Thrust tectonics of the Upper Jurassic limestones in the Pavlov Hills (Outer Western Carpathians, Czech Republic)

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Abstract: The Pavlov Hills are formed by separated limestone blocks previously identified as klippen. A new flat-ramp-flat thrust model of the Pavlov Hills is formulated in this paper. The main tectonic detachment is located at the base of the limestone plate and other subsidiary detachments are located within the nodular limestone horizon and also at the base and top of the Upper Cretaceous deposits. The ramps are situated in the Klentnice Fm and Ernstbrunn Lst. The ramp angle was determined by structural evidence combined with interpretation of seismic profiles. Two parallel antiformal structures plunging to the NE are recognized within the study area. The antiformal fold axes are gently plunging to the NE so the anticlines are not ideal for 3-point hydrocarbon trap setting. These anticlines were subsequently cut by sinistral strike-slip faults perpendicular to the fold axis which resulted in the formation of a large-scale pseudo en-echelon structure in an approximate north–south direction.

The Western Carpathians and the associated foredeep are located in the area of south-eastern Czech Republic (south Moravia) and north-eastern Austria. These areas are relatively rich in hydrocarbon resources when compared to other local discoveries. This area represents the westernmost segment of Carpathian Orogenic Belt which is closely connected to the geological evolution of the Eastern Alps which has proven to contain structures that are suitable for hydrocarbon genesis, migration, and trapping in both stratigraphic and structural settings. All known oil and gas fields in the Western Carpathians are located both in the flysch nappes and in the Neogene basins. However, in our study area only the Neogene sediments hold the known hydrocarbon accumulations.

The aim of this paper is to unravel the present structure and tectonic evolution of the Pavlov Hills as a frontal part of the Ždánice Nappe (Fig. 1) in order to better explain the absence of oil and gas fields in an area which has significant structural and stratigraphic trap possibilities when compared to an area that has been subjected to a similar geological and tectonic evolution. This research will take into account known structural data as well as utilizing seismic data. As the Jurassic limestones in this unit are easily discernable in lithological and geomorphological respects, this research utilized this marker as the basis of the structural interpretations. The current study area was recently mapped at 1:10 000 by Ivan Poul in 2002–2006. Field, borehole, structural and stratigraphic data were supplemented and supported by new geological interpretations of two perpendicular seismic profiles. Balanced cross sections were hand-drawn and their construction was completed with AutoCAD software. Conservation of bed length and area principles were assumed following the studies of Suppe (1983), Marshak & Mitra (1988), amongst others.

Regional setting

The study area is situated in south-eastern Moravia in the frontal portion of the Carpathian accretionary wedge (Figs 1 & 2). This wedge involves two nappe groups (Krosno and Magura groups) which are formed by several flysch nappe units, which consist mainly of Cretaceous to Palaeogene siliciclastic flysch sediments but also contain Mesozoic pre-flysch sediments. These sediments were folded and thrusted during the Neo-Alpine Orogenesis.

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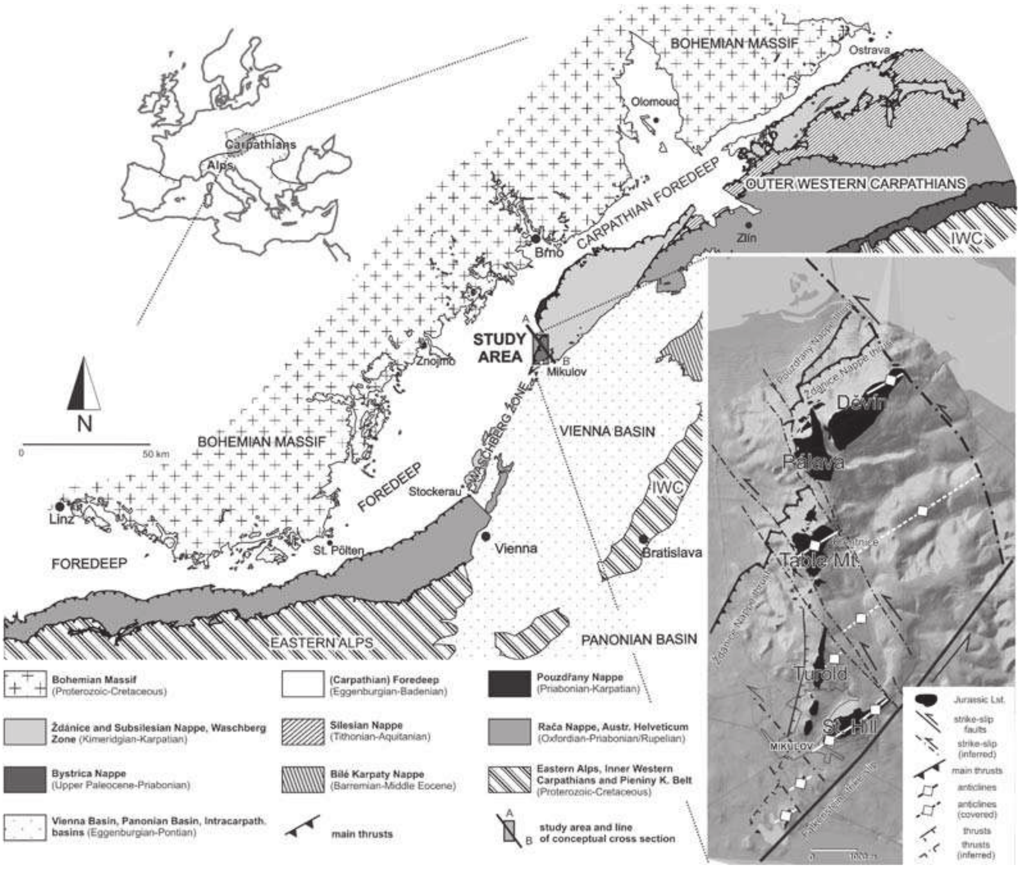

Fig. 1. Structural map showing the location of the study area (box in the central portion of the map) in the northern margin of the Waschberg Zone, Outer Western Carpathians (based on Fusán *et al.* 1967; Beck *et al.* 1980, simplified and modified by authors): IWC, Inner Western Carpathians. See Figure 2 for conceptual cross section A–B.

The typical direction of the fold axes is NE–SW while transversal faults are typically perpendicular to the fold axes trend.

In the south of Moravia, the Krosno Nappe Group is composed of the Pouzdřany Nappe and the overlying Ždánice Nappe which are mostly composed of hemipelagic and flysch sequences (Stráník *et al.* 1999). These nappes are surrounded by younger Neogene basins; the Carpathian Foredeep in the west and the Vienna Basin in the east. Both Neogene and Palaeogene sediments are friable and easy erodable, which results in a flat landscape of the study area. The only exception to this is the Waschberg Zone: a chain of small morphological elevations arranged into a longitudinal NNE–SSW belt (Fig. 1). The Waschberg Zone starts in the Danube river valley in Austria close to the town of Stockerau and ends in the Thaya river valley in the south Moravia near the town of Mikulov. The northernmost (Moravian) part of this ridge with an anomalous north–south direction is called the Pavlov Hills located in Czech Republic.

Such elevations, which are normally underlain by the Upper Malm carbonates, were found at several localities in the Outer Western Carpathians and the term 'klippen' is usually employed for their description. As these large eye-catching limestone bodies are set in the younger Palaeogene flysch sediments on a regional scale, their emplacement mechanism has been the focus of several authors concerned with an exact explanation of the formation.

The first speculations were introduced by Suess in the 19th Century, who considered these limestone bodies as a relict of an island ridge which had ascended from the Palaeogene sandstones to the surface (Andrusov 1959). Another hypothesis introduces the concept that perhaps limestone were derived as hard exotic bodies from the basement and 'flowing' in younger soft sediments (Uhlig 1903;

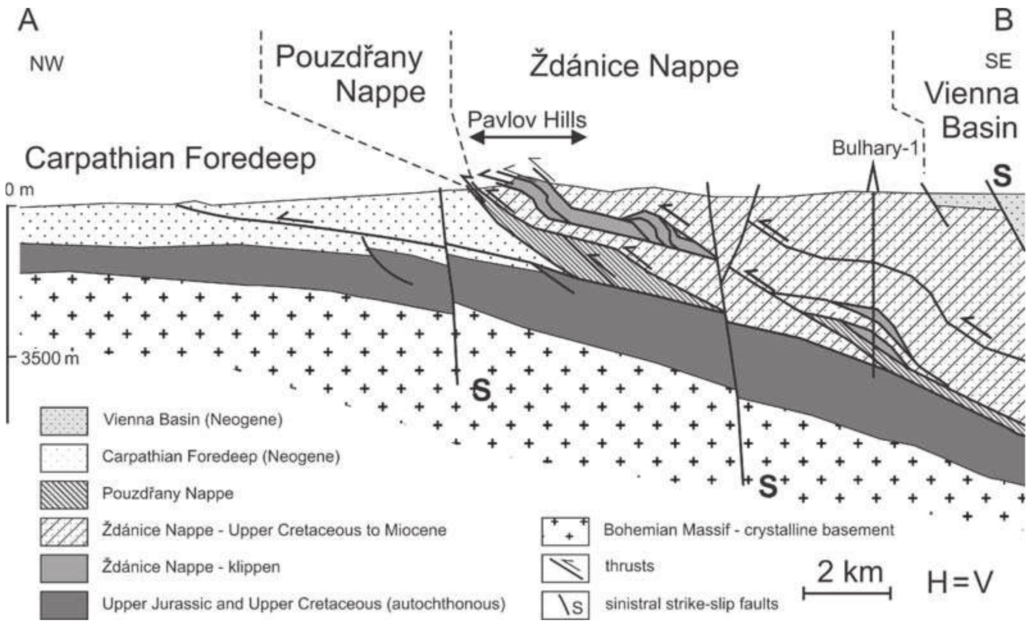

Fig. 2. Conceptual cross section of the frontal part of the Outer Western Carpathians. See Figure 1 for location of the line A–B.

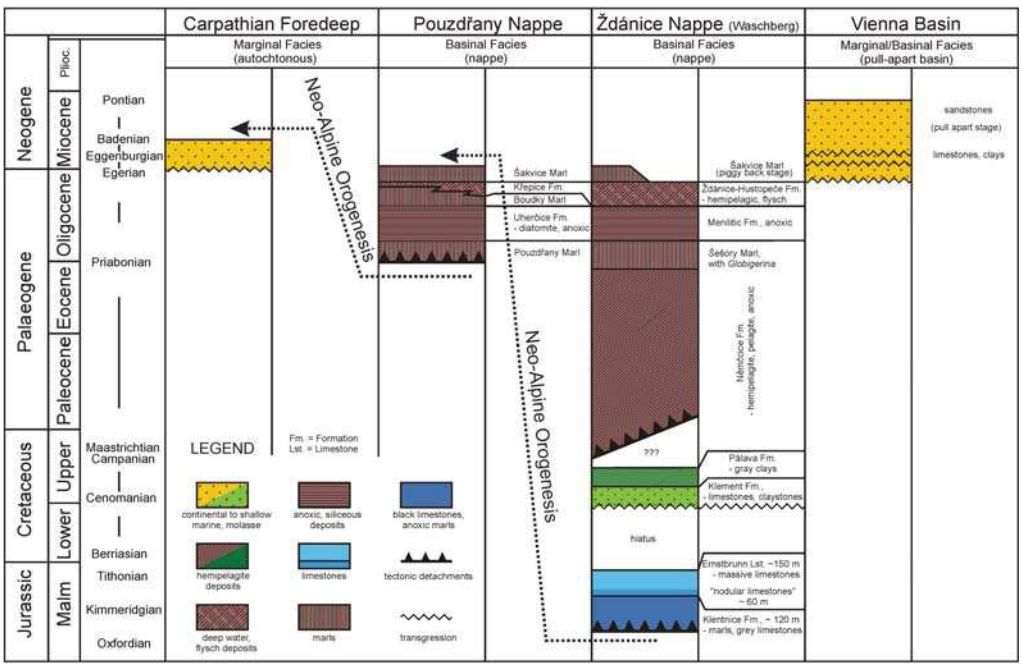

Fig. 3. Stratigraphy of Jurassic–Neogene strata of the Waschberg Zone and adjacent areas (after Stráník *et al.* 1996; Pícha *et al.* 2006, modified and completed by authors).

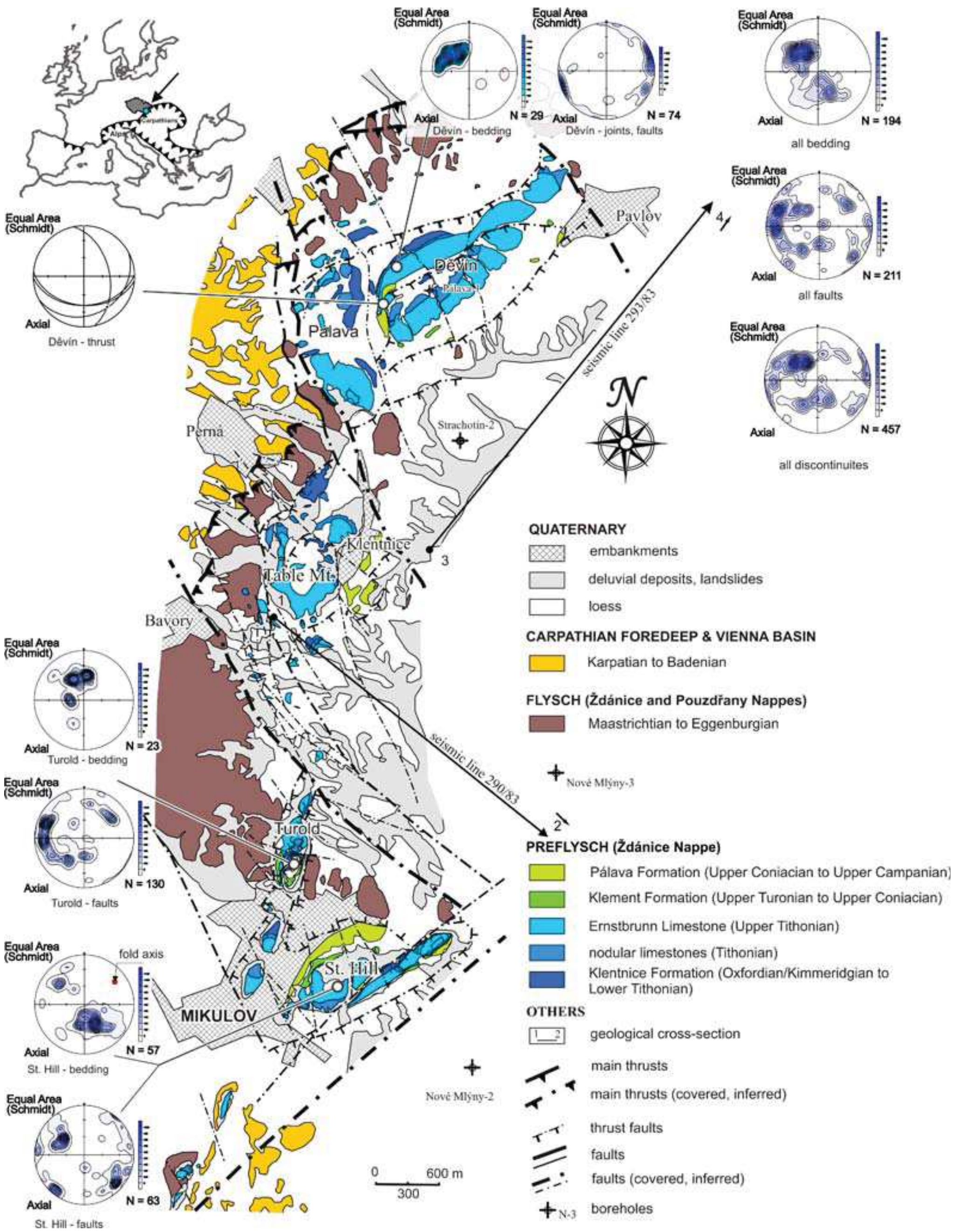

Fig. 4. New geological map of the Pavlov Hills (based on authors' detail geological mapping 1:10 000, simplified). Equal area projections (lower hemisphere) show orientation of structural elements. See Figures 6 and 8 for seismic profiles 1–2 and 3–4 respectively.

Jüttner 1940; Wessely 2006). A more allochthonous hypothesis was presented by Stejskal (1935), who suggested that the limestones cover the Palaeogene sediments and form only the upper parts of elevations as 'caps' which are cut off by subhorizontal thrusts. Ideas of a sedimentary origin of the limestones emplacement were formulated during the 1960s by Eliáš & Stráník (1963), who recognized olistoliths which are located in the Silesian Nappe (northern Moravia); this idea was recently developed by Golonka *et al.* (2006). Glaessner (1931) regarded limestone bodies as small tectonic slices at the base of the Ždánice Nappe and his idea is still currently accepted (Stráník *in* Hanzlíková 1965; Stráník *et al.* 1979, 1999). In a published geological map of the Pavlov Hills (Čtyroký *et al.* 1988, 1995; scale 1:25 000), the limestone blocks are interpreted as tectonic blocks bounded by two post-thrust perpendicular systems of faults in west–east and north–south directions which do not agree with the other tectonic features in the Outer Western Carpathians regions.

Stratigraphy

The lowest part of the Ždánice Nappe is composed of Jurassic calcareous sediments (Fig. 3). The latter sediments are divided into three distinct lithostratigraphic units: Klentnice Formation (?Oxfordian/Kimmeridgian–Lower Tithonian), nodular limestones (Tithonian) and Ernstbrunn Limestone (Upper Tithonian). The Klentnice Fm consists of dark-grey, deep-marine calcareous claystones, marls and limestones (Glaessner 1931; Jüttner 1940; Eliáš 1992). The Ernstbrunn Lst. is typically light coloured, shallow-marine, massive calcareous rocks (Eliáš 1962; Eliáš & Eliášová 1984, 1985, 1986). Problematic transitional beds between these formations are termed 'nodular limestones' in this article. These nodular limestones are represented by clayey limestones, usually brecciated. The Upper Cretaceous siliciclastic sediments (Klement and Pálava Formations) unconformably overlie the Jurassic limestones (Glaessner 1931; Stráník *et al.* 1996). The Jurassic and Upper Cretaceous rocks are surrounded by Palaeogene hemipelagic and flysch claystones and sandstones (Abel 1907; Jüttner 1940; Stráník *et al.* 1979; Pícha *et al.* 2006).

Structures

Bedding is very distinct in the Klentnice Fm as well as in the nodular limestones. However, bedding recognition has proven to be problematic in the Ernstbrunn Lst. The absence of distinct bedding is the reason why we used small-scale and microscopic geopetal structures for the determination of bedding-orientation. Bedding in the area strikes mostly in the NE–SW direction and dips either to the SE or to the NW (Fig. 4). The opposite dip directions are interpreted to be a result of large-scale folding. Maxima of preferred bedding orientation are fairly sharp (Fig. 4) and, consequently, folds are classified as closed chevron folds with axial plane steeply dipping to NW.

Large antiformal structures are recognized in three locations: (1) the northernmost one at the northern edge of the Pavlov Hills (Děvín Hill; see Fig. 5); (2) the central one to the southwest of Klentnice village (Table Mt. [Stolová hora]; Stráník *in* Hanzlíková 1965); and (3) the southernmost one to the east of the town of Mikulov (Saint Hill [Svatý kopeček]; Poul & Melichar 2006).

As the fold axes plunge gently to the NE, the limestone outcrop narrows and ends in this direction. In addition, it was possible to recognize a subsurface antiformal structure by the interpretation of the seismic profile 290/83 at a depth of *c.* 500 m (see Figs 4 & 6). As the geological interpretation of the seismic profile includes young strike-slip faults, the cross section was not balanced as a single geological section but rather in separated blocks. During hydrocarbon prospecting, the antiformal structure was penetrated by the Nové Mlýny-3 borehole (Adámek 1979; Table 1). There were no hydrocarbon accumulations that were discovered by this well and an anomalous thickness of the Klentnice Fm was interpreted as a hinterland dipping duplex system in the core of the antiform. The Upper Cretaceous sediments found in outcrops or in other local boreholes (Nové Mlýny-2,

Fig. 5. View of NE slope of the Děvín Hill with remarkable antiformal structure (Ernstbrunn Lst.).

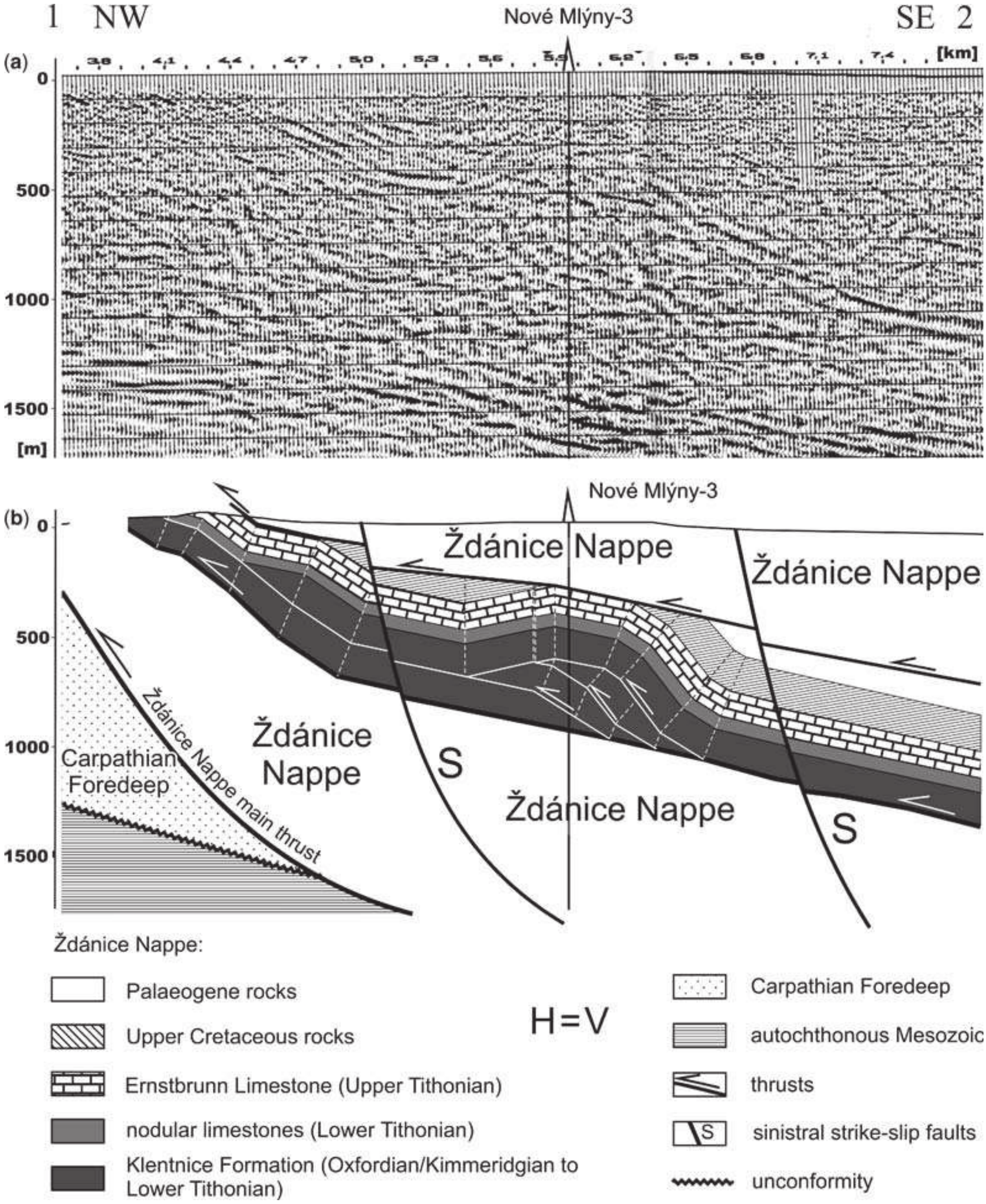

Fig. 6. Transversal seismic profile 290/83 including a projected borehole (**a**) and locally balanced cross section (**b**) obtained from the geological interpretation of the seismic profile shown in (a). See Figure 4 for location of line 1–2.

Strachotín-2; Table 1) are absent in the Nové Mlýny-3 borehole. This can be explained by the presumable presence of an out of sequence thrust that cuts down-sequence.

Thrust faults were identified by either stratigraphic inversions or repetitions of stratigraphic sequences, as Jurassic rocks are found to be physically on top of Cretaceous or Palaeogene sediments. A well-exposed thrust is situated on the Děvín Hill, where the Jurassic limestones (nodular limestones and Klentnice Fm) overlie the Upper Cretaceous beds (Jüttner 1933; see Fig. 7). This

Table 1. *Boreholes profiles*

Bulhary–1

0	– 25 m	Badenian (Vienna Basin)
	– 1192 m	Ždánice-Hustopeče Fm.
	– 1303 m	Upper Eocene – Oligocene (Menilite Fm., Němčice Fm.)
	– 1402 m	Němčice Fm.
	——	thrust
	– 1428 m	Eocene
	– 1488 m	Němčice Fm.
	——	thrust
	– 1619 m	Eocene
	– 1664 m	Menilite Fm.
	– 1817 m	Němčice Fm.
	——	thrust
	– 2210 m	Eocene
	– 2260 m	Němčice Fm.
	——	thrust
	– 2295 m	Eocene
	——	thrust
	– 2391 m	Upper Jurassic
	——	thrust
	– 2688 m	Němčice Fm.
	——	thrust
	– 2706 m	Upper Jurassic, Boudky Marl (Pouzdřany Nappe)
	——	thrust
	– 3119 m	Němčice Fm. (Ždánice Nappe)
	——	thrust
	– 3126 m	Oligocene, Uherčice Fm. (Pouzdřany Nappe)
	——	thrust
	– 3231 m	Němčice Fm. (Ždánice Nappe)
	⇌	Ždánice Nappe thrust
	– 3500 m	autochthonous Jurassic

Nové Mlýny–2

0	– 100 m	Upper Badenian
	– 455 m	Middle Badenian
	– 1225 m	Ždánice-Hustopeče Fm.
	– 2193 m	Němčice Fm. + slivers of Jurassic and Cretaceous rocks: 1292–1316 m Ernstbrunn Lst. 1350 m Upper Cretaceous (drilling fluid) 1595–1612 m Ernstbrunn Lst. 1450 m Albian (drilling fluid)
	⇌	Ždánice Nappe thrust
	– 2385 m	autochthonous Upper Cretaceous
	– 2425 m	Upper Albian (Nové Mlýny Lst.)
	– 2852 m	Kurdějov Lst.
	– 3265 m	Mikulov Marl
	– 3340 m	Vranovice Carbonates
	– 3397 m	Nikolčice Fm.
	– 3500 m	crystalline basement (granitoids)

Nové Mlýny–3

0	– 180 m	Ždánice-Hustopeče Fm.
	– 343 m	Němčice Fm.
	——	thrust
	– 485 m	Ernstbrunn Lst.
	– 559 m	Kurdějov Lst.
	– 1087 m	Mikulov Marl
	——	thrust
	– 1690 m	Němčice Fm.
	——	thrust
	– 1925 m	Ždánice-Hustopeče Fm.
	– 2031 m	Němčice Fm. + slivers of Upper Jurassic marls
	⇌	Ždánice Nappe thrust
	– 2247 m	autochthonous Middle + Upper Cretaceous (equiv. Klement Fm.)
	– 2692 m	Kurdějov Lst.
	– 3258 m	Mikulov Marl
	– 3299 m	Vranovice Carbonates
	– 3350 m	Nikolčice Fm.

Pálava–1

0	– 5.6 m	Quaternary
	– 20 m	Ernstbrunn Lst.
	– 32 m	Nodular limestones (dip 52°)
	– 147 m	Klentnice Fm.
	——	thrust
	– 150 m	Upper Cretaceous + Paleogene
	——	thrust
	– 152.3 m	Klentnice Fm.
	——	thrust
	– 153 m	Ernstbrunn Lst.
	——	thrust
	– 157 m	Klement Fm.
	——	thrust
	– 285 m	Ernstbrunn Lst. (dip 40°)
	– 288.15 m	Nodular limestones
	——	thrust
	– 323.6 m	Klentnice Fm. (dip 35°)
	——	thrust
	– 356.25 m	Nodular limestones
	– 436 m	Klentnice Fm. (dip 60°)

Strachotín–2

0	– 100 m	Ždánice-Hustopeče Fm.
	– 450 m	Němčice Fm. + slivers of Mesozoic and Pouzdřany Nappe
	——	thrust
	– 485 m	Upper Cretaceous (Klement Fm., Pálava Fm. + slivers of Němčice Fm.)
	– 660 m	Ernstbrunn Lst.
	– 805 m	Klentnice Fm. + slivers of Upper Cretaceous
	⇌	Ždánice Nappe thrust
	– 1675 m	Pouzdřany Nappe
	⇌	Pouzdřany Nappe thrust
	– 1880 m	autochthonous Upper Cretaceous (Turonian–Coniacian)
	– 2208 m	Kurdějov Lst.
	– 2750 m	Mikulov Marl
	– 2910 m	Vranovice Carbonates
	– 2997 m	Nikolčice Fm.
	– 3075 m	Gresten Fm.
	– 3147 m	crystalline basement (granitoids)

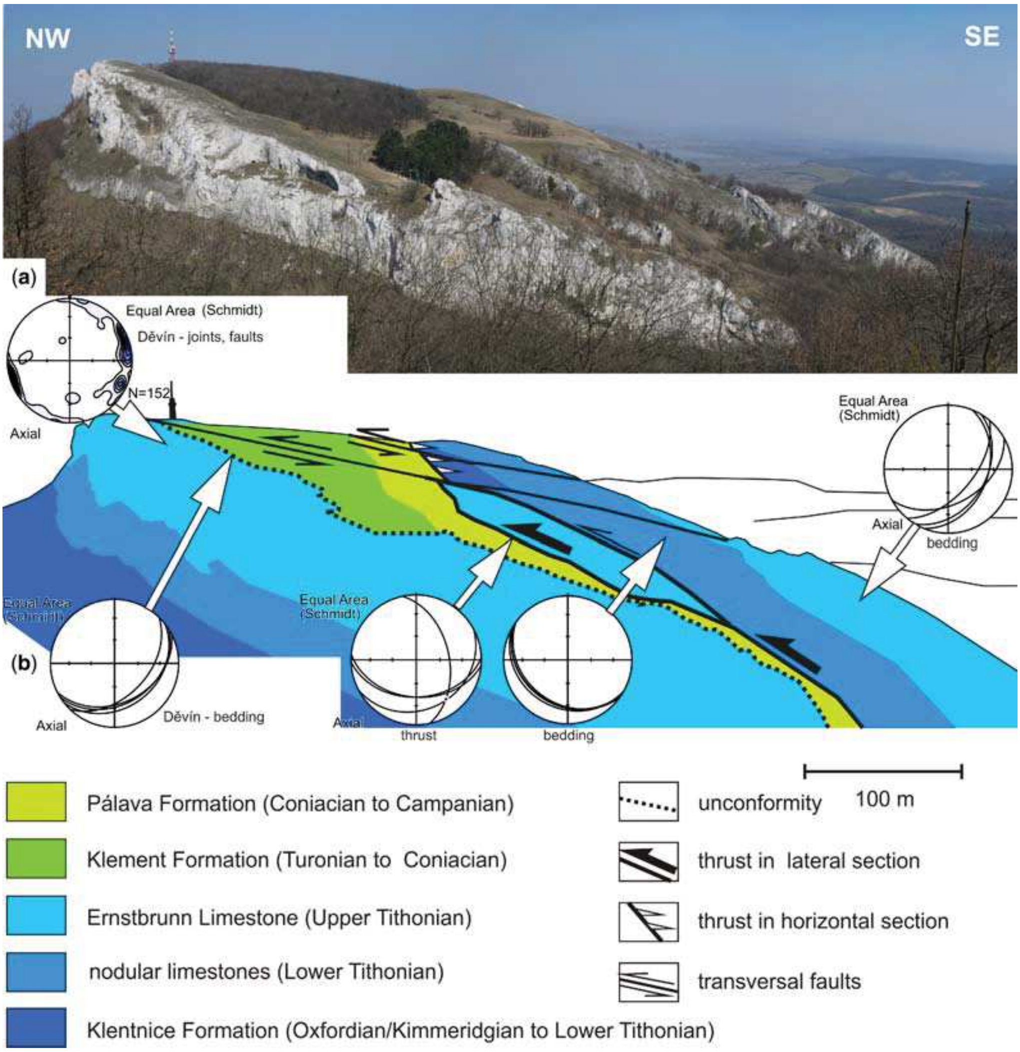

Fig. 7. View of SW slope of the Děvín Hill (**a**) and geological interpretation of the photograph shown in (a) as backlimb of an antiformal structure including a thrust (**b**). Equal area projections (lower hemisphere) show orientation of structural elements.

particular thrust dips to the SSE. The tectonic movement appears to be top-to-the NW. This same thrust is recognized at a depth of 147 m in the Pálava-1 borehole (Stráník *in* Hanzlíková 1965; Stráník *et al.* 1979; see Table 1, Fig. 4). This thrust separates slices in an antiformal stack whose NW limb was partially eroded. The main thrust of the study area (basal thrust of the Ždánice Nappe) was recognized in the Strachotín-2 borehole (Table 1, Figs 4 & 8) at a depth of 805 m and in the seismic profile 293/83. Other thrusts were identified from disrupted stratigraphic contacts interpreted from the geological map.

The thrusts are accompanied by anticlines that have compatible structural patterns and are developed in the thrust hanging walls. The main thrusts occur in the frontal portions of the anticlines and the strike of these thrusts is *c*. parallel to the subhorizontal fold axes. We interpret these anticlines as fault-related folds. The large fold interlimb angle (110–140°) suggests that a fault-bend fold mechanism is responsible for their formation (Suppe 1983, 1985; Merle 1998; Savage & Cooke 2003). The interpretation of the seismic profile displayed in Figure 6 shows the same type of folding mechanism.

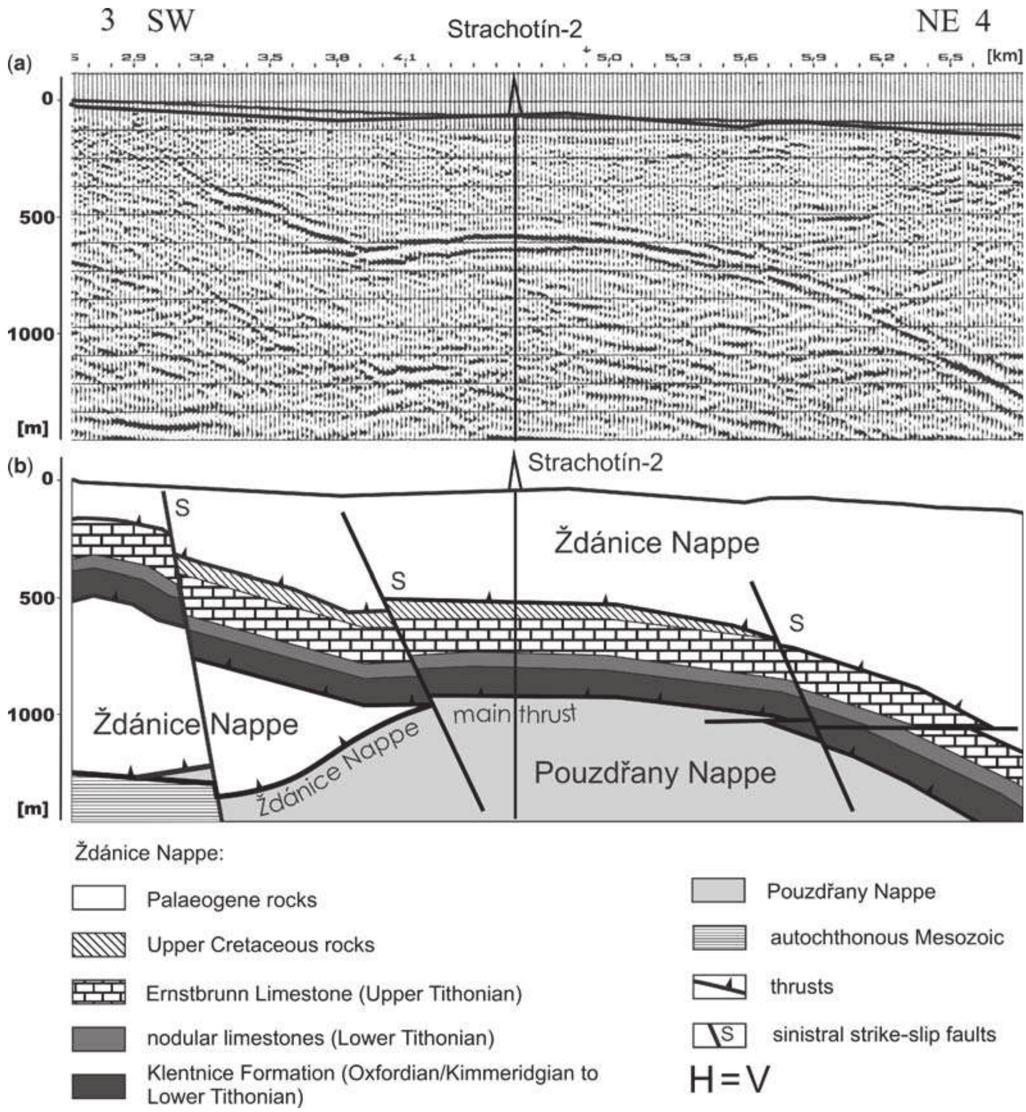

Fig. 8. Longitudinal seismic profile 293/83 including a projected borehole (**a**) and locally balanced cross section (**b**) obtained from the geological interpretation of the seismic profile shown in (a). See Figure 4 for location of line 3–4.

Small-scale transversal strike-slip faults have developed in several directions within the study area (Fig. 4). Two main directions have been identified: the strike of these faults is either parallel (NE–SW) or perpendicular to the fold axes (NW–SE). These faults are either vertical or steeply to moderately inclined, forming a pair of maxima with opposite dip directions (Fig. 4). Faults striking in the NW–SE direction are common along the whole western margin of the West Carpathians (Roth 1980). Sinistral strike-slip movements along these subvertical faults planes were proved by sinistral kinematic indicators on parallel small-scale faults and by offsets in map; the largest offset of which in map view is *c*. 1200 m. A local but distinct system of steep faults was also found in the Turold quarry (dip direction 110°, Fig. 4) and St. Hill (dip direction 330°, Fig. 4). Very distinct striae and asymmetric markers (accretional steps and/or *P*- and *T*-shears) indicate sinistral normal movement along these faults.

Tectonic model for the isolated limestone blocks

The new geological map shows patterns with two similar and approximately parallel continuous limestone belts which strike in a SW–NE direction (Děvín in the north, St. Hill in the south, Fig. 4). These two continuous belts are connected by a discontinuous chain of limestone bodies, which are separated by depressions occupied by the Palaeogene rocks which are less resistant to erosion. The presence of separated limestone blocks tends to validate the hypothesis of individual independent blocks (flowing blocks or olistoliths; Wessely 2006) but their repeated pattern and more or less identical structural style in different limestone outcrops, especially parallel fold axes of the large anticlines, are in contradiction with the hypothesis and are in favour of the thrust model. The geological interpretation of a longitudinal seismic profile (Fig. 8) demonstrates that the limestone body is a large approximately continuous plate which is cut by steep faults. Thus, problematic discontinuous distributions of limestone bodies may be explained as a result of post-thrust strike-slip faulting.

The original structure of the recently separated limestone bodies could be interpreted as a result of movements along the flat-ramp thrusts which are accompanied by fault-bend folds, that is, antiformal structures (Fig. 9a). Based upon the previously described thrust observations, the main detachment (flat) is interpreted to be situated in the basal part of the Klentnice Fm and the other subsidiary flats are located in the younger nodular limestones and also above the uppermost part of the Ernstbrunn Lst. Competent portions of Mesozoic rocks (Klentnice Fm and Ernstbrunn Lst.) are crosscut by the thrust ramps. The original angle between the detachment and the thrust ramps was around 20°. This value was verified by field compass measurements of bed orientation as well as in the geological interpretation of the seismic profiles that image that particular structure. Differences in dip direction and angle of beds measured in two small slices in the Děvín Hill (different dips 32° and 50°), in the St. Hill (50° and 72°) and in several slices in the seismic profile (Fig. 6b) can be explained assuming the same original ramp angle modified by thrust sheet stacking.

Two main anticlines, or antiformal stacks, are also recognized. The first large anticline was found in two distinct locations: Table Mt. and in the frontal position of Děvín Hill. This originally continuous anticline was cut by a sinistral strike-slip fault so that fault blocks moved in relation to each other. In their current day position, these blocks are separated by wide regions which are underlain by Palaeogene rocks. The second large anticline is situated to the east of Mikulov town in the St. Hill. The antiformal structure interpreted in the Nové Mlýny-3 borehole (Fig. 6b) may be considered to be a continuation of the anticline along the NE plunging fold axis. The disrupted axial trace of these two structures may be explained by the presence of sinistral strike-slip faulting. There were recognizable sinistral strike-slip faults which offset the anticlines and also two other equivalent faults were inferred at the SW and NE edges of

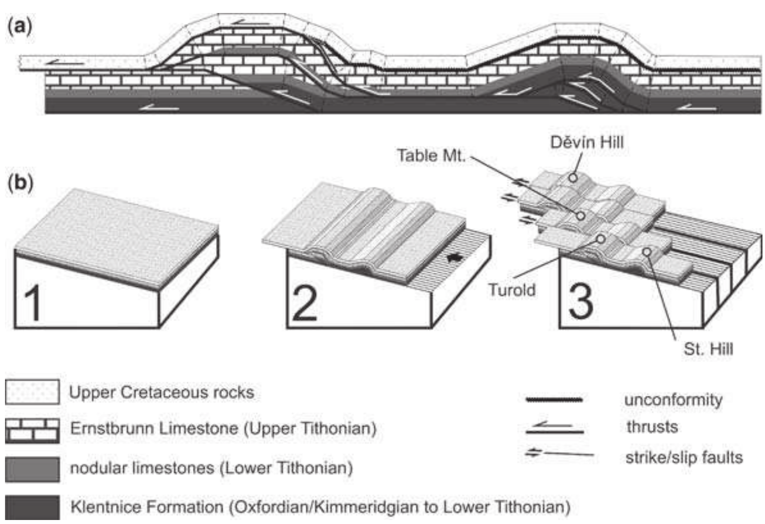

Fig. 9. Schematic model of thrust tectonics suitable for the Pavlov Hills (**a**) and principal stages of its evolution (**b**). Only Mesozoic rocks are presented, any Tertiary sediments covering this structure are not shown.

the study area. These faults, which strike in the NW–SE direction, are approximately perpendicular to the main fold axes.

Two main tectonic events could be derived from the model geometry (Fig. 9b). Originally a continuous plate of competent limestone was incorporated into the Ždánice Nappe due tectonic movements. As a result of thrusting, the plate was cut down by flats and at the ramp position was folded to antiformal structures. After that, at least two anticlines were cut by several sinistral strike-slip faults and separated. These faults rearranged the separated limestone blocks with antiformal structures into an approximate north–south-trending 'klippen zone', which is, in fact, a large-scale pseudo en-echelon structure.

Conclusions

In this study, we have proposed a new model of the tectonic architecture of the Pavlov Hills. It is shown that flat-ramp-flat geometry of thrusts and subsequent sinistral strike-slip faulting adequately explains the current geological arrangement of the area as a large limestone plate incorporated into the existing accretionary wedge. This model is in better accordance with the general structures found in the Outer Western Carpathians than other previously published models as it accepts the same principles of thrust tectonics and the same direction of transversal faults.

In the Mesozoic rocks, the main detachment of the thrusts is located at the base of the Klentnice Fm and the second order faults are located in the nodular limestones and at the base of the Upper Cretaceous rocks, whereas the ramps are situated in the competent Klentnice Fm and Ernstbrunn Lst. Their position is marked by large antiformal structures; the fold axis of which is gently plunging to the NE. This gentle plunge may be a possible escape route for the migrating hydrocarbons and may potentially be the reason why no hydrocarbon accumulations have been found in this seemingly favourable antiformal structure. Pseudo en-echelon arrangements of the limestone elevations are explained as a result of displacement along the sinistral strike-slip faults which strike in the NW–SE direction, for example, perpendicularly to fold axes of antiformal structures. Finally, the limestone elevations create chains in an approximate north–south direction.

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