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Tectonic paleostress fields and deformation state of nappe: comparison of theoretical models with natural data for elucidation of the formation mechanisms, example of Vorontsovsky overthrust (North-West Caucasus)

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The North-West Caucasus is a part of the Alpine thrust-fold belt; it is located to the south of the East European Platform and the Scythian Plate [Milanovsky, Khain, 1963; Saintot, Angelier, 2002; Saintot et.al., 2006]. Vorontsovsky nappe is adjacent to the town of Sochi within the Abkhazskaya sub-platform tectonic zone to the south of the main linear fold structures of the North-West Caucasus. Flysch deposits of the nappe (argillites, aleurolites, marlstones, sandstones, Eocene age, Mamajskaya and other suites) have the total thickness of about 1.3-1.5 km, and the monocline structure (azimuth 330-20, dip 20-40) near its frontal part. These deposits overlap the autochthon flysch (clays, aleurolites, Oligocene age, Sochinskaya and other suites). The distance of the displacement from the root zone (Chvezhepsinskaya tectonic zone of the NWCaucasus) is about 10-15 km. Data on paleostress and deformation in surface structures were collected over the area of about 3 x 6 km between rivers Sochi and Mamaika and in the underground adit.

The paleostress fields was reconstructed by methods, which use data of the fracture orientations, striations in slickensides, extension cracks and fibrous veins [Goushtchenko, 1979; Sim, 1982] as the stress-indicators. About 250 measurements and observations of these stress signs were made at 15 outcrops. Local stress state and the common stress regime were obtained. Each local stress state was matched using the stereogram (Goushtchenko's conical stereogram template) in such a way that next rules are keeping. Displacement vectors for local stress state at the template are radiating from stress axis and attract to tension axis. The plane of restriction of axes actions divides the spaces of different-directional vectors. Each displacement vector is possessed to the sharp angle that is formed by arcs of large circs. These arcs are radiating from the stress axes and tension one. Using these rules the orientations of stress and tension axes were matched for 13 local stress states. The common stress regime is matching using the 13 stress and 13 tension axes in such a way that some rules are utilizing. There are: the cone of common stress does not contain the locale tension axis, and the cone of common tension does not contain the locale stress axis. The centers of these cones are the required stress and tension axes of common stress regime for studied massif. The obtained maximum stress axis has a strike to South-West 225 and dip 20. The minimum stress axis (tension) was sub-vertical and middle stress axis has low dip (20) to South-East. As a whole, this NE – SW common stress regime was of the "compressional (thrust)" type. This stress- regime is in conformity with the regional stress field of the North-West Cuaucasus [Marinin, 2003; Saintot, Angelier, 2002]. Such regime can be produced by two models 1) lateral press (pure shearing, flattening) and 2) gravitational sliding (simple shearing). The common stress regime does not allow to choice any single model without an additional study.

The method for estimation of shortening values based on kinematic models of multilayer folds of "similar" types [Yakovlev, 1981; 2002] was used. The model uses the combination of two kinematic mechanisms of fold formation in competent layer – 1) buckling as a kind of rotation and 2) flattening acting uniformly in the flanks and hinges of the fold. Multiple iterations in computer calculations and application of various proportions of the two mechanism increments allowed us to obtain a simple diagram for determination of shortening values based on the geometry of the folded competent layer. Numerous asymmetrical folds were observed in the adit near the detachment of the nappe. Low -angle long flanks (southern for the syncline) had sub-horizontal orientation (azimuth of $\sim$300, dip 10-20) and northern flanks of the syncline were sub-vertical or overturned. Axial surfaces of the folds were inclined at middle or small dip angles to the north-east. Several hinge lines were measured, which had average strikes of about NW 300 and dips of 10-30. It is important to note that such strikes are in agreement with the common revealed stress regime, because it is almost perpendicular to the maximum stress axis. Numerous shatter zones were also observed. In the whole, they are parallel to sloping long flanks of folds and partly these zones are also folded. Detailed photos were used for measuring geometrical parameters of 40 folds. These parameters were 1) dip angles of fold axial surfaces, 2) dip angles of fold flanks (with respect to perpendiculars of the axial surfaces), 3) thicknesses of competent layers in flanks (h), 4) and those in hinges of the folds (H). Dip angles of flanks with respect to perpendiculars to axial surfaces and the ratio "h/H" were used for shortening value estimation according to the diagram [Yakovlev, 2002]. The estimated shortening values (Sh) were 2% to 95% ($-\varepsilon$ = (L1-L0)*100/L0), and the average was 61%. The dip angles (Ax) for the axial surfaces were 1 to 57 at the North-East. The tendency of increasing shortening values (Ax) with increasing sloping of axial surfaces was (Ax) found. The correlation coefficient for these two parameters was about -0,895. The regression equation (straight line) was found to be Ax = 65,5 – 0,610*Sh.

Two competing models were considered for the explanation of the deformation state as sets of deformed objects, such as, sub-horizontal shortening (resulted from possible lateral press) and simple sub-horizontal shearing (caused by gravitational sliding). As it was noted above, the stress regime are almost the same for both models. Some difference can occur for dip of the maximum stress axis. The deformation state can be study due to the existing objects, which are at different stages of the process. This means that for many objects the trends of the deformation states can be key features of the process elucidation. From this point of view, the first model (lateral shortening) can possess small shortening for low angle axial surfaces for initial stages of the process and the tendency of increasing shortening values when the axial surfaces grow to verticals. The mechanism of the horizontal shearing has just an opposite trend.

The model of the simple shearing in a flat horizontal zone was calculated for the deformation ellipse (37 mean values) with the same parameters: dip angles of axial surfaces Ax (orientation of the long axis of the ellipse) and shortening values Sh (lengths of short axes of the ellipse). The obtained values varied from 2 to 74 for dip angles Ax and from 3% to 86% for shortening values Sh. The correlation coefficient for these two parameters was -0,992. The regression equation (straight line) was obtained: Ax = 47.8 – 0,445*Sh. It is clear that these two regression lines (for natural folds and for models of simple shearing) are very close. Some deviation (about 20 degrees for small shortenings) can be explained by the total inclination of the nappe body to the North. This means that the model of simple shearing in the bottom part of the Vorontsovsky nappe during its possible gravitational sliding from the North-East to the South-West is satisfactory for the explanation of stress-regime and the trend of deformation states. From this point of view, numerous sub-horizontal shatter zones can be explained as structures, which are similar to usual Ridel's features for shear zones.

The sedimentations condition analysis of Oligocene flysch shows that depth of basin was about 1-3 km. The folding formation processes have started in Greater Caucasus tectonic zone at the late Eocene, and the Paleocene-Eocene sediments (and Cretaceous, possible) of Chvezhepsinskaya tectonic zone were hypsometrically above of the sediments surface of Abkhazskaya zone during Oligocene-Miocene. Total tilting of 3-5 degrees can be one of reason for displacement of nappe body from North to the South.

Conclusion. The comparison of stress regime and deformation states of Vorontsovsky nappe with two models (lateral shortening and simple shearing) has shown the sufficient advantage of second model as mechanism of this structure formation. The comparison of results of stress regime study with the results of deformation states study has shown the obvious benefit of the deformations study in analysis of theoretic models, i.e. in the explanation of nappe deformations and stress origin.

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