**Balanced cross-section restoration in a complicated folded hinterland structure: Shilbilisaj profile, Talas Ridge, Caledonian Tien Shan**

*F.L. Yakovlev, K. Gaidzik, V.N. Voytenko, N.S. Frolova*

**Supporting information 1**

EQUATIONS OF DOMAIN RECOVERY OPERATIONS AND SOFTWARE AVAILABILITY

Contents:

**Supporting information S1-1.** Equations of pre-folded domain state recovery operations.

**Supporting information S1-2.** The correlation of restoration operations at the hierarchical level of the "folded domain" (level III) with folded deformations at the level of the "fold" (level II).

**Supporting information S1-3.** Software availability.

**Supporting information S1-1.**

**Equations of pre-folded domain state recovery operations.**

Below, we provide a list and an order of principal equations of the main three recovery kinematic operations applied in the proposed balanced cross-section restoration. These operations can be described by the following geometrical formulas [Yakovlev, 1987; 2008b, 2009; 2015a].

Parameters used in the equations:

AX0 – the inclination of the fold axial plane;

EN0 – the inclination of the line of initial layering (or of folds envelope plane);

k0 – coefficient of shortening of folds in the direction perpendicular to the axial plane (see additional notice below);

LS0 – length of a profile line segment for a domain;

TS0 – tilting of a profile line segment;

All parameters change indexes during each of the three operations, for instance, TS0, → TS1,→ TS2,→ TS3;

D1 – layer depth in an entrance, the first point of the domain on profile segment line;

(D1 remains invariable; depth of "an output, last point" of the domain, D2, is calculated).

1. Rotation of an angle of rotation = - EN0 up to the horizontal position of initial layering (fold envelope plane) (Fig. 4A, operation 1):

(1)

(2)

Length and shortening of folds of a segment remain invariable during this operation, i.e., *LS1=LS0* and *k1 = k0.*

2. Simple horizontal shearing (Fig. 4A, operation 2) of a shearing angle  = 90 - AX1:

(3)

(4)

(5)

3. Stretching or "pure shearing" (Fig. 4, A, operation 3) of the stretching size (shortening of folds) of *k2*:

(6)

(7)

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

Horizontal length (8)

Vertical length (9)

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

 (10)

**Additional notes** for “Supporting information S1-1”.

**1.** Here, in equations above, *k= L1/L0*; if interlimb angle in the fold is “γ”, then *k0 = sin (*γ*/2),* e.g., if φ=60°, k0 =0.5, *ε = ((L1 - L0)/L0)·100* = -50%. (In main text of the paper,   
K= L0/L1 is used; i.e., if φ=60° in a fold with vertical axial plane, then K=2.0).

**2.** Using folds interlimb angle to determine the shortening value brings the offered recovery method closer to the usual technique based on the measurement of the layer length. Suppose the axial plane is vertical and the folds envelope plane is horizontal. In that case, the shortening of folds in the domain is equivalent to the common horizontal shortening of the domain. In this case, the standard techniques (i.e., measuring the layer length) can be used to determine the value of shortening. However, if the fold axial planes in the actual domain are horizontal, then the shortening of the folds is equivalent to the horizontal elongation of the domain. At the same time, the final results of such a domain restoration as a single structure (i.e., its shortening or lengthening) also depend on some other parameters. Solving such a problem of the domain restoration by the standard method (i.e., measuring layer length) is not a simple matter. In addition, the tectonic significance consists of not the horizontal contraction of one domain (such a single domain may show a local elongation) but the overall shortening of the structure, which embraces many domains. It means that in the general case, the standard technique of "measuring the length of the layer" is ineffective to restore the domain structure and the full cross-section in the Hinterland type of folding.

**3.** In our method, the standard technique for determining the shortening value in the domain is the measurement of the interlimb angle of the folds ("γ" in figures Fig. 2, A2; 3; 8). This is done under the assumption that the layers retain their length during the formation of folds. This rule may be violated in a real folded structure, especially for the hinge zone of large rounded (not chevron) folds. Complex processes of the formation of separate folds of several types (within the framework of our ideas about the hierarchy system of folded structures) are the goal of analysis within the framework of level II " separate folds" (see table 1). Here we can distinguish methods for determining the shortening value by the shape of a single viscous layer folds [Yakovlev, 1978; 2012a; 2012b]; ([Yakovlev, 2015] p. 160), as well as [Schmalholz, Podladchikov, 2001]. These methods are based on models of mechanics. A direct kinematic model of the formation of folds of layers package for a combination of competent and incompetent layers has been developed (techniques of mechanics were not used here). Based on this direct model, a nomogram for determining the shortening value was compiled [Yakovlev, 1981; 2002; 2012b], ([Yakovlev, 2015]; p. 172). Partially for the same purposes, the “isogon rosette” method to a competent layer shape in a fold ("similar" type) can be used [Srivastava, Shah, 2008]. Within the framework of the hierarchy of folded structures, it is considered that the use of such special methods in determining the shortening value in the domain is more desirable than using the interlimb angle of the folds. But real cases of using such preferable data in our practice are very rare.

References:

Schmalholz S.M., Podladchikov Y.Y. 2001. Strain and competence contrast estimation from fold shape // Tectonophysics. 340(3-4) P. 195-213.

Srivastava D.C., Shah J. 2008. The “isogon rosette” method for rapid estimation of strain in flattened folds // [Journal of Structural Geology](http://www.sciencedirect.com/science/journal/01918141). [V. 30, Is. 4](http://www.sciencedirect.com/science?_ob=PublicationURL&_tockey=%23TOC%235896%232008%23999699995%23684113%23FLA%23&_cdi=5896&_pubType=J&view=c&_auth=y&_acct=C000050221&_version=1&_urlVersion=0&_userid=10&md5=3ce05a2664f35183fd82b923cf4653e9). P. 444-450.

Yakovlev. F.L. 1978. An estimate of deformations in a folded region on the basis of disharmonic folds. Bulletin MOIP, Geoi. Depart., 53(5), pp. 43-52. (in Russian)

Yakovlev F.L. 1981. Two methods of determining the amount of horizontal shortening by the morphology of folds. In: Mathematical methods of analyzing geologic phenomena. Moscow, Nauka, pp. 70-76. (in Russian)

Yakovlev F.L. 2002. Investigation of the processes and mechanisms of the plicated deformations development in the Earth’s crust (review of the existing approaches). In: Strakhov V.N., LeonovYu.G. (Eds.) Tectonophysics today. Moscow: UIPE RAS, pp. 311-332. (in Russian)

**Yakovlev F.L. 2012a. Methods for** detecting **formation mechanisms and determining a final strain value for different scales of folded structures // Comptes Rendus Geoscience. 344 (3–4). P. 125–137.**

**Yakovlev F.L. 2012b. Identification of geodynamic setting and of folding formation mechanisms using of strain ellipsoid concept for multi-scale structures of Greater Caucasus // Tectonophysics. v. 581, 18. P. 93–113.**

**Supporting information S1-2.**

**The relation of restoration operations at the hierarchical level of the "folded domain" (level III) with folded deformations at the level of the "separated folds" (level II).**

The solution to the problem of restoring the pre-folded state of the domain in the proposed method is achieved by restoring the position of the segment of the profile line in a medium with horizontal layering. To do this, a domain is allocated in the folded structure, and a strain ellipse (2D ellipsoid) describes the deformation of the domain. The equations indicated in the "Supporting information S1" section show how the position of the profile line segment between two points on the domain boundaries is restored using the concept of the strain ellipse. These transformations concern only cross-section line segments – their length and orientation in space. With these operations in the domain, which is the object of hierarchical level III, there is no need to trace the mechanical aspects of the possible transformations of the layers crumpled into folds. Following the general approach to the problem of multiscale folding formation by introducing the concept of the hierarchy of structure levels, all aspects of the mechanics of layers deformation should be solved at level II, i.e., "separate folds” (Table 1). See also Notice 3 of S1-1.

**Supporting information S1-3.**

**Software availability.**

A computer program compiled by F.Yakovlev, for performing the domains recovery operations and the entire profile compilation is distributed freely. The program manual, the program itself, as well as the accompanying computational Excel tables and other files are freely available at the following addresses:

On the personal page of the Schmidt Institute of Physics of the Earth of the Russian Academy of Sciences (IPE RAS) server <http://yak.ifz.ru/pdf-lib-yak/Reconstruction-of-folding-Yakovlev-2017-en.pdf> - Manual book, English version;

On the personal page of the IPE RAS server (<http://yak.ifz.ru/pdf-lib-yak/Folding-Reconstruction-compact-disk.rar> ) – a compact disk of the manual;

In RESERCHGATE (<https://www.researchgate.net/profile/Fedor_Yakovlev/publications> , in sections BOOK (“Reconstruction of folded and faulted structures in zones of the linear folding using structural cross-sections“) and DATA (compact disk);

In the personal cloud, all materials (<https://cloud.mail.ru/public/6JGP/knqqR5NAs> )