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DISCUSSION

Comment on "Variable structural styles and tectonic evolution of an ancient backstop boundary: the Pieniny Klippen Belt of the Western Carpathians" by Plašienka et al. (2020)

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Abstract
Our comment is aimed to point out several controversial aspects of the paper Plašienka et al. (Int J Earth Sci (Geol Rundsch) 109:1355–1376, 2020). The Pieniny Klippen Belt marks a narrow zone at the boundary between the external and internal Western Carpathians. We appreciate efforts of the authors of the commented paper in advancing the understanding and interpretation of the geological structure of the Pieniny Klippen Belt as well as the surrounding tectonic units. However, it is essential to inform that the commented paper significantly modifies and deforms previously published maps and other data without any arguments, new data, or references to published material. We especially draw attention to the presence of the Šariš Unit and Gosau-type successions which has not been proven in the western segment of the Pieniny Klippen Belt. Due to the intricate structure and a number of unsolved fundamental questions, the Pieniny Klippen Belt area and its surroundings cannot be considered a model region of foreland–backstop boundary as is suggested by the commented paper.

Keywords Oravicum · Šariš Unit · Biele Karpaty Unit

Introduction

The Pieniny Klippen Belt (PKB) is a 2–10 km wide, yet approx. 600 km long zone separating the Internal (IWECA) and External Western Carpathians (EWECA) (Hók et al. 2019). The PKB is composed mainly of the Jurassic and Cretaceous, locally also Paleogene formations, sheared off the pre-rift basement during Cretaceous thrusting. The main and integral part of the PKB is represented by the Oravic units (e.g., Czrostyn, Kysuca-Pieniny, Grajcarek units) originated from a separate paleogeographic domain north of IWECA. The complicated structure of the PKB is additionally accompanied by syn-orogenic sedimentary rocks, olistostromes and affected by transpressional and/or transtensional deformation. Therefore, it is often interpreted as a mélange, megabreccia and/or suture zone (Mišík 1997; Plašienka 2018; Plašienka et al. 2020 and references therein). A large degree of ambiguity in the PKB structure is caused by the presence of the so-called Peri-Klippen units (including the Manín, Drietoma and Klape units), mostly consisting of Cretaceous syn-orogenic mass transport deposits or sedimentary sequences resembling the Fatricum or Tatric sedimentary cover (Mišík 1997; Plašienka 2018). The geophysical data suggest that the PKB is rather a very narrow zone and the actual geometry of the contact with surrounding units is not well constrained. Especially, in the western segment, the PKB is thrust over the Flysch Belt sedimentary complexes (Vozár et al. 1999; Šamajová et al. 2018, 2019; Bezák et al. 2014, 2020; Hók et al. 2022).

The commented paper Plašienka et al. (2020) and its online supplement present several controversial aspects of the PKB. Our comment draws attention to some errors and/or problematic conclusions, mainly concerning the western sector of the PKB (Fig. 1).

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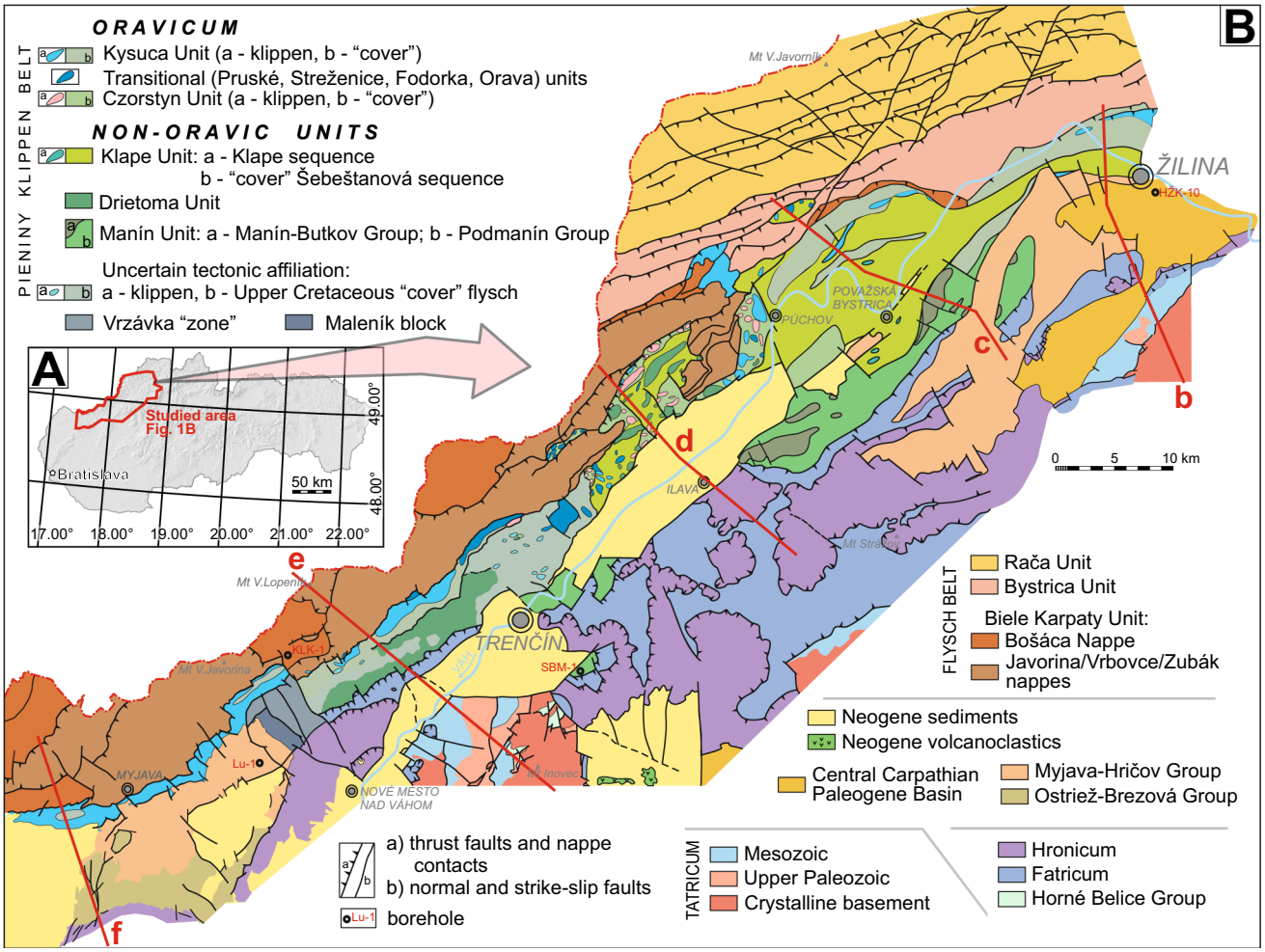

Fig. 1 **A** Location of the investigated territory in Slovakia. **B** Tectonic map of the western part of the Pieniny Klippen Belt (compiled from Potfaj et al. 2014; Pešková et al. 2021; Mello et al. 2005; Ivanička et al. 2007; Maheľ et al. 1981; Hraško et al. 2021; Havrila and Olšavský 2015; Káčer et al. 2013). The positions of the cross sections b, c, d, e and f are taken from Plašienka et al. (2020, Fig. 1). The boreholes shown in the figure are located in geographically correct position. It should be noted that none of these boreholes are located on the cross section, in contrast to the boreholes shown in Plašienka et al. (2020, Fig. 2)

Reinterpretation of previous data in general

Figures 1 and 3 of Plašienka et al. (2020) differ from the published geological maps (Bezák et al. 2008; Mello et al. 2005; Káčer et al. 2013 and references therein). The paper by Plašienka et al. (2020) lacks arguments for substantial changes in the interpretation of the origin of several tectonic units, especially for the western sector of the PKB compared to published maps.

Javorina nappe vs. Šariš Unit issue

The Biele Karpaty Unit represents the southwestern portion of the Magura Group of nappes and is structurally divided from the bottom to top into the Bošáca, Zubák and Javorina nappes (Potfaj et al. 2014; Pešková et al. 2021; Fig. 2). Part of the Javorina Nappe according to Fig. 3 of Plašienka et al. (2020) is separated and considered as the Šariš Unit, which has never been described

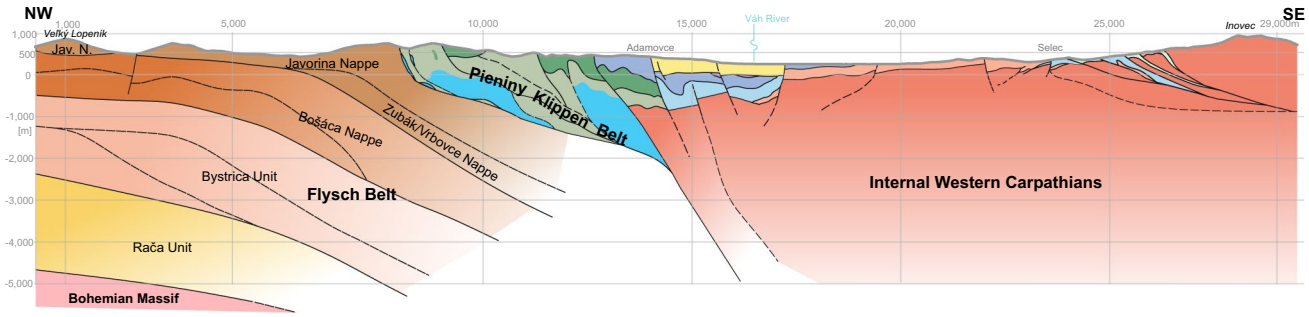

Fig. 2 Reinterpreted cross section (e), from the Biele Karpaty Mts. to the Považský Inovec Mts. See Fig. 1 for legend

from the western sector of the PKB (Fig. 1). No arguments for such an interpretation are provided by Plašienka et al. (2020). The Javorina Nappe is considered to be the southernmost unit of the Carpathian Flysch Belt and is composed of the deep sea flysch of the Lopeník and Svodnice formations of Campanian to lower Eocene age (Potfaj 1993; Potfaj et al. 2014). The Šariš Unit (an augmented version of the Grajcarek Unit of Birkenmajer and Gedl 2017) is considered to be originally the northernmost one of the Oravic units (Plašienka and Mikuš 2010; Plašienka et al. 2012). The sedimentary succession of the Šariš Unit, which ranges stratigraphically from the Middle Jurassic to lower Eocene, differs from the Javorina Nappe mainly by presence of the PKB rocks as the Lower Cretaceous Pieniny Limestone or the Aptian–Albian black shales and the characteristic lower Eocene Milpoš Breccia olistostrome (Plašienka and Mikuš 2010; Plašienka et al. 2020). The Upper Cretaceous-to-Paleogene formations of the Šariš Unit typically contain syn-orogenic clastic material derived from the Oravic units, especially from the Czorsztyn Unit (Plašienka and Mikuš 2010; Plašienka et al. 2012). However, the Javorina Nappe contains no material from the PKB. The pebble analysis shows that the Javorina Nappe sandstones and conglomerates consist exclusively of dolomite and metamorphosed arenites (various types of quartzite) (Potfaj 1993). Dolomite, most likely of Triassic age, is almost missing in the PKB. The reasons for attributing the Javorina Nappe to the Šariš Unit by Plašienka et al. (2020) are unclear and erroneous. Furthermore, in the cross section in Fig. 2f (in Plašienka et al. 2020) the Šariš Unit is also interpreted in the borehole Lu-1. This speculation is not supported by any arguments or data (compare Leško et al. 1982). Similarly, the Kvašov "development" W of Púchov town (Salaj et al. 1983; Teťák 2021) is displayed on Fig. 3 (Plašienka et al. 2020) as a tectonic half-window of the PKB, mostly consisting of the Šariš Unit. Arguments for such an interpretation are again missing.

Origin of the Klape Unit

The structural position of the Klape Unit of the proposed Fatric origin (e.g., Plašienka 1995, 1996, 2019) is controversial and has several noted pitfalls (Mišík 1996; Rakús and Hók 2005). According to Plašienka et al. (2020), Albian–Turonian syn-orogenic siliciclastic rocks of the Klape Unit were originally situated in the internal parts of the Fatric Zliechov Basin and internally of the Drietoma Unit. It is problematic to explain why the Klape Unit is not structurally higher than the main body of the Fatricum and why it is not overlain by the structurally higher Hronicum. In fact, the Klape Unit is located below the Manín Unit, which was situated paleogeographically more northerly (e.g., Plašienka 2019). The swap from the hangingwall of the Fatricum (and the Drietoma Unit) to the footwall of the Fatricum, Drietoma and Manín units is explained by diverticulation—gravitational movement as a gliding nappe resulting in the inverted stratigraphy (e.g. Plašienka 1996, 2019). However, apart from the inverted stratigraphy, no direct evidence of gravitational movement of the Klape Unit has been provided. It is also not clear why only the Drietoma and Klape units of the Fatricum were emplaced in this complicated manner, while the rest of the nappe moved as a more or less competent tabular body. In this context, we would like to point out that the structurally simpler interpretations are equally possible (see Mišík 1996 for a review).

According to the interpretation of Plašienka et al. (2020), the Klape Unit was transported into the PKB in the Upper Cretaceous—presumably Albian–Turonian (Plašienka 1995, 1996, 2019). Such transport of the Klape Unit in the hangingwall of the Tatricum is in contradiction with the presence of the Upper Cretaceous sediments in the Tatricum of the Považský Inovec Mts., where a continuous sedimentary succession from Triassic to Santonian is documented (Pelech et al. 2017a).

Gosau-type sedimentary successions

The presence of the Gosau Group above the Klape Unit has never been described in this region properly (including the cited paper Plašienka and Soták 2015). The term Gosau (Super-) Group and Gosau-type sedimentary succession should be reserved for the Upper Cretaceous to Eocene formations overlying the internal units of the Alpine chain, located peleogeographically south of the Penninic Ocean. In the Alps, the Gosau Group covers the Austroalpine units (Wagreich and Faupl 1994; Piller et al. 2004) and in the Western Carpathians the Gosau-type sedimentary successions are found mainly in the IWECA (Lexa et al. 2000), representing equivalents of the Austroalpine units. Therefore, the Gosau Group above the Klape and Drietoma units according to Plašienka and Soták (2015) and Plašienka et al. (2020) represents an anomalous occurrence of the Gosau-type sedimentary succession transported from the IWECA into the Penninic (Vahic) domain. The presence of Gosau Group rocks in the PKB is, therefore, unique and would require a better explanation supported by a new data.

Borehole and cross-sectional issues

The position of some boreholes depicted at the cross sections in Fig. 2 of Plašienka et al. (2020) is a great simplification and may be considered misleading (Fig. 1). The Lu-1 Lubina borehole (Leško et al. 1982) in the westernmost cross section (Fig. 2f in Plašienka et al. 2020) is in fact located 16 km NW of the cross section and it is closer to the cross section shown in Fig. 2e (in Plašienka et al. 2020). The SBM-1 Soblahov borehole (Maheľ and Kullmanová, 1975) is actually located 20 km SE from the cross section in Fig. 2d (in Plašienka et al. 2020). In the cross-sectional Humenné-Zbudza (Fig. 2z in Plašienka et al. 2020), the boreholes H-1 and ZB-2 are in fact located approx. 32 km west of the Humenné-Zbudza area. In addition, the interpretation of the Lu-1 and MLS-1 boreholes log (Fig. 2 in Plašienka et al. 2020) is locally in contradiction to published data (Leško et al. 1982; Soták et al. 1997).

The cross section across the Žilina-Turie-Kozol (Fig. 2b in Plašienka et al. 2020) ignores without any arguments the recent detailed study of Havrila and Olšavský (2015). On the contrary, Plašienka et al. (2020) present the backthrusting that has never been documented in the region (cf. Rakús and Hók 2003; Hók et al. 2020). The interpretation of the profile ignores the results of the HŽK-10 borehole (2258 m deep, Šalagová et al. 1996). The sedimentary sequences of the Gosau Group, Klape and Manín units, as shown in the cross section, were not described in the borehole (Šalagová et al. 1996).

The presence of the hypothetical Oravic crystalline basement below the Považský Inovec Mts. (Fig. 2e in Plašienka et al. 2020) is a speculation. The interpretation of the structure of the Považský Inovec Mts. shown in Fig. 2e has been partly questioned (e.g., Pelech et al. 2016, 2017b). The tectonic affiliation of the Belice Unit (Horné Belice Group) to the Tatricum was proven (Pelech et al. 2016, 2017a, 2017b). On the contrary, the presence of an oceanic crust between the Oravic and Tatric units is a speculation, and should not be presented as a fact (Bezák et al. 2014; Pelech et al. 2017b).

In the cross section of Fig. 2y (in Plašienka et al. 2020), the Veporic crystalline basement and the Mesozoic complexes are thrust over the Fatricum (i.e. Krížna nappe in cross section). Such arrangements of the mentioned tectonic units have not been documented anywhere. Similarly, the position of the Krížna (i.e., Fatric nappe system) above the Szolnok–Krichevo Belt is speculative and has no factual support. The Veporic crystalline basement was not recognized in the Šariš-1 borehole (e.g., Koráb et al. 1986) (Fig. 4).

Concerning the number of the interpreted deformation phases in Figs. 2 and 5 (in Plašienka et al. 2020), the existence of a number of them is not sufficiently documented. Tectonic phases should be defined based on a combination of standard and independent criteria of structural overprinting, stratigraphic and/or geochronologic evidence. There is no need for interpreting 8 discrete, but abstract, deformation stages, which are problematic to be defined in the field, both in outcrop and map scale.

Conditions of backthrusting

The Javorina Nappe duplexes and bedding are predominantly dipping approx. 45° to the SE in the area shown in Fig. 3 (Mello et al. 2005). The nappe was clearly thrust to the NW and contains blocks of the nappe footwall incorporated to its basal décollement plane (Pešková et al. 2021). However, the nappe plane of the Javorina Nappe is shown as a backthrust (Fig. 3 of Plašienka et al. 2020). It is possible to interpret some smaller scale backthrusting in the Biele Karpaty Unit, however, not on the nappe décollement plane (Teťák 2021).

In Figs. 2 and 3, Plašienka et al. (2020) prefer the depiction of the backthrusts with a movement of dozens to 100 s of meters, instead of a depiction of more prominent nappe décollement plane of the Javorina Nappe, which was thrust several tens of kilometers. If Plašienka et al. (2020) interpret the backthrust structures, which have not been recognized before, it is necessary to provide an evidence and a new data. Otherwise, they are hardly credible.

The contact of the Bystrica Unit with the PKB and the Biele Karpaty units and the thrust faults inside the Bystrica Unit are shown as the backthrusts by Plašienka et al. (2020). Such interpretation does not have a justification in any published work and would require an explanation in the text.

The backthrusting in the area of Dobrá Voda village drawn in Fig. 2f (Plašienka et al. 2020) was proposed by several authors (e.g., Began et al. 1984; Marko et al. 1991), without direct structural evidence from the area around the Dobrá Voda village and based only on data from the Horné Mlyny and the Lipiny quarry in the Pezinské Karpaty Mts. (see Marko et al. 1991). A recent geological mapping in the area of Dobrá Voda did not confirm any backthrusting (Hók et al. 2018).

Paleogeographic schemes

The Krynica Unit is thrust in the Priabonian according to Plašienka et al. (2020 Figs. 6d and 7f). However, during the Priabonian–late Oligocene the deposition of the Racibor Fm or the Poprad Mb (in Poland) took place in the Krynica Unit (Potfaj et al. 1991; Teťák et al. 2016; Cieszkowski et al. 1998; Soták et al. 2012; Oszczypko-Clowes 2010). It is known that the Racibor Fm contains Magura-type greywacke sandstones of debris flow origin. The source of the Racibor Fm clastic material originated from the eastern margin of the Magura Basin. The thrusting of the Krynica Unit in the Priabonian is incompatible with the presence of the Magura type sandstones (Teťák et al. 2019).

Were the PKB units really nappes?

Plašienka et al. (2020) interprets the PKB units as nappes in a perfectly fitting succession of structures always reflecting the approximate S–N polarity. The geological structure of the PKB is mostly sub-vertical and affected by transpression (e.g., Vozár et al. 1999; Mello et al. 2005; Plašienka 2019). As a result, slices and bodies of tectonically and/or paleogeographically different units are placed in between the PKB units, which point to the non-existence of the perfect ordering (e.g., in the Vršatec area, Schlögl et al. 2000). This casts legitimate doubts on the nappes' presence in the PKB.

Conclusions

Our contribution is aimed at pointing out several disputable interpretations presented by Plašienka et al. (2020). The authors neither published geological maps, nor did they provide any fundamental evidence of the plausability of their interpretation of geological structures. It is necessary to state that the presence of the Šariš Unit has not been proven in the western segment of the Pieniny Klippen Belt. The backthrusting in the Biele Karpaty Mts. and Kozol (Malá Fatra Mts.) were never proven; and to the contrary in the Dobrá Voda area (Brezovské Karpaty Mts.) their supposed presence was disproved recently. Due to the intricate structure and a number of unsolved fundamental questions, the Pieniny Klippen Belt area and its surroundings cannot be considered a model region of foreland–backstop boundary as is suggested by the commented paper.

Declarations

Conflict of interest The authors declare that they have no conflicts of interest.

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