REFERENCES

Hancock P.L. 1985. Brittle microtectonics: principles and practice. *Journal of Structural Geology*, **7**, 439-457.

Osokina D.N., Yakovlev F.L. & Voitenko V.N. 2007. Second rank fractures and 3D stress & strain local fields of fault with sides friction as ones development's stages evidence: theory, experiment and natural examples (on the basis of «fracture-crack» and «fracture – shear zone» models study). *Geophysical Research Abstracts*, **9**, 10465.

Stoyanov S. 1977. Mechanism of formation of shear zones, 144 pp. *Nedra*; Moscow. [*In Russian*]

Yakovlev F.L. 2008. About the diagnostics of strain state of fault sides and of its internal zone using types of secondary fractures. *In*: Common and regional problems of tectonics and geodynamics. Materials of the XLI Tectonic Meeting, v. 2. *GEOS*; Moscow, 516-519. [*In Russian*]

Strain values in folded complexes as a factor of metamorphism – examples from Greater Caucasus

Fedor Yakovlev[1]

[1]O. Schmidt's Institute of Physics of the Earth RAS, Moscow, Russian Federation; *yak@ifz.ru*

The main processes of continental crust forming and transformation ("granitic" layer) are magmatism, metamorphism and folding. These three processes take place almost simultaneously during orogenesis in the frame of the Wilson cycle. The process and main factors of metamorphism are well described by numerical models, because a large number of methods of

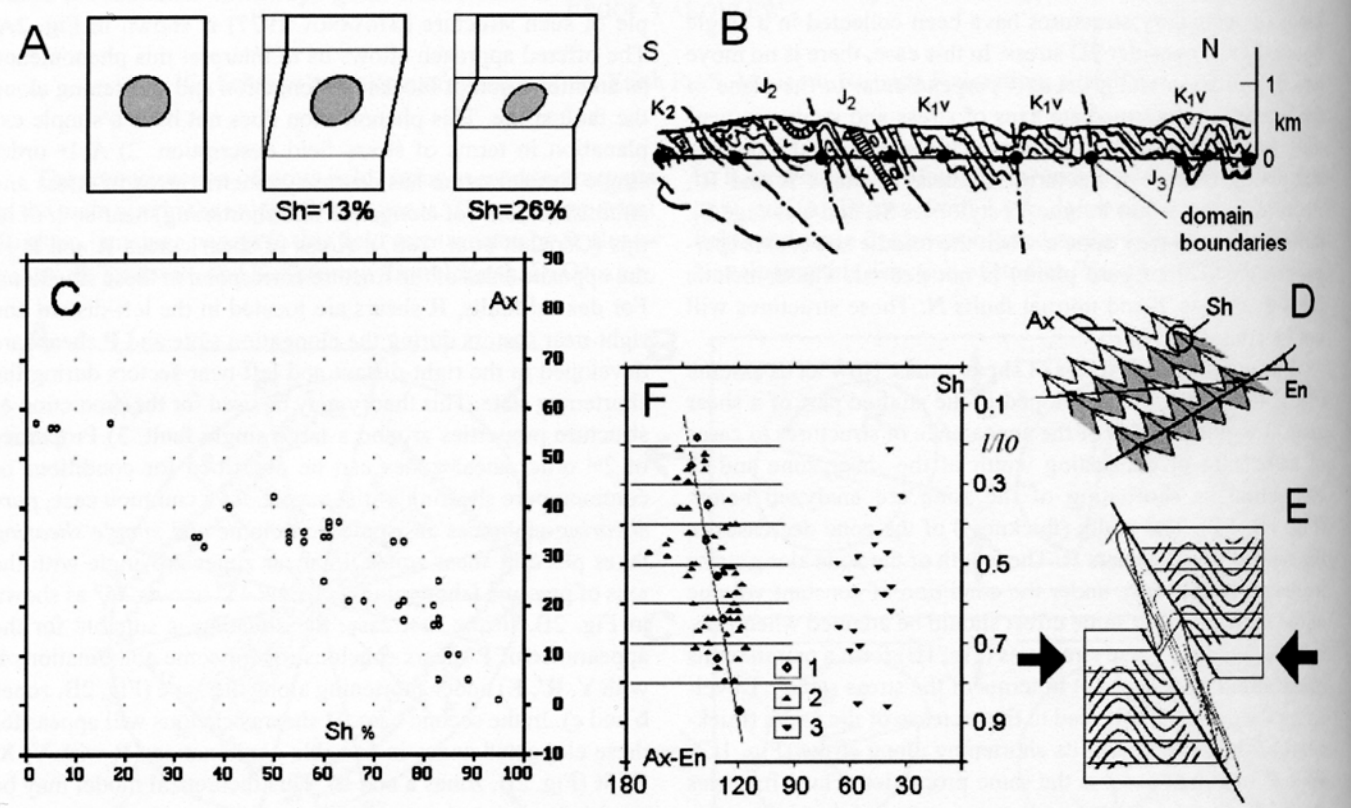

Fig. 1. Shortening of folds and domains for simple shearing cases. A – Common scheme of deformation for different thickness of the zone. B – Part of detailed structural section with splitting into domains. C – Point of folds parameters for the Vorontsovsky nappe detachment (axial surface vs. shortening value); area of points corresponds to simple shearing law. D – Axial surface dip, folds enveloping plain dip, and shortening value as parameters of domain. E – Common scheme of inclined zones of ductile shearing. F – Scattering diagram for domains parameters (difference between axial plain dip and envelope plain dip vs. shortening value, estimated as L/L_0); plotted regression line corresponds to simple shearing law. 1 – Average points for shortening intervals, 2 – Points with southern vergence, 3 – Points with northern vergence.

their study have been developed. On the contrary, the estimation of the strain value for rock massifs is not a simple operation. Thus the relation of strain and P/T conditions of metamorphism is commonly described with regard to quality. This study does not aspire to present a full quantitative description of this relation, but suggests a setting of this problem.

First of all, we should distinguish two main types of deformations that may occur in folded structures in term of mechanics. They include simple shear and pure shear. These types of deformation produce different results concerning 1) strain values for the same P-T conditions and 2) appearance of factors of metamorphism.

Structures of simple shearing. Simple shearing takes place in relatively narrow zones. Two situations were found in natural structures. The first one is related to separate folds in a detachment zone of the Vorontsovsky nappe (southern margin of the Greater Caucasus, near the town of Sochi). The second one is inclined zones of ductile shearing in the entire NW Caucasus. The main feature of this type of deformation is that the same amplitude of block displacement will give a different "shear angle" for a different thickness of the shear zone (Fig. 1A). It will be expressed in different values of shortening.

The thickness of the Vorontsovsky nappe detachment is about 100 m. This structure was well studied during field work and on numerous photographs of outcrops which were made during the digging of the tunnel. The value of fold shortening (Fig. 1C) varied from 10–20% to 85–90% (ten-folded) for different inclinations of the axial plains (Yakovlev et *al.* 2008). Diagenetic exchange of argillites and sandstones was minimal. This is in agreement with the total thickness of the nappe (not more than 1.5 km) and it does not depend on the strain value. Inclined zones of ductile shearing were found when studying the geometry of domains (Fig. 1B, D, E). These zones exist as narrow 0.5–3.0 km strips, which have higher values of shortening than other blocks (Fig. 1F). There is no evidence that metamorphic changes of rocks are higher than those in the neighbouring blocks.

Structures of pure shearing. Pure shearing (flattening) ensures a relatively uniform horizontal shortening of large blocks of the sedimentary cover (Fig. 2A). Methods of their

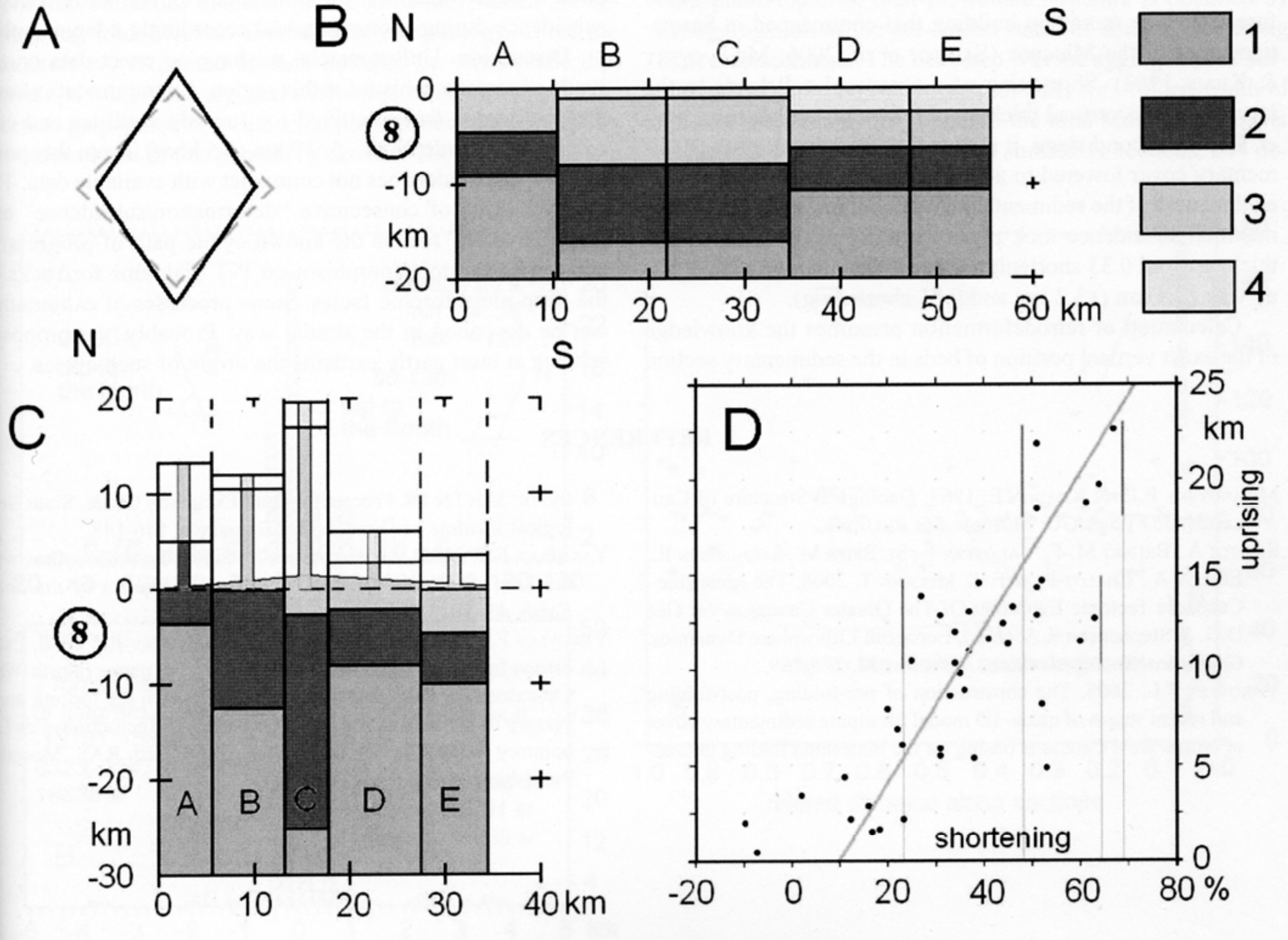

Fig. 2. Shortening of domains for the pure shearing case. A – Common scheme of deformation for pure shearing (square transformed into a rhomb). B – Prefolded model for section 8 including 5 structural cells (A – E from north). C – Post-mountain building model for the same section and cells; eroded part of sedimentary cover shown in air (upper 0 km). D – Scattering diagram for structural cell parameters (shortening value vs. magnitude of uplift); regression line and intervals of shortening values are shown. For B and C: 1 – Basement, 2 – Jurassic deposits, 3 – Cretaceous deposits, 4 – Palaeogene deposits.

study are based on the allocation of domains in detailed structural sections (Fig. 1B). Three geometric parameters allow describing the strain ellipsoid for such structures. They are: axial surface dip, fold envelope plain dip, and shortening value in a direction perpendicular to the axial surface (Fig. 1D). The recent shape of domain is transformed to its prefolded state in three kinematic operations. They include: rotation to a horizontal position of the envelope plain, horizontal simple shearing to a vertical position of the axial surface, and elongation to the disappearance of folds (Yakovlev 2009). The study of folding in NW Caucasus includes the allocation of 244 domains in 11 structural sections. To compensate the influence of deformation inhomogeneity, the domains were aggregated into structural cells by attaching of one to another, with a typical length along the section equal to the thickness of the sedimentary cover. Shortening values were estimated for 42 such selected cells. Three relative stages of a model of the sedimentary cover development were created for this region. There are: 1) pre-folded postsedimentary stage (Fig. 2B), 2) pre-mountain building post-folded stage and 3) recent post-mountain building stage (Fig. 2C). The second stage was defined based on the fact that the main folding (Pre-Oligocene) forestalled the mountain building that commenced in Sarmatian times of the Miocene (Saintot et *al.* 2006; Milanovsky & Khain 1963). Shortening of a structural cell leads to the increase of the vertical thickness of the total sedimentary cover. For the second stage, it means that the bottom of the sedimentary cover lowered to a depth equal to the new post-folded thickness of the sedimentary cover column. Such theoretical maximal subsidence took place as 48.8 km (16.1 km initial thickness and 0.33 shortening value). The average of this value was 22.4 km (13.2 km and 0.65 shortening).

Calculation of retrodeformation presumes the knowledge of the exact vertical position of beds in the sedimentary section for each domain. A new post-folded position of bedding in total sedimentary section and the elevation (topography) of a profile line for this bedding in recent outcrops can also be recognized. It allows calculating the thickness (new, post-folded) of the upper part of the sedimentary section that was eroded. It is supposed that the value of this erosion is equal to the magnitude of the uplift of the basement from the second to the third stage (Fig. 2C). This value may be considered as mountain building uplift. For NW Caucasus, the average value is ~9 km and varies from 0.5–2 km to 22 km. The distribution of this value over the region appears natural (Yakovlev 2008).

According to this model, the rocks in recent outcrops obviously were earlier at a certain depth. The rocks were next subjected to metamorphic factors. Data of 42 cell parameters show a good correlation (r=0.78) between the shortening value and the magnitude of erosion (Fig. 2D). Some scattering of these points on the diagram along the horizontal axis shows the estimated shortening value for rocks, which were at a certain depth (vertical axis). Correlation of other parameters also shows an important regularity. Cells, which initially accumulated a larger thickness of sedimentary cover, suffer deeper subsidence during shortening, and accordingly a larger uplift.

Discussion. Unfortunately, we have no exact data on the grade of metamorphism for this region. Literature data shows that the zeolite facies is fixed for Jurassic argillites and corresponds to the depth of ~5–10 km (3.5 kbar). From this point of view, our model does not contradict with available data. The outlined cycle of consecutive "deformation/subsidence" and "uplift/erosion" recalls the known cyclic path of progressive and regressive metamorphism on P-T diagrams for rocks of the deep metamorphic facies. Some processes of exhumation can be described in the similar way. Probably, the proposed scheme at least partly explains the origin of such cycles.

REFERENCES

Milanovsky E.E. & Khain V.E. 1963. Geological Structure of Caucasus, 357 pp. *MGU*; Moscow. [*In Russian*]

Saintot A., Brunet M.-F., Yakovlev F., Se´Brier M., Stephenson R., Ershov A., Chalot-Prat F. & Mccann T. 2006. The Mesozoic–Cenozoic Tectonic Evolution Of The Greater Caucasus. *In*: Gee D.G. & Stephenson R.A. (*Eds*), European Lithosphere Dynamics. *Geological Society, London, Memoirs*, **32**, 277-289.

Yakovlev F.L. 2008. The construction of pre-folding, post-folding and recent stages of quasi-3D model for alpine sedimentary cover of North-West Caucasus basing on the hinterland folding geometry. *In*: SlovTec 08. Proceedings and Excursion Guide. State Geological Institute of Dionyz Stur, Bratislava, 146-148.

Yakovlev F.L. 2009. Reconstruction of Linear Fold Structures with the Use of Volume Balancing. *Izvestiya, Physics of the Solid Earth*, **45**, 1023-1034.

Yakovlev F.L., Marinin A.V., Sim L.A. & Gordeev P.P. 2008. Paleostress fields and strain fields of Vorontsovsky nappe (North-West Caucasus). *In*: Problems of tectonophysics. On the fortieth anniversary of the foundation by M.Gzovsky the Tectonophysics Laboratory in the Institute of Physics of the Earth RAS. Moscow. Publishing of IPE RAS, 319- 333.