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The role of the proto-Alpine Cenerian Orogen in the Avalonian-Cadomian belt

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Abstract

The proto-Alpine Cenerian orogen (Ediacaran-Ordovician) and the Cadomian orogen (Ediacaran-Cambrian), remnants of which are exposed in the central European Variscides, should be defined as two distinct and spatially separated coastal orogens within the Avalonian-Cadomian belt. The Cadomian orogen originally lay in front of the Sahara metacraton. It underwent a change from an active to a passive margin setting during the Cambrian. The Cenerian orogen, represented by intra-Alpine rocks, was located farther east near the Arabian Nubian Shield, from where it inherited a characteristic Tonian/Stenian detrital zircon signal. Subduction persisted in the Cenerian Orogen until the Ordovician. The Cadomian orogen was akin to Andean type whereas the Cenerian orogen was more akin to Alaskan type. This paper explores why the two orogens have such different characteristics and tectonic evolutions despite their probable proximity in the Avalonian-Cadomian belt. One explanation could be that they were at nearly right-angles to each other due to a strong concave bending of the northern Gondwana margin ahead of the Arabian-Nubian Shield.

1. Introduction

It is generally accepted that the oldest (i.e., late Neoproterozoic to Ordovician) rocks in central Europe stem, with a few exceptions (Lindner et al., 2021), from the Afro-Arabian sector of the north Gondwana margin. They were part of the so-called Avalonian-Cadomian belt as defined by Nance et al. (2008) and are now prominently exposed in the Saxothuringian (Linnemann et al., 2004) and Tepla-Barrandian (Žak et al., 2023) units of the Variscides, but also in the Alps (Siegesmund et al., 2021) (see Fig. 1).

During the Neoproterozoic to Cambrian, there is wide consensus that the entire northern Gondwana margin was an active margin (Nance et al., 2008). However, the subsequent development of north Gondwana during the Cambrian and Ordovician is controversial topic, especially with regard to the proto-European sector. Von Raumer et al. (2013) and Zurbriggen (2015) have suggested that the proto-Rheic ocean was subducted along the entire African Gondwana margin until, at least, the middle Ordovician. In contrast, other authors have reported evidence that this area (summarized as Armorica by some authors) had already changed from an active to a passive margin by the early/middle Cambrian (Linnemann et al., 2004; Franke et al., 2017; Žak et al., 2023). Nevertheless, there are unequivocal signs for Ordovician subduction-accretion processes in parts of the Alpine orogenic belt (Zurbriggen, 2015; Spahic et al., 2023; Starijaš-Mayer et al., 2023; and references therein). The aim of this short communication is to accommodate the available regional geological observations into a unified tectonic model.

2. The Cenerian and the Cadomian Orogen

The main hypothesis of this paper is that the late Neoproterozoic and early Palaeozoic units in the Alps (Fig. 1) define a distinct and discrete peri-Gondwana coastal orogen that originated in front of the Arabian Nubian Shield. Following Zurbriggen (2015), the term "Cenerian" is used

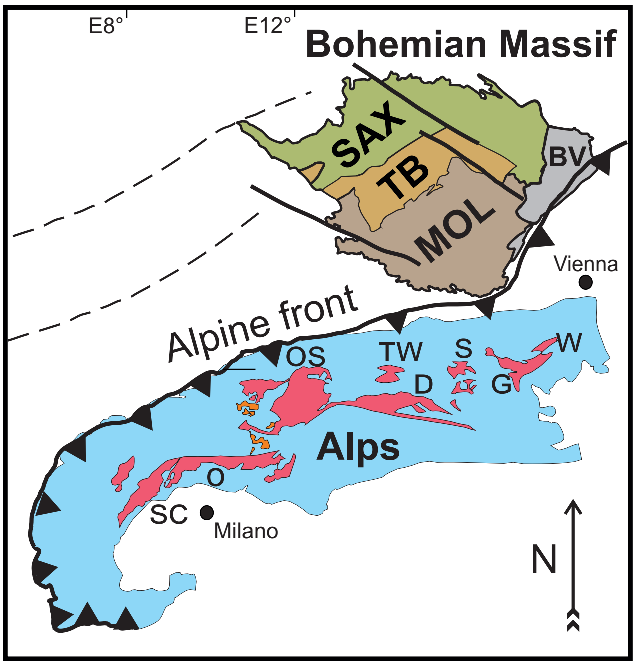

Figure 1: Sketch map showing areas and units in the Alps (red) where Late Neoproterozoic, Cambrian and Ordovician rocks are exposed (D = Defereggen, G = Gleinalm, HT = Hohe Tauern, O = Orobic Alps, OS = Ötztal-Silvretta, S = Schladming, SC = Strona Ceneri Zone, W = Wechsel). Note that most of these areas experienced a variably strong Variscan and/or Alpine metamorphic overprint (for review see Neubauer et al., 2022). Following Zurbriggen (2015) these oldest Alpine rocks are interpreted as part of the Cenerian Orogen (CENO). In contrast, we assign the Late Neoproterozoic, Cambrian and Ordovician rocks in the Bohemian Massif to a separate north-Gondwana orogen, which we interpret to be part of the Cadomian Orogen (CADO). See model in Figure 3 and main text for further explanation. Classical exposures of CADO rocks occur in the Saxothuringian (SAX) and Tepla-Barrandian (TB) zones of the Bohemian Massif and correlatives are likely hidden in the high-grade metamorphic Moldanubian Zone (MOL) (Teipel et al., 2004). The CADO rocks can be followed westwards into France (Armorican Massif) and Iberia (Franke et al., 2017). Note that the Bruno-vistulian terrane assembly (BV) in the eastern Bohemian Massif is not part of the CADO, but represents exotic Amazonian crust (Lindner et al., 2021).

for this orogen, although we emphasize that the palaeogeographic interpretations of Zurbriggen (2015) are different from our own. Unlike Zurbriggen (2015) and most other previous workers (e.g., Huang et al., 2021; Neubauer et al., 2022), we hold the view that the proto-Alpine Cenerian Orogen (CENO) was spatially separated from (and not superimposed on) the Cadomian Orogen (CADO), remnants of which are preserved in the extra-Alpine Variscides, for example in the Bohemian Massif (Fig. 1). Following Linnemann et al. (2004), Franke et al. (2017), Žak and Slama (2018) or Siegesmund et al. (2021), we interpret the CADO as an Andean type orogen that lay in front of the Sahara metacraton.

We make the simple assumption here that all pre-Silurian rocks in the Alps were included in the CENO. However, because research in this field is only in its infancy, we readily concede that refined assumptions will most probably have to be made in the future. Indeed, complicated terrane transfers from the CADO to the CENO may have taken place in the Early Palaeozoic (see discussion section). Our key proposition that the CADO and the CENO were spatially separated orogens is based on the following arguments:

1) Subduction activities are documented in proto-Alpine units (i.e., in the CENO) until the early/middle Ordovician (Zurbriggen, 2017; Starijaš Mayer, et al., 2023; and references therein). In contrast, subduction in the CADO ceased in the early Cambrian and was replaced by an extensional setting (see recent work of Žak et al., 2023; and references therein).

2) A continental arc setting with a relatively thick crust can be inferred for the CADO based on the numerous relics of late-Proterozoic/early Cambrian, mainly crustal-derived, high-K granitoids in the Armorican Massif (Brown and D'Lemos, 1991), the Saxothuringian Zone (Kröner et al., 1994) and the Tepla-Barrandian Unit (Dörr et al., 2002). The youngest of these granitoids (in the Tepla-Barrandian) may be, in part, the product of local arc-continent collision (Zulauf et al., 1999) or perhaps slab break-off (Žak et al., 2023). In contrast, late Neoproterozoic and early Cambrian granitoids are rare in the Alps, but oceanic and subduction-related mafic rocks of the same age are fairly widespread (e.g., Eichhorn et al., 2001; Melcher and Meisel, 2004) (see compilation in von Raumer et al., 2015). This implies that the CENO was initiated in an oceanic setting or on a very attenuated marginal Gondwana crust. We concur with the position of Zurbriggen (2015, 2017) that the CENO likely had the character of a sediment-rich, Alaskan-type subduction-accretion orogen, in which crustal thickening and topographic elevation remained moderate. Fast erosion of this orogen could account for the voluminous Ordovician clastic sediments in the Alps (Nievoll et al., 2022; Neubauer et al., 2022).

3) Detrital zircon spectra from the proto-Alpine units indicate a considerably greater input of Tonian/Stenian zircons relative to Palaeoproterozoic zircons than observed in the CADO realm: The ratio of Palaeoproterozoic (1600–2500 Ma) relative to Tonian/Stenian (800–1200 Ma) detrital zircons is typically greater than 3 in the Bohemian Massif, whereas it is mostly below 3 in the Alps (Fig. 2). In fact, it is below 1 in an overwhelming number of Alpine samples (red points in Fig. 2). This indicates that the CENO and the CADO received detrital material from different hinterlands and different sectors of the Gondwana margin, respectively (see also Siegesmund et al., 2021).

3. Palaeogeographic aspects and tectonic model

As mentioned before, it is a common assumption that the Late Neoproterozoic to Cambrian units of the extra-Alpine Variscides (the Armorican units) were formerly

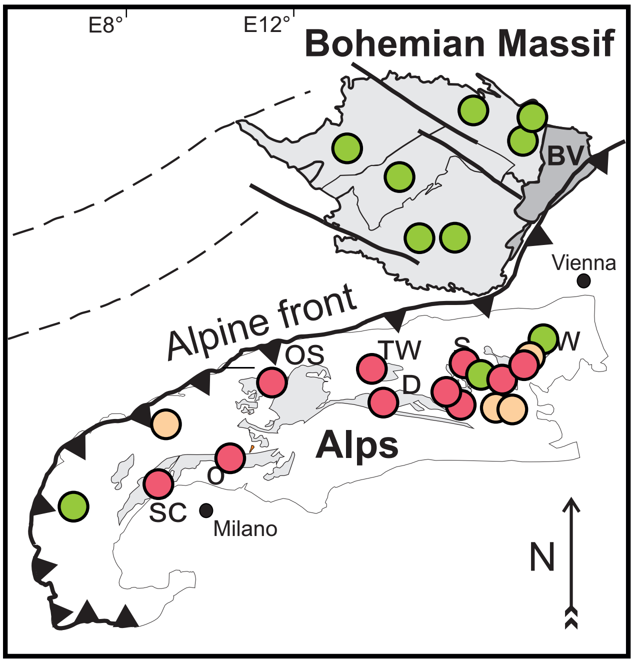

Figure 2: Frequency ratio of Palaeoproterozoic zircons (1.6-2.5 Ga) relative to Tonian/Stenian (0.8-1.2 Ga) zircons in Ediacaran and Palaeozoic (meta)sediments of the Alps and the Bohemian Massif (see Tab. 1 for data sources, map as in Fig. 1). Green symbols: strong dominance (>3:1) of Palaeoproterozoic zircons over Tonian/Stenian zircons. Pink symbols: weak dominance (<3:1) of Palaeoproterozoic zircons relative to Tonian/Stenian zircons. Red symbols: dominance of Tonian/Stenian zircons relative to Palaeoproterozoic zircons.

Bohemian Massif (points from W to E in Fig. 2)	
Saxothuringian metasediments, Thuringia	Linnemann et al. (2007)
Tepla-Barrandian metasediments	Drost et al. (2011)
Moldanubian metasediments Český Krumlov	Friedl et al. (unpubl.)
Moldanubian metasediments (mean)	Košler et al. (2014)
Saxothuringian quartzite, Krkonoše–Jizera Massif	Žáčková et al. (2012)
Saxothuringian quartzite, Orlica-Śnieżnik dome	Szczepański et al. (2020)
Paragneiss, Góry Sowie Massif	Tabaud et al. (2020)
Alps (points from W to E in Fig. 2)	
Grand Paradiso Massif	Manzotti et al. (2014)
Strona-Ceneri Zone	Siegesmund et al. (2023)
Gotthard Massif	Siegesmund et al. (2023)
Silvretta	Siegesmund et al. (2023)
Tauern Window	Veselá et al. (2022)
Defreggen Group	Siegesmund et al. (2018)
Radenthein Complex	Frank et al. (2020)
Millstadt Complex	Frank et al. (2020)
Wölz Complex	Frank et al. (2020)
Seckau Complex	Mandl et al. (2018)
Saualpe	Frank et al. (2020)
Koralpe	Frank et al. (2020)
Plankogel	Chang et al. (2021)
Raabalpe	Frank et al. (2020)
Raabalpe	Chang et al. (2021)
Waldbach and Wechsel Gneiss Complex	Chang et al. (2021)

Table 1: Data sources for Figure 2.

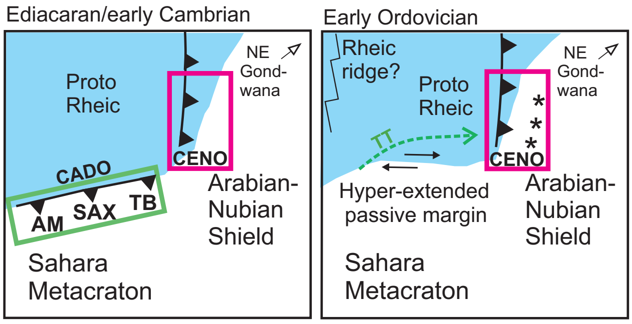

Figure 3: Palaeogeographic sketches illustrating the inferred positions of the Cenerian (CENO) and Cadomian orogens (CADO) within north Gondwana during the Ediacaran/early Cambrian (left) and the early Ordovician (right) (modified after Stampfli et al., 2013). Abbreviations: AR: Armorican Massif, SAX: Saxothuringian, TB: Tepla-Barrandian. Stars highlight crustal extension (rifting) inboard on the CENO. Green arrow labelled "TT" indicates a possible along-margin terrane transfer from the CADO to the CENO during the Ordovician (Wechsel Gneiss; see main text).

located somewhere in front of the Sahara metacraton. These represent the CADO in the terminology of this paper. We interpret the CADO in the classical way as an Andean-type accretionary orogen adjacent to the proto-Rheic oceanic plate (Fig. 3).

The proto-Alpine units, on the other hand (representing the CENO in our terminology), probably occupied a more easterly position on the Gondwana margin (Fig. 3). This can be concluded from the characteristic Tonian/Stenian detrital zircon signal (Fig. 2), which comes most probably from the Arabian-Nubian Shield (Dörr et al., 2015; Haas et al., 2020; Meinhold et al., 2021; Siegesmund et al., 2021). Published reconstructions of the Avalonian-Cadomian belt (e.g., Siegesmund et al., 2021; Žak et al., 2023) commonly imply that the CENO and the CADO were laterally aligned on the same active margin of the same peri-Gondwana subduction system. But in this arrangement it is difficult to explain why the tectonic conditions were so strikingly different, especially during the Ordovician.

The palinspastic reconstructions of Stampfli et al. (2013) for the Cambrian and Ordovician offer a reasonable solution to this problem. These reconstructions show a marked bend in the Gondwana coastline ahead of the Arabian-Nubian Shield at the transition from NW to NE Gondwana. Note that NW and NE Gondwana were separate landmasses until their collision in the late Cryogenian (Scotese, 2014; Merdith et al., 2017). This could have been responsible for the striking embayment of the Ediacaran Gondwana megacontinent in front of the Arabian-Nubian Shield.

As a consequence of the concave coastal embayment between NW and NE Gondwana, it is feasible that the CADO and CENO were at nearly right-angles to each other (Fig. 3) and, as such, would develop individual tectonic evolutions during the Ordovician. In this interpretation, it is envisaged that as subduction came to an end in the CADO, the proto-Rheic oceanic crust continued to be subducted in the CENO (at least intermittently) until the early/middle Ordovician. This resulted in subduction-accretion processes in the frontal parts of the CENO and a dextral transform regime in the CADO realm as the proto-Rheic oceanic plate moved east. Recent ideas of Syahputra et al. (2022), who proposed that the Rheic ocean grew along a broadly N-S trending ridge superimposed on proto-Rheic oceanic crust (see Fig. 3 and also Murphy et al., 2006), kinematically fit this scenario. The tectonic configuration sketched in Figure 3 gives reason for speculations that ridge-trench-transform interactions (Sisson et al., 2003) played an important role in the CENO and the CADO realm. It also allows for the possibility that microterranes could have detached from the CADO, moved along the Gondwana margin and finally attached to the CENO (green arrow in Fig. 3). An example for such a "transferred terrane" could be the Alpine Wechsel Gneiss Unit, for which Neubauer et al. (2020) credibly proposed a west African ancestry based on detrital zircon data (note the green point labelled W in Fig. 2).

4. Discussion

This work builds on the work of von Raumer et al. (2013, 2015) and Stampfli et al. (2013). However, we challenge some of their interpretations: For example, von Raumer et al. (2013) positioned the proto-Alpine units far to the NE, adjacent to South China. In contrast, in our model (Fig. 3), the position of the CENO is ahead of the Arabian Nubian Shield, proximal to the transition between NW and NE Gondwana. A second difference is that we propose that all late Neoproterozoic to Ordovician rocks of the Bohemian Massif (except the Brunovistulian) were proximal to the Sahara metacraton (see Fig. 3), whereas von Raumer et al. (2015) placed the Tepla-Barrandian together with the proto-Alpine units close to South China.

Given our interpretation that the CENO and the CADO were indeed spatially distinct orogens in the Ordovician (Fig. 3), then the question must be asked as to when and how did the CENO-derived units come into their present-day position south of the CADO units (Fig. 1). Like von Raumer et al. (2013), we propose that, after a major rifting event in the Devonian (opening of the Palaeotethys), the CENO and CADO units detached from Gondwana and were subsequently juxtaposed via dextral strike-slip processes in the Carboniferous. Parts of the Carboniferous CENO/CADO suture zone are now hidden under the northern front of the Alps (Finger and Riegler, 2022). Of course, it should be noted that the Permian arrangement of the CENO-derived units was massively disturbed by Alpine tectonic events. A comprehensive attempt to restore the Permian constellation of the intra-Alpine Palaeozoic domains has recently been presented by Neubauer et al. (2022).

An important subject of debate concerns the tectonic evolution of the CENO and the CADO during the Early Palaeozoic. There is wide agreement with the idea that the African periphery of Gondwana (i.e., CADO in our terminology) was under strong extension during that period (e.g., Franke et al., 2017; Žak et al., 2023). However, the extent to which this phase of extension changed the overall geological structure of the plate margin remains contentious. Many authors (e.g., Linnemann et al., 2004; Kroner and Romer, 2013; Romer and Kroner, 2019; Žak and Slama, 2018) suppose that the African sector of the peri-Gondwana crust, although thinned out to form a hyperextended passive margin (Žak et al., 2023), underwent no substantial oceanisation during the Early Palaeozoic and, therefore, did not split into mobile terranes. In contrast, Franke et al. (2017) suggested that major crustal fragments (the Thuringian/Saxonian terrane) drifted far from Gondwana in the early Palaeozoic giving birth to the Saxothuringian ocean. Similarly, Stampfli et al. (2013) proposed that a large elongated Hun ribbon terrane detached from the African sector of north Gondwana during the Ordovician and travelled towards Asia.

The same discussion can be translated to the CENO, which may have started to break-up into terranes during the Early Palaeozoic (Neubauer et al., 2022). In the Ordovician, subduction/accretion processes likely dominated at the outboard flank of the CENO, while back-arc rifting and contemporaneous passive margin type sedimentation occurred inboard and on the Gondwana facing side. In fact, Nievoll et al. (2022) describe Ordovician shelf sedimentation in the eastern Greywacke Zone of the Alps that supports the hollowing of a rift basin. Felsic volcanism of Ordovician age in the same area (Blasseneck porphyry) is also considered extension-related (Haas et al., 2020; Nievoll et al., 2022) with a possible petrogenetic connection to slab roll back (Best et al., 2016; Lewis et al., 2022). Likewise, the numerous Cambro-Ordovician mafic complexes in the Alps (Chamrousse, Speik, etc.) have often been interpreted in terms of oceanic rift basins that formed inboard from the Gondwana margin (e.g., Schulz et al., 2004; Haas et al., 2020; Huang et al., 2021). It should be noted, however, that many of these mafic complexes can also be interpreted as obducted oceanic crust from the outboard side of the CENO (Zurbriggen, 2017; von Raumer et al., 2015; Neubauer et al; 2020). Therefore, the important issue of whether Early Palaeozoic oceanic rifts did open in the CENO realm remains open for discussion, and, as in the case for the CADO, obviously requires further research.

At a larger scale, evidence is mounting that the north Gondwana margin (the Avalonian-Cadomian belt of Nance et al., 2008) should be divided into several discrete segments, each with a significantly different tectonic evolution, especially during the Ordovician. We tentatively distinguish from west to east:

1) The westernmost (Amazonian) segment with the Brunovistulian terranes, which detached from Gondwana in the Cambrian (Lindner et al., 2021).

2) The Avalonian segment that broke up into terranes during the Ordovician in a sinistral transtensional regime (Syahputra et al., 2022; and references therein). It is noteworthy that, according to recent papers by Van Staal et al. (2021) and Murphy et al. (2023), this segment may contain exotic, non-native crustal fragments of peri-Baltic origin (W-Avalonia) in addition to true Gondwana terranes (E-Avalonia).

3) The Cadomian segment, which, during the Ordovician, represented a hyper-extended passive margin in front of the Sahara metacraton with dextral transtensional kinematics (Žak et al., 2023).

4) The Cenerian segment in front of the Arabian-Nubian Shield, at the transition between NW and NE Gondwana, that records Ordovician subduction tectonics on its outboard side and inboard back-arc extension.

5) The large, but little known NE Gondwana segment in Asia, for which intensive data collection is now underway (e.g., Dan et al., 2022; 2023). This segment will likely require further subdivision.

Finally, widespread Ordovician granitic magmatism, which is seen in both the Alps and the extra-Alpine Variscides, deserves further attention. Although it is mainly of S-type to I/S transitional character (Schulz et al., 2004; Zurbriggen, 2015; René and Finger, 2016; Žak et al., 2023; Nievoll et al., 2022), some geologists working in the Alps have, understandably, related this igneous event to arc magmatism associated with Cenerian subduction and slab roll-back (Siegesmund et al., 2023). However, similar felsic magmatism of the same age also occurs in equal intensity in the CADO, where no Ordovician subduction activities are documented. This supports crustal thinning and mantle upwelling as the main tectonothermal causes, although slab roll back may have additionally contributed to a high heat flow under the CENO (Siegesmund et al., 2023).

Dan et al. (2023) have recently shown that Cambro-Ordovician S-type granitic magmatism plays a major role in NE Gondwana (Asia) and propose that it forms a prominent large igneous province (LIP). The intensive Ordovician magmatism in the CENO and the CADO could represent the western extension of this so-called Pinghe silicic LIP, which is potentially related to a major mantle plume. This aspect should be considered in future studies.

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References

Best, M.G., Christiansen, E.H., de Silva, S., Lipman, P.W., 2016. Slab roll back ignimbrite flare-ups in the southern Great Basin and other Cenozoic American arcs: A distinct style of arc volcanism. Geosphere 12/4, 1097–1135. https://doi.org/10.1130/GES01285.1.

Brown, M., D'Lemos, R.S., 1991. The Cadomian granites of Mancellia, northeast Armorican massif of France: relationship to the St. Malo migmatite belt, petrogenesis and tectonic setting. Precambrian Research, 51/1–4, 393–427. https://doi.org/10.1016/0301-9268(91)90110-V

Chang, R.H., Neubauer, F., Liu, Y.-J., Yuan, S.-H., Genser, J., Huang, Q.W., Guan, Q.-B., Yu, S.-Y., 2021. Hf isotopic constraints and detrital zircon ages for the Austroalpine basement evolution of Eastern Alps: review and new data. Earth Sci. Rev., 103772. https://doi.org/10.1016/j.earscirev.2021.103772

Dan, W., Murphy, J.B., Tang, G.J., Zhang, X.Z., White, W.M., Wang, Q., 2023. Cambrian– Ordovician magmatic flare-up in NE Gondwana: A silicic large igneous province? GSA Bulletin, 135/5–6, 1618–1632. https://doi.org/10.1130/B36331.1

Dan, W., Murphy, J.B., Wang, Q., Zhang, X.Z., Tang, G.J., 2023. Tectonic evolution of the Proto-Qiangtang Ocean and its relationship with the Palaeo-Tethys and Rheic oceans. Geological Society, London, Special Publications, 531/1. https://doi.org/10.1144/SP531-2022-146

Dörr, W., Zulauf, G., Fiala, J., Franke, W., Vejnar, Z., 2002. Neoproterozoic to Early Cambrian history of an active plate margin in the Teplá–Barrandian unit – a correlation of U-Pb isotopic-dilution-TIMS ages (Bohemia, Czech Republic). Tectonophysics, 352/1–2, 65–85. https://doi.org/10.1016/S0040-1951(02)00189-0

Dörr, W., Zulauf, G., Gerdes, A., Lahaye, Y., Kowalczyk, G., 2015. A hidden Tonian basement in the eastern Mediterranean: age constraints from U–Pb data of magmatic and detrital zircons of the External Hellenides (Crete and Peloponnesus). Precambrian Research, 258, 83–108. https://doi.org/10.1016/j.precamres.2014.12.015

Drost, K., Gerdes, A., Jeffries, T., Linnemann, U., Storey, C., 2011. Provenance of Neoproterozoic and early Paleozoic siliciclastic rocks of the Teplá-Barrandian unit (Bohemian Massif): evidence from U–Pb detrital zircon ages. Gondwana Research, 19/1, 213–231. https://doi.org/10.1016/j.gr.2010.05.003

Eichhorn, R., Loth, G., Kennedy, A., 2001. Unravelling the pre-Variscan evolution of the Habach terrane (Tauern Window. Austria) by U-Pb SHRIMP zircon data. Contributions to Mineralogy and Petrology, 142, 147–162. https://doi.org/10.1007/s004100100284

Finger, F., Riegler, G., 2022. Is there an Upper Devonian rift zone under the northern front of the Alps separating East and West Armorican crustal segments? Geologica Carpathica, 73/3, 181–185. https://doi.org/10.31577/GeolCarp.73.3.1

Frank, N., Hauzenberger, Ch., Skrzypek, E., Schuster, R., Gallhofer, D., He, D., Kurz, W., 2020. U/Pb ages of detrital zircons of the Koralpe-Wölz nappe system (Eastern Alps) - New evidences of varying provenance and protolith ages of different metasedimentary complexes by LA-ICPMS analyses. DMG Virtual Poster-Session 2020. https://doi.org/10.13140/RG.2.2.21099.16161

Franke, W., Cocks, L.R.M., Torsvik, T.H., 2017. The Palaeozoic Variscan oceans revisited. Gondwana Research, 48, 257–284. https://doi.org/10.1016/j.gr.2017.03.005

Friedl, G., Finger, F., McNaughton, N.J., Fletcher, I.R., 2000. Deducing the ancestry of terranes: SHRIMP evidence for South America–derived Gondwana fragments in central Europe. Geology, 28/11, 1035–1038. https://doi.org/10.1130/0091-7613(2000)28%3C1035:DTAOTS%3E2.0.CO;2

Friedl, G., Finger, F., Paquette, J. L., von Quadt, A., McNaughton, N.J., Fletcher, I.R., 2004. Pre-Variscan geological events in the Austrian part of the Bohemian Massif deduced from U-Pb zircon ages. International Journal of Earth Sciences, 93, 802–823. https://doi.org/10.1007/s00531-004-0420-9

Haas, I., Eichinger, S., Haller, D., Fritz, H., Nievoll, J., Mandl, M., Hippler, D., Hauzenberger, C., 2020. Gondwana fragments in the Eastern Alps: A travel story from U/Pb zircon data. Gondwana Research, 77, 204–222. https://doi.org/10.1016/j.gr.2019.07.015

Huang, Q., Genser, J., Liu, Y., Neubauer, F., Yuan, S., Bernroider, M., Guan, Q., Jin, W., Yu, S., Chang, R., 2021. Cambrian-Ordovician continental magmatic arc at the northern margin of Gondwana: Insights from the Schladming Complex, Eastern Alps. Lithos, 388–389. https://doi.org/10.1016/j.lithos.2021.106064

Košler, J., Konopásek, J., Sláma, J., Vrána, S., 2014. U-Pb zircon provenance of Moldanubian metasediments in the Bohemian Massif. Journal of the Geological Society London, 171, 83–95. https://doi.org/10.1144/jgs2013-059

Kröner, A., Hegner, E., Hammer, J., Haase, G., Bielicki, K.H., Krauss, M., Eidam, J., 1994. Geochronology and Nd-Sr systematics of Lusatian granitoids: significance for the evolution of the Variscan orogen in east-central Europe. Geologische Rundschau, 83, 357–376. https://doi.org/10.1007/BF00210551

Kroner, U., Romer, R.L., 2013. Two plates - Many subduction zones: The Variscan orogeny reconsidered, Gondwana Research, 24/1, 298–329. https://doi.org/10.1016/j.gr.2013.03.001

Lewis, Ch.T., de Silva, S.L., Burns, D.H., 2022. Rhyolitic melt production in the midst of a continental arc flare-up - The heterogeneous Caspana ignimbrite of the Altiplano- Puna volcanic complex of the Central Andes. Geosphere, 18/6, 1679–1709. https://doi.org/10.1130/GES02462.1

Lindner, M., Dörr, W., Reither, D., Finger, F., 2021. The Dobra Gneiss and the Drosendorf Unit in the southeastern Bohemian Massif, Austria: West Amazonian crust in the heart of Europe. Geological Society, London, Special Publications, 503/1, 185–207. https://doi.org/10.1144/SP503-2019-232

Linnemann, U., McNaughton, N.J., Romer, R.L., Gehmlich, M., Drost, K., Tonk, C., 2004. West African provenance for Saxo-Thuringia (Bohemian Massif): did Armorica ever leave pre-Pangean Gondwana? U/Pb-SHRIMP zircon evidence and the Nd-isotope record. International Journal of Earth Sciences, 93, 683–705. https://doi.org/10.1007/s00531-004-0413-8

Linnemann, U., Gerdes, A., Drost, K., Buschmann, B., 2007. The continuum between Cadomian orogenesis and opening of the Rheic Ocean: Constraints from LA-ICP-MS U-Pb zircon dating and analysis of plate-tectonic setting (Saxo-Thuringian zone, northeastern Bohemian Massif, Germany). Geological Society of America Special Paper, 423, 61–96. https://doi.org/10.1130/2007.2423(03)

Mandl, M., Kurz, W., Hauzenberger, Ch., Fritz, H., Klötzli, U., Schuster, R., 2018. Pre-Alpine evolution of the Seckau Complex (Austroalpine basement/Eastern Alps): Constraints from in-situ LA-ICP-MS U-Pb zircon geochronology. Lithos, 296–299, 412–430. https://doi.org/10.1016/j.lithos.2017.11.022

Manzotti, P., Ballèvre, M., Zucali, M., Robyr, M., Engi, M., 2014. The tectonometamorphic evolution of the Sesia-Dent Blanche nappes (internal Western Alps): review and synthesis. Swiss Journal of Geosciences, 107/2, 309–336. https://doi.org/10.1007/s00015-014-0172-x

Meinhold, G., Bassis, A., Hinderer, M., Levin, A., Jasper, B., 2021. Detrital zircon provenance of north Gondwana Palaeozoic sandstones from Saudi Arabia. Geological Magazine, 158/3, 442–458. https://doi.org/10.1017/S0016756820000576

Melcher, F., Meisel, T., 2004. A metamorphosed Early Cambrian crust–mantle transition in the Eastern Alps, Austria. Journal of Petrology, 45/8, 1689–1723. https://doi.org/10.1093/petrology/egh030

Merdith, A.S., Collins, A.S., Williams, S.E., Pisarevsky, S., Fodenc, J.D., Archibald, D.B., Blades, M.L., Alessio, B.L., Armistead, S., Plavsa, D., Clark, C., Müller, R.D., 2017. A full-plate global reconstruction of the Neoproterozoic. Gondwana Research, 50, 84–134. https://doi.org/10.1016/j.gr.2017.04.001

Murphy, J.B., Gutierrez-Alonso, G., Nance, R.D., Fernandez-Suarez, J., Keppie, J.D., Quesada, C., Dostal, Murphy, J.B., Nance, R.D., Wu, L., 2023. The provenance of Avalonia and its tectonic implications: a critical reappraisal. Geological Society, London, Special Publications, 531/1, SP531-2022. https://doi.org/10.1144/SP531-2022-176

Nance, R.D., Murphy, J.B., Strachan, R.A., Keppie, J.D., Gutiérrez-Alonso, G., Fernández-Suárez, J., Quesada, C., Linnemann, U., D'Lemos, R., Pisarevsky, S.A., 2008. Neoproterozoic - early Palaeozoic tectonostratigraphy and palaeogeography of the peri-Gondwanan terranes: Amazonian v. West African connections. Geological Society, London, Special Publications, 297, 345–383. https://doi.org/10.1144/SP297.17

Neubauer, F., Liu, Y., Dong, Y., Chang, R., Genser, J., Yuan, S., 2022. Pre-Alpine tectonic evolution of the Eastern Alps: From Prototethys to Paleotethys. Earth-Science Reviews, 226, 103923. https://doi.org/10.1016/j.earscirev.2022.103923

Neubauer, F., Liu, Y., Chang, R., Yuan, S., Yu, S., Genser, J., Liu, B., Guan, Q., 2020. The Wechsel Gneiss Complex of Eastern Alps: an Ediacaran to Cambrian continental arc and its Early Proterozoic hinterland. Swiss Journal of Geosciences, 113/1, 1–23. https://doi.org/10.1186/s00015-020-00373-3

Nievoll, J., Fritz, H., Gallhofer, D., Hauzenberger, C., Pfatschbacher, M., Gritsch, B., 2022. From shallow into deep sea: Sedimentary facies and U-Pb zircon ages in the early Paleozoic Noric Group at Veitsch (Eastern Greywacke Zone, Austria). Austrian Journal of Earth Sciences, 115/1, 41–73. https://doi.org/10.17738/ajes.2022.0003

René, M., Finger, F., 2016. The Blaník Gneiss in the southern Bohemian Massif (Czech Republic): a rare rock composition among the Early Palaeozoic granites of Variscan Central Europe. Mineralogy and Petrology, 110, 503–514. https://doi.org/10.1007/s00710-016-0427-5

Romer, R.L., Kroner, U., 2019. First direct evidence for a contiguous Gondwana shelf to the south of the Rheic Ocean. Geology, 47/8, 767–770. https://doi.org/10.1130/G46255.1

Schulz, B., Bombach, K., Pawlig, S., Brätz, H., 2004. Neoproterozoic to early-Palaeozoic magmatic evolution in the Gondwana-derived Austroalpine basement to the south of the Tauern Window (Eastern Alps). International Journal of Earth Sciences, 93, 824–843. https://doi.org/10.1007/s00531-004-0421-8

Scotese, C.R., 2014. Animation: Paleogeography (750 Ma - Present-day), PALEOMAP Project, Evanston, IL. http://youtu.be/tObhGzHH2aw

Siegesmund, S., Oriolo, S., Heinrichs, T., Basei, M.A.S., Nolte, N., Hüttenrauch, F., Schulz, B., 2018. Provenance of Austroalpine basement metasediments: tightening up Early Palaeozoic connections between peri-Gondwanan domains of central Europe and Northern Africa. International Journal of Earth Sciences, 107, 2293–2315. https://doi.org/10.1007/s00531-018-1599-5

Siegesmund, S., Oriolo, S., Schulz, B., Heinrichs, T., Basei, M.A.S., Lammerer, B., 2021. The birth of the Alps: Ediacaran to Paleozoic accretionary processes and crustal growth along the northern Gondwana margin. International Journal of Earth Sciences, 110/4, 1321–1348. https://doi.org/10.1007/s00531-021-02019-7

Siegesmund, S., Oriolo, S., Broge, A., Hueck, M., Lammerer, B., Basei, M.A.S., Schulz, B., 2023. Cadomian to Cenerian accretionary orogenic processes in the Alpine basement: the detrital zircon archive. International Journal of Earth Sciences. https://doi.org/10.1007/s00531-023-02305-6

Sisson, V.B., Pavlis, T.L., Roeske, S.M., Thorkelson, D.J., 2003. Introduction: an overview of ridge-trench interactions in modern and ancient settings. In: Sisson, W.B., et al. (eds.), Geology of a Transpressional Orogen Developed During Ridge-Trench Interaction Along the North Pacific Margin. Geological Society of America, Special Paper, 371, 1–18. https://doi.org/10.1130/SPE371

Spahić, D., Tančić, P., Barjaktarović, D., 2023. Early Paleozoic Cenerian (Sardic) geodynamic relationships of peripheral eastern north Gondwana affinities: Revisiting the Ordovician of the Getic/Kučaj nappe (eastern Serbia). Geological Quarterly, 67/4. http://dx.doi.org/10.7306/gq.1675

Sisson, V.B., Poole, A.R., Harris, N.R, Gaudenyi, T., 2019. Primordial geodynamics of Southern Carpathian-Balkan basements (Serbo-Macedonian Mass): Avalonian vs. Cadomian arc segments. Proceedings of the Geologists' Association, 130/2, 142–156. https://doi.org/10.1016/j.pgeola.2018.10.006

Stampfli, G.M., Hochard, C., Vérard, C., Wilhem, C., 2013. The formation of Pangea. Tectonophysics, 593, 1–19. https://doi.org/10.1016/j.tecto.2013.02.037

Starijaš-Mayer, B.S., Zeh, A., Krenn, E., Gerdes, A., Finger, F., 2023. Tracing the cryptic Sardic (Ordovician) metamorphism across Alpine Europe: the Krndija region in the Slavonian Mountains, Croatia. International Journal of Earth Sciences, 112, 829–853. https://doi.org/10.1007/s00531-022-02282-2

Syahputra, R., Žák, J., Nance, R.D., 2022. Cambrian sedimentary basins of northern Gondwana as geodynamic markers of incipient opening of the Rheic Ocean. Gondwana Research, 105, 492–513. https://doi.org/10.1016/j.gr.2021.10.004

Szczepański, J., Turniak, K., Anczkiewicz, R., Gleichner, P., 2020. Dating of detrital zircons and tracing the provenance of quartzites from the Bystrzyckie Mts: implications for the tectonic setting of the Early Palaeozoic sedimentary basin developed on the Gondwana margin. International Journal of Earth Sciences, 109, 2049–2079. https://doi.org/10.1007/s00531-020-01888-8

Tabaud, A. S., Štípská, P., Mazur, S., Schulmann, K., Míková, J., Wong, J., Sun, M., 2021. Evolution of a Cambro-Ordovician active margin in northern Gondwana: Geochemical and zircon geochronological evidence from the Góry Sowie metasedimentary rocks, Poland. Gondwana Research, 90, 1–26. https://doi.org/10.1016/j.gr.2020.10.011

Teipel, U., Eichhorn, R., Loth, G., Rohrmüller, J., Höll, R., Kennedy, A., 2004. U-Pb SHRIMP and Nd isotopic data from the western Bohemian Massif (Bayerischer Wald, Germany): implications for upper Vendian and lower Ordovician magmatism. International Journal of Earth Sciences, 93, 782–801. https://doi.org/10.1007/s00531-004-0419-2

Van Staal, C.R., Barr, S.M., McCausland, P.J.A., Thompson, M.D., White, C.E., 2021. Tonian-Ediacaran tectonomagmatic evolution of West Avalonia and its Ediacaran-early Cambrian interactions with Ganderia: an example of complex terrane transfer due to arc-arc collision? Geological Society, London, Special Publications, 503/1, 143–167. https://doi.org/10.1144/SP503-2020-23

Veselá, P., Oriolo, S., Basei, M. A. S., Lammerer, B., Siegesmund, S., 2022. The detrital zircon record of Variscan to post-Variscan tectonosedimentary and magmatic processes in the Tauern Window (Eastern Alps). International Journal of Earth Sciences, 111/4, 1273–1287. https://doi.org/10.1007/s00531-022-02179-0

von Raumer, J.F., Stampfli, G.M., Arenas, R., Sánchez Martínez, S., 2015. Ediacaran to Cambrian oceanic rocks of the Gondwana margin and their tectonic interpretation. International Journal of Earth Sciences, 104, 1107–1121. https://doi.org/10.1007/s00531-015-1142-x

von Raumer, J.F., Bussy, F., Schaltegger, U., Schulz, B., Stampfli, G.M., 2013. Pre-Mesozoic Alpine basements - their place in the European Paleozoic framework. Geological Society of America Bulletin, 125, 89–108. https://doi.org/10.1130/B30654.1

Žáčková, E., Konopásek, J., Košler, J., Jeřábek, P., 2012. Detrital zircon populations in quartzites of the Krkonoše-Jizera Massif: implications for pre-collisional history of the Saxothuringian Domain in the Bohemian Massif. Geological Magazine, 149, 443–458. https://doi.org/10.1017/S0016756811000744

Žák, J., Sláma, J., Syahputra, R., Nance, R.D., 2023. Dynamics of Cambro–Ordovician rifting of the northern margin of Gondwana as revealed by the timing of subsidence and magmatism in rift-related basins. International Geology Review (accepted, in press). https://doi.org/10.1080/00206814.2023.2172619

Žák, J., Sláma, J., 2018. How far did the Cadomian `terranes´ travel from Gondwana during early Palaeozoic? A critical reappraisal based on detrital zircon geochronology. International Geology Review, 60/3, 319–338. https://doi.org/10.1080/00206814.2017.1334599

Zulauf, G., Schitter, F., Riegler, G., Finger, F., Fiala, J., Vejnar, Z., 1999. Age constraints on the Cadomian evolution of the Teplà Barrandian unit (Bohemian Massif) through electron microprobe dating of metamorphic monazite. Zeitschrift der Deutschen Geologischen Gesellschaft, 150/4, 627–639. https://doi.org/10.1127/zdgg/150/2000/627

Zurbriggen, R., 2015. Ordovician orogeny in the Alps: a reappraisal. International Journal of Earth Sciences, 104/2, 335–350. https://doi.org/10.1007/s00531-014-1090-x

Zurbriggen, R., 2017. The Cenerian orogeny (early Paleozoic) from the perspective of the Alpine region. International Journal of Earth Sciences, 106, 517–529. http://dx.doi.org/10.1007/s00531-017-1496-3

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