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Recent Geodynamics of Tensile Faults

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Abstract—The results of the analysis of extensive data about the local anomalies of recent surface displacements in the fault zones estimated from repeated geodetic observations in seismically active and weakly seismic (platform) regions are presented. It is shown that the local, symmetric sags of the Earth's surface in the vicinity of the faults are the predominant type of anomalies. The simultaneous recording of the vertical and horizontal displacements shows that the local subsidence is accompanied by horizontal deformations of elongation along the lines that are orthogonal to the fault's strike. Different kinematic types of faults are considered, and it is shown that the revealed anomalies correspond to the recent activation of the local joints within the fault zones resulting in the subsidence of the Earth's surface. Three variants of the models describing the formation of the joint-type anomalies are considered: the block model, the dislocation model, and the parametric model. The comparison of the calculated distributions of the horizontal and vertical displacements in the vicinity of the fault with the observations shows that the parametric model fits the field data best. The parametric model describes a fault as a zone with varying internal parameters in two variants: as an inhomogeneity with a reduced stiffness or as an inclusion with anomalous strain according to the terminology of John D. Eshelby. By the example of regularly shaped objects, the equivalence of both approaches is demonstrated.

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INTRODUCTION

In the vast majority of works on structural geology and recent geodynamics, the kinematics of motion in the fault zones is currently represented by shear displacements. According to the existing classification of the faults, these displacements, depending on the pattern of the relative movement of the fault walls and the dip angle of the fault plane, are classified into normal faults, reverse faults, thrusts, strike-slip faults, and transitional forms combining the dip-slip and strike-slip displacement components (oblique-slip faults with the predominance of the dip- or strike-slip displacement). In accordance with Anderson's fault formation theory, three main types of faults are distinguished: normal, strike-slip, and reverse faults (Turcotte and Schubert, 2002). Naturally, all these fault types refer to the pure shear displacements of the walls of a fault.

At the same time, fracture mechanics distinguish three main mechanisms of crack formation (fracture crack separation modes): opening (mode I crack), in-plane shear (mode II crack), and out-of-plane shear (tearing, mode III crack, or antiplanar deformation). Thus, there are only two genetic types of fracture: opening and shear.

In 1954, M.V. Gzovskii (Gzovskii, 1975) suggested a physico-genetic classification of discontinuous dislocations, which was based on two main fracture mechanisms in solids (including geological materials): opening and shear. In this classification, a new class of faults was distinguished—the joints or tensile faults that are formed by the opening-mode fractures emerging under the activation of tensile stresses. This fault type was also repeatedly noted by V.V. Belousov, for example, in his textbook on structural geology (Belousov, 1985), which has been edited thrice since 1961. This approach was subsequently developed by S.I. Sherman (Sherman, 1877; Sherman et al., 1983) who expanded this classification by taking into account the position of the perturbing source in the lithosphere.

To date, most of the specialists in fault tectonics admit the opening-mode character of the fracture of a rock but describe the kinematics of the slip on the newly formed rupture mainly in terms of shear displacement (in the mechanical sense). The pull-apart (opening) type of the displacement in the fault zone is practically not considered.

This is largely explicable because the main methods that are used for studying the faults (remote methods, drilling, exploration geophysics) much more easily and naturally reveal shear displacements of the neighboring crustal volumes (blocks) along the boundaries of the fault dislocations.

Indeed, the remote methods most adequately reflect the horizontal shear displacements on the Earth's surface. The lineaments of the different ranks are typically identified with shears, although direct

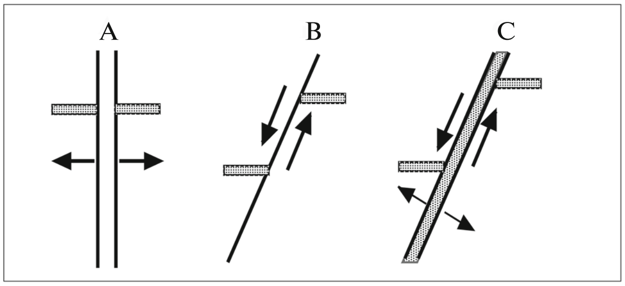

Fig. 1. Kinematic types of discontinuities: (A) joints, (B) faults, (C) dilational faults.

evidence supporting this interpretation is frequently absent. The drilling and geophysical data can only provide efficient detection for the vertical shear displacements of the blocks of the basement, geological boundaries, etc.

In this situation, it is very interesting to analyze the results of repeated geodetic observations in the fault zones which are direct indicators of the recent kinematics of rupture dislocations. Naturally, the kinematic type of deformational activation of the fault zone is determined over a time interval that corresponds to the period of measurements.

Below, we present empirical generalizations of a large volume of repeated highly accurate geodetic observations, which reflect the spatiotemporal structure of the vertical and horizontal movements of the Earth's surface in the fault zones. These results can be used as a stable indicator for revealing the kinematical type of the recent active faults. In order to more reliably establish the formation mechanism of anomalous deformations, the results of the field geodetic observations are compared to the model calculations of the spatial distribution of the vertical and horizontal displacements of the surface in the vicinity of the fault zones.

1. TERMINOLOGICAL PECULIARITIES OF CLASSIFICATION OF FAULTS

In the works on typifying the faults, the professional dedication of the researchers matters significantly. As a rule, the experts in fault tectonics mainly focus on the morphological (kinematic) aspects of the classification. In the works on tectonophysics and geomechanics, the emphasis shifts towards studying the genetic identity of different fault types. Generally, it should be noted that as of now there is no unambiguous definition of the notion of a fault.

The inconsistencies are particularly manifest if we compare different dictionaries, both Russian and international. In 2012, a fundamental treatise was published—the Geological glossary (*Geologicheskii…*, 2012), which was prepared by a team of representatives of the academic, university, and specialized Russian science. This glossary offers the following definition of a disjunctive dislocation: "A fault in structural geology—a type of disjunctive dislocation—is a fracture surface in the rock mass which is identified by the visible offset of the layers and other formations intersected by the fault or, in the case when the markers of the displacement are absent, by the tectonic contact of rocks of different ages and compositions." It is also noted there that "Mechanically, all faults are subdivided into two categories: shear (modes 2 and 3) and opening (mode 1) fracture types." However, the further particularization of this definition is mainly based on the notion of the shear kinematics of the displacements.

The glossary also contains the definitions of the joints. "A joint is a general term to denote the faults or fractures that emerge and develop under extension and whose walls move apart forming a gap." This definition of joints corresponds to the definitions suggested by M.V. Gzovskii and V.V. Belousov.

It would be interesting to compare these definitions with the similar taxonomy reflected in foreign dictionaries and glossaries. It should be noted that our foreign colleagues mostly follow the geomechanical aspect when describing faults. At the same time, there is a discrepancy between the standpoints of European and American–Asian experts. European scientists distinguish two notions: a joint and a fault. In the first case, it is the analog of our definition of a joint. In the second case, it is the definition of our term *fault* with predominant shearing (in the mechanical sense) kinematics of the displacements. This dichotomy corresponds to the terminology of the International Association of Geomechanics (Mandl, 2005) and is present in the recent Glossary (Peacock et al., 2016), which is compiled by experts in structural geology and devoted to various definitions of faults and other dislocation types.

Mandl (2005) presents a clear illustration of the European approach (Fig. 1).

From this it follows that the notion of a fault does not mean a mere break in the rock but denotes the shearing type of faulting in the mechanical sense. The American and Asian researchers hold a somewhat different opinion (He et al., 2003; Okada, 1985; 1992; Yang and Davis, 1986; Singh et al., 2002). They use the notions *tensile faults* and *shear faults*, which correspond to the opening-type and shear-type faults, respectively. The mechanical approach to typifying faults is evident also in this case. This is quite understandable because these definitions are naturally consistent with the dislocational models of calculation of the local stress-strain state that develops in the vicinity of the activated faults. In these models, the morphology of the displacement is unambiguously specified by *tensile* or *shear*, in accordance with the two main mechanisms (types) of fractures in solids.

Thus, it is evident that the American and Asian researchers implicitly share the physico-genetic classification. Gzovskii underlined that the morphological and genetic peculiarities of the taxonomy of disjunctive dislocations should not be identified with each other. The predominant criterion for classifying the fault type is the particular kinematic type of the slip, whereas the genesis of the dislocation is a secondary factor. This is especially pertinent to the type of the force conditions governing the activation of the motion on the existing faults. The shear displacements of a fault's sides can be generated, e.g., by both the shear stresses and normal stresses (tension or compression). The opening (pull-apart) displacements can be implemented under the tension oriented orthogonal to the fault's strike, under the compression in the direction of the fault's strike, or under bending . This circumstance significantly complicates the identification of the type of the stress state based on the examination of the types of displacement of the fault's walls.

I adhere to the physical–genetic classification and American–Asian typification of the faults as these approaches are closest to the commonly adopted elementary mechanisms of fracture formation (modes 1, 2, and 3) (Broeck, 1986). In this case, what is shown in Fig. 1, A is a joint or a tensile fault and in Fig. 1, B it is a slip in the mechanical sense or a shear fault.

If we imagine that Fig. 1 reflects a cross section of the geological medium with a fault, then, under the activation of the tensile fault (A), the vertical displacements of the "Earth's surface" (the upper edge of the plot) will undergo local symmetric subsidence in the vicinity of the fault. Under the activation of the (shear) fault (B), the Earth's surface will be crumpled by asymmetric *S*-shaped vertical displacements which are localized in the vicinity of the fault. Clearly, the activation of the dilatational fault (C) will result in a complicated distribution of the vertical displacements in the near-fault zone.

If we assume that Fig. 1 depicts the "planned" location of the fault on the Earth's surface, then, under activation of the tensile fault (A), horizontal displacements in the vicinity of the fault will have an axisymmetric character of the deformation of elongation with the amplitude decreasing with distance from the fault's axis. Activation of the shear fault (B) will naturally result in the formation of an asymmetric *S*-shaped distribution of the horizontal displacements in the vicinity of the fault. Activation of the dilatational fault (C) will significantly complicate the pattern of the horizontal displacements, which will become sharply heterogeneous in the near-fault area.

These considerations can be used as a test for typifying the recent deformational activity of the faults based on the analysis of the morphology of the local distributions of the vertical and horizontal displacements of the Earth's surface along the lines of the geodetic measurements intersecting the faults. In particular, the symmetric local subsidence on either side of the fault unambiguously testify to the tensile activation of the fault. In contrast, the asymmetric *S*-shaped distribution of the vertical displacements suggests the shear activation of the vertical fault.

2. TYPIFYING THE ANOMALOUS DEFORMATIONS OF THE EARTH'S SURFACE IN FAULT ZONES BASED ON GEODETIC OBSERVATIONS

As is well known, the information about the spatiotemporal structure of the recent geodynamical state of a medium is based on the repeated (ground-based and satellite) geodetic measurements that are conducted on different scale levels of the description of the studied processes: global, regional, zonal, and local.

The global and regional geodynamic processes are mainly studied by the methods of satellite geodesy (GNSS, GLONASS/GPS) as part of the studies of the kinematics of the lithospheric plates. However, for describing the fine structure of the processes in the fault zones, it is necessary to consider the key spatiotemporal characteristics of the movements on the zonal and local scales of observations. To date, the most complete information has been obtained based on the data of repeated leveling (vertical components of surface movements). This is due to a number of factors. The leveling measurements are technologically more efficient than the ground-based methods of recording the horizontal displacements and are much more accurate. The satellite geodesy methods mainly use networks with large distances (dozens and hundreds of kilometers) between the measurement points (long baselines). However, with all the other conditions remaining unchanged, the vertical component of the anomalous displacements of the (stress free) Earth's surface is noticeably larger than the horizontal component.

With this taken into account, below we mainly focus on the results of the leveling observations which were conducted at the specialized geodynamical sites designed for different purposes (Kuzmin, 1999; 2009; 2013; 2014a; Khisamov et al., 2012). In some cases, these results were complemented by the vertical displacement data obtained by ground-based and satellite geodetic measurements (Kuzmin, 2014b; 2015; 2016; 2017).

The mentioned publications concerning studies of the spatiotemporal structure of the recent deformational processes in the fault zones suggest the following empirical synopsis.

• There are persistent types of local anomalies in the vertical movements of the Earth's surface in the fault zones (Fig. 2). Here, the horizontal size (L) of the anomalies is 0.1–2 km in the case of γ-type anomalies, 5–10 km in the case of *S*-anomalies, and 10–30 km in the case of β-anomalies. The amplitude Δh and horizontal extent L for each type of anomaly are linked through the scaling $m = 10^{-6}$ (with the amplitude expressed in mm, the width of the anomaly is expressed in km).

• The main spatiotemporal characteristics of the anomalous movements are identical for the seismically active and aseismic fault zones. Here, the intensity of the deformational process in the faults of the aseismic regions is higher than in seismic regions.

• The established types of anomalous movements are to a certain degree correlated to the regional types of the stress state of the Earth's crust. The foredeep regions and intermountain troughs, which are areas of compressive stresses, are dominated by β-anomalies, whereas γ-anomalies prevail in the rifting zones (areas of extension).

These regularities were formulated at the end of the 20th century. Since that time, new data have been accumulated for deformational anomalies in the fault zones. Quite naturally, most of these data were derived from the releveling measurements on the lines that intersect the fault zones. Considerable contribution in the overall collection of deformational anomalies was provided by the measurements at the geodynamical sites organized on the oil and gas fields and UGS. Thus, 2037 near-fault anomalies of the different-type vertical surface displacements were reliably revealed to date. It turned out that the vast majority of these anomalies have a form of local (quasi) symmetric displacements of the Earth's surface in the fault zones, i.e., pertain to the γ-type. The *S*-type local displacements are least common (Fig. 3).

Thus, the γ-anomalies are predominant. According to the criteria for typifying the faults described above, these anomalies clearly classify the faults on which local pull-apart (opening type) displacements of the walls are activated. In turn, this leads to the local symmetric subsidence of the Earth's surface in the vicinity of the fault. The occurrences of the anomalies of the *S*-type vertical displacements of the surface which could have been associated with the dip-slip activation (normal, reverse, or thrust) on the fault are extremely rare.

The ubiquitous occurrence of this type of anomaly is demonstrated in Fig. 4, where the examples of γ-anomalies for different regions are presented on the same scale. Remarkably, the morphology and intensity of the anomalies are practically identical for seismically active and aseismic regions. Moreover, if we compare the strain rates, we will see that, in the case of the aseismic faults, they are even slightly higher. The detailed examination shows that some anomalies, e.g., for the Perm region of the Urals and the piedmont Dagestan, have a more complicated morphology. It appears that we observed the effect of mixing (overlapping) of two neighboring anomalies. In (Kuzmin, 2015), this question was considered in detail, and the notion of a mixed anomaly that is created by the superposition of the displacements from two spatially close faults was introduced. In the cited work, also the results of the mathematical modeling of the vertical displacement field under the activation of a system of closely located faults were presented, and the threshold distance between the faults at which the faults (anomalies) cease to interfere with each other was determined. This result should be taken into account when planning the systems of geodeformational measurements in the fault zones and interpreting the observations.

It should be noted that γ-type anomalies are observed wherever there are highly accurate observations with benchmark spacing of at most 1–1.5 km. The morphological features of the anomalies (the shape, amplitude, and width) do not depend on the geographical, climatic, and soil conditions of the surface segments where metrologically significant displacement anomalies are detected. These features are identical for the bedrocks of the Kopet Dag and Caucasian regions, for the boggy territories of Belarus and West Siberia, and the arid areas of Kazakhstan.

An illustrative example is presented in Fig. 5, which shows the very recent results of highly accurate leveling in the seismically active mountainous segment of Central Alboz, North Iran (Saberi et al., 2017). It is clearly seen that the γ-type anomaly that is confined to the Kandovan fault successively develops with time and reaches the subsidence amplitude of 115 mm over the period between the first measurement cycle in 1992 and the last cycle in 2014. If we estimate the annual average strain rate of symmetric bending by formula $\Theta = 2\Delta h/L$ (Kuzmin, 2016) where Δh and L are the amplitude and width of the anomaly, respectively, we obtain the value of 6×10^{-5} per annum. At the same time, the backgroun strain rates (those within the block part of the profile) are about 10^{-7}–5×10^{-8} per annum. This proportion between the strain rates when the anomalous values measured in the immediate vicinity of the faults are by 2–3 orders of magnitude higher than the strain rates in the block part of the medium was repeatedly noted in (Kuzmin, 1999; 2013; 2014a; 2017).

Another interesting result, also a very recent one, refers to the detailed repeated observations of the vertical and horizontal surface displacements at the Stepanovskoe underground gas storage (UGS) which is located in the European part of Russia and is currently in use (Kuzmin, 2016; 2017). UGS is an excellent testing object for analyzing and interpreting the results of geodynamic monitoring. For these objects, the geological model and the amplitude of cyclic loading are well known.

Based on conducting the repeated geodetic observations, we can determine the deformational response of the Earth's surface to the changes in the reservoir pressure. The specificity of UGS operation consists in the fact that the geological object used as UGS is either an aquifer or a depleted gas field. Gas is extracted from the reservoir during autumn and winter

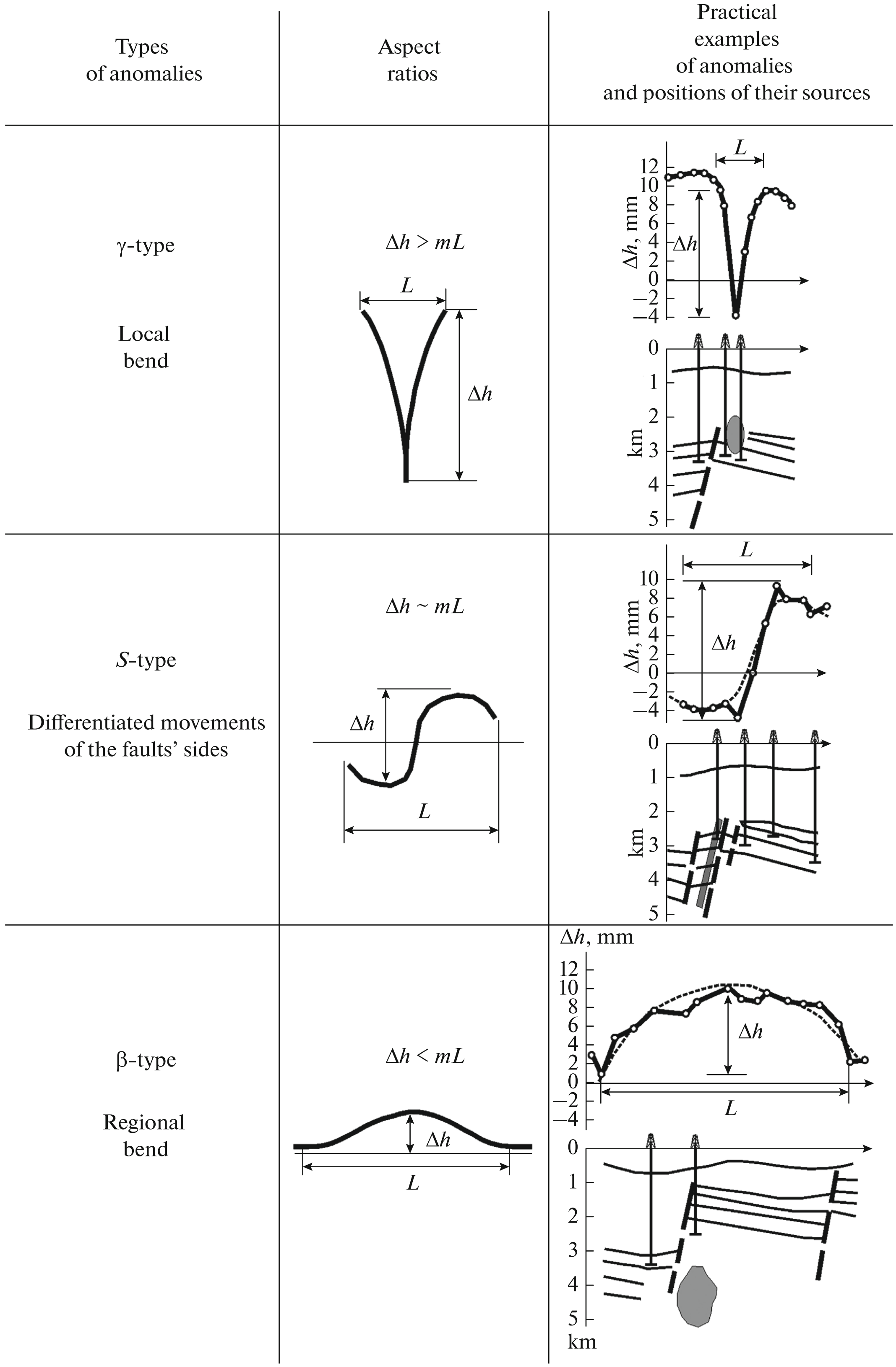

Fig. 2. Main types of anomalous variations of recent vertical movements of Earth's surface within fault zones.

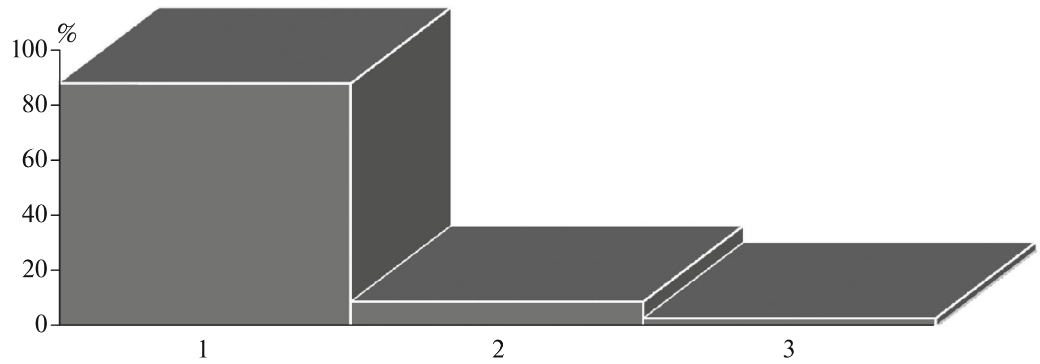

Fig. 3. Histogram of distribution of anomalies by type: (1) γ; (2) β; (3) *S*.

and injected into the reservoir during the spring and summer period. The necessity to closely check the gas leaks and the volumes of the extracted and injected gas ensures good knowledge of the main UGS parameters: the geometric dimensions and configuration of the object, the physical properties of the rocks, and the amplitude of cyclic variations in the reservoir pressure.

Furthermore, monitoring the objects that are deformed by periodical loads allows us to pass from the procedure of *observation* to the procedure of *measurement*. As is well known, observations are not measurements in the strict sense because the specificity of the field surveying poses limitations that are absent in the laboratory methods. The recurrent monitoring measurements are not reproducible because they cannot be repeated in the same conditions. In the case when monitoring is conducted on the object that periodically (semiannually) varies and the repeated cycles occur during strictly the same climatic seasons, the observations become maximally close to the procedure of measurement.

Below, we present the results of four cycles of the repeated leveling and GNSS observations that were conducted at the Stepanovskoe UGS on the network of the combined points concentrated in the fault zones. Here, the following fundamental point should be borne in mind. The monitoring information is typically represented in two forms: evolutional and pulsational. In the first variant, all the changes in the displacements of the Earth's surface are determined by the subtraction of the current values from the values obtained by the first observation, i.e., 2–1, 3–1, 4–1, etc. This form of representation allows tracking the time dynamics (time history or evolution) of the behavior of the Earth's surface when each epoch characterizes the displacements that have been accumulated to a given instant of time. In the second case, differences between the neighboring epochs are calculated: 2–1, 3–2, 4–3, etc. With this form of the representation, it is possible to detect periods marked with the emergence of the pulsations of movements and determine the duration of an anomalous process. For analyzing the cyclic processes, it is reasonable to use those pulsation curves which are exactly the ones capable of revealing the alternating-sign component of the movements. Therefore, Fig. 6 is constructed in this way.

The leveling observations are repeated on average every six months. The interval between the second and first observations corresponds to gas extraction. Therefore, the overall behavior of the curve demonstrates the subsidence in the central part of the gas reservoir. The period between the third and second observations corresponds to the neutral interval when the extraction is over, whereas intense injection has still not started. During this period, the average displacement over the profile tends to zero. Finally, during the period 4–3, gas injection takes place, which leads to the surface uplifting in the central part of the profile.

Estimating the strain along the entire profile (the background component) has shown that the alternating-sign strains of surface bending are 1.3×10^{-6} during both the extraction and injection periods. The strains in the fault zones (benchmark nos. 50, 45, and 29) vary from 2×10^{-5} to 8.7×10^{-5}. Thus, the fault zones amplify the cyclic deformations during the operation of UGS by about 1.5 orders of magnitude.

The analysis of the local anomalies of the vertical displacements in the vicinity of the fault zones shows that both the γ-anomalies, canonical in shape, and the *S*-anomalies caused by the local shear displacements of the different signs take place. This is characteristic of the rightmost fault. Here, in contrast to the monotonic local subsidence taking place within this fault during the extraction period, the morphology of the anomaly during the neutral period becomes more complicated, and a typical *S*-type anomaly is formed during the injection period.

There is yet another peculiarity in the morphology of γ-anomalies which is characteristic of many oil and gas objects. Sometimes, local subsidence areas complicated with the change of the sign of the displacements at the end parts of the anomalies are observed in the areas of the UGS and oil fields. The γ-anomaly

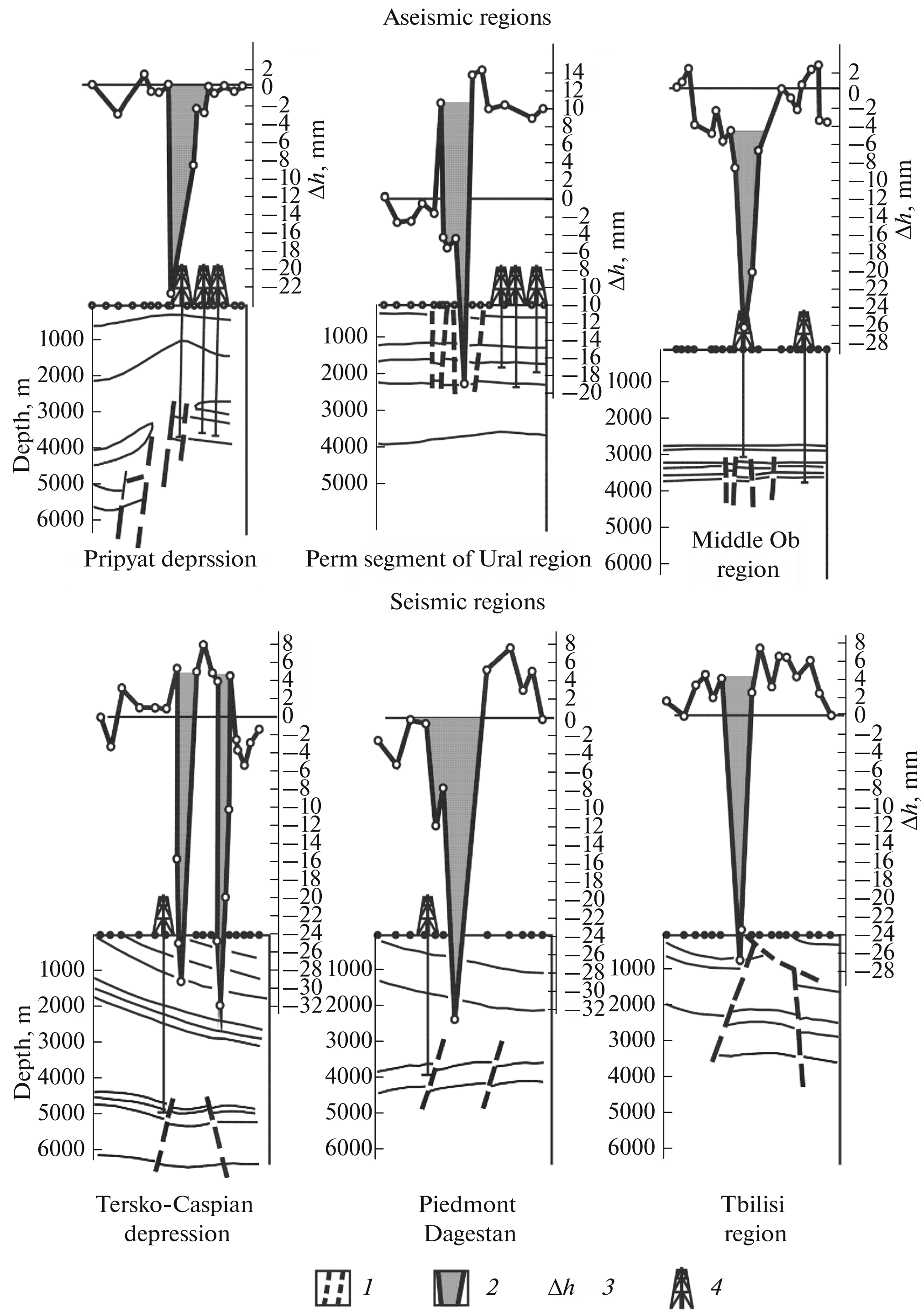

Fig. 4. Examples of γ-type local anomalies of recent vertical surface displacements for different regions: (*1*) zones of disjunctive dislocations; (*2*) zones of anomalous vertical movements; (*3*) amplitudes of recent vertical movements; (*4*) boreholes.

present in the leftmost fault during the period between the second and the first cycles of observations is a typical example. It can be seen that both the upper edges of the anomaly are somewhat elevated above the background level. The sign of the anomalous displacements changes as the displacements leave the region of the local minimum. This variety of the γ-anomaly can reasonably be referred to as an inverted γ-anomaly, in contrast to the typical monotonic shape of the anomaly, e.g., in the vicinity of the second fault from the left.

In the gas fields where gas is recovered through the monotonic reduction of reservoir pressure, mainly the

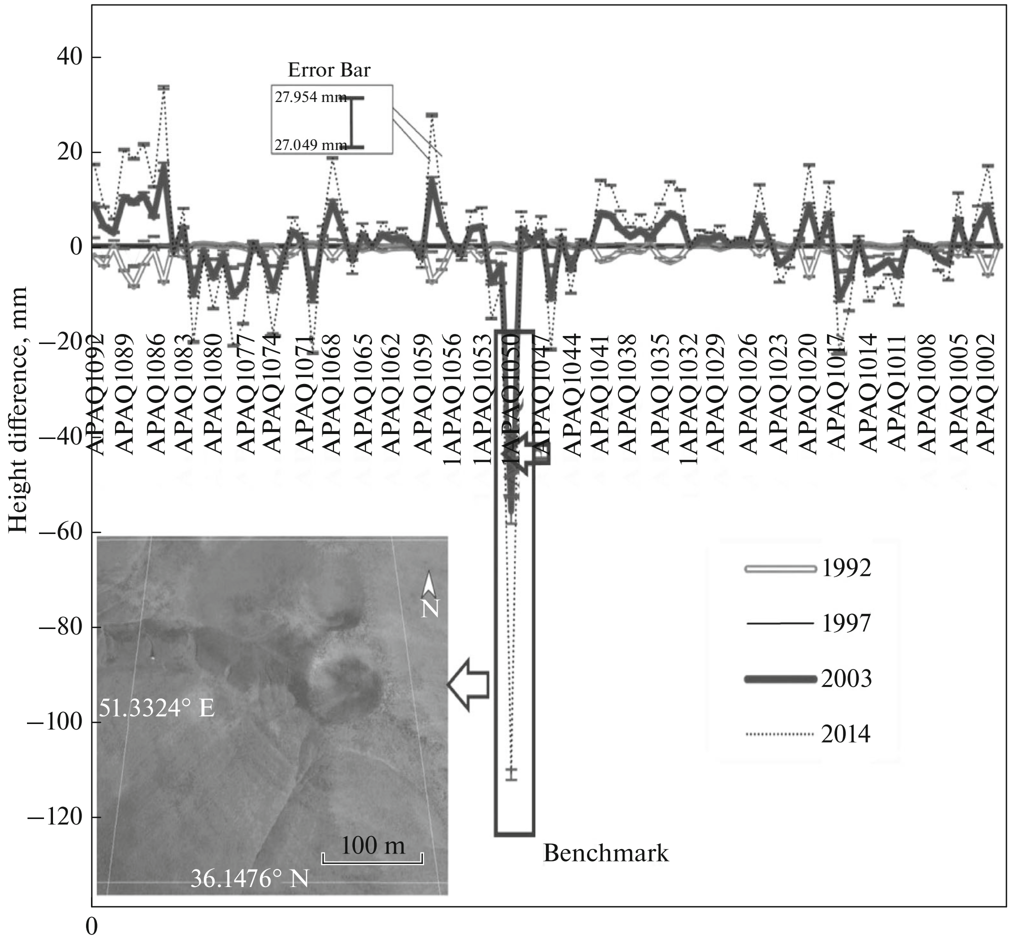

Fig. 5. Benchmark elevation differences during four time cycles of measurements. Error bar is equivalent to unit rms error of measurements. Photo image in bottom part of figure shows position of Kandovan fault in vicinity of benchmark APAQ1049.

monotonic anomalies of the vertical displacements are observed. In the oil fields where the falling production is enhanced by water injection into the oil reservoir, inverted anomalies are sometimes detected.

3. FORMATION MECHANISM OF THE RECENT TENSILE ACTIVATION OF FAULTS

For establishing an adequate formation mechanism of the deformational activation of faults, we need to compare the field observations of the vertical displacements of the Earth's surface with the similar characteristics that follow from the analytical and numerical models describing the formation of the local stress-strain state of the fault zones. An extensive review of the analytical and numerical models was presented is (Kuzmin, 1999); the subsequent publications (up to 2017) complement this review.

All the currently known models describing the formation of anomalous surface displacements in the fault zones form three fairly distinct groups.

(1) Block models in which extensional or shear displacements of the basement blocks are specified. These displacements create surface displacements of the continuous sedimentary cover that is underlain by the basement. The fault is a separating surface along and across which the blocks move relative to each other. In this sense, the type of the surface displacement anomaly is fully determined by the external, regional kinematic conditions of the block movements.

(2) Dislocation models of the faults, when the jumps of the local displacements are specified inside an infinitely thin segment of the fault, and these jumps form the distribution of the surface displacements. This is a typical problem with internal sources which does not depend on the character of the regional conditions but is fully determined by the tensile or shear character of the jump of the displacements on the fault.

(3) Parametric fault models whose characteristic feature is that the fault zone is considered as a domain (inclusion, inhomogeneity) with reduced mechanical (stiffness) characteristics. In this case, the local opening-type (pull-apart) movements of the fault sides in the fault zone are formed due to the reduction in the bulk modulus K in the setting of the regional constant horizontal tension stress. The shear displacements in the fault

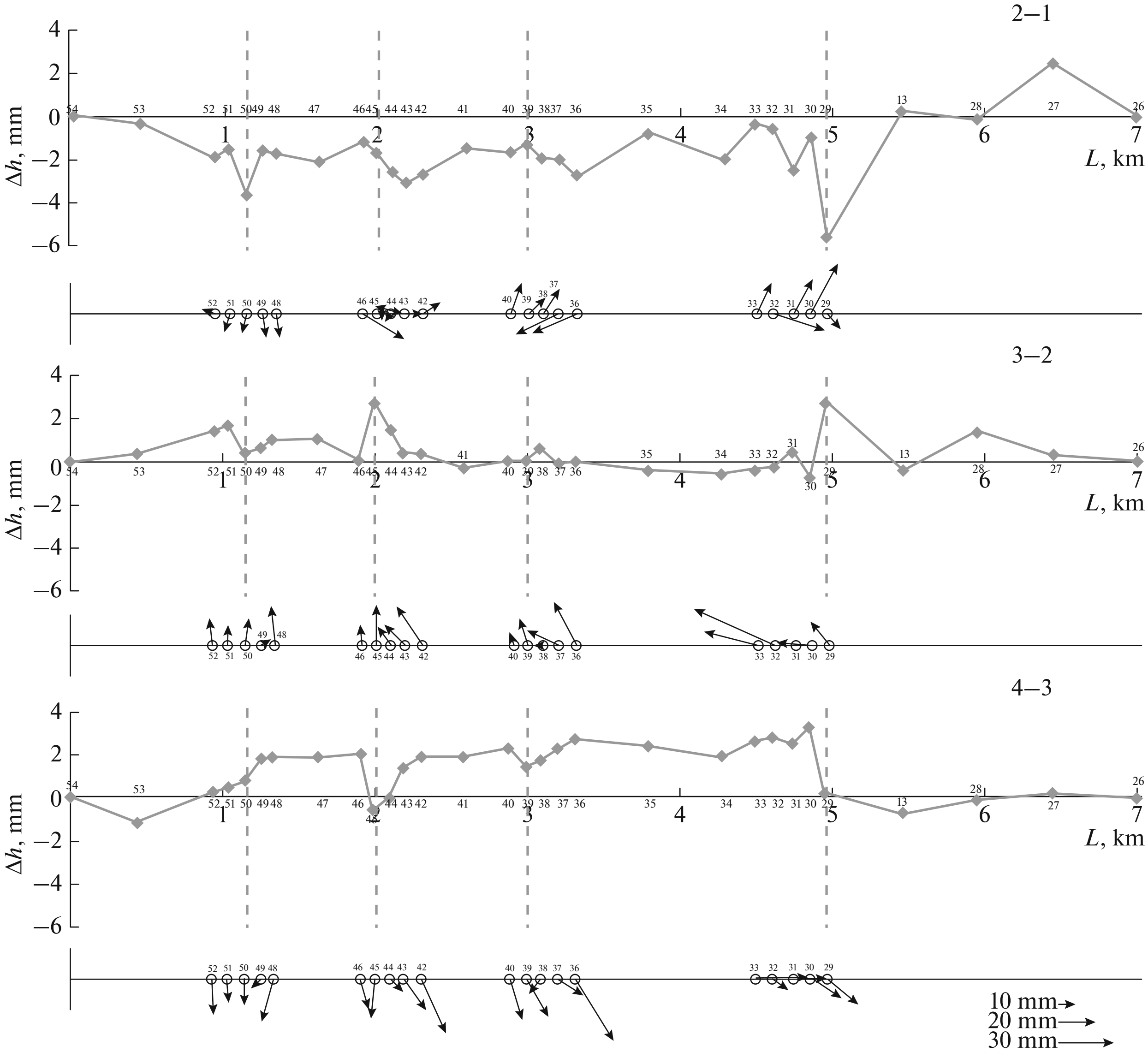

Fig. 6. Comparison of leveling (dots) and GPS (arrows) observations along profile. Dashed line shows positions of fault zones according to geological and geophysical data.

zone occur under the reduction in the shear modulus μ in setting the constant regional stresses (normal and shear) of any sign.

Below, the results of the comparative analysis of the existing models are presented for the cases when the opening-type displacement of the fault walls occurs in the fault zone (a model counterpart of a fault), because the observed anomalies of the recent surface displacements are dominated by the γ-type.

3.1. Block Model of Tensile Fault Formation

Among the existing block models of the formation and evolution of tensile faults, the model developed by a team of scientists of Schmidt Institute of Physics of the Earth of the Russian Academy of Sciences under the leadership of A.G. Grigor'ev is most elaborate (Grigoryev et al., 1988). The model considers the process of deformation of the layered sedimentary cover due to the horizontal movements of the basement blocks across the strike of the fault separating these blocks. Closed-form analytical solutions are obtained for the stress-strain state of the layered cover with allowance for the ponderability of the medium.

Figure 7 shows the distribution of vertical surface displacements and their horizontal gradients (tilts) across the strike of the vertical tensile fault. If we assume that the abscissa marks the position of the fault, we can see that the spots of the maximal subsidence appear in the vicinity of the fault and that the

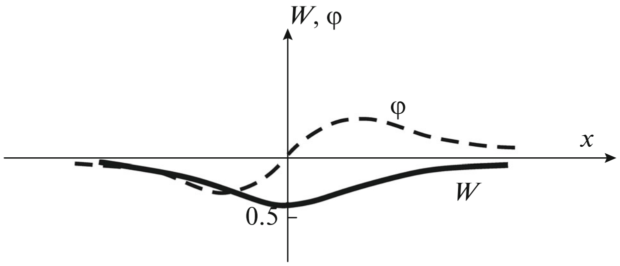

Fig. 7. Distribution of calculated vertical displacements (solid line) and tilts of Earth's surface (dashed line) along profile intersecting tensile fault.

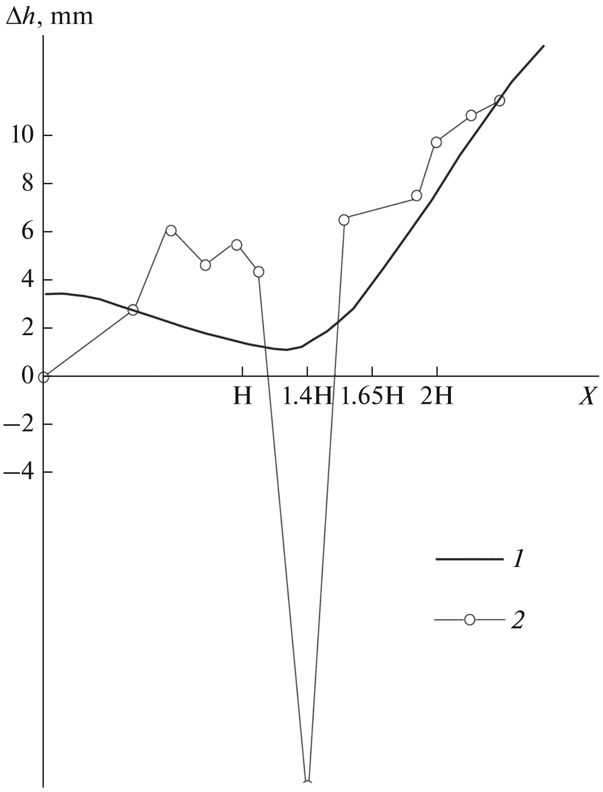

Fig. 8. Distribution of calculated (*1*) and (*2*) observed vertical displacements along leveling profile intersecting tensile fault (block model).

subsidence monotonically decays on either side of the fault. The graph shows the distribution of the displacements normalized to the thickness of the sedimentary layer and the tilts along the line intersecting the fault. Passing to the dimensional values, we see that the width of the area of the maximal subsidence is commensurate with the thickness of the sedimentary cover. A more detailed comparison between the calculated and observed subsidence values can be made based on Fig. 8 which shows the results of leveling observations on one of the oil fields in Belarus.

The calculated displacements were obtained for the real conditions of a segment of the leveling profile intersecting the Rechitskii fault in the Pripyat depression, Belarus. Calculations were conducted with allowance for the physical properties of the rocks and the detailed structure of the sedimentary cover and the top portion of the basement according to the geological and geophysical data. From Fig. 8 it follows that the calculated values significantly differ from the observations. Neither the widths of the anomalies nor their amplitudes coincide.

Furthermore, for implementing the block model, the time variations of the horizontal displacements of the blocks are required to correspond to the time behavior of the local near-fault subsidence and their amplitudes need to be commensurate with the amplitudes of the block displacements. However, the synthesis of the works on studying the surface deformations by the methods of satellite and ground-based geodesy in different regions and on different spatiotemporal scales shows that the annual average strain rates range within 10^{-8}–10^{-9} per annum and weakly depend on the base and duration of the observation period (Izyumov and Kuzmin, 2014; Kuzmin, 2013; 2017). Of course, this does not apply for the local measurement systems that are organized in the fault zones.

Therefore, the block model describing the formation of local subsidence of the Earth's surface in the zones of activation of tensile faults cannot be used as the mechanism of the formation of the observed spatiotemporal range of the recent surface displacements.

3.2. Dislocation Model of Tensile Faults

The dislocation models of surface displacements in the fault zones have been developed with a high degree of detail. There is a broad class of analytical and numerical models that take into account the curvature of the Earth's surface, the rheology, layering, and ponderability of the hosting medium. For more than 70 years, these models have been used in the problems of seismology (focal mechanisms, coseismic and postseismic movements, etc.) and in the analysis of the results of geodetic observations in the volcanic regions (Dzurisin et al., 2007; Segall, 2010).

Overall, these models quite adequately describe the local pattern of the near-fault surface displacements. For example, the predicted extensional jumps of the dislocations in the fault are fairly commensurate with the observed values. Moreover, within the scope of the dislocation models, the inverted forms of the γ-anomalies are revealed (Fig. 9).

Figure 9 illustrates a comparison of the point and finite-length opening dislocation. This model uses the scheme when the horizontal opening dislocation (double couple without torque) is summed up with the source of bulk dilatation (dilatation center). This is done in order to avoid the zero vertical displacements at the point $L = 0$, i.e., above the very fault. If we only use a double couple without torque, then from (Singh et al., 2002) it follows that vertical displacements of the surface above the fault are zero irrespective of the depth of the fault. Moreover, if a fault reaches the surface, an intense uplifting appears above the fault, which contradicts both the in situ observations and the deformation mechanism in the case of the tensile fault (a joint). This is due to the fact that the absence of the width of a joint in the dislocation models leads to the emergence of singular points in the solutions when the displacement curve approaches the fault line.

This is why in (Okada, 1985; 1992) the scheme with the superposition of two mechanisms is assumed. In this case, a characteristic feature of the distribution of the vertical displacements, besides the inverted pattern of the anomaly, is the fact that the amplitude of the subsidence per se is commensurate with the amplitude of the uplift. Of course, this is the consequence of the action of the dilatancy center. This is particularly evident in the case of a finite source (b). Such phenomena were never observed in the real data.

It is also important to note the zero values of the horizontal displacements at the point $L = 0$, which is located on the fault axis. From Fig. 9 it follows that the character of the curves reflecting the distributions of the vertical and horizontal displacements are largely similar. The amplitude of the horizontal offset in the fault is identical in both models and equal to 10 cm. The depth to the center of the point source is 500 m. In the case of the finite model, the depth to the top and bottom edges of the dislocation (the fault) is 100 m and 1 km, respectively. The length of the fault along the strike is 5 km. From the figure it can be seen that as the fault comes to the surface, the anomaly becomes localized.

A major shortcoming of the dislocation models consists in the absence of the width of the faults in these models. This renders these models impractical for describing the interrelation of local deformations and variations in the different geophysical and geochemical parameters. Besides, in the dislocation model, the morphology and amplitude of the anomalous surface displacements in the fault zone do not depend on the character and intensity of the regional conditions—the setting in which the local anomaly develops. However, it has been noted above that the analysis of a large amount of the data revealed a correlation between the type of the near-fault anomalies and the character of the regional geodynamic regimes. These facts significantly reduce the potential of the dislocation models as a candidate mechanism of the formation of γ-anomalies.

3.3. Parametric Model of Tensile Faults

The parametric model was developed by the author and consistently described in (Kuzmin, 1999). To a certain degree, this model generalizes the block and dislocation models with due regard of their limitations. Just as the block model, the parametric model has the regional (external) conditions of the formation of the local anomalies corresponding to the measurements. However, just as the dislocation model, the parametric model can describe the local anomalies, albeit, for a finite width of the fault zone. This model is based on a number of the empirical and model generalizations that have become a fairly solid part of the customary understanding of the processes of formation and development of faults including their recent deformational activity.

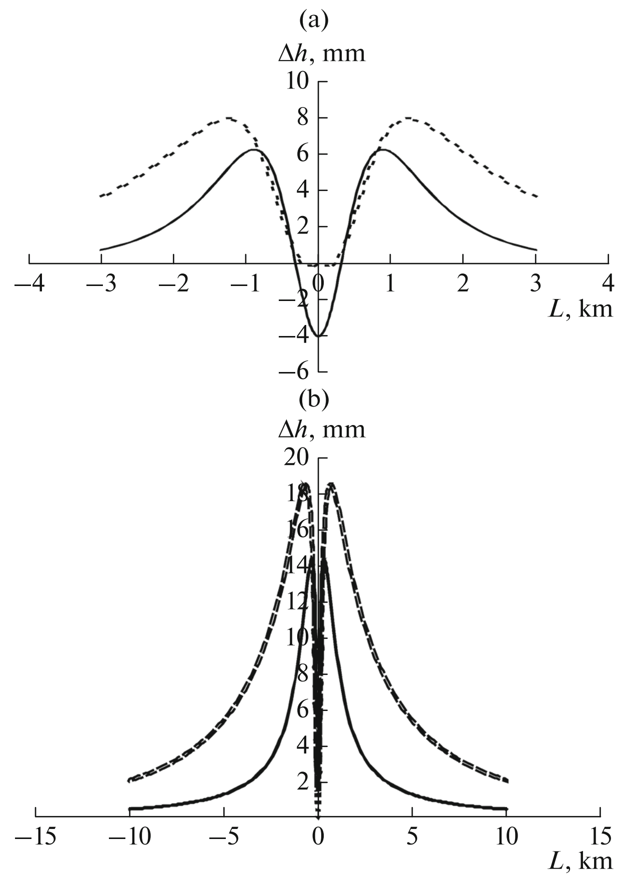

Fig. 9. Distribution of calculated vertical (*1*) and (*2*) horizontal surface displacements along leveling profile intersecting tensile fault for (a) point and (b) finite dislocation model (Okada, 1985; 1992).

Firstly, within the scope of the ideas of S.I. Sherman's tectonophysical school (Sherman, 1977; Sherman et al., 1983; Seminskii, 2003; 2014; etc.), the author notes that the faults should be considered as the specific geological bodies—as a certain volume of the Earth's crust with an anomalous structure and high degree of fracturing that emerged as a result of the linear destruction of the medium. Therefore, in the quantitative estimates in this work, the notions of a fault, a fault zone, a zone of disjunctive dislocations, and a zone of increased fracturing (or a highly fractured zone) are considered as synonyms. Here, the key point is that *a fault zone is a domain that accommodates rocks with anomalous physico-mechanical, geological–geophysical, fluid–geochemical, and other characteristics*. In this case, the fault zones are natural concentrators of the recent anomalous stress-strain state and, hence, are the key object for studying recent geodynamical processes.

Secondly, based on analyzing the character of the deformation of the fault zones, together with the geodynamical and petrophysical settings in the studied regions, a mechanism was suggested that explained the emergence of the γ-type anomalies of the vertical displacements by the activation of the opening-mode vertical fractures and local subsidence of the overburden in the setting of quasi-static subhorizontal tension. This mechanism largely corresponds to the ideas of V.N. Nikolaevskii (2010). In these works it was shown that the evolution of the faults in the upper crustal layers can be characterized in the following way. Down to a depth level of 2 to 3 km, a domain is distinguished which is dominated by the opening-mode brittle fractures with a vertical orientation. Below, down to a depth of ~8–10 km, there is a domain with the predominant development of shear-mode brittle fracturing. Next, at the depths of 10 to 15 km, the fracture formation localizes into the subhorizontal band associated with dilatant deformations. As was demonstrated by the mass solution of the inverse problems of recent geodynamics of faults, the sources of γ-anomalies are formed in the depth interval ranging from a few hundred meters to a few kilometers.

Very recently, E.A. Rogozhin with his colleagues in a series of works (Rogozhin, 2013; Rogozhin et al., 2014) obtained the results indicating that in the upper portion of the crust there are subvertical segments with low seismic velocities which are confined to the fault zones (seismic sutures) located in seismically active regions and in the regions with weak seismicity (platforms). The subvertical orientation and the depth intervals of these zones surprisingly closely agree with the data about the presence of the zones of reduced stiffness (enhanced fracturing) in the fault areas established by the geodetic methods.

Finally, it was noted above that, relative to the duration of local deformations, the external, regional loading is quasi-static, i.e., fixed. If we specify constant deformations at the boundary, this means that the Earth is a deformation machine corresponding to the hard loading scheme that is used in the experiments with rock specimens. With this character of loading, the Earth's surface displacements should be fully hereditary with respect to the movements of the basement blocks. However, in the vast majority of cases, local geodynamic anomalies neither inherit the adequate shear displacements of the adjacent domains of the consolidated portion of the crust along the fault zones nor the shape of the basement top (Kuzmin, 1999; 2008). All these facts testify in favor of the soft scheme of regional loading, i.e., the setting of the quasi-static fixed stress state. Besides, as it follows from the principles of mechanics of deformable solids, energy accumulation in the case of soft loading takes place within the inhomogeneities that have a lower stiffness relative to the stiffness of the hosting medium.

The term *parametric model* means that the model is based on the mechanism of the parametric excitation of the fault zone–hosting medium system. From physics it is well known that any system can be disturbed from equilibrium (excited) in two ways: either by the external force action on the system overall or by perturbing the internal parameters of the system that has been preliminarily loaded from outside. Therefore, the cause of the emergence of anomalous deformations in the vicinity of the faults is a local and sometimes small action, and this allows us to classify the emerging anomalies to the category of parametrically induced processes. The internal parameters of the medium should be understood as the characteristics such as stiffness, density, friction, permeability, and porosity.

The quantitative framework for this model is adopted from the theory of the nuclei of strain (inclusions) located in the interior segments of a solid, which was developed for solving the problems of physics of inhomogeneous media and mechanics of composite materials. The work (Mindlin and Cheng, 1950) is most generalized in this field. It is worth noting that in application to geophysics, the notions of faults as inclusions in the elastic semiinfinite solid have been used by many researchers.

The paper of Sezava (1929) was perhaps the first publication on the subject. In the cited work, analytical expressions were obtained for the tilts and strains of the surface of elastic semi-infinite solid in the vicinity of strain inclusion (nucleus of strain—the domain of the medium that contains anomalous deformation). I.P. Dobrovol'skii (2009) obtained the formula for free surface displacements in estimating anomalous deformations as precursors of earthquakes. S.M. Molodenskii (1984) used these notions for evaluating the influence of faults as sift inclusions on the amplitudes of the Earth's tidal deformations and tilts.

At the same time, these works have not yielded the general formalism that would not only allow us to obtain formulas for estimating the local surface displacement field in the vicinity of the faults as inhomogeneities (inclusions) with reduced stiffness but also to correlate them to the dislocation models within a single approach. In (Kuzmin, 1999), based on the reciprocity theorem for the medium with distortion and with the use of the apparatus of Green's functions, formula (1) was obtained for the displacements of elastic half-space $U_r(\xi)$, where the role of the source of local anomalies can be played by the variations of stiffness, jumps of displacements, changes of poroelastic parameters, etc.:

$$U_r(\xi) = \varepsilon_{ij}^0 \iiint \sigma_{ij}^{(r)}(x,\xi)\, dV_\zeta, \quad (1)$$

where $\varepsilon_{i,j}^0$ is the distortion or excess strain that creates a local source of strain anomalies within volume V of the medium (within the inclusion) and $\sigma_{i.j}^{(r)}(x,\xi)$ is Green's stress tensor.

Obtaining the closed-form analytical expressions for calculating the stress-strain state is seriously challenged by the necessity to perform fairly simple but cumbersome and tedious calculations. With the discovery of the so-called gravideformational analogy it became possible to largely avoid this difficulty. This analogy consists in the fact that the formulas for the vertical gradient of the gravitational potential g (the potential of a unit mass) and vertical gradient of the displacement potential (the potential of the unit force) are geometrically identical. The formula for calculating vertical displacements U_3 from an arbitrarily shaped inhomogeneity (inclusion) is

$$u_3 = -\frac{\alpha(1-2\nu)\sigma}{6\pi\mu} \iiint \frac{z}{R^3} dV, \quad (2)$$

where α is the relative variation of the bulk modulus, σ is the regional stress, and μ and ν are the shear modulus and Poisson ratio, respectively.

The formula for the variation of the free-fall acceleration has the following form:

$$\Delta g = -\delta\rho f \iint \frac{z}{R^3} dv, \quad (3)$$

where f is the gravitational constant and $\delta\rho$ is the density variation.

A comparison of formulas (2) and (3) shows that they can be represented by the product of two factors: **P** × **G,** where the physical factor **P** describes the intensity of the strain or gravity anomaly and the geometrical factor **G** describes the spatial configuration of the strain or gravity anomaly depending on the shape of the inclusion (anomalous body).

Considering the established analogy and using the formulas for the geometrical factor known from the theory of the gravitational potential, we can obtain the analytical expressions for the displacements and strains of the free surface of the elastic half-space containing bulk inclusions of different configurations within which their internal parameters (stiffness or strain) vary.

Figure 10 shows model distributions of the vertical and horizontal surface displacements in a profile variant (however, for three-dimensional problems) for the inclusions of different regular shapes. For a comparative analysis of the distributions of the surface displacements caused by different inclusions, Fig. 10 shows the curves on a common horizontal and vertical scale. For the model analogs (a sphere and infinite and finite-length cylinders), the depths to the centers of the inclusions (9 km), the radii (3 km), the relative variation in the bulk moduli ($\alpha = 0.03$), the regional stress ($\sigma = 100$ MPa), and the stiffness of the hosting medium ($\mu = 10^4$ MPa) are identical.

As seen from the figure, thee different types of inclusions (analogs of the sources of the anomalies of regional bending) correspond to the different amplitude levels and decay patterns of the curves for the vertical and horizontal surface displacements. It is characteristic that the displacement distribution for the finite cylinder (with a horizontal-to-vertical aspect ratio of 4 : 1) occupies an intermediate position between the sphere and infinite cylinder, which should be considered as the limiting variants.

Similar results were also obtained for two different types of prisms—vertical and horizontal. Estimates were obtained with the same parameters σ and μ as previously. The width and the length of the vertical prism were 0.25 and 1.6 km, respectively; the corresponding dimensions for the horizontal prism were 1.6 and 0.25 km, respectively. The depth to the centers of the inclusions was 1 km in both cases.

The graphs of the distributions of the vertical and horizontal displacements show that the pattern of the amplitude decay in the cases of the vertical and horizontal prism is fundamentally different. The distribution of the vertical surface displacement for the vertical prism (the analog of the fault zone) has a clearly pronounced peak shape which was noted in numerous field observations and is the canonical shape of the γ-anomaly. The model analog of the fault zone in the form of a horizontal prism fairly adequately approximates a horizontal layer. This variant is used for assessing the influence of the mode of development of the oil and gas horizons on the deformations of the Earth's surface.

Overall, it should be noted that γ-anomalies are ubiquitous and less dependent on the character of regional stresses. This is due to the fact that this type of anomaly has a relatively shallow (0.1–3 km) depth of the sources. Besides, the upper layers of the geological medium are always less compressed (i.e., relatively stretched), which creates a favorable orientation of the external stress field with respect to the vertical joints (opening-mode fractures) and, hence, leads to the generation of γ-anomalies. If we directly compare the calculated and observed distributions of the displacements, we see that in all cases there is a ~15–20% difference in amplitude between these distributions. This is explained by the fact that the formula for the displacements is obtained by the exact analytical solution for an imponderable medium. The real curve of the subsidence reflects the effect of the internal source acting in the ponderable medium.

As follows from (Kuzmin, 1999), the comparison of the Earth's surface displacements for imponderable and ponderable media calculated within the numerical boundary-element method shows that the amplitude of vertical displacements for γ-anomalies in the

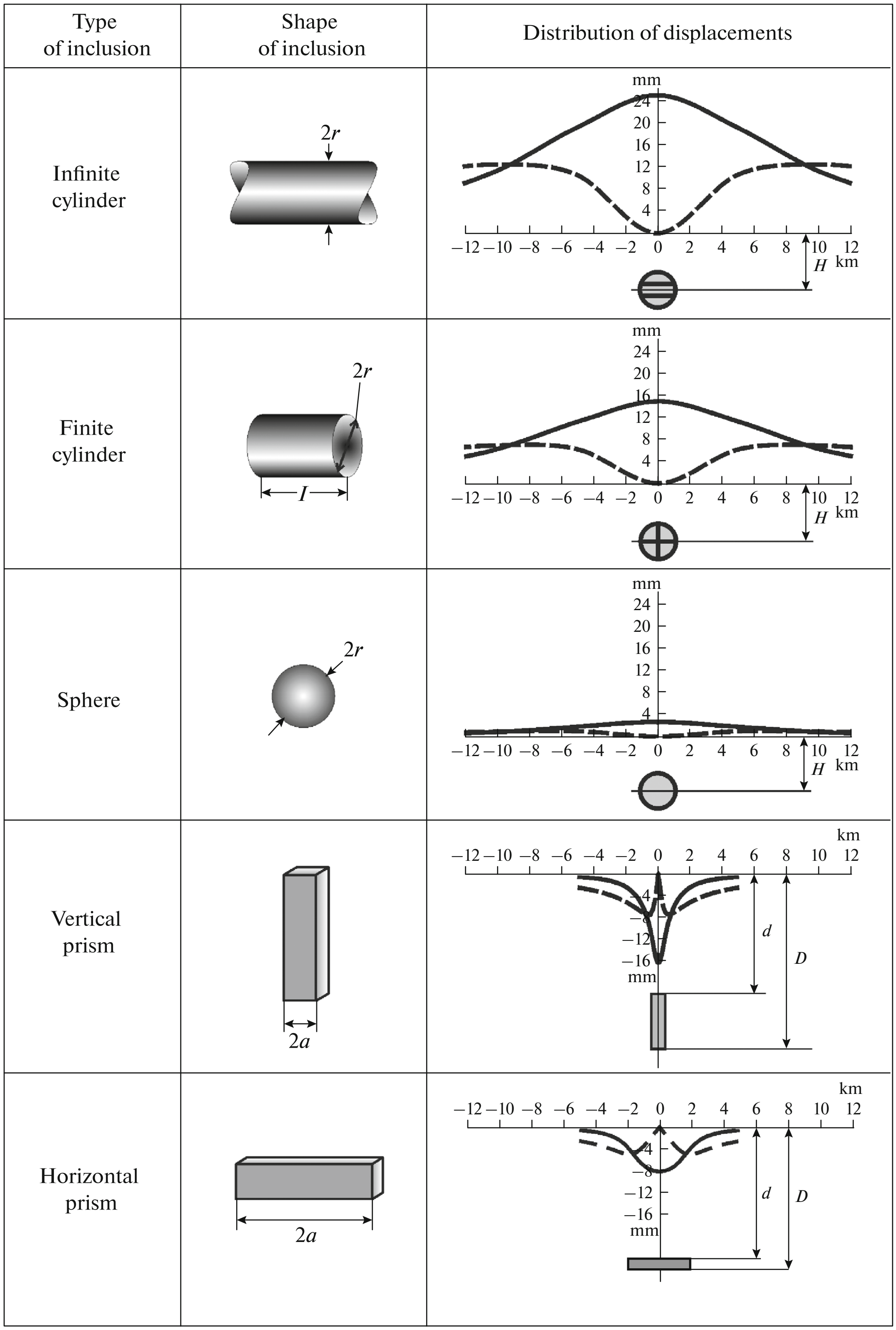

Fig. 10. Distribution of vertical (solid line) and horizontal (dashed line) displacements along leveling profile intersecting inclusions of different shapes.

ponderable medium is 15–20% higher than in an imponderable medium. It is remarkable that the singular points of the curves coincide for both types of the media, which allows us to interpret the observations using the analytical model of an imponderable medium with the corresponding correction of the displacement amplitudes for the weightiness of the medium. Hence, it becomes clear that, for exciting the observed values of the anomalous deformations, it is sufficient to create the conditions under which the stiffness within the local fragments of the prestressed fault zones are reduced by as little as a few percent.

The established gravideformational analogy provides us with the possibility to construct quantitative models of the distributions of the surface displacements and their derivatives (tilts and strains) with the use of the apparatus of the theory of the nuclei of the strain since the gravitational potential theory deals with the notions of the point masses (potential as the work on displacing the point masses) buried in a half-space, whereas the theory of the nuclei of strain uses the notions about point displacements (strains) at the internal points of the same half-space.

In this case, the formula for the distortion (internal excess strain), which is the source forming the anomalous displacements of the Earth's surface, can be used in different variants. In the figure shown above, the role of the source is played by a parametric deformation, i.e., the variation of the bulk modulus inside the inclusion (inhomogeneity) as the analog of the fault zone in the setting of quasi-static loading at infinity. For describing the processes associated with the development of hydrocarbon deposits or the cycling operation of UGS, the source can be specified by the change of the formation pressure within a fluid-saturated layer (horizontal prism) or within a fault (vertical prism). A comparison of the model curves with the results of numerous observations demonstrated their full coincidence. The main morphological feature of the vertical displacements is monotonic subsidence, gentle above the layer and steep above the fault. The subsidence reaches the maximum above the center of the object and then decays with the distance from the object. Similar behavior was also noted in the works of A.S. Grigor'ev et al. for the problem of drawing apart the basement blocks and subsidence of the sedimentary stratum. Horizontal displacements are always zero above the centers of any objects that experience bulk deformation.

However, the curve of the vertical displacements has a somewhat different morphology in the immediate vicinity of the fault for the dislocation models of the faults. From Fig. 9a it can be seen that the morphology of the curve of vertical displacements has the characteristic inflections and the intersection of the abscissa axis (inversion of the sign) at the exit of anomalous displacements from the area of the local minimum. Comparing this curve with a similar graph for the model of bulk inclusion, we see that the curve in this case does not intersect the abscissa axis. The decay takes place in the area of negative displacement values. Of course, this is due to the fact that dislocation models are the limiting case for both the models with inhomogeneities (inclusions) for the model with finite blocks because the width of the dislocation is zero.

Throughout this paper, I used the notions of inclusions and inhomogeneities as a single notion of *inhomogeneity (inclusion)*. However, in physics of solids and in the mechanics of composite materials, a distinction is made between these two notions, following the well-known work of J. Eshelby (1961). An inhomogeneity is the domain of the medium within which the stiffness (elastic moduli) differs from the hosting medium. In this sense, the fault zone is a region with a different (frequently reduced) stiffness of the rock compared to the hosting medium, which is in the field of external stresses (forces). An inclusion is the domain with an internal deformation which does not depend on the external boundary conditions. UGS when gas injection creates local deformation can serve as an example of such a domain.

The energy profile of the formation of anomalous deformations within an inhomogeneity is that the external (regional) forces work on the internal (local) displacements within the homogeneous domain which emerge due to the changes of the internal parameters of the medium with time. The energy profile of local deformations in the vicinity of an inclusion is that the internal forces (stresses) that caused local offsets work on the external displacements.

As is known from the mechanics of deformed solids (Timoshenko and Goodier, 1970), in accordance with Maxwell–Betti's reciprocal theorem, both works considered above are equal to each other because they are done on the same medium. In this case, the mathematical formalism based on Eq. (1) will be equally applicable for both a problem with an inhomogeneity and for a problem with an inclusion.

To prove this, we may consider the most transparent problem, e.g., about vertical displacements of the surface of a semiinfinite solid containing a spherical domain within it. In the case of an inhomogeneity in which the relative change of the bulk moduli is α, the formula for vertical displacements u_{3s} will be

$$u_{3s} = -\frac{\alpha(1-2\nu)2r^3h}{9\mu\left(x^2+h^2\right)^{\frac{3}{2}}}, \tag{4}$$

where r is the radius of the sphere, h is the burial depth, μ is the shear modulus, and ν is the Poisson ratio.

From (Mindlin and Cheng, 1950) it follows that for a spherical inclusion of radius r located at a depth h and deformed with a bulk strain level $\varepsilon = 3e$ (where e is the linear strain), the surface displacement u_{3s} will be

$$u_{3s} = -\frac{4e(1+\nu)r^3 h}{3\left(x^2+h^2\right)^{3/2}}. \quad (5)$$

Considering the fact that the bulk modulus is linked with the shear modulus by the relationship

$$K = \frac{2(1+\nu)\mu}{3(1-2\nu)}, \quad (6)$$

from (4) and (5) we obtain the evident equality $\varepsilon = \frac{\alpha\sigma}{3K}$. Thus, the equivalence of the approaches for calculating the displacements for both problems is proven.

Therefore, as an adequate mechanism of formation of γ-anomalies, it is necessary to use the parametric model because within this model, with the use of the formalism of the deformational (strain) inclusions (inhomogeneities), it is possible to describe the formation of both the monotonic anomalies of subsidence and the inverted anomalies.

4. DISCUSSION

Such a low annual average strain rate—at a level of 10^{-8}–10^{-9} per annum—indicates that the annual average rate of change of the regional stresses is extremely low. If we assume that the strain rate is linearly proportional to the rate of the applied stresses, then, with the typical values of the stiffness of the medium, the time variations of regional stresses will be on the order of 10–100 Pa per annum or 0.1–1 mbar (0.1–1 atm) per annum. This is a surprising result, especially if we take into account the fact that the estimates of the strain rates are obtained based on the results of geodetic observations in seismically active regions.

The low representativity of the local shear displacements in the faults, at least based on the observations of the vertical surface displacements, is a sort of discord for many studies where the main mechanism of the recent activation of the faults is exclusively the shear (in the mechanical sense) displacements of the fault's walls.

This is largely understandable when coseismic and postseismic deformations in the source zones of strong earthquakes are studied or when the regimes of strike-slip faulting are explored on a model and in situ levels of a description of the process (Kocharyan, 2016). However, there is yet another reason which I would dare to name methodological.

The outstanding French physicist Pierre Curie, the author of fundamental studies on the symmetry of natural processes, characterized the main principle of the evolution of nature in the following way: "Dissymmetry creates the phenomenon." As applied to the phenomena of deformation of the solid, liquid, and gaseous bodies, this principle was repeatedly stressed by M. Reiner, a noted scientist in rheology, in his numerous works. For example, in the case of a hydrostatic (spherically symmetric) compression and the subsequent removal of the loading, the beads of steel, plasticine, and water will behave identically (Reiner, 1960). All of them will *elastically* restore their volume after the removal of loading. The rheological dissimilarity between these beads will only appear after applying the shearing force or the deformations of the change of shape (shear). Thus, the symmetrical bulk deformations do not determine the phenomenon. They cannot identify the medium that was subjected to deformation, whether it was elastic, plastic, or liquid. Here, it is necessary to use the deformation of the change of the shape for establishing the rheological state of the medium.

In this case, the shear mechanism of the formation of local strains is preferable. This is why the *S*-type anomalies are asymmetric. The following question then naturally raises itself: how should we regard the solidly established facts that it is the symmetric γ-anomalies that are the predominant type of the recent local displacements of the Earth's surface in the fault zones? The γ-anomalies certainly reflect the bulk, not shear, deformations.

The oddity of this question consists in the fact that in the mechanics of deformed solids (Timoshenko and Goodier, 1970) it is assumed that the stress and strain deviators do not change the volume of the deformed body. Therefore it is stated that the deviator tensors only describe the phenomenon of the change of shape which is identified with shear deformation. Therefore, γ-anomalies are the reflection of bulk deformations, whereas *S*-anomalies are associated with the deformations changing the shape.

However, under, e.g., the uniaxial tension of an elastic cube-shaped body, the shape of the cube will change. The cube will become a parallelepiped. At the same time, also the initial volume will simultaneously increase. It is clear that the change of the shape is accompanied by the change of the volume and does not necessarily determine only the shear deformation.

The apparent oddity of the situation disappears if we consider the fact that separating from the stress and strain tensors their parts corresponding to the uniform tension or uniform compression does not mean completely separating all the components related to the bulk effects. Besides the shear strain components, the deviator tensors also contain the diagonal components which are directly connected with linear deformations. Therefore, the deviators generally do not only describe the effects of the shear, and the deformation of the change of shape is not a one-to-one reflection of shear deformations (Kuzmin, 2014b).

From this it follows that the formation mechanism of γ-anomalies is caused by the horizontal deviatoric tension (elongation) of the local fault zone that is in the field of the stationary regional tension. The local vertical displacement anomalies that are observed in the conditions of the operation of UGS are caused by similar factors because the excess of the injected pressure in the fluid-saturated faults over the hydrostatic pressure creates the local deviatoric deformation of elongation across the strike of the fault.

Thus, the phenomenon of the local pull-apart movements within the activated fragments of the fault zones, which leads to the local subsidence of the Earth's surface, is determined by the presence of deviatoric deformations in full agreement with P. Curie's principle. In this case, the dissymmetry is the deviation of the anomaly-forming deformation (which creates the phenomenon) from the spherically symmetric (globular) stress-strain state of the medium.

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