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 anonymous referee review is considered. 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 #2: Anonymous reviewer

1.Introduction

Line 35 (now 36-37): references are required at the end of this sentence.

We added references to studies with both tectono-stratigraphic analysis and thermochronology analysis used to retrieve accretionary system development in orogenic wedge.

Modifications line 33-37: "These basins frequently evolve from rifted passive margins to orogens (e.g., Stockmal et al., 1986) and the stratigraphy of these basins provides a record of convergence-zone dynamics and the onset of orogeny, in particular when the sedimentary record is combined with subsequent exhumation paths that can be retrieved from detrital zircon and apatite grains using low-temperature thermochronology (Merten et al., 2010; Fillon et al., 2013; Vacherat et al., 2014; Andreucci et al., 2015; Castelluccio et al., 2016). »

Line 43 (now 48): as before, references are required at the end of this sentence.

We added the following references line 47-48: Davis et al., 1983; Dahlen et al., 1984; Konstantinovskaia and Malavieille, 2005; Hoth et al., 2007.

2. Geological context

Line 89 (now 95-97): this statement should be supported by references to recent papers.

One recent paper discusses the subduction system in the Carpathians embayment and was added to the references. We want to keep the model of slab break-off adapted to the regional case of the Carpathians, and not many recent papers have treated this subject. We nevertheless added a reference to the more recent paper of Handy et al., 2015

Modifications line 95-97: "The cessation of contraction in the belt has been linked to break-off of the European slab, which also propagated from northwest to southeast (Nemcok et al., 1998; Wortel, 2000; Cloetingh et al., 2004; Handy et al., 2015)."

Line 102 (now 108): Change "sedimentation" to "sedimentary"

Modification done

Line 132 (now 163): “Due to the absence of evidence for transient heating and in line with present day well data, an average geothermal gradient of 25°C/km for the Carpathian wedge and its antecedent basin is used in this study.”. This statement requires a more detailed discussion and should be supported by adequate references.

In order to address this rightful criticism we have supported our assumption for the geothermal gradient with references to available data and explained the reasoning we employ to justify the admittedly slightly broad-brush approach. Transient thermal fields are very difficult to quantify, even worse in past times, and we don't think anyone has gotten through this elegantly without detailed thermo-kinematic modelling, which is outside the scope of this study. The impact of uncertainties in the geothermal gradient on the tectonic scenarios put forward in the paper are on the other hand probably not excessive.

Modifications line 149-163: “Well data reveal that present-day geothermal gradients in the Skyba nappe range from 20 to 24 °C/km (Kotarba and Kołtun, 2006), in broad agreement with the values obtained in external domains of other mountain belts (e.g. Husson and Moretti, 2002). Because tectonic reconstructions of the belt at crustal and lithospheric-scale indicate a cylindrical structure (Docin, 1963; Vachtchenko et al., 2003; Gerasimov et al., 2005; Matskiv et al., 2008, & 2009), we suggest that the thermal regime only varies at large wavelengths, and that an average near-surface geothermal gradient of 25°C/km might be extrapolated to the entire Carpathian wedge at present-day. We are on the other hand aware that a range of near surface processes distort the thermal field in orogenic domains. These include in particular the topography that imposes a rough thermal boundary condition, heat advection in areas undergoing sustained erosion and, conversely, the blanketing effect in domains with fast sedimentation (e.g., Husson and Moretti, 2002). Because data are scarce, the magnitude of these processes and the associated uncertainties can only be inferred indirectly. Nevertheless, expected sedimentation and erosion rates and durations in the region are sufficiently low (< 1 mm/yr, Shlapinskyi 2007; Shlapinskyi et al., 2015; Fig.2) to only perturb the thermal regime by a maximum of 10 to 15% (Husson and Moretti, 2002). Considering the present-day reference value, it implies that the geothermal gradient could have varied within an approximate range of 22 to 28°C/km. Thermo-kinematic models could help alleviate this uncertainty, but for the current study, we deem 25°C/km to be a conservative estimate.”

4.1 Low-Temperature Thermochronology

Line 184 (now 222): Here you may also quote the book “Fission-track thermochronology and its application to geology (pp. 147-164). Springer, Cham”

The Book Chapter was added to references

Line 189 (now 232): An appropriate citation is: Malusa and Fitzgerald 2020 -The geologic interpretation of the detrital thermochronology record within a stratigraphic framework, with examples from the European Alps, Taiwan and the Himalayas. Earth-Sci Rev. 201,103074

The reference was added

Line 210 (now 250): Please specify to which author this zeta value is referred to.

We added line 249-250: “Three Durango and three Fish Canyon Tuff standards were used to determine a ζ-calibration value (Hurford and Green, 1983) of 282±12 yr.cm^{-2} for MR.”

Line 212 (now 252): More recent papers concerning Dpar should be mentioned at the end of this sentence.

We added a reference to Sobel and Seward, 2010.

6.1 Burial and exhumation pathways in the Ukrainian Outer Carpathians

Line 359 (now 415): “The amount of additional heating after the end of sedimentation, as well as the time lag between the end of sedimentation and the onset of cooling, reflect the relative importance of tectonic thickening due to thrusting, and surface erosion (Husson and Moretti, 2002; Ter Voorde et al., 2004).” This sentence suggests that exhumation is exclusively related to erosion, which is not the case during slab rollback (see for example Brun and Faccenna 2008 EPSL, Malusa et al 2015 G3).

In the case of the Carpathians, the degree of Cenozoic syn-tectonic metamorphism is very low in both the thin-skinned thrust belt and the inner Carpathian basement units, with rocks only exceptionally reaching the greenschist facies. The models discussed in Brun and Facenna (2008) and Malusa et al. (2015) which look into mechanisms for the exhumation of HP metamorphic rocks along the margin of orogens during slab roll-back are therefore not directly relevant. Moreover, material is exclusively exhumed in these models in areas where slab roll-back leads to extension. In the Carpathian case, slab-roll-back did lead to extension, but this was focussed in the upper plate, where the Pannonian Basin developed. The thin-skinned fold and thrust belt of the Outer Carpathians evolved in a compressive setting, which means exhumation of the corresponding nappes occurred primarily due to erosion of relief built-up through nappe stacking. To make it clear that our reasoning applies primarily to thin-skinned fold and thrust belts we have added this explicitly. The models of Brun and Faccenna (2008) and Malusa et al., 2015 may have some importance regarding exhumation of the internal units of the Carpathians during slab-roll-back, even though these hardly experienced any Cenozoic metamorphism, but this is outside of the scope of the current paper and has not been tested elsewhere to our knowledge.

Modifications line 415-417: "The amount of additional heating experienced after the end of sedimentation, as well as the time lag between the end of sedimentation and the onset of cooling, reflect the relative importance of tectonic thickening due to thrusting, and surface erosion in thin-skinned, thrust-fold belt (Husson and Moretti, 2002; Ehlers and Farley, 2003; Ter Voorde et al., 2004)."

Line 362: What are the independent constraints supporting this assumption?

As mentioned at the comment on line 132, we now justify this approach in more detail in section 2 of the paper. A reference to the respective section was added here.

Modifications line 418-419: "To estimate how much tectonic burial a sample underwent, we used a geothermal gradient of 25°C/km for the evolving wedge as was justified in section 2."

Line 460 (now 537): "This pattern of low-temperature thermochronology ages, showing burial heating to maximum temperatures in the core of the wedge (Fig. 10) and decreasing toward both the internal and external limits, is consistent with models of steady-state orogenic wedges (Barr and Dahlen, 1990; Batt et al., 2001; Willett and Brandon, 2002). It is also comparable with exhumation patterns in other orogenic wedges, including the Olympic Mountains (Brandon et al., 1998; Batt et al., 2001); Taiwan (Beyssac et al., 2007) and the Apennines (Thomson et al., 2010; Erlanger et al., 2022)." I recommend here a more open discussion about this point since there is no general consensus on the fact that Taiwan and the Apennines have reached a steady state.

We meant to say that this pattern was once thought to show that an orogenic wedge had reached steady state, but that recent papers show that this thermochronological pattern is also present in orogens not in steady state. As the meaning seems to not have come across, we modified these paragraphs, albeit avoiding to get into a detailed discussion about which of the example orogens are or aren't in steady state, which would lead to a lengthy discussion outside of the scope of our paper. We do explicitly address the question of steady state for the Carpathians and the subsequent phrase, however.

Modifications line 537-542: "This pattern of low-temperature thermochronology ages, showing burial heating to maximum temperatures in the core of the wedge (Fig. 10) and decreasing toward both the internal and external edges, is consistent with the exhumation pattern observed in other orogenic wedges including the Olympic Mountains (Brandon et al., 1998; Batt et al., 2001; Michel et al., 2019); Taiwan (Fuller et al., 2006 Beyssac et al., 2007) and the Apennines (Thomson et al., 2010; Erlanger et al., 2022). It also corresponds to the pattern observed in several modelling studies of orogenic wedges (Barr and Dahlen, 1990; Batt et al., 2001; Willett and Brandon, 2002)."

Figure 2: Symbols in the keys should be the same size as in the main figure they refer to.

done

Figure 3: I suggest using the same Dpar range for all the color bars in the radial plots.

We agree that this would be useful but unfortunately RadialPlotter does not allow adjusting the Dpar range to a common colour scale for the various radial plots. For each sample the scale is automatically adjusted based on the measured Dpar values. For each plot, the maximum and minimum Dpar values are indicated next to the colour scale beneath the radial plot and the mean Dpar values for each sample are given in the data table.

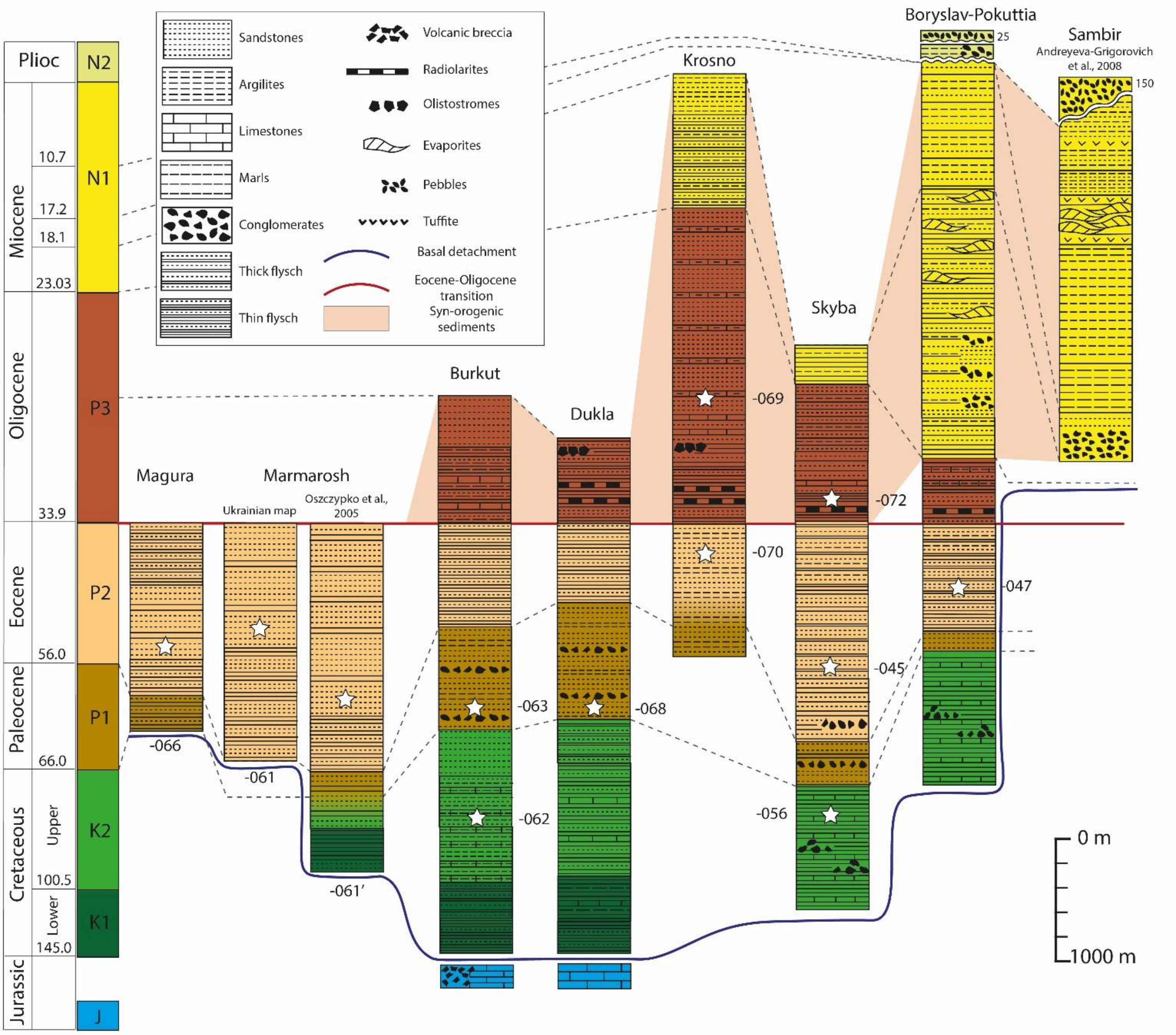

Figure 1: Regional stratigraphy of the Ukrainian Carpathian nappes, mainly from Ukrainian geological maps (Docin, 1963; Vachtchenko et al., 2003; Gerasimov et al., 2005; Matskiv et al., 2008, 2009). Stars mark the sample locations in the nappe stratigraphy; samples are identified by their suffix. Dark 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.