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Original paper

Substantiation of the main concepts for the deformation model of the crustal earthquake source preparation

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Abstract: Relevance. The article reasonably shows that the uppermost layer of the Earth's crust up to 25 kilometers is seismogenic. **Aim.** The article provides the evidence that crustal seismicity is generated not by regional stress fields of a homogeneous shear, as it was adopted in the strategy for solving the problem of earthquake forecast, but by local fields of exponential elastic stress. Such fields arise in one or another section of a seismogenic fault due to the occurrence of a stress concentrator in this section. According to the Saint Venant principle, such a stress concentrator (an additional load in the system) generates a local stress field of an exponential form. In this field the maximum stress is localized in the areas of an increment load application (in the fault) and decreases very quickly (exponentially) on both sides of the fault. Such stress concentrators arise in those areas of a seismogenic fault, where displacements along the fault stop due to various reasons. G. A. Gamburtsev foresaw this situation and very precisely called such concentrators as "seams". The origin of a local stress field at the place, where a seam appears, is caused by the following fact: the power impulse generated by the seam is small compared to the linear momentum of the entire system of blocks of the considered fault and, therefore, it will stop the displacement of blocks only within the seam; but the displacements of blocks outside the seam will continue in the same mode. One can single out the following reasons causing stress concentrators in the fault: variations in different stress fields, changing the value of the friction coefficient in the fault; variations in fluid processes; the influence of temperature and pressure; mechanical "hooks" of blocks due to irregularities of their contacting surfaces, etc. **Methods.** The fact of the existence of the considered local stress fields is confirmed by geodetic studies, i. e. the results of repeated geodetic measurements in the epicentral zones of strong earthquakes. **Results.** These results allow drawing the following conclusions: 1) the sign of the preparation of a crustal earthquake source was reliably determined. This sign means the increasing deformation of the elastic bending of rocks in the source in the course of time; 2) from the standpoint of solving the problem of earthquake forecast, the main and decisive result of these studies is that the deformation processes occurring in the impending source also capture the Earth's surface, because this is precisely what opens up great opportunities in solving this problem; 3) with the help of special geodetic systems (forecast profiles), one can detect the places of the impending earthquake source preparation, i. e. make an accurate forecast of the site of a future earthquake; 4) since the energy of the earthquake source is functionally related to its size, one can realize the correct prediction of the maximum possible intensity of the future earthquake by determining the length of the seismogenic fault section, elastically deformed by the preparation of the earthquake using the forecast profiles.

Keywords: regional and local stress fields, Saint Venant principle, elastic bending, geodetic monitoring, earthquake forecast.

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ГЕОФИЗИКА

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Оригинальная статья

Обоснование основных положений деформационной модели подготовки очага корового землетрясения

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Резюме: Актуальность работы. В статье обоснованно показано, что сейсмогенным является самый верхний слой земной коры мощностью до 25 километров. **Цель работы.** В статье приведены доказательства того, что коровая сейсмичность порождается вовсе не региональными полями напряжений однородного сдвига, как это было принято в стратегии решения проблемы прогноза землетрясений, а локальными полями упругих напряжений экспоненциального вида. Такие поля возникают в том или ином участке сейсмогенного разлома из-за появления на этом участке концентратора напряжений. Согласно принципу Сен-Венана такой концентратор напряжений (дополнительная нагрузка в системе) порождает локальное поле напряжений экспоненциального вида. Максимальная величина напряжения в этом поле расположена в месте приложения дополнительной нагрузки (в разломе) и очень быстро (экспоненциально) убывает в обе стороны от разлома. Такие концентраторы напряжений возникают на тех участках сейсмогенного разлома, на которых в силу тех или иных причин прекращаются смещения по разлому. Г. А. Гамбурцев провидчески предвидел данную ситуацию и очень метко такие концентраторы назвал «спайками»». Возникновение локального поля напряжений в месте появления спайки обусловлено тем, что импульс силы, порождаемый спайкой мал по сравнению с количеством движения всей системы блоков рассматриваемого разлома и, следовательно, он остановит смещение блоков лишь в пределах спайки, но смещения блоков вне спайки будут продолжаться в прежнем режиме. Среди причин, порождающих концентраторы напряжений в разломе можно назвать следующие: вариации различных полей напряжений, изменяющие величину коэффициента трения в разломе; влияние температуры и давления; вариации флюидных процессов; механические «зацепы» блоков из-за неровностей их соприкасающихся поверхностей и др. **Методы исследования.** Факт существования рассматриваемых локальных полей напряжений подтвержден геодезическими исследованиями – результатами повторных геодезических измерений в эпицентральных зонах сильных землетрясений. **Результаты работы.** Эти результаты позволяют сделать следующие выводы: 1) достоверно определен признак подготовки очага корового землетрясения, которым является нарастающая во времени деформация упругого изгиба горных пород в его очаге; 2) с позиций решения проблемы прогноза землетрясений главным и определяющим результатом этих исследований является то, что происходящие в готовящемся очаге деформационные процессы захватывают и земную поверхность, ибо именно это открывает большие возможности в решении этой проблемы; 3) с помощью специальных геодезических систем (прогнозных профилей) можно обнаруживать места подготовки очагов готовящихся землетрясений, т. е. осуществлять точный прогноз места будущего землетрясения; 4) так как энергия очага землетрясения функционально связана с его размерами, то определив с помощью прогнозных профилей длину участка сейсмогенного разлома, упруго деформированного подготовкой землетрясения, можно осуществить и точный прогноз максимально возможной силы будущего землетрясения.

Ключевые слова: региональные и локальные поля напряжений, принцип Сен-Венана, упругий изгиб, геодезический мониторинг, прогноз землетрясений.

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Introduction

Regarding the issue of earthquake forecast, one ought to bear in mind that the Earth is exposed to the crustal and the deep-focus seismicity. The earthquakes of the first type occur in the Earth's crust, and the second ones take place in the Earth's mantle which is located under the Earth's crust. This article deals with the forecast of crustal earthquakes.

Taking considerations of G.A. Gamburtsev into account, one have a reason to believe that the crustal type of seismicity is a consequence of the Earth tectonic activity, caused by deep endogenous processes that are displayed on the surface of the Earth in its continuous movement. Due to these processes energy the mountains and depressions are forming and the continents and vast areas of the deep-sea floor are moving. They split the lithosphere into a lot of blocks and make these blocks move relative to each other along the deep faults separating them. The velocities of block systems` relative displacements along the mentioned faults have significant differences for various tectonic structures of the Earth. The highest displacement velocity is observed in the blocks in orogens, i. e. in tectonically active mountain structures of the Earth. These velocities are measured in centimeters per year. Thus, this velocity on the San Andreas Fault in California (Fig. 1) is 5 cm/year, and in Pamir and Tien Shan conjunction zone (Vakhsh thrust) is 2.5 cm/year. The Pacific Ocean bed is shifting with the maximum, measured by geodetic methods, speed which is equal to 10 cm/year.

The blocks of the Earth's crust have much lower displacement velocities in tectonically less active structures of the Earth. Platforms, i. e. large plain areas of the Earth's crust, are referred to such structures. The displacement velocities of blocks on platforms are by an order lower than in orogens. They are measured in millimeters and even tenths of a millimeter per year.

Structures with high displacement velocities in faults are considered as the most seismically hazardous. And tectonically low-active structures are less seismically hazardous. G.A. Gamburtsev foresaw it: “Relatively slow young and modern movements of the Earth's crustal blocks may not be accompanied by strong earthquakes” [Gamburtsev G.A., 1960, p. 431].

Fig. 1. The San Andreas Fault, like a giant scar, crosses the Carrizo Plain in California, according to: [Bolt, 1981]

Thus, one can draw a conclusion about the direct correlation between the tectonic structures` seismic activity and the displacement velocities of crustal blocks in these structures. Therefore, the reason of seismicity should be sought in the features of the behavior of these velocities. The type of velocity variations at which the initiation of an earthquake source is possible in a particular section of the fault is determined quite simple. The case when the block surfaces, which are separated by the fault, hinder their movement (i. e. the blocks seem to "slide" relative to each other) excludes the possibility of the origination of a strong crustal earthquake in this segment of the fault. However, if a stress concentrator arises in any section of a seismogenic fault, which prevents the free movement of blocks in this section of the fault, then conditions arise for the initiation of an earthquake source. G.A. Gamburtsev very precisely called such stress concentrators as "seams" [Gamburtsev, 1982, p. 306].

In the theory of elasticity, such situations correspond to the following Saint Venant principle: "If a balanced system of forces is applied in any small part of the body, then it causes stresses in the body that very quickly decrease with distance from this part (exponential decay of stresses)" [Bezukhov, Luzhin, 1974, p. 6].

The origin of a local stress field at the place, where a seam appears, is caused by the following fact: the power impulse generated by the seam is small compared to the linear momentum of the entire system of blocks of the considered fault and, therefore, it will stop the displacement of blocks only within the seam, but the displacements of blocks outside the seam will continue in the same mode.

Variations in different stress fields, changing the value of the friction coefficient in the fault; variations in fluid processes; the influence of temperature and pressure; mechanical "hooks" of blocks due to irregularities of their contacting surfaces, etc. can be considered as the reasons causing stress concentrators in the fault.

Thus, studying the possible reasons of the earthquake source initiation, i. e. the start of the process of seismogenic deformations` accumulation in this source, it is suggested that the beginning of these processes is due to tectonic movement stop in a certain section of the seismogenic fault.

Theoretical considerations about the reality of the occurrence of sections of displacement delays in seismogenic faults are as follows: a tectonic crustal earthquake is the rapid destruction of a certain volume of rocks (an earthquake source) that generates seismic waves, caused by the ultimate elastic deformations (stresses) accumulated in this source.

Thus, a required condition for the earthquake source preparation is the existence in the fault zone of a mechanically strong, consolidated medium (rigid inclusion). This medium has elastic properties and due to this it is capable of potential elastic energy accumulation.

So, an earthquake source in the phase of initiation (i. e. at the stage of potential elastic energy accumulation) has to be a stable, plastically slightly deformable inclusion in the seismogenic layer of the Earth's crust.

Thus, it can be considered that the main condition for the initiation of the crustal earthquake source is the occurrence of a stress concentrator (seam), which prevents tectonic displacements in the place of its formation.

This seam, which means the stopping of block displacements in one or another section of the fault, with the permanent motion of two extended, mutually displacing systems of blocks, will generate an elastic stress field in this section, i. e. this area will be the nucleus of the earthquake focus.

The following condition is necessary and sufficient for the formation of a strong earthquake source: the source, initially or at the stage of formation, must be a body, the predominant deformations of which are elastic seismogenic deformations. This is the way of origination and formation of the source of a crustal earthquake.

The existence of "Gamburtsev's seams" can also be considered according to the variations of the seismic regime in the earthquake source during its preparation and immediately after the destruction (strong earthquake). During the preparation of the source, it is either completely aseismic or generates rare seismic impulses, the so-called foreshocks (weak earthquakes that occur before a strong earthquake). Previously, scientists hoped to use the foreshocks in the problem of forecasting earthquakes; however, they did not come true, since it was not possible to find a logical connection between the preparing source and the so-called foreshocks. And this is not surprising, since foreshocks do not differ from ordinary weak earthquakes and they are recognized only after strong earthquakes.

After a strong earthquake, the seismic regime in the source changes very sharply: it is accompanied by a trail of aftershocks (weak earthquakes), which can last for many months or more decreasing with time.

This abrupt change in the seismic regime after a strong earthquake in the source is an objective indicator that the source of the impending earthquake was a consolidated volume of rocks with one modulus of elasticity – in the case of mechanically homogeneous rocks in the earthquake source, this will be their natural modulus of elasticity. As for the modulus of elasticity in the impending source with mechanically heterogeneous rocks, it can be assumed that an effective modulus of elasticity arises in such a source.

The modulus of elasticity, which is common in the rocks of the source, allows accumulating ultimate elastic stresses in the entire volume of the source, and that is why, during the accumulation of these stresses, it either doesn`t emit or emits weakly this energy. After the discharge of the main part of the accumulated energy (strong earthquake), this consolidated body returns to its original state and in it, in the form of aftershocks, the final discharge of the seismic energy accumulated in the focus occurs.

Considering the question of possible reasons for the occurrence of an effective elastic modulus in an incipient source, in which there are blocks of rocks with different elastic moduli, one can bear in mind the following. During the earthquake source initiation, its entire volume is in the local field of compressive stresses, which compact the rocks. It can be believed that due to this compaction, an effective modulus of elasticity arises.

The occurrence of strong earthquakes in the upper layer of the crust indicates that in seismogenic faults of this layer, in certain parts of them, conditions for the accumulation of ultimate elastic seismogenic deformations in a particular volume of rocks arise for one or another reason.

Thus, it can be considered that the main condition for the origin of a crustal earthquake source is the occurrence of a stress concentrator, which prevents tectonic displacements in the place of its formation and leads to the formation of a mechanically strong, consolidated volume of rocks (seam) in a particular fault zone.

So, one can conclude that the reason for the crustal seismicity, which is caused by mutual tectonic displacements of blocks of the Earth's crust, is a delay in these displacements of blocks in one or another section of the seismogenic fault.

It is necessary to notice that the seismic energy emitted in the course of earthquakes is a very insignificant fraction of the tectonic energy, which is spent on tectonic displacements of block systems along the faults separating them. Considering the studies of

Yu. V. Riznichenko [Riznichenko, 1985], this share does not exceed 1% for the Caucasus region. It is hardly to imagine what would happen on Earth in case of this share were equal, for example, 40-60%. It is reputed that, fortunately for us, the system of tectonic displacements of the blocks of the Earth's crust works with a small "defect", which, nevertheless, is very tangible for the Earth.

Methods

The type and size of real deformation fields generated by local fields of elastic stresses of the exponential form. Deformation precursor of the preparation of the crustal earthquake source

According to the above considered Saint Venant principle, due to the stress concentrator (seam), a local elastic stress field arises, being maximum at the place where the seam originates (in the fault) and exponentially decreasing with distance from this section of the fault.

It is quite obvious that a local elastic stress field with exponential decay of stresses should generate an exponential field of elastic deformation of rocks in the impending earthquake source, i. e. rocks must be elastically bent.

Thus, we have obtained a theoretical basis for the type of deformation precursor of a crustal earthquake – **this is the elastic bending of rocks in the impending earthquake source.**

With the help of the existing geodetic experimental data one can check the rightness of these theoretical considerations. These data are the results of recurrent geodetic measurements that have been performed before and after strong crustal earthquakes in their epicentral zones (Fig. 2) [Gamburtsev, 1960; Kasahara, 1985].

The data of repeated triangulations carried out in the epicentral zones after the strong earthquakes are shown in the Fig. 2. Vertical lines denote seismogenic faults, along which horizontal movements occurred in the process of the earthquakes. The dots are fixed offsets of triangulation points; the scale of displacements is shown on the vertical axis. The abscissa denotes the location of these points from the certain fault.

According to the figure, the same pattern is traced for all the five earthquakes given above. The displacements are maximum in the vicinity of the fault and rapidly (exponentially) decrease with distance from it. For different earthquakes, these displacements become minimal (zero) at distances from 20 to 40 km from the fault. This suggests that the exponential distribution of the displacements of geodetic points on the curved lines in Figure 2, as well as the manifestation of these displacements no further than 40 km from the fault, reflect the actual form of stress fields and their sizes, caused by the earthquakes, that generated them. The validity of this assumption is substantiated below (see Fig. 3).

These data and other sources [Kanamori et al., 2006; Ohta et al., 2012; Tong et al., 2012; Wang et al., 2013, 2020; Zeng, Shen, 2017; Zeng et al., 2018; Liu, Rogozhin, 2018; Bulut et al., 2019; Toulkeridis et al., 2019; Kazimova, Kazimov, 2020; Li et al., 2020] also convincingly indicate that the displacements of geodetic points which take place in the course of strong earthquakes carry the information about the unified mechanism for the preparation of these earthquakes. It should also be noted the fact that this mechanism is the same for different continents. It can be believed that it is universal.

They also confirmed the previously expressed theoretical considerations that the process of crustal earthquake preparation is the accumulation of elastic bending seismogenic deformations in its source, and therefore the deformation sign (precursor) of preparation

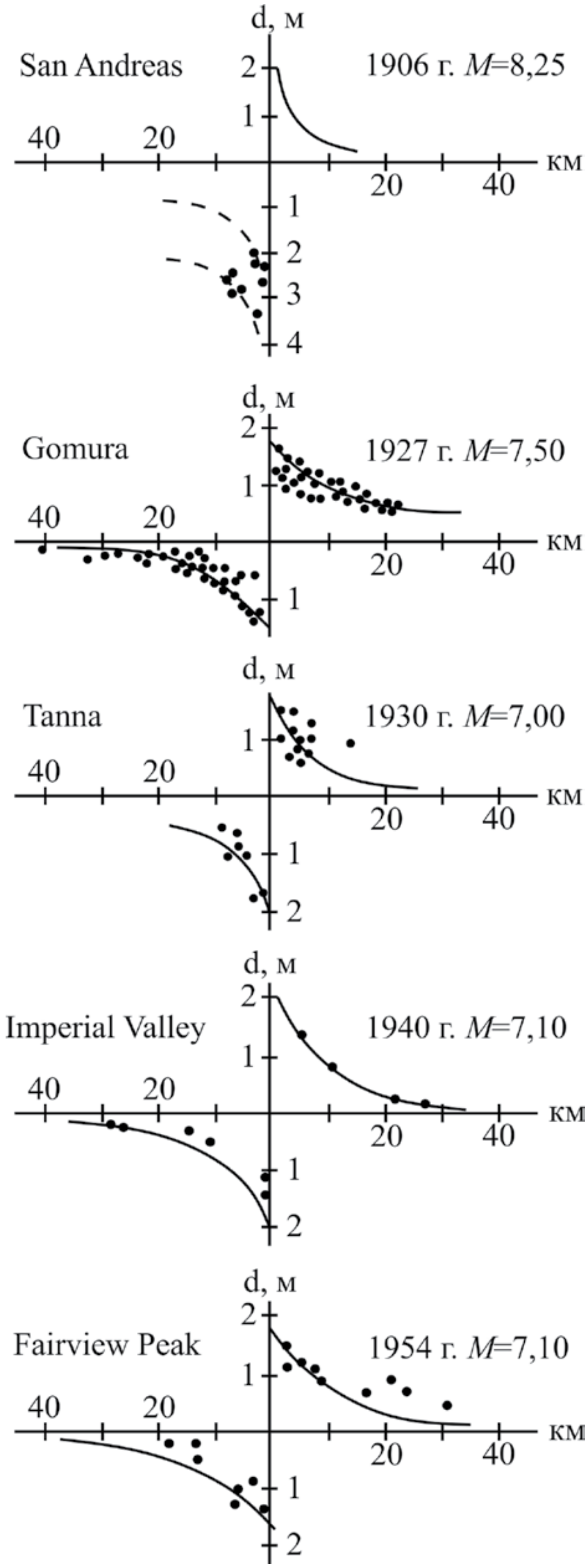

Fig. 2. Actual distribution of displacements of triangulation points (d) in zones of seismogenic faults during strong crustal earthquakes depending on the distance of geodetic points from faults, according to [Gamburtsev, 1960; Kasahara, 1985]

and maturation of the crustal earthquake source is **the elastic bending of rocks in this source.**

One should note that according to the information of this figure, one can determine the width of the earthquake source, which can be considered equal to the width of the zones of penetration of elastic displacements into the bodies of the crustal blocks contacting along the fault. In order to realize this, it is necessary to determine the interval between the points of these blocks exponential curves exit to the asymptotes. These distances are evaluated in several tens of kilometers (from 40 to 60m) agreeably the data in Fig. 2.

However, in the light of the problem under discussion, the main importance of these data lies in the fact that they contribute to the real forecast of earthquakes as they confirm the participation of the Earth's surface in the process of the earthquake source preparation.

Local stress fields generating sources of crustal earthquakes arise due to the appearance of stress concentrators in a seismogenic fault, which are fault sections in which displacements along the fault have ceased for one or another reason. As noted above, such stress concentrators G.A. Gamburtsev called "seams". According to the Saint Venant principle, "seams" represent additional loads in the system of shifting blocks of the Earth's crust. It is they that generate local fields of elastic stresses of an exponential type, which is confirmed by geodetic studies.

So, based on the analysis of geodetic data in Fig. 2, the following conclusions can be drawn:

1. Crustal seismicity is generated by local exponential stress fields ranging in size from 20 to 40 km.

2. The similarity of the identified displacements of geodetic points for all five earthquakes convincingly suggests that these data carry information about a single mechanism for the preparation of these earthquakes.

3. The process of crustal earthquake preparing is the accumulation of elastic bending seismogenic deformations in its source. The deformation sign of the preparation of the crustal earthquake source is the elastic bending of rocks in this source.

4. The process of preparing the earthquake source also captures the Earth's surface, which is the upper surface of the impending earthquake focus, and this is what makes it possible to track this process directly on this surface.

5. The process of preparation of earthquake sources can be monitored only by geodetic methods, which allow determining the elastic displacements of the Earth's surface at bases of tens of kilometers, thereby determining the actual shape of the curve of the line of these displacements.

For better understanding the above-mentioned considerations, we should consider the reason for the appearance of regular displacements of triangulation points during earthquakes (Fig. 2). It is clearly demonstrated in Fig. 3.

Vertical line in figure 3A shows the same section of a seismogenic fault at times t_0, t_1, and t_2, which correspond to different stress states of rocks. The directions of tectonic displacements on the fault are denoted by arrows. Moment t_0 – there are no seismogenic stresses in the rocks, which is shown by the straight line **ab**. Moment t_1 – rocks are extremely stressed by a local field of exponential elastic stresses (elastic bending): curve **ab**. Moment t_2 – the position of rocks after the earthquake, in which the following events occurred: the main rupture of rocks in the source; displacement of rocks along this rupture and, due to this, the discharge of the previously accumulated flexural seismogenic deformations – straight line segments **a** and **b**.

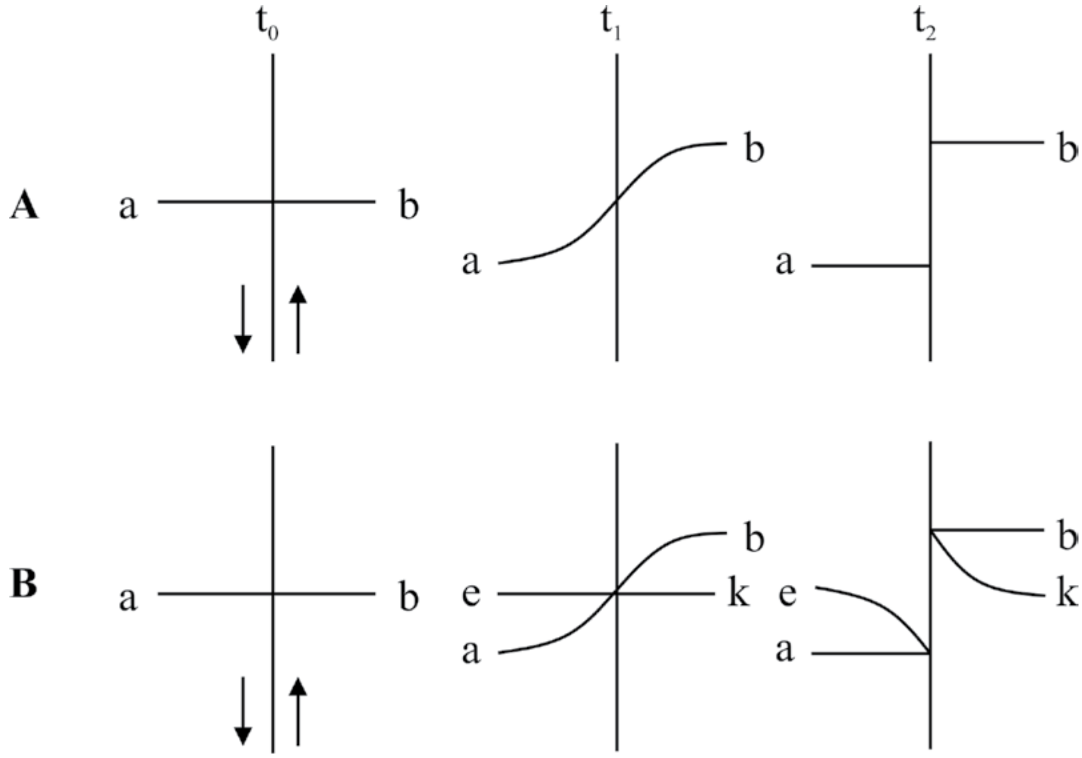

Fig. 3. An explanation of the phenomenon of the exponential distribution of displacements of geodetic points in the epicentral zones of strong crustal earthquakes

Now let's turn to Figure 3B. This figure has only one difference compared to the Figure 3A: it has a straight line **ek**, which means a rectilinear geodetic construction (geodesic profile) formed at time t_1, over the maturating earthquake source. At first glance it seems that the view of the rectilinear geodesic profile is characterized by paradoxical changes after the earthquake, changing into two curved segments that are displaced relative to each other. But it is easily explained by the following. Due to the conditions of the problem, we know that the profile was formed over the rocks that already have been distorted by elastic bending of the impending earthquake source. It appears from this that the rocks have been displaced along the fault and straightened at the same time in the course of the elastic stress release. As for the rectilinear geodesic profile above the source, it turned into two curved segments. They have retained the curvature of the **ab** curve.

E and **k** curved segments are a mirror image of two halves of the **ab** elastic curve. It is explained by the fact that the curve **ab** and the straight line **ek** exchanged their shapes due to the earthquake. Hence these curved segments kept the information about the elastic deformations magnitude that have been accumulated in the source to the moment of this geodetic profile formation.

According to this conclusion, there is a reason to believe that in all the cases shown in Fig. 1, the initial triangulation measurements were performed over the already impending earthquake sources, i. e. they have already accumulated, by the time of the initial (performed before the earthquake) triangulation, seismogenic stresses. If it was otherwise, then in the course of an earthquake, initially rectilinear geodesic profile would only be broken at the fault line but did not experience any bending. It would be represented by two rectilinear segments similar to the behavior of rocks at the moment t_2. This indicates the fact that strong earthquakes are being prepared for many tens and more years.

Thus, we successfully explained the mysterious occurrence of the curves in Figure 2.

Seismogenic layer of the Earth's crust

Taking the considered by us problem into account, it is essential to know whether the entire thickness of the Earth's crust is seismic. It is very important as the probability of the impending source detection is greater the shallower it is located in the Earth's crust.

It is traditionally assumed in seismology that crustal earthquakes take place at depths of up to 70 km. However, this does not correspond to reality, since not the entire crust is seismically active, but only its upper horizons [New catalog…, 1977; Rogozhin, 2013].

The rheological heterogeneity of the rocks of the Earth's crust along the vertical is the explanation of this phenomenon. According to [Bott, 1974; Sherman, 1977; Zharkov, 1983; Pavlenkova, 1988; Pevnev, 1988, 2014, 2020] the Earth's crust can be divided in the first approximation into elastic and plastic layers.

The upper layer of the Earth's crust, which is considered as conditionally cold and has a thickness of 10-25 km, is seismogenic, i. e. elastic, capable of accumulating significant elastic deformations and brittle fracture when the accumulated elastic stresses reach the ultimate strength of rocks. If we consider the rocks of the plastic, conditionally hotter layer, which do not have elastic properties, then this layer is considered as aseismic. It is explained by the fact that such rocks are plastic or viscoplastic.

Let`s present the existing theoretical considerations and experimental data to substantiate this statement.

The English geophysicist M. Bott writes about the state of rocks in the upper part of the Earth's crust in his book:

"The results of experimental studies have shown that the mechanical properties of rocks at a depth of 10-25 km undergo two significant changes. First, there is a transition from a brittle state to a plastic one; Griggs, Turner and Hird… did not observe sudden cracks in any rocks except quartzite at pressures above 5 kbar and temperatures above 500° C, which corresponds to the conditions at a depth of about 20 km. Second, the compressive strength should be expected to decrease with depth under the dominant influence of temperature; for example, the tensile strength of dunite, pyroxenite and granite under all-round compression of 5 kbar decreases from 20 kbar at 25° C to 10 kbar at 500° C and to 7 kbar at 800° C" [Bott, 1974, p. 280].

"There is reason to believe that the lower part of the crust under the condition of a sufficiently high temperature and large stress differences can experience noticeable deformations in the form of unstationary and stationary creep" [Bott, 1974, p. 281].

The division of the lithosphere material into layers with different elastic characteristics in a vertical section is also confirmed by the distribution of mechanical quality factor (Q_μ) in it. Now let`s quote the work of V. N. Zharkov:

"The quantity Q_μ can also be considered as a "measure of ideality" of the elasticity of the medium. The larger the value of Q_μ, the smaller part of the mechanical energy dissipates during vibrations and turns into heat, the closer the medium is to ideally elastic" [Zharkov, 1983, p. 90].

"The outer hard layer of the Earth (its lithosphere) is divided into three zones: high-quality factor (0-19 km), $Q_\mu \sim 600$; medium quality factor (19-38 km) $Q_\mu \sim 300$, and low-quality factor (38-90 km), $Q_\mu \sim 150$" [Zharkov, 1983, p. 92] (Fig. 4).

It is worth mentioning the good agreement between the proved by Bott boundary of the transition of crustal rocks into a plastic state at a depth of about 20 km, and the thickness of the layer of the Earth's crust with the highest quality factor, equal to 0-19 km. It should be noted that this is the maximum figure of merit not only in the lithosphere but also in the Earth's mantle (Fig. 4).

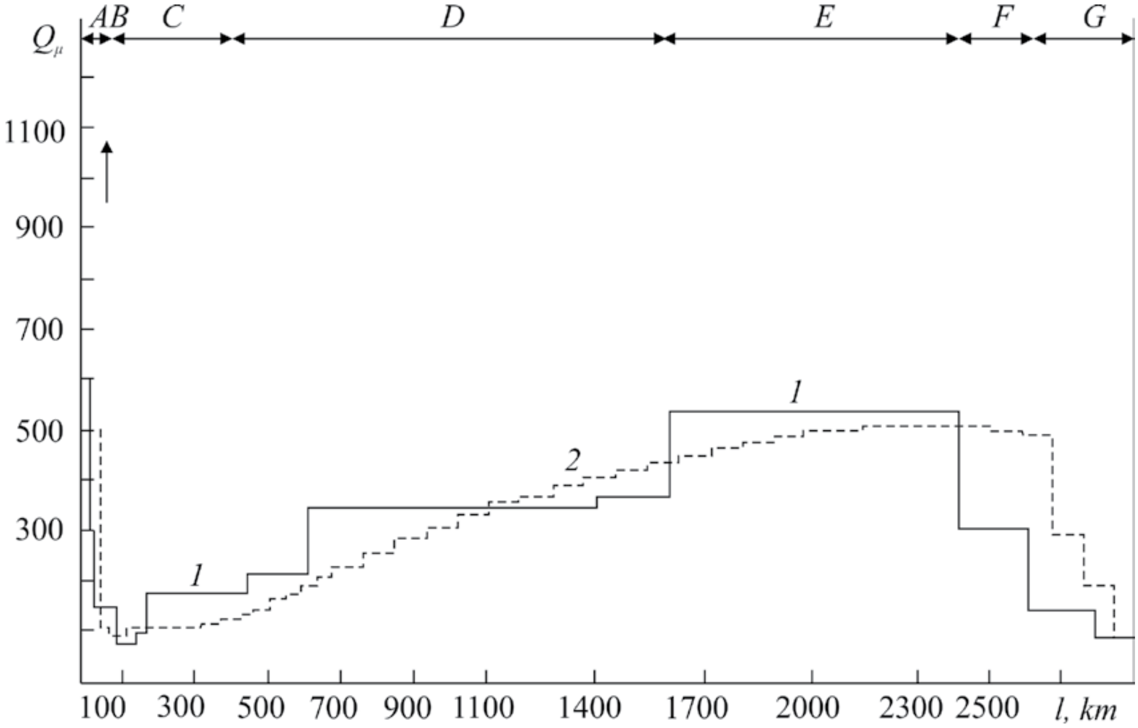

Fig. 4. Distribution of mechanical quality factor Qμ (l) in the crust and mantle of the Earth. A (0-38 km) – 1st zone of high Qμ (elastic lithosphere); B (38-90 km) – inelastic lithosphere; C (90-450 km) – 1st zone of low Qμ; D (450-1600 km) – 1st zone of intermediate Qμ; E (1600-2400 km) – 2nd zone of high Qμ; F (2400-2600 km) – 2nd zone of intermediate Qμ; G (2600-2885 km) – 2nd zone of low Qμ. 1 – modified distribution Qμ obtained by V.M. Dorofeev and V.N. Zharkov (1978); 2 – model SL8 (Anderson, Hart, 1978), according to [Zharkov, 1983]

It is very interesting to consider the diagram of the fault structure in Figure 5, proposed by D.I. Sherman in relation to the considered problem.

According to D.I. Sherman crustal rocks in the fault retain elastic properties (to one degree or another) only in the first three horizons shown in Figure 7 (I, II and III). The total thickness of these horizons is approximately 25 km. Within these 25 km, with increasing depth, there is a transition from brittle fracture (Hookian solid) – an approximate depth interval of 0-5 km – to quasi-brittle fracture (Burgers viscoelastic body) at approximately 5-10 km depths and, finally, to a quasi-plastic flow (Maxwell viscoelastic body) at depths of about 10-25 km. At greater depths (horizons IV and V), only plastic deformations take place: plastic flow (Saint-Venant plastic body) in horizon IV transforms into a viscous flow (Bingham viscoplastic body) in horizon V.

Data on the distribution of the depths of aftershocks of strong crustal earthquakes confirm and vividly illustrate the division of the Earth’s crust into two layers by rheological parameters, the reliability of the location of the most elastic layer in its uppermost part and the reality of the above-mentioned thickness of this layer. Aftershocks are weaker earthquakes that occur in the source zone of a strong earthquake. Actually, aftershocks remove the elastic stresses remaining in the source after a strong earthquake, i. e. “finish off” what the main seismic shock did not do. Consequently, aftershocks can occur only in a medium capable of accumulating elastic seismogenic deformations (stresses). Therefore, one can determine the thickness of the seismogenic layer in the area under study with the help of studying the aftershocks` distribution in the depth. Racha earthquake of 1991 can be considered as the typical example of such data (Fig. 6).

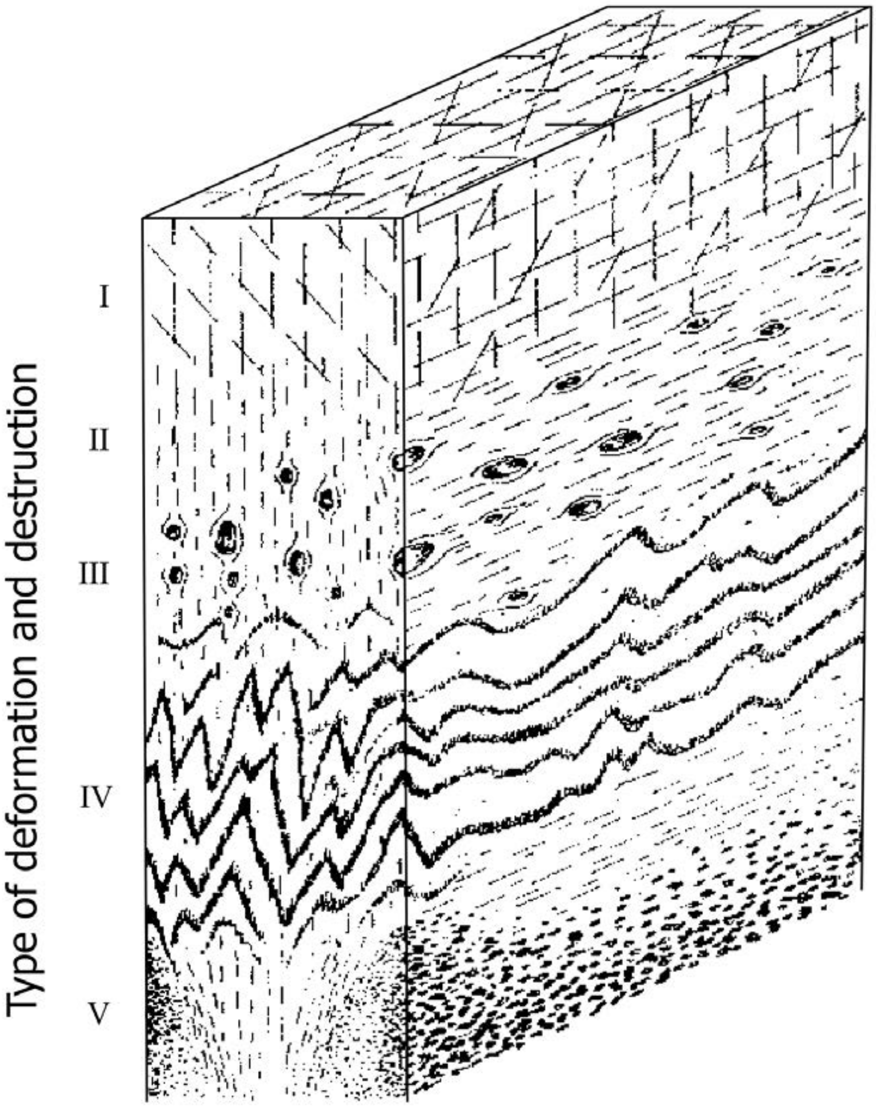

Fig. 5. Scheme of the structure of the general fault along the vertical section (I – brittle fracture, II – quasi-brittle fracture, III – quasi-plastic flow, IV – plastic injection, V – viscous flow), according to [Sherman, 1977]

Figure 6 clearly shows that after the earthquake the elastic stresses were relieved in the Earth's crust with the thickness of 0-25 km. Nevertheless, the most homogeneous aftershock field occupies only the 0 to 10 km depth interval. The number of aftershocks drastically decreases with the depth, and only single aftershocks are recorded at the maximum depth, equal to 25 km. Based on the information about such a distribution of aftershocks one can assume that this layer of the Earth's crust is responsible for crustal seismicity, i. e. it is the very layer, that can be considered as seismogenic.

Thus, we can assume that the thickness of the seismogenic layer is 10-15 km in the studying area. It cannot be doubted that such investigations of aftershocks are the most reliable method for determining the seismogenic layer thickness in those areas where the existing seismic grid allows recording weak earthquakes and determining the depths of earthquake hypocenters with sufficient accuracy within 1-5 km.

As it is known, there is a dense network of seismic stations at the San Andreas Fault in California with the help of which it is possible to record even very weak earthquakes

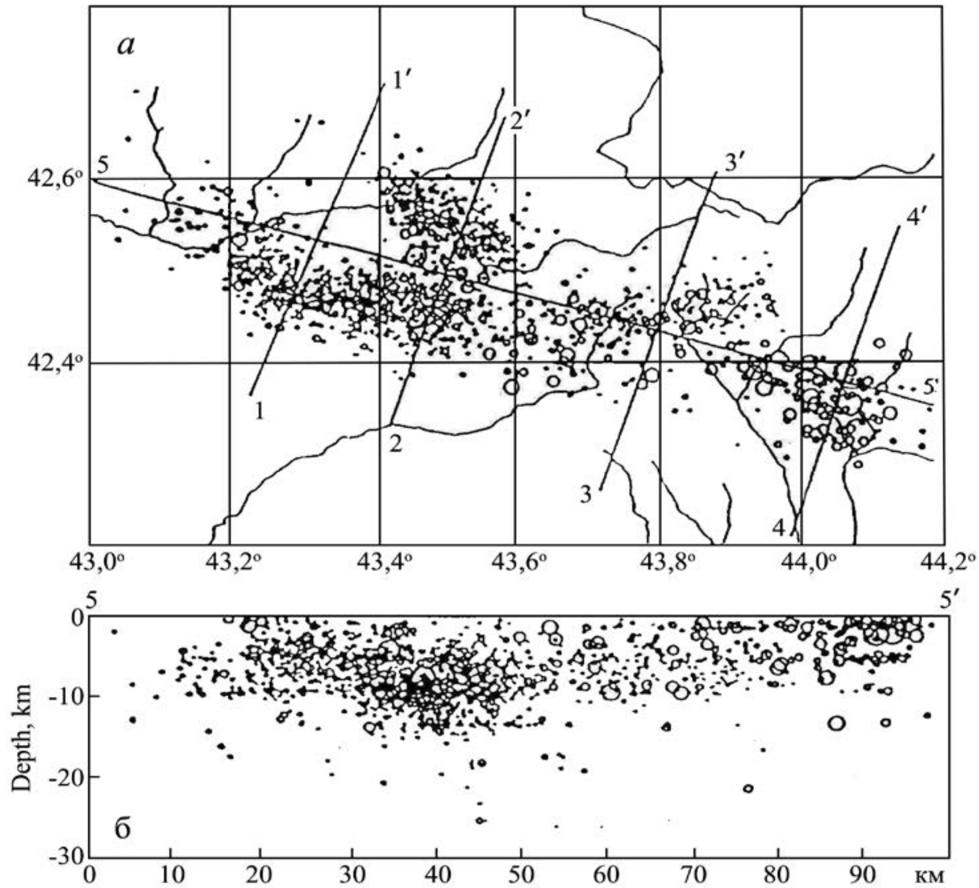

Fig. 6. Map of the epicenters of the Racha earthquake (a) and a vertical section along the 5-5` line (b), according to [Arefiev et al., 1993].
All seismic events for the aftershock period are projected onto the cutting plane. The depth of the main shock is 10 km, the source is about 100 km long, and the magnitude is 7.3

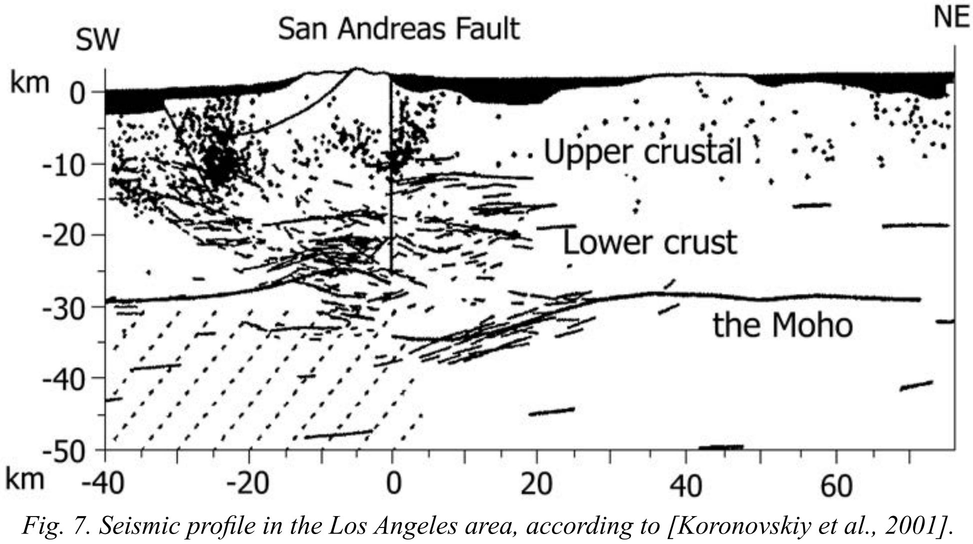

Fig. 7. Seismic profile in the Los Angeles area, according to [Koronovskiy et al., 2001].
Thick lines are the Moho and other interfaces, thin lines are reflectors. Diagonal shading denotes abnormally high-velocity upper mantle according to seismic tomography. Points are hypocenters of earthquakes for the period from 1981 to 1998

and determine with high accuracy the depths of the hypocenters of all local earthquakes. Field seismological observations in the San Andreas Fault confirm the above concepts about the thickness of the seismogenic layer of the Earth's crust. Figure 7 illustrates some of such observations results.

Based on the data of Figure 7 it can be reliably indicated that the seismicity of the San Andreas Fault is presented only to the depth of 15 km.

The fact that the thickness of the seismogenic layer of the Earth's crust is indeed 10-25 km is confirmed both by theoretical considerations, and experimental laboratory studies, and field seismological observations. It is also defined that seismogenic, elastic stresses accumulate in the entire thickness of the mentioned layer. And the main conclusion is that **the crustal earthquakes sources originate, mature and are realized** exactly in the seismogenic layer.

Apparently, the wrong ideas about the seismicity of the entire layer of the Earth's crust were formed because of the significant errors (up to tens of kilometers) in determining the depth of earthquake hypocenters. A rare seismic grid was the cause of these errors. One have to take into account the fact that the larger the distance of the seismic stations from the earthquake epicenter, the greater the error in the depth of the hypocenter determining.

Conclusions

The issues of geodesy possibilities for the crustal earthquake forecast

Taking the above-mentioned concepts and analysis as well as the information about the recurrence geodetic measurements in the epicentral zones of strong earthquakes into account we can draw the following important conclusions for the considered problem.

1. Crustal seismicity is caused by the delay of tectonic displacements in certain areas of seismogenic faults.

2. A deformation sign of the preparation of an earthquake source is the accumulated elastic bending in the rocks of this source.

3. The specified elastic bending is satisfactorily described by the curves $d = Ae^{ax}$; where d is the value of the elastic displacement of the considered point on the Earth's surface; x is the removal of this point from the fault; A is the value of the maximum displacement of the sides of the fault during an earthquake, a is an integral characteristic of the elastic properties of rocks in the earthquake source.

4. Being the upper boundary of the seismogenic layer the Earth's surface above the source of the impending earthquake take part in this source preparation.

5. The fact that elastic deformations penetrate into the bodies of blocks contacting along the fault at a distance of 20-30 km in the course of an earthquake preparation, allows evaluating the total width of a strong earthquake source equal to 40-60 km.

6. It is possible to determine reliably the shape of the elastic curve on such bases (tens of kilometers) i. e. to track the preparation process of the earthquake source, only with the help of the geodetic method: using geodetic forecast profiles – geodetic straight-line constructions orthogonal to the seismogenic fault (Fig. 8). This is the way to predict the location of the maturing earthquake source.

7. Since the intensity of a future earthquake is determined by the size of its source [see tab. 1], then to predict this intensity, it is sufficient to use one or another number of predicted profiles, sufficient to determine the length of the elastically deformable section of the Earth's surface (*L*, Fig. 9).

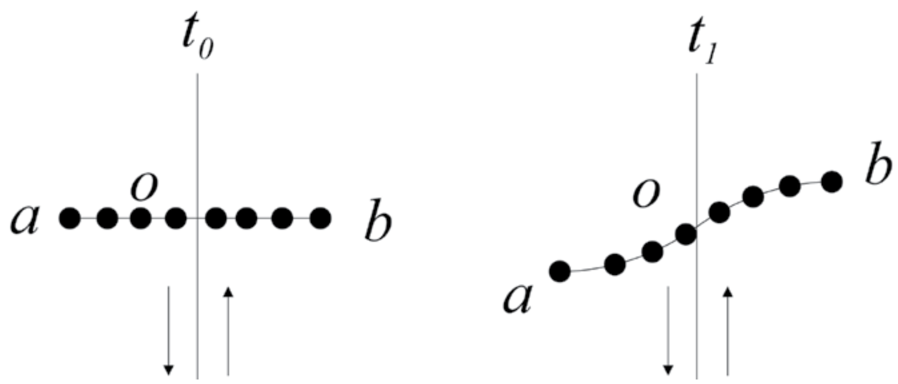

Fig. 8. Geodetic profile for the implementation of the forecast of the source of the impending earthquake

In this figure vertical lines denote seismogenic fault, displacements along which are shown by arrows; t_0 is the moment of creating a straight-line geodetic forecast profile *aob*, black dots on the profile are geodetic points. t_1 is the moment of repeated measurements on the profile. If a rectilinear profile was created over an already preparing source of an earthquake, or the preparation of the source began in the interval between t_0 and t_1, then the points of the geodetic profile at time t_1 will be located on the exponential curve *aob.* This curve is the only reliable sign that indicates the accumulation of elastic seismogenic deformations, take place in the studied segment of a seismogenic fault.

Exactly such use of the geodetic method will encourage the prediction of the impending earthquake source.

Yu. V. Riznichenko [Riznichenko, 1985] has determined the functional relationships between the earthquake intensity (magnitude M), the length of the source (L) and the maximum accumulated elastic deformation in the source (D) (see table. 1).

Table 1

Dependence of the earthquake intensity (M) on the source length (L) and displacement in the source (D) according to Yu. V. Riznichenko

M	L, km	D, sm
3	1.1	0.11
4	3.0	0.62
5	8.3	3.5
6	23	20
7	62	120
8	170	660
9	470	3800

So, if we know the length L of the impending earthquake source, it is possible to forecast the maximum intensity (M), which can be generated by the impending earthquake source. It is quite obvious that this can be realized with the help of the geodesic method.

So, the research results made it possible to construct a model of elastic deformation of the Earth's surface above the source of an impending earthquake at time t_1 and a

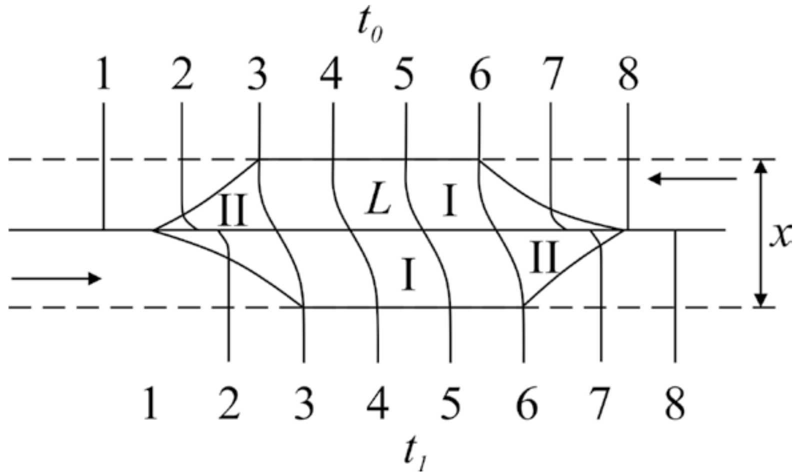

Fig. 9. Model of elastic deformation of the Earth's surface above the source of the impending earthquake (at time t_1) and a scheme of the geodetic forecasting system designed to predict its intensity

scheme for implementing forecasts of the location and intensity of an impending earthquake (Fig. 8)

Lines (1–1,… 8-8) are geodetic forecast profiles, which were solid straight lines at the moment of origin of the source (t_0). In the process of the source preparation they were broken and displaced along the fault (1-1 and 8-8), deformed and displaced (2-2 and 7-7) and elastically deformed over the source (3–3,… 6-6). I – compression zone; II – stretch zone; *L* – line of termination of displacements along the fault (length of the "seam"); *x* is the width of the earthquake source; arrows denote directions of compressive fields of local stresses generated by the seam.

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