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Revisiting the (pre-Variscan) Galatia/Ligeria – Armorica terrane conception from an Austrian perspective

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Abstract

According to the original Galatia/Ligeria-Armorica terrane model, almost all pre-Variscan units in Austria (i.e., in the Alps as well as in the Bohemian Massif) were part of the Galatian/Ligerian microplate. We raise arguments against this interpretation based on a lithological and geochronological comparison of key regions (southern Bohemian Massif, Alps, Massif Central). We propose that the (non-Avalonian) parts of the southern Bohemian Massif actually belong to the Armorican microplate. A Trans-Mid-European belt of Upper Devonian ophiolite remnants and coeval primitive arc granitoids strikes from the northern Massif Central over the southern Vosges and the southern Black Forest onto the basement under the northern front of the Alps. It is interpreted as remnant oceanic and island-arc-type crust that marks the boundary between the Armorican and the Galatian/Ligerian terrane. Like most previous authors, we consider Armorica to be a Cadomian/Early Palaeozoic peri-Gondwana terrane that originated in the fore field of the Sahara metacraton and the West African craton. However, Galatia/Ligeria can be interpreted as Cadomian/Early Palaeozoic peri-Gondwana crust that formed farther east in front of the Arabian-Nubian Shield. After their Devonian off-drift from Gondwana, the two terranes approached each other and finally collided during the Variscan orogeny.

1. Introduction

In most reconstructions of Pangea, the pre-Permian rocks in Austria are restored in the southern half of the freshly consolidated Variscan orogeny, but their palaeo-plate-tectonic fate during, and prior to the Variscan orogeny is illusive and needs further investigation. In the widely cited palaeogeographic model of von Raumer et al. (2013), the intra-Alpine units and the southern Bohemian Massif (except the Avalonia-derived Moravian and Drosendorf units) are interpreted as constituents of the Galatian/Ligerian terrane and defined as peri-Gondwana crust that detached from NE Gondwana in the Devonian (Fig. 1). Rift-related destabilization of this part of Gondwana already began earlier in the Ordovician (late Cambrian?), more or less synchronously with the opening of the Rheic ocean. A marginal Hun terrane may have left Gondwana in the direction of N China at that time, opening the eastern Rheic ocean. Intraoceanic subduction zones and related arcs (termed "Ligerian arcs") probably formed in this eastern Rheic realm during the Silurian, causing convergence and obduction of oceanic material onto more proximal Gondwana crust. Later, in the Lower Devonian, the eastern Rheic started to be subducted under Galatia. This finalized the birth of the composite Galatian/Ligerian terrane in front of east Gondwana (see Fig. 7 in von Raumer et al., 2013). After its detachment from main Gondwana during the Devonian (opening of the Palaeotethys), Galatia/Ligeria approached and finally

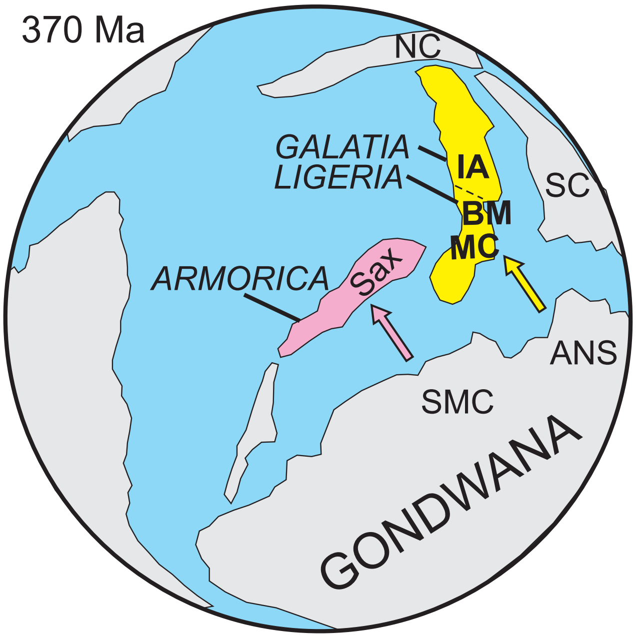

Fig. 1: Schematic representation of the Armorica-Galatia/Ligeria terrane model as proposed by von Raumer et al. (2013) for the middle Devonian (Early Frasnian). The Galatian/Ligerian terrane (yellow) represents peripheral Gondwana crust that detached from NE Gondwana during the opening of the Palaeotethys. The Armorican terrane (pink) represents crust that detached from the North African Gondwana sector (SAX=Saxothuringian). The Ligerian sector of the Galatian/Ligerian terrane includes the Massif Central (MC) and the (non-Avalonian parts of the) Southern Bohemian Massif (BM). The Galatian section of the Galatian/Ligerian terrane includes intra-Alpine units (IA). Armorica and Galatia/Ligeria approached and collided during dextral transpression in the Carboniferous. Further abbreviations: NC=North China, SC=-South China, ANS=Arabian-Nubian Shield, SMC=Sahara Metacraton.

collided with Armorica, an independent Peri-Gondwana microcontinent derived from the North African Gondwana sector (Fig. 1). This terrane collision was a major event during the Variscan orogeny.

Late- to post-collisional (Carboniferous-Permian), dextral, strike-slip movements have later split the Galatian/Ligerian terrane into a northern Ligerian block and a southern Galatian block (see tectonic sketches in von Raumer et al., 2013). The Ligerian block comprises, according to von Raumer et al. (2013), the Massif Central and the main (Moldanubian) parts of the Vosges, Black Forest and Bohemian Massif. The Galatian block is mainly represented by the intra-Alpine basement units. The present day north-south arrangement of the Bohemian Massif and the intra-Alpine, pre-Permian units may, thus, principally have existed since the Pangea period, although further lateral displacements during the opening and closure of the Alpine oceans did certainly occur.

The scenario outlined above is based on von Raumer et al. (2013). Finger and Riegler (2022) deviated somewhat from this interpretation and tentatively proposed a first-order terrane boundary between the Bohemian Massif and the intra-Alpine units, based on a chain of Upper Devonian-aged, mantle-magmatic rocks that can be traced from the northern Massif Central over the southern Vosges into the basement of the Alps and further into the West Carpathians (Fig. 2, Tab. 1). Finger and Riegler (2022) also speculated that these mantle-derived magmatic rocks could represent a rift zone inside the Gondwana margin that gave rise to the birth of different pre-Variscan terranes. They surmised that the closure of this rift zone finally ended up in the dextral East Variscan Shear Zone.

In this paper, we attempt a more detailed interpretation of the Trans-Mid-European, Upper Devonian, mantle-sourced magmatic zone within the framework of the Armorica – Ligeria/Galatia terrane model of von Raumer et al. (2013), as we consider this model as one of the strongest approaches for restoring the early Palaeozoic evolution of central Europe. In order to accommodate this Upper Devonian magmatic structure, the model of von Raumer et al. (2013), however, must be modified to some extent; specifically, the southern Bohemian Massif (except its Avalonia-derived part, i.e., the Moravian and Drosendorf units) is reinterpreted as Armorican crust and not as NE Gondwana derived Galatian/Ligerian crust.

Updated descriptions of the aforementioned belt of Upper Devonian mantle-sourced magmatic rocks are provided below. The following brief lithological and geochronological comparison between the southern Bohemian Massif, the intra-Alpine pre-Permian units and the French Massif Central provides a context for the interpretation of these rocks and tests the Armorica-Ligeria/Galatia terrane model of von Raumer et al. (2013).

2. The Trans-Mid-European Upper Devonian magmatic belt

The existence of this magmatic belt (Tab. 1, Fig. 2) was proposed by Finger and Riegler (2022) and is based mainly on two observations:

(1) There is a striking similarity between the so-called Cetic granitoid boulders (Frasl and Finger, 1988) in the Austrian Flysch and Helvetic units (which represent basement related to the European plate) and the Limousin granitoids in the northern Massif Central: In addition to their similar Frasnian to Famenian age (Thöni, 1991; Shaw et al., 1993; Humer and Finger, 2006), granitoids in both places have an unusual primitive chemical and isotopic composition (Finger et al., 1997; Berger et al., 2024). This feature distinguishes the Cetic and Limousin granitoids from the main mass of mainly crustal-derived Variscan granitoids in the Moldanubian and the Alps (see Finger et al., 1997). Based on the most recent data (Berger et al., 2024), the Limousin granitoids are slightly (approximately 10 Ma) younger than the Cetic granitoids (ca. 360 vs. ca. 370 Ma).

(2) According to Faure et al. (2009, and references therein), the Limousin granitoids intruded approximatively coeval with the opening of a nearby oceanic rift in

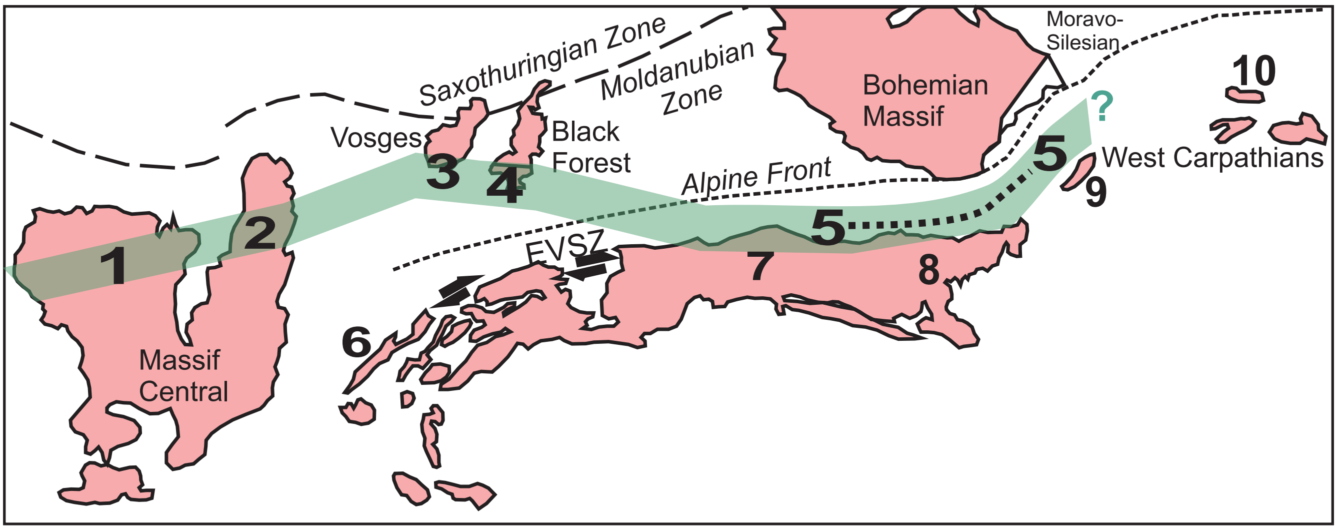

Fig. 2: Location of Upper Devonian ophiolite remnants and approximatively coeval primitive arc magmas in Austria and neighbouring areas. See text and table 1 for additional information.

the Brevenne region. Importantly, the same association of ophiolitic rocks and primitive arc granitoids of Upper Devonian age is encountered in the southern Vosges and the southern Black Forest (Skrzypek et al., 2012; Hann et al., 2003). Exotic mafic and ultramafic rocks associated with the Cetic granitoids (Vielreicher, 1991; Zirkel, 1957) could be Upper Devonian ophiolite remnants, but there are no age data available. In addition, hidden (only aero-geophysically identified) ultramafic bodies under the northern Alpine front (Blaumoser, 1992) could also be remnants of Upper Devonian ophiolites that belong to the basement of the European plate. The proposed Upper Devonian ophiolite zone can possibly be further traced in subcrop of the Outer Western Carpathians, where abundant chromspinel detritus in Paleogene sedimentary rocks has been interpreted to indicate a buried Palaeozoic ophiolite source (Winkler and Slaczka, 1992).

It should also be noted that potential remnants of oceanic crust of Upper Devonian age have been reported from the Belledonne Massif (Guillot and Ménot, 2009; von Raumer et al., 2009). Considering that these rocks were likely shifted westwards along the East Variscan Shear Zone (Fig. 2), they could possibly be restored to the east of the Cetic occurrences.

Furthermore, Upper Devonian ophiolite remnants are reported from the basement of the Adriatic plate, e.g., from the Austroalpine Defreggen and Sieggraben areas (Neubauer et al., 2022; Putiš et al., 2024), or the High Tatra (Burda et al., 2021) and the Pezinok area (Putiš et al., 2009) in the West Carpathians (Fig. 2). Neubauer et al. (2022) have recently related these occurrences to a Carpathian-Balkan ocean. Interestingly, mantle-derived I-type granitoids, chemically and in age similar to the Cetic and Limousin granitoids, have been reported from the West Carpathians by Burda et al. (2013). It is, thus, tempting to speculate that an eastern continuation of the Brevenne-Cetic magmatic belt is recorded in the Adriatic plate. Taking the late Variscan dextral wrenching regime (Arthaud and Matte, 1977) and the potential effects of the Alpine tectonogenesis into consideration, these Adriatic units were possibly shifted far westwards relative to their counterparts in the European plate.

3. Comparing the early crustal evolution of the Southern Bohemian Massif and the Alps

This comparison excludes the Brunovistulian rocks in the SE Bohemian Massif (Friedl et al., 2000, 2004; Kroner and Romer, 2013; Lindner et al., 2021), because they are not claimed to be part of Galatia/Ligeria by von Raumer et al. (2013). Therefore, we focus on the Gföhl, Raabs, Ostrong and Bavarian units of the Southern Bohemian Massif (SBM). If von Raumer et al. (2013) are correct and the latter units were indeed part of the Galatian/Ligerian terrane, a widely sympathetic pre-Variscan crustal evolution could be expected with the intra-Alpine units. However, there are a number of marked geological differences between the two terrains, the most important of which are:

(1) The non-Avalonian parts of the SBM expose several remnants of a relatively mature Ediacaran granitoid crust (see Tab. 2), which point to an Andean-type continental-arc to ensialic back-arc basin setting (Teipel et al., 2004). In contrast, the preserved Precambrian remnants in the Alps are almost exclusively mantle-derived mafic rocks of Ediacaran age (Tab. 2). The initial stages of crustal evolution in the Alps, therefore, are consistent with an island-arc or fore-arc environment with either no or only a thin layer of continental crust beneath. Magmatism in the Austrian Alps apparently changed somewhat in the Eocambrian/Cambrian in that felsic (granitic) intrusions became relatively more common. These, however, represent mainly A-type and I-type melts (Müller et al., 1996; Huang et al., 2021; Reiser et al., 2024) and do not seem

Tab. 1: Exposures that are considered to define the Trans-Mid-European Upper Devonian Magmatic Belt (see figure 2).

Location (numbers as shown in figure 2)	Relevant literature
Massif Central	
1) Limousin arc-type granitoids and ophiolite remnants	Shaw et al. (1993), Berger et al. (2024), Faure et al. (2009) and references therein
2) Brevenne ophiolite and Morvan arc	Pin and Paquette (1998), Faure et al. (2009) and references therein
Vosges and Black Forest	
3) Ophiolite remnants in the southern Vosges	Skrzypek et al. (2012)
4) Arc-type granitoids in the southern Black Forest	Hann et al. (2003)
Alps/Carpathians	
5) Granitoid and mafic exotics from Cetic Massif/Helvetic basement	Frasl and Finger (1988), Zirkel (1957), Vielreicher (1991), Thöni (1991), Humer and Finger (2006)
6) Mafic/felsic bimodal magmatic rocks in the Belledonne Massif	Guillot and Ménot (2009); Von Raumer et al. (2009)
7) Metagabbro, northern Defreggen Complex	Neubauer et al. (2022)
8) Eclogite gneiss, Sieggraben ophiolite, Austroalpine Unit	Neubauer et al. (2022), Putiš et al. (2024)
9) Metagabbro/Dolerite, Pernegg group, Tatric Unit	Putiš et al. (2009)
10) Amphibolites and arc-type granitoids from the High Tatra	Burda et al. (2013, 2021)

to indicate a mature continental source. Overall, the Galatian/Ligerian crust was probably still fairly thin at that time. According to Putiš et al. (2009), some thicker pieces of a Cadomian continental crust are perhaps present in the West Carpathians.

(2) A widespread phenomenon in the intra-Alpine region is Cambro-Ordovician bimodal (felsic-mafic) volcanism (Neubauer et al., 2022). Such rocks have not been recorded in the SBM. Note, most amphibolites of the SBM have recently been constrained to be Ediacaran and not Cambro-Ordovician in age (Teipel et al., 2004; Mayer et al., 2024).

(3) There is increasing evidence for an important Ordovician (Cambro-Ordovician?) orogenic event with subduction-type metamorphism in the Alps (the Cenerian orogeny of Zurbriggen, 2015). In contrast, the SBM was under extension at this time and likely part of a hyperextended passive margin setting (Linnemann et al., 2004; Žák et al., 2023). It must be mentioned here that there are also extension-related rocks of Ordovician age in parts of the Alps (e.g., Nievoll et al., 2022) that Finger and Riegler (2023) argued could represent proximal parts of Galatia/Ligeria in the sense of a syn-Cenerian back-arc rift zone.

(4) Detrital zircon geochronology shows a clear Gondwana heritance in both the Alps and the southern Bohemian Massif, with abundant zircons of Late Proterozoic (Panafrican) age (e.g., Kosler et al., 2014; Stephan et al., 2019; Haas et al., 2020). However, when we look at pre-Panafrican detrital zircons, there is a significantly greater ratio of Tonian/Stenian (0.72–1.2 Ga) relative to Palaeoproterozoic (1.6–2.5 Ga) aged zircons in the Alps. The ratio of Tonian/Stenian to Palaeoproterozoic zircons (TS/PP ratio) is typically <0.3 in the Bohemian Massif and commonly (although not everywhere) >0.3 in the Alps, which suggests a different continental hinterland (Finger and Riegler, 2023).

4. Comparison of the Austrian Moldanubian unit with the French Massif Central

The southern Bohemian Massif has been traditionally correlated with the central parts of the Schwarzwald, the Vosges and the Massif Central, subsumed under the term Moldanubian Zone (Kossmat, 1927; Zwart and Dornsiepen, 1981). This "Moldanubian correlation" plays a crucial role, not only in the Galatia/Ligeria-Armorica terrane model of von Raumer et al. (2013), but importantly in all prominent tectonic models for the Variscides (e.g., Franke, 2000). As such, this correlation is revisited here.

The original definition of the "Moldanubicum" mainly included high-grade metamorphic rocks and Variscan granitoids. These high-T Moldanubian rocks are of Carboniferous age. However, almost no parallels can be drawn between the pre-Carboniferous evolution of the Massif Central domain and the southern Bohemian Massif. Lardeaux et al. (2014), for example, emphasized that the Massif Central comprises an accretionary wedge that formed prior to the mid Devonian. No analogue to this relatively old accretionary system exists in the Bohemian Massif. The main phase of HP to MP collisional metamorphism in the French Massif Central is dated at Silurian to Lower Devonian. In contrast, the metamorphic evolution of the southern Bohemian Massif is almost entirely Early Carboniferous in age, perhaps with a minor Late Devonian precursor phase (Sorger et al., 2020). To date, Silurian-Lower Devonian metamorphic events have not reliably been documented in the Moldanubian sector of the southern Bohemian Massif.

Tab. 2: Summary of Precambrian events recorded in the Austrian Alps and the southern Bohemian Massif (Avalonian units not considered).

Lithology	Reference	Protolith, Age	Isotopic maturity
Southern Bohemian Massif			
Weitendorf gneiss, Raabs Unit	Frank et al. (1990)	S-type Granite, ca. 600 Ma	$^{87}Sr/^{86}Sr_i$=0,714
Amphibolites, Raabs Unit	Mayer et al. (2024)	MORB and ARC-type basalts, 580-650 Ma	
Leonfelden orthodiatexite, Bavarian Zone	Unpubl. Univ. Salzburg data	S-type granite, 559 ± 3 Ma	
Kfsp orthogneisses, Bavarian Zone	Teipel et al. (2004)	Crustal-derived granites/rhyolites, ca 550 Ma	eNd_i -1,7 to -4,6
Amphibolite, Bavarian Zone	Teipel et al. (2004)	Basalt (back-arc), ca. 550 Ma	eNd_i 1,2
Alps			
Metadiorite, Silvretta	Schaltegger et al. (1997)	Diorite (island arc), 609 ± 3 Ma	eNd_i +6,4
Eclogite, Silvretta	Schaltegger et al. (1997)	Basalt (MORB), ca. 620 Ma	eNd_i +7.1
Banded amphibolite, Hohe Tauern	Von Quadt (1992)	Basalt (MORB), ca. 650 Ma	eNd_i +1,2 to +4,7
Metaharzburgite, Speik Complex	Melcher and Meisel (2004)	Harzburgite, ca. 550 Ma	
Metagabbro Speik, Complex	Melcher and Meisel (2004)	Gabbro, ca. 550 Ma	eNd_i +0,7
Eclogitic amphibolite, Defreggen	Schulz et al. (2004)	N-MORB, ca. 590 Ma	
Hbl-Pl gneiss, Defreggen	Schulz et al. (2004)	Andesite (island arc) ca. 550-530 Ma	

In addition, clear lithological differences are apparent in the Early Palaeozoic magmatic evolution: In the Massif Central, a prominent bimodal magmatic association (leptinite-amphibolite formation) of Ordovician age is widespread (Faure et al., 2009). Such rocks are rare or absent in the Austrian part of the southern Bohemian Massif (see last section). Also, Devonian basic magmatism and granitic magmatism is lacking in the southern Bohemian Massif, whereas they are characteristic for the Massif Central (Faure et al., 2009). It is also striking that both massifs have completely different tectonic positions in the Variscan plate tectonic framework: in contrast to the Massif Central, the Moldanubian part of the southern Bohemian Massif directly borders Avalonian crust (Moravian and Drosendorf units, Brunovistulicum) (Finger et al., 2000).

The scarcity of detrital Tonian-Stenian relative to Palaeoproterozoic zircons in the Moldanubian part of the southern Bohemian Massif (Finger and Riegler, 2023) is comparable to the North-African Gondwana sector (Sahara Metacraton). In contrast, relatively abundant detrital Tonian-Stenian zircons have been reported from the Massif Central (Padel et al., 2017; Couzinié et al., 2019), consistent with a NE Gondwana ancestry as proposed by von Raumer et al. (2013).

Lastly, it is important to note that the Variscan (Visean-Namurian) high-T evolution recorded in HP-HT granulites, LP-HT granulites and high-T granitic magmatism (Durbachites and Weinsberg-type granitoids) is not strictly confined to the Moldanubian Zone. Similar rocks are also reported from neighbouring areas such as the Saxonian Granulitgebirge (Rötzler and Plessen, 2010), the Erzgebirge (Tichomirowa et al., 2001), the External Massifs in the Alps (von Raumer et al., 2009), the Tauern Window (Vesela et al., 2011), the Montagne Noire (Roger et al., 2020), Sardinia and Corsica (Rossi et al., 2009). Together with the Moldanubian, these areas seem to define a relatively young subdomain in the Variscan orogen with a particularly strong mantle heat flow during the Carboniferous (von Raumer et al., 2014). This Moldanubian and peri-Moldanubian high-heat-flow domain is essential in the reconstruction of Pangea palaeogeography (see discussion section), but it has, as a syn- to post-collisional feature, little relevance for Variscan terrane models. By no means can it be taken to support a pre-Variscan terrane relationship between the southern Bohemian Massif and the Massif Central.

5. Lithological comparison of the intra-Alpine basement with the French Massif Central

If the pre-Permian intra-Alpine crust and the Massif Central were part of the same terrane (Ligeria/Galatia), they should share a similar Early Palaeozoic crustal evolution. Based on the valuable data compilation by Neubauer et al. (2022) for the Austroalpine and the review paper by Faure et al. (2009) for the French Massif Central, the following similarities are compelling. They have been emphasized also, at least in part, in earlier work (e.g., Putiš et al., 2009). Both terrains have:

- a scarcity of Precambrian rocks (in difference to the Bohemian Massif and Armorica);
- a high concentration of acidic and bimodal magmatic formations of Ordovician age, which locally have a distinct alkaline character;
- evidence of Early Palaeozoic crustal extension, which is proposed to have resulted in the formation of small oceanic basins;
- widespread late Devonian – Early Carboniferous Barrovian metamorphism; and
- a high abundance of late Devonian – Early Carboniferous granitic intrusions.

Conversely, notable differences are also evident:

- Traces of the Silurian HP metamorphic event, which is significant in the Massif Central, have yet to be recognised in the Eastern Alps.
- Early Carboniferous HP metamorphism is reported in the Alps, but only rarely so in the French Massif Central.
- Documented effects of a Cenerian (Ordovician) metamorphic event are common in the Alps, but are lacking in the French Massif Central.

In summary, there are similarities in the Early Palaeozoic evolutions of the Massif Central and the intra-Alpine units, but there are significant differences as well.

6. Discussion

6.1. The necessity for a re-definition of the Galatian/Ligerian terrane

There are three main arguments why we should consider the southern Bohemian Massif (except the Avalonia-derived Moravian and Drosendorf units) as crust related to the N-African Gondwana sector, i.e., as Armorica, and not as part of Ligeria/Galatia. The first refers to the lithological and geochronological differences that exist between the southern Bohemian Massif and the Alps in the Early Palaeozoic (see section 3). Second, the Upper Devonian, mantle-sourced, magmatic rocks under the northern front of the Alps suggest the existence of a terrane boundary (Finger and Riegler, 2022). Third, detrital zircon geochronology supports a primary connection between the southern Bohemian Massif and the Saxothuringian crust (Finger and Riegler, 2023; and further references therein). We also concur with Zeh et al. (2024) that the Moldanubian parts of the Black Forest and Vosges are Armorican crust, and the rocks to the south represent a boundary zone to Ligeria/Galatia (Fig. 2).

In the Alps, the Armorica-Galatia/Ligeria boundary is obscured by the East Variscan Shear Zone (Tauern Window, French and Swiss External Massifs, Sardinia). In fact, parts of the East Variscan Shear Zone could be a complex tectonic melange that includes marginal crust of Armorica and Galatia/Ligeria as well as Upper Devonian ophiolitic and island arc rocks.

If we are ready to accept the theory that the plate boundary between Armorica and Galatia/Ligeria is spiked with Upper Devonian mantle rocks, then a problem arises with the interpretation of the Upper Devonian oceanic rocks in the West Carpathians and the Austroalpine Unit. An interpretation of these rocks (the Carpathian-Balkan oceanic suture of Neubauer et al., 2022) as marking the boundary between Armorica and Galatia/Ligeria would imply that substantial parts of the Austroalpine and West Carpathian (in particular the Tatric) basement would belong to Armorica and not to Galatia/Ligeria (see the geological profiles in Putiš et al., 2009; Neubauer et al., 2022). Alternatively, the Carpathian-Balkan ocean could be a single oceanic rift in Galatia/Ligeria. We will come back to this issue in section 6.5.

6.2. Ancestry and key evolution stages of the Galatian/Ligerian crust

Research on the Galatian/Ligerian terrane is still in its infancy compared to the relatively well-studied extra-Alpine Variscides (see e.g., the works of Zulauf, 1997; Franke, 2000; Franke et al., 2017; Schulmann et al., 2014). The so far published scenarios are strongly regionally focused and only moderately consistent with each other. They are mainly based on local observations in the Polish Tatra Mountains (Burda et al., 2021), the Slovak part of the West Carpathians (Putiš et al., 2009), the Austroalpine units (Schulz et al., 2008; Mandl et al., 2018; Haas et al., 2020; Neubauer et al., 2022), the Swiss and French External Massifs (von Raumer et al., 2009) and the Southern Alps (Zurbriggen et al., 1997). Considerably more work is needed to construct a unified evolution model for Ligeria/Galatia. However, there are three key aspects, where a consensus is slowly beginning to emerge:

6.2.1. The Saudi-Arabian connection

Typical Gondwana zircon populations are reported in many intra-Alpine Palaeozoic metasedimentary units with large abundances of late Proterozoic (Panafrican) zircons, a wide Mesoproterozoic gap between 1.2 and 1.6 Ga and a variable number of Palaeoproterozoic and Archaean zircons (Siegesmund et al., 2023; Chang et al., 2021; and further references therein). Based on the mostly high proportions of Tonian-Stenian zircons, Finger and Riegler (2023) proposed a palaeogeographic proximity between the Alpine basement and the Arabian-Nubian Shield. A new detrital zircon study on Cambro-Ordovician, clastic, cover, sedimentary rocks from Saudi-Arabia (Yeshanew et al., 2024) further supports this "Saudi-Arabian trace". When comparing the data published therein with those from Early Palaeozoic Alpine metasedimentary units, significant similarities emerge with regard to both the zircon age distribution and the εHf variation (cf. e.g., see Fig. 14 in Chang et al., 2021). The most remarkable parallels are: (i) the ratio of Ediacaran zircons relative to Cryogenian plus Tonian/Stenian zircons (E/CTS ratio) is typically around 1; (ii) the ratio between Tonian/Stenian and Palaeoproterozoic zircons (TS/PP ratio) is relatively high (>1 in the Saudi-Arabian sedimentary rocks and many Alpine samples; see Finger and Riegler, 2023); and (iii) the late Neoproterozoic zircons record a similar range of positive and negative εHf values between ca. +15 and -30 (outliers neglected). A characteristic scarcity of zircons with negative εHf values is observed between 0.68 and 0.78 Ga (see the diagrams and Fig. 7 in Yeshanew et al., 2024; for the Alps see Fig. 14 in Chang et al., 2021).

Following Meinold et al. (2021) and Yeshanew et al. (2024), we envisage a sediment superfan of Early Palaeozoic age transported erosional material with this very distinct zircon spectrum from the East African Orogen into Saudi-Arabia and the nearby Galatian/Ligerian segment of Gondwana. Note that Ordovician sandstones of the Armorican terrane, that likely contain detritus from the North and West African cratons, show a differ-

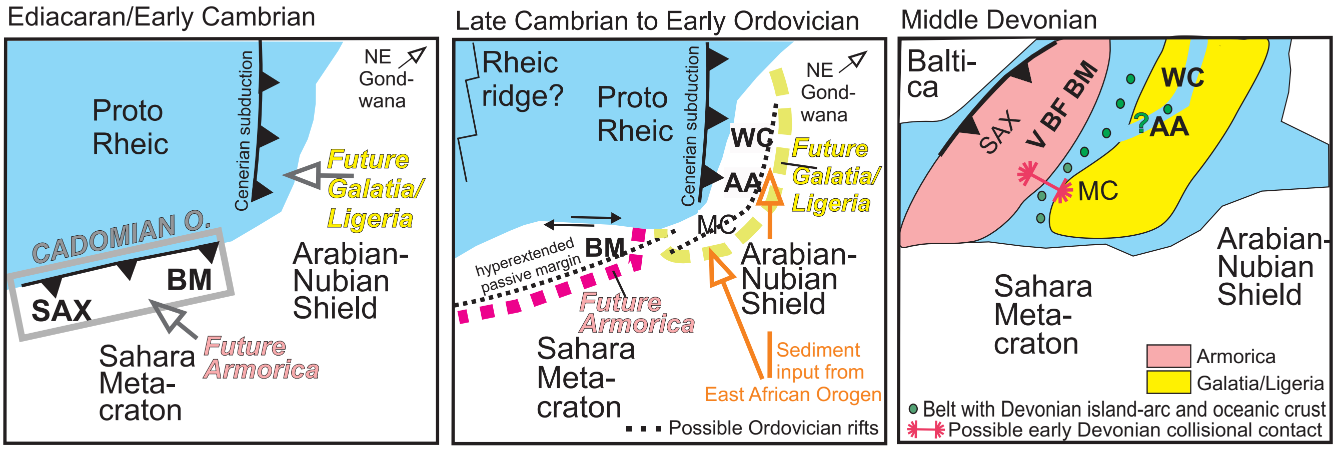

Fig. 3: Schematic representation of the major evolution stages of Galatia/Ligeria based on von Raumer et al. (2013). Modifications are based on this study, Finger and Riegler (2023), Franke et al. (2017) and Neubauer et al. (2022). Galatia/Ligeria is mainly represented by intra-Alpine basement (AA=Austroalpine, WC=West Carpathians) and the Massif Central (MC). In contrast to the model of von Raumer et al. (2013), the Bohemian Massif (BM) is here considered to be an Armorican element, as is most of the Black Forest (BF) and the Vosges (V). The early evolution of Galatia/Ligeria likely took place in an island-arc setting ahead of the Arabian Nubian Shield (left sketch). Voluminous sediment input from the East African Orogen and the effects of the Cenerian orogeny caused further crustal growth and a "continentalization" of Galatia/Ligeria during the Cambro-Ordovician (middle sketch). Ophiolitic rocks and mantle-derived arc-granitoids formed in the Upper Devonian between the Armorican and the Galatian/Ligerian terrane and were eventually also emplaced along a rift zone within the latter (right sketch). See main text for further explanations.

ent Precambrian zircon age range with a TS/PP ratio of <0.3, commonly even <0.1. In addition, the Ediacaran and Cryogenian zircons in these sandstones are on average more evolved with regard to their Hf isotopic signature than their age analogues in Saudi-Arabia (Linnemann et al., 2014; Lin et al., 2019).

6.2.2. The Early Palaeozoic "continentalization" of Galatia/ Ligeria

Unlike Armorica, Galatia/Ligeria includes only rare remnants of Precambrian rocks. These commonly represent an isotopically primitive, mafic to intermediate, oceanic or island-arc crust associated with the proto-Rheic (proto-Tethys) ocean. The "continentalization" of the Galatian/ Ligerian terrane (i.e., its evolution from a mainly oceanic/ island-arc crust to a thick continental crust) was obviously greatly accelerated in the Early Palaeozoic, when mature crustal material was introduced via the sedimentary material that came from the East African orogen. A thick layer of granitic and granulitic continental crust began to form in Galatia/Ligeria when this sedimentary material underwent anatexis during the Cenerian orogeny. The latter process is well recorded in the abundant S-type granitoids and rhyolites with an Ordovician protolith age (e.g., Schindlmayr, 1999; Nievoll et al., 2022; for more references see data compilation in Neubauer et al., 2022).

6.2.3. The Cenerian Orogeny as a specific feature of Galatia/ Ligeria

In the Eocambrian, subduction processes dominated along almost the entire North Gondwana margin (Dörr et al., 2002; Nance et al., 2008) and in both the Armorican and Galatian/Ligerian Gondwana segments. However, Armorica and Galatia/Ligeria record a contrasting Cambrian/Ordovician history (Fig. 3). In Armorica, a hyperextended passive margin started to develop at that time (Linnemann et al., 2004; Žák et al., 2023), whereas a compressional Ordovician orogenic event with Barrovian metamorphism (the Cenerian Alaskan-type orogeny of Zurbriggen, 2015) is recorded in many parts of Galatia/ Ligeria (see e.g., the recent work of Petrik et al., 2024, and further references therein). Finger and Riegler (2023) considered the Cenerian orogen as a local orogenic zone that lay ahead of the Arabian-Nubian Shield, perpendicular to the more western Armorican Gondwana segment (see sketch in Fig. 3). In this zone, subduction of proto-Rheic oceanic crust continued and contributed to the formation of the Cenerian Orogen. A number of proto-Rheic oceanic and island arc rocks possibly became obducted during that period (von Raumer et al., 2015). Whereas the proto-Alpine rock units, that lay close to the Cenerian subduction zone were under Cenerian compression, coeval extensional (back-arc) basins (Nievoll et al., 2022; Neubauer et al., 2022) could have opened in the direction of Gondwana. Whether these basins reached an oceanic stage and whether they can be correlated with the so-called Massif Central ocean of Matte (2001) is controversial. At the end of the Cenerian orogeny, slab-role-back may have set the stage for enhanced crustal extension in Ligeria/Galatia.

6.3. The situation in the Upper Devonian

The Trans-Mid-European belt of Upper Devonian ophiolite remnants and primitive arc granitoids can be integrated into the model of von Raumer et al. (2013) if interpreted as an intra-oceanic island arc/back-arc-basin complex between Armorica and Galatia/Ligeria (Fig. 3). This scenario would require, however, that the Moldanubian parts of the Southern Bohemian Massif, the Black Forest and the Vosges are re-interpreted as Armorican crust (section 6.1). In this context, a new paper by Zeh et al. (2024) is highly relevant. Zeh et al. (2024) studied metasedimentary rocks from the southern Black Forest (Wiese-Werra gneiss), which were obviously deposited in the oceanic interspace between Armorica and Galatia/Ligeria in the Devonian. Zeh et al. (2024) found many detrital zircons with a ca. 370 Ma age and a positive εHf signature in the Wiese-Werra samples. These zircons indicate an isotopically primitive granitoid source comparable to the Limousin and Cetic massifs. The work of Zeh et al. (2024) not only corroborates the existence of an elongate, mantle-derived, subduction-related, granitoid belt between Ligeria/Galatia and Armorica, but also gives crucial information on how this magmatic system evolved. Importantly, Silurian to Ordovician zircons with a suprachondritic Hf isotope ratio were also found with the ~370 Ma zircons in the Wiese-Werra samples, suggesting a long-lived island arc setting (Zeh et al., 2024).

In the intra-Alpine units extension prevailed during the Silurian (Neubauer et al., 2022), and evidence for Silurian, subduction-type magmatism is absent. The Silurian-Devonian island arc, recorded in the Wiese-Werra zircons, must, therefore, be restored either close to Armorica or in the oceanic interspace between Armorica and Galatia/Ligeria. Likewise, spreading of new oceanic crust in the Upper Devonian, as documented in the Brevenne area and the southern Vosges, may have occurred intra-oceanic through back-arc rifting. Note, von Raumer et al. (2013) have already suggested a similar intra-oceanic evolution model for the northern Massif Central, whereas Berger et al. (2024) have recently interpreted the same area as Upper Devonian continental-arc/back-arc-basin system situated at the southern margin of the Armorican plate.

6.4. A brief comment regarding the status of the Massif Central (Ligeria)

As mentioned above, the tectonostratigraphic evolution of the Massif Central is only moderately similar to that in the Alps. This creates a certain challenge for the von Raumer et al. (2013) model, which combines the proto-Alpine crust and the Massif Central as one Galatian/Ligerian terrane. The missing (or arguably weak) Cenerian record in the Massif Central could eventually be explained by its distant position within the Galatian-Ligerian ribbon terrane, outside of the influence of the Cenerian subduction activities (Fig. 3).

On the other hand, the Silurian-early Devonian accretionary complex in the Massif Central has no identifiable counterpart in the Alps. It is plausibly maintained in many French studies that, at least, some Massif Central units were already subducted under the Armorican Massif during the Silurian/early Devonian, but this is incompatible with the model of von Raumer et al. (2013). A possible compromise would be if the Armorican terrane detached from Gondwana earlier during the Ordovician (as proposed by e.g., Matte, 2001). If this was the case, then Armorica and Galatia/Ligeria could have been in a similar parallel constellation as shown in figure 3c (Devonian configuration) by the end of the Silurian. The two terranes may had come into contact in the early Devonian with a local (?) collision in the Massif Central sector, before drifting apart again during ocean floor production later in the Devonian. This scenario would explain the observed Silurian-Devonian accretionary setting in the Massif Central without deviating from the fundamentals of the von Raumer et al. (2013) model. In fact, there is evidence for Ordovician rifting and oceanization in both the Alps and the Massif Central, and a detachment from the Gondwana mainland may, indeed, have occurred in both cases. In other words, the oceanic domains that separated Armorica and Gondwana and Galatia/Ligeria and Gondwana in the Devonian, may not be entirely Palaeotethys ocean floor but also contain older Early Palaeozoic oceanic crust.

6.5. An embarrassing question: Why do some Adriatic basement units show an Armorican-type detrital zircon spectrum?

Neubauer et al. (2020) reported a typical west-African detrital zircon population (with a particularly low TS/PP ratio) in the Lower Austroalpine Wechsel Unit. Similar zircon age spectra were recently recorded in Early Palaeozoic metasedimentary rocks of the Tatric Unit (Kohút et al., 2022). Several possibilities could account for this:

Firstly, the Galatian/Ligerian Gondwana segment in front of Saudi-Arabia could have been locally supplied by sediments containing Armorican-type zircons. In this case, the Armorican zircon component would be a "primary feature", and as such, would limit the value of detrital zircon spectra as Armorica-Ligeria/Galatia terrane markers. The second possibility is that the Alps and Carpathians contain tectonic fragments from the Armorican terrane, which became attached to Galatia/Ligeria during the Variscan collisional event. In this case, the Alps and Carpathians would include true Armorican crust, in the sense of von Raumer et al. (2013), and re-definition of the actual terrane boundaries would be necessary. In this context, the Variscan tectonic model of Faure and Ferrière (2022) deserves a mention. Although very different from the von Raumer et al. (2013) model, it contends that Saxothuringian (i.e., Armorican-type) crust was brought into the Alpine realm through an east Variscan oroclinal bend. Thirdly, there is the possibility that tectonic fragments from the Armorican Gondwana segment were transported to the (easterly positioned) Galatian/Ligerian Gondwana segment in the framework of the Cenerian orogeny, as discussed in Finger and Riegler (2023). The fourth and final possibility is that Armorica and Galatia/Ligeria initially collided in the Silurian/Lower Devonian before drifting apart again in the Upper Devonian (see section 6.4.) leaving marginal parts of Armorica still adhered to Galatia/Ligeria. To sum up, there are several theoretical possibilities to account for how Armorican tectonic fragments are preserved in the Alps and Carpathians, and this issue deserves to be followed up in future studies.

6.6. The Variscan developments: many open questions

According to von Raumer et al. (2013), the Galatian/Ligerian terrane collided with the Armorican terrane during the late Devonian/early Carboniferous in a dextral transpressional regime. This collisional event is probably one of the least researched events in European geology. This is the consequence of several facts, namely, the boundaries of the two terranes are still only vaguely defined (see 6.5.), much of the collisional zone is hidden underneath the Alps and, last but not least, the terranes were reworked during rifting to form Mesozoic oceanic domains in Pangea and ocean re-closure during Alpine tectonogenesis.

The time is certainly not ripe yet for discussing detailed collisional models. Nevertheless, some basic aspects can be briefly considered. Accepting the Armorica-Galatia/Ligeria terrane model of von Raumer et al. (2013) as fundamentally valid, the convergence of the two terranes in the Variscan likely involved subduction of the intervening oceanic crust. It can also be argued that the general south vergence of Variscan structures in the Bavarian Zone, Black Forest, Vosges and Massif Central indicates that subduction of this oceanic crust was in the direction of Armorica (Zeh et al., 2024). Subduction type magmatism of early Carboniferous age in the Black Forest (Hegner et al., 2001) would be compatible with this.

Megerssa et al. (2023) have recently proposed that ca. 330 Ma old tectonic structures in the Bavarian unit of the Bohemian Massif signify the frontal push of a continental mass from the south that is now under the Alps. This hidden continental mass, termed "Augustiner terrane" or "Salzburgia" (Megerssa et al., 2023) most likely includes the Cetic granitoid massif. If the southern Bohemian Massif is Armorica, as proposed above, the aforementioned structures in the Bavarian unit may record the final collision of Galatia/Ligeria and Armorica. The Variscan evolution of the Austrian part of the Bohemian Massif has long been described only in terms of the Moldanubian-Moravian collision. The advance of a southern Variscan unit has been rarely considered so far, although some authors have long highlighted the necessity for a larger scale approach (Neubauer and Handler, 2000).

A characteristic, and so far not fully understood, Variscan phenomenon in Galatia/Ligeria is widespread 370–340 Ma granitoid magmatism. This event comprises emplacement of I- and S-type granitoids in the Alps, the West Carpathians and also in the Massif Central. In the Alps and West Carpathians, they are most commonly interpreted as continental-arc magmatism, related to northward subduction of the Palaeotethys on the Gondwana facing side of Galatia/Ligeria (Haas et al., 2020; Mandl et al., 2022; Broska et al., 2022). According to Neubauer et al. (2022), northward subduction of the Carpathian Balkan ocean has caused arc magmatism in parts of Galatia/Ligeria. Looking at the tectonic sketches in von Raumer et al. (2013) it appears also possible that a southward dipping subduction zone under Galatia/Ligeria has triggered this granitic magmatism. As outlined here, the Variscan tectonic developments in and around Galatia/Ligeria remain controversial and are currently far from being understood. To date, no clear, consistent consensus exists on the interpretation and explanation of the available magmatic and metamorphic data (Variscan metamorphism is documented in many places).

Another intriguing point is that the Moldanubian (and peri-Moldanubian), late Visean/Namurian high-heat flow event affected only a few parts of Galatia/Ligeria. Rocks considered as typical products of this event (i.e., Durbachites/Vaugnerites, late Visean to Upper Carboniferous LPHT meta- and diatexites, Upper Carboniferous S- and I-type granitoids) are known from the Massif Central, the Tauern Window and the External Massifs (Vesela et al., 2011; von Raumer et al., 2014; Ruiz et al., 2022, Fréville et al., 2024), suggesting that these units were located proximal to the Moldanubian Zone subsequent to the Variscan collision event. In contrast, equivalent rocks have not been documented in the Austroalpine and West Carpathian basement units, implying that these were distant at that time. Importantly, Haas (2024) encountered detrital, late Visean/Namurian zircons in Permian metasedimentary rocks in the Schladming crystalline complex and considered the Zentralgneise of the Tauern Window as the potential source. If this interpretation holds true, then the Austroalpine basement units could have shifted significantly westwards along the East Variscan Shear Zone with the result that the Palaeozoic rocks of the Schladming Massif and the Hohe Tauern were proximal to each other in the Early Permian. This would mean that the opening and closure of the Penninic Ocean did not cause any significant lateral displacement of the European plate relative to the Adriatic plate.

7. Conclusions

A series of Upper Devonian, mantle-sourced, magmatic rocks (I-type granitoids plus back-arc ophiolites) extending from the northern Massif Central over the southern Vosges and the southern Black Forest into the basement of the Alps, are interpreted to mark the boundary between Armorica (occidental peri-Gondwana crust) and Galatia/Ligeria (oriental peri-Gondwana crust). This zone could represent an arc/back-arc-rift system that was located between the two terranes before their Variscan collision. However, further study is necessary to find out whether this magmatic system was in an intra-oceanic position or straddled one of the terrane margins.

As discussed above, the two-terranes-model of von

Raumer et al. (2013) is supported by the lithological and geochronological data from the key regions, Southern Bohemian Massif, Alps/West Carpathians and Massif Central, with some refinements. One such refinement is a re-definition of the Moldanubian parts of the southern Bohemian Massif, the Vosges and the Black Forest as Armorica (i.e., derived from the N-African Gondwana sector and not from NE Gondwana). Another refinement to the von Raumer et al. (2013) model in the Massif Central is a two-stage collision between Armorica and Ligeria/Galatia, with the first local collision in the early Devonian followed by Upper Devonian re-separation of the two terranes through ocean floor spreading and renewed convergence during the late Devonian/early Carboniferous.

In the Alps and West Carpathians, contention still remains as to whether they contain any tectonic Armorican remnants. An important aspect for future research is, therefore, to identify and delineate potential Armorican elements in these areas.

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This paper is a tribute to the trendsetting work of Jürgen von Raumer in the Alps. During writing we received the sad news that he died in June 2024 in the age of 92. The obituary is to be found in GMIT 98, Dec. 2024. Two thorough reviews by Piotr Wojtulek and Harald Fritz are gratefully acknowledged as well as helpful additional e-mail discussion and data exchange with the latter reviewer. Hugo Ortner is thanked for editorial handling and Noreen Vielreicher for linguistic improvements on the text.

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