Trabajos de Geología, Universidad de Oviedo, 30 : 140-144 (2010)

Rock mechanics as a significant supplement for cross-section balancing (an example from the Pavlov Hills, Outer Western Carpathians, Czech Republic)

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Abstract: Methods of rock mechanics and mechanical testing are a suitable supplement to tectonic analysis and structural reconstruction in areas where structures are not clearly visible. Rock mechanics enhances tectonic research of young non-deep eroded orogenic belts, where past lithostatic stress acquired quite similar values to present-day ones. This paper focusses on cross-section balancing in frontal parts of nappes of the Outer Western Carpathians.

Keywords: rock mechanics, cross-section balancing, limestones, angle of internal friction, Mohr-Coulomb criterion, thrusts, Western Carpathians.

The Jurassic limestones under study are situated at the western margin of the Zdanice Nappe of the Outer Western Carpathians in the easternmost part of the Czech Republic. The limestone plate consists of three stratigraphic units: Klentnice Fm (Oxfodian-Tithonian), "nodular" limestones (Tithonian) and Erstbrunn limestones (Tithonian). Dark-gray deep-marine carbonatic claystones (Klentnice Fm) continuously grade to tectofacies of thin "nodular" limestones and consequently to light shallow-marine massive limestones (Ernstbrunn Lst). The Upper Cretaceous, mostly siliciclastic sediments overlie the Jurassic limestones. The Jurassic and Cretaceous "pre-flysh" sediments are surrounded by the Paleogene hemipelagic and flysh claystones and sandstones. As the Ernstbrunn limestones are not easily eroded, these rocks form significant morphological elevations (Pavlov Hills).

The structure of the Pavlov Hills was formed during folding and thrusting within the Outer Carpathian accretionary wedge in the younger phase of the Alpine orogeny (Lower Miocene). The pre-flysh Mesozoic sediments form basal parts of the Zdanice Nappe, but their uppermost part was cut off by the second thrust. The mechanical features of the stratigraphic units under consideration depend on lithology. The claystones of Klentnice Fm as well as pelagic Paleogene sediments are soft with reduced shear strength in contrast to competent Ernstbrunn limestones.

Mechanical rock tests and their results

The mechanical properties of various rocks could be described through different physical and mechanical analyses. The most important features in the structural studies are stiffness and angle of internal friction. The relationship between limit of shear stress τ_{crit} and normal stress σ_n is expressed by the terms of Mohr-Coulomb criteria:

$$\tau_{crit} = \tan \varphi \cdot \sigma_n + \tau_0 \quad (1),$$

where φ is angle of internal friction and τ_0 is shear cohesion (Goodman, 1989). This linear model predicts failure occurrence when the applied shear stress τ exceeds the frictional resistance τ_{crit}.

The test in unconfined compression and the Brazilian test (in splitting tension) allow us to determine the angle of internal friction, given by $\varphi = 90 - 2\alpha$, where α is an angle between fracture surface and the σ_1 direction (Fig. 1), and the value of stiffness (in unconfined compression σ_c and in splitting tension σ_d). We obtain some points of the Mohr envelope by combining φ and σ_c, other points were obtained by σ_d. Using the least square method for the best solution we obtain the Mohr-Coulomb criteria equation with averaged angle of internal friction in the interval from σ_d to σ_c. Although the angle of internal friction varies greatly under normal tensile stress conditions, it is more or less constant under low compression stress conditions, and the Mohr-Coulomb criterion can be accepted. The values of the angle of internal friction acquired in the unconfined compression test will be applied in the following text. Averaged experimental results are outlined in table 1. The final angle of internal friction $\varphi_{aw} = 50°$ used for cross-section balancing was counted as a thickness-weighted average of experimental data. Consequently, the angle between bedding planes and ramps may be estimated at $\Phi = 20°$.

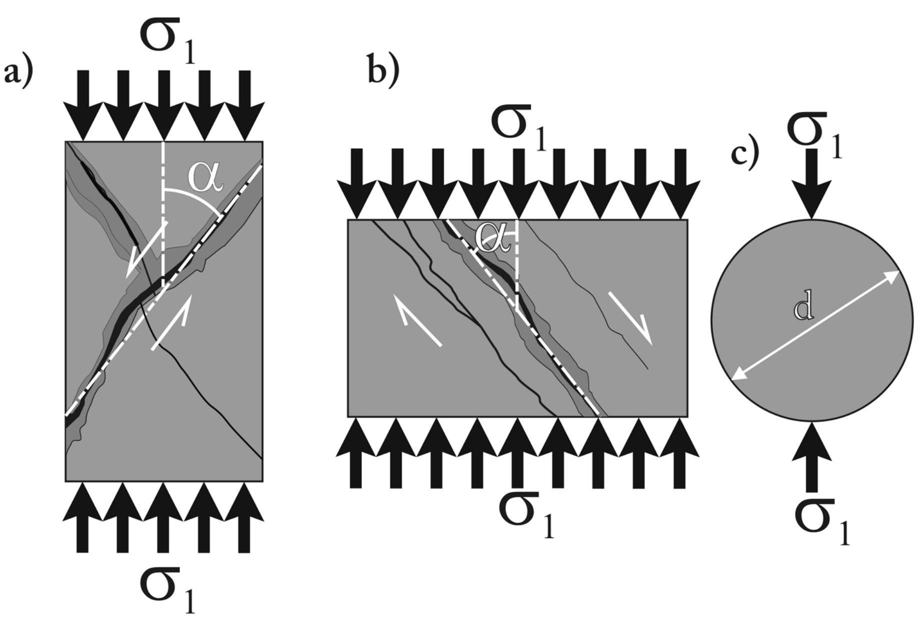

Figure 1. Ruptured rock samples after laboratory tests: (a) unconfined compression, (b) Brazilian, (c) Brazilian, cross-section.

Rock	**Lithology**	ϕ [°]	σ_c [MPa]	σ_d [MPa]	thickness [m]
Ernstbrunn Lst	massive limestones	68	152	–	142
"nodular" limestones	tectonically disturbed limestones	53	52	0.46	74
Klentnice Fm	mudstones, claystones	23	111	0.47	109
Zdanice-Hustopece Fm	flysch formation – sandstones	43	74	–	–

Table 1. Mechanical parameters of significant rocks from the Pavlov Hills.

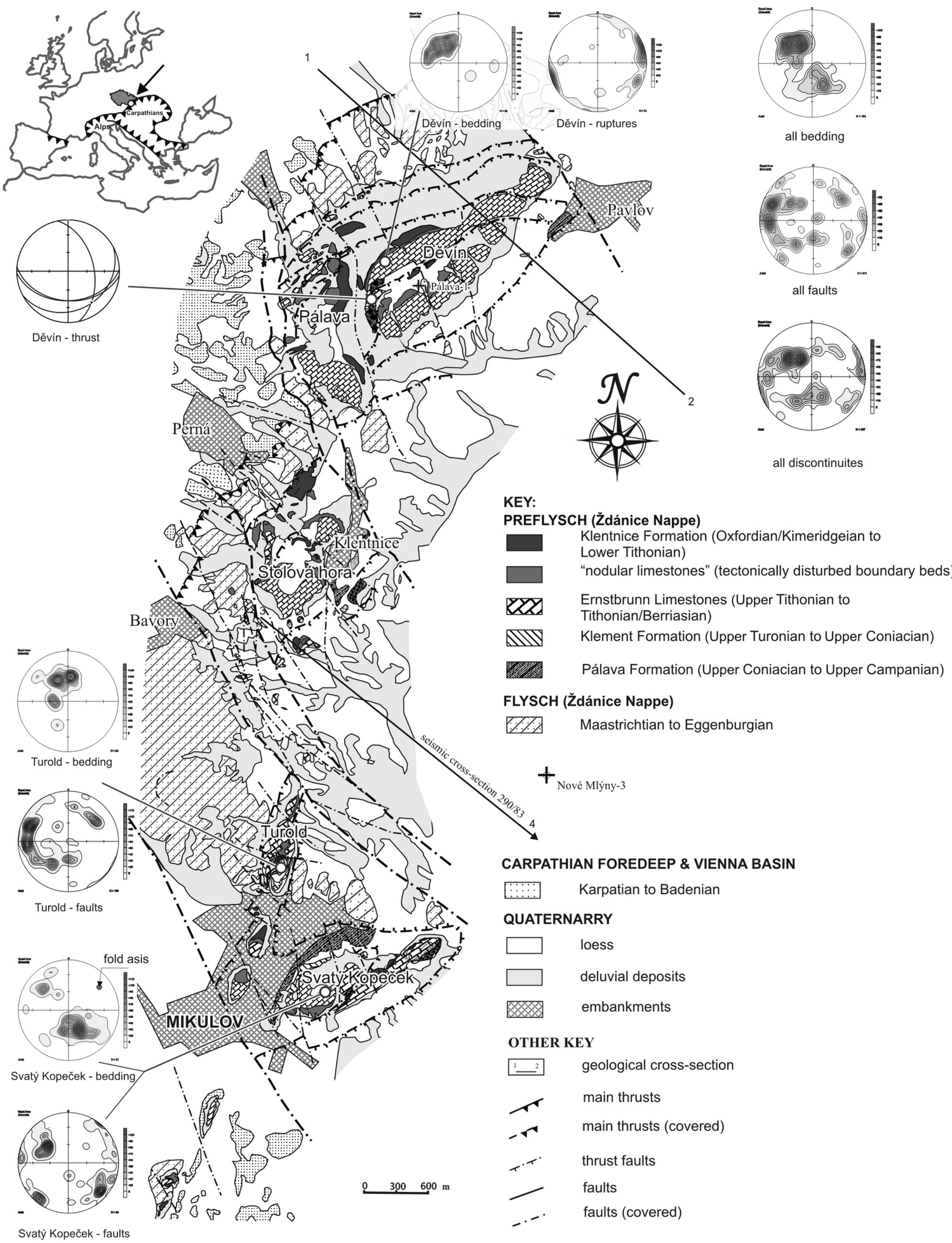

Figure 2. Simplified structural map of the Pavlov Hills.

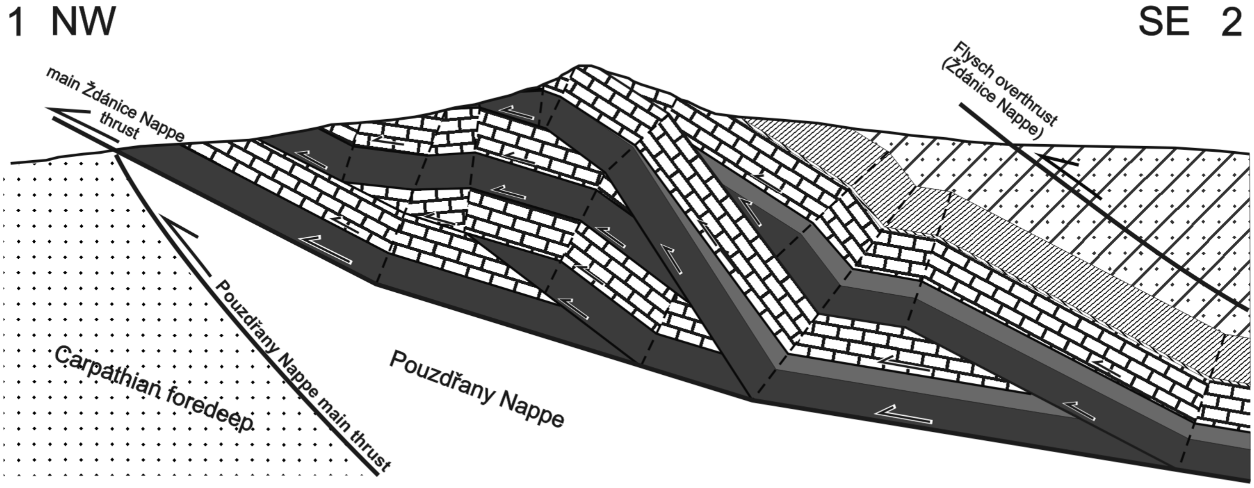

Figure3. Balanced cross-section 1-2 through Devin Hill.

Tectonics of the Pavlov Hills and cross-section balancing

The area under study was subjected to detailed geological mapping including the collection of compass data. Several anticlines associated with thrusts were recognized (Figs. 2 and 3). Anticlines are slightly plunging to the NE, i.e. in the same direction as the thrusts strike. We interpret this structure as fault-bend folds. En echelon arrangement was explained as block displacement along NW-SE striking faults (Poul and Melichar, 2006).

Thus, the principles of cross section were outlined, but not all information for balanced ones was available. We used hand-made balancing based on structural and lithological data supplemented by two seismic cross-sections, five boreholes and mechanical data. Conservation of bed length and area principles were assumed (Suppe, 1983), construction and testing were made with AutoCAD software.

Thrusts and ramps exposed on Devin Hill are documented in stratigraphic repetitions of the Jurassic and Cretaceous beds in outcrops (Jüttner, 1922) as

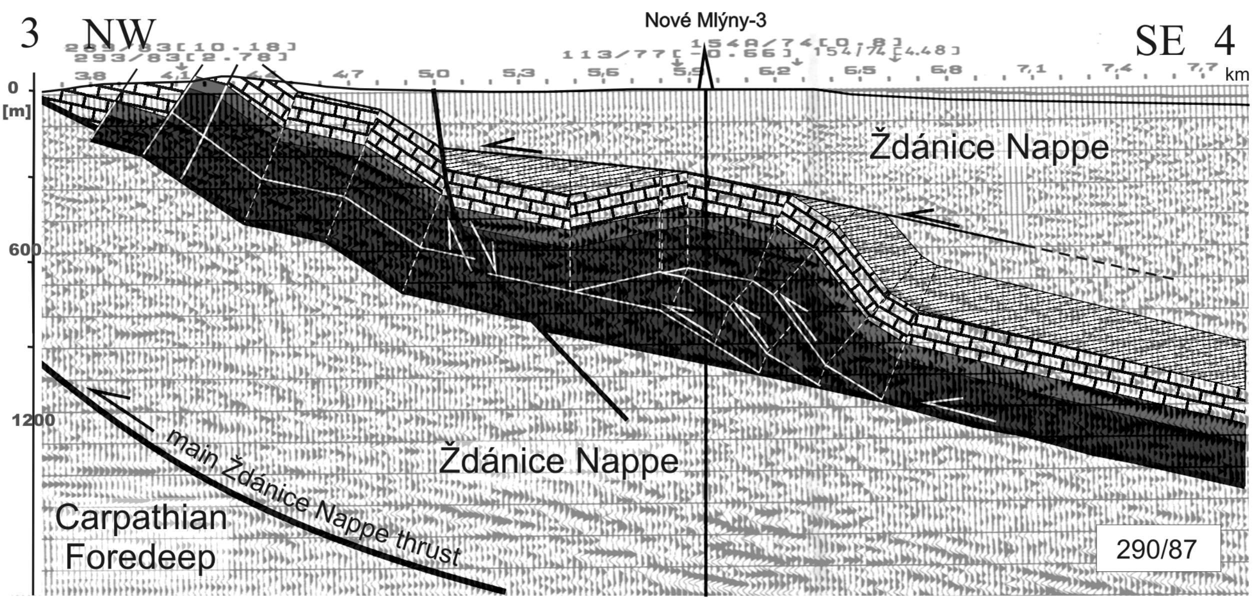

Figure 4. Balanced cross-section 3-4 through Stolova Hora Mountain with seismic section (290/87).

well as in the borehole Palava-1. Beds are dipping about 30-50° to the SE. Some changes in bed dips were recognized in compass data and beds in the SE dip at almost double the angle of those in the NW. Differences between bedding dips correspond to the ramp forming angle as well as to the experimental φ-angle. Some inconsistency in the thickness of "nodular" limestones is regarded as the result of tectonic sliding.

The Svaty Kopecek [Saint Hill] anticline is situated in the eastern vicinity of Mikulov. As the fold axis plunges to the NE, it was possible to recognize its NE prolongation in the seismic cross sections (figure 2, cross section 3-4; see figure 4). This anticlinal structure was drilled through at depth by Nove Mlyny-3 borehole, where anomalous thickness of Klentnice Fm was discovered. In our cross section this structure is constructed as an antiformal fault-bend fold stack of several slices cut by ramps under 20°. The main detachment is set at the base of Klentnice Fm and the second one is in "nodular" limestones, whereas the ramps are situated in the rigid Ernstbrunn limestones.

Discussion and conclusions

The original angle of ramp dip is one of the critical limits for balanced cross section constructions. Our experimental data predicted ramps under 20°. This value was verified by field compass bed orientation as well as by seismic cross section. Differences in dips of beds from two upper slices on the Devin Hill (32° and 50°) and from two lower ones in cross-section (Figs. 3 and 4, 12° and 32°) can be explained assuming the same ramp forming angle. In this way the mechanical testing of rock may be used as an additional method for ramp-angle determination.

It is very important to note that the experimental ramp angle makes it possible to construct a correct balanced cross section. Limitations to the application of the method are connected with conditions of deformation, which have to be reproducable in laboratory equipment, i.e. have to be comparable to Earth surface conditions. Such a situation exists in young orogenic belts, where denudation processes have not eroded the youngest rocks.

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