Reply to the Comment on "Structural position of the Upper Cretaceous sediments in the Považský Inovec Mts. (Western Carpathians)"

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Abstract: Despite a relatively small areal extent of the Upper Cretaceous sediments (Horné Belice Group) in the Považský Inovec Mts. their importance for the geodynamic interpretation is significant. The composition, structural position and geodynamic setting of the sedimentary sequence is the object of the open discussion. Authors answers to previous comments (Plašienka et al., this issue) are expressed in the text below.

Key words: Western Carpathians, Upper Cretaceous, Považský Inovec Mts., Tatricum, Horné Belice Group

1. INTRODUCTION

We welcome the comments by Plašienka et al. (2017), which raises some important questions and allows us to further clarify some concepts. Our reply has no ambition to give reliable solutions, our idea is to provide reliable facts about the Upper Cretaceous sediments and tectonics in the Považský Inovec Mts.

After recognition of the Upper Cretaceous rocks in the Považský Inovec Mts. by Kullmanová & Gašpariková (1982) in the north and later by Havrila & Vaškovský (1983) in the south; Soták et al. (1993), Plašienka et al. (1994) and Plašienka (1995) conducted further research and interpreted them as relicts of the Vahicum – former continuation of the oceanic Penninicum from the Alps.

Understanding the structural position of the Upper Cretaceous rocks should at first take into account their distribution. The Upper Cretaceous sediments are present not only in the northern ("Selec") block of the Považský Inovec Mts. but also in the middle ("Bojná") block (Józsa & Pelech, 2014) as well as in the southernmost ("Hlohovec") block (Pelech et al., 2016[a]; Ivanička et al., 2007; Geological map of Slovakia, 2013). Beside these occurrences, sediments of the Late Cretaceous age were described from SBM-1 borehole situated less than 5 km north from the Selec Block, in the western Strážovské vrchy Mts. (Maheľ, 1985). This is important point in frame of our discussion, because these sediments are tectonically covered by the Fatricum complexes or overlying the Tatricum.

2. GEOLOGICAL STRUCTURE

The Selec block is more tectonically complicated than it is pictured in Putiš et al. (2006, 2008, 2009, 2016), and consists of three geologically and tectonically distinct segments arranged in an east-west direction (Pelech, 2015, p. 66). Easternmost segment represents the Inovec Nappe (*sensu* Putiš et al., 2008) formed mainly by crystalline basement (mica schist, less gneisses) and rudimentary preserved sediments of the Permian and Early Triassic. It also includes locally preserved Upper Cretaceous rocks (hence the Horné Belice Group *sensu* Rakús in Ivanička et al., 2011).

The Inovec Nappe is thrust over the middle segment consisting of gneisses and sedimentary cover in the stratigraphic range from the Late Carboniferous to the Middle Triassic, without any documented Upper Cretaceous rocks. The Upper Cretaceous sediments are present below the thrust plane of the Inovec Nappe SW of elevation point Jakubová (Ivanička et al., 2007; Geological map of Slovakia, 2013; partly also Plašienka et al., 1994 p. 182; fig. 1).

The geological structure of the western segment is prevailingly built of the Hronicum and Fatricum, with lesser amount of the Tatricum and without the Upper Cretaceous rocks.

Crystalline basement rocks of the Inovec Nappe (the Selec Block) were dated by $^{40}Ar/^{39}Ar$ method (coarse-grained muscovite), and accessory apatite, coarse-grained muscovite and whole rocks were also analyzed by Rb-Sr method (Kráľ et al., 2013). Obtained $^{40}Ar/^{39}Ar$ muscovite plateau ages and calculated Rb-Sr ages for two-point accessory apatite – coarse-grained muscovite pairs are identical (307–310 Ma) and they are interpreted as age of diaphtoresis of this crystalline basement. Both isotopic systems in minerals do not register Alpine metamorphic overprint. But in whole rocks, increasing of the Rb/Sr ratio is documented that can be explained by loss of ordinary strontium from acid plagioclases during low temperature alteration under significant Alpine tectonics influence.

Obtained ZFT ages of 256.3 ± 20.6 to 255.4 ± 20.3 Ma from the Inovec Nappe revealed that the crystalline basement was not thermally affected during the Alpine tectogenesis. In addition, these ZFT ages document that crystalline basement was not exposed to temperature of >200°C which would cause partial annealing of the ZFT system. Thus, the aforementioned ZFT data are considered to be post-orogenic cooling ages after collapse and exhumation of the Variscan orogen (Králiková et al., 2016).

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Existing geophysical survey (Bošanský et al., 2013; Pelech et al., 2014) shows that the Upper Cretaceous sequences (Hranty locality of the Selec Block) do not form larger rock body that increases its volume with depth (as proposed by Plašienka et al. 1994). On the contrary it forms approximately 90 m thick folded tectonic lens, bounded from the top and bottom by the crystalline basement complexes of the Tatricum. This is confirmed by the combination of longitudinal and transverse electrical resistivity tomography profiles.

Among other the Hranty locality is suitable example how the position of the Upper Cretaceous sediments is misinterpreted against facts. The concept of the Vahicum/Penninicum and the Belice Unit *sensu* Plašienka et al. (1994) also partly the Infratatricum *sensu* Putiš et al. (2008, 2016) which authors of the comment (Plašienka et al., 2017) favour, is not taking into account the latest research by Ivanička et al. (2007, 2011), Kráľ et al. (2013), Králiková et al. (2016), Bošanský et al. (2013), and Józsa & Pelech (2014).

3. DISCUSSION

The comment of Plašienka et al. (2017) contains three main issues which should be discussed: (i) the inferred transgressive character of "Senonian" clastic deposits; (ii) the position and provenance of the Upper Jurassic radiolarites; and (iii) the metamorphic conditions recorded in rocks of the Belice Unit.

(i) The transgressive character of the "Senonian" clastic deposits.

Plašienka et al. (2017) state that: *"the (Late Cretaceous) transgression has not been documented anywhere and is highly improbable"; "... transgressive character (of the Upper Cretaceous rocks) is not supported by any relevant data"* and further repeat the results of their older investigations, e.g. for this discussion the irrelevant position of the Čierny vrch Conglomerate (cf. Plašienka et al., 1994). These sediments always have been considered an integral part (Member) of the Horné Belice Fm. (sensu Plašienka et al., 1994) or the Rázová Fm. (sensu Rakús in Ivanička et al., 2011; see also Pelech et al., 2016b, figs. 2 and 3). We consider this debate as unfair and confusing. Rakús (in Ivanička et al., 2011 or Ivanička et al., 2006) described so called "basal breccias" as the lowermost and transgresive member of the Horné Belice Group. Despite uncertain stratigraphic age (?Albian to Coniacian), their structural position and cooccurrence with younger Upper Cretaceous rocks, suggests that they represent the basal part of the Upper Cretaceous succession.

Plašienka et al. (2017) also concluded that "...*"Senonian" deposits are nowhere present in Tatricum domain as overlying its basement and/or cover complexes*."

At the locality Striebornica, transgression of the Middle Turonian–Santonian mass flow deposits above the Albian–Cenomanian Poruba Formation and bellow the Fatricum Unit is documented (Józsa & Pelech, 2014). The fact that this information has not been published in the journal yet, cannot be considered as the reason for its ignorance. The geological structure of the southern Považský Inovec Mts. (Hlohovec Block) with Upper Cretaceous rocks overlying the crystalline basement was ignored by Plašienka et al. (2017) as well. This is also very peculiar, because such situation was documented by borehole HPJ-1 near Hlohovec (Pelech et al., 2016[a]).

In their discussion Plašienka et al. (2017) also pointed to inconsistencies of our interpretation considering tectonic contact of the Upper Cretaceous sediments and crystalline basement rocks (Pelech et al., 2016[b], figs. 6 and 7). Our field observation support our idea, that the Upper Cretaceous sediments were folded together with crystalline complex after their deposition i.e. present day contact should be draw as the tectonic. The incompetent "basal breccia" horizon was probably tectonized and served as a basal décollement, which also caused largely the destruction of its sedimentary record. Moreover, a sedimentary i.e. non-tectonic contact is evident in the field and from the geological map (Ivanička et al., 2007; Geological map of Slovakia, 2013).

(ii) The position and provenance of Upper Jurassic radiolarites.

Méres & Plašienka (2009, 2013) reported (without localisation) that "*radiolarites are formed by red pelagic shales alternating with tiny laminae of radiolarian ooze and pigmented by primary Fe-Mn oxi-hydroxides. Geochemical proxies of red shales indicate their derivation from submarine weathering products of a mafic protolith, presumably oceanic crust magmatites. Accordingly, these are "true" abyssal, totally calcite-free radiolarites deposited entirely below the CCD level, likely in proximity of an active oceanic spreading centre and reworked by bottom currents"*. We agree with their data, however disagree with interpretation, and still consider radiolarite bodies as olistoliths, that is also the crucial difference of our concept from interpretation published by Plašienka et al. (1994). It is, as well, necessary to remark, that similar geochemical analyzes were not carried out on any other Western Carpathian radiolarites.

All blocks/olistoliths situated in the Upper Cretaceous sediments are consider as a "true" olistoliths (with the exception of radiolarites!) or redeposited blocks (so called Humienec Succession *sensu* Plašienka et al., 1994). Their stratigraphic range is from the Palaeozoic (crystalline basement rocks, continental basalts) to the Upper Cretaceous (limestone with *Globotruncana* sp.). Especially the cooccurrence of radiolarites and basalts in the same olistostrome may lead to *simplistic interpretations* (Soták et al., 1993). However, the geochemical analysis of basalt olistolith by Putiš et al. (2008) which disprove its possible oceanic origin and conversely indicate their affinity to the Permian basalts occurring in the Tatricum of northern Považský Inovec Mts. is consistent with previous assumptions (cf. Ivanička et al., 2006; compare also Korikovsky et al., 1995). If the radiolarites represent only original remnants of the oceanic floor, then from the perspective of other olistolithes, the radiolarites occurrences (the Lazy Fm., *sensu* Plašienka et al., 1994) appear to be "exotic" among the other olistoliths. Therefore, the source of the radiolarites could be as exotic as the source of the Campanian light grey micritic limestone (Rakús et al., 2006).

In their discussion Plašienka et al. (2017) suggest that the Lazy Fm. (i.e. radiolarites and siliceous shales) between the localities Horné Belice – Čierny vrch and Blatina form one continuous lenticular body (1.5 km long), too large for normal olistolith. The same is concluded for the occurrence of the radiolarites at the Humienec Hill (believed to be 500 m long). However, according to official map (cf. Ivanička et al., 2007) the largest radiolarite body at the Čierny vrch is ca 690 m long. Beside mentioned, also smaller bodies less than 50 m long, exist. Important fact is that, the radiolarite body on the northern slopes of Humienec Hill (ca 230 m long) is folded, while the Upper Cretaceous sediments are monoclinally diping without signs of fold deformation. Moreover, the radiolarite blocks are from both the bottom and the top wrapped into the Upper Cretaceous sediments (Ivanička et al., 2007; Geological map of Slovakia, 2013). Both Plašienka et al. (1994) and Putiš et al. (2006; 2008) picture the Belice Unit or Nappe more or less cropping out in tectonic windows from below the mica schist crystalline basement. These "windows" are however usually situated topographically on crests and ridges (see Ivanička et al., 2007; Geological map of Slovakia, 2013) and do not continue into the valleys as it should be geometrically correct, if they would represent the tectonic unit below the Tatricum.

(iii) The metamorphic conditions recorded in rocks of the Belice Unit.

The note of authors of the Comment that "*Pelech et al. (2016) do not thoroughly discuss another principal feature of rocks of the Belice Unit – their metamorphic alteration. They only claim that the lack of HP/LT metamorphism speaks against the oceanic character of the Belice Unit. However, this was in fact documented. Despite the metamorphic transformation reached only higher diagenetic or anchimetamorphic conditions, not exceeding ca 250°C, it is well expressed in the rock fabrics. According to Putiš et al. (2008), composition of newly-formed phengitic micas in shales of the Belice Unit indicate metamorphic temperatures of ca 200°C and pressures of up to 600 MPa indicating burial depths of more than 20 km.*"

This is not correct and rather misleading, because facts are more complex. The metamorphic conditions of the Belice Unit (or Belice Nappe *sensu* Putiš et al., 2008) as well as the Panská Javorina Nappe were published mainly by Putiš et al. (2008, 2016). It can be summarized as follow:

Putiš et al., (2008) "*Our alumino-celadonite to celadonite muscovite phases from the Belice Nappe contain 0.66–0.73 alkalis p.f.u. indicating temperatures of 200–250°C at the given pressures (6 kbar). This means a high-pressure/low-temperature regime for the D2 anchimetamorphic overprint. The depth of the burial of the Belice Nappe rocks was clearly more than 20 km.*"

Or (Putiš et al., l.c.) "*The Belice Nappe formed during the Early Tertiary orogeny, which is only poorly constrained by a single whole-rock K–Ar analysis from metabasalt (near Humienec Hill) in an olistolith yielding a Middle Eocene age (46 ± 3 Ma). During this event the rocks of the Belice Nappe were underthrust below the thick basement-cover complexes of the Inovec and Panská Javorina Nappes and metamorphosed under a highpressure regime but very-low (low-anchizonal) grade.*"

Later (Putiš et al., 2016) "*the Early Cretaceous slates (clast to km-size fragments in late Santonian to Maastrichtian flysch) indicates medium-anchimetamorphic conditions of 200–270 °C at minimum medium pressure of 5–6 kbar or burial to ca 15–20 km depth (15°C/km gradient). The newly formed white mica of metamorphic illite-phengite to normal phengite (= celadonite-rich muscovite) composition, yielded $^{40}Ar/^{39}Ar$ plateau ages of 114.0±2.4 and 106.2±3.7 Ma.*"

And in the same contribution (Putiš et al., 2016) "*The Belice Nappe Couches-Rouges type shales (Cenomanian–Santonian) and flysch sediments contain newly formed white mica (3.13–3.29 Si pfu) of illite-phengite composition with the very low (K+Na) values from 0.5 to 0.7 pfu and K_2O from 5 to 7 wt.%, being typical for the diagenesis, but also for the lowest-temperature metamorphic overprint (150–200 °C at 4–5 kbar; ca 12 °C/km gradient).*"

Regarding the Panská Javorina Nappe – the Tatricum unit *sensu stricto* (Putiš et al., 2016) "*The underthrusting of the Infratatric (IFTA) Inovec Nappe below the north-Tatric nappes is recorded by the age of 102.3±1.9 Ma from the Tatric Unit hanging wall granite blastomylonite white micas. Termination of the Eocene tectonometamorphic overprint, dated by newly formed celadonite-poor muscovite (3.1–3.2 Si pfu; Sulák et al., 2009) $^{40}Ar/^{39}Ar$ plateau age of 48 ± 2 Ma from the Tatric Unit hanging wall greenschist-facies granite blastomylonites (ca 300 °C at minimum 4–5 kbar; Putiš et al., 2009; 25 °C/km gradient). The IFTA Inovec Nappe lacks the Paleogene sediments, because at that time it was underneath the Tatric Unit overloaded with the Mesozoic Fatric and Hronic nappes as a lid. The Fatric and Hronic nappe fragments may have been gravitationally slided on the already being exhumed IFTA Unit most likely since the Paleogene-Neogene boundary period.*"

Summarizing mentioned data – the olistolith of the Early Cretaceous slates in Late Santonian to Maastrichtian "flysch" of the Belice Nappe (without localisation!) was metamorphosed under stated conditions (200–270°C / 5–6 kbar) during 114.0±2.4 and 106.2±3.7 Ma. Approximately in the same time the Panská Javorina Nappe was thrusted over the Inovec Nappe (102.3±1.9 Ma, or Putiš et al., 2008, fig. 14) and the Inovec Nappe was thrust (101.2±2.9 Ma) over the middle segment of the Selec Block (Putiš, 1983; Putiš et al., 2008).

The Upper Cretaceous sediments of the Belice Nappe (Couches-Rouges type shales of the Cenomanian–Santonian, and flysch sediments (containing olistoliths) were metamorphosed under 150–200 °C at 4–5 kbar during Middle Eocene (46 ± 3 Ma). It means the olistolith of the Early Cretaceous slate was metamorphosed (ca 114–106 Ma), exhumed from depth ca 15–20 km and deposited in the Upper Cretaceous sediments. It requires removal at least 15 km thick column of the higher units (Inovec Nappe?, Panská Javorina Nappe?).

Therefore, interpretation that underthrusting of the Inovec Nappe started at 102.3±1.9 Ma and terminated at 48 ± 2 Ma should be revised. Also, information about absence of the Paleogene sediments in hanging wall of the Inovec Nappe as the proof of its tectonic burial below the Panská Javorina Nappe is not correct (Putiš et al., 2016). The Paleogene sediments (the Borové Fm., Lutetian – Bartonian i.e. 47.8–37.8 Ma) cover the Inovec Nappe crystalline basement rocks ca 1.5 km south of Dubodiel village (Ivanička et al., 2007; Geological map of Slovakia, 2013). These are the main arguments why we can suppose deposition of the Upper Cretaceous sediments directly above the crystalline of the Inovec Nappe (the other arguments see above). The Upper Cretaceous rocks were folded after their deposition together with crystalline basement (ca 46 Ma metamorphism of metabasalt block), while the Inovec Nappe was not completely underthrust below the Panská Javorina Nappe and never was reheated above 200°C (Králiková et al., 2016). Moreover, the terminal metamorphism of the Panská Javorina Nappe (structurally the highest nappe) is dated to 48 ± 2 Ma, under ca 300°C at minimum 4–5 kbar. It means the lowest (Belice Nappe) and the highest structures (Panská Javorina Nappe) indicate in the same time the same pressure conditions. In fact, such conditions are usually interpreted as transitional assemblage, greenschist or prehnite-pumpellyite facies below the blueschist facies (Turner, 1981; Yardley et al., 1990; Putiš, 2004; Bucher & Grapes, 2011).

According to our interpretation there are two main Alpine tectonometamorphic events recorded in the Považský Inovec Mts. First event was connected with disintegration of the Tatricum unit prior to the displacement of the Fatricum and Hronicum tectonic units in its hanging-wall. This tectonometamorphic event was related with subduction of the basement or distal continental margin and accretion of the Upper Penninicum (*sensu* Schmid et al., 2004) between 114.0±2.4 and 102.3±1.9 Ma (Albian). The olistoliths/blocks/tectonic fragments (e.g. radiolarite and Cretaceous slates) from the previously imbricated thrust stack were derived into the Late Cretaceous sedimentary basin as a part of the wedge-top basin of the Lower Penninicum realm (Schmid et al., 2004, 2008) which overlapped a different lithostratigraphic members of the Tatricum Unit (crystalline, Albian flysch; *see* Pelech et al., 2016[b]; Hók et al., 2016).

The second event is connected with displacement of the Fatricum and Hronicum units above the Upper Cretaceous sediments during 48 ± 2 – 46 ± 3 Ma. It is obviously documented in the borehole SBM-1 Soblahov (Maheľ, 1985) and in the Striebornica Valley (Józsa & Pelech, 2014). The Upper Cretaceous sediments were during this event folded together with crystalline basement into shallow synform structures (Bošanský et al., 2013) in the Selec Block of the Považský Inovec Mts.

4. CONCLUSIONS

The comment of Plašienka et al. (2017) criticizes our paper also because "it is based on arbitrary chosen facts" and is "overlooking the general context" and "only reinterpret results of previous research without presenting new sound data" which we consider to be inadequate, although we must admit that some facts were formerly not taken into account. We however tried to solve it in this discussion. We also believe that the reinterpretation of older data is in this case vital for understanding the complex problem regarding the Upper Cretaceous rocks in the Považský Inovec Mts. and we leave our interpretation to assessment of readers and professional community. The new sound data were published and are listed above but a new sound data of authors of the Comment are missing. Our paper published in 2016 cannot answer all the questions concerning the Upper Cretaceous sediments in the Považský Inovec Mts. and do not even attempt to do so. However, it offers more answers than previous papers published by Leško et al. (1988), Plašienka et al. (1994) and Putiš et al. (2006, 2008).

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