with the surrounding blocks moving upward and downward, respectively. The possible energy release at „*O*" is due to closing of the contour of the internal block *A* when partly upheaved.

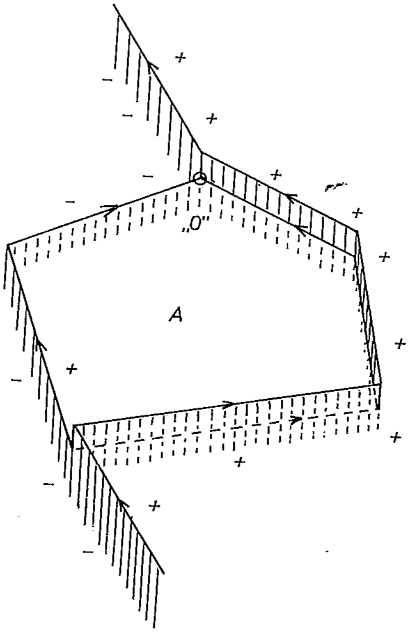


Fig. 11. Block diagram representing block upheaving. Part of dislocation energy is released at „*O*".

3. *Horizontal shift of Finnish earthquakes*

The distribution of the epicenters of earthquakes occurred in Finland since the seventeenth century, as seen in Fig. 12 (PENTTILÄ, [2]), appears to follow a system of crossing lines (see also TALVITIE, [3]).

After 1930 fifty earthquakes have occurred in the country. These earthquakes are used for the purpose of this paper. The location of epicenters (Fig. 13) shows a good fit to the lines of Fig. 12. It is obvious that these lines are traces of faults along which dislocations are taking place. All the fifty foci have been in the crust, most of them above Conrad. The intensity of the shocks has been from III to VI.

Fig. 14 shows three »chains» of these earthquakes. The chronological sequences of the earthquakes are indicated by arrows and numbers. The verity of the block boundaries derived from the material studied is evidenced by geological fault data as well. In case *A* the events seem to have rotated clockwise along the boundaries of a center block. A successive shift of the earthquakes is also seen in cases *B* and *C*, which are exemples selected from a number of similar chains. In these cases,

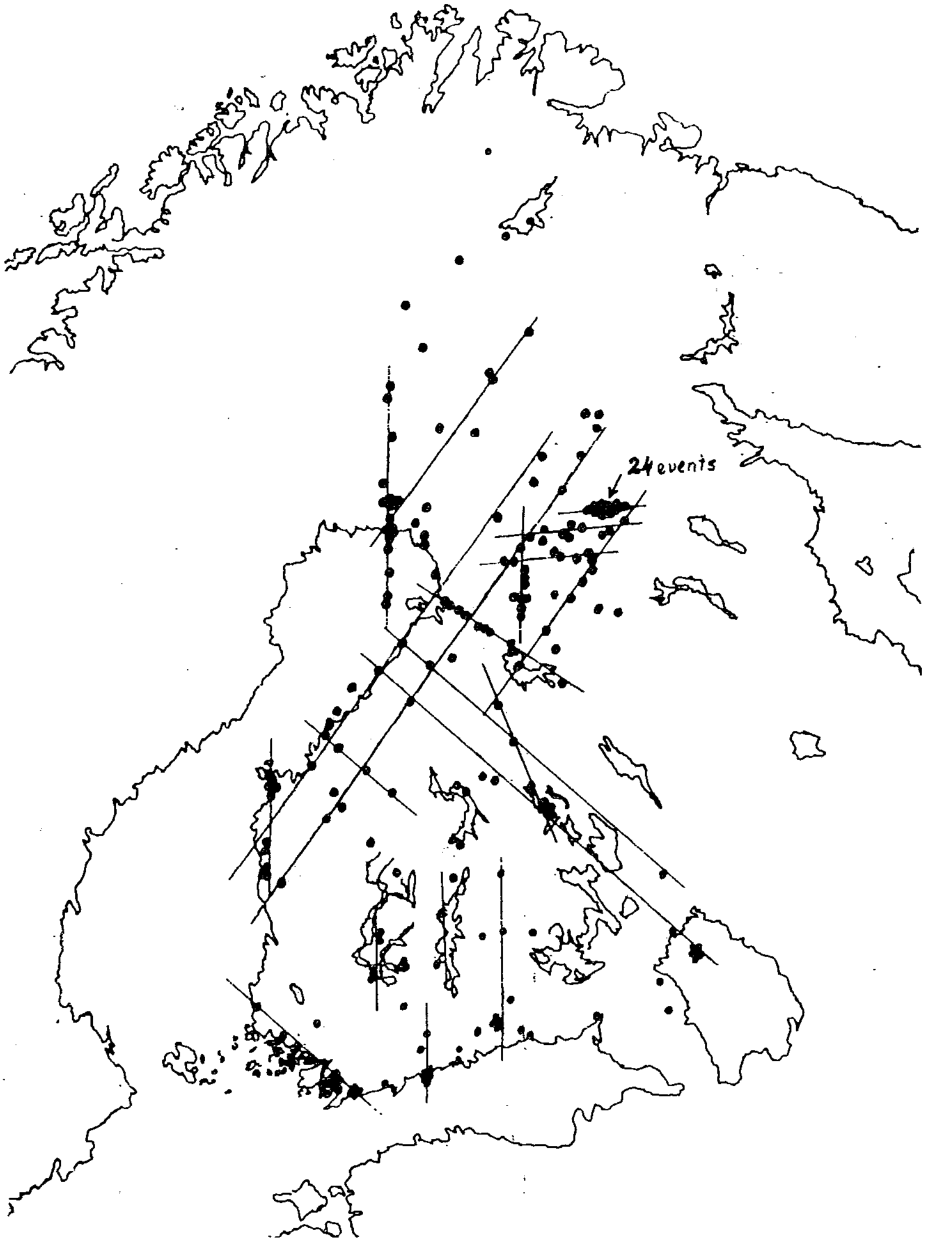


Fig. 12. Epicenters of Finnish earthquakes since seventeenth century. (PENTTILÄ, [2]).

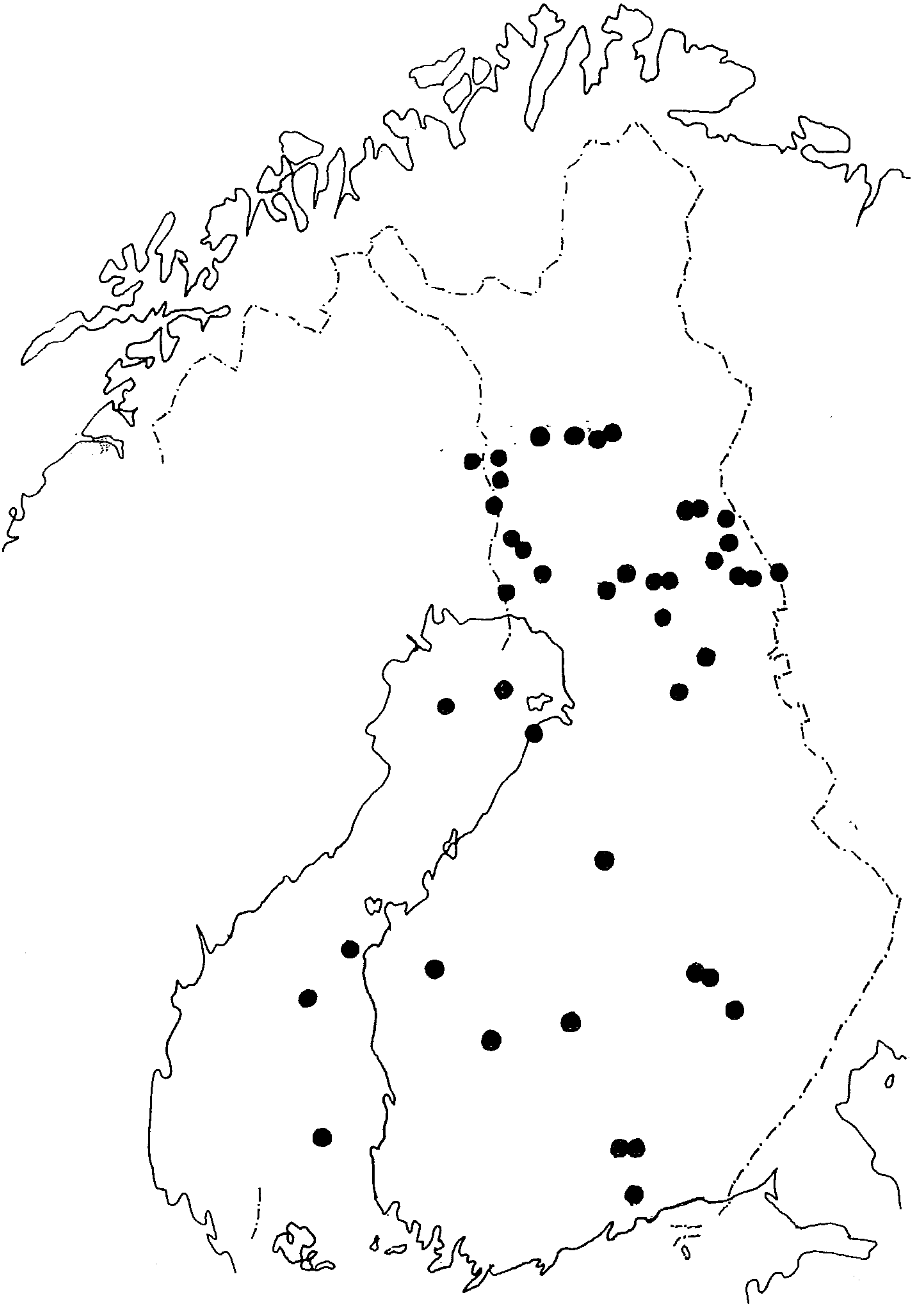


Fig. 13. Earthquakes felt in Finland 1931—1968.

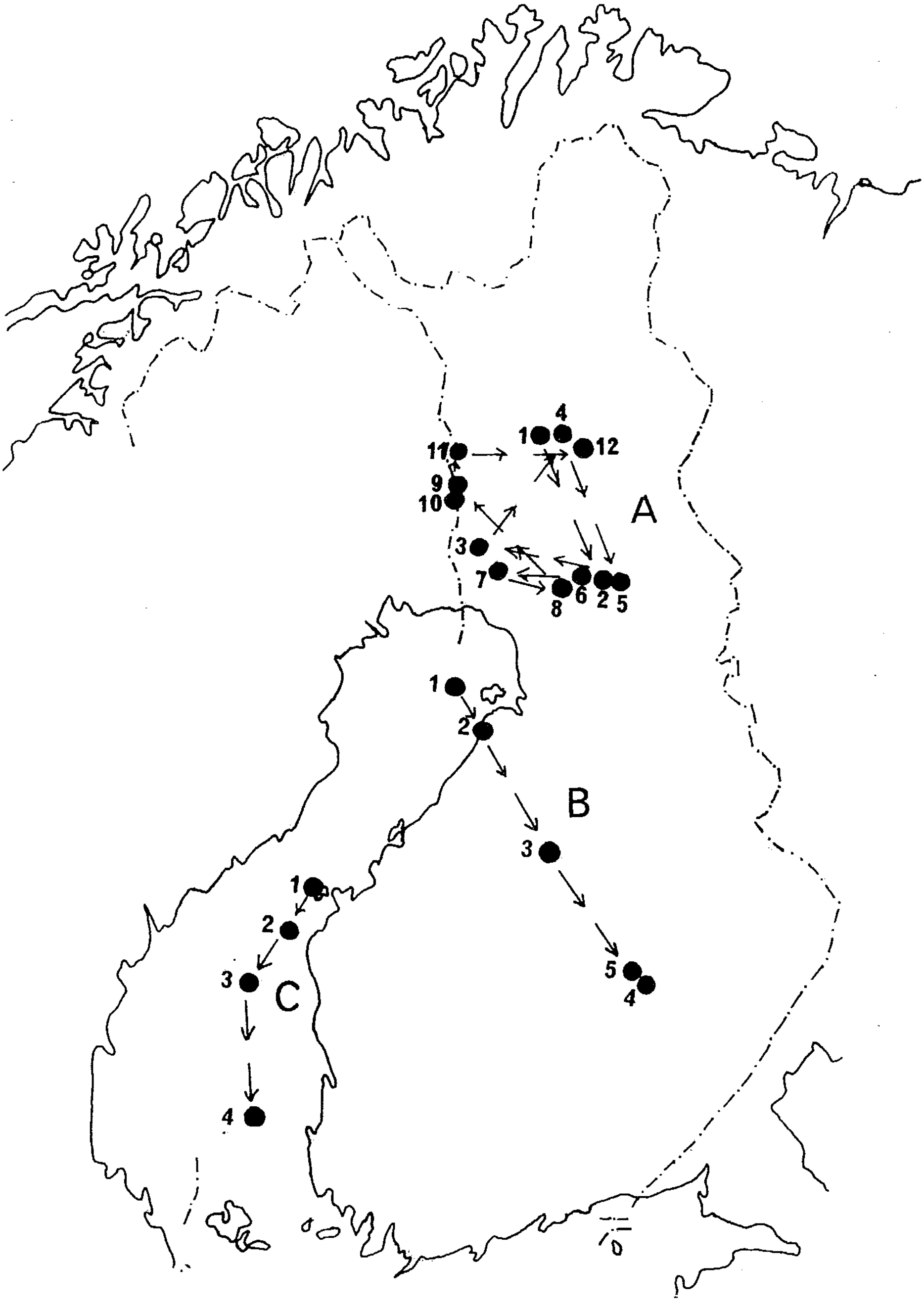


Fig. 14. Chronological sequence, indicated by arrows and numbers, of earthquakes along certain fault lines of Finland.

however, the data are insufficient for ascertaining closed contours of the type of case A.

The time-space distribution of all these earthquakes seems to be in good harmony with the models of horizontal stress propagation discussed in the foregoing chapter. The disturbances (earthquakes) appear to have advanced horizontally along boundaries of geologically well definable blocks.

On the other hand, it is not clear from the available data whether the horizontal advance of earthquakes has resulted from horizontal or vertical displacements along the block boundaries. As the recorded earthquakes probably result from the recent uplift of Fennoscandia, it would seem reasonable to assume vertical displacements. It could also be argued that horizontal displacements would have resulted in stronger shocks. However, no measurements of the possible horizontal components of the recent displacements seem to exist.

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