ORIGIN AND GROWTH OF THE WESTERN CARPATHIAN OROGENIC WEDGE DURING THE MESOZOIC

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Abstract: The Western Carpathian orogenic wedge nucleated by collision after closure of the Meliata Ocean and then grew by accretion of crustal material mainly from the lower, Slovakocarpathian plate of the convergence system. This was enabled by its preceding stretching and attenuation by important Jurassic rifting events. The principal tectonic phases, which are either distensional or compressional in general, are briefly characterized and the tectonostratigraphic chart of the Western Carpathians is presented.

Key words: Western Carpathians, Mesozoic, prowedge, retrowedge, progradation, tectonic regimes

Introduction

It is known for a long time, that the Western Carpathians (WC) evolved as a northward-prograding thrust system during the Mesozoic (e.g. Andrusov, 1968; Mahel', 1974). However, the driving force for this progradation, or "polarity", has remained unexplored until the recent time. There are two possible solutions that should be considered nowadays. The first, "indentation" model relies on the tectonic plates motion framework within the Alpine-Carpathian-Mediterranean region, particularly on the well-constrained Apulia/Adria movement path relative to Europe. The second, "subduction" solution assumes a driving force exerted locally by a subducting slab. To test these hypotheses, I present a brief summary of the Mesozoic tectonic evolution of the WC, with the help of its tentative systematisation into regional tectonic events depicted in Fig. 1.

Tectonic evolution of a particular regional domain is usually interpreted in terms of deformation stages, which are time slices characterized by development of a mutually related (though not inevitably synchronous) set of tectonic structures having originated under corresponding P-T conditions, and deformation and stress regimes. However, in a majority of cases only the relative succession of deformation stages can be defined, as long as their "absolute" dating is seldom possible. Since the orogens do not deform uniformly, it becomes clear that, in principle, we cannot presuppose the structural succession reconstructed in one domain corresponds in time with the succession ascertained in any other domain, notwithstanding the morphology, kinematics and superposition of structural elements seem to correlate well. In reality, the sedimentary and other datable rock records provide evidence about the migration of orogen-scale tectonic processes, usually in one dominant direction. Consequently, the individual deformation stages in different domains cannot be directly correlated according to their successive position, but other criteria must be found to define the time equivalence of individual deformation stages given by various successive positions in diverse domains. These criteria might be: (1) geochronological data relevant to deformation events, if available at all; (2) lithostratigraphic criteria, especially at higher structural levels; (3) obvious continuity of particular, presumably coeval structures or regimes between neighbouring domains. The first two criteria have been already evaluated in numerous works (e.g. Plašienka, 1998, 1999 and references therein); the latter criterion is assessed in the following.

In addition to the deformation stages, the concept of regional tectonic phases is introduced here. The regional tectonic phase means a time episode of accentuated tectonic movements producing discernable deformation structures in the scale of the entire orogen, or at least in its substantial or decisive part. The tectonic phase may embrace one or more deformation stages in a particular structural domain, which are characterized by stable, or evidently continuously changing physical conditions (P-T estimates, stress field properties) and deformation mechanisms in that domain. Since various structural levels are exposed in an orogen, correlation and grouping of deformation stages into a regional tectonic phase may be ambiguous, especially for older stages. However, the combination of structural evidence with lithostratigraphic, magmatic, metamorphic and geochronologic rock record is very helpful and was successfully applied in a classification of regional tectonic phases, for instance in the Swiss Alps (Schmid et al., 1996; Froitzheim et al., 1997). One remark more – this view on the regional tectonic phases has little in common with the Stillean globally regarded tectonic phases, which should be abandoned definitely when a particular orogen or its part is being analysed.

Regional tectonic phases

The classification of the WC Meso- and Cenozoic regional tectonic phases is synoptically presented in Fig. 1. The intent is to show their approximate duration and regional extent, as well as their general character (compressional or extensional). The regional extent can be only schematically shown with the help of isotectonic zones, which are 3D regional units exhibiting a comparable tectonic history (succession of deformation stages being the principal criterion). It is clear, however, that this may be valid only for limited periods of time and the columns depicted in Fig. 1 cannot be regarded as constantly existing domains.

Colours in Fig. 1 essentially denote tectonic regimes. Pale tone indicates general regime inferred, the dark one symbolizes a culmination of the corresponding regime, i.e. the regional tectonic phase. Green tones represent late- to post-orogenic extension after a decline or complete cessation of convergence within a part of the WC orogen considered, blue colours denote pre-orogenic extension within the lower plate of the already established new convergence system. Large, bright green triangles designate the oceanic crust production. Yellow colour depicts synorogenic flysch sedimentation. Violet colours correspond to principal shortening phases, including subduction, collision, and thrust stacking. Red shades stand for extensional regimes within the active, temporarily collapsing orogenic wedge. White fields might be labelled “Hic sunt leones”, since reliable data are absent. Red balloons mean silicic plutonism, vertical lines mean dykes, and triangles symbolize volcanism. Red colour of the latter indicates acid, blue – intermediate and green – basic character. “A” is for alkaline or subalkaline, “CA” for calc-alkaline geochemistry. “WP” refers to within-plate basalts, “S” and “I” correspond to the respective granite typology. Red asterisks point to principal collision events. Circled numbers refer to local deformation stages. All this is a mere interpretation, sometimes more, sometimes less substantiated, of a huge amount of data sources produced over the past decades by numerous authors. It is not possible to quote either a fraction of them here; the readers are referred to Plašienka (1998, 1999) for at least a part of the data sources.

It is evident, that data about the pre- and post-orogenic distensional tectonic regimes come chiefly from the sedimentary, and partially from the magmatic rock record, whereas various regimes operating within the active WC orogenic wedge have been recorded predominantly by deformation structures. The sedimentary and structural records can be equally combined when the initial shortening phases at the toe of the prograding orogenic wedge are considered. Though the coincidence of tectonic events with important sea-level changes may have amplified the expressions of the former at certain time intervals, it is generally inferred that the tectonically driven surface subsidence and uplift intervals described below considerably exceed in magnitude (usually in one order, or even more) the eustatic effects. The following brief characterization of the individual regional tectonic phases discerned is based on this approach.

The Early Mesozoic rifting was preceded by significant distensional tectonic events during the Permian, indicated by rift-related red-bed basins and associated volcanism in several WC zones.

Duration of rifting-related silicic magmatism has been recently recognized to persist as late as the Middle Triassic (Fig. 1). The site of the future Meliata oceanic rift was marked by strong Scythian subsidence and shallow marine terrigenous sedimentation. These features indicate that the terminal Variscan event – orogenic collapse and lithospheric attenuation could have been genetically related to the early Alpine rifting in the southern CWC zones, which ultimately led to the Upper Anisian (Pelsonian) opening of the Meliata Ocean, which is designated as the **Žarnov Phase**. In units derived from areas adjacent to the Meliata rift, this event is indicated by a breakup unconformity between the Lower Anisian ramp and platform carbonates and Pelsonian red pelagic limestones.

The Jurassic was the time of extensive rifting of the northern, European passive margin of Tethys, which brought about drowning of Triassic carbonate platforms and finally led to disintegration of the European shelf crust into numerous elevated and subsiding domains, some of them presumably floored by a newly-formed oceanic crust. The Hettangian–Sinemurian **Zliechov Phase** led to a more-or-less uniform stretching of the epi-Variscan continental lithosphere and created broad subsiding intracontinental basins (Zliechov, Šiprúň, Kysuca-Czorsztyn-Magura) separated by narrower subaerial highs (South-, or High-Tatric and North-Tatric Ridges). The less distinct Toarcian **Devín Phase** was probably the main stage of extensional block tilting and coastal onlap.

The Bajocian **Krasín Phase** initiated asymmetric extension along the foreland-ward dipping lithospheric detachment fault. This brought about additional crustal extension in the Kysuca Basin and, finally, its probably Bathonian breakup and opening of the Vahic (South Penninic) Ocean. The Czorsztyn Ridge originated at the distal upper plate margin by thermal uplift above a subcrustal part of the detachment fault. The Berriasian – Valanginian **Walentowa Phase** marks further foreland-ward migration of rifting and records breakup of the Magura Ocean. The breakup was preceded by asymmetric rifting again. In this case the detachment fault is interpreted as hinterland dipping. Lithospheric extension and mantle upwelling triggered the second thermal uplift event of the upper plate Czorsztyn Ridge, which became separated by oceanic basins from both sides (Oravic ribbon continent).

The above defined rifting phases are culminations of long-lasting extensional and/or transtensional tectonic regimes operating either in the hinterland or foreland position with respect to the active orogenic front. The breakup of the Meliata Ocean occurred in a back-arc position relative to subduction of Paleotethys (e.g. Stampfli, 1996), while the other rifting phases represent events affecting exclusively the lower plate of the developing WC convergence system. Evidently, they were necessary to prepare the epi-Variscan crust, by its stretching and attenuation, and eventually by oceanic breakups, for extensive contractional deformation later. The contractional regimes operated within the growing orogenic wedge representing the upper plate of the Mesozoic WC convergence system and were accentuated by the following phases.

The oldest Alpine structural association related to a compressional event in the WC is fixed by a blueschist mineral assemblage in the Meliatic Bôrka Nappe. Its kinematics provide evidence for a southward (in present coordinates) subduction polarity. This association embraces probably two deformation stages and is older or partly coeval with the HP metamorphic event, constrained by white mica cooling ages to the Middle – Late Jurassic. It represents the subduction and then collision event after closure of the Meliata Ocean and is designated as the **Šugov Phase** herein (Fig. 1).

The collision event after closing of the Meliata Ocean halted development of the orogenic prowedge (in the sense of Beaumont et al., 1996) for some time and a phase of the retrowedge progradation occurred during the latest Jurassic – earliest Cretaceous. The WC retrowedge involves units of the Pelso composite terrane (Kovács et al., 2000) exposed mainly in the Transdanubian Range and Bükk Mts. In the Bükk Mts., the pre-Cretaceous termination of sedimentation (e.g. Kozur, 1991), the south-vergent nappe stacking and two ductile deformation stages (Csontos, 1999), and Early Cretaceous cooling ages (Árkai et al., 1995) define the **Bátor Phase**. In the Transdanubian Range, the Early Cretaceous SW-ward thrusting is indicated by the coarsening-upward synorogenic flysch sequence in the Gerecse Mts. (e.g. Tari, 1995), its climax is manifested by SE-directed retrothrusting during the Albian **Litér Phase**.

In mid-Cretaceous times, orogenic shortening returned to the prowedge and its immense growth and northward progradation took place in several phases during the Cretaceous and Tertiary. The wedge advanced by frontal and basal accretion of lower plate units attenuated by preceding rifting events. Only the upper crustal slivers were amalgamated with the orogenic wedge in the form of thick-skinned and thin-skinned thrust sheets, while the lower crust and the lithospheric mantle have been consumed by subcrustal subduction. The **Tuhár Phase** represents an emplacement of the Gemeric and uppermost Veporic thrust sheets over the central Veporic zones; it is poorly defined in time and kinematics, however. It is because this thrusting caused deep burial and consequent amphibolite-facies metamorphism, which obliterated earlier structures.

The **Solírov Phase** occurred during the Aptian – Early Albian in zones south of the Vahic Ocean and in front of the developing orogenic wedge. It is indicated by growth of Urgonian platforms on the former South-Tatric Ridge and by important tectonically driven resedimentation events around the North-Tatric Ridge. Both Tatric ridges were once more elevated from bathyal depths, which is interpreted as a contractional event generated by build-up of compressive stresses. Urgonian platforms were rapidly drowned during the Albian when the compressive stresses were temporarily relaxed.

The episodic frontal accretion includes the **Benkovo Phase**, through which the basement substratum of the wide Fatric Zliechov Basin was thrust under the Veporic thick-skinned thrust sheet in the Albian – Cenomanian. During the Senonian, shortening relocated to the northern Tatric edge, below which the Vahic oceanic crust was consumed within the **Selec Phase**. During the uppermost Cretaceous – earliest Paleogene **Jarmuta Phase**, units of the Oravic ribbon continent, presently constituting a substantial part of the Pieniny Klippen Belt, were accreted at the wedge toe. Then the orogenic front reached the Magura Ocean, which was consumed during the Paleogene and Early Miocene (Fig. 1).

In the course of its development, the WC orogenic wedge behaved as a self-organized mechanical continuum system maintaining the critical taper (see e.g. Platt, 1993). This implies that major frontal accretion and underplating events brought about thickening of the wedge and, consequently, its extensional collapse. As a result, the wedge became prone to additional shortening events that propagated from the wedge front backwards. The significant **Kohút Phase** affected the rear part of the wedge by orogen-parallel extension and exhumation of the Veporic metamorphic core complex during the Late Cretaceous (Janák et al., 2001). The exhumation was activated by underplating of buoyant Fatric crust below the wedge, which had been softened due to a thermal relaxation after the major thickening Tuhár Phase (Fig. 1). Already before, in the late Turonian, the superficial **Donovaly Phase** emplaced gravitationally the Fatric (Krížna) and Hronic (Choč) cover nappe system over the foreland Tatric Superunit. This phase reflects gravitational collapse of thin-skinned fold-and-thrust stacks that have developed in front of the orogenic wedge. The Kohút Phase was immediately followed by the **Besník Phase**, which denotes a gravity-driven emplacement event of the Silica cover nappe system (e.g. the Muráň Nappe directly overriding the Veporic core complex).

The Late Cretaceous collapse of the wedge enabled its additional internal shortening during the latest Cretaceous – earliest Paleogene **Miglinc Phase**, which reflects a retro-propagation of the Jarmuta Phase due to a collisional event between the wedge toe and the Oravic ribbon continent after closure of the South Penninic-Vahic Ocean. The Miglinc Phase is recorded by important fore- and back-thrusting structures within transpressional zones (e.g. the flower structures of the Slovenský raj and Slovenský kras megasynforms) and by oblique-slip fault zones (e.g. the Muráň fault). During the Tertiary, the collapse (**Súľov Phase**, which denotes foundation of the Central Carpathian Paleogene Basin) and shortening (Early Miocene **Kamenica-Šumiac Phase** deforming the Paleogene sediments) periods repeated within the wedge. However, the WC orogenic wedge lost the character of the mechanical continuum by the Middle Miocene and was extended by whole-lithosphere stretching triggered by a change from the advancing to retreating oceanic subduction in its front (Kováč, 2000). Therefore the Badenian **Alföld Phase** is interpreted as a hinterland, i.e. back-arc extensional event (Fig. 1).

Discussion and conclusion

The glance at the chart in Fig. 1 invokes one important implication – for a long time interval (about 80 Ma) from the Early Jurassic up to the Early Cretaceous, distinctly different tectonic regimes operated in the WC. The foreland lower plate was subjected to distensional tectonic regimes concentrated into several strong rifting phases. Contemporaneously, the pro- and retro-prograding orogenic wedge underwent contractional tectonic regimes. This would indicate either that (1) the extensional and contractional domains experienced differing tectonic histories, they had originated in remote places and came closer later on; or (2) they evolved in one system driven by one stress source, presumably by the subduction slab pull. It is hypothesized that the latter possibility was the case, whereby the Meliata slab pull exerted tensile force on the attached surface WC plate. After the Meliata Ocean closure, subcrustal mantle subduction continued and transmitted both the compressive force towards the overriding orogenic wedge and still the tensile force on the foreland lower plate. If this were valid, then the answer to the problem put forward in the introduction would be that "subduction" model governed the WC evolution during the Jurassic and Early Cretaceous. It is because the "indentation" model is not consistent with decoupling and autonomous stress regimes between the wedge and its foreland, it does not account for extension in front of the advancing indenter, and it contradicts to a considerable widening of the orogenic wedge at that time. On the other hand, these characteristics can be well explained by the mantle subduction model.

Nevertheless, the overall tectonic scenario changed dramatically in mid-Cretaceous times. The lower plate extension ceased (including probably also spreading of oceanic domains) and compressional stresses were temporarily transmitted far north to cause distinct inversion events on the foreland North European Platform during the Late Cretaceous and Paleogene (e.g. Ziegler et al., 1996). At the same time, the Adria movement vector changed from the SE to the N-NW direction (e.g. Savostin et al., 1986). Accordingly, it is inferred that by mid-Cretaceous times also the WC convergence system changed from the "subduction" to the "indentation" model. This timedependent behaviour of the WC orogen from subduction to indentation-controlled is consistent with predictions from forward mechanical modelling of collisional orogens (Ellis, 1996).

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Fig. 1. Tectonostratigraphic chart of the Western Carpathians. For a detailed explanation see the text.