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# PRELIMINARY ESTIMATE OF REALNESS OF GEODYNAMIC MODELS OF GREATER CAUCASUS DEVELOPMENT WITH DIFFERENT SHORTENING OF STRUCTURE BY USE OF CALCULATIONS OF THEIR THEORETICAL VOLUMES OF ERODED ROCKS

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## SUMMARY

Three geodynamic models of the Greater Caucasus (GC) on their parameter "volume of eroded rocks" were compared. Approximate compliance (±1/3) of its volumes of eroded rocks with the volume of the synchronous accumulated sediments in foreland basins surrounding Greater Caucasus during last 30 My was criterion of reliability.

As model of "flyash" model of the neotectonic movements [Neotectonic Map, Grachev, 1997] on which region raisings for 15 million years are shown was used (according to [Milanovsky,1968]). In the original concept of fixion, fold-related shortening of space in Greater Caucasus was ignored. Raising amplitudes in model were a maximum of 4-5 km, they are considered as standard in common opinion.

The second model had moderate shortening values of space (about 50%) in structures, relatively small by the size (5 km width), in three regions of Greater Caucasus. The model is based on a method of creation of the balanced folded structural profiles [Yakovlev, 2012, 2015, 2017]. Calculated average amplitudes of a uplift and erosion for 30 My about 10, 15, 20 km are characteristic of this model.

The third model represented the scheme of plate tectonics like "secretionary prisem". In the typical model [Dobduyev, 1986] the minimum shortening of 200 km for 50km width belt was declared. Data about raisings amplitude or about erosion of a sedimentary cover in this model were absent, however indirect information indicates that the opinion on erosion of 4-5 km for the Caucasus doesn't cause objections. Our calculations for this model have shown shortening at least in 80% (fivefold) that for the average thickness of a sedimentary cover of 13 km gives the new thickness of a cover of 65 km and with the declared basement depth in 10 km about 55 km of eroded sediments in a strip 50-60 km wide.

Thicknesses of terrigenous deposits in the Oligocene and N-Q depressions around the Caucasus were counted based on [Neotectonic Map, 1998] and, for the western part of the region, according to the scheme of thicknesses of the Mesozoic sediments from [Milanovsky, 1996]. Volumes of erosion or of the accumulated sediments were calculated on polygons 20×30 minutes of a coordinate grid on isolines of maps, which were summed up on next step. The total amount of the latest (Pg3-Q) sediments around the Caucasus was 2610 thousand km3, including 592 thousand km3 for the basin of the Black Sea.

For the calculation of volume of eroded rocks, the volume of a mountain building, which was calculated on isohypses of a relief, and which has reached 118.8 thousand km3, was subtracted from the volume of uplift. Taking into account the correction for a relief volume, model with zero shortening [Neotectonic Map, Grachev, 1997] had the volume of eroded rocks of 160 thousand km3 (279 thousand km3 : 119 thousand km3), including for the Black Sea drainage-erosion basin 87 thousand km3. These values are obviously too small for filling with material of all latest depressions around Greater Caucasus. At calculations of erosion on model of the balanced structure [Yakovlev, 2015] some averagings and extrapolations were made. Erosion volume for this model (with corrections) was 826 thousand km3, and for the Black Sea drainage/erosion basin 448 thousand km3. In model of 80% shortening [Dotduyev, 1986] the volume of eroded rocks was estimated (by us) at 2950 thousand km3 minimum. Taking into account obviously considerable share of volumes of a gathering of sediments from Lesser Caucasus, Elburs and Kopet-Dag in sediments of the Southern Caspian Sea, this model has obviously excess volume of erosion concerning the nature (2610 thousand km3).

The analysis has shown proximity of volumes of eroded rocks to natural values of the accumulated sediments only for model of the balanced structure. The volume of eroded rocks of balanced model of 826 thousand km3 had a good ratio with natural 2610 thousand km3 in general on all foreland basins. For option of a "clean" ratio erosion/accumulation of the region of the Black Sea (without additional sources of sediments, like Elburs for Southern Caspian sea), the volume of eroded rocks of balanced model 455 thousand km3 has very good ratio (0.77) with 592 thousand km3 sediments of natural appropriate sedimentary basins. Other two models, a fixism with 0% shortening and an accretionary prism with 80% shortening, are not realistic in the studied parameter.

## 1. THE ALPINE GREATER CAUCASUS

Fig. 1-1. Locations of the studied areas in the schematic map of the geological and tectonic structure of Greater Caucasus (modified after the geological map in [Dadiamov, Tarasenko, 1979]). The map shows the Scythian plate, Transcaucasian Median Massif, and Lesser Caucasus. 1 – sedimentite, 2 – Quaternary, 2 – Neogene-Paleogene, 3 – Mesozoic, 4 – Paleozoic, 5 – Precambrian, 6 – faults, 7 – boundaries of the main structural boundaries (PT – Pshekish-Tyrnyauz Fault, BP – Racha-Lechkhumi Fault), 8 – in Greater Caucasus (MF – Main Caucasian Fault), 7 – four sectors, according to [Sholpo, 1978]: NWC – North-Western Caucasus, CC – Central Caucasus, EC – Eastern Caucasus, EC – South-Eastern Caucasus, 9 – studied areas (1 – NWC, 2 – Chiatur tectonic zone, 3 – SEC: Shakhdag and Tfan tectonic zones).

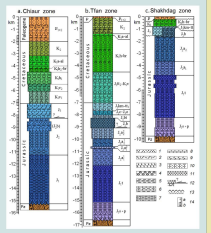



Fig. 1-2. Stratigraphic columns for three tectonic zones: a. Chiaur zone (Central Caucasus, area 2, fig.2-1), b. & c – Tfan and Shakhdag zone (South-Eastern Caucasus, area 3)

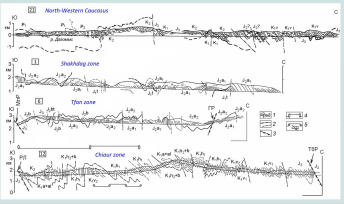



Fig. 1-3. Example of a structural section for different parts of Greater Caucasus. Division of the structure on two kind of hierarchic objects – domains and structural cells – are shown (profile 12, etc. Kezbeta, fig.2-1). 1 – faults of the boundaries of main stratigraphic boundaries, 2 – large and medium-size faults, 3 – faults at the margins of tectonic zones ПЗ – Racha-Lechkhumi Fault, ТФР – Tfan thrust; 4 – structural cells and their boundaries; 5 – folded domains and their boundaries.

## 2. METHOD OF COMPILATION OF MODEL OF THE BALANCED STRUCTURE OF THE SEDIMENTARY COVER

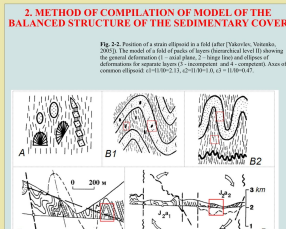


Fig. 2-2. Position of a strain ellipsoid in a fold (after [Yakovlev, Volotsko, 2005]). The model of a fold of packs of layers (hierarchical level II) showing the general deformation (1 – axial plane, 2 – hinge line) and ellipse of deformations for separate layers (3 – incompetent and 4 – competent). Axes of common ellipsoid: e1=1/D=2.13, e2=1/D=1.0, e3 = 1/D=0.47.

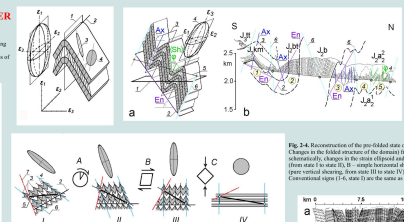


Fig. 2-3. The folded domain and the strain ellipsoid in the folded structure ("a" after [Yakovlev and Volotsko, 2008]); the structural material in the detailed profile of the folded structure (modified after [Yakovlev, 2008]). Elements of structure, 5 domains, part of section 7, Tfan zone, East-Southern Caucasus (Yakovlev, 2015a, 2015b). a – The axes of the ellipsoid for the full lengthening (*l*), intermediate (*i*), shortening (*s*). Main parameters of the strain (i.e. a combination of several folds): 1 – horizon plane; 2 – surface of the envelope plane and its dip, Ex; 3 – axial plane and its dip, Ax; 4 – strain ellipsoid, which value of shortening (SH) is measurable from the interlimb angle, *g* (SH=(1–cos(90–g/2))×100%); 5 – the segment of the profile within the limits of the domain, its length and dip; 6 – domain's boundary in the profile (parallel to the axial planes of the folds). b – Conventional signs for the same as in "a"

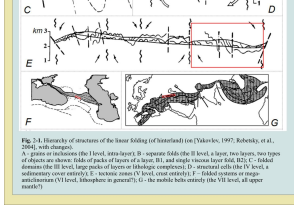


Fig. 2-4. Reconstruction of the pre-folded state of the domain (modified after [Yakovlev, 2008]). Changes in the folded structure of the domain) from the modern (I) to pre-folded (IV) state schematically, changes in the strain ellipsoid and types of operations are shown. A – rotation (from state I to state II), B – simple horizontal shearing (from state II to state III), C – lengthening (pure vertical shearing, from state III to state IV).
Conventional signs (1-6, state I) are the same as in fig. 3-3 "a"

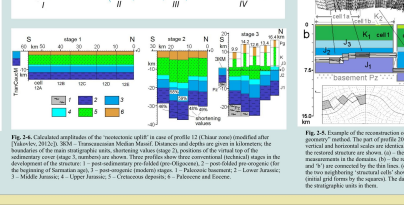


Fig. 2-5. Calculated amplitudes of the 'neotectonic uplift' in case of profile 12 (Chiaur zone) (modified after [Yakovlev, 2012c]). 3GM – Transcaucasian Median Massif. Distances and depths are given in kilometers; the boundaries of the main stratigraphic units, shortening values (stage 2), positions of the virtual top of the sedimentary cover (stage 3, numbers) are shown. Three profiles show three conventional (technical) stages in the development of the structure: 1 – post-sedimentary pre-folded (pre-Oligocene), 2 – post-folded pre-orogenic (for the beginning of Sarmatian age), 3 – post-orogenic (modern) stages. 1 – Paleozoic basement; 2 – Lower Jurassic; 3 – Middle Jurassic; 4 – Upper Jurassic; 5 – Cretaceous deposits; 6 – Paleocene and Eocene.



Fig. 2-6. Calculated amplitudes of the 'neotectonic uplift' in case of profile 12 (Chiaur zone) (modified after [Yakovlev, 2012c]). 3GM – Transcaucasian Median Massif. Distances and depths are given in kilometers; the boundaries of the main stratigraphic units, shortening values (stage 2), positions of the virtual top of the sedimentary cover (stage 3, numbers) are shown. Three profiles show three conventional (technical) stages in the development of the structure: 1 – post-sedimentary pre-folded (pre-Oligocene), 2 – post-folded pre-orogenic (for the beginning of Sarmatian age), 3 – post-orogenic (modern) stages. 1 – Paleozoic basement; 2 – Lower Jurassic; 3 – Middle Jurassic; 4 – Upper Jurassic; 5 – Cretaceous deposits; 6 – Paleocene and Eocene.

Fig. 2-7. Example of the reconstruction of the structural cross-section by the "domain geometry" method. The part of profile 20 (North-Western Caucasus), the North is in the left, the vertical and horizontal scales are identical. 30 domains for the present-day structure and 24 for the restored structure are shown. (a) – the computer model of the structure, based on the measurements in the domains. (b) – the result of the reconstruction; the identical domains ('a' and 'b') are connected by the thin lines. (c) – the scheme of the correction-type deformation in the two neighboring 'structural cells' shown by the distortions of the grid of the dotted lines (initial grid forms by the squares). The dark gray lines for (b) show the three structural cells and the stratigraphic units in them.

## 3. VOLUMES OF ERODED ROCKS OF A SEDIMENTARY COVER FOR THE MODEL OF THE GREATER CAUCASUS WITHOUT A SHORTENING OF SPACE

The main classical model of geological development and of neotectonic uplift of the Greater Caucasus has been constructed within the geosynclinal concept (Milanovsky and Khain, 1963; Milanovsky, 1968). The shortening of spaces, which may form a folding, didn't exist in the model, though the problem of structure shortening wasn't discussed in this concept especially. The time of a main folding formation of the Greater Caucasus was defined before first formations of the lower molasse, which overlapped folded sediments of the Maykop series (Oligocene: the beginning of Miocene), which usually are deposited with angular unconformity above different structures. The time of the uplift beginning of the mountain system was recognized as Sarmatian age (Early Miocene, 15 m. y.), beginning of the formation of upper molasse with conglomerates has marked this event. The map of neotectonic uplift (Milanovsky, 1968) was constructed using a "peak plain" and the peneplain surfaces, which had Sarmatian or some later age, as it was considered by E.Milanovsky. Amplitudes of the uprising in this model didn't exceed 4-5 km (fig. 3-1).

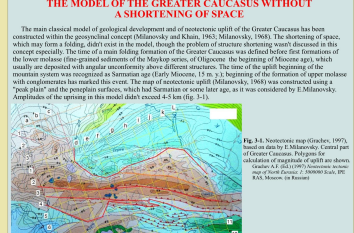


Fig. 3-1. Neotectonic map (Grachev, 1997), based on data by E.Milanovsky. Central part of Greater Caucasus. Polygons for calculation of magnitude of uplift are shown. Grachev A.F. (Ed.) (1997) *Neotectonic tectonic map of North Eurasia. 1: 5000000 Scale*. IPE RAS, Moscow. (in Russian)

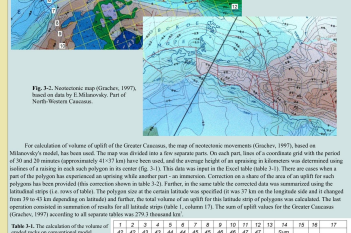


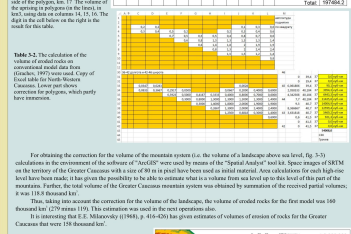
Fig. 3-2. Neotectonic map (Grachev, 1997), based on data by E.Milanovsky. Part of North-Western Caucasus.

For calculation of volume of uplift of the Greater Caucasus, the map of neotectonic movements (Grachev, 1997), based on Milanovsky's model, has been used. The map was divided into a few separate parts. On each part, lines of a coordinate grid with the period of 30 and 20 minutes (approximately 41×37 km) have been used, and the average height of an uprising in kilometers was determined using isolines of a raising in each such polygon in its center (fig. 3-1). This data was input in the Excel table (table 3-1). There are cases when a part of the polygon has experienced an uprising while another part – an immersion. Correction on a share of the area of an uplift for such polygons has been provided (this correction shown in table 3-2). Further, in the same table the corrected data was summarized using the latitudinal strips (i.e. rows of table). The polygon size at the certain latitude was specified (it was 37 km on the longitude side and is changed from 39 to 43 km depending on latitude) and further, the total volume of an uplift for this latitude strip of polygons was calculated. The last operation consisted in summation of results for all latitude strips (table 1, column 17). The sum of uplift values for the Greater Caucasus (Grachev, 1997) according to all separate tables was 279.3 thousand km³.

**Table 3-1.** The calculation of the volume of eroded rocks on conventional model (Yakovlev, Sorokin 2018), data from (Grachev, 1997) were used. The first line shows numbers of columns, the second is longitude of polygons (from 42° up to 47°, including). Columns 3-12 show amplitudes of the uprising on polygons 20 × 30 minutes of coordinate grid, before correction, in km. 13 – the latitude of the polygon in table lines. 14 The sum in the lines (for data other columns, which are not given here), 15, 16 The length of the lines of polygons (37 km), 17 The volume of the uprising in polygons (in lines), in km3, using data on columns 14, 15, 16. The digit in the cell on the right is the result for this table.

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 42 | 42 | 43 | 43 | 44 | 44 | 45 | 45 | 46 | 46 | 47 | 47 | Sum | | | | |
| 2.0 | 1.8 | 1.4 | | | | | | | | | | 5 | 40.7 | 37 | 7529.5 | |
| 2.7 | 2.7 | 1.6 | 1.0 | | | | | | | | | 7.25 | 40.7 | 37 | 10917.8 | |
| 3.0 | 6.0 | 4.0 | 1.0 | | | | | | | | | 45 | 13.8 | 40.7 | 37 | 22701.4 |
| 2.0 | 3.5 | 3.5 | 4.0 | 2.0 | 2.0 | 2.5 | 1.0 | 3.0 | 3.0 | 0.5 | | | 25.7 | 41.4 | 37 | 39307.3 |
| 2.0 | 2.0 | 2.0 | 2.5 | 3.0 | 3.0 | 3.5 | 4.0 | 3.0 | 2.5 | 2.0 | | | 28.8 | 41.4 | 37 | 44110.8 |
| 2.0 | 2.0 | 1.5 | 2.0 | 2.5 | 2.7 | 3.5 | 4.0 | 3.5 | 2.5 | 1.0 | 44 | 23.95 | 41.4 | 37 | 36696.6 |
| | | | | | 2.0 | 1.0 | 3.0 | 3.5 | 4.0 | 2.5 | | 13.3 | 42.1 | 37 | 20717.4 |
| | | | | | | | | 2.5 | 3.0 | 2.5 | | 8.75 | 42.1 | 37 | 10514.5 |
| | | | | | | | | | 3.0 | 3.5 | 43 | 4.4 | 42.1 | 37 | 6853.9 |
| | | | | | | | | | | | | Total: | | | 197684.2 | |

**Table 3-2.** The calculation of the volume of eroded rocks on conventional model data from (Grachev, 1997) by use of Excel table for North-Western Caucasus. Lower part shows correction for polygons, which partly have immersion.



For obtaining the correction for the volume of the mountain system (i.e. the volume of a landscape above sea level, fig. 3-3) calculations in the environment of the software of "ArcGIS" were used by means of the "Spatial Analyst" tool kit. Space images of SRTM on the territory of the Greater Caucasus with a size of 80 m in pixel have been used as initial material. Area calculations for each high-rise level have been made; it has given the possibility to be able to estimate what is to volume was from sea level up to this level of this part of the mountains. Further, the total volume of the Greater Caucasus mountain system was obtained by summation of the received partial volumes; it was 118.8 thousand km³.

Thus, taking into account the correction for the volume of the landscape, the volume of eroded rocks for the first model was 160 thousand km³ (279 minus 119). This estimation was used in the next operations also.

It is interesting that E.E. Milanovsky ((1968), p. 416-420) has given estimates of volumes of erosion of rocks for the Greater Caucasus that were 158 thousand km³.

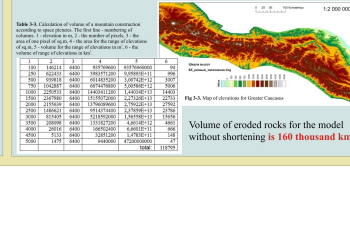


Fig. 3-3. Map of elevations for Greater Caucasus

Volume of eroded rocks for the model of balanced structure with shortening value about 80% is **826 thousand km³**

## 4. VOLUMES OF EROSION IN THE MODEL OF THE BALANCED STRUCTURE OF THE GREATER CAUCASUS

According to a technique of compilation of the balanced cross-sections of the Greater Caucasus (Yakovlev, 2017), calculations of shortening value and of amplitude of blocks uplift were carried out for 24 cross-sections with a total modern length of about 515 km (fig 4-1). Sections were constructed for the North-Western Caucasus, the Chiaur tectonic zone and the South-Eastern Caucasus (Tfan and Shakhdag zones) (Yakovlev, 2009, 2012b, 2015b). In the balanced sections, key parameters were obtained: the value of the uplift, the value of shortening, the position of the top of the sedimentary cover in the Greater Caucasus (fig. 4-1, the sign 1, zone 1) is 40-55%, on average for three tectonic zones of the east part of the Greater Caucasus (fig. 4-1, the sign 1, zone 1 and 3). The maximal values did not exceed 67%. The depth of a basement top on the Greater Caucasus is about 13-17 km, with changes from 2-5 km up to 25-30 km. For the Shakhdag, Tfan and Chiaur areas, an amplitude of a neotectonic uplift from Oligocene up to present day averaged 9.6 km (with dispersion 7.2 ÷ 12.3), 10.2 km (12.2 ÷ 24.4) and 16.1 km (9.9 ÷ 22.5) respectively (fig. 4-2). For calculation of the Northern Caucasus, estimates varied from 0 km to 22.2 km, with an average value 8.9 km.

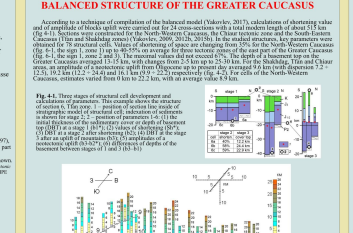


Fig. 4-1. Three stages of structural cell development and of balanced structure of the Greater Caucasus (example of section 4). Tfan zone: 1 – position of uplifts (on angle of stratigraphic roofs of structural cell), indentations of segments is shown (for stages 2, 3 – positions of indentations 1-6 - (1) the initial thickness of the sedimentary cover on depth of basement top, (2) the value of shortening (%), (3) the value of uplift, (3) DH1 at a stage 2, after shortening (%), (4) DH2 at the stage 3 after an uplift of mountains (m), (5) amplitudes of a neotectonic uplift (km), (6) differences of depths of the basement between slopes of 1 and 3 (6)–(6)1

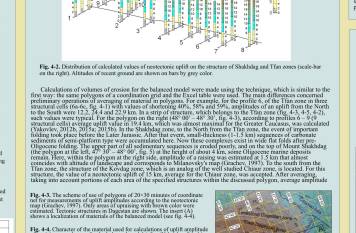


Fig. 4-2. Distribution of calculated values of neotectonic uplift on the structure of Shakhdag and Tfan zones (scale-bar on the right). Altitude of recent ground are shown on the top gray-color

Calculations of volumes of erosion for the balanced model were made using the technique, which is similar to the first way: the same polygons of a coordination grid and the Excel table were used. The main differences concerned preliminary operations of averaging of material in polygons. For example, for the profile 6, of the Tfan zone on three structural cells (no.6c, fig. 4-1) with values of shortening 40%; 58% and 59%, amplitudes of an uplift from the North to the South were 12.2, 24.4 and 22.9 km. In a strip of structure, uplift belongs to the Tfan zone (fig. 4-3, 5-6-7), such values were typical. For the polygon on the right, the value of uplift was 22.9, accounted in profile 6. Thus, averaging of values of uplift for the three structural cells (12.2 + 24.4 + 22.9 / 3 = 19.8) was almost material for the polygon, which was calculated (Yakovlev, 2012b, 2015a, 2015b). In the Shakhdag zone, to the North from the Tfan zone, the event of important folding took place before the Later Jurassic. After that event, small-thickness (1-1.5 km) sequences of carbonate sediments of series platform type were accumulated here. Now these complexes exist in wide The folds after pre-Oligocene folding. The upper part of all sedimentary sequences is eroded poorly, and on the top of Mount Shakhdag (Yakovlev, 2015b, p. 25-26, fig. 4-1, profile 12) the Lower Jurassic sediments with a small thickness of sediments remain. Here, within the polygon at the right side, amplitude of a raising was estimated at 2.5 km that almost coincides with altitude of landscape and corresponds to Milanovsky's map (Grachev, 1997). To the south from the Tfan zone, the structure of the Kovdag zone, which is an analog of the well studied Chiaur zone, is located. For this structure, the value of a neotectonic uplift of 15 km, average for the Chiaur zone, was accepted. After averaging, taking into account portions of each area of the specified structures within the discussed polygon, average amplitude

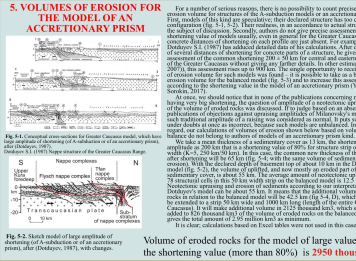


Fig. 4-3. The scheme of use of polygons of 20×30 minutes of coordinate net for measurements of uplift amplitudes according to the neotectonic map (Grachev, 1997). Only areas of uprasing with brown color were estimated. Tectonic structures in Dagestan are shown. The inset (A) shows a localization of materials of the balanced model (see fig. 4-4).

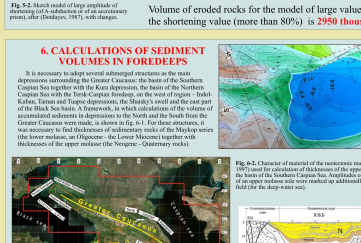


Fig. 4-4. Character of the material used for calculations of uplift amplitude of a raising on polygons for the balanced model (after [Yakovlev, Sorokin, 2016]). Bottom of polygons of 20×30 minutes of the coordinate net, tectonic zones and the areas of distribution of a different age sediments are shown. (1) – the value of a raising in the polygon (in meters), (2) – different tectonic zones, (3) – the line of a structural section, (4) – numbers, structural cells, their borders and indentation (A, B, C), shortening values are shown in a grey-colored rectangular (see a scale below on the left). 1 – The borders between tectonic zones (Shakhdag, Tfan, Kovdag zones) and large faults (MCF – Main Caucasian Fault, MdF – Mukhaversi thrust)

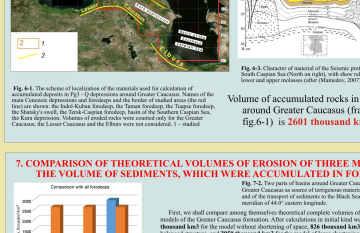


Fig. 4-5. The scheme of localization of the materials used for calculation of volumes of erosion for the balanced structure of the Greater Caucasus (example of the west Caucasian section). Tectonic structures and the border of studied areas (the red line) are shown: the Indol-Kuban foredeep, the Taman foredeep, the Tuapse foredeep, the Shatsky's swell, the Terek-Caspian foredeep, basin of the Southern Caspian Sea, the Kura depression. Volumes of eroded rocks were counted only for the Greater Caucasus; the Lesser Caucasus and the Elburs were not considered. 1 – studied

Volume of eroded rocks for the model of balanced structure with the shortening value about 50% is **826 thousand km³**

## 5. VOLUMES OF EROSION FOR THE MODEL OF AN ACCRETIONARY PRISM



Fig. 5-1. Conceptual cross-sections for Greater Caucasus model, which kind of a tectonic structure is considered: (a) a subduction or of an accretionary prism (after [Dotduyev, 1986]).
Dotduyev S.I. (1987) Nappe structure of the Greater Caucasus. Range



Fig. 5-2. Sketch model of large amplitude of shortening (of A-subduction or of an accretionary prism), after (Dotduyev, 1987), with changes.

For a number of serious reasons, there is no possibility to count precisely the erosion volume for structures of the A-subduction models or an accretionary prism. First, models of this kind are speculative; their dedicated structure has too contrast a configuration (fig. 5-1, 5-2). Their realness, in an accordance to actual structure, is very low. Second, in the literature, there are no data about a real amplitude of a shortening value of models usually, even in general for the Greater Caucasus, and concrete distances of shortening on each profile are just absent. For example, Dotduyev S.I. (1987) has adduced detailed data of his calculations. After declaration of several distances of shortening for concrete parts of a structure, he gives an amplitude of a shortening equal to 200 km (fig. 5-2). But he has not given estimates of the Greater Caucasus without giving any further details. In other estimates [Ukrainov, 2007], this assessment rises up to 900 km. The single opportunity to receive amount of erosion volume for such models was found – it is possible to take as a basis the erosion volume for the balanced model (fig. 5-3) and to increase this assessment on a value of a shortening value in the model (in an accretionary prism [Yakovlev, Sorokin, 2017]).

At once, we should notice that in none of the publications concerning models having very big shortening, the question of amplitude of a neotectonic uprasing, so of the volume of eroded rocks was discussed. If to judge based on an absence in such publications of any discussion of a problem of a neotectonic uprasing, it is possible to be such traditional amplitude of a raising was considered as normal. It gives such views under doubts at once as incorrect, because such models are unbalanced. In this regard, our calculations of volumes of erosion shown below based on volumes balance do not belong to authors of models of an accretionary prism kind.

For example, for the model of a large shortening (80%) and of a large amplitude at 200 km that is a shortening value of 80% for structure strip of 50 km width (K=5, 250 km/50 km). In this case, the common new thickness of the cover after shortening will be 65 km (fig. 5-4, with the same volume of sediments without erosion). With the declared depth of basement top of about 10 km in the Dotduyev's model (fig. 5-4, B), the volume of eroded rocks of the balanced model, for the sedimentary cover, is about 55 km. The average amount of neotectonic uplift for all 78 structural cells in this 50 km width strip on the balanced model is 12.5 km. Neotectonic uprasing and erosion of sediments according to our structures of Dotduyev's model can be about 55 km. It means that the additional volume of eroded rocks for the Dotduyev's model (fig. 5-4, B) is 55 km × 250 km × 50 km. This value can be extended to a strip 50 km wide and 1000 km long (length of the entire Greater Caucasus). It will make additional volume in 2125 thousand km3, which should be added to 826 thousand km3 of the volume of eroded rocks on the balanced model. It gives the total amount of 2.95 million km3 as minimum.

It is clear, calculations based on Excel tables were not used in this case.

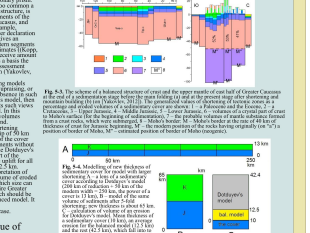


Fig. 5-3. The scheme of a balanced structure of crust and the upper mantle of east half of Greater Caucasus at the end of a deformation stage before the main folding (a) and at the present stage after shortening and formation of a "root" (b). 1 – the upper crust, 2 – the upper mantle, 3 – the contact between the upper mantle and lower crust, 4 – the contact between the upper crust and the upper mantle, 5 – Kura depression, 6 – Lesser Caucasus, 7 – Upper Jurassic, 8 – Middle Jurassic, 9 – Lower Jurassic, 6 – volumes of a crystal part of crust in Moho's stage, for the beginning of subsidence, 7 – the possible volume of sediments and volume from a crust rocks, which were subducted, 8 – Moho's border, 9 – Moho's border at the rate of 40 km of a shortening value, 10 – the contact between the upper mantle and lower crust, 11 – the shortening value for 78 % (a – position of border of Moho, M' – estimated position of border of Moho (suspect).

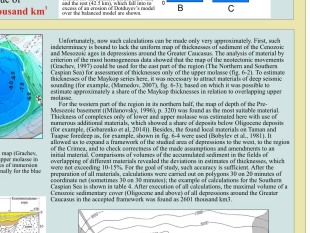


Fig. 5-4. Modelling of new thickness of a sedimentary cover (for a large shortening value) and of a volume of erosion according to Dotduyev's model (200 km of reduction = 80 km of the modern width = 250 km, the power of a cover is 13 km, the depth of a basement top is 10 km, the value of shortening after 5-fold shortening; new thickness is about 65 km. (A) – the scheme of a balanced structure for Dotduyev's model. Mean thickness of a sedimentary cover (10 km), an average value of a uplift (12.5 km), and the depth of a basement top (10 km). (B) – the scheme of a section of Dotduyev's model over the balanced model are shown.

Volume of eroded rocks for the model of large value of the shortening value (more than 80%) is **2950 thousand km³**

## 6. CALCULATIONS OF SEDIMENT VOLUMES IN FOREDEEPS

It is necessary to adopt several submerged structures as the main depressions surrounding the Greater Caucasus: the basin of the Southern Caspian Sea together with the Kura depression, the basin of the Northern Caspian Sea with the Terek-Caspian foredeep, on the west of region – Indol-Kuban, Taman and Tuapse depressions, the Shatsky's swell and the east part of the Black Sea basin, a Transcaspian, in which calculations of the volume of accumulated sediments in depressions to the North and the South from the Greater Caucasus were made, is shown in fig. 6-1. For these structures, it was necessary to find thicknesses of sedimentary rocks of the Maykop series (the lower molasse, an Oligocene – the Lower Miocene) together with thicknesses of the upper molasse (the Neogene - Quaternary rocks).



Fig. 6-1. The scheme of localization of the materials used for calculation of volumes of erosion for the balanced structure of the Greater Caucasus (example of the west Caucasian section). Tectonic structures and the border of studied areas (the red line) are shown: the Indol-Kuban foredeep, the Taman foredeep, the Tuapse foredeep, the Shatsky's swell, the Terek-Caspian foredeep, basin of the Southern Caspian Sea, the Kura depression. Volumes of eroded rocks were counted only for the Greater Caucasus; the Lesser Caucasus and the Elburs were not considered. 1 – studied

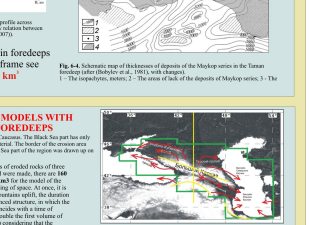


Fig. 6-2. Character of material of the neotectonic map (Grachev, 1997) used for calculation of thicknesses of the upper molasse in the basin of the Southern Caspian Sea. Amplitudes of immersion of an upper molasse sole were marked up additionally for the blue field (for the deep-water sea).

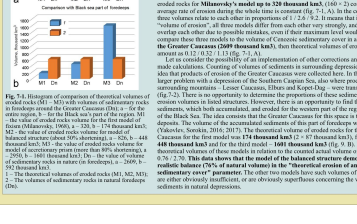


Fig. 6-3. Character of material of the Sorokin profile across South Caspian Sea (North on right), with show relation between lower and upper molasses (for Mamedov, 2007).

Volume of accumulated rocks in foredeeps around Greater Caucasus (frame see fig.6-1) is **2601 thousand km³**

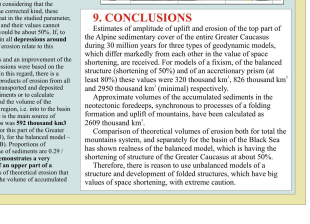


Fig. 6-4. Schematic map of thicknesses of deposits of the Maykop series in the Taman foredeep (after (Bobylev et al., 1981), with changes).
1 – The topaphytes, mantes; 2 – The area of lack of the deposits of Maykop series; 3 – The

Unfortunately, now such calculations can be made only very approximately. First, such estimation is bound to lack the uniform map of thicknesses of sediment of the Cenozoic and Mesozoic ages in depressions around the Greater Caucasus. The analysis of material by criterion of the most homogeneous data showed that the map of the neotectonic movements (Grachev, 1997) could be used for the east part of the region (The Northern and Southern Caspian Sea) for assessment of thicknesses only of the upper molasse (fig. 6-2). To estimate thicknesses of the Maykop series here, it was necessary to attract materials of deep seismic sounding (for example, [Murashev, 2007], fig. 6-3); based on which it was possible to estimate approximately a share of the Maykop thicknesses in relation to overlapping upper molasse.

For the western part of the region in its northern half, the map of depth of the Pre-Cambrian basement surface (Bobylev et al., 1981) was used as the main initial material. Thickness of complexes only of lower and upper molasse was estimated here with use of numerous additional materials, which showed a share of deposits below Oligocene deposits (for example, (Gorbatenko et al.), 2014). Besides, the found local anomalies in Taman and Tuapse foredeep as, for example, shown in fig. 6-4 were used (Bobylev et al., 1981). It allowed us to compile a framework of the studied areas of depressions to the south, to the region of the Crimea, and to check correctness of the made assumptions and amendments to an initial material. Comparisons of volumes of the accumulated sediment in the fields of overlapping of different materials revealed the deviations in estimates of thicknesses, which were not exceeding 10-15%. For the goal of study, such accuracy is sufficient. After the preparation of all materials, calculations were carried out on polygons 30 on 20 minutes of a coordinate net, which were summed up on next step. Volume of sediments in the basin of the Caspian Sea is shown in table 4. After execution of all calculations, the maximal volume of a Cenozoic sedimentary cover (Oligocene and above) of all depressions around the Greater Caucasus in the accepted framework was found as 2601 thousand km³.

## 7. COMPARISON OF THEORETICAL VOLUMES OF ERODED ROCKS WITH THE VOLUME OF SEDIMENTS, WHICH WERE ACCUMULATED IN FOREDEEPS




Fig. 7-1. Histogram of comparison of theoretical volumes of eroded rocks (M1 – M3) with volumes of sedimentary rocks (M4) in foredeeps around Greater Caucasus (fig. 6-1). a – entire region, b – for the Black sea's part of the region. M1 – the value of eroded rocks volume for the first model of fixism (Milanovsky, 1968), a – 320, b – 179 thousand km3; M2 – the value of eroded rocks volume for model of balanced structure (about 50% shortening), a – 826, b – 448 thousand km3; M3 – the value of eroded rocks volume the model of a large shortening value (about 80%), a – 2950, b – 1601 thousand km3; Dn – the value of volume of sedimentary rocks in nature (in foredeeps), a – 2609, b – 592 thousand km3.
1 – The theoretical volumes of eroded rocks (M1, M2, M3); 2 – The volumes of sedimentary rocks in natural foredeeps (Dn).

Fig. 7-2. Tracks of Sorrie around Greater Caucasus: The Black Sea part has only Greater Caucasus as source of terrigenous material. The border of the erosion area and of the transport of sediments to the Black Sea part of the region was drawn up on meridian of 44.0° eastern longitude.

First, we shall compare among themselves theoretical complete volumes of eroded rocks of three models of the Greater Caucasus formation. After calculations in initial kind were made, there are **160 thousand km3** for the model without shortening of space, **826 thousand km3** for the model of the balanced structure, and **2950 thousand km3** for the model of large shortening of space. At once, it is necessary to input one important correction. For Milanovsky's model of mountains uplift, the distribution of an uprising and erosion is 15 million years, unlike the model of the balanced structure, in which the volume of erosion was formed **for 30 million years**. The latter amount coincides with a time of accumulation of eroded rocks in depressions. Therefore it is necessary to double the first volume of eroded rocks for **Milanovsky's model up to 320 thousand km3.** (160 × 2) considering that the average rate of erosion during the whole time is constant (fig. 7-1, A). In the corrected kind, these three volumes relate to each other in proportions of 1 / 2.6 / 9.2. It means that in the studied parameter, "volume of erosion", all three models differ from each other very strongly, and their values cannot overlap each other due to possible mistakes, even if their maximum level would be about 50%. If, to compare these three models to the volume of Cenozoic sedimentary cover in all **depressions around the Greater Caucasus (2609 thousand km3)**, then theoretical volumes of erosion relate to this amount as 0.12 : 0.32 : 1.13 (fig. 7-1, A).

Let us consider the possibility of an implementation of other corrections and an improvement of the model calculations. Counting of volumes of sediments in surrounding depressions were based on the idea that products of erosion of the Greater Caucasus were collected here. In this regard, there is a large problem with a deposition of the Southern Caspian Sea, also where products of erosion from all surrounding mountains – Lesser Caucasus, Elburs and Kopet-Dag – were transported and deposited (fig.7-2). There is no opportunity to determine the proportions of these sediments, so to calculate erosion volumes in listed structures. However, there is an opportunity to find the volume of the sediments, which both accumulated, and eroded for the western part of the region, i.e. into to the basin of the Black Sea. The idea consists that the Greater Caucasus for this space is the main source of deposits. The volume of the accumulated sediments of this part of foredeeps was **592 thousand km3** (Yakovlev, Sorokin, 2016; 2017). The theoretical volume of eroded rocks for this part of the Greater Caucasus for the first model was **174 thousand km3** (2 × 87 thousand km3), for the balanced model **448 thousand km3** and for the third model – **1601 thousand km3** (fig. 9. B). Proportions of theoretical volumes of these models in relation to the counted actual volume of sediments are 0.29 / 0.76 / 2.70. **This data shows that the model of the balanced structure demonstrates a very realistic balance (76% of natural volumes) in the "theoretical erosion of an upper part of a sedimentary cover" parameter.** The other two models have such volumes of theoretical erosion that are either obviously insufficient, or are obviously superfluous concerning the volume of accumulated sediments in natural depressions.

## 9. CONCLUSIONS

Estimates of amplitudes of uplift and erosion of the top part of the Alpine sedimentary cover of the entire Greater Caucasus during 30 million years for three types of geodynamic models, which differ marked