As the manuscript

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MULTIRANK STRAIN ANALYSIS OF LINEAR FOLDING ON THE EXAMPLE OF THE ALPINE GREATER CAUCASUS

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GENERAL CHARACTERISTIC OF WORK

1. Relevance of topic of the thesis, degree of its readiness

The thesis is devoted to a problem of a structure and the mechanism of formation of areas of a linear folding (of a general flattening) which exist in the central parts of fold and thrust belts. This problem exists since the end of the XVIII century, but still is debatable, and the main features of a structure of areas of such a folding continue to remain not clear. In mobile belts, there are also other types of a folding – folds and thrusts of foothill depressions and complexes of a complicated metamorphic folding; this work does not concern an origin of these structures. In a problem of genesis of a linear folding, her two main issues aren't resolved – what size of deformation (shortening) of structure and what are mechanisms of its formation. From the middle of the XX century these issues were traditionally resolved by development of the speculative models connected with the general theoretical opinions of researchers in frame of the interpretative direction of the course of thought – from the general to the particular. It promoted an emergence of a set of models of formation of the natural folded structures having low reliability. Moreover, it was equally characteristic for the main competing concepts – both for a mobilism, and for a fixism. The pendency of this problem is one of the important reasons of the crisis existing today in a tectonic as science, which is expressed in fact that the speculative geodynamic models, which are put forward a decades ago are used, and the new verifiable quantitative models don't appear. Thus, despite the big duration of researches, a readiness of a problem remains low.

There are three main processes of formation and transformation of Earth crust from the former sedimentary rocks (or consolidations, creations of its "granitic" layer): magmatism, metamorphism and folding. These processes do not go on constantly, and it embrace rather short period at the end of large tectonic cycles (for the Phanerozoic – Caledonian, Hercynian, Cimmerian, Alpine). In the methodical relation, despite all existing problems, processes of a metamorphism have such models, which allow to put and solve specific objectives (for example, using mineral P/T sensors). Approximately the same can be told and about the level of researches of magmatic processes. From these three processes, only formation of a folding has no authentic description of the main reasons and properties now. Thus, the solution of the problem of the mechanism of formation of a folding, first of all – linear one, can be a key to understanding of the main regularities of development of Earth crust and of formation of many types of mineral deposits. In this relation, the relevance (urgency) of a thesis consists.

2. Main purpose and fixed tasks of research.

The analysis of methodical bases of the approaches, which were applied earlier, showed that qualitative speculative advancement of hypotheses of a linear folding formation (without usage of quantitative models) does not yield such result which reliability can be confirmed within a strict methodology. It is known that there are no standard ways to complete authentically of drawing of visible part of a structural section up and down from the line of a profile, therefore ideas of the general geometry of structure far from section line could be only individual and author's. As the continuation of structure was made every time under the influence of theoretical models, there was "a logical circle" – interpretation of concrete natural structure was used for confirmation of the put-forward model. At the same time, the purposes to determine authentically such important parameters of structure as "the volume of shortening" and "a type and an amplitude of the mechanism" were not set. The hopes on usage in this area of researches of methods of mechanics (studying of a tectonic stress field) existing from the middle of the XX century were are not implemented for a number of reasons, in particular, as in this discipline only small deformations are traditionally investigated. Considerable different scales of the phenomenon complicated the situation: in typical natural structure, folds by the sizes from centimeters to the first kilometers were formed at the same time.

For the progress in a solution of problem, first of all, it was required to develop a concept of hierarchy of objects of the linear folding which is connected with mechanisms of their formation. The concept of the mechanism of formation should be considerably differ from existing one within mechanics of the continuous media (but still to rely on the principles of mechanics) as it had to connect geometry of the developing structure with amplitude of this mechanism in the form of kinematic model. It was possible to solve a problem of measurement of value of shortening only within ideas of hierarchy of a folding with use of the kinematic models corresponding to the scale of object. Methods of detection of what mechanism formed the studied structure had to depend on scale and features of object. In particular, it was required to find such language of the description of objects of one scale, which would be connected with their deformation, and it could be applied both to natural, and to experimental models for the purpose of their most objective comparison. Creation of set of methodical development of this kind for all range of objects was a main objective of work.

From these aspects, the following main specific objectives of research followed:

1. Development of hierarchy of objects of a linear folding;

2. Development (or search) of models of formation of different types of separate folds and creation of quantitative methods of measurements of values of deformation on their basis.

3. Test (approbation) of methods of research of separate folds on natural material.

4. Development of idea of the folded domain and an ellipsoid of deformations for it as a basis of language of the description of deformation of structures, which are larger than separate folds.

5. Development of a method of measurements of value of shortening and restoration of the pre-folded state of structures, which are larger than separate folds (a method of creation of the balanced sections).

6. Test (approbation) of methods of restoration of pre-folded state of structures on a number of natural objects for the purpose of creation of models of their formation, which are balanced in the volume of sedimentary cover.

7. Test (approbation) of language of the description of deformations of large structures for natural and model (theoretical and experimental) structures for the purpose of their comparison and identification by that of the formation mechanisms which are operating in them.

3. Methodical bases of the realized approaches and the used methods

According to the basic principles of a tectonophysics, the physics laws (preservation of mass of substance, i.e. constancy of volume and of density of rocks) and the principles of mechanics (the description of deformations of objects through a deformation ellipsoid) and laws of geometry were used when methods of study were developed. These laws had a priority before any models of geodynamics. In work at creation of models of large structures any schemes, models and mechanisms of speculative character were ignored. Such models were created by merger of structures of the smaller size, i.e. the research course from the particular to the general was used (and not vice versa as it usually becomes at creation of geodynamic models).

The methods used in work included a number of the standard – the drawing up of structural cross-sections during the field-works, the collecting of the actual material about morphology of folds by sketches, photography and measurements of elements of geometry, the structural and historical analysis of geological maps, etc. Materials of the strain-analysis performed by V. N. Voitenko were used. The main methods of research by means of which the main results are received, rely on the principles of mechanics, were own and were developed specially. These methods are listed in the paragraph "Scientific Novelty".

4. Actual material and personal contribution of the author.

In research, the actual material of several types is used: of separate folds and of structural cross-sections of Greater Caucasus, of experimental models. Field material on morphology of separate folds within the Chiaur tectonic zone of the central sector of Greater Caucasus and Tfan zone of the South-Eastern Caucasus was collected independently in 1976-1981, material on some folds in the North-Western Caucasus for the strain-analysis was collected together with A.V. Marinin, material on morphology of folds in the Vorontsov cover is collected together and with the assistance of L.A. Sim, A.V. Marinin and P.P. Gordeev. Strain-analysis on rock samples from folds of the North-Western Caucasus is performed by V. N. Voitenko. The most detailed (1:10000) structural cross-sections of Tfan and Shakhdag zones were made during 1979-1981 by E.A. Rogozhin with the assistance of the author. Structural cross-sections across the Chiaur zone (1:100000) were made independently, cross-sections across the Northwest Caucasus are used completely from the published literature (authors – T.V. Giorgobiani and E.A. Rogozhin). Detailed photos of the experiments published earlier for reproduction of a folding by “side pressure” and “gravitational sliding” (after centrifugation) were kindly provided for usage in the 1990th years by their author – V.G. Guterman. Unpublished photos of experiments for reproduction of “advective” structures (in a layered rosin) approximately in the same time were kindly provided by M.A. Goncharov. Photos of experiments of J. Dixon were used from his publications of 1991 and 2004. All processing of material by own techniques was performed independently. The used special software is own, it was made in the software environment "Turbo-Basic" at different years.

The models of a single viscous layer developed by predecessors [Hudleston, Stephansson, 1973] and mathematical model of advection of M.A. Goncharov [1988] are used in research. Other models and all methods are original. V.N. Voitenko participated in justification of need of use of an ellipsoid of deformation for the description of deformation of a fold and of the domain [Yakovlev, Voitenko, 2005]. Methods of research of separate folds in initial versions and results of their application in the Chiaur zone composed the material of the PhD thesis of the author earlier [Yakovlev, 1979].

5. Reliability of the received results.

High reliability of results regarding researches of separate folds is provided by a base on the principles of mechanics (a fold of package of layers) and on computational model (a method of final elements for folds of a single viscous layer) and by high correlation between results of use of these two methods. These results in general are confirmed by the standard methods of the strain-analysis. High reliability of results of restoration of pre-folded structure by method of "geometry of folded domains" is provided by a adherence to the principles of mechanics and by the checked calculations, and also by usage of the most correct and detailed material of structural cross-sections. The available structural material validates the used idea of flat deformation, i.e. of lack of lengthening of folds along their hinges. The values of shortening of structures of different scale received by means of the developed methods, thus, are proved by use of the principles of mechanics and by usage of laws of geometry. The quasi-three-dimensional and three-stages models of a structure of a sedimentary cover balanced on volumes of the stratigraphic sequences are reliable on the same bases, and also where it is possible, generally are confirmed by geophysical data.

6. Scientific novelty

Work represents the new direction in a tectonophysics , structural geology and a tectonics called "the multirank strain analysis of a linear folding structures". Novelty of work consists of new methodical approaches (points 1 – 4), methods and models (5 - 8), and also the received results (9 – 17).

1. It is offered to allocate as objects of research not the traditional folded structures convenient for the mapping purposes, but hierarchically coordinated objects which

formation within a certain volume of sedimentary layering is described by the kinematic models (mechanisms) developed for them.

2. The language of the description of deformations of structures which are more largely than the domain (which consists of a number of folds) based on the geometrical properties of the domain (an inclination of an axial surface, an inclination of a envelope surface of folds and value of shortening of folds are measured) and which is associated with an ellipsoid of strain, and which is including the new concept " amplitude of mechanism" is offered.

3. The multi-stage computing procedures are offered and realized for reconstruction of large folded structures by generalizing results from small to large (from the particular to the general) that allows to restore methodically correctly geometry of natural objects. Such geometry is not relating to the existing theoretical (geodynamic) schemes.

4. The method of comparison of natural and model structures is offered and approved to use of quantitative parameters of geometry of the folded domain (look point 2, language of the description of deformations) which allows to find objective regularities of theoretical mechanisms and to reveal possible results of their action in natural objects thereby receiving valid conclusions about genesis of natural structures.

5. The kinematic model of formation of folds of packs of layers (the modified version of 2002) is offered. The method of measurement of value of shortening and of a ratio of the operating mechanisms based on it is developed.

6. With usage of the principles of mechanics, the procedure of measurement of shortening value of structures in size from the folded domain and more largely is developed. This procedure is a basis of “the method of creation of the balanced sections on domain geometry”. At the moment, it is the only existing method of creation of such sections within a hinterland folded structures.

7. It was offered to compile balanced quasi-three-dimensional models (on the basis of Euclidean geometry and value of deformation) in the volume of whole sedimentary cover for three main stages of development of structures of a linear folding (a. result of sedimentation, b. the created a folded structure without of mountain building, c. modern structure after mountain building). It allows to estimate the modern depth of the basement top and volume of eroded part of the top part of a sedimentary cover.

8. The systematic description of results of modeling for reproduction of folded structures of different genesis with use of quantitative measurements of geometrical parameters of “folded domains” that allowed to characterize at the semi-quantitative level the main mechanisms of formation of such structures (lateral pushing/shortening, horizontal simple shearing, advection/convection, inclined zones of shearing, structures of accretionary prism) or their combinations (advection plus shortening and a quasi-buckling) is given. Semi-quantitative procedures of comparison allow to distinguish them from each other and to compare with natural structures.

9. Statistically significant series of estimates of shortening values and of parameters of mechanisms of formation for two types of separate folds (a single viscous layer and packs of layers) are received. Values from 25% to 83%, at average 56% were found. It was established that the value of shortening is connected with local rather steady tectonic situation in structures of the middle size under the conditions of the general shortening/flattening or pure shearing. Under the conditions of simple horizontal shearing (in a zone of a sole fault or of a detachment of the Vorontsov nappe), there is the extremely non-uniform deformation for which values of deformation/shortening of folds from 2% to 95% (an average of 61%) are registered.

10. Values of shortening for large objects, like "structural cell" and "a tectonic zone", are determined. They change for structural cells from 36% to 67% for east part of Greater Caucasus at average values of 49 - 57% (for different tectonic zones) and from 2-10% and stretching of -10%, to 67% for the North-Western Caucasus at average value of 35%. For tectonic zones, a shortening varied from 41% to 53% for east part of Greater Caucasus and for long profiles of the North-Western Caucasus – from 12% to 52%, and 35% in average.

11. Quasi-three-dimensional models of a sedimentary cover of three regions of Greater Caucasus on the basis of data on shortening within structural cells were compiled. Distribution of modern calculated depths of the basement top has intricate, but regular character. Depths (in absolute values) change from -2.2 and -4.4 km to -13, -19, -26.3, -31.7 km, and at average values in different parts of structures from -10.2 and -12.0 to -13.2 and -20.5 km. It was shown (with an accuracy connected with the accepted stratigraphic model) that the thickness of eroded part of a sedimentary column (or raising amplitude at mountain building) reaches 12.5 km, 24.4 km, 22.2 km, and at average

values in 9.6, 19.2, 16.1, 8.9 km that by 3 – 5 times exceeds the standard values. These data are independent information in relation to parameters of any geodynamic models.

12. The gravitational character of the Vorontsov nappe on the basis of the diagnosed mechanism of formation of folds in a zone of its sole fault is proved.

13. The deformation structures, called "inclined zones of ductile shearing", which are usually located close to large thrusts, were allocated for the North-Western Caucasus on the basis of study of morphology of folded domains. It was shown that their formation is connected with action of simple shearing along this inclined zone in a combination with the minimal horizontal shortening. For this sort of folded deformations, the special type of the local mechanism – "the near-thrust mechanism" – is offered.

14. It is shown that the mechanism of formation of a folding of tectonic zones of Greater Caucasus is well described by models of "advection (limited convection) plus shortening" ("quasi-buckling") in a combination with "the near-thrust mechanism".

15. On base of a complex of indications, the impossibility of use of the standard schemes of formation of an accretionary prism (A-subduction) for an explanation of a folding of Greater Caucasus in general is proved. Including, it was established on the base of balanced models that the structure of Greater Caucasus at the level of a top of the Pz basement was undergo of subsidence on 10-15 km deeper than basement of Transcaucasian massif along a zone of the Racha-Lechkhum regional Fault dividing them. It is indicated that joint shortening of a sedimentary cover and basement below for the southern part of Greater Caucasus took place. It is eliminating of existence of "sole fault" at all. Thereby, the known proposition for rather northern blocks about joint deformation of a cover and the basement extends on whole construction of Greater Caucasus.

16. At the quantitative level, on the example of the constructed balanced structures of Greater Caucasus, it is shown that the linear folding couldn't arise without transformation of rocks of the lower and average crust to more dense mantle modifications.

17. At the quantitative level, with use of correlation of a number of parameters of "structural cells" of Greater Caucasus, the existence of earlier known "geosynclinal" regularities of development of crust is proved: those blocks in which big thickness of specific terrigenous sequences collected, then experienced a bigger shortening, and in them at the end of development there are bigger amplitudes of a neo-tectonic raising.

7. THE STATEMENTS, PRODUCED FOR DEFENSE

1. The new principles of allocation of objects of a linear folding, which allowed to create system of hierarchy of objects. For the characteristic of objects the sets of kinematic models, which are bean the basis for a complex of methods of research and of the used methodical receptions are used.

2. Mechanisms of formation of local "near-thrust" structures of the Vorontsov nappe and of the North-Western Caucasus. The mechanism revealed according to descriptions of deformation of folds in a detachment of the Vorontsov nappe corresponds to horizontal simple shearing (in kinematic relation) and to gravitational sliding (in geodynamic relation). The mechanism of formation of a series of the "near-thrust" local inclined zones of ductile shearing revealed on morphology of folded domains in the North-Western Caucasus corresponds to the conjugate zones of shear fracture with horizontal pressure axis.

3. The characteristic features of trends of development of mechanisms of formation of the main experimental and theoretical models allowing to distinguish them from each other. On the basis of descriptions of these trends, natural structures in Chiaur, Tfan and Shakhdag tectonic zones are compared in the best way with quasi-buckling model (a combination of kinematic mechanisms of diapirism and a flattening) in a combination with the local “near-thrust” mechanism of formation of inclined zones of ductile simple shearing.

4. The value of shortening of fold and thrust structure of the studied part of the Alpine Greater Caucasus on the scale of structural cells (jointly for a sedimentary cover and for the basement below) has average values from 35% to 57%. The reconstructed calculated modern position of the basement top for structural cells forms the regular structures at depths of 5-30 km absolutely and at average values from 10 to 20 km and at maximum immersions of the basement on the southern flank of Greater Caucasus. The eroded upper part of a sedimentary cover has average amplitudes of destruction from 9 to 19 km for the studied tectonic zones.

8. Scientific and practical importance

The main scientific value of work consists that the developed approaches and methods allow to confirm or disprove reasonably at the quantitative or semi-quantitative level geodynamic models of structures of a linear folding by their comparison with natural objects. Results of the multirank deformation analysis can be used for suggestion of new, more reliable geodynamic models. The method of balancing of structural cross-sections on base of volume of sedimentary cover can be used for the forecast of structure for depth of 20-30 km (that can save funds for geophysical surveys) and for restoration of pre-folded structure, and also for calculation of volumes of rocks of stratigraphic units or reserves of minerals.

9. Approbation of results of research and publications.

Results of researches on a thesis which are formulated in the form of the basic statements, produced for defense, were repeatedly represented by the author at conferences and meetings of various levels, including international. Among them there are All-Russian tectonic meetings (2003, 2006, 2007, 2008, 2010), thematic meetings and the All-Russian conferences (1987, 1990, 1997, 2003, 2005, 2008, 2009, 2012), including of tectonophysical, reports in MOIP (1978, 2004), the international meetings in Europe on EGU (1993, 2005, 2006, 2007, 2011), at the GEOMOD (2012) conference, on CETeG (2008, 2010), at the ILP Marseille (2013) conference. The majority of the presented reports was given individually. Besides, results of different stages of researches and their generalization repeatedly were reported in different years at various seminars, conferences, sessions of colloquiums in IPE Russian Academy of Sciences, GIN Russian Academy of Sciences, IG KarSC RAS, in other organizations.

The developed approaches, methods of researches and results of their application in studying of natural folded structures, and also theoretical and experimental models are published in the form of 12 articles in the main journals from the VAK list – Bulletin MOIP (1978, 2001, 2006), Geotectonics (1983, 1987, 1987), Reports of the Russian Academy of Sciences (2008), Physics of the Earth (2009), the KRAESC Bulletin (2010, 2012) and international – Tectonophysics (2012), Comptes Rendus Geoscience (2012), in the form of articles or chapters in monographs (7 publications) – "Problems of Tectonophysics" (2008), "Planet Earth. Encyclopedic reference book" (2004), "Diagnostics of mechanisms of formation of a linear folding..." (1997), the reviewed journals "Geological Society, London, Memoirs" (2006), "Geophysical surveys" (2008). Other large or important articles were published in thematic collected articles, materials of conferences and meetings. The vast majority of publications are individual. The total amount of publications makes about 45 quire.

Structure and volume of the thesis

The thesis consists of introduction, 8 chapters, the conclusion, the list of references and the appendix. The total volume of the thesis – the 470 pages (without appendix), from them 438 pages of the text, including 194 drawings and 44 tables. The list of references consists of 419 sources on 32 pages.

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MAIN CONTENT OF WORK

Chapter 1. Review of methodical approaches and main results of researches on a problem of folding formation.

At the beginning of the chapter, the historical review of development of tectonics in the XX century is briefly adduced. In the review it is shown that for the solution of the new problems of tectonics and structural geology, which arose in the middle of the last century, the tectonophysics started developing, as the branch of tectonics and structural geology, directed on a solution of the problem of an origin of a folding, to which this work belongs.

The general analysis of methodology of tectonics, structural geology and tectonophysics led to a conclusion about insufficient attention to a number of important aspects with what the observed phenomena of crisis in a tectonics are connected, including – a pendency of problem of folding formation mechanism. First of all, it concerns hierarchy of folded and fault structures of the lithological complexes occupying the central parts of fold-thrust systems in which the 10-15 km thickness of thin-layer sedimentary cover forms folds of the most different sizes from the first centimeters to the first kilometers. Only single folds are rather fully theoretically described, therefore, it is possible to consider that approaches to research of multi-scale structures weren't found. It is noted that methods of measurement of deformations value in folded structures weren't developed. It was shown that the main movement of researchers' thoughts was limited by an offering of qualitative (not quantitative) speculative models within both "fixism" and "mobilism" and by attempts to give interpretation of concrete structures on their basis (deduction, the movement of thought from the general to the particular). It caused basic impossibility of appearance of new models of a configuration and development of folded structures, including quantitative one.

In the chapter the main methods and the received results are analyzed in detail in three main directions of structural geology connected with researches of a folding: use of mechanics of the continuous media for the analysis of folds, methods of the strain-analysis and creation of the balanced cross-sections. It is shown that important results were obtained only in researches of single folds by mechanics methods – there were models, which can be used for the solution of the inverse problem. The limitation of opportunities of the analysis of tectonic stress fields in an explanation of formation of folded structures was specified. Methods of the strain-analysis yield rather reliable results only at the scale level for rocks specimens. The reasons, by which the methods of creation of the balanced cross-sections, which are widely used in foreland structures, are inapplicable for internal parts of folded systems, are considered.

Whole review of a methodological position of the folding formation problem is followed by examples of concrete researches, both domestic, and foreign. The most part of results in the USSR and the Russian Federation was received in different years by V. V. Belousov's employees in IPE Russian Academies of Sciences and MSU laboratories. In this regard, the offered dissertation work is the continuation of these long-term researches on a wide range of questions – collected field data on single folds (F.L. Yakovlev, 1978) and materials of detailed structural cross-sections (E.A. Rogozhin, V.N. Sholpo) are used; also as data about joint deformation of a sedimentary cover and basement of Greater Caucasus (M.L. Somin), a number of theoretical results of researches of mechanisms of formation of large structures (V.N. Sholpo, M.A. Goncharov, V.G. Talitsky); works for the purpose of measurement of deformations value (V.N. Sholpo, 1978) are continued. The analysis of foreign researches on a problem of formation of folds and folded complexes showed lack in them of system consistency, and the main results were limited to an application of methods of the strain-analysis and by development in 2000 - 2010 of two methods of research of the single folds, which are seldom used. Approaches to the analysis of larger structures in other countries aren't developed. It is possible to claim that the level of researches in Europe and North America (in this direction) lags behind the level of a domestic tectonophysics approximately at 20 years.

On the example of three long-term complex researches of the Baijansay anticlinorium, Talass Ala-Tau and Greater Caucasus the difficult way of development of tectonophysical methodology from simple diagnostics of folds of a lateral/horizontal buckling and transversal bending up to a proposition of combined models of formation of folded complexes of the general flattening and attempts of comparison of several geodynamic schemes with natural structures is shown.

The general assessment of a condition status of methodology in geotectonics which is characterized as “acute crisis” is given. Important aspects of the crisis are connected with lack of a solution of the problem of a configuration and the mechanism of formation of structures of internal parts of folded systems as bases of understanding of processes of formation of crystal part of continental crust. As results of the review, the main needed directions of researches of doctoral work are formulated.

The text of the chapter occupied 78 pages, is followed by 14 drawings, and in the review material about 250 publications was used.

Chapter 2. Short sketch of a geological structure of Greater Caucasus and description of character of structural material.

In the chapter, a well-known data on a structure and the main stages of development of the Alpine folded system, which embraced the Mesozoic-Cenozoic sedimentary cover and the Paleozoic basement of the Greater Caucasus (GC) are briefly described. The main folded structure is located between two large subvertical faults of a great depth – Pshekish-Tyrnyauz Fault in the North and Racha-Lechkhum in the South of region (fig. 1A). The next on a rank/scale is the large fault named "Main Caucasian Fault" (MCF, earlier – MC Thrust). It divides blocks with different types of the Paleozoic basement, and, at the same time, – zones with an intermediate Cimmerian episode of folding formation (before Late Jurassic) in the North and, zones of the continuous Alpine sedimentation, which finished with the late Alpine deformations in the South.

In the review of the most known speculative models of folded structure of GC, it was shown that in the mobilistic type of models, a broad development of scaly thrusts and existence of the main detachment in a basement top at depths of 7-12 km in folded structure is generally supposed. In the southern part of GC, the existence of such structures is obligatory [Dotduyev, 1986, Robinson et al., 1996], in the central part of GC the common detachment can be absent [Rastsvetayev, 2002]. The general transversal shortening of structure in these models is usually estimated not less than at 200 km. For models within a fixism [Sholpo, 1978] the shortening of space is denied, the basement top on these models is at depths of 5-10 km.

The main properties of a structure and of development of three regions (fig. 1A) which structural materials formed the basis of researches – the Northwest Caucasus (NWC), the Chiaur tectonic zone in the central part of the Caucasus and two zones of the South-Eastern Caucasus (SEC) – Tfan and Shakhdag, are considered. It is shown that the general thickness of the Alpine sedimentary cover reaches 10-15 km (fig. 1B). As a first approximation, in the history of development of structure three main stages can be marked out: an accumulation of sediments (up to an Oligocene), development of a folding (approximately from Oligocene – up to Early Miocene), mountain building/arising (since Sarmatian time, an Middle Miocene, to the present).

Existence and reliability of the structural material necessary for researches (fig. 1C) is analyzed. The cross-sections of SEC are the most detailed and reliable (authors – E.A. Rogozhin, F.L. Yakovlev), profiles of the NWC (E.A. Rogozhin, T.V. Giorgobiani) and of the Chiaur tectonic zone (F.L. Yakovlev) are considered as rather detailed enough. As a whole this material allows to receive reliable ideas of full crossing of the main structure of Greater Caucasus between its boundary Faults for two of its parts: in North-Western sector and in its East half. The chapter volume is 39 pages of the text and 21 drawings.

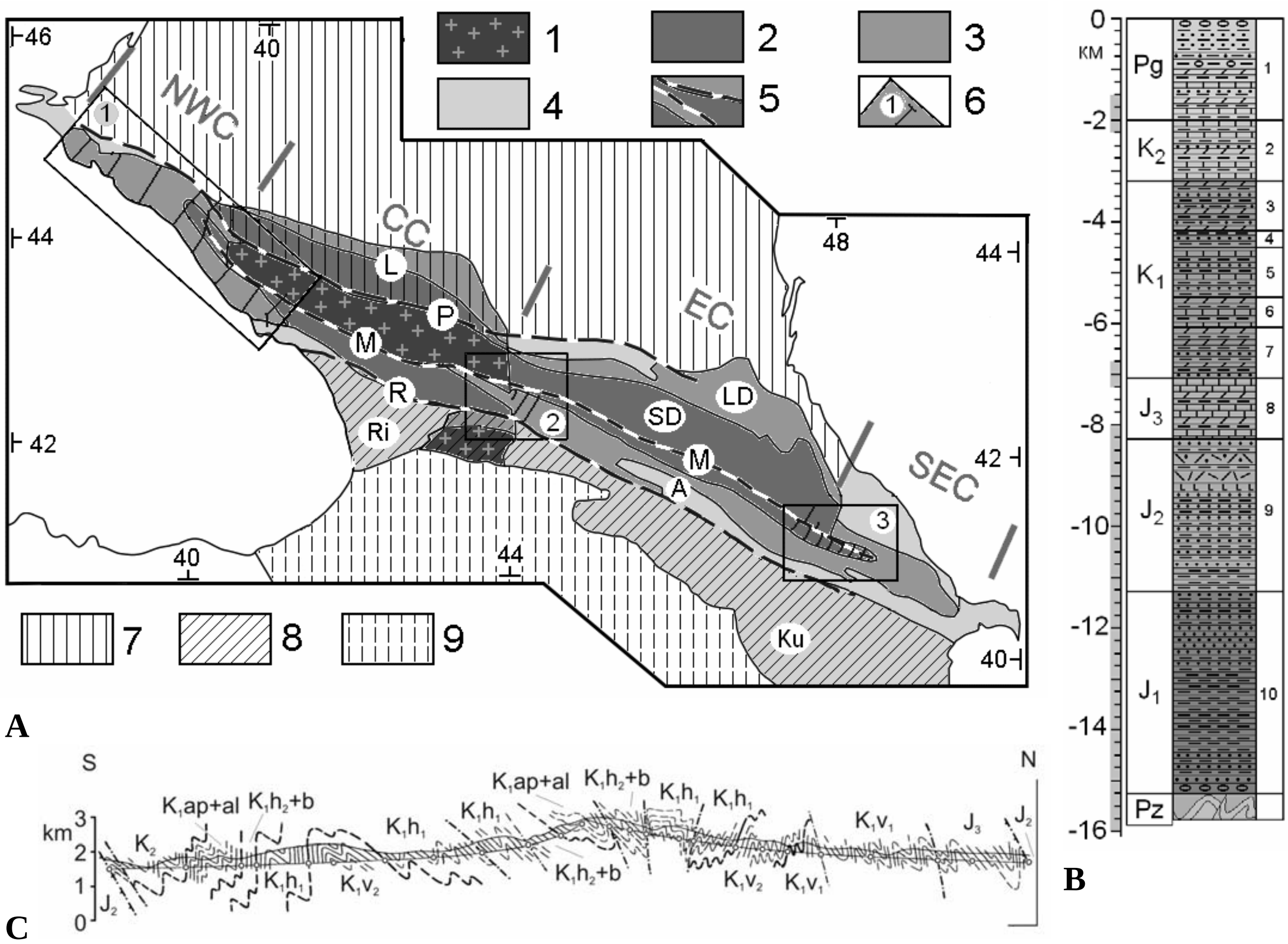

Fig. 1. Geological structure of Greater Caucasus.

A – The structural and geological scheme (on [Yakovlev, 2010], with changes, materials are used after [Sholpo, 1978]). Four sectors are shown: NWC – the North-Western Caucasus, CC – Central Caucasus, EC – Eastern Caucasus, SEC – the South-Eastern Caucasus. Structures are shown selectively: L – Laba-Malka zone, LD – Limestone Dagestan, SD – Slate Dagestan, A – the Alazan Depression, Ri – the Rioni depression, Ku – the Kura depression. 1 – outcrops of the Paleozoic basement, 2 – the Jurassic deposits, 3 – Cretaceous deposits, 4 – the Paleogene and the Neogene, 5 – faults (P – Pshekish-Tyrnyauz, M – the Main Caucasian Fault, MCF, R – Racha-Lechkhum), 6 – the studied regions and, schematically, – structural cross-sections in them (1 – the North-Western Caucasus, 2 – the Chiaur tectonic zone, 3 – the South-Eastern Caucasus: Shakhdag and Tfan tectonic zones, 7 – structures of the Scythian plate, 8 – structures of the Transcaucasian median massif, 9 – Lesser Caucasus.

B – A full stratigraphic column (model) of a sedimentary cover of the Chiaur zone.

C – A structural profile through the Chiaur zone (full, between two boundary faults).

Chapter 3. Hierarchic levels of complicated folded structure, methodological approaches to a solution of the problem of a folding formation.

The analysis of domestic and foreign literature in which hierarchical interrelations of structures of a linear folding (common flattening) of the different scales are broached is carried out. It is shown that there are no standard criteria of allocation of ranks of structures and of any only system of opinions showing hierarchical ratios of such objects. Respectively, there are no methods of measurements of shortening values of structures of the different size and methods of diagnostics of mechanisms of their formation. The accordance of ideas existing in literature to those statements which are the cornerstone of the offered methods – 1) about preservation of volume of rocks in development of deformations (that corresponds to thicknesses of units in the stratigraphic columns at the modern density of rocks) and 2) about lack of movements and deformations along hinge axis both in separate folds, and in larger structures (2D deformation), was shown.

The new principles of distinction of several hierarchical ranks of structures of a linear folding, which were not occurred earlier in literature, are offered and proved. The basic is selection of such objects with which borders the kinematic models coincide, which are describing their form, and also of a certain volume of layered medium which is embraced by these structures. There is important also to refuse from usage of those, already known objects, which were been distinguished earlier, and which are applied for geological mapping, but which can't be fully described by kinematic models. Seven hierarchical levels of objects of a linear folding, from intra-layer to whole folded-thrust belts which are connected with volume of layering from grains and a layer to whole upper mantle are offered. There are: I. intra-layer objects, II. folds (layers, pairs of layers, fig. 2A), III. "folded domains" (large packs of layers, several folds join in them, fig. 2B), IV. "structural cells" (whole sedimentary cover, unites of several domains, fig. 3), V. tectonic zones (consists of several structural cells, whole crust is captured, usual/conventional structures on a surface – fig. 1C), VI. folded systems (allegedly – whole lithosphere, on a surface – Greater Caucasus), VII. mobile belt. It is shown that

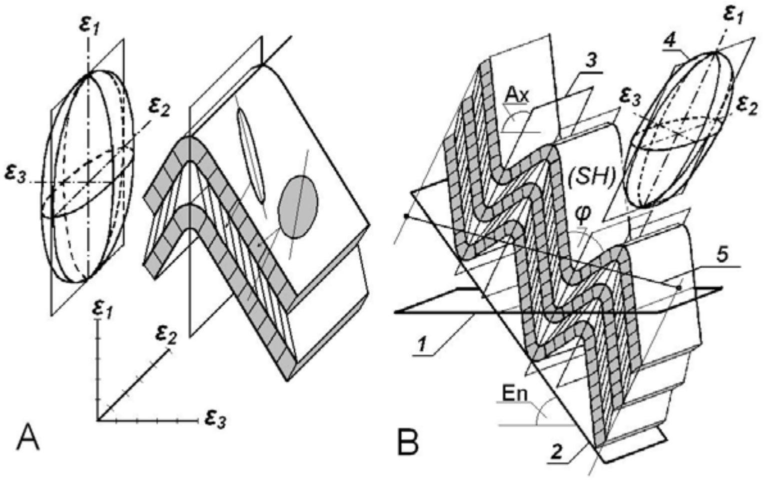

Fig. 2. Position of a strain ellipsoid of in a fold and in the “folded domain” concerning their morphological elements (after [Yakovlev, Voitenko, 2005]). **A** – the model of a fold of packs of layers (hierarchical level II) showing the general deformation and ellipses of deformations for separate layers (competent and incompetent). Axes of ellipsoid: $\varepsilon 1=l1/l0=2.13$, $\varepsilon 2=l1/l0=1.0$, $\varepsilon 3 = l1/l0=0.47$. **B** – Key parameters of the domain as sets of several folds (hierarchical level is III). 1 – the horizontal plane, 2 – an envelope plain of folds and an angle of its dip (En), 3 – the axial plane and an angle of its dip (Ax), 4 – a strain ellipsoid, value of shortening SH = (1-l1/l0) *100% (ε3), 5 – part of the line of a cross-section inside domains borders.

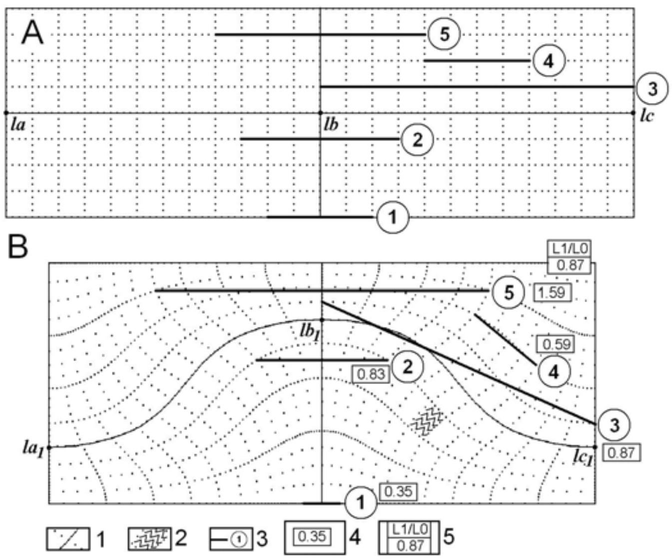

Fig. 3. Two adjacent “structural cells” (M. A. Goncharov's term) on the scale of a sedimentary cover volume from a core of a large anticline to a core of the large syncline (hierarchical level III, on [Yakovlev, 2008], on a basis the elementary mathematical model of advection [Goncharov, 1979]). The quasi-buckling model, in which the central layer length (the continuous line connecting points of la, lb, lc) remains constant, is shown. Shortening of a cell (a piece 3) coincides in quantity with the caused by "tectonic" horizontal shortening of a sedimentary cover against a wide deviations of shortening values in other structures smaller and bigger in size (1, 2 and 4, 5). 1 – an initial grid (A) and its distortion (B); 2 – symbolical folds within one of conventional “folded domain”; 3 – piece and its number; 4 – the value of horizontal shortening for a piece, 5 – the general shortening of structure.

some of objects of the offered hierarchy was used already by other researchers (M.A. Goncharov and V.G. Talitsky), but their systematizations were based on other criteria of distinction of levels. The detailed description of the main types of structures within these seven levels is given; the main opportunities of their research are shown.

The chapter contains 22 pages of the text, 3 drawings, one table. Material of the chapter is justification of point 1 of the statements for defense in which the new principles of distinction of objects of a linear folding and the description of system of the hierarchy of objects consisting of 7 levels were included.

Chapter 4. Separate folds, mechanisms of their formation and methods of measurement of shortening value

Models of formation of folds of a single viscous layer and of folds of layers packs which are the cornerstone of two methods of measurement of shortening value of space [Yakovlev, 1978; 1981; 2002] are considered. Methods are realized in the form of system of measurements of geometry of a layer and of nomograms (fig. 4). They remain at the moment almost single approved methods for structures of this rank. As other similar method, the model and the nomogram for a single viscous layer folds can be considered also [Schmalholz, Podladchikov, 2001].

Results of measurement of shortening value based on morphology of layers for a single viscous layer folds and folds of layers packs on the example of structures of the Chiaur tectonic zone showed a considerable stability of values for parts of a zone.

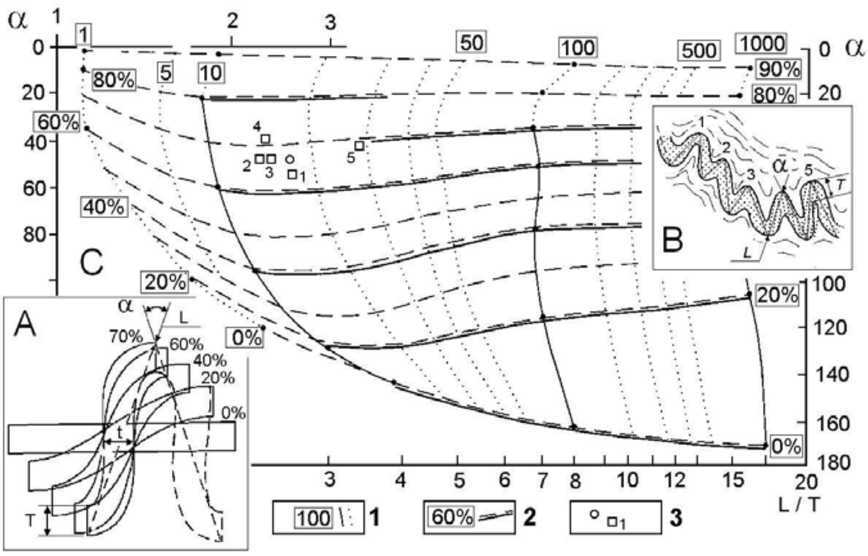

Fig. 4. The nomogram for measurement of value of shortening of folds for a single viscous layer and size of viscosity contrast η1/η2 layer / medium (after [Yakovlev, 1978; 2008]). There are: A – model [Hudleston, Stephansson, 1973] and measurements of its parameters, and also a natural fold (B) and its measurements on the nomogram (C). 1 – isolines of viscosity contrast, 2 – isolines of shortening, 3 – values of natural folds

Among 72 folds of the first type, the shortening values varied from 25% to 82%, at average value of 56%. Distribution of values on the area of the region showed obvious relation of this parameter with deformation of structures of middle sizes, including – of large folds and their flanks. Shortening in 36 folds of layers packs has the same values – from 27% to 83% at average 56%. For folds of a single viscous layer the pair "sandstone/slate" shows viscosity contrast from 2 to 25 (average value 8.6). Materials of researches show preservation of layer length during the forming folds as a whole.

Reliability of results on a single viscous layer folds is assured with a support on basic model of mechanics of the continuous medium [Hudleston, Stephansson, 1973]. Check of model of layers packs was realized by comparison of results of two methods for two types of folds for 8 local natural structures. Comparison showed considerable convergence and high correlation of two rows of values. An inspection of kinematic model of folds of layers packs was carried out also by comparison of theoretical with real (strain-analysis) of values of intra layer deformation [Yakovlev, etc., 2003] and its realness was confirmed.

The chapter contains 35 pages of the text and includes 23 drawings and 6 tables. Materials of chapter is justification of position 1 of the statements for defense in which it is told about sets of kinematic models (model of packs of layers) and a complex of methods of research (methods of research of a single viscous layer folds and folds of layers packs).

Chapter 5. The description of deformation in a fold and in the folded domain; study of mechanisms of formation of local structures.

Deformation of a separate fold at the following hierarchical level is considered not as the scalar value of deformation, but as a strain ellipsoid (with its orientation) within the domain integrating some folds (level III in the hierarchy system) and for that some parameters of geometry of the "folded domain" are used. These parameters include (fig. 2B): an inclination of axial surfaces of folds (an inclination of a long axis of an ellipsoid, AX), an interlimb angle of layers at hinge of folds (φ) which is evaluated in the shortening value SH (i.e. as length of a short axis of an ellipse; a value of long axis of an ellipse is calculating from short axis, constancy of volume and from an opinion of flat 2D deformation), an inclination of an envelope plain of folds (orientation as a whole of its initial layering, EN). The basic rules of allocation of borders of domains in natural structures are described in details. Methodical reception of use of geometrical parameters of the domain as language of the description of deformations of model and natural structures entered in the 1st statement, produced for defense.

In the chapter, deformations and mechanisms of formation of the structures that associated with faults and which aren't included into the offered hierarchical system, are analyzed. These objects belong to "local" structures. For the analysis of structures in a sole of the Vorontsov nappe, measurements of parameters of single folds (an inclination of the axial planes and value of shortening) in photos of outcrops in a nappe detachment zone were used. As two alternative models, mechanisms of horizontal/lateral shortening and of horizontal simple shearing were considered (within kinematics). It was shown that in the field of signs of the domain "inclination of the axial plane / value of shortening" (on 2D diagram) these models sharply differ on a trend of shift of parameters at increase in "amplitude" of mechanisms (fig. 5). On the diagram of comparison of models in the field of the specified two parameters of a points of 39 natural folds formed a cloud (fig. 5), which obviously is close to model of simple shearing. In the geodynamic relation this mechanism was associated

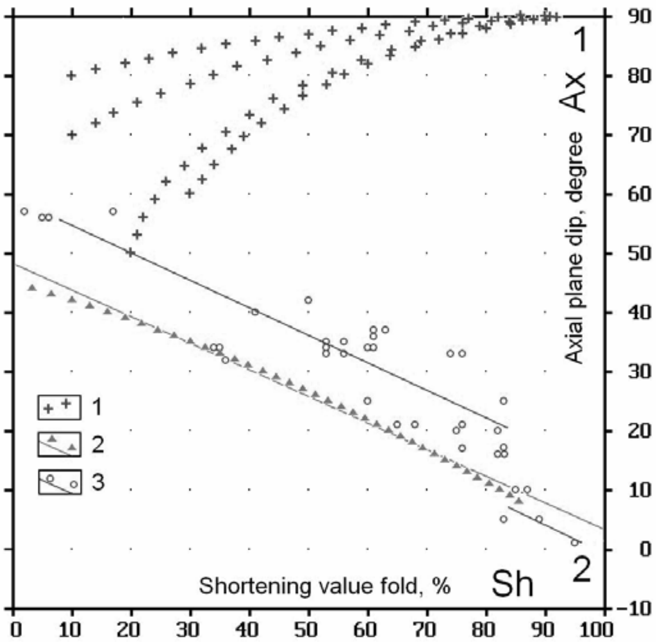

Fig. 5. Results of measurements of deformation parameters of folds for the Vorontsov nappe of AX and Sh. After [Yakovlev, etc., 2008; Yakovlev, 2012]. Comparison of natural data with model is shown.

1 – model of horizontal shortening/flattening, 2 – model of simple horizontal shearing 3 – positions of measurements of natural folds as elements of a strain ellipse

with model of gravitational sliding of a nappe. The alternative model of lateral pressure wasn't confirmed by these data. This result was included into point 2 of the statements, produced for defense.

The corpus of measurements of geometry of 250 domains in structure of NWC showed two sets (59 and 20 points) which are allegedly connected with inclined zones of ductile simple shearing on three-dimensional diagram of key parameters of domains (AX/SH, EN/SH, AX/EN). Two kinematic models of such structures combining simple shearing along the inclined plane with horizontal uniform shortening were compiled. Two options of an initial inclination of such plane in model were used: 20° (sub-horizontal thrust along layering) and 45° (thrust along a usual shear angle of a horizontal stress axis). It was shown that the option of an inclination 45 ° in the version of iterations of big shearing (6 °) and small shortening (1%) well satisfies to natural structures. This result was also included into point 2 of the defended statements. The chapter contains 30 pages of the text, 22 drawings and 3 tables.

Chapter 6. Domains, structural cells and tectonic zones – measurement of strain value and restoration of structure

Methods of measurement of shortening of space in structures, which are more largely in size than a single fold, i.e. the method of excess length of a layer (L1/L0), J.G. Ramsay's F-function method [Ramsay, Huber, 1987], "dynamic" retro-balancing [Lechmann et al., 2010] were considered. It is shown that or the model structure, but not natural one is measured in them, or they can be applied only to objects, small by the sizes. The conclusion is drawn that the offered method of construction of the balanced profiles on “geometry of folded domains” [Yakovlev, 1987, 2009] is the only efficient method of measurement of shortening value of space and of restoration of folded and faulted structure within hinterland blocks.

The sequence of operations, in result of which the sizes of the pre-folding basin of sedimentation, value of shortening of space on the scale of “structural cells” are defined, is considered in detail. In addition, the sequence of creation of the balanced models of three stages of development of GC – pre-folding, post-folded and modern, is shown. Sources of initial structural material are detailed cross-sections across of natural structures, in which "folded domains" are localized. Measurements of parameters of domains are used for reduction of each domain to a pre-folding state as a result of kinematic/geometric operations of rotation, simple horizontal shearing and stretching/lengthening (fig. 6). As a result, the initial, recent piece of a natural section (segment of line), having some length and inclination, gets the new length and a new inclination in horizontally layered medium (pre-folded) of the domain.

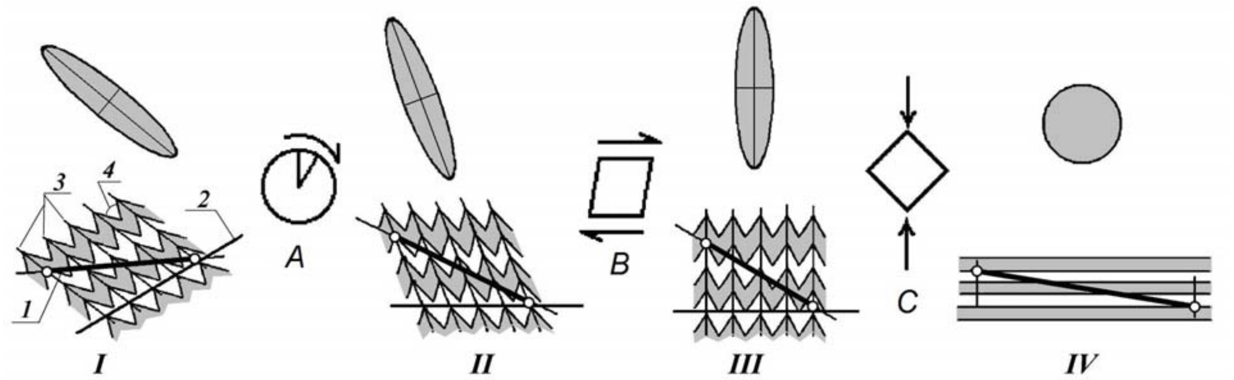

Fig. 6. Operations of restoration of a pre-folded state of the domain [Yakovlev, 2008]. The folded structure of the domain (1-4) is shown for states from modern (I) to pre-folded (IV) together with corresponding strain ellipses. A – rotation (from state of I to state of II), B – horizontal simple shearing (from II to III), C – stretching (vertical pure shearing, from III to IV). 1 – segment of the line of a profile (length and inclination); 2 – line of a envelope plain of folds (inclination); 3 – axial surfaces of folds (inclination); 4 – interlimb angle (value of shortening of folds)

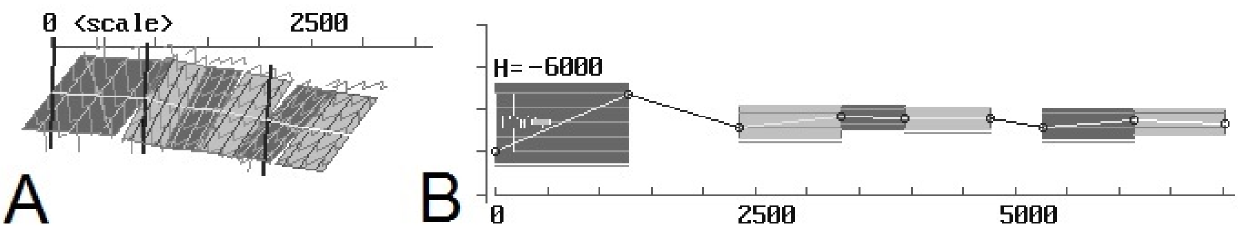

Fig. 7. Operations of restoration of a pre-folded state of structural cross-section with use of the computer program (copy of the screen; 6 domains and 2 thrusts for a part of section 3, the Tfan zone). In parts are shown: A – an image of the folded structure constructed by PC based on measurements of geometry of natural domains, B – the same structure, a pre-folded state.

The plains of faults are transformed by the same operations to a pre-folded inclination. On a difference in the stratigraphic level of the next blocks (on vertical amplitude) and to an inclination of a fault, the calculation of horizontal amplitude are done. By consistently joining domains to each other, it is possible to receive structures from several domains or structure of whole profile, having thus both the modern width, and their pre-folded one (fig. 7). The value of shortening of any structures of the size more largely than the domain is determined by these results.

Structural cells were used in a method of creation of the volume balanced structures (fig. 3) which in a pre-folded state in a cross of strike had width comparable to the thickness of a sedimentary cover (fig. 8A). For restoration of recent geometrical parameters of each structural cell its stratigraphic model (fig. 1B) was used. Respectively, for each domain (for its piece of a section line) its depth inside a stratigraphic model, and for part of a profile which is the corresponding to each structural cell – its average depths in the same model were calculated. For a cell also average geodetic elevation of a profile on landscape was defined. Value of shortening for the end of a conventional stage of purely folded deformations (the second stage) allowed to find the greatest possible depth of immersion of top of basement in a cell and the new depth (fig. 8B) of those deposits in an average cell which now came to a landscape surface (fig. 8B). The difference between profile depth of cell at the second stage and on modern (third stage) gave the amplitude of a conventional neotectonic raising of a basement top. Everything together it allowed, according to the accepted stratigraphic model, to calculate the modern depth of a sole of a sedimentary cover and calculated/conventional height of eroded top part of a sedimentary column (fig. 8B). On materials of a series of profiles, it is possible to compile the quasi-three-dimensional model of depth of a basement top, of amplitude of eroded upper part of sedimentary column and of distribution of other parameters.

Results of application of these methods to three regions of GC showed similar results concerning structure of the main strip of a linear folding in a cross of its strike.

Two tectonic zones of the South-Eastern Caucasus (Shakhdag and Tfan) and Chiaur zone were considered together. In the structure presented on 13 profiles (2 + 8 + 3) 262 domains (40 + 156 + 66) and 36 cells were allocated (5 + 18 + 13).

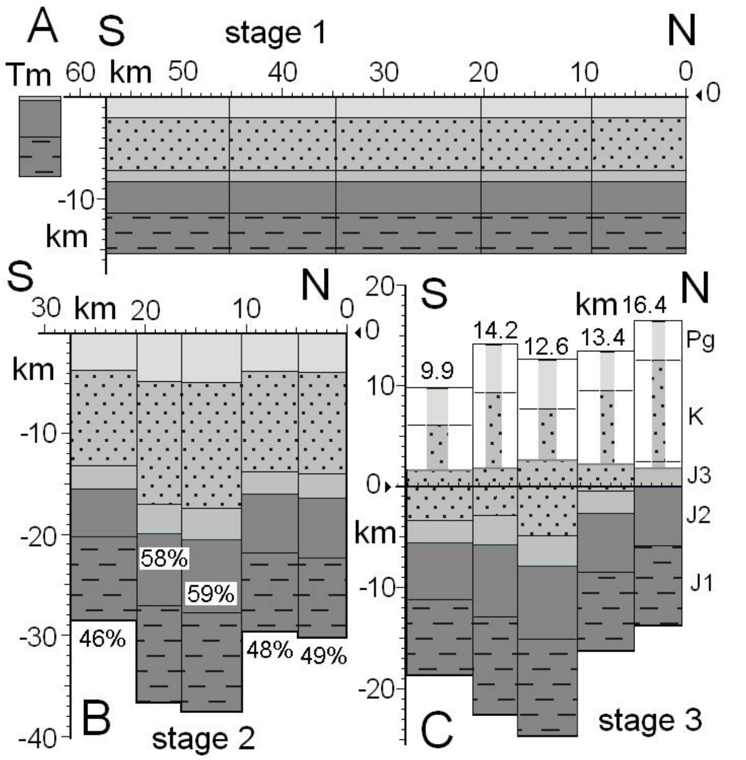

Fig. 8. A succession of operations of restoration of modern structure, based on shortening values in structural cells (the Chiaur zone, five cells, see profile on fig. 1B). There are: a stage 1 (A) with an initial thickness of a sedimentary cover and the restored width of cells, a conditional stage of 2 (B), after a folding before mountain building with new thicknesses of columns and values of shortening (in %), a modern stage 3 (C), after finishing of mountain building and of erosion / destruction. On geodetic height for each cell those deposits which came out in a natural structural profile are placed. Total amplitudes of a upraising and erosion of a top of sedimentary cover in five cells are specified (for C). Tone of gray color and specks showed deposits of three units of the Jurassic system, Cretaceous and the Paleogene. After [Yakovlev, 2012] with changes. For a profile A (a stage 1) a thickness of cover for the Transcaucasian massif on the South is shown (a column with the Tm index, the thickness of 7-8 km). Its modern thickness is not more than 9 km.

On average from 2 to 4 folds got on each domain. The general width of structure for pre-folded stage was found in 113 km (32 + 24 + 57), and shortening value on the scale of tectonic zones, respectively, equaled 41%, 53%, 52% with a total modern width in 57 km.

Shortening value of space on the scale of tectonic cells on zones varied within 37 ÷ 62% (average 49%), 36 ÷ 67% (55%), 46 ÷ 67% (57%). In spite of the fact that in some crossings, thrusts play a noticeable role in shortening of space of a (the maximum quota is 0.44), on average the quota of thrusts in shortening is relatively small (0.13). Depth of a basement top for the end of a stage 1 (before of folding formation) for the same three zones from the North to the south was -9.8 km,-13.4 km (-11.9 ÷ -16.7 for the Tfan zone) and -15.3 km. After a folding formation, the immersion according to model at a stage 2 (conditional) could make up, on average, respectively -20 km (-15.6 ÷ 25.8), -31 km (-19.8 ÷-42.7) and -36.6 km (-28.7 ÷ -45.8). Modern calculated depth of a basement top after a neotectonic upraising was -10.2 km (-7.6 ÷ -13.7),-12.0 km (-4.4 ÷ -19.4) and-20.5 (-13.6 ÷ -26.3). Amplitude of uprising and erosion of an upper part of a sedimentary cover (or difference of positions of a basement top between stages 2 and 3) was, also from the North to the South on zones, for structural cells on average 9.6 km (7.2 ÷ 12.5), 19.2 km (12.2 ÷ 24.4) and 16.1 km (9.9 ÷ 22.2). Distribution of all parameters on the area shows obvious natural relation with structure. Northern cells, are more uplifted on the modern depth of the basement top and most southern cells are more depressed. On the level of basement top, there are escarps between cells with an amplitude up to 10 km (allegedly, in cases of existent faults). The greatest values of erosion are fixed for the cells in the center of east part of system of GC, which are having the maximum pre-folded immersions and the maximum values of shortening.

The structure of the Northwest Caucasus presented in 11 profiles of different length was divided into 243 domains which were aggregated in 42 cells, forming up to 5-6 cells on a profile. Width of structure on pre-folded stage on incomplete cross-sections in the center of the region (where there is a northern border, but there is no south edge of structures) was 80-85 km (49-55 km of actual width), and in the east to the South from Main Caucasian Fault (only for a zone of a carbonate flysch of J3-Pg2) – 42-47 km (30-35 km of modern width). According to these data it is possible to assume width of whole basin in the central part of the region about 100 - 120 km that is comparable to similar width for east half of Greater Caucasus. Shortening values for the allocated 42 structural cells changed over a wide range – from 2-10% up to 67%, at average – 35%. The weak shortening are observed on the western pericline of GC with increasing of values to the central part of NWC sector. The ratio of shortening due to faults regarding common fold-thrust shortening changes over a wide range, but averaging was 0.11. Depth of a basement top for a stage 1 on structural cells deviate from -7.3 up to-17.3 km, having tendency to increase in the southern cells of central part of NWC. Average depth was -13.4 km. At the end of a hypothetical stage 2 (after folding) values of calculated subsidence of basement top were from-8.7 km to-48.8 km, at average value -22.2

km. The actual calculated positions of a basement top (at the stage 3) has values of -2.2 ÷ -31.7 km at the average value of -13.2 km. In this connection three parts of structure as kind of features of distribution of this value are observed: western with the central “depression” (profiles 1-2), middle part has deep subsidence of the southern flank (profiles 3-5) and east part has kind of the central subsidence again (fig. 9). Hypothetical amplitudes of a neotectonic uplift (of erosion of an upper part of sedimentary cover) changed from 0 to +22.2 km at average value of +8.9 km (fig. 10A). From a pericline, these values gradually grow to the east up to the central part, then decrease a little, remaining further rather stable. Across strike of structure, values grow from the periphery to the central axis of structure. The "difference of depths of the basement top" parameter (difference between stages 3 and 1) shows aggregated displacement of a basement top as a result of folding formation and of mountain building. Distribution of this parameter on the region emphasizes its segmentation into three parts also, and the maximum immersions on South are usually compensated by an upraising in northern parts of profiles (fig. 10B).

Materials of calculations of depths of a basement top on the southern border of Greater

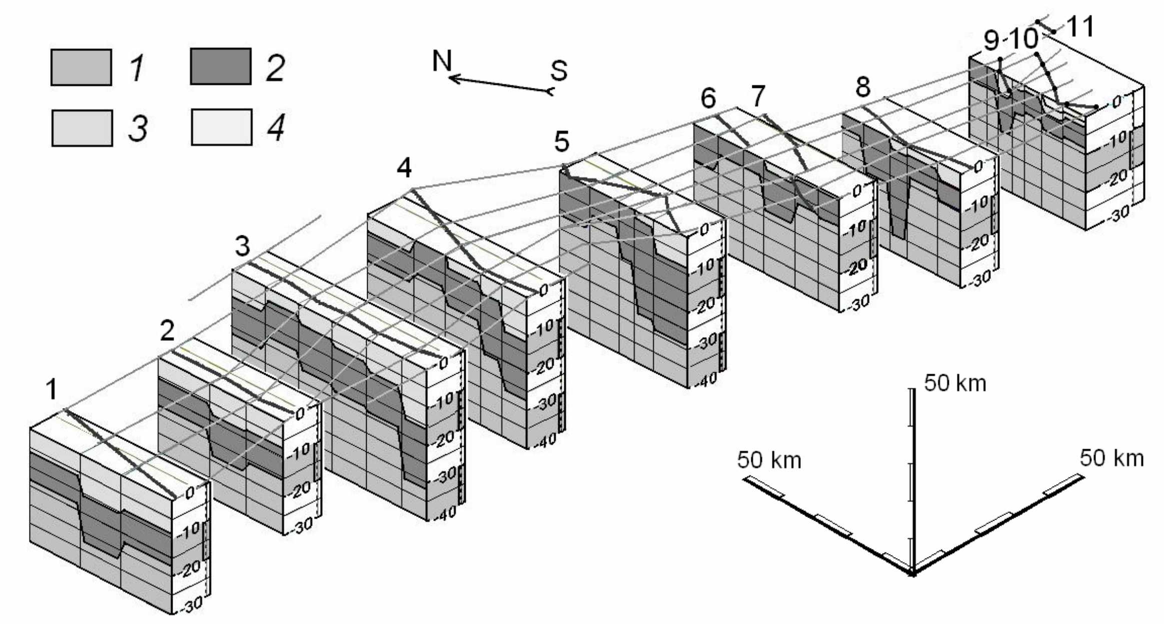

Fig. 9. Post-mountain-building, recent structure of a Mezo-Cenozoic sedimentary cover of the North-Western Caucasus [Yakovlev, 2009; 2010] (a stage 3), shown in the form of quasi-three-dimensional model for 42 structural cells. 1 – The Paleozoic metamorphic basement, 2 – the Jurassic deposits, 3 – Cretaceous deposits; 4 – deposits of a Paleocene and Eocene.

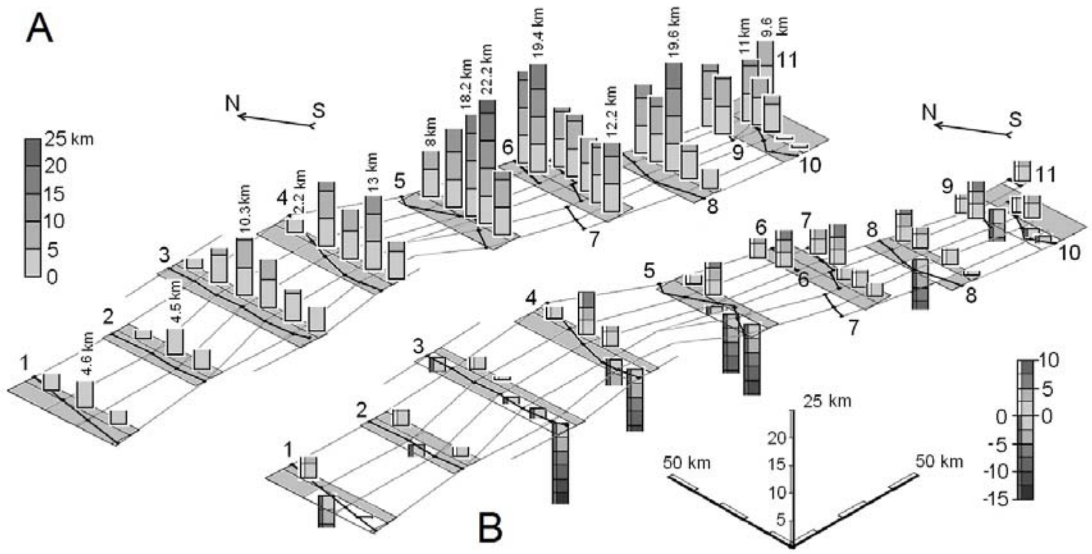

Fig. 10. Distribution of calculated parameters of "a neotectonic upraising / amplitude of erosion" (A) and "differences of depths of the basement top (stages 3 – 1)" (B) on the region of NWC. Vertical scale is doubled.

Caucasus were used for consideration of geological aspects of possibility of existence of "thrusts of the southern slope" as the structures defining the main style of a structure of GC. It was shown that on a stratigraphic level of basement top, basement of Chiaur zone is located more deeply than of the neighboring Transcaucasian massif on 10-12 km (fig. 8, A, C). These and other data completely disprove realness of known schemes of A-subduction of this massif to the north under GC.

At the end of the chapter, materials of geophysical study of a structure of GC crust [Krasnopevtseva, 1984; Pavlenkova, 2012; Shempelev, etc., 2001; Rogozhin, etc., 2014] are considered. It is shown that determination of depth of a basement top meets difficulties, and Moho's depth was found reliably only in several points. The subvertical borders of blocks of crust belonging to Greater Caucasus and the Transcaucasian massif are well defined. Existence of a sharp difference in a structure of such blocks contradicts schemes of A-subduction of the basement of the median massif under structure of Greater Caucasus. In some cases immersion of structures of a cover and crust from the North to the South is shown, including evidences of NWC structure where the position of a sedimentary cover sole (from 7 to 25 km) coincides in general with our calculated data.

The chapter 6 contains 112 pages of the text, the 57 drawing and 25 tables. The materials of chapter connected with the description of techniques of calculation of shortening value and of restoration of pre-folded and modern structures were included into point 1 of the statements, produced for defense (a complex of methods of research); results of calculations by these techniques formed point 4 of the defended statements (the description of character of folded and faulted structure of Greater Caucasus).

Chapter 7. Diagnostics of mechanisms of formation of structures of a linear folding on the scale of a whole sedimentary cover

The first paragraph is devoted to consideration of different mechanisms. There are distinctions between mechanisms of formation of structures, different in volume, and also distinctions between of mechanisms of appearance of faults and (vs) folds. It is specified that at the quantitative or semi-quantitative level, it is possible to consider only those theoretical or model mechanisms, which can be described in a formalized way (uniformly). In this case, it is possible to find differences between such calibrated, standard mechanisms, and also to find similarity between models and natural structures.

In the following paragraphs, results of research of the main types of those experiments on formation of folded structures which have sufficient detail are described: J. Dixon (with use of the centrifuge, 1991, 2004), V. G. Guterman (with use of the centrifuge, 1987), M.A. Goncharov (thermal advection, 1979), and also several computational kinematic models (the simplest mathematical model of advection [Goncharov, 1976]; models synthetic and quasi-buckling [Yakovlev, 1987, 2003]). For the analysis of mechanisms of formation, all structures profiles in models were divided on domains in which the same three parameters of morphology were measured (fig. 2B) – an inclination of an axial surface of a folds (AX), coefficient of shortening perpendicular to the axial plane (K=L1/L0) and an inclination of a envelope plain of a folds (EN). On the example of multistage experiments [Dixon, Tirrul, 1991], it was shown that the relative positioning of points of measurements of domains on scattering diagrams of these three signs (AX/K, EN/K, AX/EN) forms the areas which are typical for each mechanism. The increase in amplitude of the mechanism (mainly at increase of value of shortening in domains) leads to shift of such areas in the field of all three signs, showing development trends, diverse from each other that is diagnostic properties of mechanisms. By means of these diagrams, it was shown that models of the side / lateral pressure of J. Dixon and V.G. Guterman possess similar trends. Trends of next mechanisms were studied. There are gravitational sliding (V.G. Guterman), thermal (analog) advection or limited convection (M.A. Goncharov), the simplest mathematical model of advection (ideal, kinematic) by M.A. Goncharov (1976, 1979), synthetic model (an advection in combination with uniform shortening, [Yakovlev, 1997]), a quasi-buckling as option of synthetic model ([Yakovlev, 2003], as sort of buckling on the scale of whole sedimentary cover, but not of one layer). In one of V.G. Guterman's models, the particular, local mechanism of deformation was found in an inclined zone of simple shearing ("near-thrust", [Yakovlev, 1997]); it was described also. All these models on scattering diagrams (AX/K, EN/K, AX/EN) have the characteristic features allowing to distinguish them from each other (fig. 11A). It was shown that the divergent structure with properties of the general shortening of space can be created only by synthetic model, which is combining advection and flattening (its special case – a quasi-buckling). Set of manners, such as a division of structural profiles into domains, measurements of three structural signs in each domain and consideration of areas of points of measurements on scattered diagrams represents language of the description of mechanisms of formation (deformation) of any folded structure relating to a linear folding. These descriptions were a subject of **point 1 of the statements**, produced for defense (a description method) and **point 3** (the characteristic of concrete mechanisms).

Language of the description of mechanisms of folding formation in the form of measurements of three structural signs was used for the specification of natural structures.

A

B

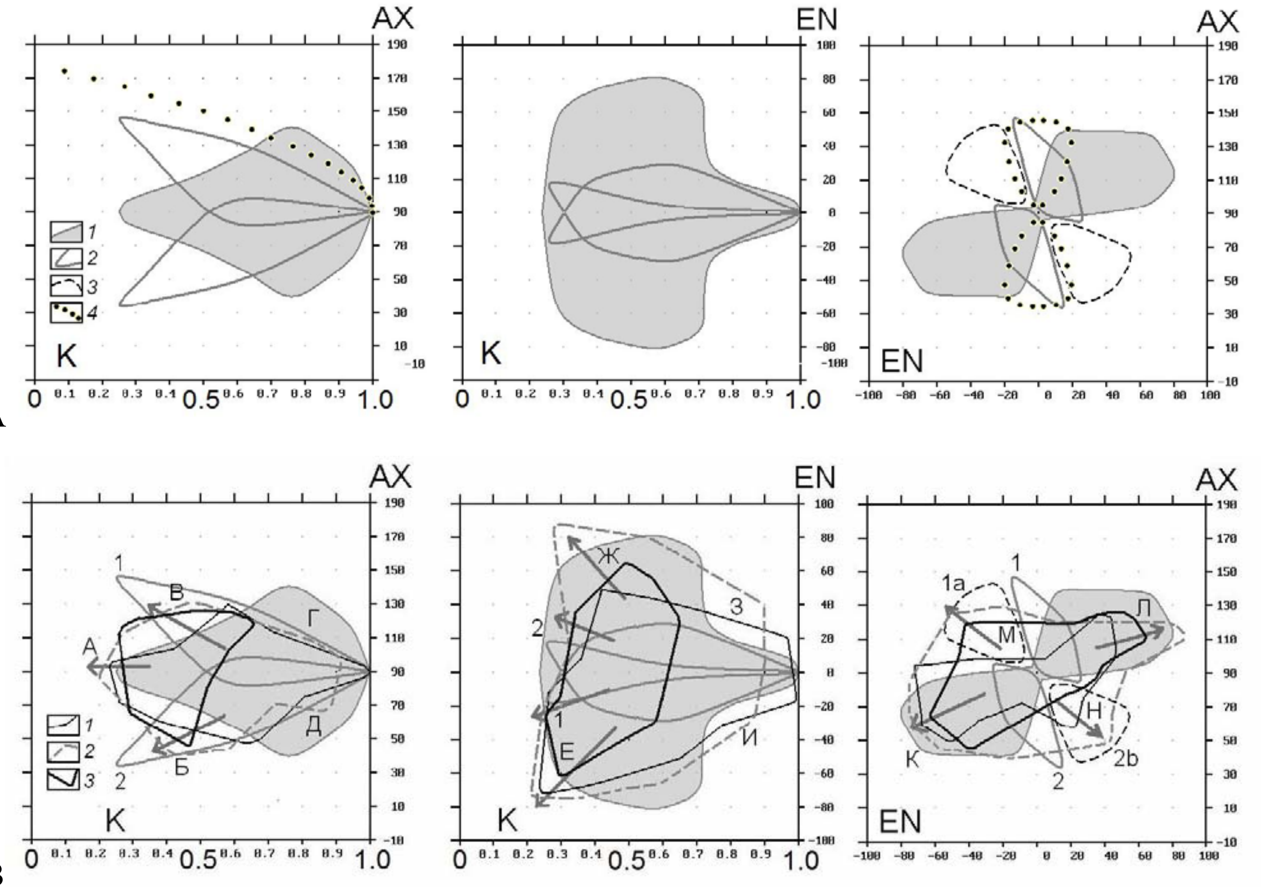

Fig. 11. A semi-quantitative method of diagnostics of mechanisms of formation of folded structures on the scale of a whole sedimentary cover (structural cells and tectonic zones).

A – Contours of the main calibrated, standard mechanisms on diagnostic diagrams:

1 – The synthetic model "advection plus shortening", a gray contour, 2 – the “near thrust” mechanism (according to experiment), 3 – the “near thrust” mechanism (a theoretical contour), 4 – horizontal simple shearing (it is shown for AX/K - one and for AX/EN – both vergences).

B – Comparison of contours of a natural folding to reference mechanisms. Tectonic zones: 1 – The Shakhdag zone, 2 – the Tfan zone, 3 – the Chiaur zone.

For this purpose, these parameters were measured in 151 domains of Shakhdag, Tfan and Chiaur tectonic zones of east half of GC [Yakovlev, 1997]. All three tectonic zones are having properties of similarity and of difference among themselves (fig. 11, B, signs 1-3). First of all, in all three zones large parts of structure (approximately in the rank of structural cells) show properties of divergent structure both on an inclination of an envelope surfaces of folds, and on an inclination of axial plains. Most developed domains (with the greatest values of shortening, first of all) in all three zones are in limits of SH = 80 ÷ 60% of shortening (or K = 0.2 ÷ 0.4), and configurations of lines of the maximum advance of domains ("front" of process) on diagrams of dispersion (AX/K, EN/K, AX/EN) were very similar: on an inclination of an envelope plain of folds from +45° ÷ +80° to -60° ÷ -80°, on an inclination of axial surfaces – from 45° to 130°. The brightest difference is the different position of the least developed domains on shortening value – in the Shakhdag zone it is SH = 0%, in Tfan – 10%, in Chiaur – 35% (or K = 1.0, 0.9, 0.65). Asymmetry of structure in the form of noticeable concentration of points on trends of "inclined zones of simple shearing" is observed. It took place in form of the southern vergence – in the Chiaur zone, a northern vergence (insignificant) – in Shakhdag and both trends – in Tfan zones. These observations show that the mechanism of formation of folded structures for all three zones was almost identical.

Comparison of contours of natural zones of a linear folding on diagnostic diagrams with contours and trends of a number of reference mechanisms (fig. 11, B) didn't confirm possibility of realization of widespread (conventional) model of an accretionary prism for an explanation of structure of Greater Caucasus – for instance, the structure according to model had to possess property of a mono-vergence (fig. 11, A, a sign 4 in values 90-150 AX) while the real natural structure is divergent. Possibility of use of model of pure advection isn't confirmed, because the value of shortening of natural structures on average much higher, than in this model, and the general configuration of points in the field of values "inclination of axial surfaces / inclination of a mirror of folds" significantly differs from the model. The most successful is the synthetic (combined) model "advection plus shortening" which closes as a first approximation to a fields of natural points in all three diagrams. The remained free spaces of natural areas cover on these areas by contours of the "near-thrust" mechanism. Thus, as a first approximation the formation mechanism of a natural folding is described by a combination of synthetic model (quasi-buckling) with the local “near-thrust” mechanism. The description of morphology of natural structures and its comparison with model mechanisms, and also a conclusion about possible genesis of natural structure were made by a subject of the second part of the 3d statement, produced for defense.

The chapter contains 57 pages of the text, 36 drawings and 4 tables.

Chapter 8. About significance of the received results for the analysis of models of geodynamics of Greater Caucasus

In the final chapter, debatable problems are presented for discussion.

The model of an accretionary prism (A-subduction) which often is used for an explanation of an origin of the folding of GC is discussed in details. On the basis of the analysis of a number of the published speculative models, and experimental models (J. Dixon, 1991, 2004), it is shown that signs of such model are: a) a sub-horizontal surface of the general detachment at a depth about 10 km, b) mono-vergence of structure on inclinations of axial surfaces and on inclinations of thrust surfaces, c) a dominance of thrust-related shortening in the general fold-thrust shortening of structure, d) more gentle (more sub-horizontal) vergence of structures (on inclinations of the planes of thrust and the axial planes of folds) downward to a surface of the general detachment. Big statistical material (measurements of geometry of 243 domains in NWC) testifies that the real structure is divergent (not mono-vergent), a ratio of thrust and normal faults approximately equal on their number, thrust have a weak contribution to the general shortening (it share is about 0.1). The basement top has so considerable fluctuations on depth (see materials of chapter 6) that building of the general detachment along this surface, which is necessary according to accretionary model, is impossible at all. The coincidence of values of ductile shortening of the basement and sedimentary cover was fixed that contradicts the main feature of model of a underthrusting (a condition of the rigid basement). On the geological map to the south from MCF, outcrops of detachment near outcrops of the Paleozoic basement, which is necessary on model, aren't registered. On these bases, the A- subduction model (an accretionary prism) is rejected, as not finding any confirmation in natural data on a complex of signs.

Information about values of shortening of the space in scales of tectonic zones, which is embracing both sedimentary cover, and the basement, was used for creation of model of a structure of crust and of behavior of border of Moho within Greater Caucasus and in the neighboring blocks of crust. For moment of sedimentation start in Early Jurassic, the initial depth of Moho (M) was assumed at a depth of 40 km (standard continental crust) on a condition of existence of the basal conglomerate of Lower Jurassic. The subsequent immersion of these rocks during accumulation of whole sedimentary column (fig. 12A), immersion during of shortening of space and then – after some upraising at a mountain building stage, has to be led to displacement of rocks of initial level M (from 40 km) to depth of 100-110 km (fig. 12B). As the phenomenon of an isostasy wasn't able to afford to realize subsidence on such depths of rocks of crystal part of crust in the parameter of their rather low density, it is necessary to expect that the noticeable part the crustal rocks got density of mantle rocks (with relatively high density). The volume of such transformed crustal rocks could make in the southern part of GC to 50-60% from initial one that forces to assume action not only iso-chemical transformations (transitions like gabbro-eclogite), but also by replacements of ions of potassium and sodium with ions of iron and magnesium with change of total chemism of rocks. Materials of this paragraph weren't presented as defended statements.

In the following paragraph, relations of the received materials with problems of mountain building processes are discussed. The history of development of the region at stages of a folding formation and of mountain building, a interrelationship of processes of a folding and of mountain building is analyzed, possible mechanisms of observed swell -

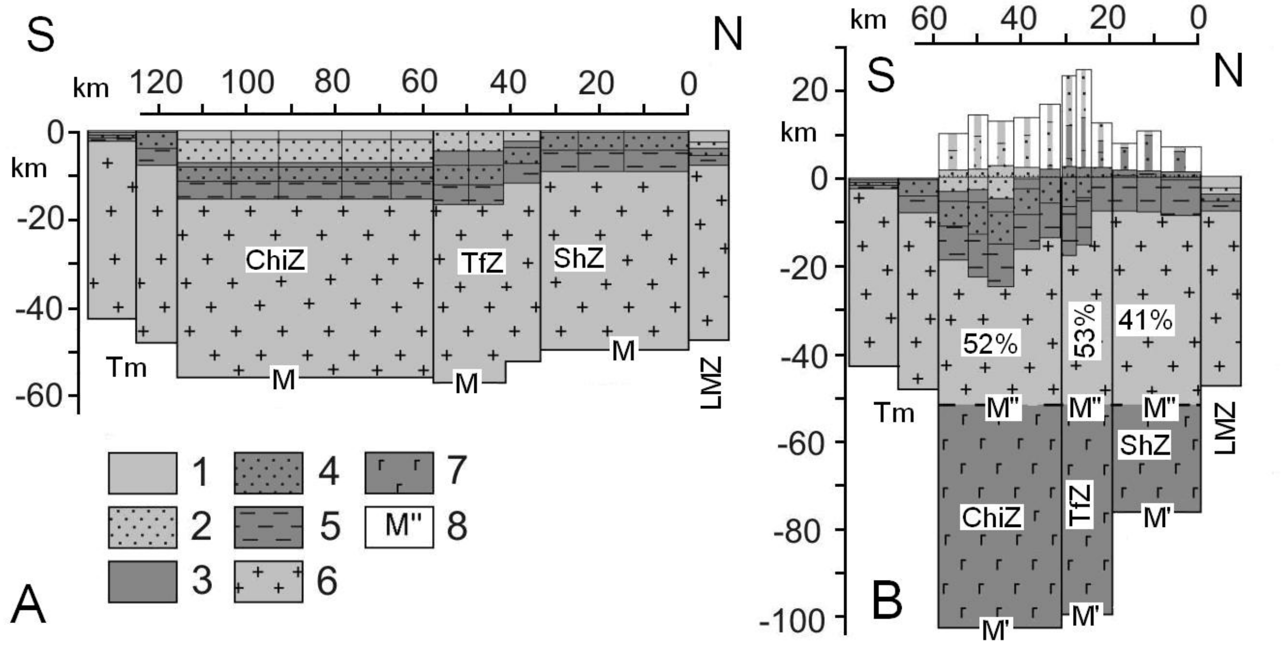

Fig. 12. The hypothetical generalized scheme of deep structure of east part of Greater Caucasus [Yakovlev, 2012] at the end of sedimentation (a stage 1) before the main episode of a folding formation (A) and at the moment (a stage 3) after a folding and a mountain building (B). Values of shortening for three tectonic zones (in %, see also fig. 8 of the abstract) and eroded volumes of a sedimentary cover (+0 ÷ +20 km) are shown. ChiZ, TfZ, ShZ, LMZ – Chiaur, Tfans, Shakhdag, Laba-Malka tectonic zones. Tm – two structures of the Transcaucasian median massif (from the North to the South - the Okribo-Sachkhery zone, the Dzirula block). It is well visible that the top of basement on the southern border of Greater Caucasus (Tm/ChiZ) has an escarp (normal fault) with an amplitude of 10-15 km.

1 – Palaeocene and Eocene, 2 – Cretaceous, 3 - Upper Jurassic, 4 – Middle Jurassic, 5 – Lower Jurassic, 6 – volumes of crystal part of crust above Moho (for a stage 1), 7 – the presumable volume of a neogenic mantle which were created from the lowered part of crust, 8 – Moho's border: M – border of Moho at the standard "continental" thickness of 40 km at the start of sedimentation (at the beginning of the Jurassic Period), M' - the calculated position of rocks on the former border of Moho, fig. A, M" – the estimated position of modern border of Moho (above a "new" mantle).

blocked uplift of a mountain construction, etc. are considered. The main discussed problem – very big amplitudes of erosion of the top part of a sedimentary column (10 - 15 km) in relation to rather standard (conventional) amplitudes of a neotectonic upraising (3-5 km), which was found by calculations. The assumption that an erosion of the top part of a sedimentary cover could take place synchronously with a process of a folding formation is made. Material of such erosion could compose a part of volume of the Maikopian sedimentary sequence (the lower molasse, P3-N1) which was accumulated in foreland depressions of Greater Caucasus. Possibility of check of the offered balanced models of a structure and development of GC (regarding amplitudes of erosion) on comparison of volumes of theoretical and real Cenozoic deposits in lower and upper molasses, accumulated in surrounding depressions is discussed. At the moment such check can't be realized as there are no enough full data on volumes of eroded sedimentary sequences on the area of whole mountain construction. Besides, such check can't be crucial as the most reliable verification of the offered constructions is possible only by a checking of logic of all calculations and direct repeated recalculation of known data. The basis for such conclusion is the priority of laws of logic, geometry and physics before any speculative geodynamic constructions or models.

On the example of collected initial data and the received calculated parameters of structural cells of NWC, the possible usage of the offered approach for geodynamic researches (tab. 1) was shown. It was shown that relationships exist between parameters as of strong, moderate and the average force, which can have a genetic meaning. Strong relation of r=0.79 is found for the parameters "shortening value/amplitude of a upraising" (1/5), moderate value of r =-0.40 for "shortening cells / difference of depths of the basement" (1/6) and moderated value of r=0.40 – for "initial thickness of cover / difference of depths of the basement" (2/6). These ratios are interpreted as the following cause and effect sequence: there is more initial thickness, there is more shortening, the upraising and erosion and the more resultant immersion of the basement is more. It is noted that such relationships bear to the classical scheme of development of geosynclines a strong resemblance. It is shown on

Table 1. A matrix of correlations of parameters for the Northwest Caucasus, for two sets: for a full set of the 42 cells and for selected set of 32 cells. Parameters 3 – 6: 3. post-folded depth of a basement top (stage 2); 4. modern depth of a basement top (stage 3); 5*. amplitude of upraising (difference, stages 3 and 2); 6. a difference of depths of basement top (between stages 3 and 1). (* – the measured parameters, the others – calculated)

for the 42 cells (selected 32)	**1***	**2***	3	4	**5***	6
1*. Coefficient of shortening	1.000	-0.147 (0.029)	0.011 (-0.701)	-0.353 (-0.418)	0.790 (0.593)	-0.397 (-0.582)
2*. Initial thickness of cover (depth of basement, stage 1)		1.000	0.399 (0.633)	0.755 (0.783)	-0.048 (0.246)	0.395 (0.537)

Table 2. Average values of depths of a basement top and amplitudes of a neotectonic upraising for three stages of development of NWC (42 cells) and for three zones of east half of Greater Caucasus (37 cells)

	Value of shortening	Pre-folded depth	Post-folded depth	Actual depth	Neotecton. upraising	Differ. of depths
NWC	35%	-13.38 km	-22.2 km	-13.25 km	8.9 km	0.13 km
SEC and Chiaur zone	55%	-13.6 km	-31.7 km	-15.1 km	16.6 km	-1.5 km

the tab. 2 that for two parts of Greater Caucasus the preservation of constant average value of depth of the basement from an initial stage (-13.4 km for NWC and -13.6 km for east half of GC) to modern (-13.3 km and -15.1 km) is observed, at noticeable dispersion as for initial depths (from -7.3 to -17.3 km and from -9.8 km to -16.7 km), and for modern (from -2.2 km to -31.7 km and from -4.4 to -24.8 km). These data testify to strong influence of the phenomenon of an isostasy on geodynamics of GC development in aspects of a folding formation and of mountain uplift. Research of these data can make the new perspective direction of researches in geodynamics. Results of the first efforts made in this direction are shown (V. G. Trifonov, 2012).

Due to very large amplitudes of erosion (up to 20 km) the problem of an observed weak metamorphism of the rocks of the lower part of a sedimentary cover, which came to a surface, is discussed. It is shown, in particular, that the phenomenon can be explained with possible very weak geothermal gradient (10-15°/km against usual 20-30°/km). Such gradient can arise due to of supposed, according to calculated values of deformation, strong immersion (to 100 km, fig. 12, B) of the cold lower part of crust. In this case the warming up of rocks of whole column of lithospheres expected at a depth of 20 km will require a long time.

The chapter contains 45 pages of the text, 18 drawings and 4 tables.

CONCLUSION

As a result of the executed works on development of methodology of researches, on creation of methods of studying of multi-scale folded structures and on application of these methods to a number of experimental and natural structures, the following results were received.

A. Development of the general methodology of researches in structural geology and a tectonophysics.

1. It was established that a lack of methods of detection of type and value of deformation in multi-scale folded complexes of internal parts of folded-thrust systems of mobile belts is one of important reason of phenomena of crisis in tectonics and geodynamics.

2. The system of hierarchy of objects of a linear folding consisting at least of seven levels, each of which covers a certain volume of layering, is developed: 1. intra layer objects, 2. folds (layers), 3. folded domains (large packs of layers), 4. structural cells (whole sedimentary cover), 5. tectonic zones (Earth crust), 6. folded systems (lithosphere), 7 mobile belt. Types of objects at each level are characterized by the certain cinematic models of the development, which are different from models of other types.

3. The main object for research of folded structures, which are larger than separate folds, is the folded domain that uniting in itself some folds of identical morphology and

possessing rather uniform deformation. Deformation in the domain is described by three geometrical parameters, which correspond to a strain ellipsoid: inclination of axial surfaces of folds (inclination of a long axis of an ellipsoid), shortening value (length of a short axis of an ellipse), inclination of a envelope of folds (orientation of initial layering). These parameters are used as a basis of language of the description of mechanisms of formation of structures, and also at realization of operations of restoration of pre-folded structure.

4. For the solution of a number of tasks of reconstruction of geometry of large structures outside an its observation zone (outcrops) the principle of their consecutive formation (compilation) from level to level with use of results of research of small and more reliable structures to more large is used. The inefficiency of the practiced methodology of creation of speculative (interpretative) models of concrete natural folded structures based on of known theoretical models is shown.

Results 1 – 4 are expounded generally in chapters 1, 3, 5, 7; these results formed point 1 of statements, produced for defense.

B. Development of methods of researches

5. Methods of measurement of shortening values in separate folds of two types are developed: for folds of a single viscous layer and for folds of packs of layers. The reliability of results is provided by usage of calculated finite element model as a basis of the first method. It is shown by comparison of results of research of folds in a number of natural structures by both methods that the cinematic model which is the cornerstone of the second method (for folds of packs of layers) gives the values of shortening comparable to data of the first technique that also confirms the reliability of all results.

6. The method of restoration of pre-folded structure based on "domain geometry" is developed. Measurements of parameters of domains are transformed to an initial (pre-folded) state of domain by use of operations of rotation, simple horizontal shearing and stretching. As a result, the initial piece of a natural profile line having some inclination gets the new length and a new (pre-folded) inclination in horizontally layered medium of the domain. Consecutive junction of domains allows to receive structures from several domains, both for part of cross-section, and for whole profile that gives the chance to calculate the pre-folded width and value of shortening of these structures.

7. On the basis of a method of restoration of pre-folded structure based on “domain geometry” the method of compilation of the balanced structure of whole sedimentary cover is developed for three stages of development on the scale of structural cells (for whole sedimentary cover) – for the finish of sedimentation, for the end of a stage of folding formation and for modern post-mountain-building structure. The combination of several next

profiles in region allows to create quasi- three-dimensional models of a structure of a sedimentary cover for the same three stages of development.

8. The method of the semi-quantitative description of morphology of experimental and natural folded structures is developed. The geometrical parameters of the folded domain measured in structures are used for this purpose. Clouds of points of measurements in three-dimensional space are analyzed on three diagrams of dispersion. Comparison of areas and the revealed trends of development allows to define the features of similarity and distinction of structures connected with mechanisms of their formation. Combinations of comparison of structures "model / model", "natural / natural" and "model / natural" are used.

Results 5-8 are expounded in chapters 4 (point 5), 6 (points 6 and 7), 7 (point 8). They formed a subject of part of point 1 of statements, produced for defense (about of a complex of methods of research).

C. Results of measurement of shortening values and of restoration of the balanced sections.

9. Systematic measurements of shortening values on the scale of separate folds for the Chiaur tectonic zone were made. For 72 folds of a single viscous layer and for 36 folds of packs of layers, shortening values varied from 25% to 83% at the average size of 56%. Stability of relation of shortening values with a tectonic situation of local level (due to condition of pure shearing in terms of mechanics) in large folds was revealed.

10. Measurement of shortening values for folds in a zone of a sole fault of the Vorontsov nappe (39 values) were made. For conditions of simple shearing (in terms of mechanics) very wide and casual scattering of values (from 2% up to 95%) is revealed.

11. On the scale of structural cells, shortening values from 37% up to 67% in 36 cells for east part of Greater Caucasus (Chiaur, Tfan and Shakhdag tectonic zones) with average values of shortening of 57%, 55% and 49% and with a pre-folded width of 57 km, 24 km and 32 km respectively were determined by the method of restoration of pre-folded structure by “domain geometry”. Shortening values for 42 structural cells of the North-Western Caucasus from 2-10% (and stretching to -10%) up to 67% at average value in 35% were measured. Weak shortening is observed in pericline of GC folded system. Pre-folded width of whole basin of sedimentation of the North-Western Caucasus reaches 100-120 km, and a modern full width of structure is 50-65 km.

12. Quasi-three-dimensional models for three stages of development of Shakhdag, Tfan and Chiaur zones were reconstructed. Depth of basement top at the time of the end of a pre-folded stage for them from the North to the South on the scale of structural cells were estimated as -9.8 km, -13.4 (from -11.9 km to -16.7 km) and -15.3 km. Calculated depth of the basement top after folding formation and after neotectonic uplift for a modern stage 3

were estimated as -10.2 km (-7.6 ÷ -13.7), - 12.0 km (-4.4 ÷ -19.4) and -20.5 (-13.6 ÷ -26.3). Quasi-three-dimensional models for the North-Western Caucasus for the end of a pre-folded stage had depths of the basement top varied from -7.3 km up to -17.3 km (an average -13.4 km). The modern post-folded and post-mountain-building positions of the basement top (a stage 3) have a number of values, -2.2 ÷ -31.7 km, and at average -13.2 km. Three parts of natural structure on distribution of this value are observed: the central subsidence in the western segment of NWC, deep subsidence of the southern flank in the central segment (up to -31.7 km) and the central subsidence in the eastern segment.

13. The volumes of eroded top part of a sedimentary cover on the scale of structural cells which are allegedly connected with a neotectonic uplift of the basement top between a post-folded stage 2 and a modern stage 3 are determined. For Shakhdag, Tfan and Chiaur zones, these values were calculated as averaged 9.6 km (7.2 ÷ 12.5), 19.2 (12.2 ÷ 24.4) and 16.1 (9.9 ÷ 22.2). For the North-Western Caucasus these parameters are varied from 0 km up to 22.2 km at average value of 8.9 km.

Results 9 - 13 are expounded in chapters 4 (point 9), 5 (point 10), 6 (points 11 - 13). They formed a subject of point 4 of statements, produced for defense.

D. Results of diagnostics of formation mechanisms of folded structures of various scales.

14. It was shown on the scale of local structures in zones near large faults with use of theoretical kinematic models and due to analysis of experimental models that the Vorontsov nappe has the mechanism of kinematic simple shearing; and that in the Northwest Caucasus the part of domains satisfies models of a zone of inclined simple shearing ("the near-thrust mechanism").

15. With use of language of the description of deformations (point 3 in the section "A" of CONCLUSIONS, see above), on the scale of folded domains, an experimental and theoretical mechanisms of formation of folded structures on the scale of structural cells and tectonic zones were characterized. There are mechanism of lateral pressure, gravitational sliding, diapiric and convective structures, the synthetic model "advection plus shortening (flattening)", "quasi-buckling" on the scale of a sedimentary cover, local "the near-thrust mechanism". The received areas and trends of development of structures on diagrams allowed to distinguish these mechanisms from each other that gives the chance to accomplish diagnostics of natural structures.

16. With use of language of the description of deformations, the main features of similarity and distinction of folded complexes of Shakhdag, Tfan and Chiaur zones were established. It is shown that in all three zones, large parts of structure (approximately in the rank of structural cells) showed properties of divergent structure, both on an inclination of an

envelope surfaces of folds, and on an inclination of axial surfaces. The domains having the maximum development of processes of formation in all three zones have close structural parameters. The maximum difference of data on zones was observed in values of shortening for the minimal developed domains. It was shown that as a first approximation, folded structures are well described in kinematic aspect by a combination of synthetic model ("advection plus shortening") with inclined zones of simple shearing ("the near-thrust mechanism").

The **result 14 is expounded in chapter 5** and it formed a subject of **point 2 of statements**, produced for defense. **Results 15 and 16 are expounded in chapter 7**. They formed a subject of **point 3 of statements**, produced for defense.

E. Preliminary results of application of the data obtained with using of the "multirank strain analysis" for study of some geodynamic aspects based on a geometry of structure and features of a development of structures of the Alpine sedimentary cover of Greater Caucasus. Possible directions of further works.

17. On the basis of an established fact of ductile deformation of the basement of whole Greater Caucasus, by a comparison of a relief of a basement top in models and in reconstructed natural structure and by a comparisons of statistical parameters of morphology of a folding in models and in natural structure, the conclusion is drawn that widely used schemes of a structure of Greater Caucasus which have in their basis the scheme of an underthrusting of rigid blocks of crust of Transcaucasian median massif under a flysch-like sedimentary cover ("A-subduction" or "an accretionary prism"), don't correspond to real natural structure.

18. It is established that accumulation of large thickness of a sedimentary cover and formation of a folding is connected with the large-scale phenomena of change of density of crustal rocks to more compact "mantle" values (up to 60% of volume of its crystal part). It is shown due to the geometrical modeling on the basis of the established shortening values on the main tectonic zones. Thereby the correctness of usage of modern border of Moho as the marking surface for calculation of values of deformations in geodynamic models in areas of mobile belts is denied.

19. The essential role of the phenomenon of an isostasy in processes of a folding formation and of mountain building is established. It is proved by the facts of very close average values of pre-folded and modern depths of a basement top on the scale of structural cells on regions, and also by constancy of the size of this parameter, average for a profile, along structure of the Northwest Caucasus. The revealed essential correlations between

several parameters of structural cells can be used for further research of geodynamic developments of the region.

The result 17 is expounded in chapters 6 and 8. Results 18 and 19 are expounded in chapter 8 and they are of interest as the possible directions of further works.

On the basis of the received results in sections "A", "B" and "C", the presented work is characterized as the new direction in a tectonophysics, structural geology and a tectonics, called "the multirank strain analysis of structures of a linear folding". Results in sections "D" and "E" show that there are elements of large generalization on a structure and development of the important region – the Alpine Greater Caucasus in the thesis.

LIST OF MAIN PUBLICATIONS

In journals from list of Highest Certifying Commission (HCC)

1. **Yakovlev, F.L.** Identification of geodynamic setting and of folding formation mechanisms using of strain ellipsoid concept for multi-scale structures of Greater Caucasus / F.L. Yakovlev // Tectonophysics. – **2012.** – V. 581, 18. – pp. 93–113.
2. **Yakovlev F.L.** Reconstruction of the balanced structure of the eastern part of alpine Greater Caucasus using data from quantitative analysis of linear folding – case study // Bulletin of "KRAESC". Earth Sciences. No. 1 (19), **2012.** pp. 191-214. (in Russ.)
3. **Yakovlev, F.L**. Methods for detecting formation mechanisms and determining a final strain value for different scales of folded structures / F.L. Yakovlev // Comptes Rendus Geoscience. – **2012.** – 344 (3–4). – pp. 125–137.
4. **Yakovlev F.L.** Strain multirank analysis and a structural paragenesis: the comparison of approaches and of results // Bulletin of "KRAESC". Earth Sciences. No. 2(16), **2010.** pp. 179 - 193 (in Russ.)
5. **Yakovlev F.L.** Reconstruction of linear folding structures with the use of volume balancing // Izvestiya, Physics of the Solid Earth, **2009,** Vol. 45, No. 11, pp. 1025–1036. (in Engl.)
6. **Yakovlev F. L.** Multirank Strain Analysis of Linear Folded Structures // Doklady Earth Sciences, **2008,** Vol. 422, No. 7, pp. 1056–1061. (in Engl.)
7. **Yakovlev F.** Greater Caucasus as collision structure which has interior activity (auto-abstract of report at 13-04-2004) // Bull.MOIP, Geol. depart., **2006**, 81(1), pp. 89-90. (in Russ.)
8. **Yakovlev F.L.** Study of linear folding mechanism as one of tectonophysics branch. Bull.MOIP, Geol. depart., **2001**, 76(4), pp. 7-15. (in Russ.)
9. **Yakovlev F.L.** A Study of the Kinematic of Linear Folding (on the Example of the Southeastern Caucasus). - Geotectonics, **1987,** Vol. 21, No. 4, P. 316 - 329. (in Engl.)
10. **Yakovlev F.L.** The Problem of the Factors of Fold Development. - Geotectonics, **1987**, Vol. 21, No. 4, pp. 392 - 393. (in Engl.)
11. Rogozhin Ye.A., **Yakovlev F.L.** A Quantitative Estimate of the Morphology of Folding in the Tfan Zone of the Greater Caucasus.-// Geotectonics, **1983,** Vol.17, No 3, pp. 242-251. (in Engl.)
12. **Yakovlev. F.L.** An estimate of deformations in a folded region on the basis of disharmonic folds. Bull. MOIP, Geol. depart, **1978**, 53(5), pp. 43-52. (in Russ.)

Monographic publications

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16. Rebetsky Yu.L., Mikhailova A.V., Osokina D.N., **Yakovlev F.L.** Tectonophysics. In.: The Earth planet. Encyclopedic handbook. Volume "Tectonics and geodynamics". Editors: L.Krasnii, O.Petrov, B.Bluman S-Petersburg., VSEGEI Edition, **2004**, (652 pp.) p. 121-134. (in Russ.)

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18. **Yakovlev F.L.** Tectonophysical methods of an estimation of strain value for structures of linear folding of different ranks: examples of the decision of geotectonic problems // «Tectonophysics and actual problems of Earth’s sciences. To 40-years anniversary of tectonophysics laboratory foundation by M.V. Gzovsky.». Conference materials. Moscow. IPE RAS Publishing. **2009**. v. 1. p. 133-146. (in Russ.)

19. **Yakovlev F.L.** Quasi-3D three-phasic model of the Alpine development of a folded sedimentary cover of North-West Caucasus by data about sizes of deformations // «Tectonophysics and actual problems of Earth’s sciences. To 40-years anniversary of tectonophysics laboratory foundation by M.V. Gzovsky.». Conference materials. Moscow. IPE RAS Publishing. **2009**. v. 1. p. 439-448. (in Russ.)

20. **Yakovlev F.L.** Tectonophysical methods of study of linear folding structures // Modern tectonophysics. Methods and results. Proceedings of first youth tectonophysical school-seminar. Moscow. IPE RAS Edition. **2009.** pp. 318-347. (in Russ.).
21. **Yakovlev F.L.** The experience of faults typology for linear folding structures, on the Greater Caucasus example // Faults forming and seismicity in lithosphere: tectonophysical ideas and effects. Irkutsk: IEC SD RAS. **2009.** pp. 128-131. (in Russ.).
22. **Yakovlev F.L.** Vladimir Vladimirovich Belousov and the problem of folding formation. // Geophysical Researching. (IPE RAS Journal) **2008.** т. 9, No 1. pp.56-75. (in Russ.)
23. **Yakovlev F.L.** Investigation of the processes and mechanisms of the plicative deformations development in the Earth's crust (review of the existing approaches). // Tectonophysics today. Moscow.: UIPE RAS, **2002**. pp. 311-332. (in Russ.)
24. **Yakovlev F.L.** A Study of the Linear Folding Kinematic Features on Example of the Greater Caucasus. / Experimental tectonics and field tectonophysics. Kiev, Naukova doumka, **1991**, pp. 181-186. (in Russ.)
25. **Yakovlev F.L.** Two methods of determining the amount of horizontal shortening by the morphology of folds./ (Mathematical methods of analysing geologic phenomena). Moscow, Nauka, **1981**, pp. 70-76. (in Russ.)

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26. Saintot, A. The Mesozoic–Cenozoic tectonic evolution of the Greater Caucasus / A. Saintot, R. Stephenson, M.-F. Brunet, M. Sébrier, **F. Yakovlev**, A. Ershov, F. Chalot-Prat, T. Mccann // Ed.: D.G. Gee, R.A. Stephenson. – European Lithosphere Dynamics. – Geological Society, London, Memoirs, **2006**. – 32. – pp. 277–289.

Materials, additional to Russian version of abstract of the thesis (for English version only)

A. SOME NOTES ABOUT RULES FOR PROCEDURE OF DEFENSE OF DOCTORAL THESIS IN RUSSIAN FEDERATION (RF):

1. All regulations are determined by special documents of Highest Certifying Commission (HCC) of RF.
2. All main results of dissertation preliminarily should be published in main journals. Special List of such journals is approved by HCC. Minimal number of publications for doctoral thesis is 10 in journals of special List. Some monographic publications may be accepted as equal to such List's publication. Results of researching in thesis should be relevant / important, new and considerable. The subject of thesis may form a new direction a researching or may form a large scale generalization of material in actual direction of researching.
3. The basis of defense of doctoral thesis should be written thesis (about 300 pages volume), and abstract of thesis. These materials and some documents should be presented to Doctoral Council, which consists of 25-30 experts (doctors of science).

Materials and all documents also presented in site of Council. For F. Yakovlev link is (full line!): http://www.ifz.ru/novosti/?tx_ttnews[tt_news]=736&cHash=d149e3ee9c48ae122f92d46bd4774843 (in Russian)

4. Before main procedure of defense, three obligatory responses on thesis from three official opponents, and one obligatory response from leading organization should be presented to Council. Several responses from any other scientists on abstract are desired (about 5-7 is usual). All references should contain solution about validity of statements, produced for defense, also as the opinion of author of response "yes/no" regarding possibility of graduation of Doctoral degree to competitor (and its reasons). Responses may contain points of criticism, of course.
5. Main procedure of defense has several obligatory parts: **A.** Presentation of competitor (the oral report during about 40 minutes), **B.** Questions to the competitor; **C.** Interruption (cafe break), **D.** Announcements of official responses on the thesis and of responses on abstract, **E.** Replies of competitor on points of criticism in responses, **F.** Common discussion (oral expression of an opinion of any scientist about the work and conclusion "yes/no"), **G.** Secret voting procedure of members of Council (based on materials of all points of procedure; positive solution take place at 67% and more of votes "yes"). **H.** Confirmation of voting result.

Result of defense procedure for Fedor Yakovlev at 28 May 2015 (duration was 5.5 hours).

1. All three obligatory responses on thesis from official opponents have had estimation "yes". First opponent (V.G. Trifonov) has had some doubt regarding point 4 of statements, produced for defense. Obligatory responses on thesis from leading organization has had estimation "yes". Responses contained points of criticism.
2. Total amount of responses on abstract was 19; all estimates were "yes". Responses were written by 16 doctors (both grades) in geology-mineralogy (geology) and by 5 doctors (both grades) in physics-mathematics (geophysics). Five responses have had no points of criticism.
3. Quantity of questions was 29 from 8 scientists.
4. Total quantity of points of criticism of different quality was about 60.
5. 8 scientists participated in discussion. First speaker (Valentin O. Mikhailov, Dr. in physics-mathematics sciences, he is not member of Council) expressed his extremely negative estimate of dissertation ("No"), second speaker expressed his abstain, others appealed to vote "Yes".
6. Result of voting. There are 20 votes = 15 yes, + 4 no, + 1 abstain; i.e. 75% yes = OK. (Total members of Council was 30. Attended 20, including 5 in geol.-mineral. sciences, 10 – phys.-math., 5 – technical)

Notes about criticism. Nobody doubted straightly in main points of statements, produced for defense or in logic of methods or in way of calculations. Criticism include next some points: doubts in structural evidences of 2D deformation in folds and of constant volume of rocks; doubts in high value of shortening (50%), based on reasons that in this case the Moho should testify a subsidence to 100 km depth, and crust's rocks should change their density (opinion was that it is not possible); doubts in amplitude of erosion in 15-20 km, based on a conventional opinion that it is 3-5 km; doubts in very low value of shortening (50%), because conventional opinion was 200 km minimal or 5-time and more. (F.Y.: It is very funny, that a calculated amplitude of erosion at this case should be 65 km**!**). All these points of criticism are easily parrying by geological facts or by logical inferences.