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LANDFORM EVOLUTION IN MOUNTAIN AREAS

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ESTIMATION OF THE MISSING ERODED SEDIMENTS IN THE BÍLÉ KARPATY UNIT (OUTER WEST CARPATHIANS)

Abstract. The erosion of up to 1,400 m of the rock column in the Bílé Karpaty Unit (Magura Nappe, Czech Republic) since the Sarmatian is inferred on the basis of anisotropy of magnetic susceptibility (AMS), vitrinite reflection analysis, rock–eval analysis, K/Ar radiometric dating, and detailed geological mapping. The erosion of nearly 1.5 km of rocks since the Sarmatian contradicts the idea of the presence of planation surfaces of Sarmatian age in this part of the Outer West Carpathians. Evolution of the topography has probably been the result of dynamic equilibrium between uplift and erosion. Thus, the present-day topography should be young, as indicated by the fact that the oldest dated landslides are no older than 13,000 years BP.

Key words: topographic evolution, denudation, planation surfaces, geochemical analysis of rocks, Magura Nappe

INTRODUCTION

The age of the topography of the Flysch Belt of the Outer West Carpathians (OWC) is still not well known. This is due mainly to the absence of rocks suitable for radiometric dating. Moreover, no other suitable dating technique (e.g., fission-track analysis) has yet been applied to this region. So far, the only approach to dating that has been used extensively in this area is that of planation surface analysis (Lukniš 1964; Stehlík 1964; Dzurovčin 1994). This very speculative method has often been criticized in the international geomorphological literature (cf. Summerfield 2000, chapter 1) and in the flysch Carpathians themselves (e.g., Zuchiewicz 1998; Bíl 2002, 2003).

The present work is a synthesis of geological research that was not primarily focused on dating the topography. Nonetheless, based on our results, we believe it is possible to obtain some important conclusions concerning the age of the present day topography for one particular area in the Bílé Karpaty Unit.

STUDY AREA

Our study area is situated in the westernmost part of the OWC, close to the Czech/Slovak border, about 20 km east of Uherské Hradiště, between the towns of Nezdenice and Starý Hrozenkov (Fig. 1.). The area is comprised of an almost horizontally bedded sandstone block, which is a part of the Svodnice Formation (Bílé Karpaty Unit, Magura Nappe). It has an area of 16 km^2, its mean altitude is 510 m a.s.l., and the difference between its highest (735 m a.s.l.) and lowest (333 m a.s.l.) points is 402 m (Fig. 1.). The surrounding topography is more rugged. The highest mountains (Velký Lopeník at 911 m, and Velká Javořina at 970 m) are situated 2 km and 16 km to the south, respectively. The deeply incised valley of the Klanečnica River occurs between these two mountains. The elevation at the bottom of this valley is about 340 m. The main divide between the Morava and Váh watersheds runs through the study area.

GEOLOGICAL SETTING

The Bílé Karpaty Unit is a hinterland partial nappe of the Magura Nappe. However, as to its areal extent and thickness it is by no means as significant as the frontal Rača Unit. Whereas a minimum sediment thickness of the Rača Unit in excess of 5,578 m has been documented in borehole Jarošov-1 near Uherské Hradiště, the main thrust fault of the Bílé Karpaty Unit has been drilled at a maximum depth of 602 m in borehole Blatnička-1 (Menčík and Pesl 1966). Taking the 238 m altitude of the borehole and the 970 m altitude of the highest peak on the present-day surface (Velká Javořina — 970 m) into consideration, the maximum documented sediment thickness of the unit is 1,234 m.

Later exploration works did not confirm higher sediment thicknesses but, on the contrary, the unit was found having generally lower thickness. In the Klanečnice valley in Slovakia, near the Czech border, the unit was confirmed to have thickness of 75.6 m (Potfaj et al. 1986). In both of the boreholes, the Bílé Karpaty Unit was found to be underlain by the Zlín Formation belonging either to the Bystrica or the Rača Unit. During geological mapping (Geological map the Czech Republic 1:50,000, sheet Strání) in Strání village, the Zlín Formation was discovered lying directly on surface, in a partial tectonic slice of the Bystrica Unit (Fig. 2). In a dug trench near Blatnička, commissioned by the Czech Geological Survey staff in 1992, the Beloveža Formation of the Bystrica Unit has been found cropping out in the Bílé Karpaty Unit. Tectonic slices of the Púchov marls and Antonínek Formation, both belonging to the Pienniny Klippen Belt, are known from surface exposures at the thrust front of the Bílé Karpaty Unit. The afore-mentioned statements suggest that the Bílé Karpaty Unit is tectonically interfolded not only with the Rača Unit and, in particular, the Bystrica Unit but also with the Pienniny Klippen Belt. The interfolding is relatively young and it is considered be-

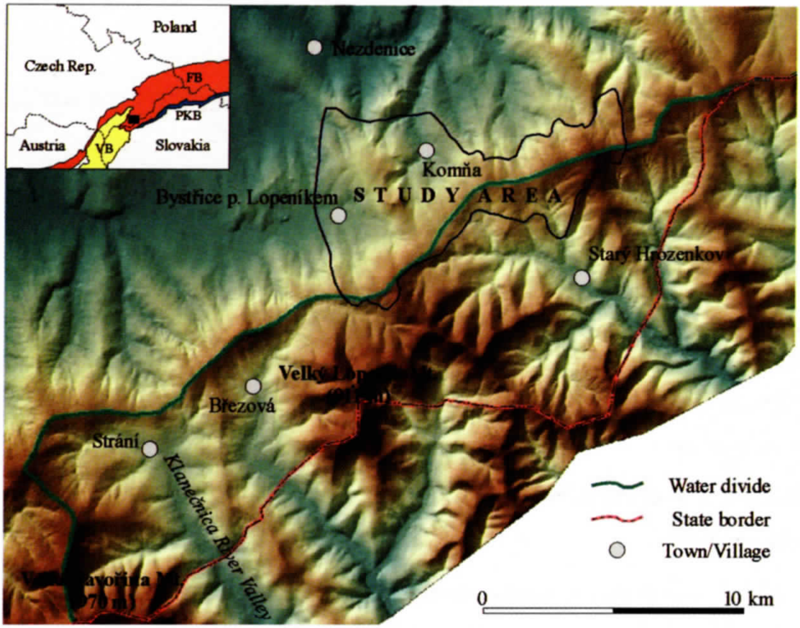

Fig. 1. Topography around the study area; the Outer Carpathian flysch belt is shown in purple. FB — Flysch Belt, PKB — Pienniny Klippen Belt, VB — Vienna Basin

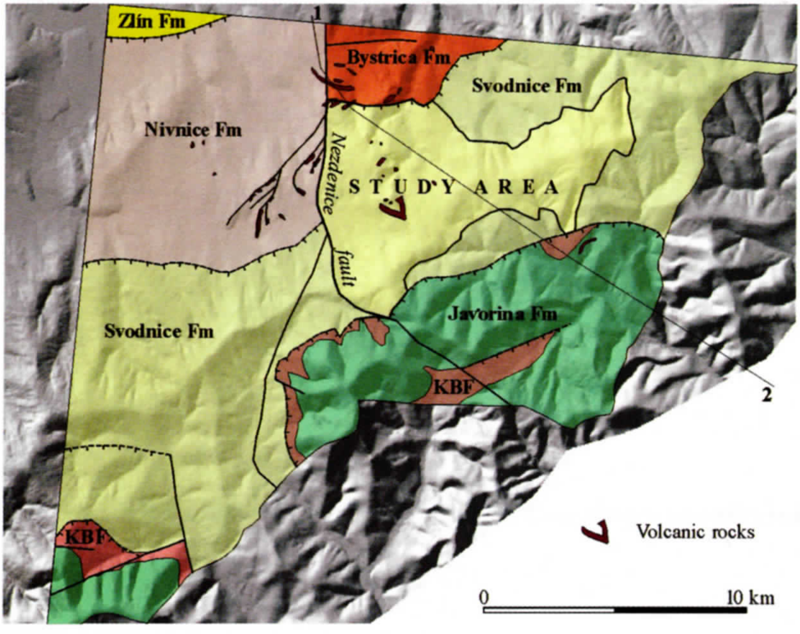

Fig. 2. Geological map of the study area and its surroundings, showing alluvial and colluvial covers. 1–2 — geological cross-section shown on Fig. 3, KBF — Kaumberg Formation

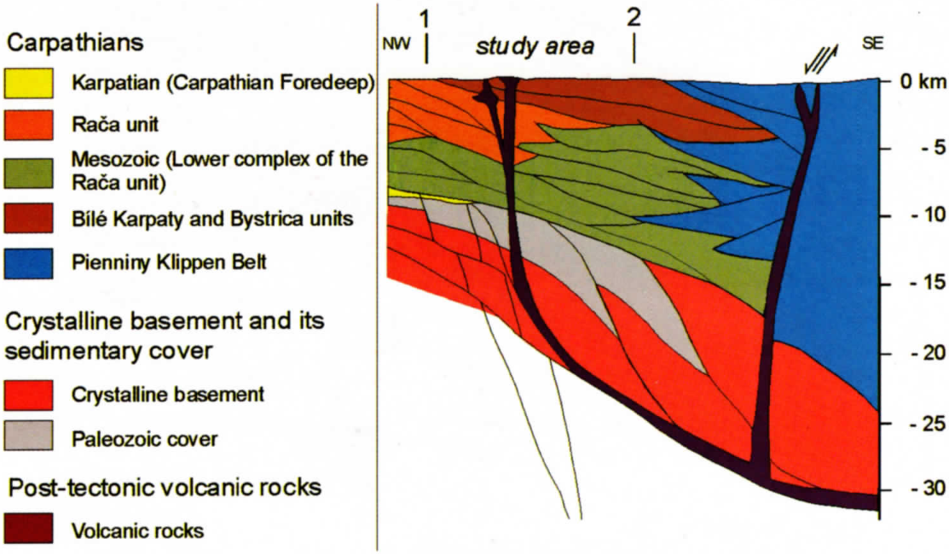

Fig. 3. Geological cross-section through the flysch Carpathians in the study area

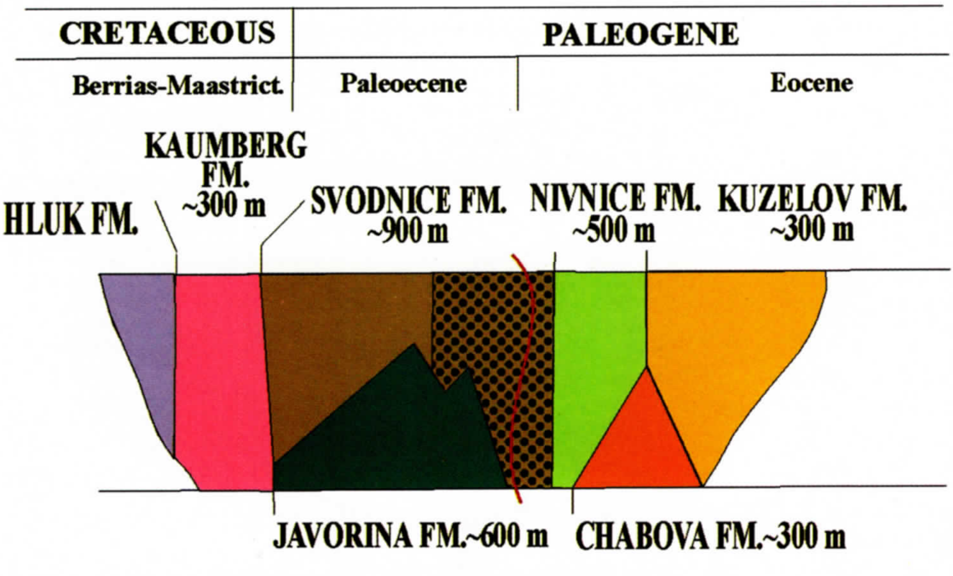

Fig. 4. Stratigraphic sequence of the Bílé Karpaty Unit. Red line shows the current erosion surface

ing related to the final thrusting and internal shortening of the underlying flysch units associated with out-of-sequence thrusting of the underlying duplex nappe, consisting of the Rača and Bystrica units in the nappe fan of the Bílé Karpaty Unit. Integrity of the Bílé Karpaty Unit as a whole was not affected and the unit was carried piggy-back on top of the evolving accretionary wedge of, above all, the Rača Unit (Hrouda et al. 1999). In the Bílé Karpaty Unit, a duplex stacked structure is located solely in the footwall of the partial Javorina Nappe. Presence of an undisturbed original lithostratigraphic succession of sediments was confirmed in the course of drilling works (borehole Komňa-1; Eliáš and Plička 1962) and geological mapping (detailed lithological and sedimentological logs in the Velká Javořina and Velký Lopeník Hills, documented the by co-author of the present paper, O. Krejčí).

The Rača Unit can be subdivided into three partial nappes: the Hluk development nappe in the east and the Vlára development nappe with the Javořina partial nappe in the west and south. The Magura Nappe represents a typical example of thin-skinned orogen with multiple stacking of low-angle (subhorizontal?) duplex horses (see cross-section on Fig. 3). This geological structure is cut through by deep erosional valleys, which developed along the Nezdenice and Vláry Pass fault systems. Both systems provided feeding paths for young volcanics.

We believe that there has been both vertical and horizontal (dextral) movement along this fault in the past. South-east of Bánov, a small system of sinistral faults leads off from the Nezdenice fault. This fault system was used as a rising path for volcanic rocks (Fig. 3). The western side of the Nezdenice fault is the downthrown side, whereas the eastern side is the upthrown side and is, therefore, more denuded.

The complete stratigraphic sequence of the Bílé Karpaty Unit is shown on Figure 4 (for detailed description see Stráník et al. 1995, Švábenická et al. 1997) The current erosional surface is a part of the Svodnice Fm., which is 900 m thick. The upper Nivnice and Kuželov Fms. have already been denuded.

METHODS

In addition to detailed geological mapping (Krejčí 1987, 1990; Krejčí and Havlíček 1993; Krejčí et al. 1994), evidence from the following methods have also been used in the current study:

1. Anisotropy of magnetic susceptibility (AMS). This method is one of the most sensitive indicators of strain in rocks. It depicts the orientation and degree of alignment of the preferred orientation of minerals as an ellipsoid. The orientation of the principal susceptibility axes are commonly coaxial with those of the strain ellipsoid — the orientation of X_{max} is almost always parallel to the orientation of the axis of maximum shortening strain (Borradaile 1991; Housen et al. 1996; Housen and Kanamatsu 2003). The AMS technique has

been applied to the sandstones of the entire Czech part of the flysch belt (Hrouda et al. 1999).

2. Microscopic photometry (vitrinite reflection) — *Ro*. This technique is mainly used in petroleum geology. It is able to determine the palaeoheat flux evolution of a sedimentary basin (Franců et al. 2000). The *Ro* can thus establish the maximum burial depth of a rock sample. It does not distinguish between sedimentary and tectonic burial. These palaeoheat approximations are based on changes in palaeoclimate together with ocean depth, which influence the sediment surface temperature and the heat flow at the bottom of sedimentary basins. The thicknesses of sedimentary units are considered without taking into account compaction. The organic petrography of the macerals from vitrinite, inertinite, and liptinite groups were examined in polished specimens. Vitrinite reflections were measured in accordance with the International Commission for Coal Petrography (International Handbook of Coal Petrography, ICCP, 1971 and 1976). The critical *Ro* values are as follows: 0.2% — peat stage (non-altered sediments); 0.6–1.3% — oil-genesis stage (liquid hydrocarbons), rock temperatures approximately between 90–150°C; 1.3–2.4% — gas-genesis stage, rock temperatures 150–200°C; 2.4–4.2% — anthracite stage, metamorphosis of very low level, rock temperatures (up to 300 C).
3. Rock–Eval pyrolysis. This technique is used for identifying the type and maturity of organic matter, and to detect petroleum potential in sediments. It is based on the heat disintegration of pulverized samples in an inert atmosphere of N_2. The samples were heated under a thermal gradient of 25°C/min. This method allows the assessment and reconstruction of the physical conditions (especially pressure and temperature) to which the rock samples were exposed during their geological evolution, and thus also determines burial depth. The Rock–Eval pyrolysis was carried out by the Oil and Gas Institute in Kraków. PetroMod 7.1 software (IES Jülich, Germany) was used for calculating the maximum burial depth and palaeoheat history. The model solution was solved by finite-difference elements and by the direct method.
4. K/Ar dating of volcanic rocks.

RESULTS

ANISOTROPY OF MAGNETIC SUSCEPTIBILITY

The AMS results (Hrouda et al. 1999) show that part of the Magura Nappe of the Bílé Karpaty Unit (thrust) has undergone a distinct tectonic history. Anomalously weak AMS values for the Bílé Karpaty Unit suggest that it was probably squeezed out of the sedimentary basin during the early phases of its shortening, and that it "flowed" onto the other thrust sheets during basin closing. It thus played a passive role in the process of subduction and/or collision (Fig. 5).

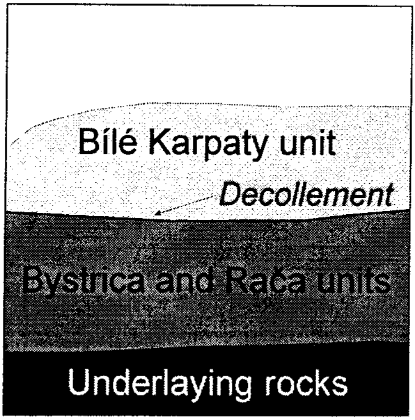

Fig. 5. According to AMS results, the Bílé Karpaty Unit flowed on the other thrust sheets during basin evolution

VITRINITE REFLECTION AND ROCK-EVAL PYROLYSIS

With one exception, there are only calcareous claystones with organic C contents between 0.6–2%. The dominant organic component in all samples is plant kerogen of terrestrial origin. Rocks from the Svodnice Fm. were found to have the highest hydrocarbon potential, and are thus suitable for the determination of maximum burial depths and palaeoheat alterations. The resulting degree of palaeoheat-rock alteration is very close to the conditions of oil genesis (Tissot and Welte 1984). The characteristic *Ro* values for the rock alteration lie between 0.79–0.83% (Localities: Komňa–Nový dvůr, Rasová quarry a Bzová active quarry), and the T_{max} pyrolysis index is 432–444°C. The heat conditions mentioned above are normally observed at depths between 1.5–2 km. A probable palaeoheat evolution and burial history is shown on Fig. 6.

RADIOMETRIC DATING

Neovolcanic rocks were dated by A. Přichystal et al. (1998) and Z. Pécskay et al. (2002). The samples show ages clustering in two intervals, corresponding to the Late Badenian and Early Sarmatian: Hrádek — 14.76 Ma, Starý Hrozenkov — 14.39 Ma, Bánov — 13.49 Ma, Bystřice pod Lopeníkem — 13.39 Ma, and Nezdenice — 13.36 Ma. These ages are only slightly older than those of similar intrusions in Hornie Srnie, western Slovakia (e.g., 11.8 Ma; Kantor et al. 1984). This volcanic activity is the oldest and the westernmost of the entire Carpathian mountain arc. The fact that there is only evidence for subsurface volcanism (Adamová et al. 1995), and the observation that the emplacement of intrusion appears to have been post-tectonic relative to the thrusting in the Magura Nappe, are very important for the further considerations.

DISCUSSION

The weakly deformed structure of the Bílé Karpaty Unit and its almost horizontal bedding can be observed and mapped in the field (Krejčí and Havlíček 1993). This, together with the results described above, leads us to a conclusion that there had not been any other units above the Bílé Karpaty Unit since the beginning of thrusting in the late Oligocene. We assume that the stratigraphy of the Bílé Karpaty Unit west of the Nezdenice fault (the downthrown side) was also present on the eastern, upthrown side prior to the onset of the Nezdenice fault activity. We thereby approximate that the thickness of the "missing" eroded members east of the Nezdenice fault reaches up to 1,400 m (the sum of thicknesses of the missing Nivnice and Kuželov Formations). The absence of this material is attributed to denudation loss since Sarmatian times (Fig. 7). We believe that the range of this "eroded column" encompasses at least the rest of the Bílé Karpaty Unit. Thus, the topographic relief of this part of the Magura Nappe has probably been subjected to 1,400 m of denudation since the Sarmatian.

On the basis of these results we conclude that the topographic relief of the Outer Western Carpathians has probably evolved continuously, without the need for proposing Sarmatian age planation surfaces. The erosional unloading probably caused passive isostatic uplift, which brought the relief into a state of dynamic equilibrium between uplift and denudation. Additional evidence against the former presence of planated surfaces in this part of the OWC comes from the abundance of landslides localized in the highest parts of the mountains (e.g., Krejčí 2003). The oldest dated landslides in the Outer West Carpathians are of Late Dryas age, 13,000 years BP (Margielewski 1998). The highest parts of these mountains are thus undergoing very intense denudation at present. We expect, therefore, the former presence of Miocene surfaces in these parts of the mountains to be unrealistic. We believe that further investigation based on other modern geological methods, such as fission-track analysis and Be^{10} dating, will bring further support to our findings.

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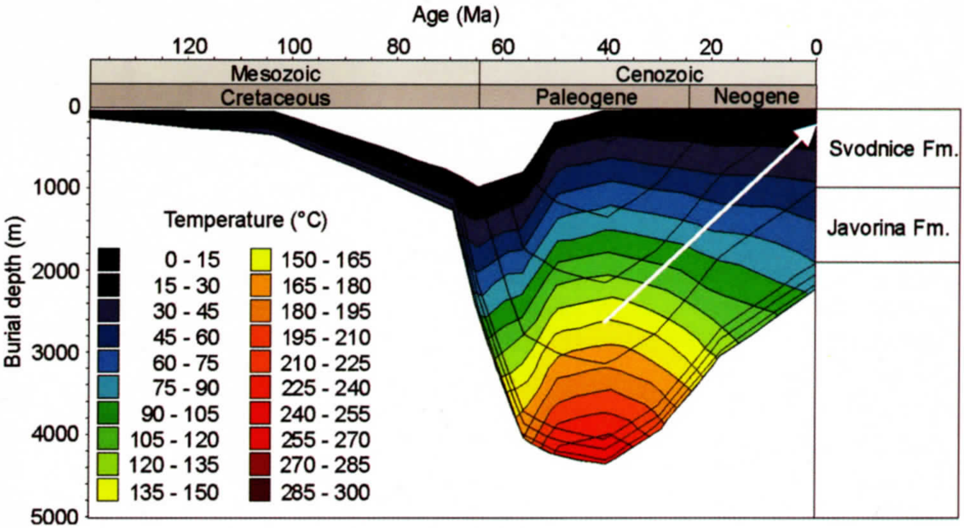

Fig. 6. The reconstruction of burial depth and palaeo-heat evolution for the upper parts of the Bílé Karpaty Unit. The white arrow shows the exhumation path for the Svodnice Fm from the depth to the present-day surface

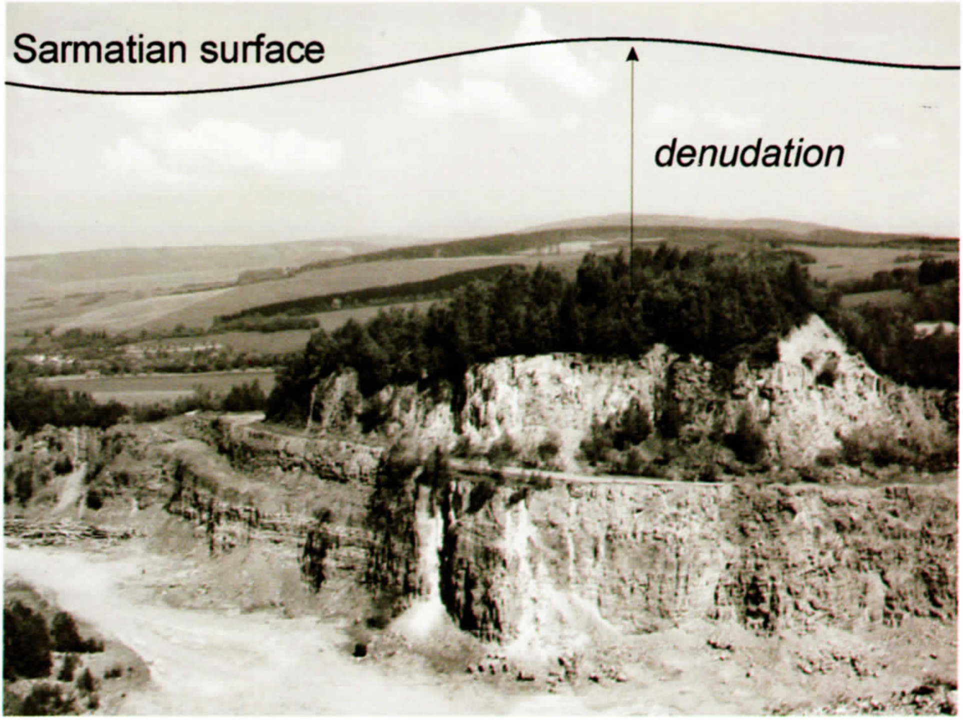

Fig. 7. The Bučník quarry showing exposures of volcanic rocks. There are not indications for lava flows and, therefore, during this volcanic event there had to be a former Sarmatian surface which has been denuded

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STRESZCZENIE

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OSZACOWANIE MIĄŻSZOŚCI ZERODOWANYCH OSADÓW W JEDNOSTCE BIAŁOKARPACKIEJ (ZEWNĘTRZNE KARPATY ZACHODNIE)

Artykuł dyskutuje możliwość zachowania powierzchni zrównania w obrębie Białych Karpat na Morawach (SW część wewnętrznych Karpat Zachodnich). Strefa ta jest zbudowana z utworów fliszowych podjednostek białokarpackiej i bystrzyckiej płaszczowiny magurskiej, na NW przedpolu pasa skałkowego. Szczegółowe wyniki kartowania geologicznego uzupełniono o rezultaty metod geofizycznych i geochemicznych, w tym analizy: anizotropii podatności magnetycznej (AMS), refleksyjności witrynitu, pirolizy Rock-Eval oraz datowania K/Ar skał wulkanicznych.

Uzyskane wyniki wskazują na pogrzebanie, a następnie denudację badanej części Karpat. Obecność neowulkanitów badeńsko-sarmackich sugeruje, że w trakcie ich formowania ponad współczesną powierzchnią terenu znajdowała się 1,5 km grubości warstwa skał, później usunięta. A zatem nie było możliwe zachowanie się sarmackiej powierzchni zrównania na obszarze Białych Karpat. Kwestią otwartą pozostaje zagadnienie przetrwania spłaszczeń tego wieku w innych częściach łuku karpackiego. Datowania ruchów masowych w polskim segmencie Karpat (por. Margielewski 1998) sugerują bardzo młody wiek rzeźby Karpat fliszowych. Potwierdza to nasze przypuszczenia, że ewolucja rzeźby dokonywała się w warunkach równowagi dynamicznej między wypiętrzaniem a denudacją, nie sprzyjających długotrwałemu rozwojowi rzeźby.