Construction of the Ukrainian Carpathian Wedge from low-temperature thermochronology and tectono-stratigraphic analysis

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Rebuttal letter

To Solid Earth editor:

Each comment of the referees is taken in the line order of the manuscript, the comments on the figures are considered afterward. The review of Piotr Krzywiec is treated in this rebuttal letter. In this letter, we show the reviewer comments in Roman font highlighted, our responses in *italics*, and we quote the modifications to the manuscript in quotation marks "".

Referee #1: Krzywiec Piotr (contact: piotr.krzywiec@twarda.pan.pl)

This is interesting paper that provides new data on evolution of the Ukrainian segment of the Outer Carpathians. Before publication however it must be corrected as currently there are some drawbacks requiring additional work. My main points are listed below, additional comments could be found in attached annotated pdf files:

1. substantial flexural extension related to extensional reactivation of the Teisseyre-Tornquist Zone influenced evolution of the orogenic wedge and its foreland basin in the E Polish and the W Ukrainian Carpathians but hasn't been included in the analysis

We recognize that there was significant extensional reactivation of the Teisseyre-Tornquist zone due to loading of the foreland and have incorporated this important aspect of the evolution of the mountain belt and its foreland in the geological setting and the scenario presented. However, this does neither affect our thermochronological results, nor the thermal modelling presented, nor the inferences we make from the constructed burial diagrams.

2. compressionally undeformed foreland basin located in front of the Sambir nappy is only very brielfy mentioned but should be also more fully described and included in the analysis

We acknowledge that this was an omission and we now include a description of sedimentation in the foreland in line with our descriptions of sedimentation in the rest of the area.

3. references to the lower plate, its structure and evolution, must be substantially improved

While in our opinion this does not significantly impact on our results and the scenarios of wedge evolution derived from them, we have nevertheless improved referencing to the geology of the lower plate, including its extensional re-activation.

These corrections will require some time and effort but I'm confident that Authors could easily incorporate them, and I'm looking forward reading the final version of this paper.

Abstract

Line 26: correct terminology should be used; S / SW margin of the East European Platform

We have adopted this suggestion.

Modifications line 24-27**: "**Non-reset ZHe ages indicate that sediments in the inner part of the Carpathian embayment were mostly supplied by the Inner Carpathians, while sediments in the outer part of the basin were derived mostly from the Teisseyre-Tornquist Zone (TTZ) or the south-western margin of the East-European Platform.**"**

Line 27: derived

We have adopted this suggestion.

Modification line 27: "Our results suggest that during the accretionary phase, few sediments were recycled from the wedge to the foredeep. Most of the sediments derived from the Ukrainian Carpathian wedge were likely transported directly to the present pro- and retro- foreland basins."

1 Introduction

Line 37 (now 39): or more or less, all the options are possible

This is exactly why we have written "may". This indicates that this is an option, not a necessity.

Line 39 (now 40): and possibly also of the foreland plate, uplifted within the flexural bulge area

We have added the forebulge as an area of possible erosion/sediment sourcing.

Modifications line 40-43: "Sediment accumulation is bound to accelerate as the orogenic belt propagates toward the basin, by a combination of enhanced erosion of the growing wedge, the backstop and the forebulge area,creation of accommodation space by flexure of the underlying plate (e.g., Simpson, 2006; Sinclair, 2012) and increasing dynamic subsidence of the foreland (e.g. Husson et al., 2014; Flament et al., 2015)."

Line 40 (now 43): or stacking of nappes could bring sediments towards the surface if they become incorporated into the orogenic wedge

We have reformulated this section to better express the scenario of nappe integration. While we keep the scenario general and of relevance to other accretionary wedges, it is particular importance here that most of the nappes in the Carpathians do not show signs of shallowing before deposition ends. So this needs to be explained.

Modification line 43-48: "Tectonic nappe stacking integrates the pre-existing basin step-by-step into the growing wedge. When the frontal thrust propagates part of the former basin becomes a nappe that overrides more external areas of the basin. Overthrusting of the nappe by the more internal part of the orogenic wedge subsequently buriesburies the newly formed nappe, this time by means of tectonic loading.loading. As thrusting propagates outwards and the wedge evolves, the respective nappe isis eventually uplifted and exhumed. This processrepeats until plate convergence stops (Davis et al., 1983; Dahlen et al., 1984; Konstantinovskaia and Malavieille, 2005; Hoth et al., 2007)"

Line 49 to 51(now 54-57): that is only partly true - these early flexural modelling studies did not take into account the fact that in E Polish and in W Ukrainian segments of the Carpathians there was very substantial flexural extension with displacement on particular normal synsedimentary faults in order of up to 3-4 km. These faults formed due to flexural reactivation of the Teisseyre-Tornquist Zone that in this segment of the Carpathians undelies Carpathian orogenic belt and its foreland basin. Such substantial flexural extension is a reason why orogenic load could not be regarded as a sole mechniasm for flexure of the lower plate and formation of the foreland basin. More details on that could found in:

Krzywiec P., 2001, Contrasting tectonic and sedimentary history of the central and eastern parts of the Polish Carpathian Foredeep Basin - results of seismic data interpretation. Marine & Petroleum Geology, 18(1), 13-38.

Oszczypko N, Krzywiec P., Popadyuk I., Peryt T., 2006, Carpathian Foredeep Basin (Poland and Ukraine) - its sedimentary, structural and geodynamic evolution, [in] Picha F., Golonka J. (ed.), The Carpathians and Their Foreland: Geology and Hydrocarbon Resources, American Association of Petroleum Geologists Memoir 84: 293-350

Thank you for this clarification. We have added several phrases to address this additional mechanism.

Modifications line 55-60: "The elevation and width of the wedge are insufficient for the weight of the wedge to have created the observed foreland basin, which suggests that subduction dynamics primarily drove subsidence (Royden and Karner, 1984; Royden and Burchfiel, 1989; Royden, 1993; Krzywiec and Jochym, 1996, 1997).

Foreland subsidence was furthermore enhanced by the reactivation of pre-orogenic normal faults at pre-Mesozoic plate-sutures during the Miocene (Krzywiec, 2001; Tărăpoancă et al., 2003; Oszczypko et al., 2006), probably also predominantly due to slab rollback."

Line 51 (now 60): these results, due to the fact that the lower plate is differently composed in bot areas, have only limited applicability to the W Ukrainian Carpathians described in this paper

We completely agree with this remark. We think it is necessary to shortly summarise previous work on Carpathian wedge dynamics, even if these were performed in regions different from the one under consideration here, but have added a sentence at the end of the paragraph addressing the caution that needs to be taken with simple extrapolation of wedge dynamics along the Carpathian arc due to differences in the properties of the downgoing plate. In fact, this provides support for our study because it means that the wedge dynamics in the Ukrainian Carpathians need to be assessed independently.

Modifications line 68-69: "One should, on the other hand, be very cautious with simple extrapolation of wedge dynamics along the Carpathian arc, because the characteristics of the downgoing plate change markedly along strike."

Line 56 (now 58): please clarify what exactly do you mean by these segments

We have added the word Romanian to make the location more precise here. Further details are given in section 2 "Geological context"

Modifications line 63-67: "Further studies, however, inferred that the doubly-vergent wedge concept cannot be directly applied to the Romanian East and Southeast Carpathians, and that this belt is a singly-vergent wedge that evolved through forward propagation of deformation over the subducting plate followed by significant out-of-sequence deformation (Matenco et al., 2010; Merten et al., 2010)."

Line 60 (now 69): this is strange term, I have never encountered it in other papers ... I'd suggest using well established terminology such as East European Craton, East European Platform, Teisseyre-Tornquist Zone etc., I do not see any reason for introducing new terms

We changed it to East European Platform (EEP).

Modifications line 69-70: "Convergence in the Carpathians was mostly oblique to the East European Platform (EEP), except in the Ukrainian Carpathians, where it occurred perpendicular to the margin."

Line 61(now 70): "indee, but all regional geodynamic mechanisms must be taken into account, including substantial flexural extension of the lower plate, which is especially well visible in this segment of the Carpathians"

Thank you for this useful suggestion. We have added a specific address of this mechanism to section 6.2 "Evolution of the Ukrainian Carpathians wedge" where we found it more appropriate to discuss the flexural extension during the Badenian and its potential impact on wedge evolution.

Modifications line 517-527: "Thick-skinned Mesozoic extensional faults on this margin were re-activated during the Badenian-early Sarmatian phase of wedge propagation and show up to 2.5 km of post middle Badenian offset (Krzywiec, 2001). Modelling studies indicated that stresses are focalized on the sharp transitions of lower plate effective elastic thickness that occurs at these suture zones (Leever et al., 2006). Rheological variations at the margin of the East European Platform (e.g., elastic thickness varies from 40-80 km, Kaban et al., 2018) and the presence of pre-orogenic faults probably determined the location and magnitude of syn-orogenic extension, 50-70 km away from the orogenic front (Krzywiec et al., 2001; Tărăpoancă et al., 2003, 2004; Leever et al., 2006). The vertical displacement on the normal faults appears to have been higher in the western part of the Ukrainian foreland, decreasing eastward (Oszczypko et al., 2006). The Badenian-Sarmatian depocenter that developed in the hanging wall of these normal faults (~2 km) was subsequently overthrust by the Sambir nappe. The observed large-magnitude flexural extension on pre-existing normal faults may have facilitated the 70 km propagation of the Ukrainian Carpathians wedge onto the foreland during the middle to late Miocene."

2 Geological context

Line 75 (now 82): see above

East European margin was modified to East European Platform.

Modifications line 82; "The Carpathian belt is the result of the collision of the Tisza-Dacia and Alps-Carpathian-Pannonian (ALCAPA) micro-plates with the East European Platform (Csontos et al., 1992; Schmid et al., 2008)."

Line 97 (now 106): explain how they are defined

We have added some text that explains the differences between inner and outer Carpathians.

Modifications line 106-113: "The Carpathians consist of an Inner and an Outer belt, separated by the Pieniny Klippen Belt (PKB). The inner Carpathians formed in the Cretaceous by thick-skinned stacking of nappes comprising the basement of the ALCAPA and Tisza-Dacia blocks and their Permian-Cretaceous sedimentary cover (Csontos and Vörös, 2004; Schmid *et al.*, 2008). The Outer Carpathians are a thin-skinned accretionary prism, which developed from the Oligocene to late Miocene, and which is composed of flysch nappes from the Carpathians embayment (Ślączka et al., 2005). In Ukraine, most of the thick-skinned Inner Carpathian units are covered by the Neogene volcanics that erupted on the edge of the Pannonian basin; they only crop out in a limited area next to the border with Romania."

Line 99 and 101 (now in modified text line 106-112): text errors are commented by the reviewer

The text was modified as mentioned by the reviewer

Line 111 (now 129): text errors are commented by the reviewer

We prefer "onto" because emplacement is a movement and "above" indicates a static position.

Line 117 (now 163): what about strike-slip movements along the Pieniny Klippen Belt?

Strike-slip movement in the Pieniny Klippen Belt (PKB) occurred during the early to middle Miocene and is especially well documented on the Western end of the Carpathians in Poland and Slovakia. Castelluccio et al. (2016) attributed an early to middle Miocene age to the exhumation of the PKB, as constrained by LT thermochronology in the Polish Outer Carpathians. In addition, the strike slip movement of the PKB is especially apparent in the southwest-northeast oriented Western Carpathians. Picha et al. (2006) argue that stress measurements by Nemcok et al. (1998a, b) indicate that the proportion of shortening accommodated by sinistral strike slip is the highest in the southwestern part of the Western Carpathian arc and decreases toward the north, where most of the shortening is accommodated by the frontal compression. There are no estimates for the strike-slip movement along the PKB in Ukraine. It may very well be that the Miocene deformation switches to pure thrusting, due to the change in the orientation of the belt to more NW-SE in Ukraine.

The PKB is attributed generally to the Inner Carpathians. Because the manuscript is focused on the Outer Carpathians two do not discuss the details of the PKB at length in the text. However ,we modified the text to include the nuance of the PKB as part of the Inner Carpathians outcropping in Ukraine.

Modifications line 113-118: "The PKB is the outermost unit of the Inner Carpathians outcropping in Ukraine. The PKB was thrust onto the Outer Carpathians (Fig. 1) during early to middle Miocene convergence (Castelluccio et al., 2016). Whether the PKB accommodated strike-slip motion and/or back-thrusting during the emplacement of the Inner Carpathians in Poland is debated (c.f., Ratschbacher et al., 1993; Picha et al., 2006; Castelluccio et al., 2016; Nemčok et al., 2006), but further eastward strike-slip motion along the belt was limited (Picha et al., 2006). Moreover, the structures and position of the PKB in Ukraine is clear on its thrusting vergence, onto the Outer Carpathians units (Fig.1)."

3 Stratigraphy of the Ukrainian Carpathians

Line 134 (now 163): add information which sediments in each of the described nappes have you regarded as pre-, -syn- and post-compressional

We have added this information to Fig. 2 with the stratigraphy of the Ukrainian Outer Carpathians where it can be represented in a much more compact way than in the text.

Line 136 (now 165): add: Ślączka, Andrzej, Stanisław Krugłov, Jan Golonka, Nestor Oszczypko, and Igor Popadyuk, 2005, Geology and Hydrocarbon Resources of the Outer Carpathians, Poland, Slovakia, and Ukraine:

General Geology, in J. Golonka and F. J. Picha, eds., The Carpathians and their foreland: Geology and hydrocarbon resources: AAPG Memoir 84, p. 221 – 258.

This paper is much more relevant than those two that are focused on Romanian and Polish segments

The suggested reference was added to the text as follows (line 165-166): "As mentioned above, the Ukrainian Carpathians consist of a number of nappes or thrust sheets, which are differentiated based on their position, stratigraphy and tectonic evolution (Sandulescu, 1988; Ślączka et al., 2005; Oszczypko, 2006).".

Line 138 (now 167): Those ridges (referred to as "cordillieras" in classic Carpathian literature) might have formed during convergence and compression as thick-skinned structures so comparison with the passive margin is not very appropriate.

It is clear that these cordilleras efficiently supplied sediment to the adjacent basin in the Late Cretaceous to Paleogene (Poprawa and Malata, 2006), i.e., during the phase of compression that led to thick-skinned nappe stacking in the Inner Carpathians, which at that time were located several hundreds of kilometres away from the cordilleras (e.g., Handy et al., 2015). However, we consider it likely that these ridges initially formed as horsts during extension (as shown for instance on figs. 5 and 6 of Picha et al., 2006) and where subsequently uplifted by far-field compressive stresses when the region went from extension to compression (equally indicated on the figures of Picha et al., 2006). We consider the arguments for thick-skinned deformation of the Silesian ridge not relevant enough for the current paper to enter into a detailed discussion on the subject. However, in order to accommodate the comment, we now indicate that the Carpathian embayment formed as a passive margin with submarine highs, but then experienced compressional stresses from the Late Cretaceous, which uplifted the ridges. This leaves the tectonic style (thick skinned, thin skinned, inversion of former extensional faults, buckling) open for interpretation.

Modifications line (166-171): "Broadly speaking, the Carpathian embayment originated as a passive-margin basin, subdivided by several mostly submarine ridges (known as cordilleras). Changes in sedimentation pattern in the adjacent parts of the Carpathian embayment indicate that these ridges were periodically uplifted during convergence, possibly by long distance transfer of compressive stresses (Poprawa and Malata, 2006; Oszczypko et al., 2006)."

Line 151 and 153 (now 183-185): text errors were commented by the referee

The text was modified according to comments

Line 155: why not Krosno beds?

Geological maps in Ukraine name the Krosno beds, Krosno suite in their stratigraphy.

Modifications line 186-187: "The Krosno beds were deposited from the middle-Oligocene to the early Miocene, i.e., up to the regional Eggenburgian stage (~18.1 Ma)."

Line 167 to 179, and line 251(now 199-204-208): here and in many other places: nappe is tectonic unit formed during accretion, sedimentation was taking place in a basin, not nappe, that was then deformed and gave rise to the tectonic unit such as nappe / thrust sheet

Where we address sedimentation in the area of a future nappe (e.g. the Sambir nappe), we now address this as the Sambir area, in order to indicate that the nappe, as a structural entity, did not exist yet at the time of sedimentation. We did this throughout the manuscript. This seems the most straightforward resolution of the issue.

Modifications: through the manuscript in section 3, 6.1 and 6.2 mainly.

Line 178 (now 210): unclear – what do you mean by "Remaining"?

We agree that this wording was a little vague. Remaining refers to the late Miocene sediments in the Sambir nappe that are in discordance with the other Miocene sedimentation in this part of the basin/accretionary system. We have rephrased two sentences to make the meaning clearer.

Modifications line 210-212: "Deposition there continued concordantly to the end of the early Sarmatian (10.7 Ma) with grey clays and sandstones with intercalated tuffites; These are overlain discordantly by syn-tectonic conglomerates dated around 9 Ma (Andreyeva-Grigorovich et al., 2008)."

Line 179 (now 217): briefly describe also undeformed deposits of the Carpathian foreland basin

We have added a brief description of the sediments in the foreland, with emphasis on the directly adjacent foredeep, in style with the description of the sediments from the various nappes.

Modifications line 212-217: "In the Ukrainian Carpathians, the middle to late Miocene foredeep is represented by the Bilche-Volytsa Zone, with the oldest sediment being of Badenian age (16-12.65 Ma; Andreyeva-Grigorovich et al., 2008). These show a similar facies as the Badenian deposits of the Sambir nappe, with marls and clays at the base and tuffites intercalated by evaporites layers. Early Sarmatian facies are also similar to those of the Sambir nappe and constitute the uppermost preserved strata in the foredeep. The more distal foreland deposits are shallower-water equivalents of the foredeep sediments."

4.2.2 Tectono-stratigraphic analysis

Line 243 (now 282): also post-orogenic

We incorporated this modification (line 282-284): "The stratigraphy of the wedge (Fig. 2) contains important information on the pre-, syn-, and post-orogenic evolution of the Ukrainian Carpathians: the age, thickness, lithology, depositional environment and provenance of the corresponding sediments provide insight into the former topography and tectonic activity in the region."

Line 250 (now 290): error on figure number

Modification line 290: "The burial diagrams in Fig. 6 to Fig. 9 indicate to which minimal depth …"

Line 251 (now 291): sedimentation was within the sedimentary basin, not in the nappe

We have revised the sentence to clarify this.

Modification line 290-292: "The burial diagrams in Fig. 6 to Fig. 9 indicate to which minimal depth samples were buried by sediment accumulation, when the sedimentation rates of the paleo-basin changed and give a maximum age for cessation of sedimentation."

6.1 Burial and exhumation pathways in the Ukrainian Outer Carpathians

Line 356 (now ~390): thrust, not thrusted, it is irregular

After substantial modifications of this paragraph the error is no longer present in the text.

Line 358 (now 395): and there was no syn-tectonic sedimentation whatsoever ...? This is strange assumption

We realise our wording was vague. In fact, we did not assume that there was no syn-tectonic sedimentation. We have revised the start of this section thoroughly to avoid confusion.

Modifications line 396-414: "We identify two ways in which this additional heating may be explained: First, part of the sediment column of the nappes may have been eroded during the evolution of the wedge. Which would mean our burial diagrams are truncated prematurely and actual heating due to sedimentary burial was more intense and continued for longer than we can determine. However, the nappes are internally deformed, so it is unlikely for none of the corresponding sediment to have been preserved in the cores of synclines or under intra-nappe thrusts. The only sediment likely to have been completely eroded are wedge-top deposits that may have accumulated unconformably on top of each of the nappes. There is some evidence that these existed, e.g. the unconformable Radych conglomerate in the Ukrainian Carpathians (Andreyeva-Grigorovich et al., 2008), or the 850 m thick Comaneşti piggy-back basin in Romania (Dumitrescu et al., 2000). However, accommodation space on the wedge top was probably too limited to explain the magnitude of additional heating observed (up to 2 km, Fig.11).

A second and more likely explanation for the surplus in heating is tectonic burial. In this scenario, sedimentation first accelerated as the thrust front progrades over the basin (as shown by several of the burial diagrams, Fig. 6-9), and then stopped when the site was overthrust by the advancing wedge. The absence of shallow water facies at the top of the sedimentary column of all but the outermost two nappes (which were originally situated on thicker crust), suggests most of the nappes were overthrust while situated in a deepwater environment. This means sedimentation did not end due to a lack of accommodation space. While we cannot exclude that part of the original sediment column has been eroded, we consider that the observed overheating is due to tectonic burial. In any case, the time-temperature diagrams have a record of the additional heat provided by the potentially missing sediments of the nappes, traduced into tectonic burial phase in the time-depth diagrams."

Line 385 (now 442): clarify what SE and NW exactly means here

We added the respective sample numbers in order to pinpoint what location we mean.

Modifications line 442 – 444: "The Magura and Marmarosh nappes were accreted at approximately 34 Ma and had a stage of tectonic burial that lasted to 30 Ma in the SE (CAR19-061) and to 20 Ma in the NW (CAR19-066) of our study area that brought the rocks 2.5-3 km deeper than the prior sedimentary burial."

Line 404 (now 461): needs to be explained

We specified the nappes.

Modifications line 461: "The southeast part of the Skyba nappe (sample CAR19-045), on the other hand, continued its tectonic burial until 12 Ma."

Line 406: Text errors commented by the referee

We changed nappe to area, in line with approach explained in response to the comment at line 167-179.

6.2. Evolution of the Ukrainian Carpathian wedge

Line 419 (now 475): Poprawa 2002, not in the references

Modifications: additions of Poprawa 2002 in the references.

Line 421 (now 477): that does not make sense: existence of nappes implicates that thrusting has already occured so active front was not forwarding towards nappes, it must have already formed them ...

Line 424: created by what?

Line 427: unclear, please clarify this

Line 435-436: unclear, rephrase

Line 438: what does it exactly means, initial in what sense?

Line 439: under Krosno napps or under Krosno basin in which sediments of the Krosno nappe were deposited?

Line 440-442: unclear, rephrase

Line 442-444: explain in more details

Line 447: what does it mean?

Line 450-452 (now ~513): rephrase, incomplete sentence

Response: All the above comments are treated as a whole, as they have the same purpose of clarifying the section 6.2. of the manuscript. We have substantially modified the paragraphs and hope the explanation we provide is now clearer and more precise.

Modifications lines 474-511: "Several of the burial diagrams show an increase in sedimentation rate just before respective part of the antecedent basin was accreted into the wedge (Fig. 11). Such increasing sedimentation rates are expected in a pro-foreland basin adjacent to an approaching frontal thrust (Naylor and Sinclair, 2008), as also suggested for the Polish Carpathians (Oszczypko, 2006; Poprawa et al., 2002). In the Magura area, depositional rates increased in the early-middle Eocene, especially in the Marmarosh Unit, until the end of the Eocene (Fig. 2). In the Burkut and Dukla areas, the youngest sediments preserved are middle Oligocene in age; the approach of the active front toward the Burkut and Dukla areas is reflected by a coarsening of the grain size and olistostromes in the flysch without a marked acceleration of the sedimentation rate. For the Krosno nappe, the two-kilometres-thick sandstones show a rapid increase in sedimentation rate within the basin starting in the late Oligocene, probably due to a high sediment supply from the internal Carpathians, uplifted by the wedge that was growing underneath. Sedimentation in the proximal units of the Skyba area was similar to the Krosno area, with Oligocene sandstones and Miocene syn-orogenic sediments. Miocene layers are absent from the more distal units of the Skyba nappe, where the stratigraphic series ends with late Oligocene sediments, possibly because of erosion of the overlying strata, or because the external part of the nappe was uplifted while it started to overthrust the Boryslav-Pokuttia area at this time (see e.g. Nakapelyukh et al., 2018, fig. 8, reconstruction 5). The Boryslav-Pokuttia and Sambir nappes preserve the majority of their Miocene deposits, with levels of sandstones (and olistostromes), followed by evaporites lenses and fossil-rich clays, marking the evolution of the environment to a shallow sea, located in front of the wedge in the middle Miocene (Fig. 2).

We observe diachronous building of the wedge with periods of increased tectonic activity. For the Magura nappe, the onset of accretion is at 34 Ma and exhumation is between 30-22 Ma, coeval with the accretion of the Burkut and Dukla nappes (around 28-22 Ma). Exhumation of the Burkut nappe started immediately afterwards at ca. 20 Ma (Fig. 7) and the next nappes in line, Krosno and Skyba, were being accreted at 18 Ma. Tectonic burial was very rapid for the Krosno nappe and exhumation started very shortly afterwards, ca. 16 Ma whereas it occurred later, around 12-8 Ma, for the Skyba nappe (Fig. 8 and 9). Out-of-sequence thrusting in the wedge also occurred during this period, with the onset of the exhumation of the Dukla nappe at 14 Ma (Fig. 8). In this scenario, the thick mid-late Oligocene sedimentation over the Krosno area can be linked to the onset of the Carpathians wedge growth and related erosion of the Inner Carpathians. Exotic pebbles of granite, amphibolite, gneiss, and limestone as well as large blocks of mafic volcanics are only found in the Burkut nappe and in the retro-wedge side of the Dukla nappe, in mid-Cretaceous strata, which suggests that a basement high separated these parts of the Carpathian embayment (Shlapinskyi, 2007; Nakapelyukh et al., 2017; Nakapelyukh et al., 2018), although Cretaceous units of the Krosno nappe -possibly contain similar exotic pebbles- do not outcrop. It was suggested that the original position of this basement high was between the Dukla and Krosno areas, and that arrival of the basement high at the subduction zone, may have disrupted the progradation of the wedge and led to the formation of duplexes and out-of-sequence thrusting in the Dukla nappe (Roure et al., 1993). The basement high might correspond to a south-eastward extension of the Polish Silesian ridge, or a branch of it known as the Bukowiec ridge in the vicinity of the Ukrainian border (Oszczypko, 2006).

Apart from some minor Pliocene conglomerates, the youngest deposits within the Boryslav-Pokuttia nappe are dated to 17.2 Ma (Fig. 2), with local pockets of sediment dated at 13.5 Ma, which are however only present in the most external parts of the nappe (Andreyeva-Grigorovich et al., 2008). This indicates that most of the nappe was tectonically buried just after 17.2 Ma, while syn-tectonic deposition continued locally, and in particular on the more external parts of the nappe, up to 13.5 Ma. The nappe started its exhumation simultaneously with the Skyba nappe, as marked by its late Miocene AHe ages (12.8 ± 0.2 Ma and 9.5 ± 0.1 Ma)."

Comment on the 6.2 section: at least short analysis of the relationship of the Sambir Nappe to the deposits of the undeformed Miocene foreland basin would be useful

We revised this section to better incorporate the final stages of wedge advance including the relationship of the Sambir Nappe to the deposits of the foreland. We furthermore added text mentioning the flexural extension of the lower plate during the Miocene.

Modifications line 512-528: "This probably happened when the wedge was thrust over the Sambir area. Badenian (16-12.65 Ma) sediments were found under the Carpathian wedge up to 70 km inward of the frontal thrust (Oszczypko et al., 2006). This means that the Sambir nappe overthrust the foreland by at least this distance after the Badenian. The thrust that delimits the eastern margin of Sambir nappe, i.e. the frontal thrust, crosscuts the early Sarmatian Dashava formation and must have therefore been active until 11.5 Ma (Andreyeva-Grigorovich et al., 2008), and ceased afterwards (Nemčok et al., 2006; Nakapelyukh et al., 2018), coincident with the arrival time of the wedge at the margin of the rigid East European Platform. Thick-skinned Mesozoic extensional faults on this margin were re-activated during the Badenian-early Sarmatian phase of wedge propagation and show up to 2.5 km of post middle Badenian offset (Krzywiec, 2001). Modelling studies indicated that stresses are focalized on the sharp transitions of lower plate effective elastic thickness that occurs at these suture zones (Leever et al., 2006). Rheological variations at the margin of the East European Platform (e.g., elastic thickness varies from 40-80 km, Kaban et al., 2018) and the presence of pre-orogenic faults probably determined the location and magnitude of syn-orogenic extension, 50-70 km away from the orogenic front (Krzywiec et al., 2001; Tărăpoancă et al., 2003, 2004; Leever et al., 2006). The vertical displacement on the normal faults appears to have been higher in the western part of the Ukrainian foreland, decreasing eastward (Oszczypko et al., 2006). The Badenian-Sarmatian depocenter that developed in the hanging wall of these normal faults (~2 km) was subsequently overthrust by the Sambir nappe. The observed large-magnitude flexural extension on pre-existing normal faults may have facilitated the 70 km propagation of the Ukrainian Carpathians wedge onto the foreland during the middle to late Miocene."

6.3 Thermochronometric pattern and wedge dynamics

Line 467 (now 543): rephrase

While it is not exactly clear what the reviewer means, we have rephrased the sentence for it to be clearer.

Modifications line 541-545: "The increasing thermochronometer ages toward the innermost Magura nappe may indicate that the latter acts as a relatively stable backstop (e.g., Brandon et al., 1998) or that the Ukraine Carpathians constitute an "immature" wedge, where steady state has not been reached, or was not maintained sufficiently long to exhume reset thermochronometers within the inner wedge (e.g., Willet and Brandon, 2002; Konstantinovskaia and Malavieille, 2005)."

Line 473 (now 549): comment on non-understood text.

Indeed, we have corrected the sentence.

Modifications lines 549-551: "We can infer from what we see in our time-depth diagrams (Fig. 11), that the accretion-exhumation phases are shorter in the period between 22-18 Ma when the main nappes (Burkut, Dukla, Krosno and Skyba) were accreted."

Comment on section 6.3: substantial flexural extension caused be extensional reactivation of the Teisseyre-Tornquist Zone has also played important role here, and should not be neglected

Paragraph 6.3. of the manuscript focusses on the thermochronological ages pattern of the wedge and its significance compared to other accretionary prism in subduction zones, in retreat or not. We include a dynamic interpretation of the region focussing on the accretion of the nappe regarding the roll-back of the subducting slab. We do not think this paragraph needs an additional text mentioning the reactivation of pre-orogenic structures of the lower plate during flexure due to slab pull because we do not see how this reactivation would have impacted upon the thermochronological ages. The reactivation will be mentioned later in section 6.4. of the manuscript

6.4 Sediment provenance from ZHe ages

Line 490-491 (now 564-567): unclear, possibly incomplete sentence

We agree and the sentence was modified. In fact we rewrote large parts of the provenance section to accommodate justified criticism. A number of comments of the reviewer relate to section 6.4 Sediment provenance from ZHe ages. In order to accommodate this criticism, we have rewritten substantial parts of this section of the paper.

Response to specific comments:

- Comment on section 6.4: add discussion of your results versus:
  - Roban et al., 2022, Provenance of Oligocene lithic and quartz arenites of the East Carpathians: Understanding sediment routing systems on compressional basin margins. Basin Research, https://doi.org/10.1111/bre.12711
  - Roban et al., 2020, Lower Cretaceous Provenance and Sedimentary Deposition in the Eastern Carpathians: Inferences for the Evolution of the Subducted Oceanic Domain and its European Passive Continental Margin. Tectonics, https://doi.org/10.1029/2019TC005780

We now compare our results with the recent work of Roban et al., 2020 and 2022 at the end of the provenance section.

- Line 507-508: intra-basinal ridges, or "cordillieras", were uplufted and eroded during thrusting

Indeed, this is correct. After careful analysis we realised that these intra-basinal ridges only supplied sediment to the basin during the late Cretaceous to early Paleogene and particularly to the Dukla and Burkut nappes. We now make specific reference to the possibility that the intra-basinal ridge(s) sourced some of the Late Cretaceous to Early Paleogene zircons.

- Line 509-510: East European Craton does not contain any Variscan faults as Late Carboniferous compressional defomations in this region are thin-skinned; also, they do not show any specific Ordovician persiod of activity. More details could be found here (cf. also Roban et al., 2022):
    - Krzywiec et al, 2017, Late Carboniferous thin-skinned compressional deformation above the SW edge of the East European Craton as revealed by reflection seismic and potential fields data - correlations with the Variscides and the Appalachians. [in]: R. Law, R. Thigpen, H. Stowell, A. Merschat (eds.), „Linkages and Feedbacks in Orogenic Processes", Geological Society of America Memoir 213, 353 - 372 doi:10.1130/2017.2013(14)
    - Krzywiec et al., 2017, Variscan deformation along the Teisseyre-Tornquist Zone in SE Poland: thick-skinned structural inheritance or thin-skinned thrusting? Tectonophysics, 718: 83-91, doi: 10.1016/j.tecto.2017.06.008

We have substantially modified this section removing references to specific tectonic events of the TTZ and East European Platform. A full review of their protracted tectonic history is outside the scope of this paper. What is important is that, contrary to the Inner Carpathians and the intra-basinal ridges, this area was tectonically quiescent since the mid-Triassic.

- Comment next to lines section 6.4: this part must be substantially modified and extended

As mentioned above, the source area for the 450-230 Ma population of zircons must have experienced substantial exhumation between 450-230 Ma and, probably more importantly in the context of the Carpathians, then have remained relatively quiescent since the mid Triassic. Finally moderate erosion took place to supply sediments to the Carpathian embayment. We aim to infer the source area as simply as possible without making references to specific tectonic events that are not directly linked with the evolution of the Carpathian wedge. Documenting the whole protracted history of the TTZ and the East European Platform and sifting it for corresponding with individual ZHe ages is outside of the scope of our paper. The obligatory tectonic quiescence of the sediment source area since the mid Triassic simply points to the East European Platform and the TTZ as the most likely sources.

Modifications of section 6.4: "While the reset and partially reset AFT and AHe thermochronometers provide insight into the sedimentary and tectonic evolution of the wedge, the non-reset ZHe ages provide insights into the sediment supply to the evolving wedge and its precursor deep-water basin (Fig. 12). ZHe ages of this study can be divided in two groups containing ages of 60-130 Ma and 230-450 Ma, respectively. The younger age group is mainly found in the inner nappes of the UC (samples CAR19-061, -062, -063; Fig.s 4, 12), while the older ZHe age population (230-450 Ma) is dominant in the outer nappes of the Ukrainian Carpathians (samples CAR19-045, CAR19-047 and CAR19-056; Fig.s 4, 12). Whereas ZHe ages from Andreucci et al. (2015) are reset and partially reset in the core of the orogenic wedge (i.e. in the Burkut and Dukla nappes), their non-reset 232-250 Ma ZHe ages from the inner and 55 and 413 Ma ZHe ages from the outer parts of the wedge provide useful complementary information about sediment provenance.

Our data indicate that the sources of the sediment in the inner nappes, which bear mostly 60-130 Ma non-reset ZHe ages, are the Bucovinian units of the Inner Carpathians (basement units of the Dacia plate; Sandulescu, 1988; Schmid et al., 2008) and their sedimentary cover. ZFT studies in the infra-Bucovinian units, located in the Maramures mountains, show fully reset ages from a cooling phase starting in Cenomanian times (~100 Ma), with another cooling event in the Coniacian-Campanian (90-72 Ma; Gröger, 2006). Sedimentation in the Bucovinian units stopped in Barremian times (129-125 Ma; Krautner, 1975) and the onset of thrusting is dated as Aptian-Albien (125-101 Ma) by the discordant deposition of the Wildflysch formation on top of both units (Sandulescu, 1975). For the Bucovinian and sub-Bucovinian units, which structurally overlie the infra-Bucovinian unit, the ZFT system is generally partially reset depending on the tectonic overburden and stratigraphic position (Gröger et al., 2008). The ZFT ages from the Bucovinian units are very similar to our 60-130 Ma ZHe ages for the innermost nappes, suggesting a source-sink relation. The 232-250 Ma ZHe ages present in the dataset of Andreucci et al. (2015) in the internal nappes may on the other hand signify that some zircons were derived from Triassic intrusions that are present in the basement of the inner Carpathian units. In line with our results, sediment provenance analysis in the Western Carpathians showed that the Magura nappe received sediments from the inner units (Winkler and Slaczka, 1992). The intra-basinal ridge also supplied sediment to the basin, particularly during the Late Cretaceous and early Palaeogene, as demonstrated by crystalline clasts in the Burkut and Dukla nappes and paleo-currents in the Silesian Basin (Oszczypko, 2006). However, ZHe with 60-130 Ma ages require at least 6 km of uplift and erosion at the time of deposition, which seems unlikely considering that uplift occurred due to far-field transmission of compressive stresses related to collision in the internal Carpathians. Nevertheless, some poorly rounded blocks of chlorite-rich phyllite and chlorite-muscovite schists recording Albian to Cenomanian cooling were found in the Krosno Beds of the Silesian Basin in Poland (Poprawa et al., 2006), which means that some of the zircons with late Cretaceous ZHe ages preserved in the Dukla and Burkut nappes could originally have come from the intra-basinal ridge.

The Late Cretaceous to early Palaeocene ZHe ages (60-130 Ma) are dominant in the Eocene to Oligocene of the Krosno nappe, which points towards an Inner Carpathians sediment source, while the intra-basinal ridge had been overthrust by the wedge by this time. Pre-Oligocene sediments of the Skyba and Boryslav-Pokuttia nappes exclusively display 230-450 Ma ZHe ages, we infer that sediments in the outer nappes of the Ukrainian Carpathians were initially sourced from an area without significant exhumation (<(>6 km) since the mid Triassic. Within the context of the Carpathians, the East European Craton and the TTZ are the most plausible sources for these sediments (Pharaoh, 1999; Oszczypko, 2006; Roban et al., 2020). In the Oligocene sediments of the Skyba nappe, zircons from this older ZHe age population are joined by zircons from the 60-130 Ma ZHe age group, which suggests that, in addition to the sediment supply from the East European Platform, the area started to receive sediments from the inner Carpathians, either directly, or recycled from the evolving wedge.

Our results are in line with recent provenance analyses for sandstones in the Romanian Carpathians based on detrital zircons ages, sedimentology and petrography (Roban et al., 2020, 2022). These indicate that the Cretaceous sediments of the innermost Ceahlau-Severin and Teleajen nappes were sourced from the Bucovinian Units of Dacia basement, while those from the more external Audia, Tarcau and Vrancea nappes were sourced from the European foreland (Roban et al., 2020). The Oligocene series of the Tarcau and Vrancea nappes display coarser-grained lithic fragment rich sands and conglomerates of the Fusaru Fm. that were sourced from both the growing orogenic wedge and thick skinned nappes of the Inner Carpathians, while the finer grained quartz dominated sandstones of the Kliwa Fm were sourced from the East European Platform (Roban et al., 2022). This is analogous to the situation in the Krosno and Skyba nappes during the Oligocene."

6.5 Sediment recycling in the Carpathian Wedge and sediment supply to the pro-foreland basin

Line 518 (now 614): specify which exactly

done

Line 519 (now 616): above these nappes or within the basins that were then transferred into the napees ...?

We agree that lines 517-520 were not clearly formulated and have revised them to be more explicit and understandable.

Modifications line 612-617: "Our study provides a view on the sediment fluxes in the Ukrainian Carpathian wedge from the classic model of a formerly accreted nappe providing sediments to the next accreted nappe. A large volume of sediments accumulated in the part of the Carpathian embayment corresponding to the future Burkut, Dukla, Krosno and Skyba nappes during the Oligocene. This sediment cannot have been sourced exclusively from the early thin-skinned wedge, as the amount of material exhumed from the inner nappes at that time was insufficient. Our thermal modelling indicates that during the Oligocene, only the Magura part of the wedge was exhuming."

Line 526-527 (now 623-624): unclear / to brief, must be more clearly described

This sentence was simplified to make its meaning clearer. Details on the scenario were already provided in section 6.4 so are left out here for clarity.

Modifications line 622-624:" This suggests that much of the syn-orogenic sediment arriving in the basin was rather derived from the overriding plate the intra-basinal ridges and the East-European Platform. The growing wedge itself was a sediment source of minor importance at this time."

Line 531-532 (now ~628); what does it exactly mean? foreland basin should be also properly described in the Geological Setting

We modified the geological setting earlier in this review to describe the foredeep and foreland basin. We here add text to make a clear link with flexural extension and last stage of wedge propagation/foreland development.

Modifications line 626-633: "Hence a large part of the sediments eroding from the wedge was transported to the Sambir area and/or to the modern Carpathian foreland basin (i.e., the Bilche-Volytsa zone; Fig. 2, 13). In fact, the tectono-stratigraphic analysis, in combination with the kinematics of the Ukrainian Carpathians, indicates very little sediment recycling between the nappes. In the early stages of its development, the wedge provided a limited amount of sediment to the foreland area. During its subsequent rapid growth, most of the sediment eroded from it first deposited to thicken the Sambir area, and following its accretion, to the foreland basin. In addition, pre-orogenic normal faults created significant accommodation space for the recycled sediment directly in front of the advancing wedge during the final stages of wedge emplacement (Oszczypko et al., 2006)."

7. Conclusion

Line 542-545: this needs to be more clearly described / clarified, and proper terminology for the lower plate should be used

As the provenance section was thoroughly rewritten the corresponding part of the conclusions was also modified. A few textual corrections were further made to the conclusions to smoothen the text.

Modifications line 639-646: "ZHe dating shows mainly non-reset ages, except for the central part of the wedge (i.e., Burkut and Dukla nappes), that shed light on the sediment source areas for the different basins. A predominance of 130-60 Ma ZHe ages indicates that Eocene to Oligocene sediments in the Magura and Krosno nappes were supplied from the Inner Carpathian basement and/or its sedimentary cover. Pre-Eocene sediments of these nappes yield comparable ZHe ages, but could have been sourced from intra-basinal ridges. In the even more external Skyba and Boryslav-Pokuttia nappes, sediments older than 35 Ma reveal 230-450 Ma ZHe ages. We therefore interpret these sediments to have been supplied from the East European Platform. From the Oligocene onwards, zircons from the 130-60 Ma age group also appear in the Skyba nappe, suggesting the arrival of sediment sourced from the Inner Carpathians."

Comment on the section 7: flexural extension that led to extensional reactivation of the TTZ must be also taken into account

The conclusion was slightly modified to incorporate the flexural extension in the Ukrainian Carpathians wedge accretionary history. Two phrases were furthermore added to highlight the impact subduction of the basement ridge may have had on sediment supply from the wedge to the Krosno and Skyba areas, which we think is interesting to mention.

Modifications line 669-673: "In the mid- to late Miocene, roll-back and associated subduction dynamics increased subsidence of the foreland (more than the orogenic load) and reactivated pre-orogenic normal faults of the passive margin. It created an up to 2.5 km deep depocenter in front of the advancing wedge that facilitated its northward progradation, ultimately onto the East European Platform. The foreland was deformed by this last shortening episode and until thrusting stopped at 11.5 Ma , coincident with slab detachment (Nemčok et al., 2006)."

Figure 1: thise two grey units (i.e. autochthonous Miocene and the lower plate) should be also explained in the legend

Done

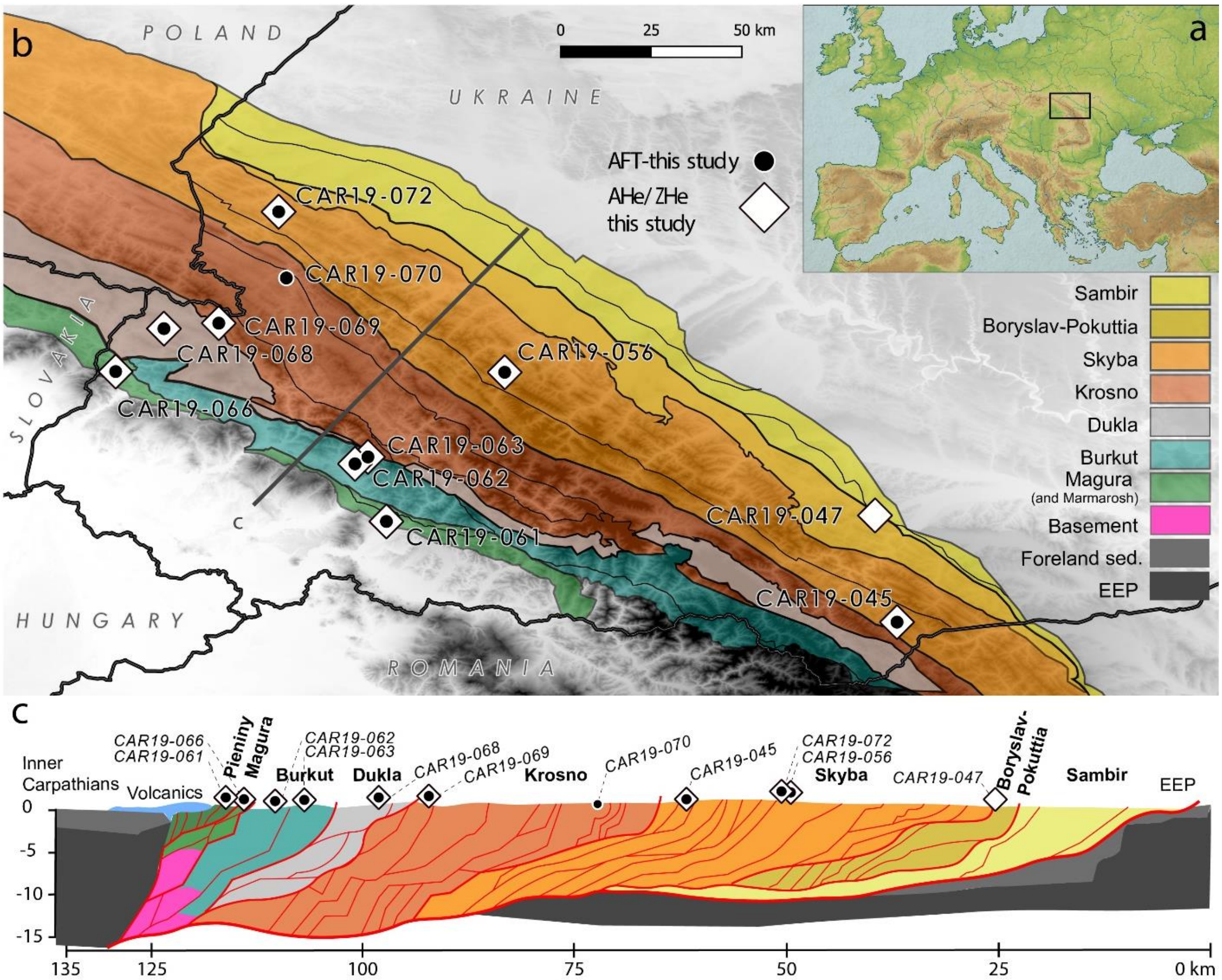

Figure 1: Overview of study area in the Ukrainian Carpathians, showing main tectonic nappes and sample locations. a) Inset shows setting of the Carpathian belt in Europe and location of the study region. b) Tectonic units are highlighted in different colours and follow Schmid et al. (2008), with reinterpreted names to be closer to the regional designation of the lithostratigraphy. Marmarosh and Magura nappes are both represented in green. Thin lines represent major intra-nappe faults. Grey thick line marks the location of the cross section. c) Simplified tectonic cross section (after Nakapelyukh et al., 2018); EEP: East European Platform. Major faults delimiting the nappes are in bold red lines, thin red lines indicate intra-nappe faults. Sample locations are projected onto the section.

As Ask by the reviewer, we also provide the syn-orogenic sediments, but in the Figure 2.

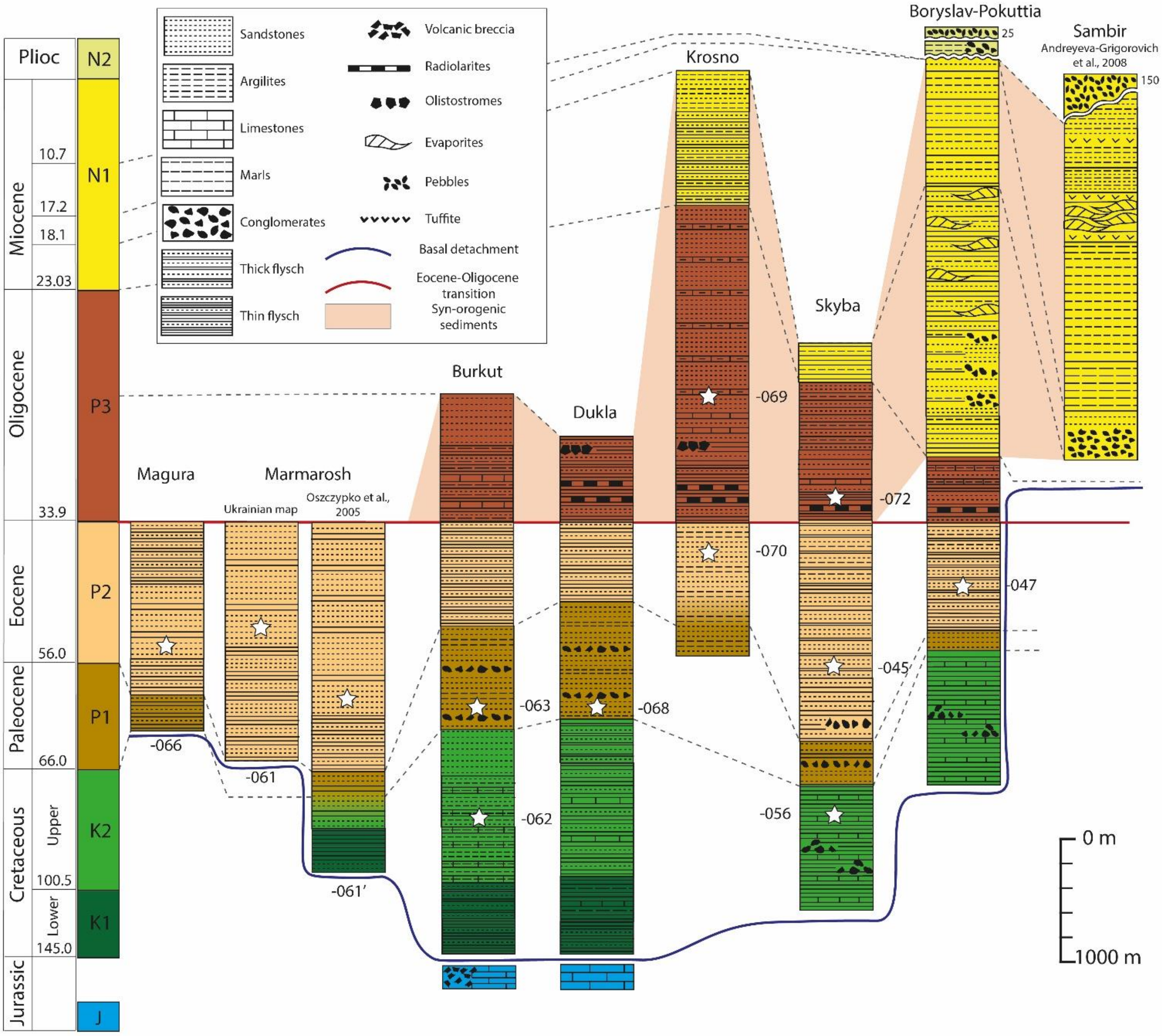

Figure 2: Regional stratigraphy of the Ukrainian Carpathian nappes, mainly from Ukrainian geological maps (Docin, 1963; Vachtchenko et al., 2003; Gerasimov et al., 2005; Matskiv et al., 2008, 2009). Stars mark the sample locations in the nappe stratigraphy; samples are identified by their suffix. Dark blue line marks the décollement horizon of the nappes. Jurassic rocks are integrated in the Burkut and Dukla nappes. Syn-orogenic sediments are indicated in the beige zone, older deposits are regarded as pre-orogenic sediments. Syn-orogenic sediments on Magura and Marmarosh nappes have been potentially eroded. Two stratigraphies are indicated for the Marmarosh nappe, one from the Ukrainian geological map, the other from Oszczypko et al. (2005). The Sambir nappe stratigraphy is after Andreyeva-Grigorovich et al. (2008) with adaptation to the new stratigraphic limits of Paratethys stages (Krijgsman and Piller, 2012). The stratigraphic columns depicted here are the closest ones available to the sampling site of each sample. The lateral variations in thickness or nature of deposition within individual nappes are not represented by these logs.

Figure 13: here and below: change to East European Platform

And

these normal faults, formed due to the flexural extension of the lower plate and reactivation of the Teisseyre-Tornquist Zone, were active during Miocene sedimentation within the Carpathian foreland basin but here they do not have any displacement, this must be corrected

and

Both scales could not be exxagerated, give estimated vertical exxageration or simply state "not to scale", this is just a cartoon

Modifications: Legend in the figure, the caption and faults were corrected.

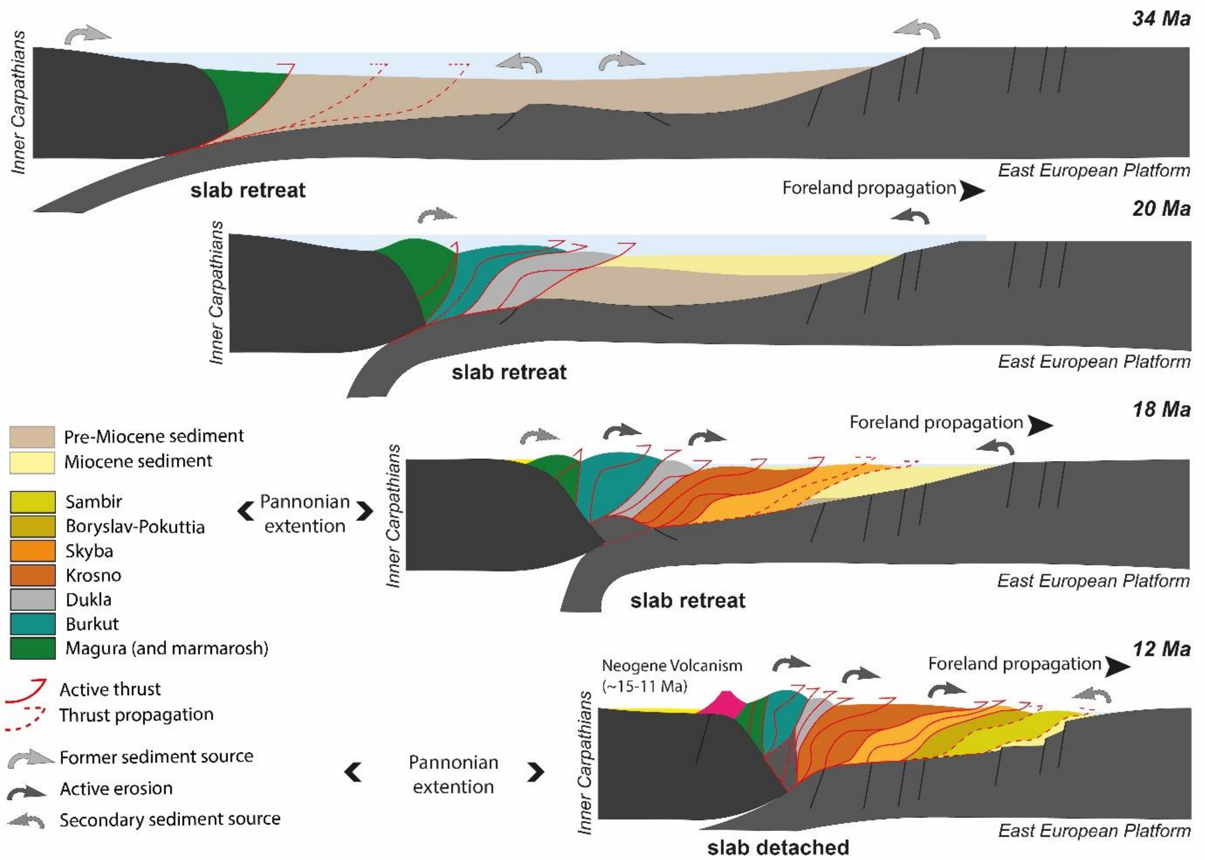

Figure 13: Sketch of the construction of the Ukrainian Carpathian wedge from 34 Ma to 12 Ma. Dashed red line are thrusts that will propagate on the next time step. Full red lines with arrows on top are thrust that are active or will reactivate, full red lines without arrows are sealed. Light grey arrows show source of sediment supply to the different basins. Dark grey arrows are for the active erosion of the nappe. For 12 Ma sketch, foreland propagation terminated around 11.5 Ma (Nemčok et al., 2006), and Neogene volcanism is linked to Pannonian extension (Tiliță et al., 2018). Not to scale.