The Western Carpathians — record of 180 Myr lasting orogenic progradation and its drivers

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Abstract: The Meso–Cenozoic Western Carpathian orogenic wedge nucleated by development of the Meliatic–Turnaic accretionary complex in the course of subduction and suturing of the Tethys-related Meliata Ocean during the Middle–Late Jurassic. This Tethyan orogenic cycle passed gradually into the Cretaceous Austroalpine cycle with stacking of the Central Carpathian basement and cover nappe systems, whereby shortening was driven by the subcrustal subduction of the lower Austroalpine lithosphere pulled by the downgoing Meliatic slab. The subsequent Pennine cycle (Senonian–Eocene) generated the forward propagating accretionary wedge of the Pieniny Klippen and Flysch belts by subduction of the two branches of Pennine oceans and intervening Oravic continental fragment. The ongoing Oligocene–Neogene convergence was related to NE-ward extrusion of the Western Carpathian domain from the Alpine collision enhanced by the subduction retreat of the remnant oceanic lithosphere in the Carpathian embayment.

Introduction

Traditionally, the Alpidic orogenic processes in the Eastern Alps and Western Carpathians have been attributed to two principal periods — the Eo-Alpine (Palaeo-Alpine, pre-Gosauian; mid-Cretaceous) and the (Neo-)Alpine (Senonian–Neogene). Several authors distinguished also the intermediate Meso-Alpine stage (Senonian–Eocene). However, this classification reflects the time constraints of the main tectonic events only and does not take into account the driving geodynamic processes. Moreover, it disregards the Late Jurassic to Early Cretaceous compressional orogenic processes that have been thoroughly documented in both the Eastern Alps and Western Carpathians during the last two decades. Hereafter, a conceptual categorization of the Alpidic tectonic evolution into the Tethyan, Austroalpine and Pennine cycles is proposed to account for the long-term convergence triggered by elimination of two major oceanic zones. Some controversies of the palaeotectonic models are briefly discussed, too.

Tethyan cycle

The Tethyan (or Neotethyan) cycle embraces orogenic shortening processes connected with the elimination of the Tethys-related Meliata Ocean from the onset of its subduction ca 180 Ma ago up to the final collision of its former continental margins around the Jurassic/Cretaceous boundary (ca. 145 Ma). However, the character and position of these margins remain among the most controversial issues of the Western Carpathian geology. According to the generally accepted palaeogeographical model, the Triassic Tethyan shelves and slopes showed a uniform facies zonation of the continent/ocean transition from the Dinarides–Hellenides, through Southern and Northern Calcareous Alps and Transdanubia up to the Western Carpathians and Tisia (e.g. Haas et al. 1995; Mandl 2000). This facies symmetry is verified also by the structural position of the previous facies zones in the resulting post-collision or post-obduction thrust stacks — ophiolitic mélanges on top, continental rise and slope below (Meliata and Hallstatt facies), and the carbonate outer and inner shelf facies (like the Wetterstein and Dachstein carbonate platforms) in the lowermost position (e.g., Missoni & Gawlick 2011). This scheme seems to be valid everywhere — except of the Western Carpathians, where this tectonic succession is upside down (Silicic carbonate platforms on top, Turnaic slope facies below and the Meliatic oceanic rocks underneath). Possible solutions of this discrepancy are fairly speculative — such as the wedging-in model of Meliatic complexes between the continental margin units proposed by Schmid et al. (2008), or the collisional suture concept of Plašienka (2018). According to the latter view, the close lithological relations of the Upper Paleozoic rocks of the Meliatic blueschist-facies Bôrka Nappe to the underlying Gemeric complexes of the same age (e.g., Vozárová et al. 2019) reveal an involvement of the distal passive Gemeric (Bôrka) continental margin into the subduction process of the Meliata Ocean, hence the overlying Meliatic–Turnaic accretionary complexes should have represented the upper plate of the convergence system, i.e. the Jurassic active margin (Plašienka et al. 2019). In consequence, could all the structurally higher units (Silica–Aggtelek, Turňa–Torna, Bükk, or even the Transdanubian; collectively known also as the Pelso block — Fig. 1 represent "the other side of the Meliata Ocean"? This question is presently far from an answer consistent with all the controversial data.

The present knowledge about the composition, structure and tectonic evolution of all units that are structurally higher than the highest Austroalpine unit Gemericum was recently reviewed in detail by Plašienka (2018). These uppermost Carpathian units were united as the Internal Western Carpathian (IWC) tectonic system distinguished by several first-order characteristics: (i) Anisian (Pelsonian) rifting and breakup of the carbonate shelf and ensuing spreading of the Meliata Ocean; (ii) early Late Jurassic closing of the Neotethys-related oceanic domains, including the Meliata Ocean. However, modes of this closing seem to have been different along-strike the Neotethyan Belt (term coined by Missoni & Gawlick 2011). Intraoceanic subduction followed by obduction and prograding thrust stacking with sequential development of the late Middle–early Late Jurassic synorogenic basins in the lower (Austroalpine, Adriatic–Dinaridic) plate position was reconstructed e.g., for the Northern Calcareous Alps (NCA; Frisch & Gawlick 2003; Missoni & Gawlick 2011), whereas the Wilsonian-type collision with development of the upper-plate Meliatic–Turnaic (+Silicic?) Jurassic accretionary wedge composed of pre- and synorogenic complexes is inferred for the Western Carpathians (Plašienka et al. 2019).)

Considering the Tethyan relationships of the Meliata Ocean, in view of its opening and closure, tectonostratigraphic data and evolutionary trends, the IWC can be referred to as the Tethyan Carpathians (as a part of the Neotethyan Belt), too (Plašienka 2017). Thus all the Meliatic and structurally higher units would represent the Tethyan tectonic system of the Western Carpathians (Fig. 1). The corresponding tectonic processes comply with a closed Wilson-type orogenic cycle, so the term Tethyan cycle is suggested for this time period.

Austroalpine cycle

The Central Western Carpathians (CWC) between the inferred Meliatic suture and the Pieniny Klippen Belt (PKB; Fig. 1) represent the eastern segment of the Cretaceous Austroalpine (AA) thrust system (e.g., Froitzheim et al. 2008; Schmid et al. 2008), thus the alias name Austroalpine Carpathians may be used as a synonym to the CWC. Unlike NCA, where the structures of the Neotethyan Belt were sealed by the carbonate platform from the Kimmeridgian onward and the

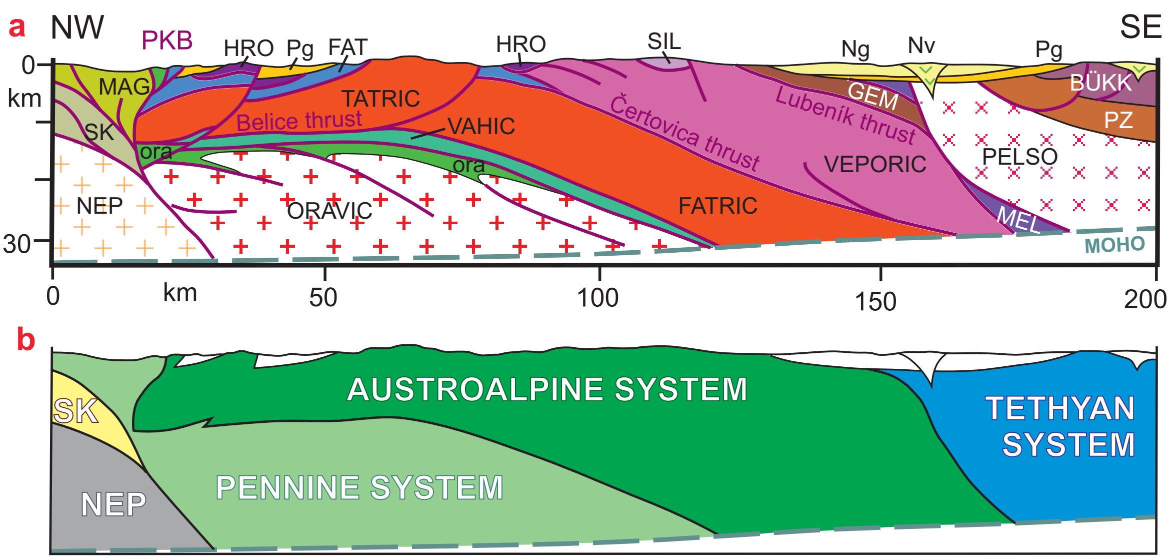

Fig. 1. A conceptual cross-section through the Western Carpathians. **a:** NEP — North European Platform; SK — Silesian–Krosno units of the EWC; MAG — Magura Superunit; ora — Oravic cover rocks; HRO — Hronic nappe system; SIL — Silicic nappes; GEM — Generic Superunit; PZ — IWC Paleozoic complexes; Pg — Paleogene overstepping sediments; Ng — Neogene deposits; Nv — Neogene volcanics. **b:** outline of the major Carpathian tectonic systems.

thrust system became inactive for a longer time (Missoni & Gawlick 2011), the continuous, though episodic northward thrust propagation is documented in the CWC (Plašienka 2018 and references therein). Firstly, the Meliatic Bôrka Nappe overrode the Gemericum during the earliest Cretaceous, then the Gemeric basement-cover sheet was thrust over the Veporicum (130–120 Ma). Afterwards, shortening relocated to a wide basinal zone between the present northern Veporic and southern Tatric margins, from where the Fatric cover nappe system was detached and thrust over the Tatric foreland by 90 Ma. Frontal Fatric elements glided beyond the outer Tatric margin and overrode the Vahic oceanic domain. Finally, the Pennine realm was seized by the contractional tectonics by transformation of the northern AA (Tatric) boundary from the passive to the active margin and subduction of the South Pennine Piemont–Váh Ocean from the 90 Ma onward.

The Carpathian AA thick-skinned thrust sheets Tatric, Veporic and Gemeric are about 10–20 km thick (Fig. 1), which means that their lower crustal portions must have been subducted into the mantle. Supposedly, this subcrustal subduction was triggered by the pull force of the descending Meliatic oceanic slab still attached to the lower AA plate (Plašienka 2018; see also Handy et al. 2010). This mechanism could explain the problem of the driving force for the Cretaceous Austroalpine orogeny. During the Early Cretaceous, the IWC units were affected by widespread backthrusting to form a transient retro-wedge that developed contemporaneously with the expanding CWC pro-wedge.

However, among others there is one important, but still unresolved problem with the CWC nappe structure. The highest thin-skinned Hronic and Silicic cover nappe systems do not respect the thrusting polarity, they were emplaced late in the structural development of the area and overlie various, in part exhumed and deeply eroded CWC units with a pronounced structural and metamorphic discordance at their base — but probably still in the latest Cretaceous. Their palaeogeographic provenance and emplacement directions are therefore questionable.

Pennine cycle

In the author´s view, the Western Carpathian Penninic units include the Magura and Biele Karpaty superunits of the External Carpathian Flysch Belt (connected with the Alpine Lower Penninic Valaisan and Rhenodanubian units), the PKB Oravic units (Middle Penninic) and the problematic and ambiguously interpreted Belice Unit of the Vahic (Upper Penninic) affiliation (Pennine system in Fig. 1). The latter unit was likely derived from an oceanic domain identified with the South Pennine Piemont–Váh Ocean (Plašienka 2012), which originated by the Middle Jurassic breakup and was eliminated by subduction under the outer AA margin. Subduction terminated by collision of the AA nappe stack in a backstop position with the Oravic continental ribbon by the end of Cretaceous. Subsequently, the Carpathian orogenic wedge annexed the Oravic and Biele Karpaty domains during the Paleocene–Middle Eocene and after that also the Magura realm in the Oligocene.

Interpretation of the structural and sedimentary development of the PKB units plays a crucial role in the tectonic models of the entire Western Carpathians. The PKB involves a heterogeneous group of units. The Oravic units (PKB proper) are composed of Jurassic to Eocene sedimentary successions that were sequentially detached from a narrow continental domain in the Middle Pennine position (Czorsztyn Ridge). It collided with the CWC wedge after subduction of the South Pennine Piemont-Váh Ocean during the latest Cretaceous, whereby the outermost CWC nappe units (like the Manín and Klape; cf. Plašienka 2019 and references therein) were partly incorporated into the PKB structure. Senonian through Eocene processes of incorporation of the PKB units into the growing Carpathian orogenic wedge were accompanied by linked synorogenic sedimentation in the wedge-top (Gosau-type) and in the foredeep trench-type basins in the Oravic units (Plašienka & Soták 2015).

Summing up, the Pennine cycle was governed by subduction of the Pennine (Alpine Atlantic) oceanic zones initiated some 90 Ma ago. In the Alps, subduction culminated by collision of the AA–Penninic thrust stack with the foreland European plate by approximately 35 Ma, but the convergence continued by additional shortening and mountain building due to the northward Adria push. The 35 Ma would be also the upper time limit of the Pennine cycle.

The Western Carpathian domain escaped this collision by its eastward extrusion, which was enhanced by the subduction retreat of the remnant Magura oceanic basin and probably also of the oceanic and/or transitional crust of the Silesian–Krosno basins connected with the Moldavian domains eastwards (Kováč et al. 2016, 2017 and references therein). Convergence continued until the Late Miocene in the NE part of the Carpathians and as late as to the sub-recent times in the Eastern Carpathians. However, the Oligocene–Neogene time period would represent a new orogenic cycle subsequent to the Pennine cycle, which has lasted from 35 Ma till present.

Conclusions

The Western Carpathians is a long-living convergent orogenic system that was driven by different geodynamic mechanisms in several cycles: (i) the Tethyan cycle (180–145 Ma) was governed by lithospheric subduction of the Tethys-related Meliata Ocean; (ii) the Austroalpine cycle (145–90 Ma) created a collisional stack of thick- and thin-skinned CWC units by subcrustal subduction of the lower AA lithosphere attached to the sinking Meliata slab; (iii) the Pennine cycle (90–35 Ma) was jointly driven by subduction of Pennine oceans and the northward push of the Adriatic microcontinent with accreted AA units; (iv) the terminal cycle (35–0 Ma) concerns the outermost Carpathian zones thrust over the European passive margin.

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References

Frisch W. & Gawlick H.-J. 2003: The nappe structure of the Northern Calcareous Alps and its disintegration during Miocene tectonic extrusion – a contribution to understanding the orogenic evolution of the Eastern Alps. *Internat. J. Earth Sci.* 92, 712–727.

Froitzheim N., Plašienka D. & Schuster R. 2008: Alpine tectonics of the Alps and Western Carpathians. In: McCann T. (ed.): The Geology of Central Europe. Volume 2: Mesozoic and Cenozoic. *Geol. Soc. Publ. House* London, 1141–1232.

Haas J., Kovács S., Krystyn L. & Lein R. 1995: Significance of Late Permian-Triassic facies zones in terrane reconstruction in the Alpine-Nord Pannonian domain. *Tectonophysics* 242, 19–40.

Handy M.R., Schmid S.M., Bousquet R., Kissling E. & Bernoulli D. 2010: Reconciling plate-tectonic reconstructions of Alpine Tethys with the geological–geophysical record of spreading and subduction in the Alps. *Earth-Sci. Rev.* 102, 121–158.

Kováč M., Plašienka D., Soták J., Vojtko R., Oszczypko N., Less Gy., Ćosović V., Fügenschuh B. & Králiková S. 2016: Paleogene palaeogeography and basin evolution of the Western Carpathians, Northern Pannonian domain and adjoining areas. *Global Planet. Change*, 140, 9–27.

Kováč M., Márton E., Oszczypko N., Vojtko R., Hók J., Králiková S., Plašienka D., Klučiar T., Hudáčková N. & Oszczypko-Clowes M., 2017: Neogene palaeogeography and basin evolution of the Western Carpathians, Northern Pannonian domain and adjoining areas. *Global Planet. Change*, 155, 133–154.

Mandl G.W. 2000: The Alpine sector of the Tethyan shelf – Examples of Triassic to Jurassic sedimentation and deformation from the Northern Calcareous Alps. *Mitt. Österr. Geol. Ges.* 92 (1999), 61–77.

Missoni S. & Gawlick H.-J. 2011: Evidence for Jurassic subduction from the Northern Calcareous Alps (Berchtesgaden Alps; Austroalpine, Germany). *Internat. J. Earth Sci.* 100, 1605–1631.

Plašienka D. 2012: Jurassic syn-rift and Cretaceous syn-orogenic, coarse-grained deposits related to opening and closure of the Vahic (South Penninic) Ocean in the Western Carpathians – an overview. *Geol. Quart.* 56, 601–628.

Plašienka D. 2017: Tethyan, Austroalpine and Pennine Western Carpathians – how do they relate? EGU Series – Émile Argand Conf., 13th Workshop Alpine Geol. Stud., Sept. 7–18 2017, Zlatibor Mts, Serbia, Abstr. Vol., p. 83.

Plašienka D. 2018: Continuity and episodicity in the early Alpine tectonic evolution of the Western Carpathians: How large-scale processes are expressed by the orogenic architecture and rock record data. *Tectonics* 37, 2029–2079.

Plašienka D. 2019: Linkage of the Manín and Klape units with the Pieniny Klippen Belt and Central Western Carpathians: balancing the ambiguity. *Geol. Carpath.* 70, 35–61.

Plašienka D. & Soták J. 2015: Evolution of Late Cretaceous–Palaeogene synorogenic basins in the Pieniny Klippen Belt and adjacent zones (Western Carpathians, Slovakia): tectonic controls over a growing orogenic wedge. *Ann. Soc. Geol. Polon.* 85, 43–76.

Plašienka D., Méres Š., Ivan P., Sýkora M., Soták J., Lačný A., Aubrecht R., Bellová S. & Potočný T. 2019: Meliatic blueschists and their detritus in Cretaceous sediments: New data constraining tectonic evolution of the West Carpathians. *Swiss J. Geosci.* 112, 55–81.

Schmid S.M., Bernoulli D., Fügenschuh B., Matenco L., Schefer S., Schuster R., Tischler M. & Ustaszewski K. 2008: The Alpine-Carpathian-Dinaridic orogenic system: correlation and evolution of tectonic units. *Swiss J. Geosci.* 101, 139–183.

Vozárová A., Rodionov N., Šarinová K., Lepekhina E., Vozár J. & Paderin I. 2019: Detrital zircon U–Pb geochronology of Pennsylvanian–Permian sandstones from the Turnaicum and Meliaticum (Western Carpathians, Slovakia): provenance and tectonic implications. *Internat. J. Earth Sci.* https://doi.org/10.1007/s00531-019-01733-7