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**RECONSTRUCTION  
OF FOLDED AND FAULTED STRUCTURES  
IN ZONES OF THE LINEAR FOLDING  
USING STRUCTURAL CROSS-SECTIONS**

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**Yakovlev F. L. Reconstruction of folded and faulted structures in zones of the linear folding using structural cross-sections** / Moscow: Published in IPE RAS, 2017, 60 p. / 65 color figures and tables; references 32 titles, compact disk (in Russian)  
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The technique of balancing (restoration) of structure of the linear folded systems by "the geometry of folded domains" for structural cross-sections is described in details. Such balanced cross-sections are created for three stages of development of structure: for pre-folded, post-folded and post-mountain-building (present day). Balancing of structure is carried out for conditions of a constancy of volume of sedimentary cover of a hinterland (10-15 km of thickness), taking into account the value of its fold-related horizontal shortening. The text of description is accompanied by a full package of structural materials, all computer programs, of files of the Excel tables for computation, etc. All explanations of technique are made on the example of initial natural structural materials, which are presented by three profiles across one of folded zones of Greater Caucasus. In the folded structure, the objects of several hierarchical levels are distinguished, such as "folds" (of 10–500 m width), "folded domains" (0.5–2 km), "structural cells" (5–7 km), "tectonic zones" (10–30 km). These levels are tied to a certain volume of the layered medium embraced by them. Requirements to the initial natural material, which is used in a technique, are described. Measurements of key parameters of structure in "the folded domain" are shown. Theoretical bases of a technique and all main restoration operations of parameters of the pre-folded domain, an aggregation of these pre-folded domains in volume of entire sedimentary cover (for "structural cells") are explained. Calculation operations of value of horizontal shortening, depth of top of the metamorphic basement, a volume of eroded rocks of the upper part of a sedimentary cover and amplitude of neotectonic uplift for "structural cells" are explained. Possibilities of creation of quasi-3D models of structure of a folded sedimentary cover are demonstrated based on these materials. Such models were created for three stages of structure development.

The book is intended for independent leaning of the method of folded structure restoration by specialists in structural geology and tectonics. It may also be used for advanced training courses for geologists, students and graduate students in the courses "structural geology" and "geotectonics".

**Яковлев Ф.Л. Реконструкция складчато-разрывных структур в зонах линейной складчатости по структурным разрезам.** М.: Изд. ИФЗ РАН, 2017. 60 с. / 65 цвет. рис. и табл.; список литер. 32 назв., компакт диск

Детально описана методика балансирования структуры комплексов линейной складчатости по «геометрии складчатых доменов» для структурных разрезов. Такие сбалансированные разрезы строятся для трех стадий развития структуры: доскладчатой, постскладчатой и посторогенной (современной). Балансирование структуры проводится для условий постоянства объема всего осадочного чехла хинтерланда (10–15 км мощности) с учетом величины ее соскладчатого горизонтального сокращения. Текст описания сопровождается полным набором структурных материалов, всех компьютерных программ, файлов таблиц Excel для вычислений и т.д. Все объяснения основного метода делаются на примере трех первичных структурных профилей через одну из складчатых зон Большого Кавказа. В складчатой структуре выделяются объекты нескольких иерархических уровней – «складки» (ширина 10–500 м), «складчатые домены» (0.5–2 км), «структурные ячейки» (5–7 км), «тектонические зоны» (10–30 км), которые связаны с определенным объемом охватываемой ими слоистой среды. Описаны требования к исходному природному материалу, который используется в методике, показаны процедуры замеров основных параметров структуры в «складчатом домене», даны теоретические основы методики и основные операции восстановления параметров доскладчатого домена, объединения этих материалов в объеме всего осадочного чехла (для «структурных ячеек»). Объяснены операции определения величины горизонтального сокращения, глубины кровли фундамента, объема размытых пород верхней части чехла и амплитуды неотектонического поднятия для «структурных ячеек». Продемонстрированы возможности построения квази-трехмерных моделей структуры складчатого осадочного чехла для трех стадий развития на основе этих материалов.

Книга предназначена для самостоятельного освоения метода балансирования складчатой структуры структурными геологами и тектонистами. Она может быть использована также в курсах повышения квалификации геологов, для обучения студентов старших курсов и аспирантов по предметам «структурная геология» и «геотектоника».

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## **1. Introduction**

The main objective of writing of the this work consists in acquaintance of everyone with the general ideas and technology of a method of balancing of structural sections of complicated folded structures of internal areas of fold and thrust belts. The chosen form of presentation in the form of the “direction for use” gives also the chance of testing of a method by the qualified researchers. Detailed statement of material and availability of all necessary software and of initial structural materials on the enclosed compact disk and on the Internet resource specified at the end of the book allows to use this book in the educational purposes in courses of structural geology and tectonics.

Initial structural information for reconstruction of folded and faulted regional structure has to represent well registered structure with folds and faults (i.e. – its documentary geometry) along the line of a profile which crosses big blocks of structure or an entire hinterland in a mobile belt. As a theoretical basis of a method, the ideas of definition of type and size of deformation in multirank structures are used [Yakovlev, 2008a]. The main method of restoration of structure or of a drawing up the balanced cross sections on the scale of entire sedimentary cover is the method of "geometry of folded domains" [Yakovlev, 1987, 2009, 2012b, 2015a, 2015b]. The expected results of actions of the researcher within the described method are folded and faulted structure in pre-folded and in modern types; shortening value for parts of structural sections (on the scale of "structural cells"); prediction (forecast) of continuation of modern structure for depth (data about depths of the basement top on the scale of "structural cells" or for entire sedimentary cover) and in "air", namely – the "virtual" or theoretical thickness of that part of a sedimentary cover which was eroded during a folding formation and a neotectonic uplift of a structure.

Statement of a method is given on the concrete natural structural material presented by three structural profiles in scale of 1:100000, which were compiled by the author [Yakovlev, 1997] in the Chiaur tectonic zone of Greater Caucasus (South Ossetia and North Ossetia). The material is a part of set of 24 structural profiles located in three regions of Greater Caucasus [Yakovlev, 2015a]. Meaning first methodical research objectives, data on structure and history of development of the Chiaur zone and all Greater Caucasus aren't cited here and not discussed. This well-known material is stated in a number of works [Milanovsky, Hain, 1963; Milanovsky, 1968; Yakovlev, 1987, 1997, 2012b, 2015a; Sholpo, etc., 1993; Leonov, 2007; Saintot et al., 2006]. The received results have an appearance of a number of numerical parameters. It can be used for a research of geodynamic processes of formation of structures, for example, of Greater Caucasus [Yakovlev, 2015a; Yakovlev, Gorbatov, 2016; Yakovlev, Sorokin, 2016], but in this work, the purposes of discussion of these prospects also were not set.

## **2. Requirements specified to natural structural material**

The described method may be applied to folded structure of internal parts of mobile belts: it have to be blocks of small intensive folds of a hinterland, but not large folds and thrust of a foreland or foothill basins. Type of sedimentary rocks – flysch or flyschoid sedimentary sequences of big thickness. Usual thickness of rhythms is 0.2–1–5 meters; there are terrigenous, terrigenous and carbonate and carbonate flysch, the full thickness of a sedimentary cover is up to 10-15-20 km. In structures, the simultaneous existence of several scales of folds is possible (the sizes of 100 meters – 10 m – 1 m); also certain degree of fractality (self-similarity) of folds may takes place. Important property of structure is the

morphology of typical single folds, usually small – they have to be "similar" that means the preservation of their form far up and down in a stratigraphic unit. The concept of "an ellipsoid of deformations" is applicable to them. If large folds of "parallel" shape, at which different layers are located in circles parts of different radius with the uniform center meet in structure, then special procedures of measurement of shortening have to be applied to them.

Character of display of rocks/structure in outcrops and a degree of study of the region (study of a stratigraphy and accuracy of reflection of structure on the geological map) has to allow to observe and to document in details a large folds with width of 1-2 km. Structural sections of initial scale 1:10 000 or 1:50 000 have to be compiled on numerous measurements of elements of folds and faults directly in the field, but not according to the geological map with rare elements of a rock layering inclination. The number of measurements has to be enough in order that at measurements of structural elements in concrete folds on drawing on a profile on a paper, there was a guarantee of that the structure was constructed according to field data, but not according to representations in a mind of the author of a profile or in agreement to his hypotheses. Geological maps may be used as the source of information in a rare exception in case when divisibility of a stratigraphic column allows to reflect the main lines of folded and fault structure in the geological map (when width of typical folds is larger than a thickness of typical stratigraphic unit). The approximate ratio of structural elements at the general thickness of a sedimentary cover in 10-15 km has to be the following: from 1 to 5 folds organize the "domain" with a modern width of 0.3 - 2 km, 3-7 domains may be aggregated in a "structural cell" with a modern width of 3-7 km, 2 – 5 structural cells organize a "tectonic zone" of 10 - 30 km width. From two or three up to five tectonic zones can participate in the structure of "folded system" [Yakovlev, 2008a, 2015a, 2015b].

### **3. The main stages of receiving result – of a creation of the balanced section and a compiling of three-dimensional models of the deformed sedimentary cover**

- a. A collecting of structural material in a fieldwork or in literature, including creation of stratigraphic model of a tectonic zone or models of parts of a tectonic zone.
- b. A choice of borders of domains in cross-section. The list of types of borders for the used computer (PC) program is given.
- c. A collecting measurements of structural parameters of the domain and their averaging by means of the table Excel (DOMAIN-1.XLS).
- d. The general description of the PC program (see details in the part 5 of this book). Preparation of the PC program data file based on measurements of parameters. Description of main parts of the data file. Filling of the data file by editing in Notepad and by creation of the file during the work of the program. Fixing (establishing) of primary initial depths of entrance points (for the first point of section and for all points after faults) by using initial stratigraphic models.
- e. An explanation of operations of a kernel of the program – the restoration of the pre-folded state of a domain, evaluations of size of displacement on a fault.

- f. Obtaining of the first, preliminary version of results of calculations; main objectives and options of balancing with use of primary stratigraphic model. An illustration of work of PC program on example of materials of cross-section “Keshelta” (see part 5 of this book).
- g. Choice of structural cells in completely pre-folded section. The explanation of general principles, the description of cells in concrete structure of a cross-section “Keshelta”.
- h. Drawing up a final stratigraphic model for each cell.
- i. Final compiling (calculation) of the balanced cross-section.
- j. An explanation of common objectives of further actions for drawing up the folded and faulted structure, which is balanced on the volume of a sedimentary cover and on values of its deformation. Calculation of shortening value for structural cells. Calculation of the average altitude of a relief for cells. Calculation of average depth of the section line in stratigraphic model. Calculation of new thickness of a sedimentary cover after shortening and folding formation. Calculation of depth of the basement top, amplitude of erosion and amplitude of "a neotectonic raising".

#### **4. Main aspects of the method in preliminary stages**

##### ***4.1 Collecting of structural material in a region***

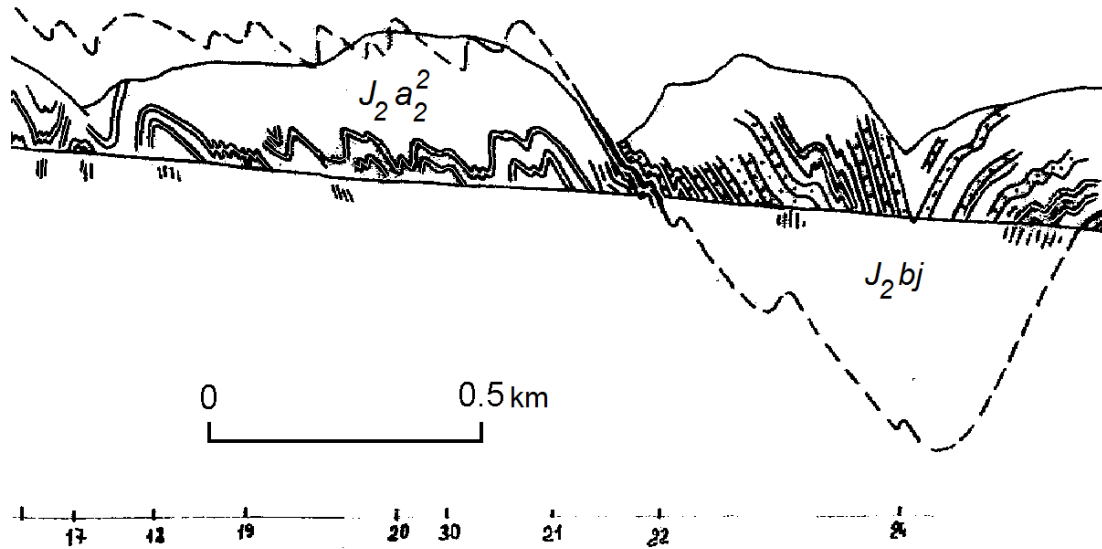
Collecting of structural material in a region is very important stage of work, because initial structural material of folded complexes morphology should be much more close to natural geometry without influence of any theoretical ideas. Main conditions for structure as object of study among other properties are existence of geological map of scale about 1:100 000, stratigraphic column with usual stratigraphic units about 0.2 – 1.0 km thickness, good quality and quantity of outcrops and existence of valleys directed across strike of structure. During the day-track along river valley or road, the geologist is finding in outcrops relatively small structures such as flysch-like layering, hinges of folds and surfaces of faults. It is necessary to draw it on picture in useful scale in field-notebook, determine key-points on this picture for measurements of fold-thrust geometry and make all measurements just in outcrops (fig. 1A).

These short sections should be fixed among exact locations on topographic map and/or to have some fixed distances for the purpose of exact reproduction of proportions of structure when drawing it on paper. The topographic map is used for compilation of base of cross-section as line of section along (bottom of) valley or along road with vertical altitudes and with some space for structure drawing along valley side. Height of this space is about 0.2-1 km for mountains regions. On the next stage, using the geological map, stratigraphic column and other materials, all groups of lithologic complexes should be identified regarding its ages and regarding its positions into morphological elements of folds and faults.

These sections should be compiled as parts of an entire structural section in certain scale (1:10 000 is preferable). This compilation should be done with using of all measurements of folds geometry (fig. 1B). This method of cross-sections compilation was

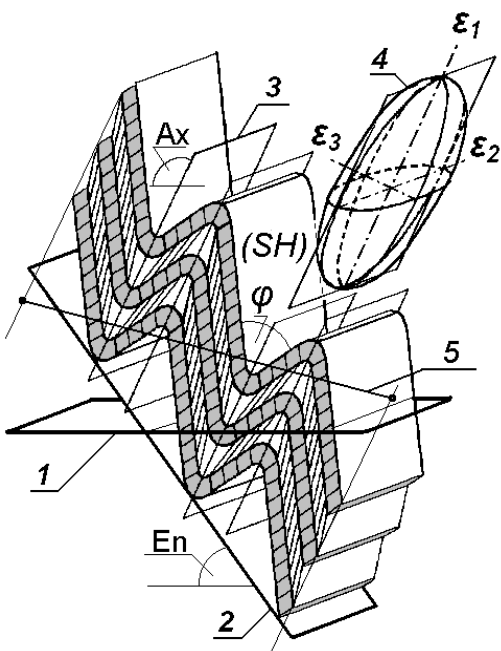


Voitenko, 2013]. An explanation of the reasons of this phenomenon and the offer on a possible method of restoration of such folds are given at the end of the book, in part 8 of the book. The most important properties of such domains are identical or close values of inclinations of axial surfaces of folds and of interlimb angles of folds. (fig. 3, A, B). If there is an essential change of one of these parameters along a profile, this place can be accepted as border of the following domain. The surfaces of large faults and boundary between stratigraphic or lithologic units can be accepted as borders also. Besides this, the condition of approximately equal volume of different domains along sections of studied structure can be criterion of installation of domains borders. Points of borders of domains should be

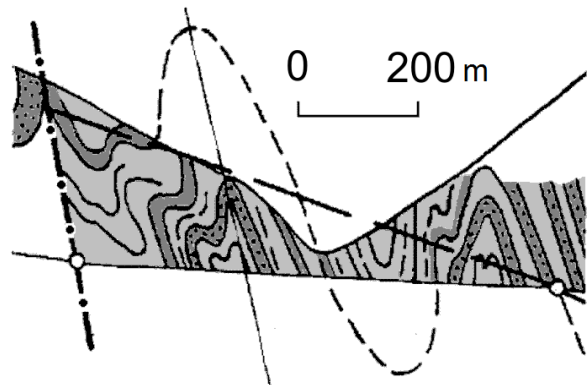


**Fig. 2.** Character of reflection of natural structure in drawn section: combination of small and large folds is observed very clear. River Kudialchay, western Azerbaijan, about 1-2 km to North from passing Salavat of main ridge of Greater Caucasus. After ([Yakovlev 2015a, p. 130, fig. 2-21], permission of coauthor Ye.A. Rogozhin for usage of part of section exists)

A



B

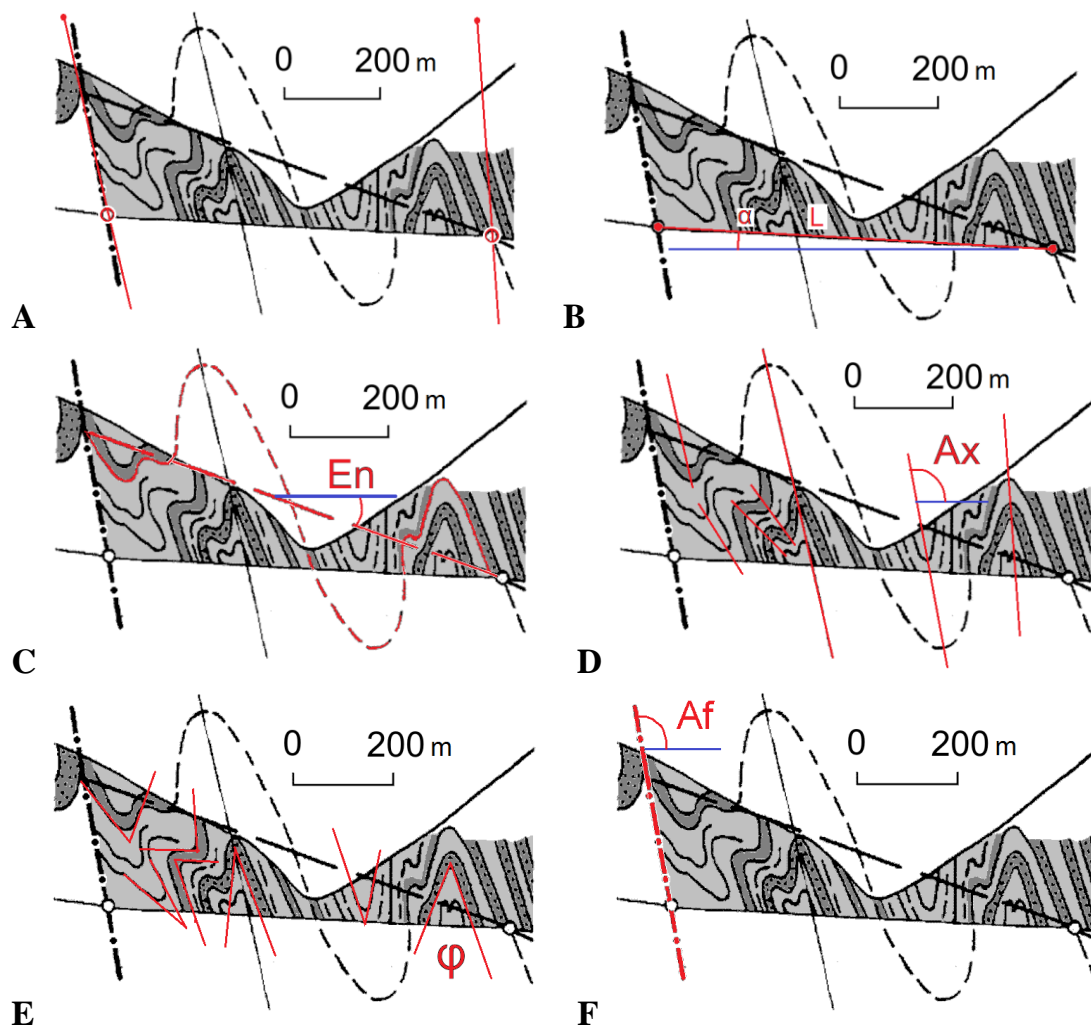


**Fig. 3.** Conception of approximation of domain morphology by strain ellipsoid (A, after [Yakovlev, Voitenko, 2005]) and kind of domain in natural structure (B, after [Yakovlev, 2012a]).

marked on the line of a profile. As a rule, it is convenient to put such end near the line of the water's edge, but its location in any place within a strip of outcrops in a slope of the valley, having usually height of 100-500 meters, is admissible. Above and below of this section line of the domain, the lines parallel to axial surfaces of folds should be laid as borders lines (Fig. 4, A, red lines). All measurements of parameters of the domain should be made in space between these lines. This way of borders installation of the domain will be justified below, in part 5 (fig. 20).

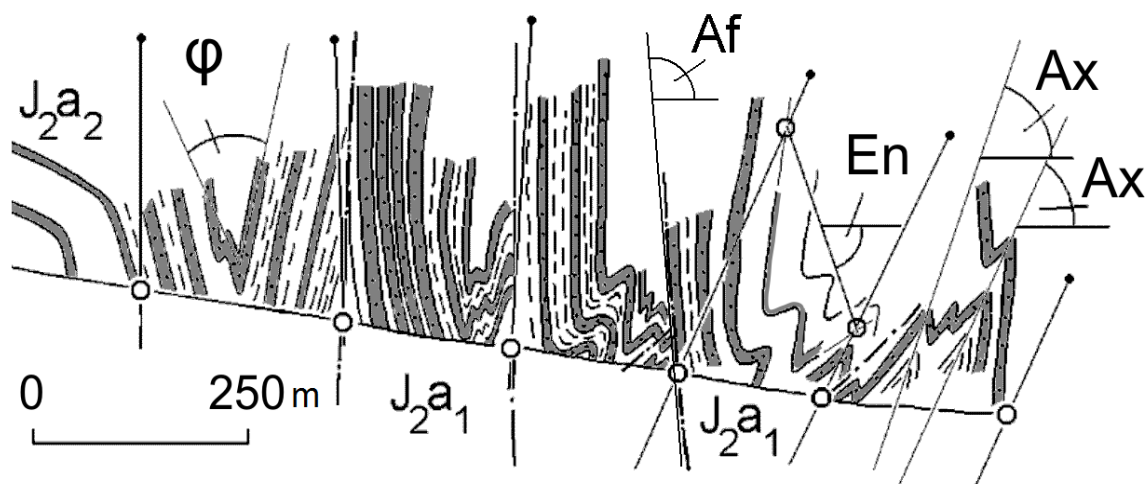
#### 4.3 Collecting of measurements of parameters of domains geometry and their averaging by using a table Excel (“DOMAIN-1.XLS”)

Elements of geometry of structure which are necessary for restoration of a pre-folded state and which are related to a strain ellipsoid have to be measured. Length of a segment of the line of a section and its dip concerning the horizon are measured in meters and degrees ( $L, \alpha$ ) (fig. 4B, red line). For measurement of an inclination of folds envelope plain, one of layers in the domain should be continued in both directions up to crossing with border lines



**Fig. 4.** Elements of domains morphology (used part of fig. 10b [Yakovlev, 2012a]). A – Boundaries of domain; B – segment of section line ( $L, \alpha$ , length and tilting); C – Envelope plain of folds and its dip (EN); D – Axial plains of folds and their dips (AX); E – Interlimb angles of folds ( $\varphi, SH$ ); F – Fault plain and its dip (Af).

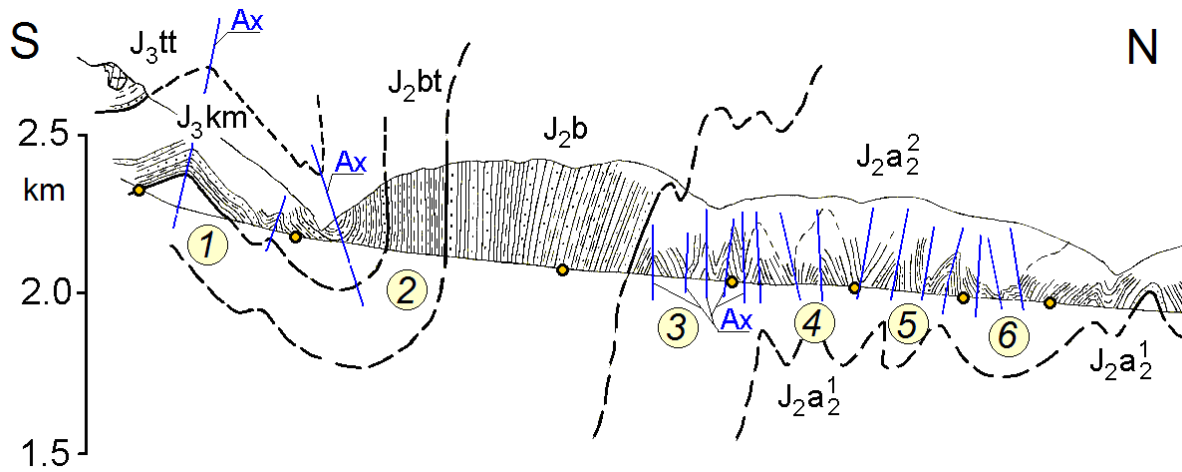




**Fig. 5.** Sequence of several domains in natural section with elements of their geometry (after [Yakovlev, 2012a] with changes).

of the domain. Then, through points of "entrance" and "exit" of this layer on the domains borders it is necessary to draw a straight line. The inclination of this line (EN) is "dip of folds envelope plain" (fig. 4B, a red layer and the line) or if absolutely precisely, this is an inclination of the line of initial layering. In the text below, non-absolutely exact but more usual term "an inclination of folds envelope plain" will be used. Inclinations of axial surfaces of almost all folds are measured. It is necessary to draw straight lines via hinges of many folds. Inclination of these lines concerning the horizon (AX, concerning line toward North, for instance, for this and for other measurements) should be measured as dips of axial plains of folds (fig. 4D). The measured inclinations for several folds are averaged; the way of averaging will be specified below. The received inclination of the axial plain corresponds to an inclination of a long axis of an ellipse of deformations (as it was considered, linear folds have 2D, plain deformation; there is no strain along hinge line). Interlimb angles of almost all folds inside domain are measured. For this purpose in many folds, two meeting lines for rectilinear parts of wings are drawn on; the angle between which ( $\varphi$ ) is measured (fig. 4E, red lines). These angles will be transformed to the shortening values (SH) in perpendicular direction to the axial plain; it reflect short axis of strain ellipse. Formulas and a way of averaging will be shown below. If the border of the domain is the fault, the inclination of plain of displacement (Af) of this fault has to be measured (fig. 4F). In part of section (fig. 5), some domains with the measured geometry elements are shown as examples of such kinds of structures.

There are two kinds of techniques of measuring: by hands using image on paper and by usage of AUTOCAD processor. For the "paper" version two sheets of image of section are using for drawing of lines and measuring: 1) for measuring of  $L$ ,  $\alpha$  - of length and tilting of section line for each domain; for EN; and for interlimb angles of folds ( $\varphi$ , SH), 2) for measuring of AX and Af parameters (fig. 6). Each measured value AX should be written on paper under domain and then should be setting to table "domain-1.xls" (fig. 7). In the same table on the left part all data of domains parameters are collecting (fig. 8). Columns "A" and "I" contain number of domain. Yellow columns B, D, F contain direct measured data. Length of section line in "mm" on paper (column B) transformed to real meters (column C)



**Fig. 6.** Sequence of several domains in natural section with lines of axial plains in domains, which should be measured and averaging (after [Yakovlev, 2015a], fig. 6-18Г, with changes). Part of section 5 “Agchai” of Tfan zone is shown.

5										
TFAN-zone										
calculation of average values 1-32										
1	AX	an-flank	SH	2	an-flank	SH	AX	an-flank	SH	3
	80	105	0,794	106	40	0,342	92	48	0,407	
	75	84	0,669				90	30	0,259	
	74	110	0,819				92	28	0,242	
							92	30	0,259	
							88	40	0,342	
	76		0,761	106		0,342	91		0,302	
4	AX	an-flank	SH	5	an-flank	SH	AX	an-flank	SH	6
	94	18	0,157	81	40	0,342	87	40	0,342	
	94	15	0,131	80	35	0,301	102	65	0,538	
	104	28	0,242	80	30	0,259	100			
	94	35	0,301	82	26	0,225				
				74						
	97		0,207	79		0,282	96		0,440	
7	AX	an-flank	SH	8	an-flank	SH	AX	an-flank	SH	9
	79	57	0,477	101	60	0,500	107	59	0,493	
	90	80	0,643	103	57	0,477	114	85	0,676	
	87	57	0,477	98	60	0,500	92	60	0,500	
				99			85	60	0,500	
							88	94	0,732	
	85		0,533	100		0,493	97		0,580	
10	AX	an-flank	SH	11	an-flank	SH	AX	an-flank	SH	12

**Fig. 7.** Part of Excel table of “domain-1.xls” with averaging of AX and SH parameters. Red rectangles for domains 3, 4, 5, 6 reflect measures data on structure on fig. 6. Dip blue (and orange for 5) xls-cells have average value of upper xls-cells. Xls-cells “an-flank” show data of interlimb angle; each value transformed to SH ( $SH = \sin(\varphi/2)$ ) in adjacent xls-cell. SH values were averaged.

in according to scale of paper image (cell C1). Columns E and G have averaged data of AX and SH for domain (see fig. 7). If first boundary of domain has fault plain, its measured inclination is reflected in column H. This part of data table (fig. 8) is used for preparation of data file “\*.bcs” for PC program “Cross-b4.exe”. The file “domain-1.xls” may be used as mould for routine work with any other sections. For this aim, data of domains 26-33 as “cells with formulae” should be copied to 1-25. Below these data, each cell (AX, an-flank, SH) without measured data should be filled by “gap” for replacing of formulae, of course, otherwise there will be an error of display of data..

	A	B	C	D	E	F	G	H	I	J
1		profil 1, mm	19,9203							5
2	domen N	domen L-ini	L, metr	domen An	Axial An	Envel An	short	fault-An	domen N	TFAN-zone
3	1	25,6	510	-16	76	-23	0,761		1	1
4	2	42,6	849	-6	106	61	0,342		2	
5	3	26,4	526	-4	91	70	0,302		3	
6	4	19,4	386	-2	97	-34	0,207		4	
7	5	17,1	341	-3	79	-20	0,282		5	
8	6	12,2	243	-3	96	-4	0,44		6	
9	7	19,2	382	-4	85	23	0,533		7	
10	8	17,6	351	-3	100	-22	0,493		8	
11	9	18,2	363	-3	97	25	0,58		9	
12	10	19,8	394	-3	104	-7	0,462		10	
13	11	20,1	400	-2	78	-24	0,359	91	11	4
14	12	16,7	333	-3	77	-23	0,436		12	
15	13	26,8	534	-2	79	-50	0,441	91	13	
16	14	27,2	542	-3	59	-25	0,472		14	
17	15	16,1	321	-2	77	-70	0,399		15	
18	16	18,2	363	-3	57	-70	0,427		16	
19	17	29,0	578	-2	68	-8	0,538	89	17	
20	18	51,6	1028	-2	72	11	0,595		18	
21	19	16,0	319	-1	101	9	0,887	90	19	
22	20	17,3	345	-3	87	-56	0,208	92	20	
23	21	15,7	313	-2	87	-74	0,208		21	7
24	22	22,4	446	-1	68	30	0,422	90	22	
25	23	25,9	516	-2	45	-22	0,574		23	
26	24	35,5	707	-2	76	18	0,572		24	
27	25	57,5	1145	-2	78	-4	0,866		25	

**Fig. 8.** Table for collecting of all parameters of domains of file “domain-1.xls”. Red rectangles are shown the averaged values from fig. 7.

Data file for PC program “Cross-b4.exe” has next structure (“KESH-12.BCS”). First line contains name of section (KESHELTA, river), scale of drawing images on screen (1000 m/sm), position of first point of image of actual section on part of screen (between 0-1; 0.7), depth of upper point of drawing scale (vertical ruler) of image pre-folded state of section (-3000), quantity of domains (26):

KESHELTA , 1000 0.70 -3000 26

Second and further lines have 11 parameters, which are necessary for calculations and as auxiliary. First columns (1-5) contain data for domain reconstructions from columns E, F, G, C, D of “domain-1.xls” (fig. 8). Column 6 is auxiliary (type of boundary; 1 is the same stratigraphy unit, 2 is next or other unit, 3 is a fault). Column 7 is angle of dip of fault plain, if it exists. Column 8 is depth of first domain and each domain after fault. Other values in column 8 were calculated as result of retrodeformation. Columns 9-11 have an auxiliary data: 9 is number of folds in domain for construct of its image (3 is usual), 10 has index of color (in codes for BASIC program language) of layering in image, 11 contains commentary – age of stratigraphy unit and current number of domain (table 1).

*Table 1. Parameters of lines in main massif of data file “KESH-12.BCS”.*

1	2	3	4	5	6	7	8	9	10	11
AX	EN	SH	L	Tlt	Bnd	Flt	dpth	nimf	clr	commnt
95	-10	0.80	1000	-2	1	0	-5000	3	5	J2-1

Common list of data file is cited in table 2.

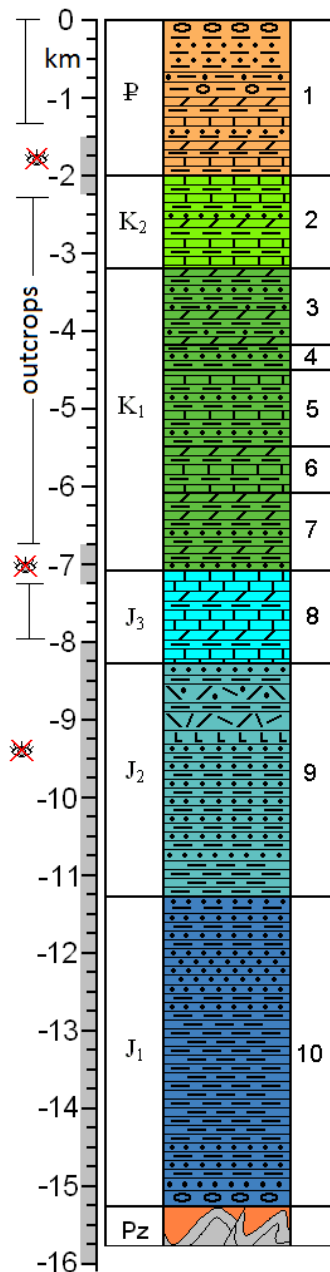
*Table 2. Data file for PC program “Cross-b4.exe”. Case of “KESH-12.BCS”.*

KESHELTA				1000		0.70	-3000	26		
95	-10	0.80	1000	-2	1	0	-5000	3	5	J2-1
118	28	0.50	2200	1	3	120	-2800	3	14	K2-2
115	60	0.52	1650	3	2	0	-3299	3	10	K1AAL-3
115	85	0.42	400	3	2	0	-4178	3	2	K1H2B4
110	70	0.45	1500	3	2	0	-4511	3	3	K1H15
115	88	0.48	750	1	2	0	-5477	3	11	K1V26
115	-35	0.48	1650	1	1	0	-6269	3	11	K1V27
117	-25	0.45	1500	7	2	0	-5338	4	3	K1H18
122	-30	0.28	1300	9	1	0	-4757	3	3	K1H19
125	-30	0.40	1350	8	3	134	-5200	3	3	K1H1-10
118	-32	0.35	1100	16	3	125	-4200	3	2	K1H2B11
105	-17	0.55	650	30	2	0	-3628	3	10	K1APAL12
120	35	0.35	750	-11	1	0	-3319	3	10	K1APAL13
118	-35	0.40	650	-10	3	120	-4150	3	2	K1H2B14
105	-10	0.55	550	-7	1	0	-3908	3	2	K1H2B15
90	45	0.55	1000	-7	3	95	-4450	3	3	K1H116
85	-65	0.30	400	-8	1	0	-5063	3	3	K1H117
85	30	0.52	1250	-7	3	80	-4850	3	3	K1H118
95	50	0.50	800	-6	2	0	-5328	3	11	K1V219
95	37	0.50	700	-6	1	0	-5797	3	11	K1V220
102	40	0.50	1000	-5	2	0	-6078	3	9	K1V121
120	-28	0.45	1500	-4	3	102	-6900	3	9	K1V122
120	30	0.40	1950	-3	1	102	-6382	3	9	K1V123
120	-18	0.40	1050	-3	3	95	-8000	3	1	J3-24
112	-30	0.30	1750	-2	1	0	-7838	3	1	J3-25
95	-20	0.30	1000	-2	3	118	-8400	3	5	J2-26

(NB!) The file should have empty line (the sign of the carriage return) after the last domain data for correct reading of last data line by BASIC program. The ERROR (of reading of the file) will appeared in contrary case and crash stop of program.

#### 4.4 Collecting of materials about stratigraphic units

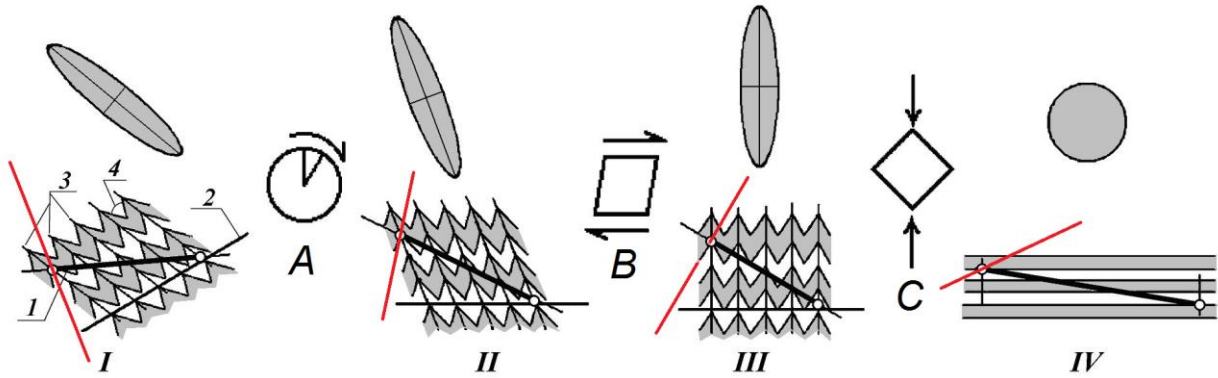
Important idea for an obtaining of final kind of 3D modelling of sedimentary cover is a compiling of a stratigraphic model of entire sedimentary cover. It may be collected from literature sources and/or from direct measurements of stratigraphic (lithological) units in field on flanks of large folds. All thicknesses of units are collecting, total thickness of the cover should to be calculated. Common drawing scale for stratigraphic model should to be establish; “0” is top of column, the soil of cover has certain depth (-15475 m, for instance) in this case. Each unit will obtain exact (for the model) estimates of depths of top and soil (table 3, fig. 9).



**Table 3.** The table of thickness and depth of a sole for ten the stratigraphic units of the Chiaur zone (numbers of divisions correspond to fig. 9):

N	age	position
1	thickness	2100
	P	sole 2100
2	thickness	1200
	K <sub>2</sub>	sole 3300
3	thickness	880
	K <sub>1</sub> ap-al	sole 4180
4	thickness	320
	K <sub>1</sub> h <sub>2</sub> -b	sole 4500
5	thickness	975
	K <sub>1</sub> h <sub>1</sub>	sole 5475
6	thickness	800
	K <sub>1</sub> v <sub>2</sub>	sole 6275
7	thickness	1000
	K <sub>1</sub> v <sub>1</sub>	sole 7275
8	thickness	1200
	J <sub>3</sub>	sole 8475
9	thickness	3000
	J <sub>2</sub>	sole 11475
10	thickness	4000
	J <sub>1</sub>	sole 15475

**Fig. 9.** Stratigraphic model for Chiaur tectonic zone (after [Yakovlev, 2015a], fig. 6-6). Ten lithologic units were distinguished. Lithologic signs are standard. Some parts of columns were directly observed in cross-sections (outcrops), other parts were established due to analogy of neighboring zones (grey color along scale line). Scale line on left part was used for aims of calculations (see table 3, which is also given above).



**Fig. 10.** Operations of restoration of a pre-folded state of the domain, after [Yakovlev, 2008b] with changes. Symbolical images of folded structure of the domain (1-4) for states from actual (I) to pre-folded (IV) are shown, the ellipses of deformations are corresponding to the same state of the domain and types of operations: A – turn (from a stage I to a stage II), B – horizontal simple shearing (from II to III), C – stretching (vertical pure shearing, from III to IV). Transformations of red line (the same kind as for segment of section) are shown changes of inclination of fault plain.

Conventional signs of geometrical parameters of the domain (in stage I): 1 – a segment of the line of a section (length and an inclination are measured) 2 – the line of an envelope plain of folds (the inclination is measured); 3 – axial surfaces of folds (the inclination is measured); 4 – an interlimb angle (corresponds to coefficient of shortening of folds ( $K=L1/L0$ ; 50% SH = 0.5 K).

#### 4.5 Core of PC program: transformation of parameters of domain during operations of retrodeformation from its actual to pre-folded state

In a technique and in the PC program the following sequence of kinematic operations is used (fig. 10):

- 1) Turn (rotation) of the domain as a whole up to horizontal position of the line of initial layering (of plain of envelope of folds),
- 2) Simple horizontal shearing up to the vertical direction of the axial plain,
- 3) Stretching (pure shearing) up to disappearance of folds according to strain ellipse (up to circle). We pay attention that all operations are made with pieces of lines and with a strain ellipse, but don't concern the morphology of folded structure (for instance, the concept that lengths of flanks are constant, is ignored).

These operations can be described by the following formulae which don't extend beyond of the geometry [Yakovlev, 1987; 2008b, 2009; 2015a]. We shall designate initial parameters as:  $AX_0$  – an inclination of the axial plain;  $EN_0$  – an inclination of the line of initial layering (envelope of folds);  $K_0$  – coefficient of shortening of folds in the direction of a perpendicular to the axial plain;  $LS_0$  – length of profile segment;  $TS_0$  – a tilting of a profile segment;  $D_1$  – layer depth in an entrance, first point of the domain ( $D_1$  remains invariable; depth of "an output, last point" of domain,  $D_2$ , is calculated).

Operation of turn, rotation (fig. 10, A) for an angle of rotation  $\Delta\alpha = - EN_0$ ; rotation up to horizontal position of initial layering (envelope plain):

$$AX_1 = AX_0 + \Delta\alpha \quad (1)$$

$$TS_1 = TS_0 + \Delta\alpha \quad (2)$$

Shortening of folds and length of a segment of a section remain invariable during the operation:

$$K_1 = K_0 \text{ and } LS_1 = LS_0.$$

Operation of simple horizontal shearing (fig. 10, B) for a shearing angle  $\Delta\gamma = 90 - AX_1$ :

$$K_2 = K_1 / \sin(AX_1) \quad (3)$$

$$tg(TS_2) = tg(AX_1) \cdot tg(TS_1) / (tg(AX_1) + tg(TS_1)) \quad (4)$$

$$LS_2 = (LS_1 \cdot \sin(TS_1)) / \sin(TS_2) \quad (5)$$

Operation of stretching or "pure shearing" (fig. 10, C) for the stretching size (shortening of folds) of  $K_2$ :

$$tg(TS_3) = tg(TS_2) \cdot K_2^2 \quad (6)$$

$$LS_3 = LS_2 \cdot K_2 \cdot \sin(TS_2) / \sin(TS_3) \quad (7)$$

In result of operations, the profile segment obtains a position in the pre-folded continuum:

$$\text{Horizontal length } L_h = LS_3 \cdot \cos(TS_3) \quad (8)$$

$$\text{Vertical length } L_v = LS_3 \cdot \sin(TS_3) \quad (9)$$

Respectively, depth of layers in the output point of domain along segment will consists of:

$$D_2 = D_1 + L_v \quad (10)$$

## 5. Operating instructions of the computer program usage

### 5.1 Start of the program, first page of the screen

The PC program "Cross-b4.exe" was compiled in software TURBO-BASIC at 1995-1998 years and renovated at 2017 year. Some additional functions were planned in software code initially, but they were not finalized later. At least one calculated parameter is not actual now (averaged shortening, Avr. SH), it was used for some other goals of study. Program has possibility to calculate and to show: 1) data of parameters for reconstructed (pre-folded) domains; 2) symbolic drawing of actual (folded) morphology of domain; and 3) drawing of pre-folded state of domain. It means, that the researcher has possibility to control of realness of actual data (a checking by comparison of the structure on screen with actual structure on paper version of section) and to control of realness of combinations of calculated pre-folded states of set of domains.

The program may be used in WINDOWS-95, 98 in full possibilities, including usage of copy-screen function. Usage of "Cross-b4.exe" in WIN-XP, images on screen will be created without function of copy-screen. Direct usage of "Cross-b4.exe" in Windows Vista and younger version is not possible. For these cases it is possible to use special program "DOSBox"; a special additional manual (app 2) for this case is located at the end of book.

Serial of figures below is showing main stages of "Cross-b4.exe" work.

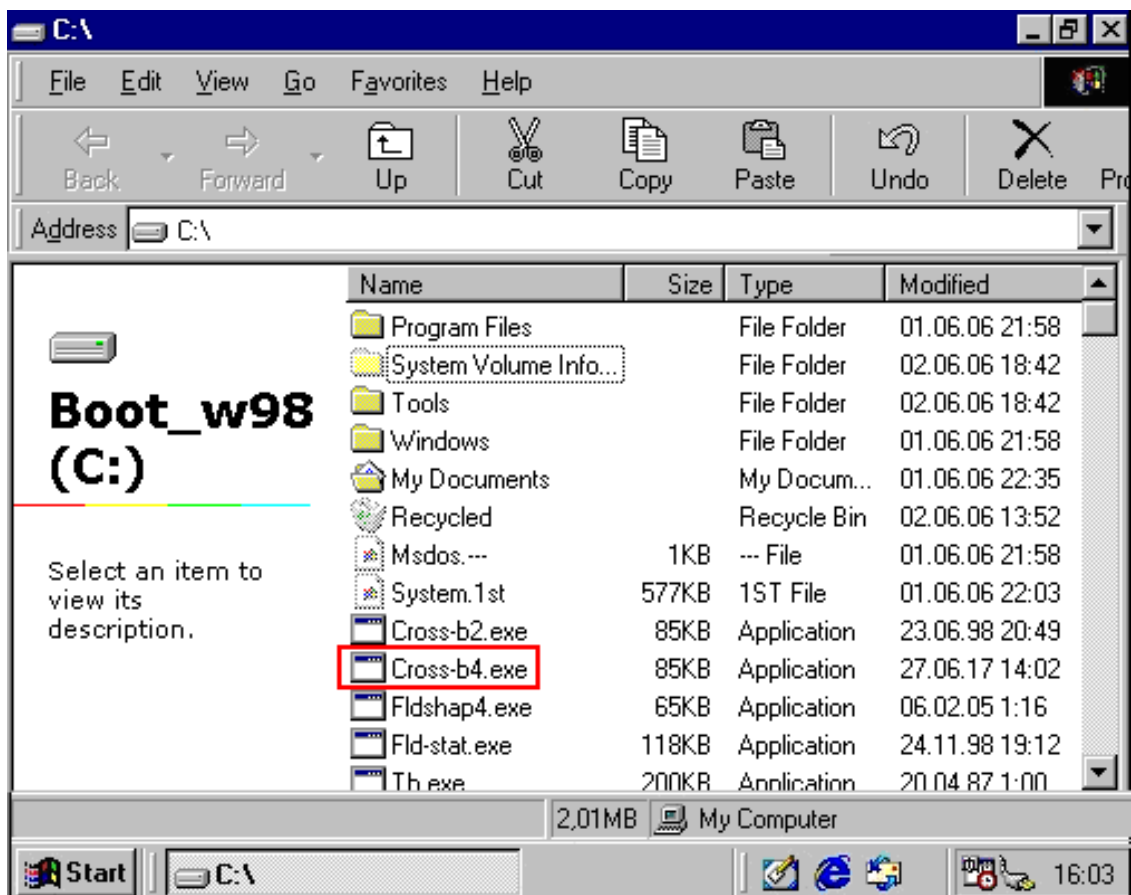


Fig. 11. Start of dos-program from “Disk C:”. The name of program is marked.

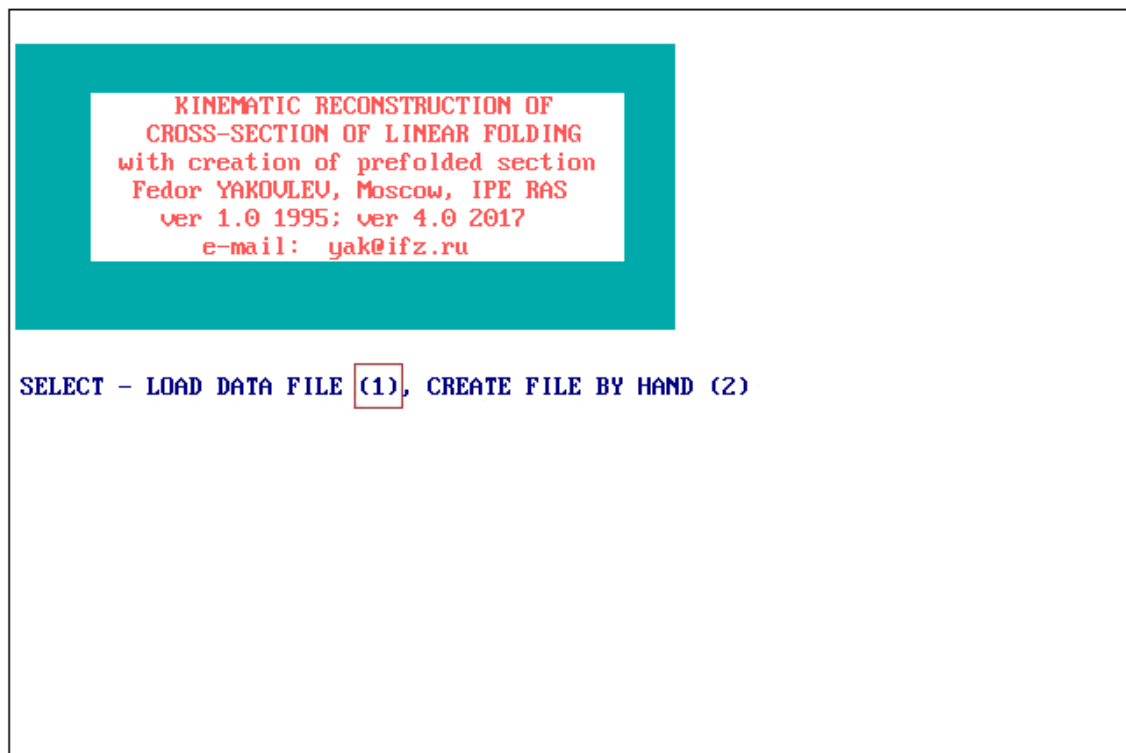


Fig. 12. First screen after a start. Title of PC program “Cross-b4.exe” and the menu with a choice (1) for further procedures. For next step of work, insert “1” and to push “ENTER”.



## 5.2 Procedures of loading of the data file from a disk, fillings or corrections of data from the keypad, a recording of the updated or corrected data file on a disk

Below, in figures 13–41, serial actions of the operator of the program are shown.

```
BDB3A .BCS      BDB-1 .BCS      BDB-3 .BCS      BDB3C .BCS
BDB3D .BCS      BDB2 .BCS       SECSEC1 .BCS     SECSEC1A .BCS
FYI-1 .BCS      KURU-1 .BCS     BABACH7A .BCS    SECSEC1B .BCS
KARACH6C .BCS   KARACH6B .BCS   KARACH6A .BCS    KARACH6 .BCS
AGCHA5A .BCS    AGCHA-5 .BCS    FILE4 .BCS       KURU-3B .BCS
SHAL-10C .BCS   MAZA9C .BCS     FYI_1 .BCS       JIMICH8B .BCS
JIMICH8A .BCS   KUDIAL4 .BCS    RAGD_2B .BCS     MAZA .BCS
CHIAUR2 .BCS    CHIAUR1 .BCS    LIAKH-3C .BCS    LIAKH-3D .BCS
LIAKH3E .BCS    LIAKH3F .BCS    LIAKH3J .BCS     MOD3 .BCS
FILE1 .BCS      CHIAUR2K .BCS   KESH-12 .BCS
250290176 Bytes free
INSERT NAME OF FILE - ?
```

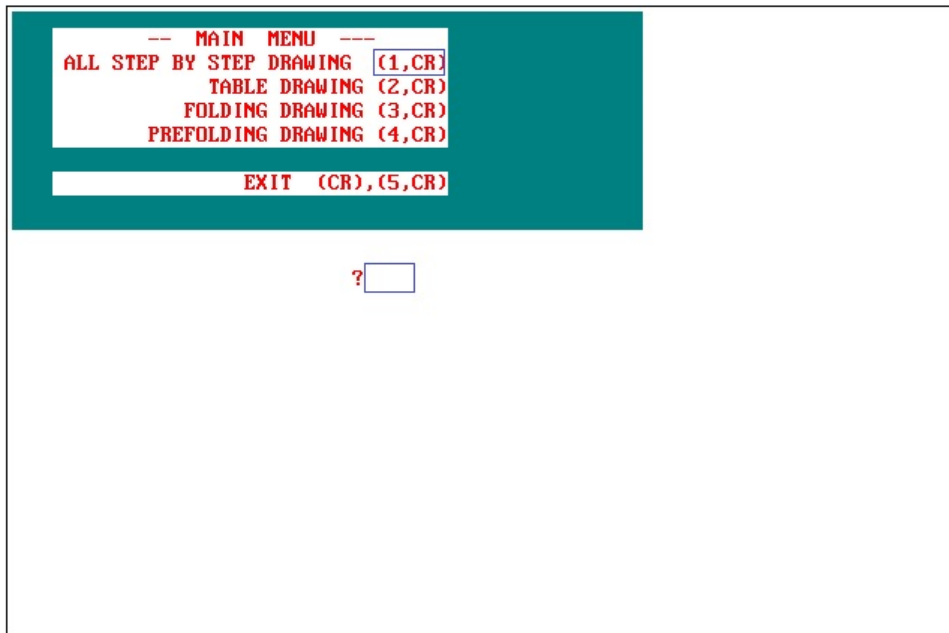
**Fig. 13.** The following screen – the reference on the content of the disk "C". The list of files with data for the structural sections which are on "disk C :\" is outputted; the chosen file is noted. The program finds and shows all files \*.BCS which are in a root of the disk "C".

```
BDB3A .BCS      BDB-1 .BCS      BDB-3 .BCS      BDB3C .BCS
BDB3D .BCS      BDB2 .BCS       SECSEC1 .BCS     SECSEC1A .BCS
FYI-1 .BCS      KURU-1 .BCS     BABACH7A .BCS    SECSEC1B .BCS
KARACH6C .BCS   KARACH6B .BCS   KARACH6A .BCS    KARACH6 .BCS
AGCHA5A .BCS    AGCHA-5 .BCS    FILE4 .BCS       KURU-3B .BCS
SHAL-10C .BCS   MAZA9C .BCS     FYI_1 .BCS       JIMICH8B .BCS
JIMICH8A .BCS   KUDIAL4 .BCS    RAGD_2B .BCS     MAZA .BCS
CHIAUR2 .BCS    CHIAUR1 .BCS    LIAKH-3C .BCS    LIAKH-3D .BCS
LIAKH3E .BCS    LIAKH3F .BCS    LIAKH3J .BCS     MOD3 .BCS
FILE1 .BCS      CHIAUR2K .BCS   KESH-12 .BCS
250281984 Bytes free
INSERT NAME OF FILE - ? kesh-12.bcs
```

**Fig. 14.** Next screen. To type the file name with ".bcs", push ENTER.

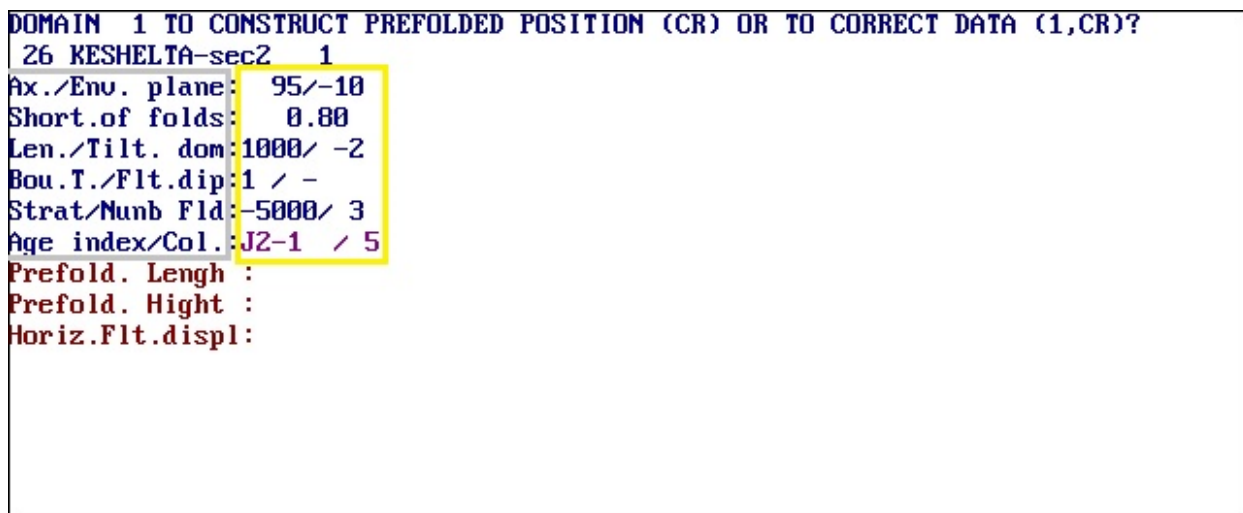
### 5.3 Choice of further actions, main option "step by step"

In the main menu, it is necessary to choose the first line. Action of other lines in the operating version of the program is blocked.



**Fig. 15.** Next screen. Choice from main menu: "1", push Enter. Other choice "5" is active also, "2 – 4" are in reserve.

### 5.4 Main screen, display of structural data, change of data, creation of modern/actual folded structure and of pre-folded structure, display of results of calculations



**Fig. 16.** Following screen. First step of creation of two statuses of a profile. Screen zones: list (names) of parameters (gray rectangle at the left). Data of the 1st (current) domain (yellow rectangle); see the data "KESH-12.BCS"; tab. 2. The line first on top of screen (DOMAIN 1 ...) offers an action choice. For creation of structure it is necessary to press Enter (CR), to go to editing of a data set from the keypad to click (1, ENTER). The second line shows the total number of domains (26) in a profile, its name (KESHELTA-sec2), number of the domain (1) which data are reproduced. Three red lines (Prefold. Lengh, etc.) are the key parameters of a pre-folded state of the domain, which are calculated in case of creation.

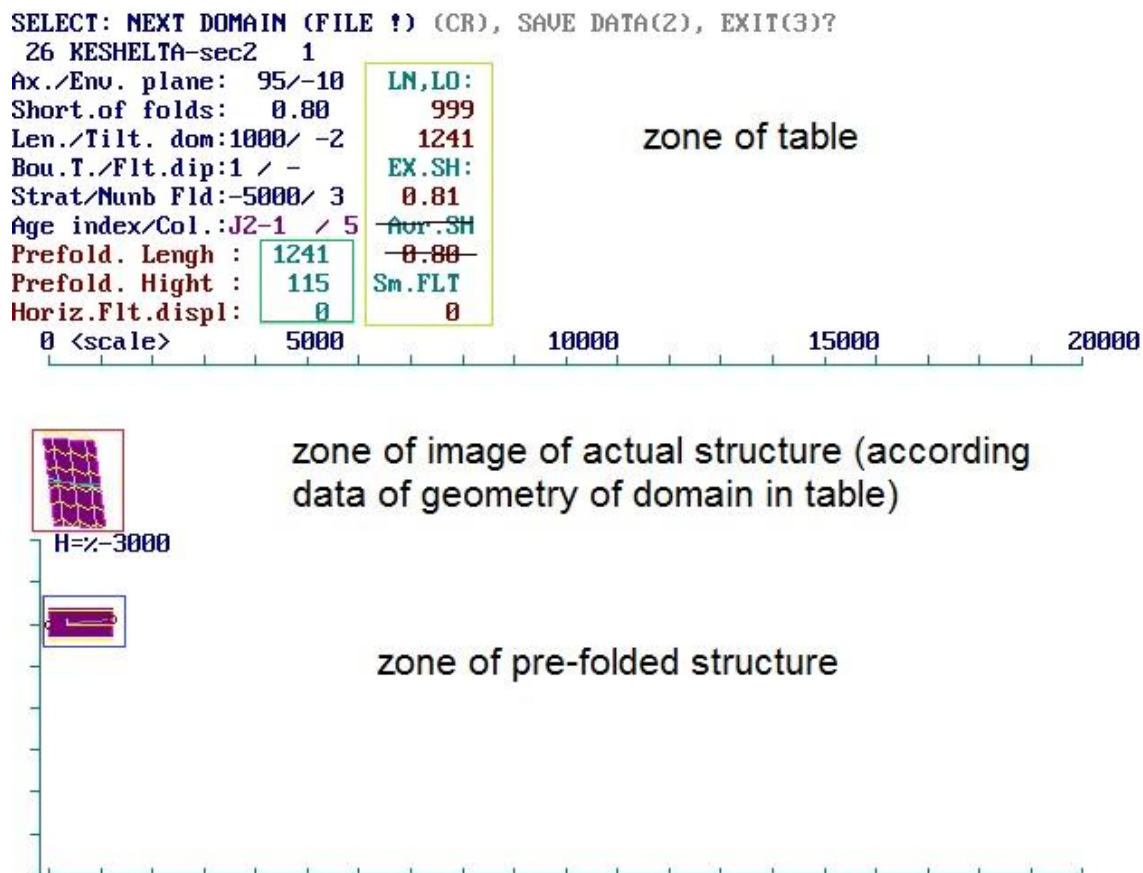


Fig. 17. Result of reconstruction of first domain (After push CR).

Three zones of screen are indicated (“table”, “actual” and “pre-folded” structures) on the fig. 17. Two horizontal scales-lines (0 – 20000 m) for actual structure (upper) and for pre-folded structure (lowest) have been drawn. Vertical scale exists with meaning of upper point (-3000 m; -11000 for lowest point). Length (horizontal) of segment of domain section line and vertical displacement from start point of domain until last point are shown (blue line in folded structure of red box). Accumulated horizontal lengths for actual (green LN, red 999) and pre-folded state of section (LO, red 1241) are demonstrated (yellow box). EX.SH. is external shortening value (accumulated), it means “total current” shortening value (LN/LO, 0.81). Line Avr.SH and meaning (0.80) was reserved for old version of method. For the actual method, it is not used. The Sm.Flt. parameter shows total horizontal displacement on faults plains (0, red figure). Green box contains next parameters: 1241 is pre-folded length of current domain (see also image in blue box in “Pre-folded structure zone”), 115 is vertical displacement of domain segment (from start point -5000, the last point of domain is -4885). Horizontal displacement along fault plane (it not presented) is 0.

The first line in upper part screen (grey color) is indicating the choice for construction of next domain (CR), save of current data table (2, CR) of finish the program (3, CR).

Further consecutive steps at which domains 2 and 3 are under construction are shown in figures 18-20. Parameters of normal fault (fig. 19) are determined on transition from the first to the second domains. Blue and red figures -291 is horizontal displacement of normal fault

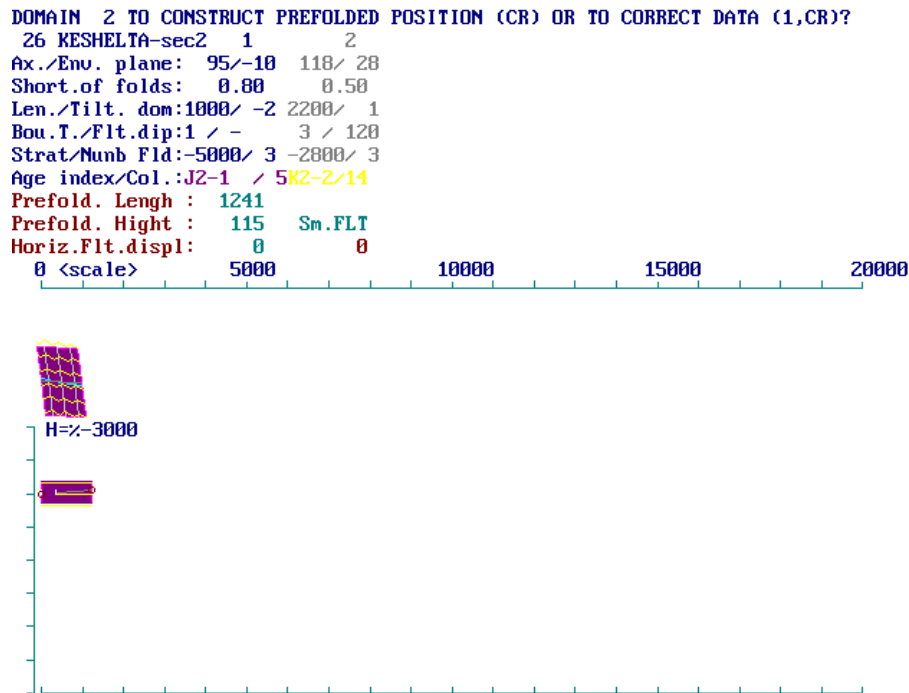


Fig. 18. Next step of reconstruction: indication of data of second domain (column of grey figures).

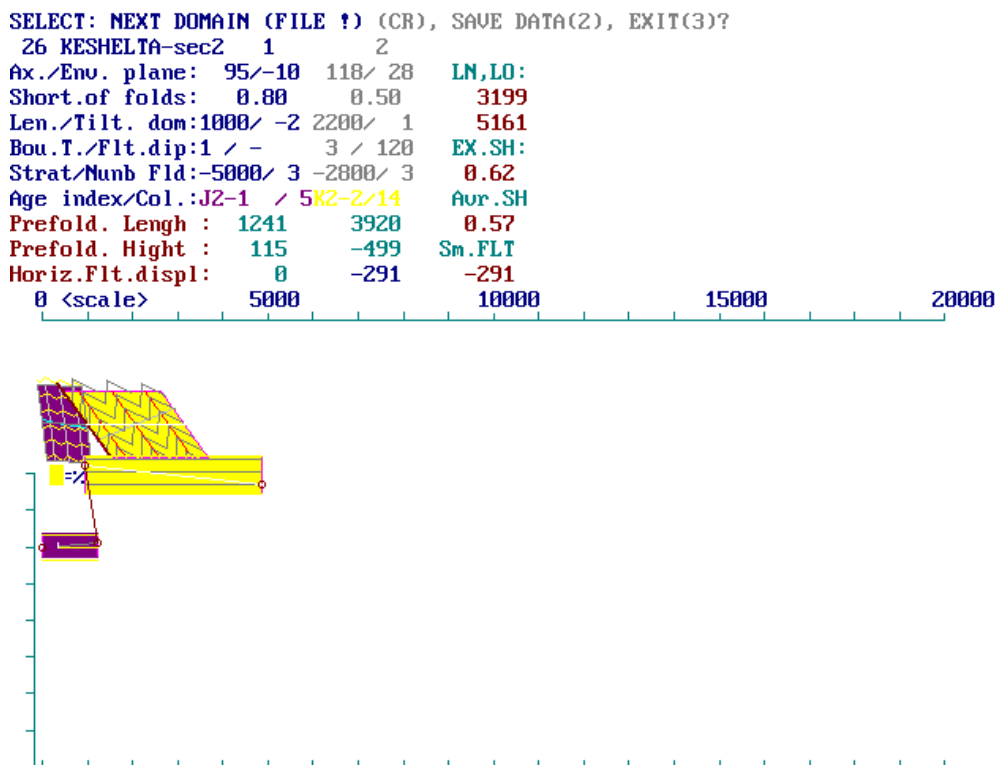


Fig. 19. Result of reconstruction of second domain.

(to compare data “Strat” for domain 1 and 2). Value of shortening “EX.SH” 0.62 don’t include displacement of faults. Line “Age index” includes indication of age of sediments (J2, K2), current number of domain (-1, -2) and index of color (“Col”) in BASIC language (/5, /14). Vertical positions of image of actual section in zone “Actual image...” (fig. 17) is regulated by parameter “0.70” in first line of “KESH-12.BCS” file, hypsometric space for further uplift of section line in domains 12-13 is reserved. “0” is most upper position, “1” is most low one.

SELECT: NEXT DOMAIN (FILE ! ) (CR), SAVE DATA(2), EXIT(3)?

26 KESHELTa-sec2	1	2	3	
Ax./Env. plane:	95/-10	118/ 28	115/ 60	LN,LO:
Short.of folds:	0.80	0.50	0.52	4847
Len./Tilt. dom:	1000/-2	2200/ 1	1650/ 3	8103
Bou.T./Flt.dip:	1 / -	3 / 120	2 / -	EX.SH:
Strat/Numb Fld:	-5000/ 3	-2800/ 3	-3299/ 3	0.60
Age index/Col.:	J2-1	5K2-2/14	K1AAL-3/10	Aur.SH
Prefold. Length :	1241	3920	2942	0.55
Prefold. Height :	115	-499	-878	Sm.FLT
Horiz.Flt.displ:	0	-291	0	-291
0 <scale>	5000		10000	

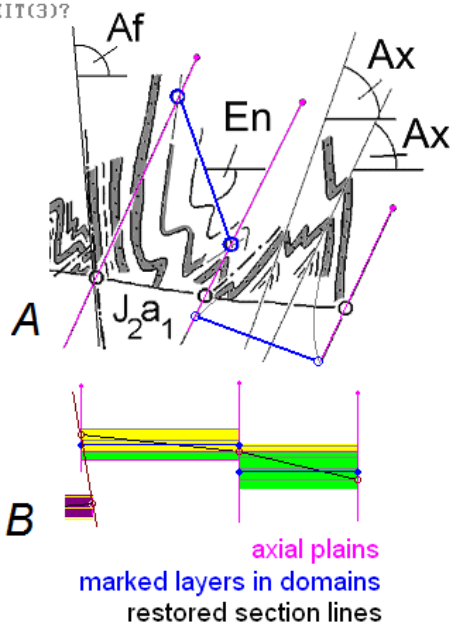
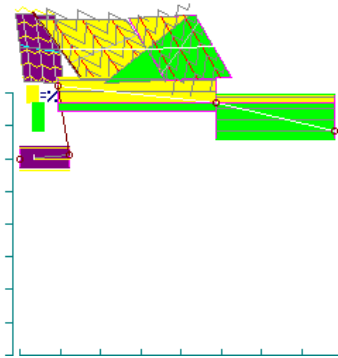


Fig. 20. Result of reconstruction of domain 3.

There is explanation of drawing of border lines in section of domains (fig. 20) in additional pictures-inset “a” and “b” (see also borders in fig.4A; structures in “a” and “b” here are not identical). Border lines should be parallel to axial plains in actual domains (“a”, pink color), which are in vertical position in pre-folded state (“b”). Two lines of initial layering (EN, “a”) are connecting points of crossings of borders with some layer (blue lines, “a”, horizontal lines in “b”). The restoration of section lines and pre-folded widths of domains has relation to restoration of marked layers (blue) and displacement of structure from domain 1 to domain 2 along axial plain up to next marked layer. Such correct shifting from previous to next domain can not be done if border lines will be not parallel to axial plains of folds in domains.

Sequence of domains 2, 3, 4 has not fault, boundaries of domains were located on point of changing of stratigraphic complexes, and thus vertical displacements of section lines were equal to thickness of complexes. On the left part of zone of “prefolded structure” near the vertical scale, an indication of stratigraphic column is compiling (yellow, light green, dark green rectangles). Stratigraphic models for domain 1 (Transcaucasian Massif) and for domains 2-4 (and go on, for Chiaur zone of Greater Caucasus) are different.

The creation of domains 5 and 6 is shown further in figures 22 and 23.

Combination of geometric parameters for domain 6 is so (fig. 23), that some ELONGATION for layered media should be supposed, but not existence of additional small folds (as it take place for domain 5). These possibilities of program code are demonstrated in picture-insets “A” and “B”. “A” is folded structure in case, when layers along envelope plain testified a shortening (blue lines). “B” is boudinage in case, when layers along envelope plain testified an elongation. PC program indicates such “elongation” by drawing of boudinage (small gaps of light blue colors in layering, “B”). Elongation has appeared as result of balancing together with domain 7 (other flank of large fold). This picture (fig. 23) includes six domains (maximal amount for screen) and it should be captured by “copy

```

SELECT: NEXT DOMAIN (FILE !) (CR), SAVE DATA(2), EXIT(3)?
26 KESHELTA-sec2  1      2      3      4
Ax./Env. plane:  95/-10 118/ 28 115/ 60 115/ 85  LN,LO:
Short.of folds:  0.80  0.50  0.52  0.42      5246
Len./Tilt. dom:1000/-2 2200/  1 1650/  3  400/  3      8986
Bou.T./Flt.dip:1 / -    3 / 120 2 / -    2 / -    EX.SH:
Strat/Numb Fld:-5000/ 3 -2800/ 3 -3299/ 3 -4178/ 3      0.58
Age index/Col.:J2-1 / 5K2-2/14 K1AAL-3/1K1H2B4/ 2  Avr.SH
Prefold. Length : 1241  3920  2942  883      0.54
Prefold. Height :  115  -499  -878  -333  Sm.FLT
Horiz.Flt.displ:  0    -291  0      0      -291
0 <scale>          5000          10000          15000          20000

```

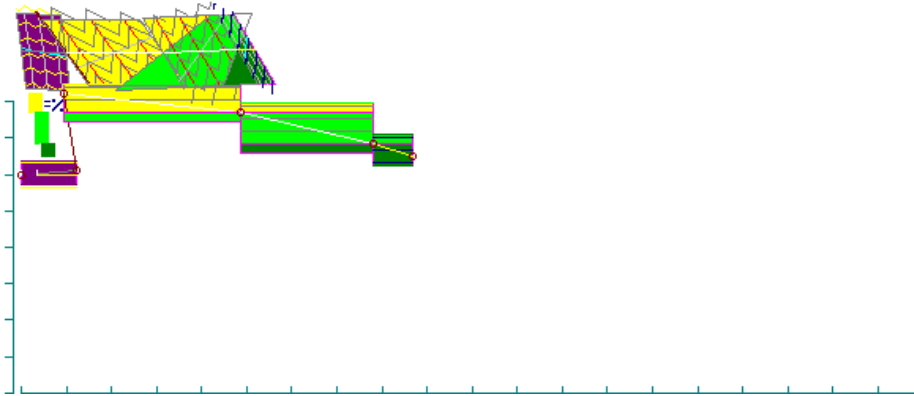


Fig. 21. Result of reconstruction of domain 4.

```

SELECT: NEXT DOMAIN (FILE !) (CR), SAVE DATA(2), EXIT(3)?
26 KESHELTA-sec2  1      2      3      4      5
Ax./Env. plane:  95/-10 118/ 28 115/ 60 115/ 85 110/ 70  LN,LO:
Short.of folds:  0.80  0.50  0.52  0.42  0.45      6744
Len./Tilt. dom:1000/-2 2200/  1 1650/  3  400/  3 1500/  3      12174
Bou.T./Flt.dip:1 / -    3 / 120 2 / -    2 / -    2 / -    EX.SH:
Strat/Numb Fld:-5000/ 3 -2800/ 3 -3299/ 3 -4178/ 3 -4511/ 3      0.55
Age index/Col.:J2-1 / 5K2-2/14 K1AAL-3/1K1H2B4/ 2K1H15/ 3  Avr.SH
Prefold. Length : 1241  3920  2942  883  3188      0.52
Prefold. Height :  115  -499  -878  -333  -967  Sm.FLT
Horiz.Flt.displ:  0    -291  0      0      0      -291
0 <scale>          5000          10000          15000          20000

```

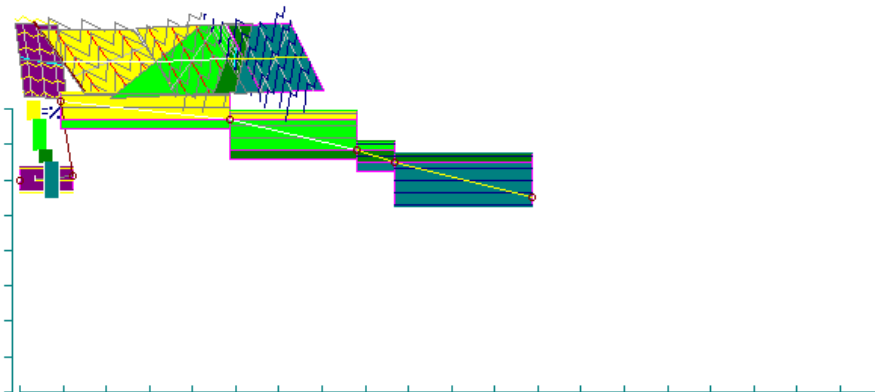


Fig. 22. Result of reconstruction of domain 5. Deepest point (end of domain 5) is -5477 [-4511 + (-967)].

screen” function. For saving the image it is possible to use the MICROSOFT PAINT program: the copy of the screen from random access memory is putted to the main window (by PASTE function) and further is saving in the form of the file with an individual name (“\* .BMP”). For the further compilation of structure, you should have several pictures (6 + 6 + 6...).

```

SELECT: NEXT DOMAIN (FILE !) (CR), SAVE DATA(2), EXIT(3)?
26 KESHELTA-sec2 1 2 3 4 5 6
Ax./Env. plane: 95/-10 118/ 28 115/ 60 115/ 85 110/ 70 115/ 88 LN,LO:
Short.of folds: 0.80 0.50 0.52 0.42 0.45 0.48 7494
Len./Tilt. dom:1000/-2 2200/ 1 1650/ 3 400/ 3 1500/ 3 750/ 1 13601
Bou.T./Flt.dip:1 / - 3 / 120 2 / - 2 / - 2 / - 2 / - EX.SH:
Strat/Numb Fld:-5000/ 3 -2800/ 3 -3299/ 3 -4178/ 3 -4511/ 3 -5477/ 3 0.55
Age index/Col.:J2-1 / 5K2-2/14 K1AAL-3/1K1H2B4/ 2K1H15/ 3 K1U26/11 Avr.SH
Prefold. Length : 1241 3920 2942 883 3188 1427 0.51
Prefold. Hight : 115 -499 -878 -333 -967 -792 Sm.FLT
Horiz.Flt.displ: 0 -291 0 0 0 0 -291
0 <scale> 5000 10000 15000 20000

```

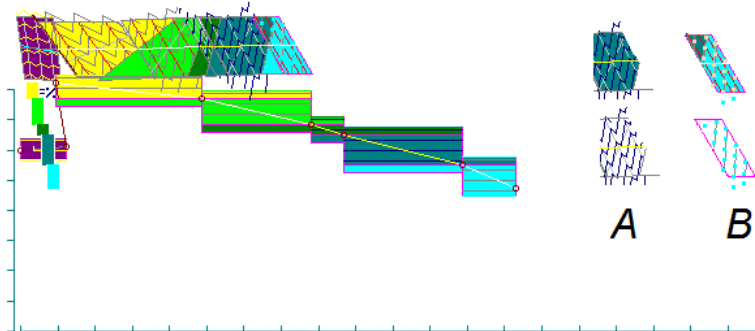


Fig. 23. Result of reconstruction of domain 6.

### 5.5 Transition from the screen N to the screen N+1 for section, which has more than 6 domains

The structure of domain 7 in nature was not open enough in outcrops. Possibly, some thrust or additional folds took place really (as other version of structure). In this case, thickness of  $K_{1V2}$  may be lesser and the ELONGATION in domain 6 may be excluded. The sole of  $K_{1V2}$  in domain 20 (text below) is -6078 m. To compare this data with -6269 m for lowest point of domains 6/7 and boundary of  $K_{1V2}$  top for domain 6 (-5477 m) and domain 18 (-5328 m). These thicknesses and positions are close.

```

SELECT: NEXT DOMAIN (FILE !) (CR), SAVE DATA(2), EXIT(3)?
26 KESHELTA-sec2 6
Ax./Env. plane: 115/ 88 LN,LO:
Short.of folds: 0.48 7494
Len./Tilt. dom: 750/ 1 13601
Bou.T./Flt.dip:2 / - EX.SH:
Strat/Numb Fld:-5477/ 3 0.55
Age index/Col.:K1U26/11 Avr.SH
Prefold. Length : 1427 0.51
Prefold. Hight : -792 Sm.FLT
Horiz.Flt.displ: 0
0 <scale>

```

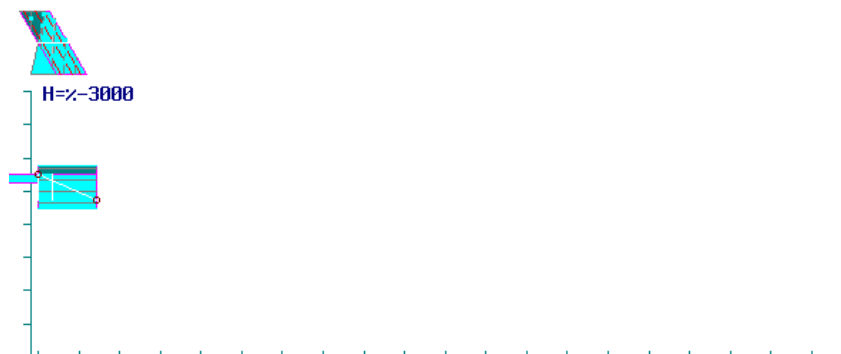


Fig. 24. Next screen (next block of 6 domains) for compilation of next block of structure (domains 6-11 after block of 1-6). Previous domain (number 6) indicates as first one on this block of structure. Parameters LN, LO, EX.SH are the same as in fig. 23.

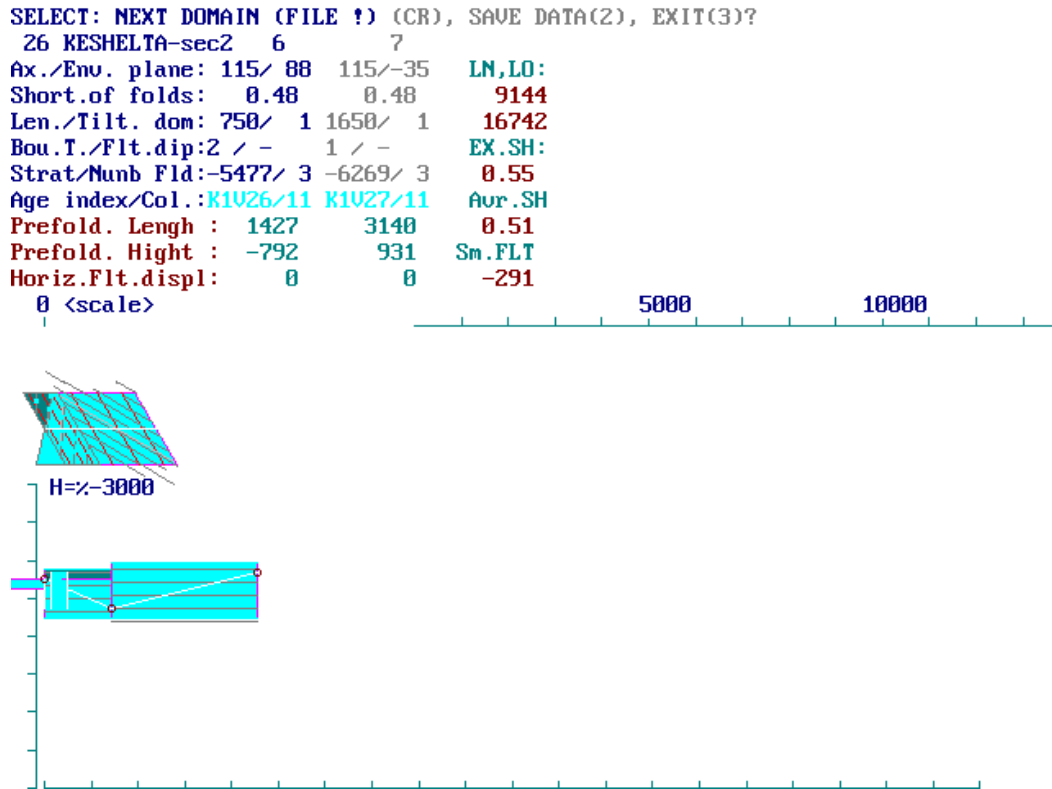


Fig. 25. Result of reconstruction of domain 7 for deposits  $K_{1V2}$  (upper Valanginian).

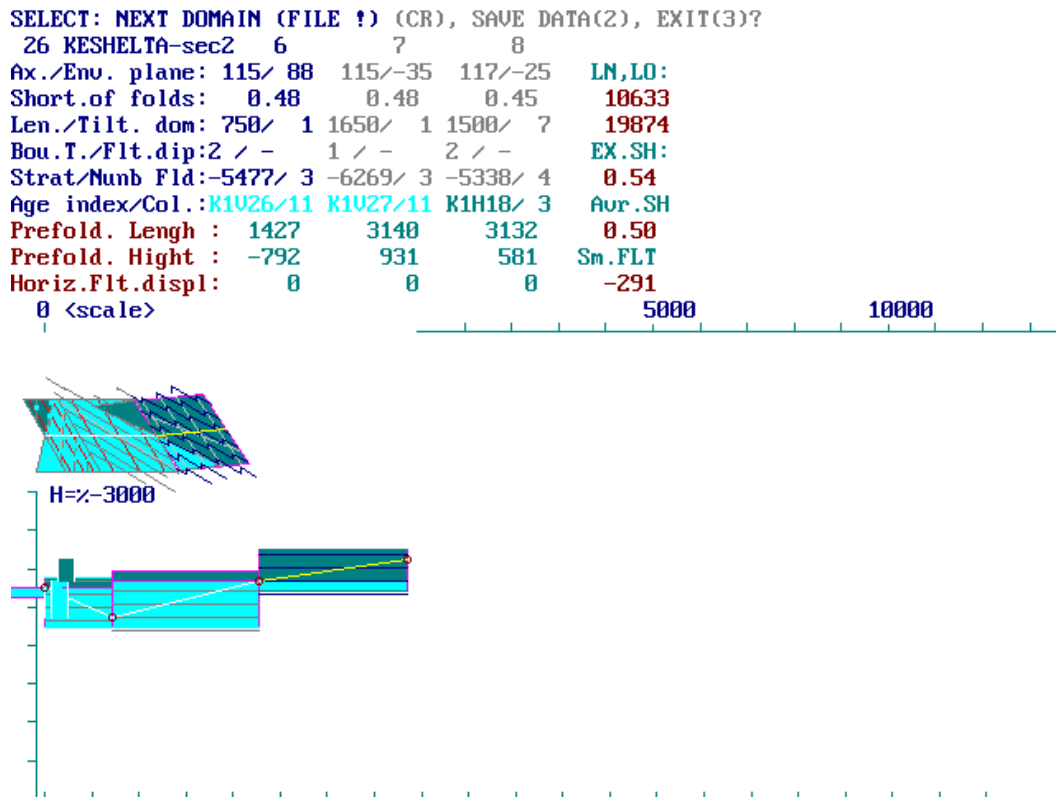


Fig. 26. Result of reconstruction of domain 8.



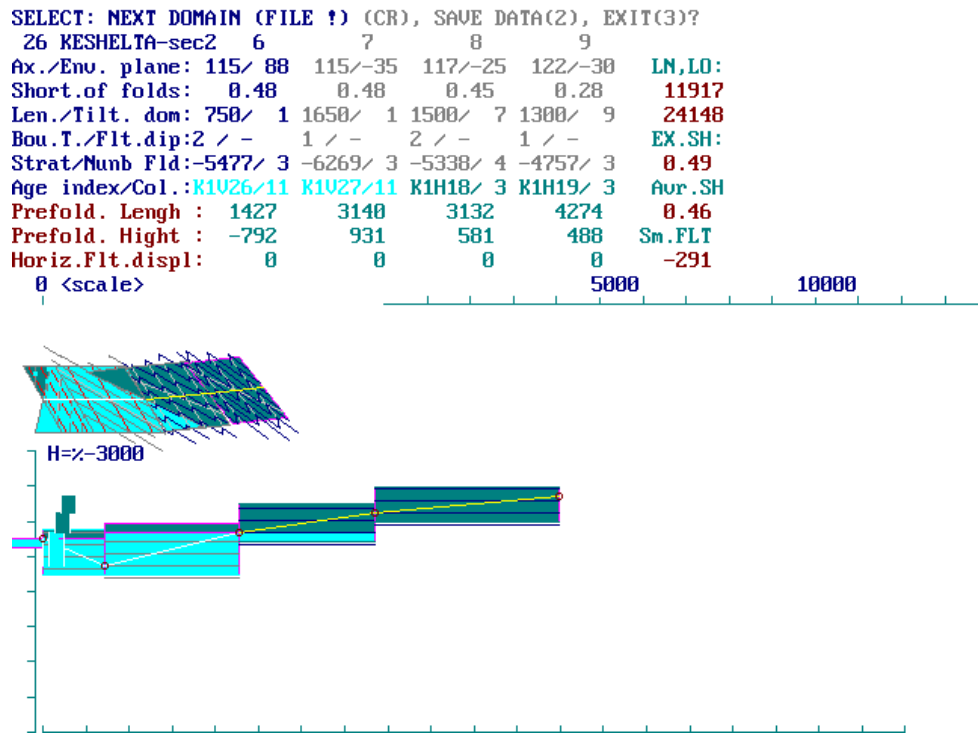


Fig. 27. Result of reconstruction of domain 9.

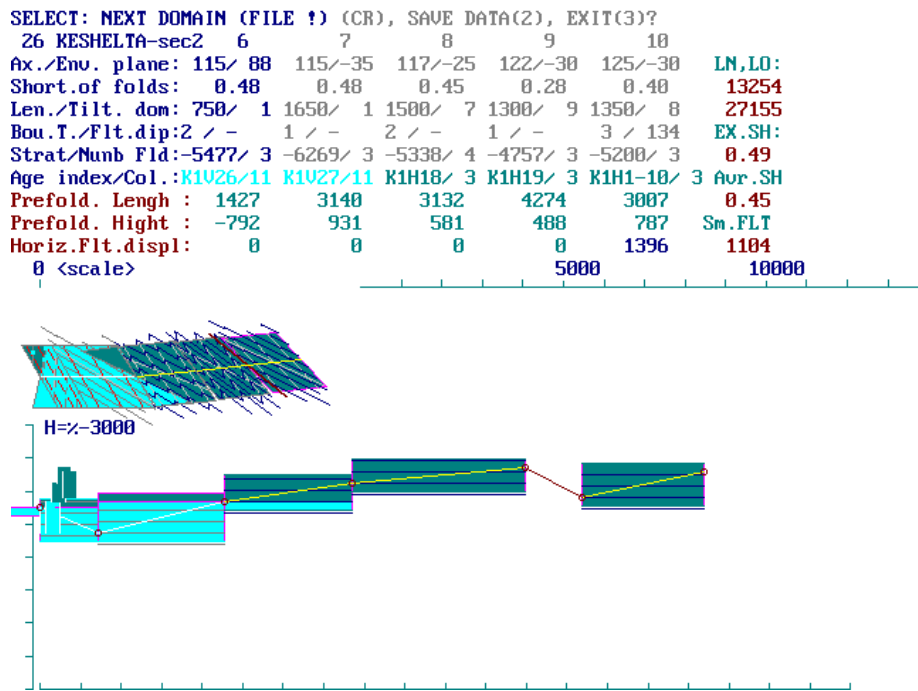


Fig. 28. Result of reconstruction of domain 10.

Domains 9 and 10 have the same deposits (Lower Hauterivian), the thrust is boundary between them. The depth of final point of domain 9 (-4269) is close to initial depth of top of K1H1 sediments -4500 (see domain 5). In combination with prescribed depth of start point of domain 10 (-5200) and calculated initial inclination of fault plain, it is formed horizontal displacement 1396 and satisfactory positions of domains inside stratigraphic model of Chiaur zone.

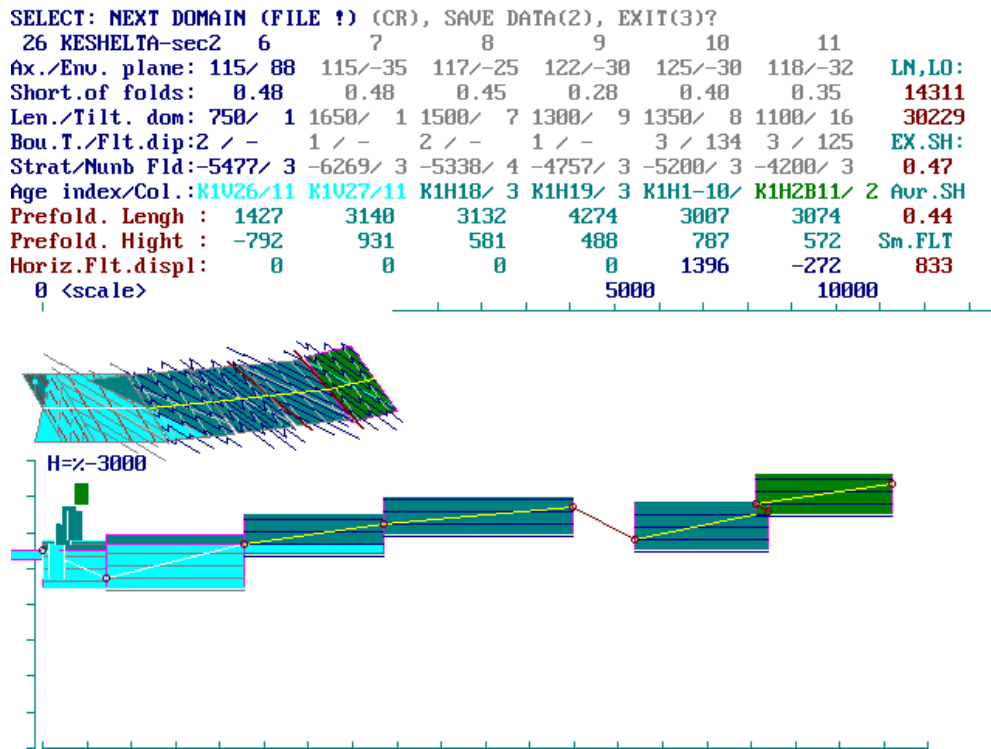


Fig. 29. Result of reconstruction of domain 11.

Vertical positions of final point of domain 10, start point of domain 11, initial inclination of fault plain and stratigraphic model are dictating result of displacement as “normal fault” - 272 m. Copy screen function should be done for the fixing of results of reconstruction of these six domains.

In figures 30-39, the creation of all other domains is shown (from 11 to 26).

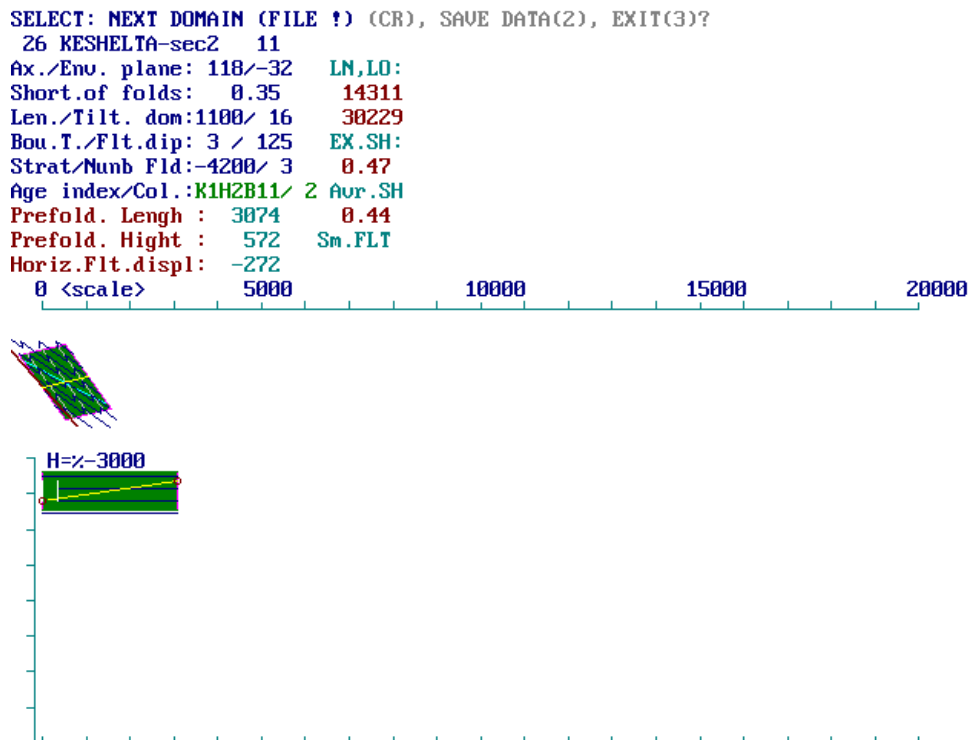


Fig. 30. Result of reconstruction of domain 11, which is using again as first domain for block 3 (domains 11-16).

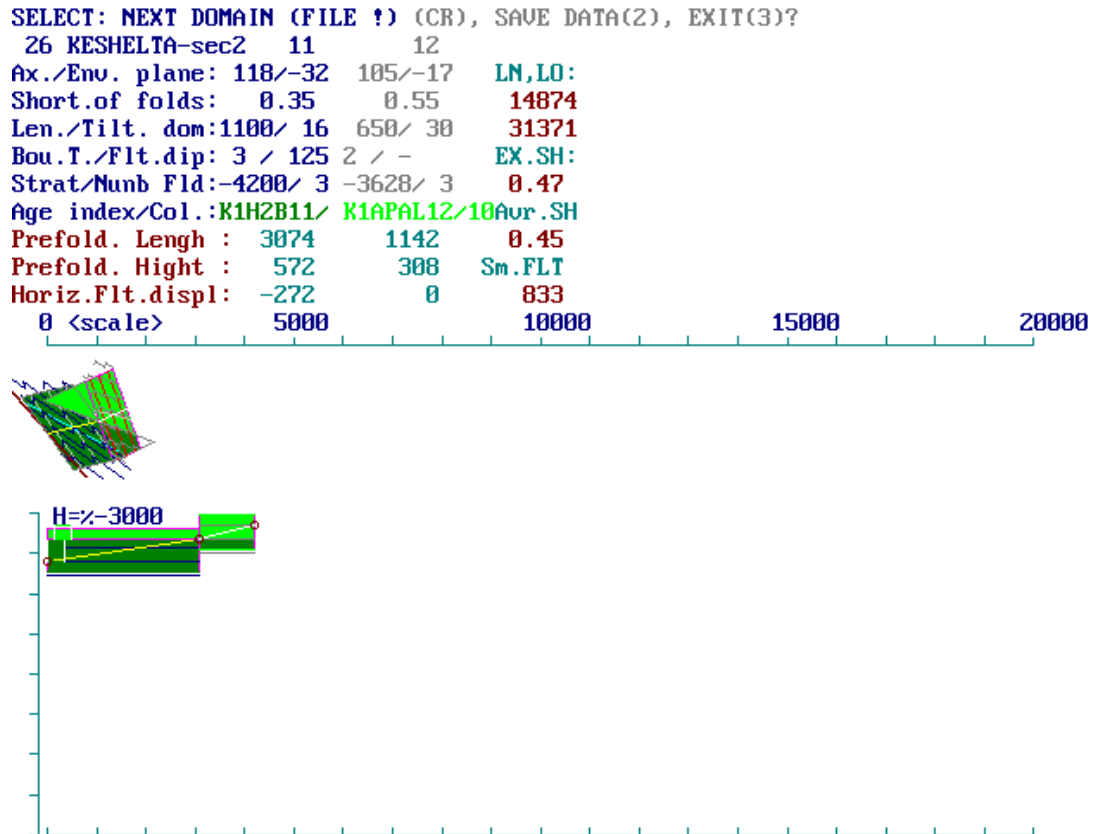


Fig. 31. Result of reconstruction of domain 12.

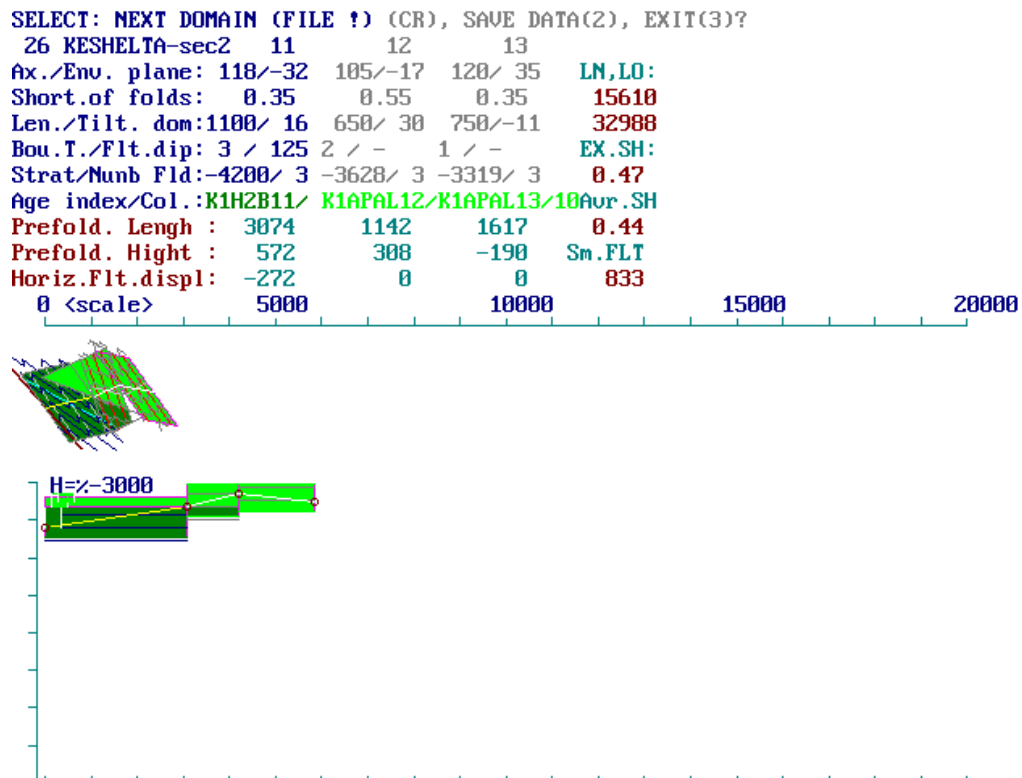


Fig. 32. Result of reconstruction of domain 13.

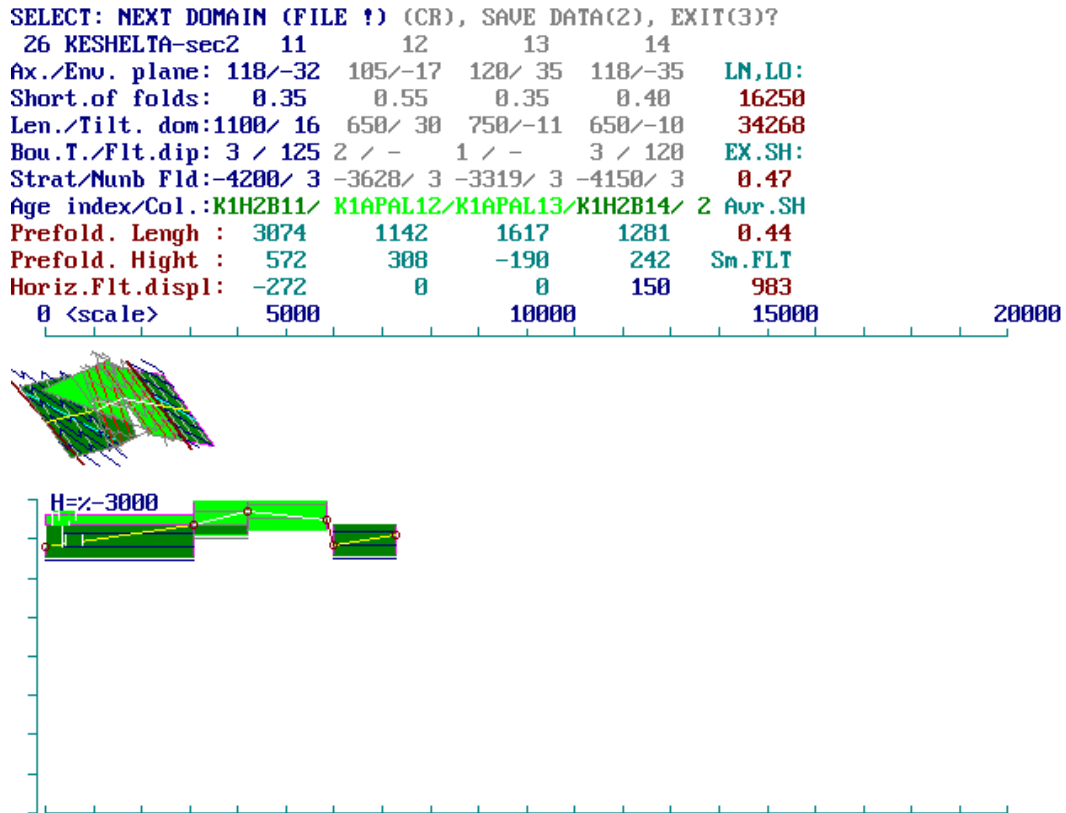


Fig. 33. Result of reconstruction of domain 14. Parameters of the thrust between domains 13 and 14 were calculated.

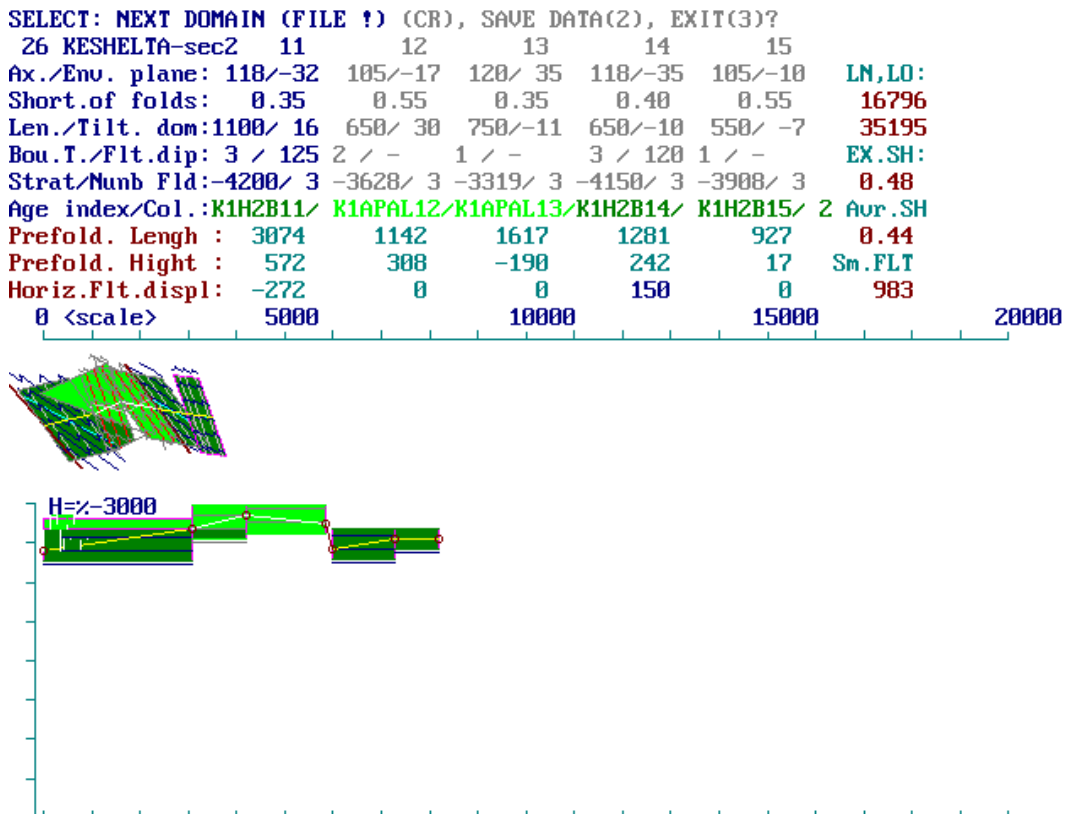
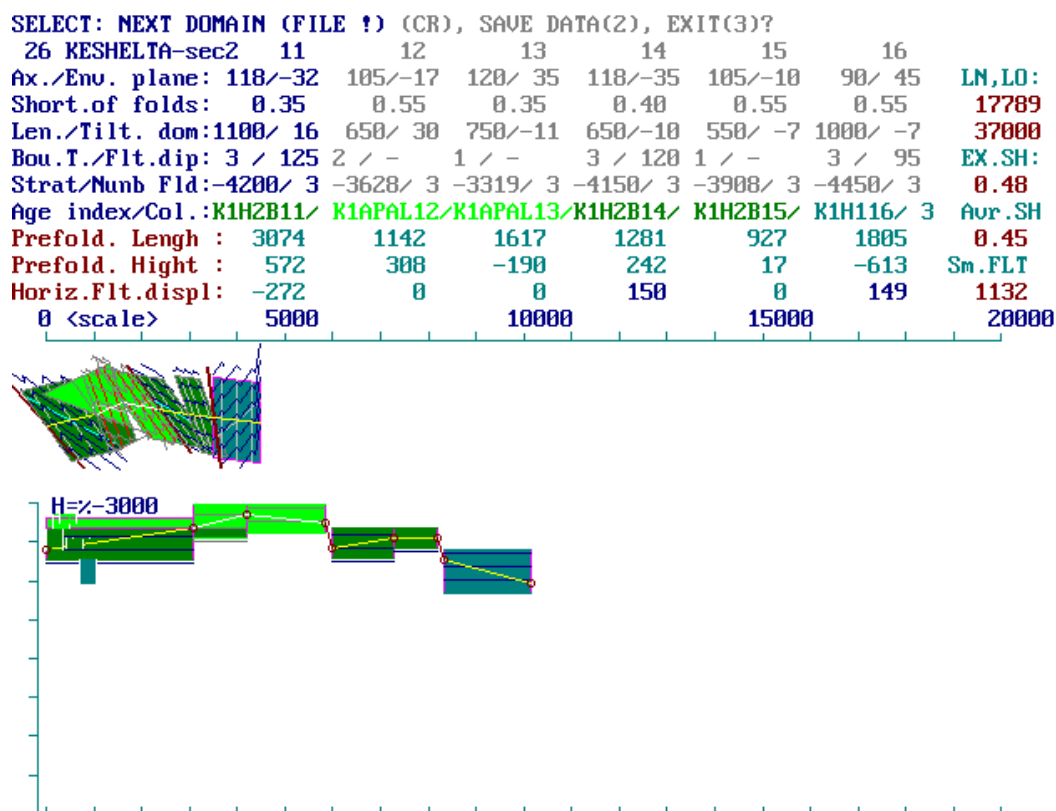
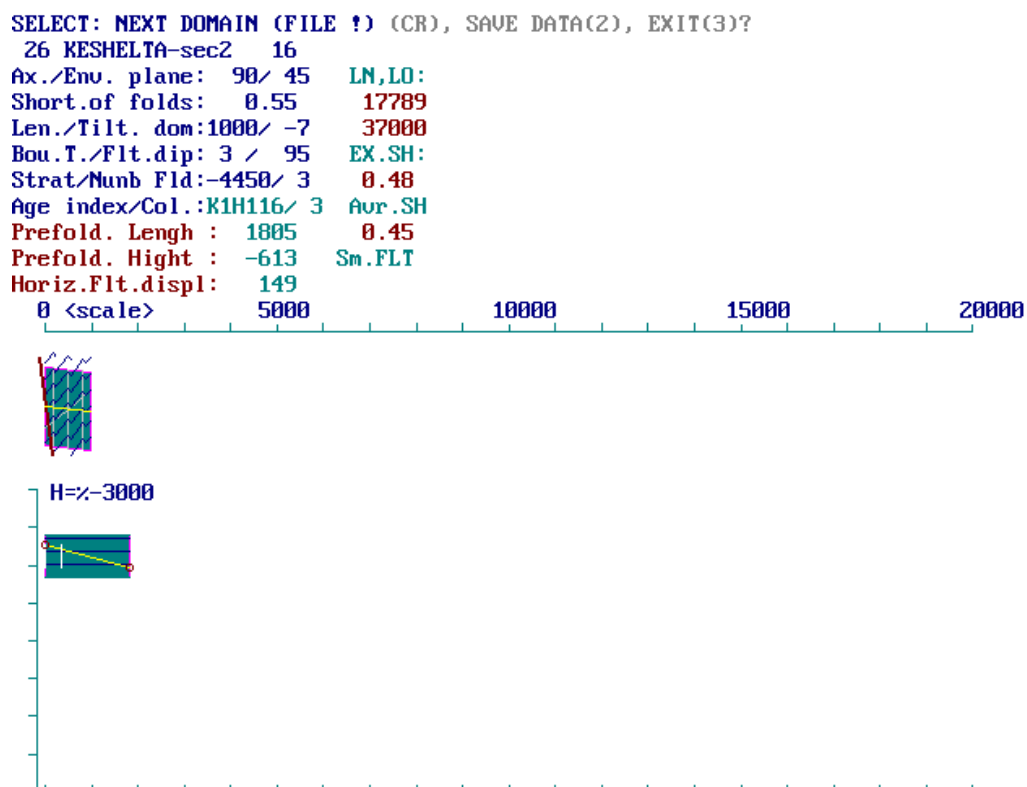


Fig. 34. Result of reconstruction of domain 15.



**Fig. 35.** Result of reconstruction of domain 16. Parameters of next small thrust before 16 were calculated. After this operation, the “copy screen” function should be done for the registration of reconstruction of domains block (11-16).

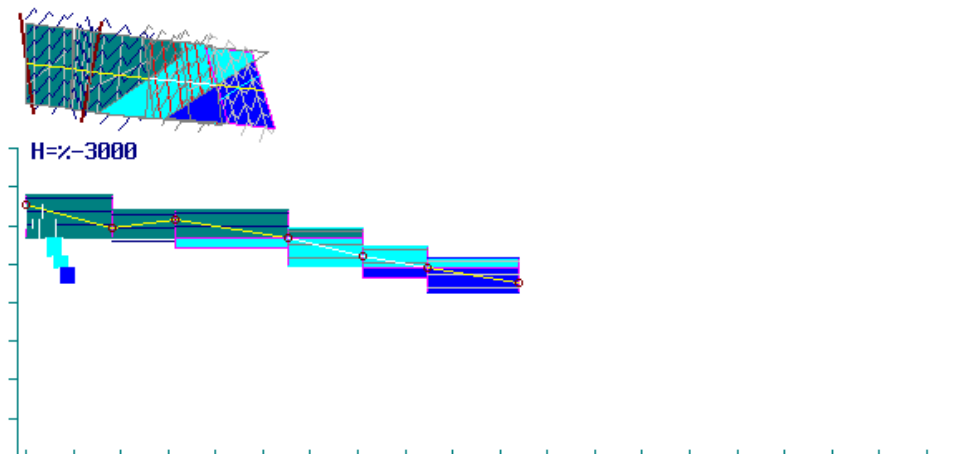


**Fig. 36.** Result of reconstruction of domain 16 is shown again. It is first domain for block 4 (domains 16-21).

```

SELECT: NEXT DOMAIN (FILE !) (CR), SAVE DATA(2), EXIT(3)?
26 KESHELTA-sec2  16      17      18      19      20      21
Ax./Env. plane:  90/ 45   85/-65  85/ 30   95/ 50   95/ 37  102/ 40  LN,LO:
Short.of folds:  0.55   0.30   0.52   0.50   0.50   0.50  21913
Len./Tilt. dom:1000/-7 400/-8 1250/-7 800/-6 700/-6 1000/-5 45591
Bou.T./Flt.dip:  3 / 95  1 / -    3 / 80  2 / -    1 / -    2 / -    EX.SH:
Strat/Nunb Fld:-4450/ 3 -5063/ 3 -4850/ 3 -5328/ 3 -5797/ 3 -6078/ 3 0.48
Age index/Col.:K1H116/ 3K1H117/ 3K1H118/ 3K1V219/11K1V220/11K1V121/ 9  Avr.SH
Prefold. Length : 1805   1332   2402   1571   1374   1913  0.45
Prefold. Hight  : -613   201   -478   -469   -281   -400  Sm.FLT
Horiz.Flt.displ:  149    0      4      0      0      0    1136
0 <scale>         5000         10000         15000         20000

```

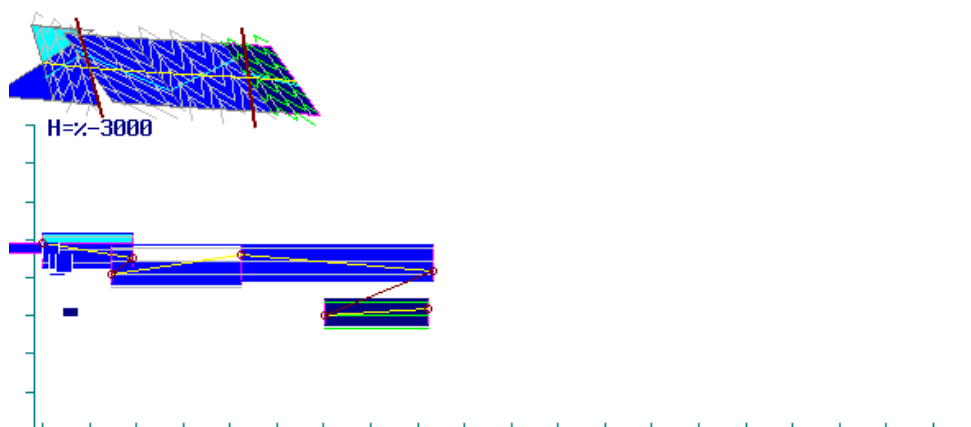


**Fig. 37.** Result of reconstruction of domains 16 -21. The fault (thrust) between domains 17 and 18 was detected as very small in amplitude of displacement.

```

SELECT: NEXT DOMAIN (FILE !) (CR), SAVE DATA(2), EXIT(3)?
26 KESHELTA-sec2  21      22      23      24
Ax./Env. plane:  102/ 40  120/-28  120/ 30  120/-18  LN,LO:
Short.of folds:  0.50   0.45   0.40   0.40  26406
Len./Tilt. dom:1000/-5 1500/-4 1950/-3 1050/-3 54645
Bou.T./Flt.dip:  2 / -    3 / 102  1 / -    3 / 95  EX.SH:
Strat/Nunb Fld:-6078/ 3 -6900/ 3 -6382/ 3 -8000/ 3 0.48
Age index/Col.:K1V121/ 9K1V122/ 9K1V123/ 9J3-24/ 1  Avr.SH
Prefold. Length : 1913   2763   4089   2202  0.45
Prefold. Hight  : -400   518   -425   162  Sm.FLT
Horiz.Flt.displ:  0     -445    0    -2291 -1601
0 <scale>         5000         10000         15000         20000

```



**Fig. 38.** Result of reconstruction of domains 21 – 24. Combinations of orientations of initial fault plains with vertical positions of started points for next domains (21/22 and 23/24) indicate displacements as “normal faults” in restored structure.

```

SELECT: NEXT DOMAIN (LAST !) (CR), SAVE resume file kesh-12.DCS - Ok! (CR)?
 26 KESHELTA      21      22      23      24      25      26
Ax./Env. plane: 102/ 40 120/-28 120/ 30 120/-18 112/-30 95/-20 LN,LO:
Short.of folds:  0.50  0.45  0.40  0.40  0.30  0.30      29154
Len./Tilt. dom:1000/ -5 1500/ -4 1950/ -3 1050/ -3 1750/ -2 1000/ -2 63282
Bou.T./Flt.dip:2 / -   3 / 102 1 / -   3 / 95 1 / -   3 / 118 EX.SH:
Strat/Numb Fld:-6078/ 3 -6900/ 3 -6382/ 3 -8000/ 3 -7838/ 3 -8400/ 3  0.46
Age index/Col.:K1U121/ 9K1U122/ 9K1U123/ 9J3-24/ 1 J3-25/ 1 J2-26/ 5 Avr.SH
Prefold. Lengh : 1913  2763  4089  2202  5329  3308  0.43
Prefold. Hight : -400  518  -425  162  400  102  Sm.FLT
Horiz.Flt.displ:  0  -445  0  -2291  0  5662  4061
 0 <scale>      5000      10000      15000      20000

```

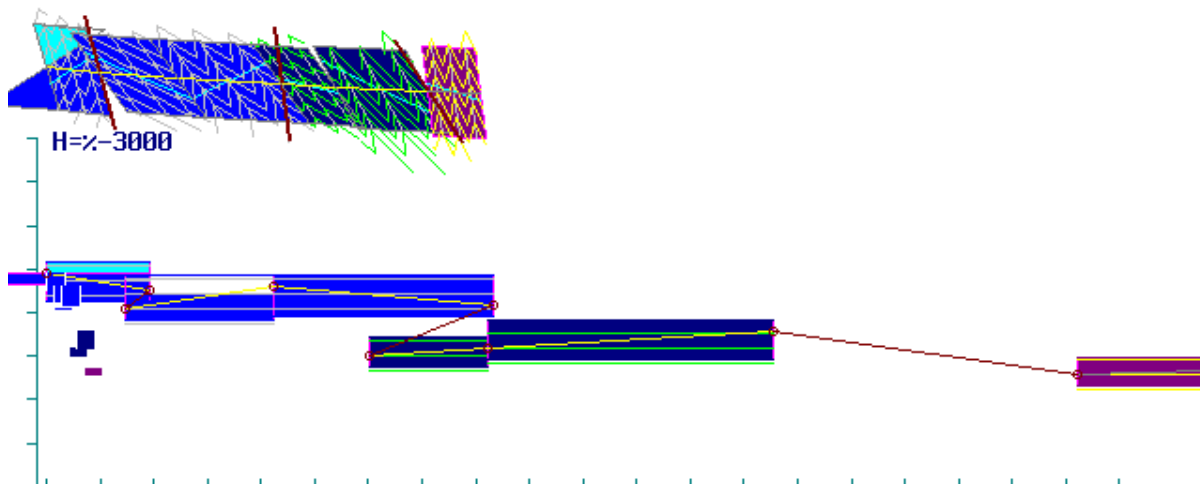


Fig. 39. Result of reconstruction of domains 21 – 26.

The domain 26 in fig. 39 belongs to the Kazbegi-Lagodekhy tectonic zone of Greater Caucasus, which is located to the north from the Chiaur zone. The structure of the domain 26 on a chain of circumstances was not studied rather well directly during the field work, and its parameters were not measured on a profile as exact. However, as the stratigraphic model of the Kazbegi-Lagodekhy zone in general is similar to the model of the Chiaur zone, and the value of the depth of the Middle Jurassic rocks could be accepted by the same (-8400 m, are 400 m lower than the sole of the Upper Jurassic), computations were made. For these operations, parameters of the domain 26 were accepted as close to domain 25 parameters. In this regard, the estimated amplitude of horizontal shortening on a thrust of 5662 m should be considered as a very approximate value.

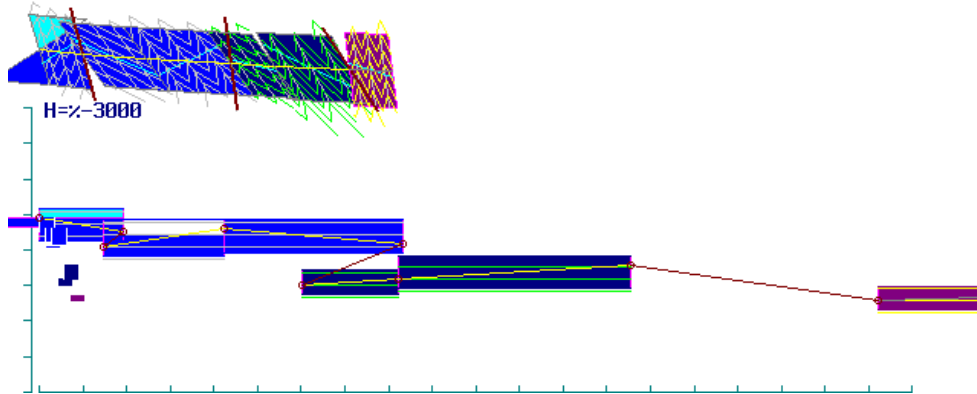
**NB!:** In the top line of the screen (fig. 39) the red word "LAST" indicates the last domain from the file of data, No. 26. At his emergence the buzzer can sound. In the same line also the request for creation of the full file of the report on calculations has been made (\*.DCS). On inquiry, the answer "yes" has been given, further the file ("KESH-12.DCS") has been written down on a disk. In this situation (fig. 39) after pressing of "ENTER" the program will pass to the following operations.

On the following step (fig. 40, 41) in the top line the request for record of the current (final) version of the file of data for a case, when changes have been made to him during the last balancing, has been made. At the same time, the calculated new depths of domains will be made in the file records. It allows to record all made changes and to repeat if necessary the successful version of the reconstruction.

```

DOMAIN 2 INSERT NAME OF FILE - ?                                CR)?
26 KESHELTA-sec2  21      22      23      24      25      26
Ax./Env. plane: 102/ 40 120/-28 120/ 30 120/-18 112/-30 95/-20  LN,LO:
Short.of folds:  0.50   0.45   0.40   0.40   0.30   0.30  29154
Len./Tilt. dom:1000/ -5 1500/ -4 1950/ -3 1050/ -3 1750/ -2 1000/ -2  63282
Bou.T./Flt.dip:2 / -   3 / 102 1 / -   3 / 95 1 / -   3 / 118  EX.SH:
Strat/Numb Fld:-6078/ 3 -6900/ 3 -6382/ 3 -8000/ 3 -7838/ 3 -8400/ 3  0.46
Age index/Col.:K1U121/ 9K1U122/ 9K1U123/ 9J3-24/ 1 J3-25/ 1 J2-26/ 5  Avr.SH
Prefold. Length : 1913   2763   4089   2202   5329   3308  0.43
Prefold. Hight  : -400   518   -425   162   400   102  Sm.FLT
Horiz.Flt.displ:  0     -445   0     -2291  0     5662  4061
0 <scale>         5000         10000         15000         20000

```

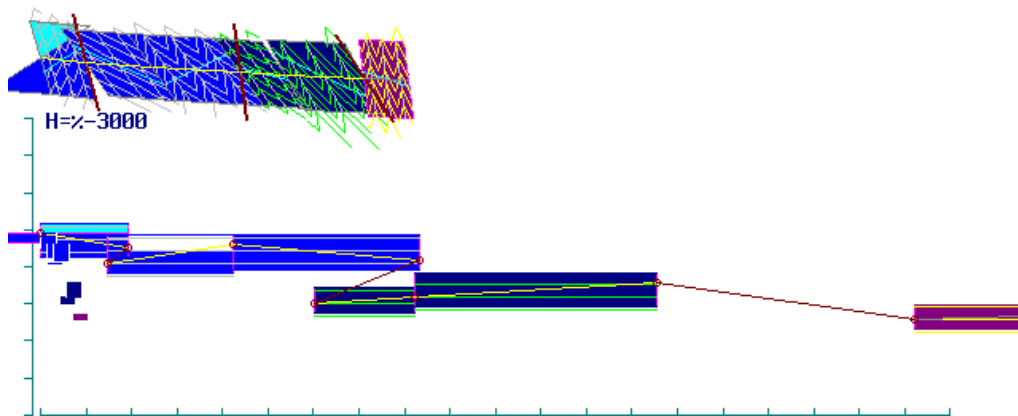


**Fig. 40.** Final procedures of reconstruction for domains 21 – 26. Request on writing of current (final) version of file data for case after some changing during balancing in the upper line. It allows to fix all changes and to repeat the successful version of reconstruction.

```

DOMAIN 2 INSERT NAME OF FILE - ? chi-2a.bcs                    CR)?
26 KESHELTA-sec2  21      22      23      24      25      26
Ax./Env. plane: 102/ 40 120/-28 120/ 30 120/-18 112/-30 95/-20  LN,LO:
Short.of folds:  0.50   0.45   0.40   0.40   0.30   0.30  29154
Len./Tilt. dom:1000/ -5 1500/ -4 1950/ -3 1050/ -3 1750/ -2 1000/ -2  63282
Bou.T./Flt.dip:2 / -   3 / 102 1 / -   3 / 95 1 / -   3 / 118  EX.SH:
Strat/Numb Fld:-6078/ 3 -6900/ 3 -6382/ 3 -8000/ 3 -7838/ 3 -8400/ 3  0.46
Age index/Col.:K1U121/ 9K1U122/ 9K1U123/ 9J3-24/ 1 J3-25/ 1 J2-26/ 5  Avr.SH
Prefold. Length : 1913   2763   4089   2202   5329   3308  0.43
Prefold. Hight  : -400   518   -425   162   400   102  Sm.FLT
Horiz.Flt.displ:  0     -445   0     -2291  0     5662  4061
0 <scale>         5000         10000         15000         20000

```



**Fig. 41.** Final procedures of reconstruction for domains 21 – 26 and entire section. The name for writing of final kind of file data was typed (chi-2a.bcs) in the upper line.



In fig. 41, the last operations of work of the PC program are shown. Further the following operations have to be executed: 1) to come back to the main menu (fig. 5) – to press 3, ENTER; and then, in the main menu 2) to press 5, ENTER for normal termination of work of the CROSS-B4.EXE program.

After execution of all operations mentioned above (chapters 5.1 – 5.5), there are several results of reconstruction of pre-folded structure of cross-section 12(Keshelta):

- a) 5 blocks of “copy screen” images,
- b) New version of data set of structure of domains (\*.bcs),
- c) Resume file of results of calculations (\*.dcs).

Further operations of reconstructions of folded structure in volume of entire sedimentary cover are disposed outside of work of “CROSS-B4.EXE” PC program.

### ***5.6 Compilation of entire structural section in pre-folded state***

Five blocks of domains (1-6; 6-11; 11-16 ...) in the form of \*.bmp or \*.tif files (it is better to have not \*.jpg !) should be aggregated in one image with three zones of information. Of course, junction of two adjacent blocks should be used by matching the last/first block (6, for example for blocks 1-6 and 6-11). Program MS Paint may be used for aggregation. It is necessary to increase images separately for three zones (fig. 42): pre-folded structure, a zone "C", modern folded structure – a zone "B" and a zone of the table "A", using copy screen images. In the fig 42, whole volume of sedimentary cover, which exists according to sedimentary model. Copies of blocks 1-6, 6-11 and other domains have been used; around these domains empty (white) strips are shown.

### ***5.7 Procedures of the structure balancing***

As it is clear from fig. 42, main goal of balancing is the compilation of such structure, which has almost constant depths positions of stratigraphic units according to stratigraphic model. As it is well visible, each of borders of 10 the stratigraphic units along a profile of 65 km long stretch section have almost constant depths; these units have almost constant thicknesses. It means that main operation of balancing should be an establishment of correct depth of stratigraphic units of each domain after an interruption of structure by the plain of fault. Choice of depth of started point of domain should be such that the position of next stratigraphic boundary should coincide with the model value. If it will be necessary, the problematic places of structure should be balancing again with other depths of started point of domain or using some deviation of other parameters – Af, SH, AX, EN.

There are two cases of difficulties which may appear during the retro-deformation of the structure. Most difficult case is when orientations of fault plain and of initial layering (of envelope surface of folds) are close. In this case pre-folded orientation of fault plain will be almost horizontal. It means, that even small vertical displacement will give a very high value of horizontal displacement (see fault domains 25/26, fig. 42). This case may produce



the error in calculations and a crash of program. Whenever possible, it is necessary to avoid such situations using an insertion of some deviation of measurements. Other case is very large vertical displacement and relatively high horizontal displacement (5-10 km and more) on a plane of large fault. Such estimate can not be exact, because dip of surface of fault on large distance can not be flat plain (relatively small displacement of fault, 1-3 km, and flat fault plane are postulates of model for calculations). If it is necessary, some corrections of main properties of domain (AX, EN, SH) may be done, because deviations of these parameters in concrete natural folds are taking place usually.

If several parallel structural sections exist, the comparison of results of reconstructions of adjacent sections makes sense. The idea of linear properties of structure and of any standard width of structure may be used in this case. If any fault in one section will produce abnormal distance of displacement (see second case above), the width of adjacent structure, which has not a large fault, should be used for calibration.

The character of faults in natural folded structure and in their pre-folded state can differ from habitual representations. For example, usual definition "thrust/normal fault", connected only with age of rocks and the direction of displacement on the fault plane can be more complicated. So, the definition of fault between domains 23/24 (fig. 41) is as "thrust" based on usual ruling (older age rocks in raised hanging wall block). However, this discontinuity was diagnosed as normal fault after restoration. There was important a ratio of angles of dips of the axial planes of folds and the plane of the fault. It is necessary to notice also, the final result after restorations of many structural sections in Greater Caucasus, in fact, is that total amount of displacements due to "thrusts" and "normal faults" separately are almost equal; the natural folding has faulting structures of both types.

### ***5.8 Ways of correction of data file (\*.bcs)***

Most suitable method is a correction of initial version of data file in MS NotePad. (Be carefully! The empty line should be last after line of final domain data). After the writing a corrected data to disk (after saving data), this file should be loaded to program "Cross-b4.exe" again. It is possible also to correct data immediately after display of domain parameters (see fig.18) during a work of program. At this case (choice: 1, enter) each parameter should be inserted, including new corrected and old one (AX, EN; SH; L, Tlt; Bnd, Dip Fault; Strat., NumFld; Age, Color). (**NB!** Parameters of all next domains at this case should be inserted by keyboard also).

For the first case of data processing in program "Cross-b4.exe", depths of domains in cases "after fault planes" should be established in file \*.bcs, of course. All depths for routine domains (not after fault) may be indicated as "0". During calculations, these parameters will be calculated and during final writing of data file it will be written to file \*.bcs. Writing of file (data recovery) may be used after any domain processing (choice 2 "SAVE DATA", fig.

38, for instance). All other domains (N+1...) will be not saved in this case, thus it is better to use a new name of file6 therefore in this case it is better to use the new name of the file, in order to avoid total loss of old. Normal termination of program without of change of data file (for further edition in NotePad, for instance) will be made in choice "3, Enter" after any domain processing.

Full information about all initial and calculated parameters may be written in "resume" file (\*.dcs, fig. 39). However, this file possesses a complicated structure, and for usual goals, information, which exists in copy-screen images, is enough.

## **6. The guide to a creation of the structure, which is balanced on the volume of a sedimentary cover. Usage of materials of execution of PC program "CROSS-B4.EXE"**

### ***6.1 Creation of the Excel table of results of calculations (based on listings of copies of the screen, there is the "SECTION-2.XLS" file)***

On the first step of a compilation of quasi-3D model of sedimentary cover, it is necessary to collect main data of in a table and to calculate a total shortening of structure in cross-section (fig. 43). For this goal, most easy method is to use copies of screen (1-6; 6-11 ...). Parameters length of section line and tilting of this line (fig. 43, B, letters F, 1500 and G,-4) should be placed in columns F and G of table "section-2.xls". Horizontal length of this line are calculated in column "H". Formula of xls-cell is  $[H(N)=F(N)*\cos(G(N))]$ . Results of calculation of pre-folded structure, such as horizontal length of pre-folded section line of domain (D, 2763, fig. 43B) and displacement on a fault plain (C, -445, fig. 43B) are placed in columns C and D (fig. 43A). Summation of lines lengths and of displacements C (N), D (N) and accumulation with previous data placed in column E; it will be pre-folded length of section. Formula of xls-cell is  $E(N) = C(N) + D(N) + E(N-1)$ . Similar accumulation as actual length of section placed in column "I"; formula is  $I(N)=I(N-1)+H(N)$ .

As result of this step, we calculated a total shortening of structural section. For domains 2-25 (Chiaur zone only) pre-folded length of section is 57134 (see column F line 40; "F"40; 58375 - 1241) and actual length of section is 27155 (see "G"40; 28156 - 999). Shortening value for domains 2-25 is 0.48 or 52.5% (see "I"42 and "I"43).

### ***6.2 Choice of structural cells in pre-folded state of structural section***

Shortening value for entire tectonic zone of 60-km initial width is important information, but it is not very interesting for the further analysis. At the discussed stage it was necessary to find a solution – what extent of such structure in which pure tectonic shortening can be defined without a distortion by disharmony. The solution was found within ideas of the "structural cell", which was used in "The Simplest Mathematical Model of Advection" (SMMA) of M.A. Goncharov [Goncharov, 1979].

	A	B	C	D	E	F	G	H	I	J
1										
2		<b>2</b>	<b>Keshelta</b>							
3				pre-folded		length		horizontal		
4			distance	length	sum	domain		domain	cumulative	
5		domain N	fault	domain		actual	tilting	length	length	
6		<b>1</b>	0	1241	<b>1241</b>	1000		-2	999	999
7		<b>2</b>	-291	3920	<b>4870</b>	2200		1	2200	3199
8		<b>3</b>	0	2942	<b>7812</b>	1650		3	1648	4847
9		<b>4</b>	0	883	<b>8695</b>	400		3	399	5246
10		<b>5</b>	0	3188	<b>11883</b>	1500		3	1498	6744
11		<b>6</b>	0	1427	<b>13310</b>	750		1	750	7494
12		<b>7</b>	0	3140	<b>16450</b>	1650		1	1650	9144
13		<b>8</b>	0	3132	<b>19582</b>	1500		7	1489	10633
14		<b>9</b>	0	4274	<b>23856</b>	1300		9	1284	11917
15		<b>10</b>	1396	3007	<b>28259</b>	1350		8	1337	13254
16		<b>11</b>	-272	3074	<b>31061</b>	1100		16	1057	14311
17		<b>12</b>	0	1142	<b>32203</b>	650		30	563	14874
18		<b>13</b>	0	1617	<b>33820</b>	750		-11	736	15610
19		<b>14</b>	150	1281	<b>35251</b>	650		-10	640	16250
20		<b>15</b>	0	927	<b>36178</b>	550		-7	546	16796
21		<b>16</b>	149	1805	<b>38132</b>	1000		-7	993	17789
22		<b>17</b>	0	1332	<b>39464</b>	400		-8	396	18185
23		<b>18</b>	4	2402	<b>41870</b>	1250		-7	1241	19425
24		<b>19</b>	0	1571	<b>43441</b>	800		-6	796	20221
25		<b>20</b>	0	1374	<b>44815</b>	700		-6	696	20917
26		<b>21</b>	0	1913	<b>46728</b>	1000		-5	996	21913
27		<b>22</b>	-445	2763	<b>49046</b>	1500		-4	1496	23410
28		<b>23</b>	0	4089	<b>53135</b>	1950		-3	1947	25357
29		<b>24</b>	-2291	2202	<b>53046</b>	1050		-3	1049	26406
30		<b>25</b>	0	5329	<b>58375</b>	1750		-2	1749	28155
31		<b>26</b>	5662	3308	<b>67345</b>	1000		-2	999	29154
32					<b>67345</b>					29154
33					<b>67345</b>					29154
34					<b>67345</b>					29154
35					<b>67345</b>					29154
36					<b>67345</b>					29154
37					<b>67345</b>					29154
38			0	0	<b>67345</b>					29154
39			0	0	<b>67345</b>	dom. 2-25	dom. 2-25			29154
40			0	0	<b>67345</b>	57134	27155			29154
41			faults	domains	<b>67345</b>	pre-folded				29154
42			4062	63283	<b>67345</b>	-1600	53072		0,48	SH
43					<b>67345</b>	fault			52,47	
44										
45										
46										

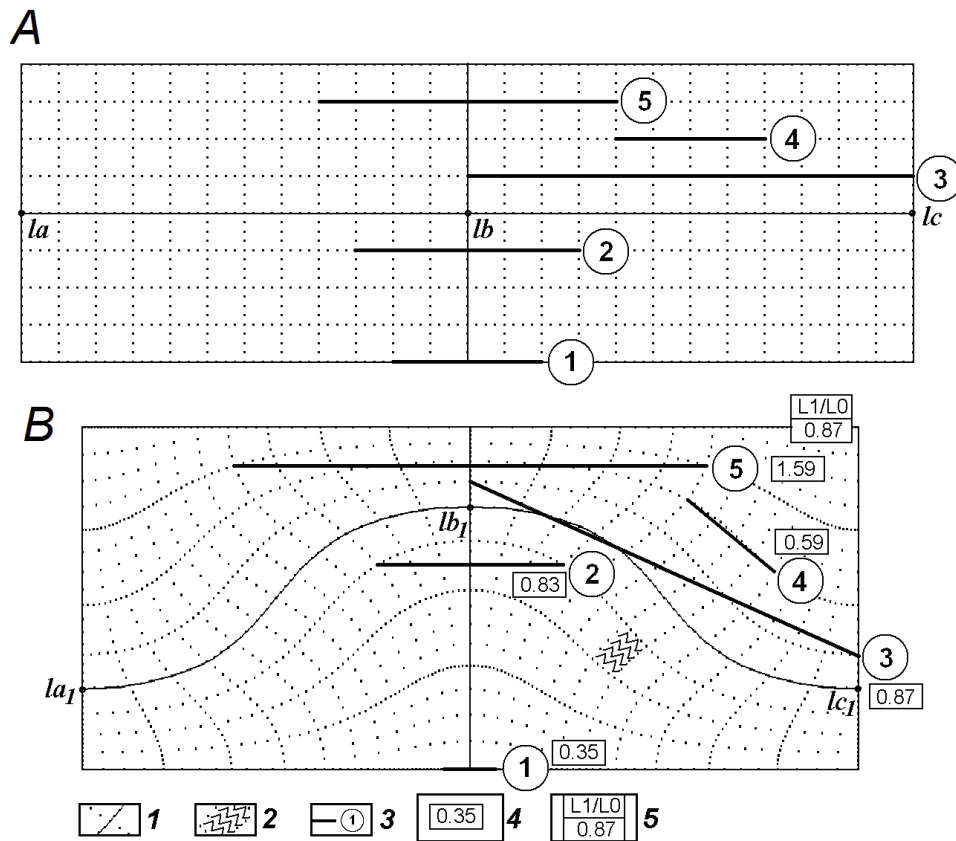
26 KESHELTA-sec2 21 22  
 Ax./Env. plane: 102/ 40 120/-28  
 Short.of folds: 0.50 0.45  
 Len./Tilt. dom:1000/ -5 1500/ -4 **F G**  
 Bou.T./Flt.dip:2 / - 3 / 102  
 Strat/Numb Fld:-6078/ 3 -6900/ 3  
 Age index/Col.:K1U121/ 9K1U122/  
 Prefold. Length : 1913 2763 - D  
 Prefold. Hight : -400 518  
 Horiz.Flt.displ: 0 -445 - C

B

Fig. 43. Table "SECTION-2.XLS" (A) and (B) as source of its information, which is copy screen of calculated table, part of fig. 41. Positions of parameters of PC program in copy-screen in "SECTION-2.XLS" are shown (C, D, F, G).

At this case, the term "advection" means a specific kind of convection at which the movement only 0.5 of one cycle from usual multiple convective cycles is implemented. Due to this theoretically possible process, sedimentary rocks of smaller density from the lower half of structure exchange places with rocks of bigger density of the top part of structure. For example, this process, undoubtedly, takes place in diapiric folds in the fields of salt tectonics. In the PMMA model of M.A. Goncharov, only the kinematics of movement of points in a cell is used, any aspects of physics or dynamics of process in it aren't considered.

The initial idea and main objective of PMMA consisted in studying of deformations in a convective cell, which covers all sedimentary cover. At the same time for an explanation of emergence of structure, the kind of thermal convection without the general horizontal shortening was used that had to interpret the origin of a linear folding within one of versions of "fixism". In the nature, increase in volume of rocks in the lower part of a cover as a result of metamorphic reactions in clay rocks was considered as an analog of "thermal" convection [Sholpo, 1978]. The treasure of this model for us consists in idea that two levels of deformation are integrated in the same model – there are deformations of domains (for a package of layering of 0.5-2-km thickness; here small folds exist) which arise in the large



**Fig. 44.** Disharmony of deformations in a structural cell [Yakovlev, 2008a] in version of “quasi-buckling”. A – two adjacent cells in an initial state, B – the same two cells after action of a combination of convective movements (stage 1, Goncharov’s SMMA model was used) and flattening  $K=0.87$  (stage 2). Combination of two stages was such, that line  $la-lb-lc$  has the same length in both stages. 1 – the initial grid and its distortion, 2 – the symbolical image of folds within the conventional domain, 3 – the studied segment and its number, 4 – the value of horizontal shortening for a segment, 5 – the value of general shortening for cells. Heterogeneity of deformation of horizontal shortening for different structures within cells is shown; shortening value coincides with the general shortening only for the segment 3.

folds embraced entire sedimentary cover (10–15 km of thickness). Modification of this model due to an including of some value of a shortening (fig. 44) was used for modeling of a longitudinal bend/buckling (in scale of entire sedimentary cover). "The structural cell" was allocated as space between the "anticlinal" axial vertical line (in points of  $lb$ ,  $lb_1$ ) and the "synclinal" line (in points of  $lc$ ,  $lc_1$ ), in other words, it is a half wave of a big fold. The analysis of disharmony of this modified model (pay attention to size of shortening of five different segments) shows that only "the structural cell" can be used for measurement of pure "tectonic" reduction (fig. 44). For our purpose, this result means that "the structural cell" (length between points of  $lb$  and  $lc$ , fig. 44) has to be allocated in such horizontal (pre-folded) space of the layered environment, which is close by the size to the size of thickness of a sedimentary cover. It is the smallest structure, which has "tectonic" shortening, and in which this result isn't influenced by internal disharmony.

Because total pre-folded width of structure of Chiaur tectonic zone is 55-60 km, and thickness of sedimentary cover is close to 15 km, an amount of structural cells inside zone may be 4-5 cells.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1														
2		<b>2</b>	Keshelta								cover	15300		
3				pre-folded		length		horizontal						
4			distance	length	sum	domain		domain	cumulative					
5		domain N	fault	domain		actual	tilting	length	length					
6		1	0	1241	1241	1000	-2	999	999					
7		2	-291	3920	4870	2200	1	2200	3199	1		3629		
8		3	0	2942	7812	1650	3	1648	4847			6571		
9		4	0	883	8695	400	3	399	5246			7454		
10		5	0	3188	11883	1500	3	1498	6744	12069	6495	10642		
11		6	0	1427	13310	750	1	750	7494	0,54		12069		
12		7	0	3140	16450	1650	1	1650	9144	46,19		3140	2	
13		8	0	3132	19582	1500	7	1489	10633			6272	10546	4423
14		9	0	4274	23856	1300	9	1284	11917			10546	0,42	10546
15		10	1396	3007	28259	1350	8	1337	13254			4403	58,06	
16		11	-272	3074	31061	1100	16	1057	14311			7205		
17		12	0	1142	32203	650	30	563	14874			8347		
18		13	0	1617	33820	750	-11	736	15610			9964		
19		14	150	1281	35251	650	-10	640	16250			11395		
20		15	0	927	36178	550	-7	546	16796	3		12322		
21		16	149	1805	38132	1000	-7	993	17789	14276	5872	14276		
22		17	0	1332	39464	400	-8	396	18185	0,41		1332		
23		18	4	2402	41870	1250	-7	1241	19425	58,87		3738		
24		19	0	1571	43441	800	-6	796	20221			5309		
25		20	0	1374	44815	700	-6	696	20917			6683		
26		21	0	1913	46728	1000	-5	996	21913	4		8596		
27		22	-445	2763	49046	1500	-4	1496	23410	10914	5821	10914		
28		23	0	4089	53135	1950	-3	1947	25357	0,52		4089	5	
29		24	-2291	2202	53046	1050	-3	1049	26406	48,50		4000	3329	4745
30		25	0	5329	58375	1750	-2	1749	28155			9329	0,51	9329
31		26	5662	3308	67345	1000	-2	999	29154			18299	49,14	
32					67345				29154					

**Fig. 45.** Calculations of shortening value for 5 structural cells in file CELL-3.XLS. Pre-folded and actual lengths of cells are shown in xls-cells of green color. Results in SH (46.19%) and K (0.54) are shown in “bold type” cells.

For the aim of choice of structural cells boundaries, the table “section-2.xls” may be used, because function of accumulation of pre-folded width of structure is implemented here (column "E", fig. 43,A). Other property of structure, which is necessary to take into account, is folds of large scale (i.e. sequences of EN inclinations in domains) and an existence of large scale faults. Based on these ideas, five cells were selected (fig. 42, 45). The boundary between cells 1 and 2 is clearest case, because it was traced in hinge of very large anticline fold.

### 6.3 Calculation of value of shortening for the chosen structural cells (modification of the SECTION-2.XLS file up to the CELL-3.XLS file)

Shortening value for each structural cell may be easily calculated based on table CELL-3.XLS. For this aim, the table SECTION-2.xls is used, which should be copied into file CELL-3.XLS. Here, a pre-folded length of cell “1” is calculated in xls-cell “J10” as  $J(10)=E(11)-E(6)$ . The actual length of the cell is calculated in xls-cell (K10) as  $K(10)=I(11)-I(6)$ . Result of calculation of shortening coefficient K is placed in xls-cell (J11) as  $J(11)=K(10)/J(10)$  and in SH% value as  $J(12) = (1-J(11))*100$ . Analogical values were calculated in xls-cells M14, J22, J28, M51. It is interesting, that pre-folded widths of cells consist in absolute values 12.1, 10.5, 14.3, 10.9, 9.3 km, which are some lesser than 15 km of thickness of sedimentary cover, nevertheless they are close enough to this value. Width of 5th cell may be the matter of discussion due to the thrust having a large displacement before 26th domain.

```

26 KESHELTA-sec2  21      22      23
Ax./Env. plane: 102/ 40  120/-28  120/ 30
Short.of folds:  0.50   0.45   0.40
Len./Tilt. dom:1000/ -5  1500/ -4  1950/ -3
Bou.T./Flt.dip:2 / -    3 / 102 1 / -
Strat/Nunb Fld:-6078/ 3  -6900/ 3  -6382/ 3
Age index/Col.:K1U121/ 9K1U122/ 9K1U123/
Prefold. Length : 1913   2763   4089
Prefold. Height : -400   518   -425
Horiz.Flt.displ:  0     -445   0

```

**Fig. 46.** Sources of material for table of "CELL-4.XLS" file. Parameters "prefolded height displacement" from first to "end" points (C) and depth of first point of domain "strat" (B) are using for calculation of average depth of section line in the cell. Length and tilting of section line (L, M) are using for calculation of average altitude (topography) of section line in the cell.

**6.4 Calculation of average "stratigraphic" depth of the line of a profile for structural cells, of average topographical height and value of "neotectonic uplift". Formation of the CELL-4.XLS file based on listings of copies of the screen**

Next step of compiling of quasi-3D model of sedimentary cover is a calculation of position of structural cell in sedimentary cover column and of amplitude of neotectonic uplift or (almost the same) magnitude of syn-folded and syn-mountain-building erosion of upper part of sedimentary cover. For this purpose materials of copy screen are used (fig. 46), which are placed in two adjacent tables ("CELL-4.XLS" file, fig. 47, 49, 50). An average stratigraphic depth of section line for each structural cell is calculating in "Table 1" of

	A	B	C	D	E	F	G	H
1	<b>table 1</b>							
2	<b>calculation of depths (stratigraphic) of section lines for structural cells</b>							
3						average		2-nd stage
4	<b>section 2</b>	<b>Keshelta</b>			depth	depth	shortening	depth
5	number	first	delta	last	average	for cell	K(SH)	post-folded
6	1	-5000	115	-4885	-4943			
7	2	-2800	-499	-3299	-3050			
8	3	-3299	-878	-4177	-3738			
9	4	-4177	-333	-4510	-4344			
10	5	-4510	-967	-5477	-4994			
11	6	-5477	-792	-6269	-5873	-4400	0,54	-8147,22
12	7	-6269	931	-5338	-5804			
13	8	-5338	581	-4757	-5048			
14	9	-4757	488	-4269	-4513	-5121	0,42	-12193,7
15	10	-5200	787	-4413	-4807			
16	11	-4200	572	-3628	-3914			
17	12	-3628	308	-3320	-3474			
18	13	-3320	-190	-3510	-3415			
19	14	-4150	242	-3908	-4029			
20	15	-3908	17	-3891	-3900			
21	16	-4450	-613	-5063	-4757	-4042	0,41	-9858,71
22	17	-5063	201	-4862	-4963			
23	18	-4850	-478	-5328	-5089			
24	19	-5328	-469	-5797	-5563			
25	20	-5797	-281	-6078	-5938			
26	21	-6078	-400	-6478	-6278			
27	22	-6900	518	-6382	-6641	-5745	0,52	-11048,2
28	23	-6382	-425	-6807	-6595			
29	24	-8000	162	-7838	-7919			
30	25	-7838	400	-7438	-7638	-7384	0,51	-14478,1
31	26	-8400	102	-8298	-8349			

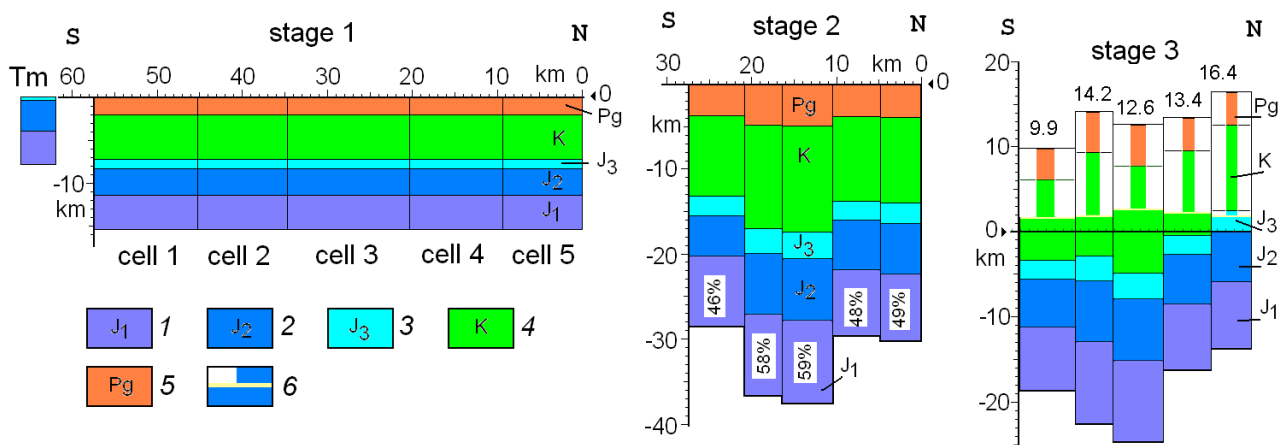
**Fig. 47.** Calculations of average stratigraphic depth of section line for structural cells 1-5 (table 1 of "CELL-4.XLS" file).



“CELL-4.XLS”. For this aim, depth of first point of domain (parameter B, fig. 46) placed in column B, fig. 47, deviation of depth between first and last points (parameter C, fig. 46) placed in column C, fig. 47. Depth of last point calculated in column D using of formula  $D(7)=B(7)+C(7)$ . Average depth for each domain was calculated in column E, using B and D. Using values of xls-cells of column E according to list of domains in cell (for instance, domains 2-6 for cell 1; E(7-11)), the average “stratigraphic” depth is calculated (xls-cells F11, F14, F21, F27, F30).

For the next steps it is necessary to establish the model of development of deformations (of tectonic events), which allows to find an algorithm of calculations. For the Greater Caucasus, the event of folding formation took place earlier, than uprising of structure during the mountain building [Milanovsky, 1968; Trifonov, Sokolov, 2014]. The period of shortening and folding began after Paleocene (35 m.y.) and, possibly, it has been terminated during Oligocene time. This stage is fixed by formation of the Maykopian series deposits, which formed the lower molasse (up to 17 m.y.). Neotectonic uplift began since Sarmatian age (15-13 m.y.), that was diagnostics by first occurrence of conglomerates in the upper molasse. The uplift was essentially accelerated in the last 5-2 m.y. Based on this opinion, model of three stages of events was established for calculations (fig. 48).

According to the model, at the end of first stage, the whole volume of sedimentary cover was accumulated and a horizontal plain layering (continuum) of sediments was formed. This stage is associated with pre-folded state of section (fig. 42 lower part “C”; fig. 48, stage 1). During the stage 2 (before stage 3) entire shortening value was realized. . It is considered that at the same time, the lower part of structure was sank down. The top part of a sedimentary layer didn't rise above sea level and wasn't exposed to an erosion (assumption exists for the model for calculation only). Last 15 m.y. at the 3d stage, already folded structure was uplifted and undergone of erosion. According to this model, post-folded average depths of structural cells were calculated (column “H”, table 1, fig. 47). This stratigraphic level of rocks was uplifted to height of present topography during the stage 3.



**Fig. 48.** Model of three conventional stages of tectonic events, which was used for calculations (section 12). (after [Yakovlev, 2012b], a part of fig. 5, p. 204, with changes). Five cells (stage 1), shortening values (stage 2) and calculated altitudes of a top of sedimentary cover (stage 3) are shown. TM – Transcaucasian massif. Deposits: 1 – Lower Jurassic, 2 – Middle Jurassic, 3 – Upper Jurassic, 4 – Cretaceous, 5 – Paleogene, 6 – the level a modern relief.

For the determining of magnitude of neotectonic uprising, the altitude of structural cells should be calculated in advance (fig. 49). Parameters of lengths and tilting of section lines were collected (L, M, fig. 46) and were placed to columns “L” and “M” of table 2 (fig. 49).

First position of section line was taken from topography map, the displacement for each domain was calculated using a formula  $N(i)=L(i)*\sin(M(i))$ . Using first and last topography positions of domain, average altitude of each domain was calculated in column “P”. Similar to table 1, average values of altitude of “structural cells” were calculated in xls-cells Q11, Q14, Q21, Q27, Q30.

Amplitude of neotectonic uplift was calculated as difference between actual altitude (topography) and 2-d stage depth of structure in table 3 (fig. 50). For example, cell 1st has neotectonic uplift  $9877=1730-(-8147)$ . It means, that mountain rocks with average stratigraphic depth of -8147 m were elevated on altitude of 1730 m. Certainly, it is necessary to consider that all sediments which were above this level were eroded. It is very possible that some part (half?) of this very large volume of eroded sedimentary column was eroded during folding formation before start of pure mountain building process. But at moment, there is no any evidences which allows to estimate this phenomenon. It means that

I	J	K	L	M	N	O	P	Q
1	<b>table 2</b>							
2	<b>calculation of altitude (topography) of line of structural cells</b>							
3								average
4	<b>section 2</b>	<b>Keshelta</b>					altitude	altitude
5	number	first	L	TLT	delta	last	average	for cell
6	1	1635	1000	-2	-35	1600	1618	
7	2	1600	2200	1	38	1638	1619	
8	3	1638	1650	3	86	1725	1682	
9	4	1725	400	3	21	1746	1735	
10	5	1746	1500	3	79	1824	1785	
11	6	1824	750	1	13	1837	1831	1730
12	7	1837	1650	1	29	1866	1852	
13	8	1866	1500	7	183	2049	1958	
14	9	2049	1300	9	203	2252	2151	1987
15	10	2252	1350	8	188	2440	2346	
16	11	2440	1100	16	303	2743	2592	
17	12	2743	650	30	325	3068	2906	
18	13	3068	750	-11	-143	2925	2997	
19	14	2925	650	-10	-113	2812	2869	
20	15	2812	550	-7	-67	2745	2779	
21	16	2745	1000	-7	-122	2624	2684	2739
22	17	2624	400	-8	-56	2568	2596	
23	18	2568	1250	-7	-152	2416	2492	
24	19	2416	800	-6	-84	2332	2374	
25	20	2332	700	-6	-73	2259	2295	
26	21	2259	1000	-5	-87	2172	2215	
27	22	2172	1500	-4	-105	2067	2119	2348
28	23	2067	1950	-3	-102	1965	2016	
29	24	1965	1050	-3	-55	1910	1937	
30	25	1910	1750	-2	-61	1849	1879	1944
31	26	1849	1000	-2	-35	1814	1831	
32								

**Fig. 49.** Calculations of average altitude of section line for structural cells 1-5 (table 2 of “CELL-4.XLS” file).

<b>table 3</b>			
cells N	depth 2nd	altitude	neotectonic uplift
1	-8147	1730	<b>9877</b>
2	-12193	1987	<b>14180</b>
3	-9859	2739	<b>12598</b>
4	-11048	2348	<b>13396</b>
5	-14478	1944	<b>16422</b>

**Fig. 50.** Calculations of neotectonic uplift amplitudes for structural cells 1-5 (table 3 of “CELL-4.XLS” file), based on materials of table 1 and table 2 (fig. 37 and 39).

relationship between folding (as function of structure subsidence) and mountain building (as function of uprising and erosion) and changes of this relationship in time duration since a beginning of Oligocene up to 5-2 m.y. remains unknown.

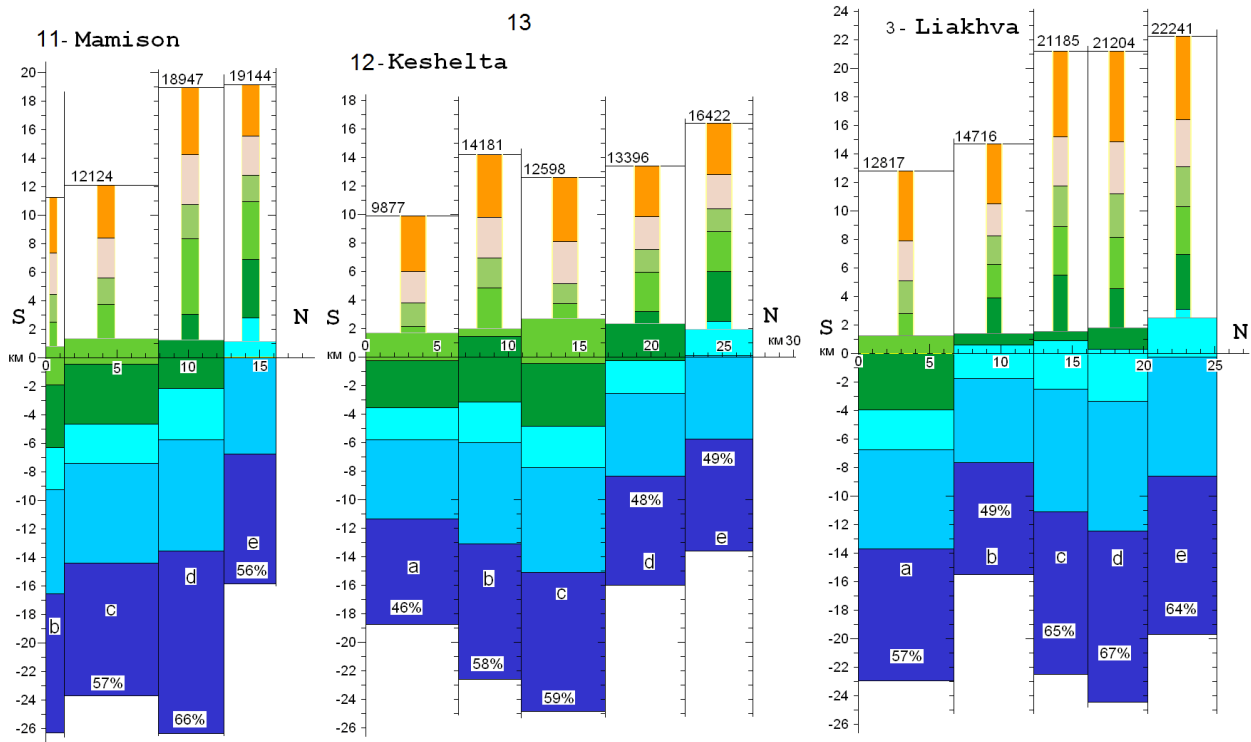
Knowledge of parameters of uplift amplitude and of shortening values with combination of model of sedimentary cover allow to calculate depths (or “virtual” heights) of boundaries of main stratigraphic units (2D-CELL-5.XLS, fig. 51). Parameters of pre-folded and actual widths of cells in file CELL-3.XLS (see xls-cells J10/K10, M13/N13 and others in fig. 45) and set of depths of stratigraphic units permit to construct topology scheme of a structure of the sedimentary cover of all three stages of cells in section (fig. 48). Actual calculated structures of three sections for Chiaur zone (for stage 3) are shown in fig. 52 and 53.

Because actual topology of 2D models of sedimentary cover in three sections for Chiaur zone are rather complicated in comparison with other regions, compilation of quasi-3D model of this tectonic zone was not very reasonable.

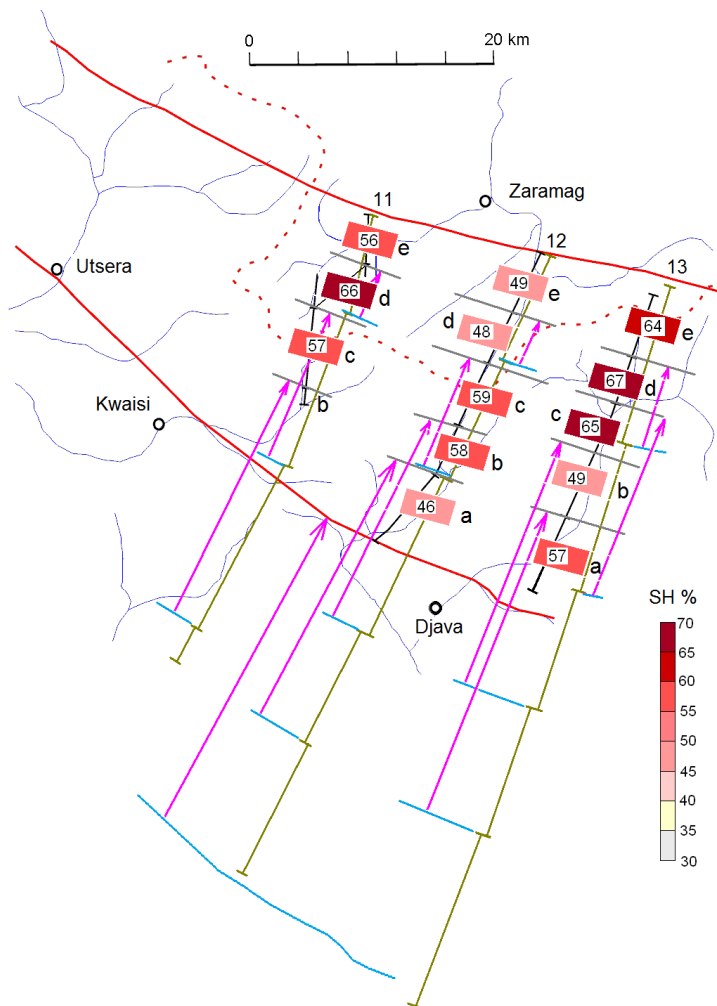
For demonstration of clearer case of reconstruction of quasi-3D model, three stages of structure of sedimentary cover of North-Western Caucasus are shown in figures 54, 55, 56

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	section 12				uplift			section 12			uplift		
2	Keshelta		K shortening	stage 2	amplitude	stage 3		Keshelta		K shortening	stage 2	amplitude	stage 3
3	cell 1 (a)	thickness	0,54		9877			cell 2 (b)	thickness	0,42		14181	
4	Chiaur zone	depth		0	9877	0		Chiaur zone	depth		0	14181	0
5		2000	0,54	3704					2000	0,42	4762		
6	Pg	-2000		-3704	9877	6173		Pg	-2000		-4762	14181	9419
7		1200	0,54	2222					1200	0,42	2857		
8	K2	-3200		-5926	9877	3951		K2	-3200		-7619	14181	6562
9		1000	0,54	1852					1000	0,42	2381		
10	K1 ap-al	-4200		-7778	9877	2099		K1 ap-al	-4200		-10000	14181	4181
11		300	0,54	556					300	0,42	714		
12	K1 g2-b	-4500		-8333	9877	1544		K1 g2-b	-4500		-10714	14181	3467
13		1000	0,54	1852					1000	0,42	2381		
14	K1 g1	-5500		-10185	9877	-308		K1 g1	-5500		-13095	14181	1086
15		600	0,54	1111					600	0,42	1429		
16	K1 v2	-6100		-11296	9877	-1419		K1 v2	-6100		-14524	14181	-343
17		1000	0,54	1852					1000	0,42	2381		
18	K1 v1	-7100		-13148	9877	-3271		K1 v1	-7100		-16905	14181	-2724
19		1200	0,54	2222					1200	0,42	2857		
20	J3	-8300		-15370	9877	-5493		J3	-8300		-19762	14181	-5581
21		3000	0,54	5556					3000	0,42	7143		
22	J2	-11300		-20926	9877	-11049		J2	-11300		-26905	14181	-12724
23		4000	0,54	7407					4000	0,42	9524		
24	J1	-15300		-28333	9877	-18456		J1	-15300		-36429	14181	-22248

**Fig. 51.** Calculations of post-folded thickness and depths of soils of stratigraphy units (stage 2) also as actual post-mountain-building depths of soils of stratigraphy units (2D-CELL-5.XLS file). Extremely great values both depths of top of the basement and amplitude of a uplift and erosion are inevitable. They are defined by a ratio of initial thickness of a sedimentary cover and of value of fold related shortening. New thickness of a sedimentary cover is shown by the value of depth of its sole at a stage 2 (D24, K24).



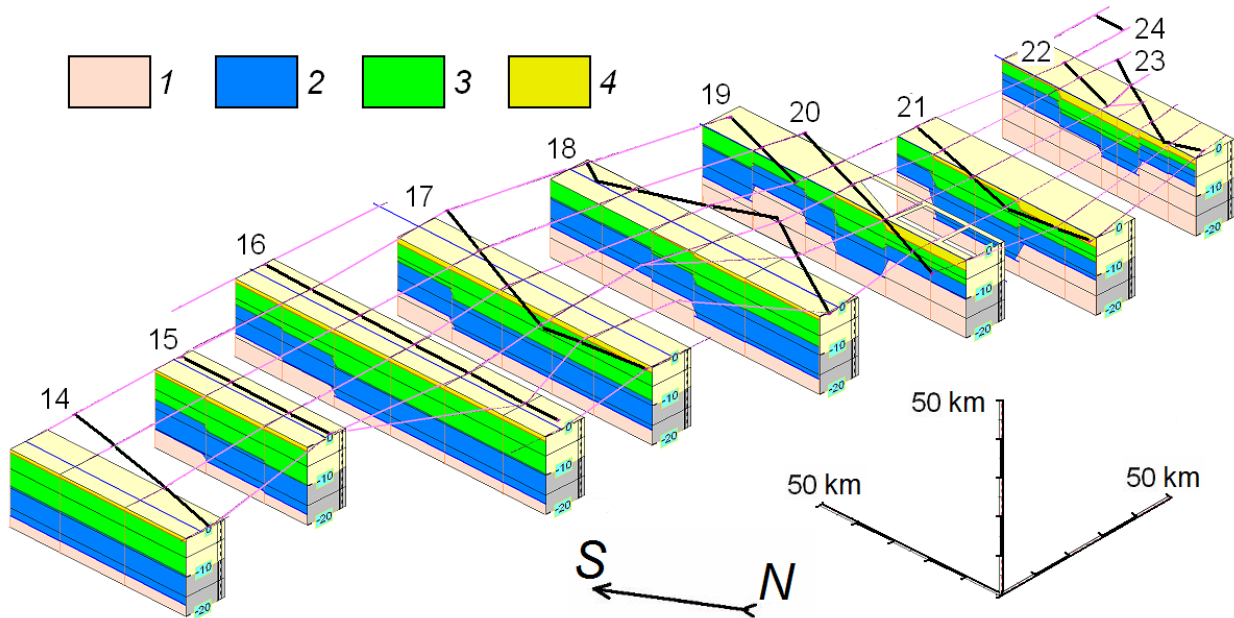
**Fig. 52.** 2D models of section 1-3 for calculations parameters of stage 3, post-mountain-building (actual). After [Yakovlev, 2015a], fig. 6-36.



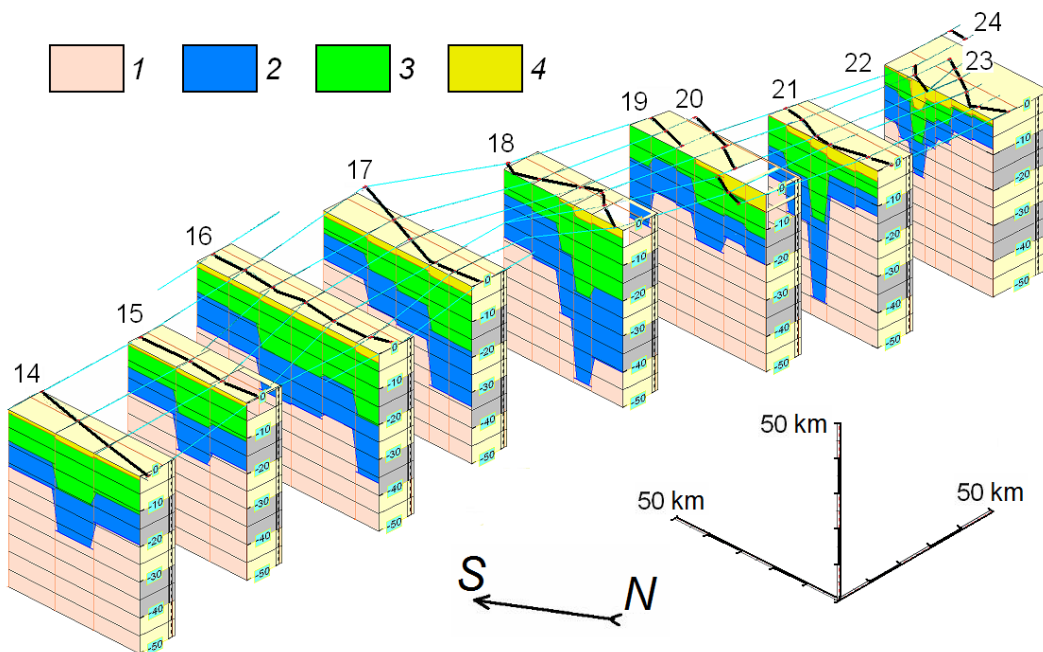
**Fig. 53.** The sketch map of positions of sections 1-3 in Chiaur zone (space between two red curved lines, which are faults) with pre-folded positions of cells (blue lines), displacements (red arrows) and actual positions (grey lines). Values of shortening are shown in rectangles according to colored scale (right, below). After [Yakovlev, 2015a], fig. 6-33.

below. These models were constructed by almost the same technique. It is well noticeable that the structure is divided into three segments having rather homogeneous structure – 1) 14, 15, 2) 16, 17, 18, 3) 19 – 24.

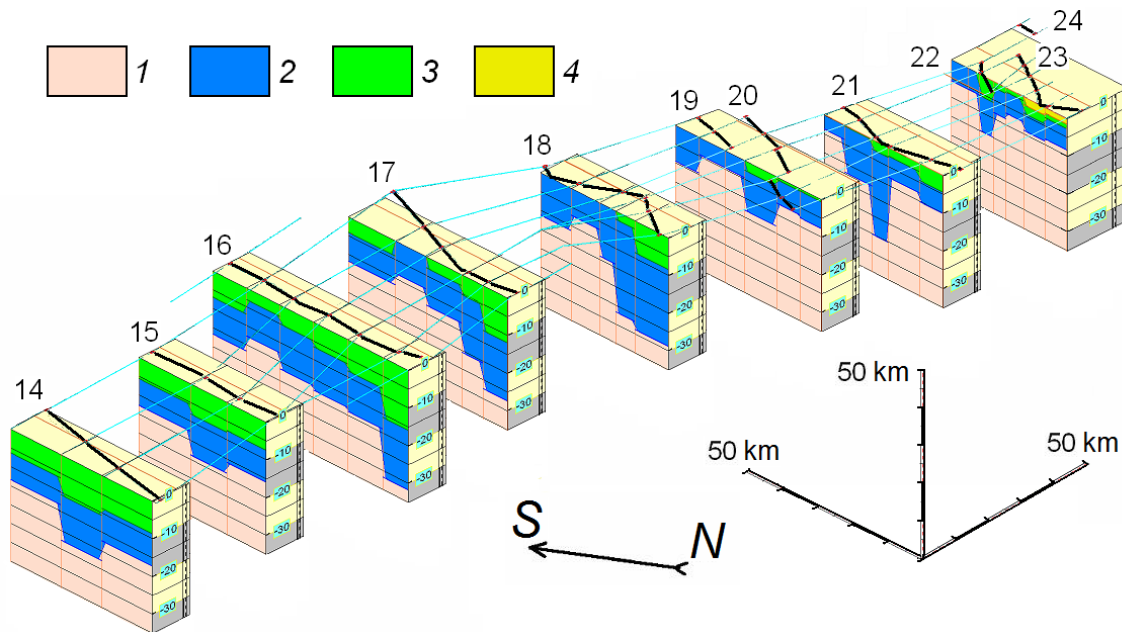
The received final results can be presented in the most different options – in tables, series of profiles, block charts, etc. At the moment, there are no standard types of representation of such material. Possibly, it is necessary to recognize creation of the block chart of a series of cross-sections (fig. 54-56) as reasonable, if there is such opportunity, because it has a good visualization of structure.



**Fig. 54.** Structure of sedimentary cover of North-Western Caucasus; stage 1, before a folding formation (after [Yakovlev, 2009b], fig. 9; [Yakovlev, 2015a], fig. 6-49, with changes). 1 – the Paleozoic metamorphic basement, 2 – the Jurassic deposits, 3 – Cretaceous deposits; 4 – Paleocene and Eocene deposits.



**Fig. 55.** Structure of sedimentary cover of North-Western Caucasus, stage 2 after folding formation, before mountain building (neotectonic uplift). After [Yakovlev, 2009b], fig. 9; [Yakovlev, 2015a], fig. 6-50, with changes. Conventional symbol - the same that in fig. 54.



**Fig. 56.** Structure of sedimentary cover of North-Western Caucasus, stage 3, actual, after the mountain building. After [Yakovlev, 2009b], fig. 9; [Yakovlev, 2015a], fig. 6-51, with changes. Conventional symbol - the same that in fig. 54.

Besides, during the preparation for data presentation in the form of the block chart, the interpretation of structure will be a necessary stage of work. It is necessary to confess that it is more useful to understanding of structure, than only presentation of tables.

The models (fig. 54-56) given above were made manually in the most ordinary graphic editor (MS PAINT), because the volume of material (quantity of "structural cells") was small – only 42 cells were used. At the same time, there were big problems. First was a tracing of structure from a section to section along strike (for identification of the same cells). Second is difficult, more precisely – the unknown, topology of structure of the basement top for transition from one cell to another along a profile. More progressive graphic editors having semi-automatic functions of interpolation of structure didn't allow to decide these problems effectively (just due to non-geologic automatism). Very possibly, the same difficulties will appear for interpretation of materials for other regions of folded complexes.

The possibilities of use of the materials 2D and 3D models of structure of a sedimentary cover for structural geology, tectonics, geodynamics, and problems, which arising at this case also aren't discussed in this book.

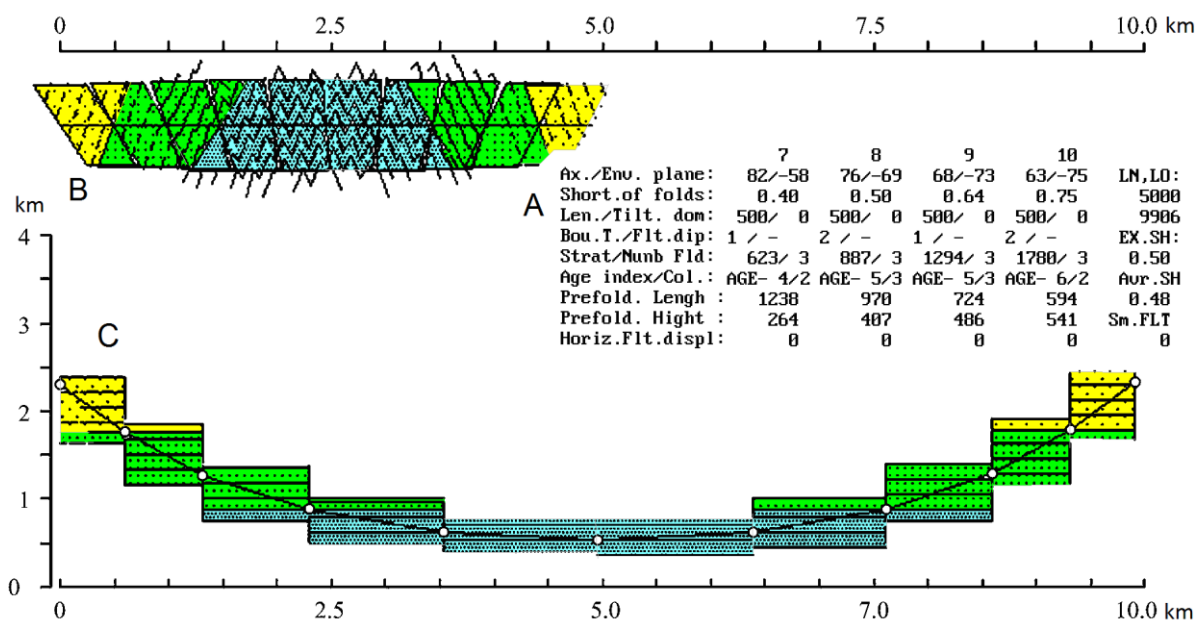
## **7. Comparison with other data on values of shortening of space for Caucasus; verification of the program regarding the accuracy of calculations**

There is a question – how precise the method of the measurements of value of horizontal shortening offered in this manual is? It can be done in two ways. First, it is possible to determine the accuracy, which is provided by technology of calculations, using a computing experiment. Secondly, accuracy of method can be estimated in the broadest possible terms by a comparison with the value of shortening of structures of the smaller size, which were received by other methods.

Besides the compiling of the program "CROSS-B4.EXE", several programs for kinematic modeling were developed also. Such programs can form various folded structures

(numerical, geometrical, not by FEM). For the verification of the "CROSS-B4.EXE" program, the experimental numerical models of folded structure has been used. The model (fig. 57, B) was formed during two stages. The first stage gives numerical general structure of convective type (Goncharov's SMMA [1979], advection/convection model) in pure form without external shortening. At the second stage, some external shortening was imposed on the model (fig. 57, B). This 2-stages model was used also for creation of structures like large folds in scale of entire sedimentary cover (meso-buckling / quasi-buckling, see fig. 44 of the manual). For the procedure of check, the standard data set for 10 domains, in which there is no direct indication on the value of general shortening (flattening), was transferred to the "CROSS-B4.EXE" program in standard file "\*.BCS". Thereafter the procedure of reconstruction of pre-folded structure was accomplished and the general shortening of the structure was calculated (fig. 57, A). The general image of structure (fig. 57, B, C) was compiled from two copy-screens. In this structure, external shortening of 50% exactly was set during the modeling (from conventional width 10000 m to 5000 m). The difference between the correct answer and result of work of the program (Fig. 57 B, C) has found as about 1% (10000 m and 9906 m). Taking into account the averaging of all parameters in the transferred data for 10 domains both on lengths, and on angles (up to 1°), the received accuracy of calculations should be considered as very high. In the course of long-term development and debugging of the CROSS-B4.EXE program, such checks were carried out repeatedly.

Two morphological types of separate folds were studied in Chiaur zone with use of two methods of shortening value estimation: a "single viscous layer folds" and a "folds of



**Fig. 57.** Use of the computer program for testing of a method, the integrated copies of the screen are shown (on [Yakovlev, 2008b], with changes). A – the table of initial parameters for domains (Ax, En etc.), the main results of calculations in domains (Pre-fold. length etc.) and the current parameters of entire profile (LN, LO, etc.), B – symbolical images of present-day model of folded structure (all 10 domains, length of a conditional modern profile – 5 km), C – pre-folded structure for 10 domains (initial length of structure of 10 km exactly, the restored length of pre-folded structure of 9.9 km, i.e. an error of calculations of a method is about 1%). Vertical and horizontal scale bars are shown; scales coincide.

package layers”. The method for study of “single viscous layer folds” [Yakovlev, 1978; 2008b, 2015a] was based on the model of morphology of sinusoid-form of competent layer among lesser viscous medium, which was developed by FEM in [Hudleston, Stephansson, 1973]. In this model, a length of flanks, thickness of layers in flanks and in hinge are changing during a fold development. There are 78 folds of this kind in Chiaur zone, which were studied and measured (Fig. 58, A) with averaged shortening value of 56%. At the second model, competent layers in pairs “competent / incompetent” changed their thickness in flanks and hinges during fold development. The model has small iterative increments of kinematic mechanisms of “buckling” (rotation of fold flank) plus “common flattening” of hinges and flanks plus “simple shearing” along axial surface of fold, which has two layers [Yakovlev, 1981; 2015a]. The study of 36 folds of this morphologic kind in the same region has shown the same average value of shortening (56%) as the first method. Shortening values of 13 structural cells after balancing method of “geometry of folded domains” were averaging also with very close result (57%; see Table 4), despite of noticeable difference of initial materials for calculations and of difference between models of deformations of folds and of folded complexes. It means that the offered method of balancing of complicated multirank objects, which are consisted from many small folds of “similar” morphology, produces reliable results.

Let's remind also that usual methods of balancing, which are using for fold-fault structures of foreland ([Prokopyev et al., 2004]), for such objects aren't applicable.

Table 4. Shortening values for 13 structural cells in Chiaur zone and its average mean.

1c	1d	1e	2a	2b	2c	2d	2e	3a	3b	3c	3d	3e	Aver.
57	66	56	46	58	59	48	49	57	49	65	67	64	57%

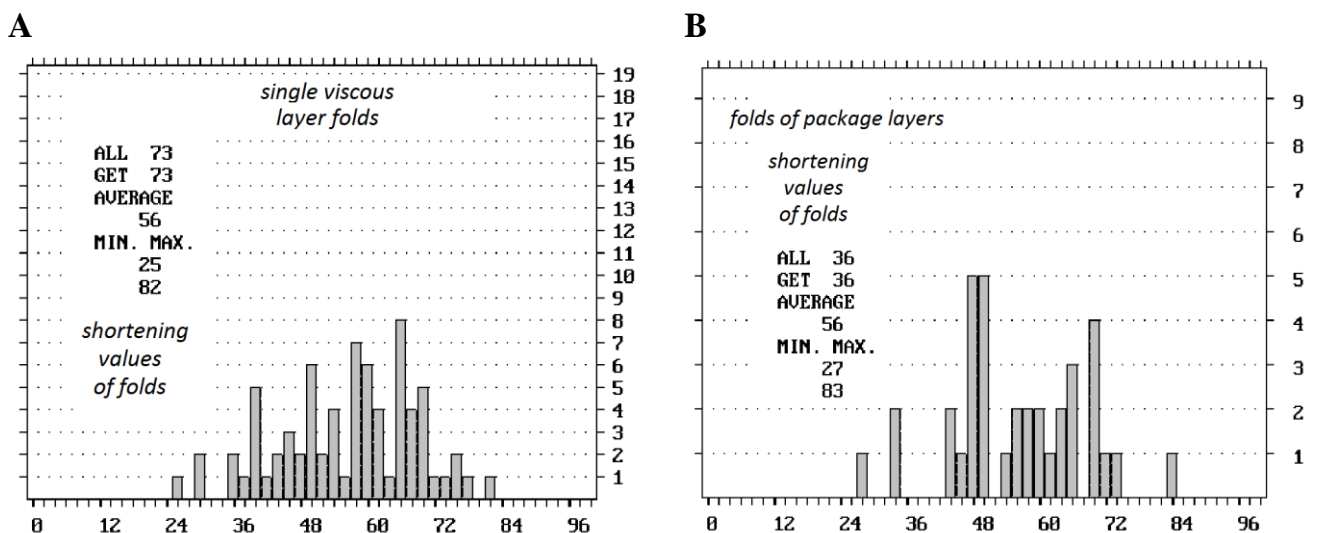


Fig. 58. Histograms of shortening values (Sh, %) and its average means for “single viscous layer folds” (A) and for “folds of package layers” (B) in Chiaur tectonic zone ([Yakovlev, 2015a] fig. 4-8 and fig. 4-20).



## 8. Debatable questions of a method of balancing of folded structures

First, it is necessary to remind that the method of balancing, which is described in the present book, is new in the sense that it is tested on a small number of objects and only by several researchers. It means that, despite substantial calendar age of a method (since 1995), an experience of its usage for the analysis of different natural folded structures should be considered insufficient. One of the reasons of such situation lies in a big rarity of good-quality initial natural structural material.

The detailed description of folded structure, including a drawing up detailed structural profiles, isn't a part of obligatory types of works at geological mapping, even large, for example, 1:25 000 scales in Russia/USSR. It refers to very thick, up to 10–15 km of thickness, the sedimentary cover of internal parts of folded belts having thin bedding of flyschoid type (0.1 m – 1 m – 10 m of thickness for competent layers) and which is forming usually small folds of the same width. The drawing up of detailed maps, plans and structural profiles is carried out only within license areas of mineral deposit and of ore fields, which are being separate parts of a whole folded belt. Because mineral deposits in folded structures of flyschoid sequences meet rather seldom, a lack of attention to such structures from ordinary geologists (experts in a geological mapping) and a lack of works experience with them are quite explainable. As a result, such structures, as a rule, remain not studied.

All materials of detailed cross-sections known to the author (from 1:25 000 up to 1:10000) were received as a result of the long-term specially organized field works of scientific character, which were carried out within studying of the nature of a folding by the academic and high-educational organizations in the USSR/Russia (review in [Yakovlev, 2015a], page 172). In this regard, we will mention works of staff members of two laboratories of prof. V.V. Belousov in Institute of physics of the Earth Academy of Sciences of the USSR and Moscow State University in the Alpine Greater Caucasus (V.N. Sholpo, Ye.A. Rogozhin, F.L. Yakovlev), in the Caledonian Talas Alatau, Northern Tien Shan (M.A. Goncharov, A.V. Vikhert, A.G. Malyuzhinets, V.G. Talitsky, N.S. Frolova), in the Hercynian Turkestan Ridge of the Southern Tien Shan (Ye.A. Rogozhin). According to the oral message of T.V. Giorgobiani (GrSSR / Republic Georgia) also, his group of staff made detailed profiles on structures of Greater Caucasus more than 1 thousand km of total length. As long-term specialized field works on studying of folded structures of internal parts of folded belts are extremely rare in world practice, there is not possible to expect a large amount of such qualitative material, brought together by other groups of researchers. It is represented in this regard that collecting and the publication of such material in the form of a public databank can be put as an important scientific task.

Other possible source of structural material – ordinary geological maps. The example of cameral collecting of rather good information is presented in recent works of V.N. Voitenko with coauthors on the Bodaybo synclinorium [Nilov, Voitenko, 2011; Konnov, Voitenko, 2013]. Existence of detailed (1:50000) geological maps and successful character of a stratigraphy allowed to compile and to restore in this area several profiles of scale 1:50000 (for example, [Konnov, Voitenko, 2013]).

Material of the listed areas generally was already used for drawing up the balanced sections. These are works of the author of the this research on Greater Caucasus in which

own profiles are used and also – sections compiled by Ye.A. Rogozhin and T.V. Giorgobiani. V.N. Voitenko reconstructed several profiles for the Talas Alatau that was included into his PhD thesis [Voitenko, 2007], the materials provided to him by N.S. Frolova (MSU) were used for this purpose. From the known materials remained not studied yet there are Ye.A. Rogozhin's profiles across Tien Shan, a small part of his sections across Greater Caucasus and the most part of sections compiled by T.V. Giorgobiani across Caucasus.

Notice that for areas of development of a Hercynian, Caledonian and Baikalian folding (The Southern and Northern Tien Shan, Bodaybo) the full method of restoration of structure of a sedimentary cover, which was described in the present edition, unfortunately, can't be used. Only an obtaining a value of shortening for parts of structure is possible here. It is connected with the fact that for these regions there is no information on a stratigraphy of the most lower parts of a sedimentary cover and, respectively, there is no opportunity to estimate depth of a top of the Pre-Hercynian and Pre-Caledonian basement. Similarly, there are practically no data on the most top parts of a section, at the moment eroded. It doesn't allow to calculate a "virtual" position of a top of a sedimentary cover at the end of these tectonic cycles and to calculate amplitudes of an uplift of structure and its erosion at Hercynian and Caledonian mountain building. All estimates of such kind of parameters can be probably made only in the form of very poorly validated hypotheses.

The technique, which is presented in the present edition, as it was already told above, is still poorly approved, and it can be developed in a number of the directions.

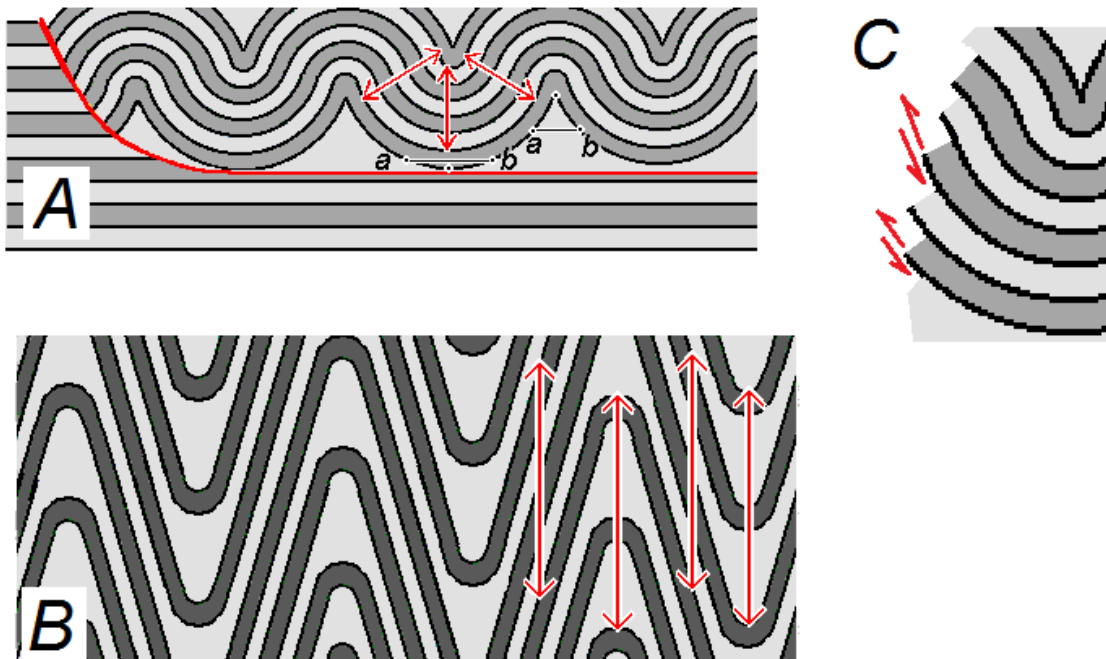
One of the perspective directions in the described method of reconstruction of structural sections is connected with a problem of an estimation of relative age of displacements on faults plains. It is rather obvious that in principle different movements can differ: offsets on the growth faults (on normal faults during syn-sedimentation, probably), syn-folded (on thrusts and, perhaps, on normal faults) and neotectonic movements, which are vertically displacing already created structure. Separation of observed modern amplitude of displacement on a fault into the specified three stages with establishment of amplitude of shift at each stage represents a considerable problem. It is impossible to exclude that the recovery of the initial orientation of the fault plane, taking into account these data, can demand an including into the method of some special operations. At the moment, these movements don't differ and aren't considered in the existing version of the method in any way.

One more direction of the method development can be offered on the parameters of "external" deformations. For "structural cells" only external horizontal shortening of space (horizontal clean shearing, flattening) is defined so far. Except this simplest deformation, it is possible to offer assessment of shift of borders of originally rectangular cell as vertical simple shearing and/or horizontal simple shearing that will allow to specify a position in space of the basement top (an tilting of the lower boundary of a cell) or a position (inclination) of its originally vertical borders. These data can be used, for example, for the prediction of amplitude of an offset of crust blocks for large faults.

Already studied large structures characterize in rather steady stratigraphy the of the thin-layer flyschoid complexes, which created a linear folding. However, it is necessary to provide a possibility of restoration of such structures, whose sedimentary cover can include deltaic sequences of deposits with clinofolds. In this case, it will be required to provide some special operations for compensation of the initial inclination of layering, which is

differing from horizontal. Possibly, it can be done by introduction of a correction angle to an inclination of initial bedding or splitting of stratigraphic model of a structural cell, which is uniform now, into several segments in a cell with different thicknesses of stratigraphic units according to character of a clinoform.

There are important differences of the folds of "similar" morphology forming a linear folding, for which the offered method of the restoration is intended, from folds of "parallel" morphology, which existence in structure causes difficulties as it was already mentioned in part 4.2. These differences concern both morphology, and mechanisms of formation of folds, and, unfortunately, are insufficiently well described in textbooks on structural geology. Folds of a "parallel" form are usually formed in competent deposits sequences of big thickness, forming the large folds having width comparable to thickness of the cover. In foothill depressions, such folds can embrace an entire sedimentary cover, up to 4-6 km of thickness. If these structures belong to foredeep, then they are usually separated by the general detachment from an autochthon (fig. 59A) and it can be broken by thrusts and nappes. One of the main properties is the parallelism of all layers, which are kind of parts of circles with the uniform center. Thickness of layering on flanks and in the hinge of such folds in general coincide (red arrows, fig. 59A). Other important property is limited expanse of structure in vertical – it is limited by two disharmony surfaces (a detachment and the Earth's surface, for example). For our purposes, it is important that the values of shortening in different parts of structure are significantly different. In a core of folds it is higher, than on their external part (you may compare distances "a – b", originally identical, in an anticline and in the syncline in fig. 59A). In contrary to "parallel" folds, folds of "similar" morphology are repeating their form in almost invariable shape up and down in sedimentary sequence along axial surfaces. At the same time, the "axial thickness" in them remain (red arrows, fig. 59B) the same. It is rather obvious that the value of shortening in such structures



**Fig. 59.** Differences of "parallel" and "similar" folds, after [Yakovlev, 2008c], with changes. A – "parallel" folds, B – "similar" folds (competent layers marked by dark color), C – slipping between layers in large "parallel" folds (mechanisms – *flexural flow*, *flexural slip*, terms after [Ramsay, Huber, 1987]).

remains in general identical in all parts of structure. Important feature of structures is the possible combination of flexural morphology (buckling, not bending) of competent layers (of "parallel" shape in a hinge!) , with "similar" morphology of incompetent layers (fig. 59, B), in which a big increase of thickness of layers is observed. Moreover, if to consider them separately, the growth of a layer thickness in incompetent layers in the hinge exceeds usual, pure "similar" growth. Thus, couples of layers competent and incompetent is forming a «similarity» of morphology of folds in the sequence of deposits. The technique of "folded domains" for a restoration of folding is intended for the analysis of such folds, which are forming folded and faulted complexes in a sedimentary cover of large thicknesses.

The problem of inclusion of large folds of "parallel" shape in the procedure of restoration of a structural section consists in phenomenon, due to which the sequence of bedding on a flank of such fold is undergo a displacement along layers (fig. 59, B). As it was noted above (part 5.3, p. 21, fig. 20, B) change of level of layers depth during transition from the domain to the domain in "similar" folds is taking place along the vertical line (in pre-folded structure), which coincides with the axial plane in actual folded structure. Because on a flank of a large "parallel" fold this former vertical line remains uncertain because of displacements along layering (due to flexural flow mechanism), such way of transition from the domain to the domain can't be used here – it will lead to mistakes. Therefore, there is no opportunity to split such fold into several domains, to measure an inclination of an axial surface, value of shortening in each of them and to restore these domains separately. For such cases, it is possible to suggest to complete a drawing of a fold along some one layer and to measure length of this layer. For measurement of length of a layer it is possible to use the chartometer or to break a layer into a series of straight segments and to measure them. Due to correlating this total length to a horizontal distance (projection) of the corresponding piece of the line of a profile, it is possible to determine the value of shortening. Certainly, it should be done in the form of separate operations, outside of work of the computer program. In this case, the final version of a profile will consists of three parts – two as the measurements made as a result of work of the program, and the third between them, as results of drawn manually for the big "parallel" fold.

## **Acknowledgements**

Author thanks Prof. Stefan Schmalholz (Lausanne, Switzerland), who suggested (at April 2015) to describe the technique of balancing of folded structure in the special manual. Researcher Marta Adamuszek (Poland) read one of the first versions of this work in English and suggested to add several methodical clarifications. Associate professor Vyacheslav N. Voitenko (Sankt-Petersburg State University) attentively read the manuscript of this research and made a number of useful comment, including – concerning the need of introduction of amendments in case of clinoforms existence in a sedimentary cover and about the description of actions in case of the presence in structure of large "parallel" folds.

## ***Appendix 1. The list of files on the enclosed compact disk; addresses of Internet resources with files of this compact disk***

The compact disk attached to this edition contains all programs and files mentioned in the text. Besides, the structure of a disk has included images of profiles, the geological map and the scheme of an arrangement of cross-sections and also files of the text of the book in Russian (official publication) and in English (the informal translation).

All information in the compact disk is distributing freely for acquaintance with method as big number of experts as possible. References to the official publication are obligatory in case of use of a technique and materials in the research purposes, scientific publications or in teaching.

### **Programs**

DOSBox0.74-win32-installer.exe – the file of installation of the DOSBox program; It should be started once, as a result on the disk "C:" the DOSBox program will be installed.

CROSS-B4.EXE – the main program allowing to carry out the balancing of a structural section.

INSTRUCTION DOS.txt – the instruction in English regarding of the start of the CROSS-B4.EXE program in the environment of DOSBox.

At the time of end of the book edition (July-August 2017) some efforts to create the version of the program of balancing the sections with the executed module for the operating system Windows-7 and younger by means of the QBasic program (64bit), which won't demand to start of "DOSBox", have been made. Need of a lot of work on adaptation of the program didn't allow to make a success immediately. In case of success of such program creation, the CROSS-B5.EXE version will be placed to the Internet-addresses mentioned below in addition.

### **Structural materials (initial)**

SECTION-11A.bmp, SECTION-11B.bmp – files of structural cross-section 11, “Mamison”, with a splitting into domains and without such splitting.

SECTION-12A.bmp, SECTION-12B.bmp – files of structural cross-section 12, “Keshelta”, with a splitting into domains and without such splitting.

SECTION-13A.bmp, SECTION-13B.bmp – files of structural cross-section 13, “Liakhva”, with a splitting into domains and without such splitting.

### **Files for CROSS-B4.EXE program**

There are files of measurements of structural parameters, corrected as a result of executing of procedures of the balancing. Because a selection of objects for measurements and measurements on the image of profiles in the field may produce some deviations, a difference between initial measurements and corrected one isn't a defect. Files \*.BCS are used as data for work with the CROSS-B4.EXE program; \* .DCS – files of the final report on calculated parameters.

MAMISN11.BCS, MAMISN11.DCS – files for cross-section 11, Mamison.

KESH-12.BCS, KESH-12.DCS – files for cross-section 12, Keshelta.

LIAKH-13.BCS, LIAKH-13.DCS – files for cross-section 13, Liakhva.

NB! Names of files \* .BCS for Dos-programs shouldn't exceed 8 signs in length.

There are **files of tables** of Excel for calculation of a number of intermediate data for the CROSS-B4.EXE program and of final parameters of structural cells.

DOMAIN-1.xls – the file for a collecting and an averaging of measurements of structural parameters and for a preparation of the data file for the *CROSS-B4.EXE* program.

SECTION-2.xls – the file, in which results of calculations on the *CROSS-B4.EXE* program are gathered and where shortening value for entire profile is calculated.

CELL-3.xls – the file, in which shortening values for the chosen structural cells are calculated.

CELL-4.xls – the file, in which next parameters are calculated for the chosen structural cells: an average "stratigraphic" depth of the section line, an average topographical altitude of the section line and an amplitude of a neotectonic uplift.

2D-CELL-5.xls – the file, in which next parameters are calculated: post-folded thicknesses and depths of soles of the stratigraphic units at a stage 2 and modern post-mountain-building depths of soles of the stratigraphic units (at stage 3).

**There are files of additional geological materials:**

Chiaur-geol-map.bmp – the copy of the part of the geological map on the region of Chiaur tectonic zone and on surrounding structures [The geological map of the Caucasus. Scale 1:500000 // Under the editorship of D.V. Nalivkin, etc. The Ministry of Geology of the USSR. VSEGEI. M.: “Aerogeology”, 1978].

Chiaur-sections-map.bmp – the space image (Google Earth) of the region of the Chiaur zone and surrounding structures. An arrangement of cross-section lines, borders of tectonic zones, the main settlements are shown.

Yakovlev-MNGR-1(1997).pdf – the small monograph about methods of a research of mechanisms of a folding formation, in which there is a short geological description of structures of the Southeast Caucasus and the Chiaur tectonic zone (in Russian).

Yakovlev-dokt-diss-2015.pdf – the full text of the doctoral dissertation, in which the geological structure of a number of folded structures of Greater Caucasus is described.

There are **files of the text of the present edition** in Russian (the official version) and in English (non-official one)

Реконструкция-складчатости-Яковлев-2017.pdf

Reconstruction-of-folding-Yakovlev-2017-en.pdf

The **additional file “equipment.doc”** contains photos of the main tools, which are convenient for measurement of parameters of structural domains in structural profiles on a paper, and explanations about methods of their use.

There are **addresses of Internet resources**, in which files of the book and of a compact disk are located.

1) The cloud, in which files were located (on 30-08-2017):

<https://cloud.mail.ru/public/6JGP/knqqR5NAs>

2) The address of author’s home page on the website of Institute of physics of the Earth:

<http://yak.ifz.ru/>

<http://yak.ifz.ru/Yak-publ-fold-r.html> – the page of publications with a function of files loading

<http://yak.ifz.ru/Yak-folding-publ.html> – English-language version of this page

3) The address of author’s page in the ResearchGate resource:

[https://www.researchgate.net/profile/Fedor\\_Yakovlev](https://www.researchgate.net/profile/Fedor_Yakovlev)

[https://www.researchgate.net/profile/Fedor\\_Yakovlev/publications](https://www.researchgate.net/profile/Fedor_Yakovlev/publications)

## Appendix 2. Use of "DOSBox" and the start of the CROSS-B4.EXE program

The installation procedure on the computer of the DOSBox program and an order of its start is specified in appendix. Unlike the modern operating systems, all commands in disk operating system (DOS) are executed only by typing by the keypad and by clicking of "ENTER".

1) Start the DOSBox0.74-win32-installer.exe file once. As a result, "DOSBox" will be unpacked and set on the disk "C:" (you will see the icon). After that, "DOSBox" is ready to operation.

2) Create the new folder \1\ on the disk "C:". To place all necessary files (CROSS-B4.EXE; \* BCS; and others) in this folder (fig. Ap-1).

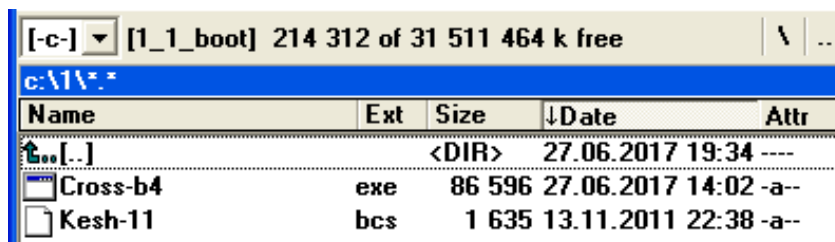


Fig. Ap-1. The contents of directory "\1\": executable file of the program CROSS-B4.EXE and data file.

3) To start work of DOSBox by click of its icon and execute other operations according to "INSTRUCTION DOS.TXT". The result is shown in the fig. Ap-2. Appointments of commands: A) command (mount c c:\1\1) – a virtual disk (z:) logically joins the existing disk (C:) and directory (\1 \1); B) command (C:) – the system switches to the disk c:\1\1, all files of this directory become available; C) (dir) – this command shows contents of directory (for reference, it is not necessary).

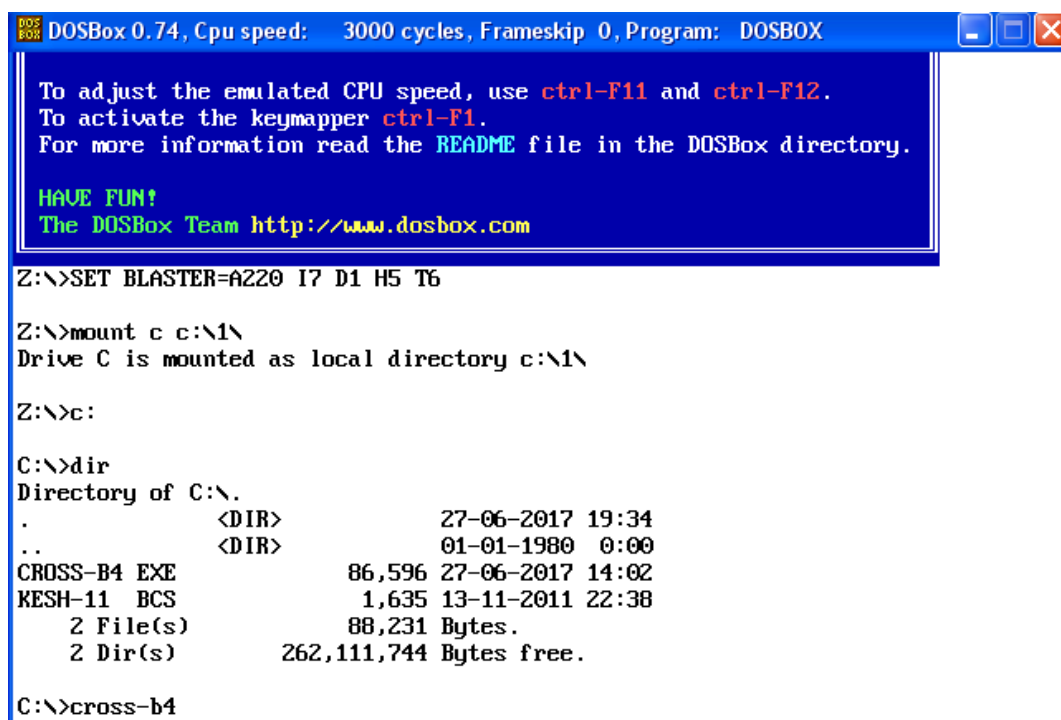
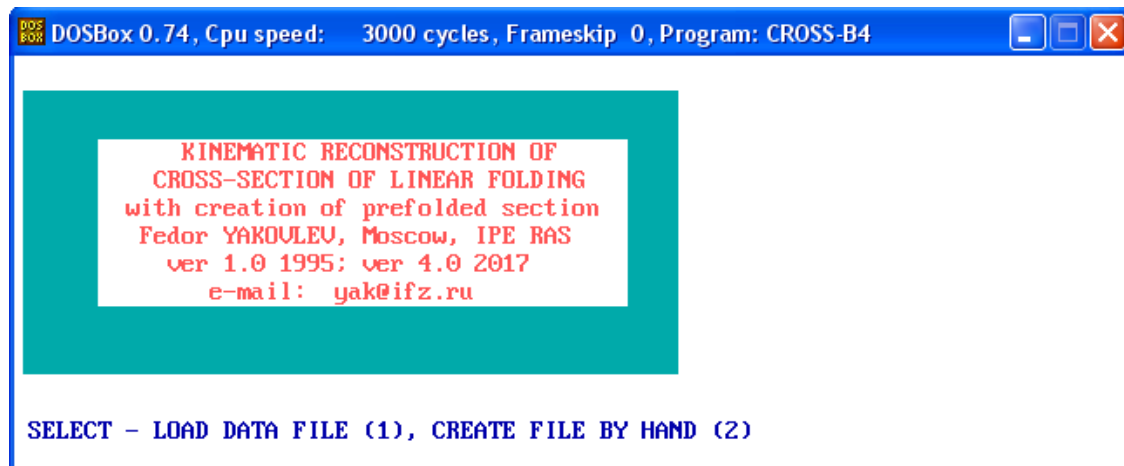


Fig. Ap-2. The copy of the screen of the DOSBox window on the Windows 7 screen. All preliminary command lines were executed (see "INSTRUCTION DOS.TXT"). The command line for execution of "CROSS-B4.EXE" is ready to pressing of "Enter".

(The central part of the image for convenience of reading is given in inversion of color: on the screen of the user, white figures on a black background will be really visible).



**Fig. Ap-3.** The copy of the screen of the started CROSS-B4.EXE program in Windows 7 in the DOSBox window (after the "Enter" command). This image and other images in the DOSBox window can be copied by the standard copy-screen function, which captures entire Windows 7 screen.

- 4) To start CROSS-B4.EXE in the DOSBox window. For this purpose, to print by keyboard the name of programm (cross-b4), it is a calling of the executed program (Fig. Ap-2). After press ENTER, the program will be started, the result is shown in the fig. Ap-3.
- 5) Further work goes regularly; it was described in part 5 of edition (page 15).



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