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Common principles of construction of 3D structural model for sedimentary cover of the hinterland part of a thrust-folded belt and the results of its first application to the North-West Caucasus

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Geodynamic models of the fold-thrust belt formation process in their geological parts are based on the geometric interpretations of the structures, which can be observed and measured on the Earth's surface. Such operations are reliable for foreland parts of belts, because of the well-known balanced cross-section methods. However, there are no similar reliable methods for a hinterland, whose structure consists of numerous "similar" morphological-type small folds, whereas these folds can provide information needed for full description of existing deformations in the hinterland. This means that the most common reconstruction can be performed based on studying of fold formation processes, step by step, from small to large structures.

The method of reconstruction is based on the system of seven hierarchic levels of linear fold structures [Yakovlev, 1997; Rebetsky et. al., 2004]. The main property of the objects is that they occupy the layered volume, in which certain mechanisms act. The objects are 1) intra-layer objects (grains and objects for strain-analysis), 2) separate folds (layers), 3) domains (unit of folds in the package of layers), 4) structural cells (locale anticlinoria as joints of domains, formed in sedimentary cover), 5) tectonic zones (usual structures as joints of structural cells in the scale of part of Earth's crust), 6) a large part of the folded belt like mega-anticlinorium of the Great Caucasus, junction of several tectonic zones, 7) the whole fold-thrust belt. The descriptions of deformations are based on the conception of the deformation ellipsoid. This is widely used for description of the results of strain analysis for the volume of specimens, but not for fold and larger objects. The kinematic model of multilayer fold formation [Yakovlev, 2002] joints the results of strain analysis with shortening value of fold. It represents the basement for the description of deformation for several folds as deformation ellipsoid for a domain [Yakovlev, Voitenko, 2005].

The main geometrical parameters for each domain are the shortening value for folds in perpendicular direction to the axial surface, the dip angle of axial surface, the dip angle of envelope plane for domains part of cross-section, length of part of line of section and its tilting angle. The pre-folded state of volume of this domain can be restored due to three cinematic operation with the ellipsoid. There are 1) rotation up to horizontal position of envelope level, 2) simple horizontal shearing up to vertical position of axial surface, 3) pure shearing in horizontal axis (extension) up to folds disappear (ellipsoid became sphere after this last operation). The line of the domains part of section is changing their length and a tilting angle as the result of these operations. This line has certain position into horizontal layering [Yakovlev, 1987; 2002]. It means that this line in pre-folded state has “stratigraphic” height of started and of ended points. If the fault plane is boundary between adjacent domains, such plane can be considered as part of domain. The pre-folded inclination of the fault plane can be found by the same operations as for the domain. The difference in “stratigraphic” heights (stratigraphic throw) of end point of previous domain and start point of the next domain gives the vertical magnitude of fault displacement. The horizontal magnitude calculates from the vertical distance (throw) and the pre-folded inclination of fault plane. A set of such domains parts of cross-section lines for pre-folded states and pre-folded states of faults plains is basement for full cross-section restoration.

North-West Caucasus is located on north part of Alpine belt and it is part of linear structure of Greater Caucasus on its west edge. The structure of NWCaucasus is plunging from east to west and outcropped Mesozoic-Cenozoic stratigraphic units have age from early Jurassic up to Neogene accordingly [Milanovsky, Khain, 1963]. There are argillite- aleurolite flysch of Low-Middle Jurassic and calcareous flysch of Upper Jurassic – Paleocene. Total thickness of sedimentary cover is near 10-17 km. Layers of Maykop suite (Oligocene – Eocene) have angular unconformity with lower sediments on slopes of anticlinorium. First conglomerates take place at Sarmatian layers as evidence of started mountain building processes. Small numerous isoclinial folds of Middle Jurassic on east of region is changing to wide gentle folds of Upper Cretaceous – Eocene on the western part. The structure of the north slope of mountains (from Tuapse meridian to the East and to the North from Main Caucasian Thrust) has a particularly. The main folding for this block took place before Later Jurassic. This structure has sub-platform type of tectonic development after this time. And this area was leaved out from the our study of Mesozoic-Cenozoic folded structure. The recent opinions on development of Caucasus can be found in [Saintot et.al., 2006].

The North-West Caucasus has studied well earlier in aspect of folding formation research [Giorgobiany, Zakaraya, 1989; Sholpo et.al., 1993] and 11 cross-sections were drawing based on measurements of fold geometry just in outcrops. These sections were used for our 3-D model construction. Westerns cross-section were compiled by T.Giorgobiany (from 1, Abrau-Dyurso - to 4, Dzhubga) and eastern ones (from 5, Tuapse – to 11, Krasnaya Polyana) were compiled by Ye. Rogozhin. Total length of cross-sections was 347 km on the area near 250 km x 50 km. These cross-sections were divided on 244 domains. Unfortunately, the information about layers morphology in small folds was absence. Therefore the angle between flanks of fold was used for shortening value estimation. This data and all other necessary parameters were measured in each domain. All 11 cross-sections were preliminary restored and total pre-folded length was 535 km.

The next stage of 3D models compiling was collecting of the data about thicknesses of all stratigraphic units for different tectonic zones. Sufficient different of thicknesses of several tectonic zones were putted in table of Excel as parameters of each domain. Thus, each domain was characterized by full list of stratigraphic units and all thicknesses. The “stratigraphic level” for any strata is depth from “0” (bottom of Maykop suite), which calculated by summarizing of all Mesozoic- Cenozoic units thicknesses above the strata. If some information was absence, this gap was filled by extrapolation or interpolation of data of thicknesses from the same tectonic zone in other sections. For instance, the Low Jurassic units thickness were taken for the western part of structure (in which Eocene layers outcrops only) from central and eastern cross-sections. Such full information allows correcting the preliminary restorations of cross-sections in aspect of “stratigraphic height” and new faults magnitudes.

After this stage the shortening value for each domain can be obtained. But sufficient deviations (due to disharmonic structure) show that common tectonic shortening can be calculated for jointed several domains only. Usually the unit between core of local anticlinorium and core of local synclinorium is free from a disharmonic influence. It is the distance across structure (its width) near 0.7-1.0 of total thickness of sedimentary cover. All restored cross-sections were divided on such 42 “tectonic cells” basing on this opinion. The initial width of each structural cell was near 10-17 km, and each time it was almost equal to total sedimentary cover thickness.

The shortening values of total sedimentary cover were calculated for these 42 cells as ratio of recent length of sections line and the pre-folded length of the same part of cross-section (Sh=L1/L0). The shortening values of total cross-sections (“recent”/”pre-folded” lengths) from West to East (numbers from 1 to 11) and for structural cells (from North to South for each cross-section) are: (1) 0,84=41,6 km/49,8 km (1,07; 0,62; 0,88); (2) 0,88=36,1/41,0 (1,10; 0,69; 0,89); (3) 0,67=55,3/82,3 (0,77; 0,78; 0,63; 0,64; 0,69; 0,47); (4) 0,68=48,7/71,7 (0,98; 0,63;

0,75; 0,48; 0,48); (5) 0,48=39,4/82,4 (0,67; 0,61; 0,39; 0,33; 0,40); (6) 0,49=13,2/27,0 (0,49; 0,49); (7) 0,60=34,9/58,4 (0,56; 0,73; 0,66; 0,55; 0,49); (8) 0,62=34,4/55,6 (0,54; 0,66; 0,36; 0,77; 0,84); (9) 0,61=11,1/18,1 (0,49; 0,69); (10) 0,68=27,2/40,1 (0,37; 0,65; 0,80; 0,82; 0,83); (11) 0,59=4,9/8,3 (0,59). Coordinates for each 42 segments of sections in recent and pre-folded states were calculated in assumption that linear folds stretch in perpendicular direction of lines of cross-sections.

The combination of pre-folded coordinates of segments (i.e. structural cells as units) and collected pre-folded thicknesses of sedimentary units (bottoms of Pg_1, K_1,J_1) was enough for compiling of first 3D-model of North-West Caucasus. Of course, the exact values of levels here and for other 3D models are the results of calculations, which can be not exact (10-15 % deviation for estimates can took place). Thus, the rounded-off values and total tendency only must be taken into account. For the Cenozoic units height (depth) levels have next main features from West to East (the cells have liters from “A” at the North to “E” at the South). Section 1 (-900 m), 2 (-900m A, -1200m C), 3 (-1200), 4 (-1350), 5 (0 A, -950 E), 7 and 8 (0 A, -2500 E), 10 (-2500 A-C, -1450 E). The segments 10D and 10E are located on sub-platform Abkhazskaya tectonic zone of Transcaucasian Massif to the south from NW Caucasus main tectonic zones. It means that the trough line is located on south margin of structure. For the Cretaceous units next main values were calculated: 1 (-3050m A, -9450 B-C), 2 (-7700 A, - 9800 B-C), 3 (-6700 A, -9600 C-F), 4 (-6150 A, -8800 D-E), 5 (-4510 A-B, -8000 D-E), 7 – 8 (-4510 A, -8000 C, -6280 E), 10 (-6280 A-C, -3640 D-E). The trough line for this unit is placed on the south margin of structure for its Western part and in central line for the Eastern one. For the Jurassic units the next main values of bottoms levels were obtained: 1 (-3850m A, -16950 B – C), 2 (-15200 A, -17300 C), 3 (-14200 A-B, -17100 C-F), 4 (-13350 A, -16200 B-E), 5 (-12810 A-C, -16100 D-E), 7(-8450 A, -15100 C, 9750 E), 8 (-9100 A, -16100 C, -10750 E), 10 (-9750 A, -10750 C, -7300 E). The trough lines for this surface have main features similar Cretaceous units one. Because the Excel table of thicknesses exist, such 3D model (depth of stratigraphic levels) can be constructed much more detail – for each suite in each cell and each domain.

After the shortening (it taken place near Pg_2/Pg_3 – Pg_3 time) the new vertical thicknesses were appeared for each stratigraphic unit. The next assumptions were done: 1) the volume of cover deposits is constant and 2) the deformation along the NW Caucasus strike is absence. It means that the plane strain for cross-sections exists. The new thicknesses (and stratigraphic columns) were calculated for each stratigraphic unit in each cell. The new vertical positions (depths) were calculated for each main stratigraphic unit in each cell as function of initial thicknesses and shortening value. It was made basing on 1) the evidence that mountain building took place much more lately and 2) the extreme assumption that there was not the erosion. The recent coordinates were used for mapping. For the Cenozoic units height (depth) levels of its bottom have such main values: 1 (-841 A, -1452 B, -1023 C), 2 (-818 A, -1348 C), 3 (-1558 A, -1905 C, -1739 E, -2553 F), 4 (-1378 A, -2813 E), 5 (0 A, -2879 D, -2375 E), 7 (0 A -1439 C, -5102 E), 8 (0 A, -1439 B, -2976 E), 10 (-6757 A, -3125 C, -1725). For the Cretaceous units them are: 1 (-2860 A, -15242 B, -10739 C), 2(-7000 A, -15556 B, -11011 C), 3 (-8701 A,15238 C, -13913 E, -20426 F), 4 (-6276 A, -18542 E), 5 (-6731 A, -24242 D, -20000 E), 7 (-5446 A, 12121 C, 12816 E), 8 (-8352 A, -22222 C, -7476 E), 10 (-16973 A, -7850 C, -3976 E). The depths of Jurassic bottom levels were calculated as: 1 (-3598 A,-27339 B, -19261 C), 2 (-13818 A, -23333 B, -19438 C), 3 (-18442 A, -27143 C, -24783 E, -36383 F), 4 (-13827 A,-21600 C, -33968 E), 5 (-19119 A, -32462 C, -48788 D, -40250 E), 7 (-15089 A, -22879 C, -19898 E), 8 (-16870 A, -44722 C, -13961 D,-12798 E), 10 (-26351 A, -13438 C, -8679 E). There are three linear troughs exist in NW Caucasus with the axes in central part on the West (1B, 3C, 5D with extreme value -48,8 km), on the south margin (3E, 4E, -36,4 km) and in central-northern part on the East (7C, 8C, 10A, -44,7 km).

The average means of relief hypsometry (RH, such as 1500) and of the stratigraphic “depth” of units at the outcrops (SD such as -10000) were calculated for each domain for the next 3D model compiling. The main assumption was that mountain building process took place without sufficient horizontal shortening. The structural cell columns were upraised (UT=RH-SC=11500) so that just calculated average levels of stratigraphic unit are outcropped on the Earth surface. The value of Uprising Total (UT) is value of uplift of bottom of whole sedimentary cover, i.e. value of mountain building uplift (if erosion and a relief deformation do not exist). The recent coordinates were used for the mapping of UT and of the new (recent) positions of stratigraphic units. The values of uplifting total were next: 1 (0.3 km A, 5.3 B, 2.1 C), 2 (2.0 A, 5.5 B, 4.3 C), 3(2.3 A, 11.0 C, 4.8 F), 4 (3.4 A,13.1 B, 10.5 C, 14.7 D, 8.2 E), 5 (8.6 A, 22.6 D, 11.5 E), 7 (12.4 A, 13.9 B, 11.4 D, 12.8 E), 8 (13.3 A, 19.6 C, 6.0 D, 2.8 E), 10 (12.6 A,7.9 C, 1.5 E). For the Cenozoic units depth (height) of its bottom have such main values: 1 (-453 m A, -3883 B, -1023 C), 2 (1141 A, 4173 B, 2827 C), 3 (734 A, 9076 C, 2288 F), 4 (1973 A, 11187 B, 11868D, 5348 E), 5 (8567 A, 19700 D, 9119 E), 7 (12397 A, 8889 C, 7222 E), 8 (13298 A, -16996 C, -130 E), 10 (5877 A, 4779 C, -260 E). For the Cretaceous units the bottom levels are: 1 (-2462 A, -9907 B, -8571 C), 2(-504 A, -6987 B, -6736 C), 3 (-6409 A, -2415 C, -15585 F), 4 (-2975 A, 3131 B, -10382 E), 5 (1836 A, 4239 C, -8506 E), 7 (6951 A, 7684 B, 1-1793 C, -492 E), 8 (4946 A, -2587 C, -130 E), 10 (5877 A, 4779 C, -260 E). The depths of Jurassic bottom levels were calculated as next: 1 (-3210 A,-22004 B, -17093 C), 2 (-11859 A, -17856 B, -15163 C), 3 (-19150 A, -12030 C, -17836 E, -31542 F), 4 (-10476 A, -7146 B, -25798 E), 5 (-10552 A, -6443 B, -13710 C, -26209 D, -28756 E), 7 (-2692

A, -1905 B, -14066 C, -9615 E), 8 (-3572 A, -25087 C, -7947 D,-9952 E), 10 (-13717 A, -6742 B, -5534 C, -7615 D -7213 E). Three linear troughs exist in NW Caucasus with the axes in central part on the West (1B, 2B with extreme value -22,0 km), on the south margin (3E, 4E, 5E maximal -31,5 km) and in central-northern part on the East (7C, 8C, 10A, -25,1 km).

These values of depth of bottom of sedimentary cover (level of J_1bottom) are rather dipper then the depths (5- 10 km) in usual models of structure of Greater Caucasus [Robinson, 1996, Dotduyev, 1987]. These models are based on conventional scheme of A-subduction for collision structures. But these models don't take into account the idea to keep the volume of sedimentary cover during the reconstruction of deep structure of Caucasus. From this point of view such kind of cross-sections are not balanced. There is geophysical cross-section Tuapse - Armavir [Shempelev et.al., 2001], which is analog of our section 5. The boundary of "sedimentary cover" – "metamorphic basement" by these geophysical data has depths near 5, 17, 25 km from North to South and it is almost equal to our data based on geological observations.

Some thrust-fold structures were selected as typical for a hinterland during the process of data collection and processing for NW Caucasus and some other parts of Caucasus. There are two for example. There is large scale fault on the hinterland-foreland boundary [Yakovlev, 2006], which has thrust movement at its top part and sufficient magnitude of normal fault on the bottom of sedimentary cover. The second is fault on the boundary of two tectonic zones, whose thickness of stratigraphic units are very different. The magnitude of low angle thrusting from small sediments thickness block to large thickness block can be calculated as not very large under this property consideration.

The result of this 3D modeling can be used for calculations of sedimentary units volumes and for eroded volumes of sediments also.

Conclusion. The base principles of 3D structural models construction were founded and realized. Three stages of NW Caucasus tectonic development were illustrated by 3D models. There are pre-folded state, post-folded (before mountain building state) and orogenic one (mountain building without shortening, recent). Thus the main structural properties of real collision object in size of mega-anticlinorium were described. The obtained depths of top of metamorphic basement were rather dipper then which are used in conventional models. The especial map was constructed also for uplifting magnitude of bottom of sedimentary cover for the movements which took place since post-folded state.

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