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A vast Caledonian fan and an Ediacaran arc: The contrasting provenance of Devonian clastics of Brunia (Bohemian Massif)

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Abstract. Brunia is a distinctive crustal block within the European Variscides, composed of a late Neoproterozoic arc complex overlain by Ediacaran–early Cambrian cover sequences. Sparse preservation of early Paleozoic strata obscures its pre-Variscan paleogeography. Proposed models suggest Brunia either shared a crustal domain with adjacent parts of the Bohemian Massif, represented a far-eastern extension of Avalonia accreted to Baltica in the early Paleozoic, or maintained long-term connections to Baltica since the late Ediacaran.

To address these uncertainties, we present the first systematic study of detrital zircons (both U–Pb and Lu–Hf isotopic data) from Devonian strata overlying Brunia's Neoproterozoic basement. Two distinct age-spectral patterns are identified. Type-1, widespread across Brunia, exhibit a near-unimodal late Neoproterozoic peak corresponding to locally preserved arc magmatism. Type-2, display a multimodal spectrum with significant Late Ordovician–Silurian and Paleoproterozoic–early Neoproterozoic age peaks, and only minor late Neoproterozoic input.

The Type-1 pattern reflects predominant recycling of local Brunia sources. Nearly-uniformly positive εHf(t) values in Neoproterozoic zircons contrast with the wide isotopic range typical of other Variscan terranes in Central and Western Europe, but are comparable with values from Avalonian strata in Newfoundland, supporting a Neoproterozoic link between West Avalonia and Brunia.

The Type-2 pattern broadly matches Devonian detrital zircon signatures from the British Isles, the Rhenish and Harz Mountains, Dobrogea, and NW Turkey delineating the northern margin of the Rheic Ocean. Strong similarity to Ordovician–Silurian Scandinavian datasets suggests original derivation from the Caledonides and confirms an Early Devonian connection between Brunia and Baltica.

Keywords. Bohemian Massif; Detrital Zircon; U–Pb; Lu–Hf; Avalonia; Caledonides

1 Introduction

The eastern termination of the European Variscan Belt is most prominently marked by the Brunia Terrane (also referred to as Brunovistulia) in the Bohemian Massif (Fig. 1a). Like the internal parts of the Bohemian Massif (Moldanubia, Teplá-Barrandia, and Saxo-Thuringia), Brunia is composed predominantly of a late Neoproterozoic magmatic arc and its (meta-)sedimentary cover (see recent review in Hanžl et al., 2025). Its western portion (Moravo-Silesian Zone) was deformed during the Variscan Orogeny and now forms allochthonous nappe units thrust over a relatively undeformed para-autochthonous pre-Variscan basement to the east. The boundary between Brunia and the rest of the Bohemian Massif is represented by the Moldanubian Thrust Zone (Fig. 1b), which has long been recognized as a significant crustal-scale boundary (Suess, 1912). However, its paleogeographic significance remains the subject of ongoing debate (e.g., Soejono et al., 2010; Jastrzębski et al., 2015; Collett et al., 2021).

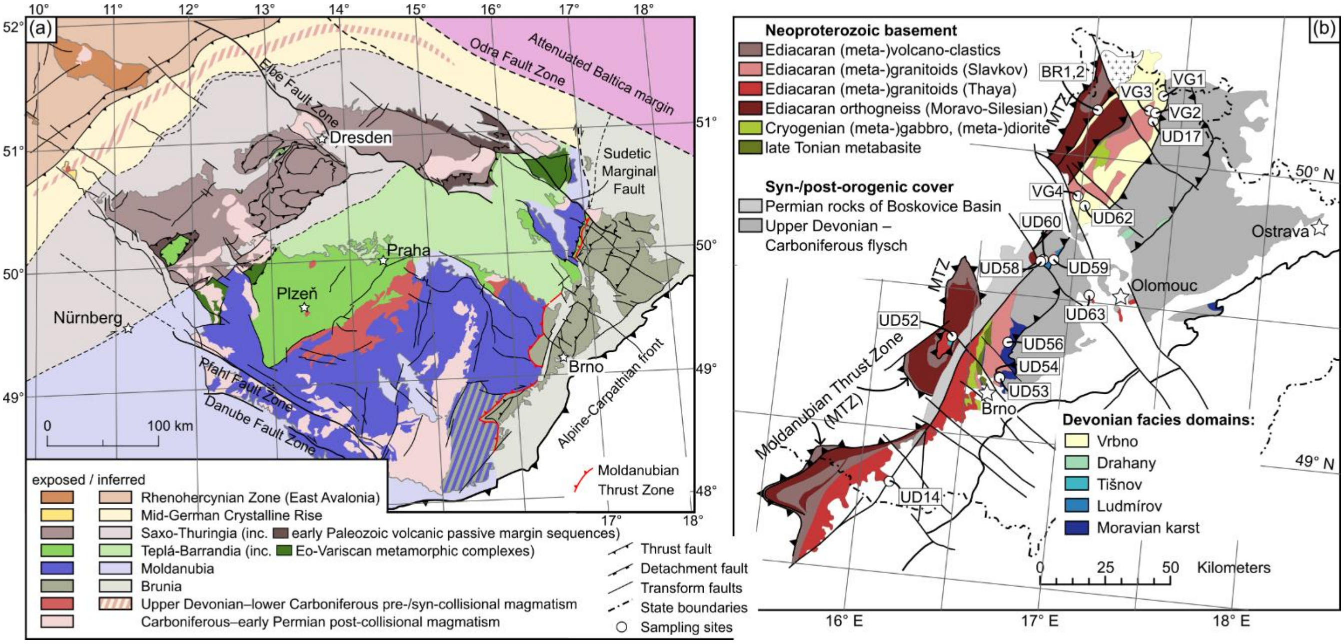

Figure 1: (a) Geological map of the Bohemian Massif (modified from Martinez Catalan et al., 2021). (b) Sample position in detailed view of the exposed part of Brunia highlighting the different Devonian facies domains (modified after Hanžl et al., 2019 and Kalvoda et al., 2025).

Geodynamically, Brunia acted as a rigid backstop against which the high-grade units of the internal Bohemian Massif were exhumed (e.g., Schulmann et al., 2009, 2014). Basic rocks are documented within the Moldanubian Thrust Zone; however, these lack true ophiolitic assemblages, and their early Cambrian age (Soejono et al., 2010; Collett et al., 2021) seemingly precludes an origin in the late Cambrian–Devonian Rheic Ocean (sensu Nance et al., 2012), which separated Laurussia from Gondwana prior to the Variscan Orogeny. These findings have led to pre-Variscan paleogeographic models proposing that Brunia, Moldanubia, and Teplá-Barrandia formed a single crustal domain (e.g., Schulmann et al., 2009, 2014; Soejono et al., 2022). This view is tentatively supported by stratigraphic parallels with the southern Variscan foreland in the Massif Central and Pyrenees (e.g., Matte et al., 1990), as well as similarities in detrital zircon spectra from Ediacaran strata across these three regions (Košler et al., 2014; Soejono et al., 2022).

However, this interpretation is challenged by both paleomagnetic and faunal data, which suggest an Ediacaran to early Cambrian connection between Brunia and Baltica (e.g., Belka et al., 2002; Nawrocki et al., 2004, 2021). In contrast, the early Paleozoic record of Teplá-Barrandia exhibits stronger Gondwanan affinities (e.g., Krs et al., 2001). Nonetheless, the Neoproterozoic arc magmatism that forms the bulk of Brunia's basement is difficult to reconcile with the coeval rift-to-passive-margin evolution observed in the adjacent Polish–Ukrainian sector of Baltica (e.g., Poprawa et al., 1999, 2018).

Recent geochronological and isotopic studies have highlighted strong affinities between Neoproterozoic magmatism in Brunia and that in the West Avalonian terranes of Atlantic North America (see Krmíčková et al., 2025 and references therein). Collett et al. (2022a) and Collett (2025) further argue that detrital zircon spectra from Ediacaran strata in Brunia correlate more closely with West Avalonia than with other components of the Bohemian Massif. West Avalonia was part of the Paleozoic Avalonian microcontinent, which is characterized by its late Ediacaran to Ordovician overstep sequence, its drift from Gondwana, and accretion to Baltica/Laurentia during the Ordovician to Silurian (Murphy et al., 2023 and references therein). However, in Brunia early Paleozoic strata are largely absent, with notable exception of the latest Ediacaran–early Cambrian clastics from which Baltica-affiliated trilobites have been documented (Belka et al., 2002).

Based on this, some tectonic models propose that Brunia represents a fragment of a Neoproterozoic volcanic arc that also included West Avalonia and developed near the Amazonian margin of northern Gondwana (e.g. Finger et al., 2000; Friedl et al., 2004). In one scenario, the Brunia segment of this arc was accreted to Baltica as it translated along the Gondwanan margin during the opening of the Iapetus Ocean (e.g., Lindner et al., 2021). An alternative hypothesis suggests that Brunia (and West Avalonia) had affinities with the Timanide–Uralide margin of Baltica and were displaced around this margin in response to the early Paleozoic rotation of Baltica. Brunia remains proximal to Baltica whereas West Avalonia is translated along the northern Gondwana margin. This model is illustrated in the paleogeographic reconstructions of Nawrocki et al. (2004) and Collett et al. (2022a).

Yet another possibility is that the allochthonous and autochthonous parts of Brunia have contrasting paleogeographic origins: the former being derived from Avalonia, and the latter representing a long-term component of Baltica. These domains may have been juxtaposed along transform faults following the Silurian docking of Avalonia with Baltica (e.g., Oczlon et al., 2007). Resolving these competing interpretations is complicated by the limited early Paleozoic record in Brunia. Apart from the upper Ediacaran–lower Cambrian clastics, Ordovician strata preserved in deep boreholes along Brunia's eastern margin, and an exotic Silurian slice within Carboniferous flysch nappes, the succession is largely absent up to the Lower Devonian (Kalvoda et al., 2025, and references therein). Devonian strata are regionally extensive, deposited in originally disconnected, initially extensional basins, and begin with clastic successions (the so-called "Basal Clastics"). These are followed by the development of a Middle Devonian to early Carboniferous carbonate platform in more proximal parts of the basin (Hladil, 1994; Kalvoda

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et al. 2008, 2025). In the northern allochthonous units, the distal parts of the Devonian–Carboniferous basin are characterized by deep-marine shales and volcanic rocks of either back-arc or within-plate affinity (Janoušek et al., 2014).

Even the interpretation of these Basal Clastics is controversial. Recent geochronological studies (Jastrzębski et al., 2021; Timmerman et al., 2023) suggest that some deposits mapped as Devonian may actually be late Neoproterozoic–early Cambrian in age. Jastrzębski et al. (2021) argued that quartzites lacking fossils in northern Brunia (allochthonous) have maximum depositional ages in the late Neoproterozoic and detrital zircon spectra comparable to known Ediacaran units. Timmerman et al. (2023), in contrast, dated ash layer within Basal Clastics from the southern (par-autochthonous) part of Brunia, obtaining single-age zircon populations of c.550 Ma.

In this study, we present a comprehensive U–Pb and Lu–Hf isotopic analysis of detrital zircon from the Devonian clastic strata of Brunia. Our sampling targeted not only biostratigraphically constrained Devonian Basal Clastics and those with hypothesised Devonian age, but also clastic intercalations within the overlying carbonate deposits. These data reveal a localized contribution from a distal source, likely derived from the Caledonides of Scandinavia, and a dominant contribution from local sources, representing erosion of the late Neoproterozoic arc. The former clearly links Brunia to Laurussia in the Early Devonian, while the latter provides insight into Brunia's late Neoproterozoic affinities. Importantly, it is also demonstrated that detrital zircon spectra alone are a poor tool to resolve stratigraphic age of the Basal Clastics.

2 Regional Geology

Brunia is a late Neoproterozoic volcanic arc terrane currently located between Baltica to the east and the highly deformed Gondwana-derived blocks of the Paleozoic Variscan orogenic belt to the west. At its western margin, parts of Brunia, specifically the Moravian and Silesian nappes, were metamorphosed during the Variscan Orogeny and thrust over a (para-)autochthonous Neoproterozoic basement (Suess, 1912; Schulmann et al., 1991). In the far eastern part of the terrane, borehole intersections reveal a horst structure containing Archean and Paleoproterozoic basement (Żelázniewicz and Fanning, 2020); however, it remains unclear whether this represents Brunia's basement or underthrust crust of Baltica. Paleoproterozoic gneiss is also documented in allochthonous units of the Silesian part of Brunia (Collett et al., 2021), and Mesoproterozoic gneiss in the Drosendorf Unit in Lower Austria has been attributed to Brunia despite occurring in the hanging wall of the Moldanubian Thrust Zone (Lindner et al., 2021).

Elsewhere, the crystalline basement of Brunia is dominated by Neoproterozoic magmatic rocks. The oldest of these crops out in a narrow north–south trending belt known as the Central Basic Belt, which includes a volcanic segment (the Metabasite Zone) to the east and a dominantly plutonic segment (the Diorite Zone) to the west (Fig.1b). The Metabasite Zone contains late Tonian (~730 Ma) tholeiitic basalts alongside sporadic primitive rhyolitic lavas and tuffs (Finger et al., 2000; Hanžl et al., 2019; Timmerman et al., 2023). In contrast, the Diorite Zone is composed of Cryogenian (~650 Ma) primitive magmatic rocks with volcanic arc affinities (Hanžl et al., 2019).

The Central Basic Belt divides two late Neoproterozoic magmatic domains with contrasting isotopic signatures: to the east, the Slavkov Domain is dominated by primitive arc-related granitoids (Finger et al., 2000; Krmíčková et al., 2025), whereas the Thaya Domain to the west consists of isotopically evolved granitoids (Finger et al., 2000; Soejono et al., 2017). Magmatism in both domains is broadly coeval, spanning the early Ediacaran (c.630–580 Ma) and are interpreted to reflect an Andean-type arc setting (see recent review in Hanžl et al., 2025).

The migmatized host rocks of the Thaya Domain contain abundant inherited zircons with Paleoproterozoic to early Neoproterozoic ages (Soejono et al., 2022), which also appear as xenocrysts in the late Neoproterozoic Bíteš orthogneiss of the Moravian nappes (Friedl et al., 2000; Soejono et al., 2017). The Bíteš orthogneiss are even more isotopically evolved that the Thaya Domain (Soejono et al., 2017); whereas orthogneiss in the Silesian nappes show isotopic and geochronological similarities to both the Thaya and Slavkov domains granitoids (Hegner and Kröner, 2000; Hanžl et al., 2007). Ediacaran paragneisses encountered in boreholes in southern and eastern Brunia and in outcrop in the Silesian nappes in northern Brunia yield nearly unimodal detrital zircon age spectra centred on the late Neoproterozoic (Jastrzębski et al., 2021; Soejono et al., 2022; Timmerman et al., 2023). Upper Ediacaran–Cambrian siliciclastics found in boreholes in NE part of Brunia record early terrestrial deposition followed by later marine sedimentation (Moczydłowska, 1997). Early Cambrian trilobites within this succession have apparent Baltica affintity (Belka et al., 2002) and detrital zircon spectra are similar to those recorded in the Ediacaran paragneisses (Habryn et al., 2020).

Ordovician to Carboniferous volcano-sedimentary sequences unconformably cover the Neoproterozoic-Cambrian basement. Siliciclastic Ordovician strata are documented only from boreholes along Brunia's northern boundary in Poland, while Silurian rocks are known solely from a single tectonic fragment within Carboniferous flysch (Kalvoda et al., 2025, and references therein). In contrast, Devonian to lower Carboniferous strata are widespread, deposited in rift basins typically beginning with coarse-grained clastic deposits that grade into fine-grained clastics, cherts, and limestone associations (Kalvoda et al. 2008; Fig. 2). Some of these rift basins are associated with magmatic rocks displaying supra-subduction signatures, suggesting rifting occurred in a back-arc setting (Janoušek et al., 2014). The clastic components of these Devonian basins are the primary focus of this study and are described in more detail below. During the early Carboniferous, a transition to a compressional regime associated with the Variscan Orogeny is recorded, with the latest Tournaisian to earliest Serpukhovian deep-marine siliciclastics of the Moravo-Silesian Culm Basin being deposited (Kumpera and Martinec, 1995).

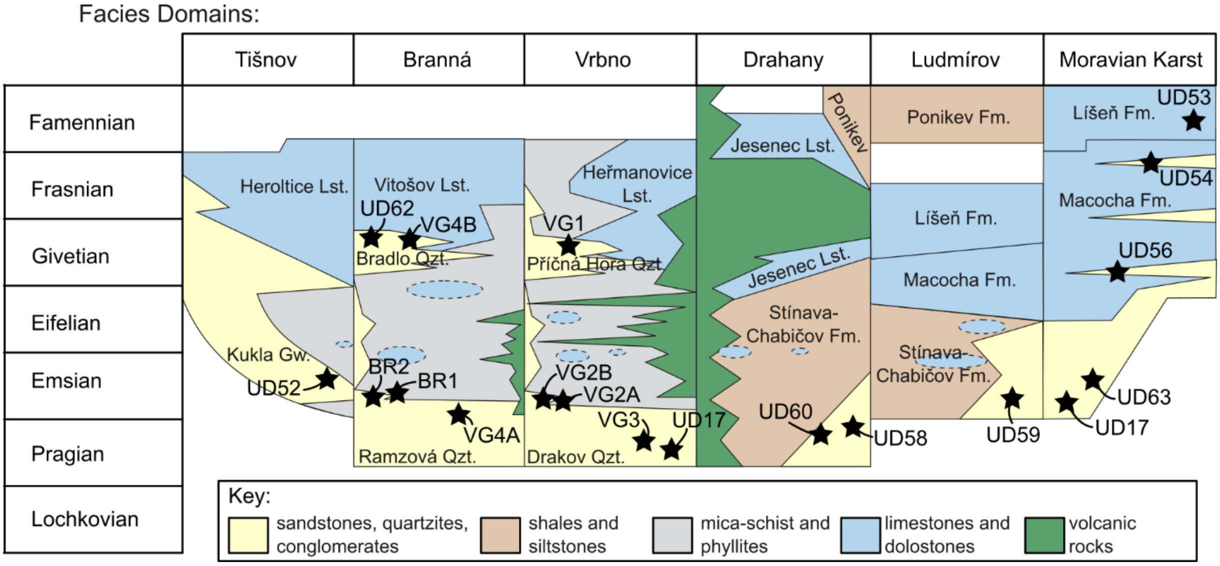

Figure 2: Lithostratigraphic chart of the Devonian facies domains of Brunia with approximate position of the studied samples marked by black stars. Modified from Kalvoda et al. (2025).

2.1 Stratigraphy and depositional settings of siliciclastics in Brunia Devonian basins

The Devonian volcano-sedimentary cover of the Brunia basement occurs in several distinct tectonic units and outcrop areas (Fig. 1b). Each of these units represents record of specific settings in basin-depth transect. The shallowest marine environments are represented by the Moravian Karst and Tišnov facies domains, which are dominated by carbonate platform deposits and preserved as (para)autochthonous units. In contrast, the platform-to-basin transition Ludmírov Facies Domain together with the more distal Vrbno and Drahany facies domains are preserved in allochthonous units incorporated into the Culm nappe structures, which crop out in narrow tectonic belts (Zukalová and Chlupáč, 1982; Kalvoda et al., 2025).

2.1.1 Moravian Karst Facies Domain

The clastic formation situated between the Neoproterozoic Brno Massif and the carbonates of the Devonian Macocha Formation was traditionally interpreted as Devonian continental deposits and referred to as the Devonian basal clastic formation (Zukalová and Chlupáč, 1982). However, subsequent analysis of drill cores from subsurface occurrences beneath the Western Carpathians revealed deposits containing marine Ediacaran to early Cambrian acritarchs, overlain by clastics with Devonian acritarchs and palynomorphs (Mikuláš et al., 2008; Vavrdová and Dašková, 2011).

Sedimentological and ichnological evidence has led to a reinterpretation of these deposits as representing alluvial and braided delta systems prograding into a marine basin. This interpretation explains the observed alternation of continental, brackish, and marine facies (Mikuláš et al., 2008; Vavrdová and Dašková, 2011). The majority of the drilled strata are now considered lower Cambrian in age, consisting of less mature clastics compared to the thinner, overlying Devonian succession (Mikuláš et al., 2008).

A late Neoproterozoic age for the lowermost part of the clastic strata within the Moravian Karst is supported by radiometric dating of a tuffitic interbed (Timmerman et al., 2023). Additionally, the lower portions (Neoproterozoic to Cambrian?) of the exposed clastic strata are generally less mature than the upper parts (Devonian?). Exceptionally large outcrops of clastic strata along the Metabasite Zone in the central Brno Massif (Babí lom Zone) exhibit sedimentological features indicative of deposition in an alluvial environment, including debris flow, braided river, and meandering river facies (Nehyba et al., 2001; Wojewoda et al., 2015). The presence of meandering river deposits and mature quartzose conglomerates tentatively supports a Devonian age, as meandering rivers are considered rare in the largely unvegetated pre-Devonian landscape (Gibling and Davies, 2012).

Consequently, similarly mature facies sampled from the Moravian Karst Facies Domain outcrop at Skalky in the Čelechovice area (sample UD63, Fig. 3a) are also assigned to the Devonian. With a considerable degree of reservation, we also assign the clastic formation overlying the Dyje Massif at Tasovice near Znojmo (sample UD14) to the Moravian Karst Facies Domain and to the Devonian. However, distinguishing between Ediacaran–Cambrian and Devonian clastic strata in the Moravian Karst, Čelechovice and Tasovice outcrops remains challenging due to the lack of definitive paleontological evidence. The age of the upper boundary of the basal clastic formation is inferred based on the surrounding earliest limestone beds, which yield Late Emsian to Early Eifelian corals in the Moravian Karst and Čelechovice (Hladil, 1994).

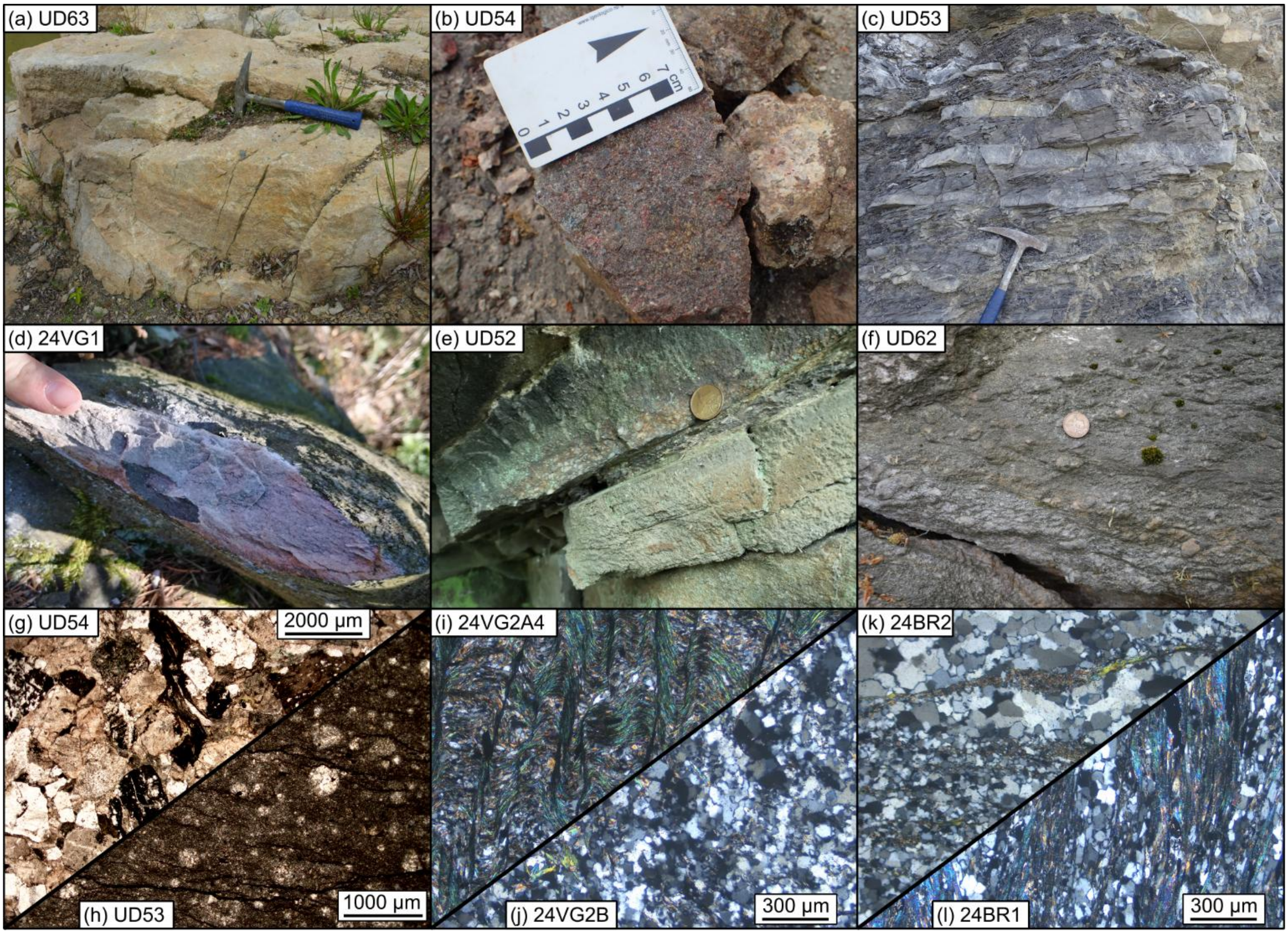

Figure 3: Selected field photographs and thin section photographs from representative samples. Refer to Table 1 for location and description of each sample.

A more reliable chronostratigraphic framework is available for clastic wedges within the fossiliferous limestones of the Macocha Formation. In this study, we sampled Lower Givetian immature sandstone between the 1st and 2nd megacycles (Lažánky–Za Zrcadlem, UD56) and Upper Frasnian petromictic conglomerate between the 3rd and 4th megacycles (Brno–Hády, UD54, Fig. 3b, g). These clastic wedges reflect the progradation of continental facies into the carbonate platform during regression phases. The clastic intercalations between the 1st and 2nd megacycles show upward coarsening from shales to sandstones, likely indicating a transition from marginal marine to continental environments (Hladil et al., 1999). The reddish petromictic Hády conglomerate at the base of the 4th megacycle containing diverse association of magmatic, metamorphic and sedimentary rocks, including Devonian limestones (Krmíček and Přichystal, 2007) represents an alluvial breccia.

The stratigraphically youngest sample (UD53) is not environmentally related to basal clastics, and comes from the lowermost part of the Líšeň Formation, where marlstones to silty limestones alternate with conodont-bearing limestones of Lower

Famennian age (Fig. 3c, h). Paleontological and sedimentological evidence consistently indicate a deep-marine lower slope setting, characterized by distal turbidite deposition (Kumpan et al., 2021).

2.1.2 Ludmírov Facies Domain

The Ludmírov Facies Domain consists of a shaly succession of the Stínava–Chabičov Formation (Petrovice Shale), which laterally transitions into basal clastics in its lower part and into the Macocha Formation in its upper part. In the Konice–Mladeč Belt, where sample UD59 was collected at Jalovčí, quartzose conglomerates and sandstones grade upward into carbonate-rich sandstones containing marine fossils, recording the transition from terrestrial to marine depositional environments. A Late Emsian fauna, including brachiopods, crinoids, and corals (Chlupáč and Svoboda, 1963), indicates nearshore marine conditions. The overlying Petrovice Shale yields a biostratigraphically well-constrained Late Emsian to Early Eifelian marine fauna, documenting a progressive marine transgression (Havlíček and Mergl, 1990).

2.1.3 Drahany Facies Domain

The Drahany Facies Domain is dominated by shales and slates of the Stínava–Chabičov Formation, which interfinger with volcanic products and the Jesenec Limestone associated with volcanic elevations. The basal clastics consist of relatively immature conglomerates and sandstones deposited under marine conditions, as evidenced by the presence of brachiopods, corals, and crinoids (Chlupáč and Svoboda, 1963). Coarser siliciclastic deposits at the base of the succession were sampled at Šubířov (UD58) and Liškovy Skály (UD60). The stratigraphic position beneath the overlying Stínava–Chabičov Formation suggests an Early Emsian or possibly Pragian age for these basal clastics (Chlupáč 1961, 2000).

2.1.4 Vrbno Facies Domain

In the Vrbno Facies Domain, the basal Drakov Quartzite is recognized as a regionally significant correlative horizon. Brachiopods and other macrofauna constrain its age to the Pragian–Emsian interval (Chlupáč, 1989). The protolith consists of mature quartzose sandstone (UD17, 24VG3, 24VG2B; Fig. 3j). Marine fauna–including bivalves, brachiopods, and trilobites–confirm deposition in nearshore settings above the fair-weather wave base, an interpretation further supported by the presence of the ichnofossil Arenicolites. Intervals containing abundant chlorite–muscovite phyllite (24VG2A, Fig. 3i) intercalations likely represent more distal environments situated between the fair-weather and storm wave bases.
The overlying succession of schists, metabasites, and quartzites is assigned to the Middle and Upper Devonian based on its stratigraphic position and the occurrence of sparse conodonts and microfossils within carbonate intercalations (Koverdynský and Zikmundová, 1966; Hladil et al., 1987). The Heřmanovice Limestone, found in the upper part of the sequence, is dated as Givetian–Frasnian in age (Hladil et al., 1999), which places the underlying Příčná Hora Quartzite (24VG1; Fig. 3d) in the Givetian. This age assignment is further corroborated by its correlation with the Bradlo Quartzites of the Branná Facies Domain (see below).

2.1.5 Tišnov Facies Domain

The Tišnov Facies Domain is characterized by a clastic succession comprising the Závist and Květnice facies. Sample UD52 (Fig. 3e) for this study was taken from the Závist Facies, represented by the thick Kukla Greywacke, which is biostratigraphically constrained to the Emsian, Eifelian, and Givetian based on palynomorphs and brachiopods (Hladil et al., 1999). The Kukla Greywacke consists of immature, matrix-rich sandstones interbedded with slates and petromictic conglomerates that also contain limestone clasts. Both petrological and paleontological evidence indicate a marine origin, with deposition likely occurring as slope sediments from submarine gravity flows.

In contrast, the thinner succession of the Květnice Facies exhibits features indicative of shallow marine or even supratidal environments (Dvořák and Skoček, 1997). This clastic sequence is overlain by carbonate rocks, which appear from the Givetian onwards, as evidenced by the presence of stromatoporoids (Koverdynský and Hladil, 1985).

2.1.6 Branná Facies Domain

The Branná Facies Domain is discriminated for the purposes of this study in light of our detrital zircon isotopic data. From the point of view of depositional settings, it shows transitional features between the distal Vrbno Facies Domain (lower part of the succession; Koverdynský, 1993) and the proximal Tišnov Facies Domain (the upper part of the succession with limestones; Koverdynský and Hladil, 1985). The basal Ramzová Quartzite (24BR1, 2; 24VG4B) of the Branná Group is unfossiliferous but has been correlated with the Lower Devonian Drakov Quartzite based on lithostratigraphic relationships (Fig. 3k, l) and regional mapping near Jeseník (Koverdynský, 1993). Similarly, the stratigraphically higher Bradlo Quartzite also lacks fossils but interfingers with the Vitošov Limestone. Givetian macrofauna identified within the Vitošov Limestone and other undifferentiated limestone bodies of the Branná Group (Koverdynský and Hladil, 1985) suggest a Givetian age for the Bradlo Quartzite (24VG4B, UD62; Fig. 3f).

The correlation of the Ramzová Quartzite with the marine Drakov Quartzite, along with the interfingering relationship between the Bradlo Quartzite and the Givetian Vitošov Limestone, strongly supports marine deposition for these quartzite units. The Bradlo Quartzite was likely deposited in nearshore marine settings along the platform margin or as siliciclastic wedges intercalated within the carbonate platform. Its high textural maturity reflects prolonged reworking in wave-dominated high-energy shallow marine environments.

3 Analytical Methods

A total of 19 samples were prepared for zircon separation, the locations and summary petrographic descriptions of these samples are provided in Table 1. Zircon grains were extracted using conventional methods, including crushing, Wilfley concentration table, magnetic, and heavy liquid separations. The majority of the zircon separates were abundant (n > 1000 grains) and highly pure (>90% zircon). Given the high quality of the separates and to avoid unintentional biases from hand-picking, zircons were mass-mounted onto acrylic.

Table 1: Summary description of studied samples and their location

Sample #	Location	Sample description	Co-ordinates		Depositional age	Number of data points		Age distribution
			Lat	Long		U-Pb	Lu-Hf	
Moravian Karst Facies Domain								
UD63	old quarry Skalky, NW of Kaple	Coarse grained sandstone to very fine-grained conglomerate, with predominance of quartz grains (>90 %), with minor muscovite (~2 %) and feldspar (<1 %) admixture. Matrix sericitic to silty-quartzose, silicified in places.	49.5349	17.0966	Emsian (Ediacaran ?)	94	n/a	Type-1
UD14	Tasovice	Medium- to coarse-grained sandstone (c. 85% quartz + quartzite and quartz siltstone clasts; ~5 % plagioclase + orthoclase; 1–2% muscovite, 1% biotite + chlorite), matrix (5 to 10 %) mostly sericitic but carbonate sparite observed locally	48.8226	16.1549	Emsian-Eifleian (Ediacaran ?)	111	n/a	Type-1
UD56	Lažánky, V zrcadlech, creek	Very coarse-grained greywacke to subarkose with predominant quartz grains (40 - 50 %), feldspar (5–15 %) and lithic fraction (5 %; granites, feldspathic rocks, gneiss). Matrix (up to ~40 %) is argillitic-sericitic and muscovitic-sericitic with strongly preferred orientation defined by deformation.	49.3441	16.6946	Givetian	130	n/a	Type-1
UD54	Hády upper bench, W corner	Matrix-supported petromict conglomerate to breccia. Matrix is coarse grained lithic arkose composed of granitoids, quartzites, sandstones, quartz and feldspar grains, slate, limestone and volcanic clasts.	49.2218	16.6670	Frasnian	108	n/a	Type-1
UD53	Hády centre of lower quarry bench	Argillaceous radiolarian wackestone. Calcified radiolarian tests are scattered in the matrix composed of coarse microsparite (calcite and dolomite) overlocking and intergrowing clay minerals. Swarms of clay and organic matter rich dissolution seams.	49.2194	16.6710	Famennian	87	18	Type-1
Ludmírov Facies Domain								
UD59	Jalovčí, block on ridge	Medium to coarse grained greywacke to quartz sandstone composed of 70 to 90 % of quartz and quartzite grains, and 30 to 10 % partly silicified matrix with predominant silt sized quartz and minor sericite. Muscovite is rare.	49.6435	16.8907	Emsian-Eifleian	119	15	Type-1
Drahany Facies Domain								
UD58	Šubířov, right creek of the Nectava river	Coarse to very coarse grained subarkose (80 to 85 % quartz, 15 to 20 % feldspars) with minor muscovite (<2 %); matrix-poor (sericitic matrix <2 %).	49.6340	16.8218	Pragian-Emsian	95	n/a	Type-1
UD60	Liškovy skalky	Medium grained calcareous sandstone to sandy limestone. Quartz grains (70-30 %) and calciclasts/bioclasts (?) in calcitic coarse grained sparite. Muscovite and plagioclase are rare.	49.6407	16.8346	Pragian-Emsian	118	15	Type-1
Vrbno Facies Domain								
UD17	Suchý Vrch	Supermature, very fine-grained quartzite with densely fitted quartz grains and minor muscovite admixture (muscovite grains coarser than quartz)	50.1545	17.3453	Pragian	122	n/a	Type-2
24VG3	Scree slope E. of Stará hora	Medium-grained super mature quartzite (>90 % Qtz) with minor interstitial muscovite and opaque minerals.	50.1894	17.3201	Pragian	163	30	Type-2
24VG2A	Bedrock foundations of Drakov castle	Chlorite + muscovite dominated phyllite strongly affected by shearing and isoclinal folding with crenulation cleavages, separated by mm- to cm-scale quartz-rich bands	50.1838	17.3535	Pragian-Emsian	163	18	Type-2

24VG2B	Bedrock foundations of Drakov castle	Fine to medium-grained mature quartzite (c. 75 % Qtz) with bands of strongly alligned chlorite and muscovite. Minor feldspar component (5 to 10 %) mostly represented by albite.	50.1838	17.3535	Pragian-Emsian	162	27	Type-2
24VG1	Small quarry above ski areál Příčná Zlaté Hory	Super mature fine to medium-grained quartzite (>90 % Qtz), with minor interstitial muscovite and opaque minerals.	50.2444	17.3878	Givetian	167	29	Type-2
Tišnov Facies Domain								
UD52	Předklášteří	Supermature coarse-grained sandstone with sericitic-quartzose matrix (1–5 %). Quartz grains predominate (> 90 %), infrequent are quartzite clasts, and muscovite, plagioclase and orthoclase are rare.	49.3435	16.3980	Emsian	142	15	Type-1
Branná Facies Domain								
24VG4A	Rock face NE from Bílý kámen	Medium-grained mature quartzite (c.70 % Qtz) with moderate feldspar (c. 15 %) and minor interstitial chlorite and muscovite (< 10 %) components.	49.8735	16.9801	Pragian (Ediacaran?)	162	38	Type-1
24BR1	Railway cutting S. of Ostružná village	Qtz-rich (c.50 %) phyllite, with strongly aligned muscovite and chlorite showing isoclinal folding with crenulation cleavages, minor feldspar component (c. 10 %) is mostly albite.	50.1740	17.0435	Pragian (Ediacaran?)	34	n/a	Type-1
24BR2	Railway cutting S. of Ostružná village	Medium- to coarse-grained mature quartzite (c.85 % Qtz) with minor interstitial muscovite and small (c.5 %) feldspar component.	50.1740	17.0435	Pragian (Ediacaran?)	162	36	Type-1
24VG4B	Rock face E from Bílý kámen	Meta-arkose with approximately even amounts of quartz and feldspars (c. 40 % of each). Minor interstitial muscovite and chlorite define weak foliation.	49.8716	16.9844	Givetian	163	n/a	Type-1
UD62	Ostrá hora, rocky ridge	Coarse qrained supermature quartzite (>90 % Qtz). Coarsely recrystallized and silicified groundmass parts interfinger with muscovite and muscovite-sericite.	49.8396	17.0251	Givetian	104	n/a	Type-1

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The mounted zircon grains were imaged by both back-scattered electron (BSE) and cathodoluminescence (CL) techniques using a scanning electron microscope at the Czech Geological Survey in Prague. These images guided the localization of U–Pb isotopic spots within coherent zircon domains larger than 25 µm in diameter. Lu–Hf isotopic spots (45 µm in diameter) have been located within significant zircon domains that yielded concordant U–Pb isotopic ages. A selection of CL images from each sample are provided in Fig. 4. The U–Pb isotopic data was acquired at the University of Bergen, Norway (UD14 and UD17 only) and at the laboratories of the Czech Geological Survey (all remaining samples). The Lu–Hf isotopic data was acquired at the laboratories of the Czech Geological Survey. The methodology and analytical conditions largely follow that reported in Soejono et al. (2022) and are detailed in Section S1. Complete reporting of isotopic data including that of analytical standards is given in Section S2.

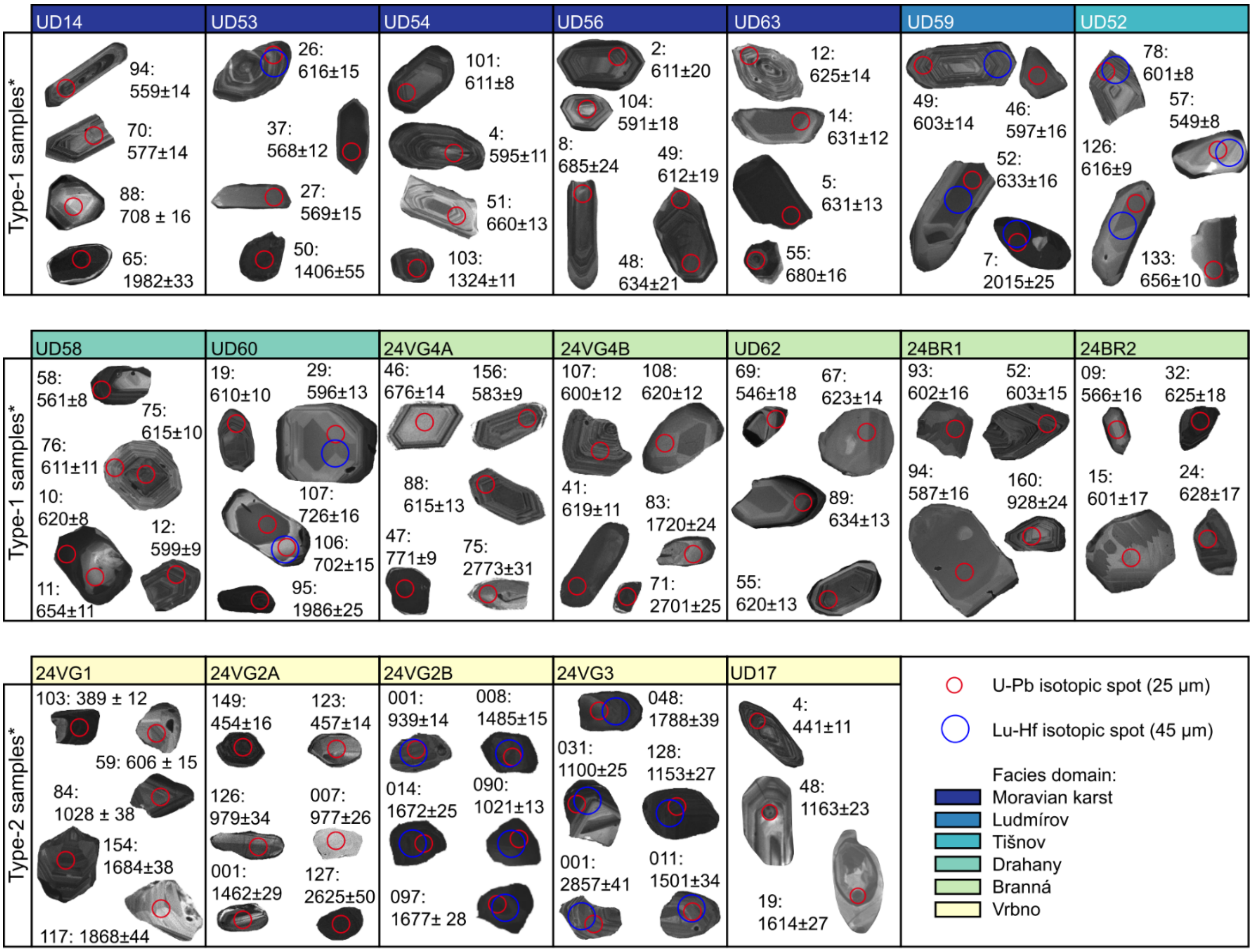

Figure 4: Cathodoluminescence images of representative zircons from each sample. All zircons in the figure gave concordant (concordia distance <5) ages and the given age is the iterative single-grain concordia age with 2s uncertainty. *classification into Type-1 and Type-2 samples according to results section.

4 Results

A total of 2,407 U–Pb isotopic analyses were conducted on the 19 studied samples. Concordant U–Pb ages(n = 2,184) are presented in both this section and Section 5 in the form of a cumulative age distribution plot and kernel density distribution plots. Concordant data are defined as those with a concordia distance <5 (formulation of Vermeesch, 2021) and reported ages are iterative single grain concordia ages in order to avoid problematic changeover in the U–Pb isotopic system.

4.1 U–Pb isotopic data

The U–Pb isotopic data revealed two internally consistent but highly contrasting datasets, which are graphically depicted in a cumulative age distribution plot (Fig. 5).

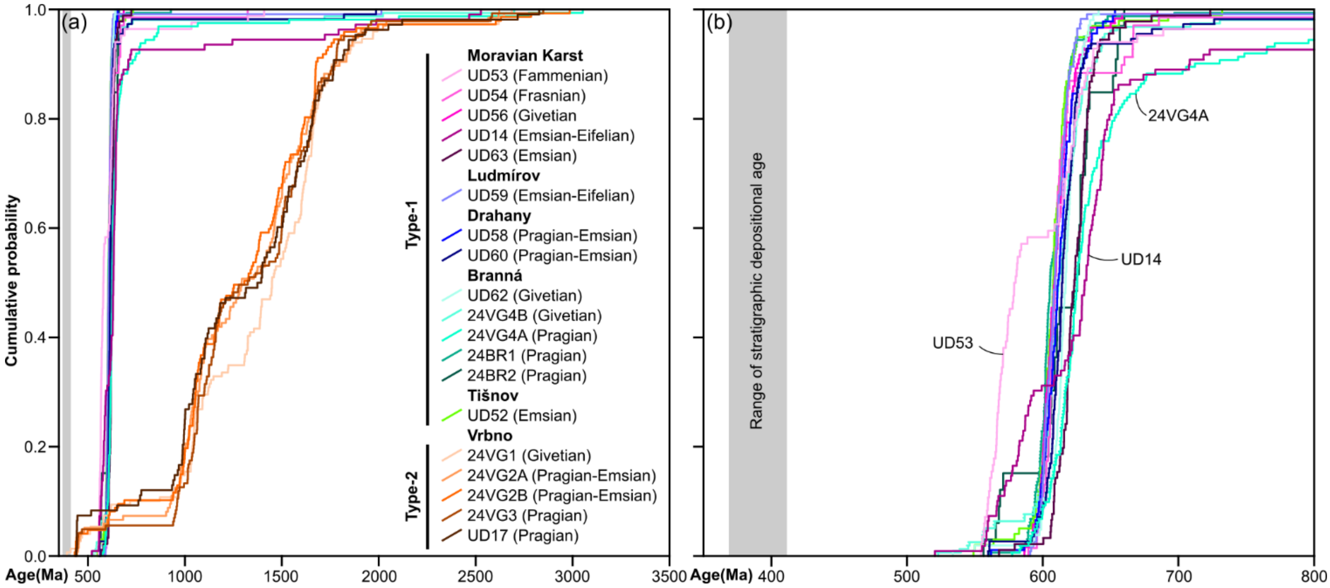

Figure 5: (a) Cumulative age distribution plot of the studied samples of supposedly Devonian clastics highlighting the difference in the Type-1 and Type-2 age distributions. (b) Close-up view of the distribution of late Neoproterozoic zircons in the Type-1 group, selected samples with slightly non-standard distributions are highlighted.

Fourteen samples display nearly unimodal age distributions dominated by late Neoproterozoic zircons. Fewer than 3 % of concordant analyses yielded Tonian or older ages (>720 Ma), and none are younger than the Terreneuvian Series of the Cambrian (<521 Ma). These are hereafter referred to as Type-1 samples. This spectral signature occurs throughout Brunia and across all facies domains, except in the restricted Vrbno Facies Domain defined here.

Type-1 samples show minimal variation, with most ages clustering between 590–620 Ma. The main exception is the youngest sample, UD53 (Famennian, Moravian Karst), which is dominated by a 550–560 Ma population and a subordinate 590–620 Ma group. The 550–560 Ma population also appears, to a lesser extent, in UD14 (Moravian Karst), 24BR2, and 24VG4B (both Branná Group).

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Samples UD14 and 24VG4A (Branná Group) stand out for a significant Cryogenian component (>20%), which is also present in smaller amounts across the other Type-1 samples. Additionally, 24VG4A includes a unique subset (n = 10) of Tonian ages, forming minor peaks at ~765 Ma and ~850 Ma. Mesoproterozoic and older grains are rare, occurring in just 7 of the 14 samples and totalling 23 analyses, with reproduced ages at ~1060, 1330, 1730, 2000, 2490, and 2740 Ma (Fig. 6).

The remaining five samples (Type-2) exhibit multimodal age distributions, with the majority of data yielding late Paleoproterozoic to early Neoproterozoic ages (Fig. 6). A total of 89% of all concordant data points fall within the 2100–900 Ma range. These Type-2 samples are restricted to the Vrbno Facies Domain, specifically in the northern part of the Silesian Domain of Brunia.

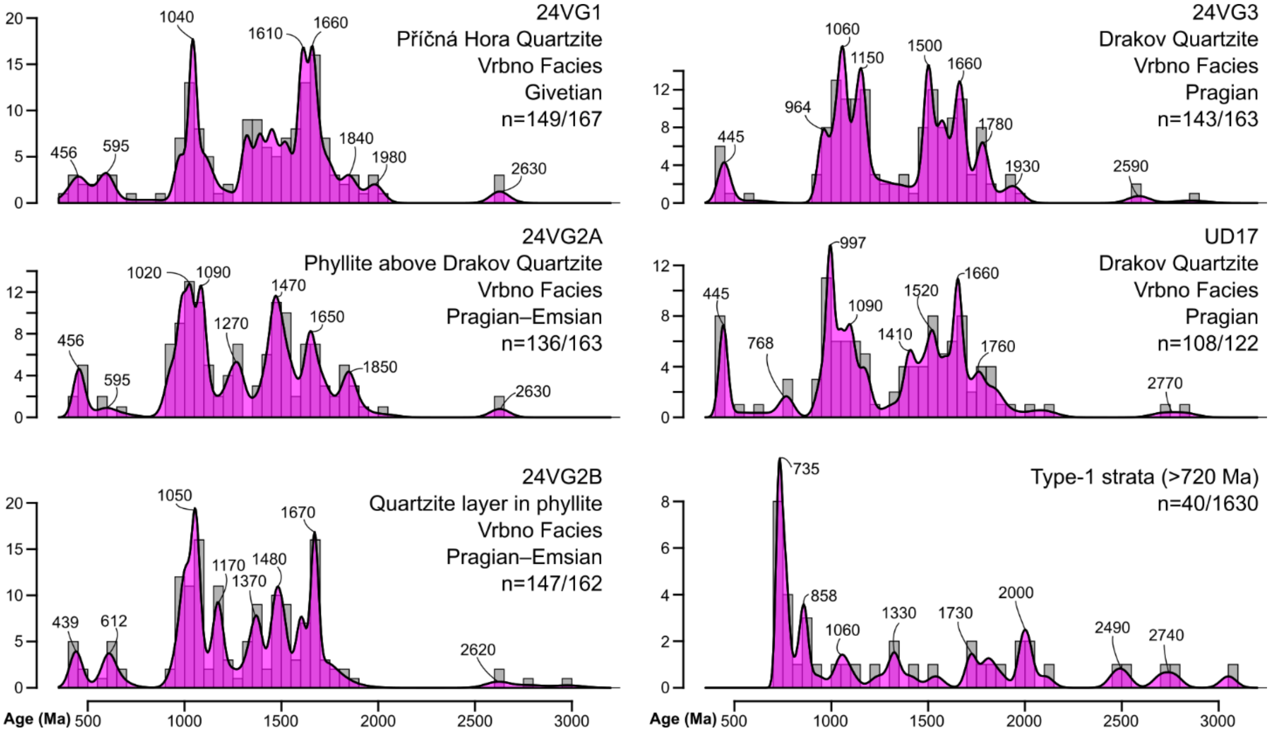

Figure 6: Kernel Density Estimates and histograms for the Type-2 samples and compiled >720 Ma zircons in the Type-1 strata for comparison.

The oldest zircons in the Type-2 samples are Mesoarchean, with a relatively consistent Neoarchean population (~2600 Ma) present in all samples except UD17. A distinct age gap follows, with the next oldest grains appearing around 2100 Ma. Pronounced age maxima occur in the late Orosirian and early Statherian, followed by a widespread late Statherian peak (~1670–1650 Ma) present in all samples. Similar, consistent peaks are observed during the Calymmian (1600–1400 Ma), while Ectasian (1400–1200 Ma) zircons are generally sparse, except for discrete maxima in sample 24VG2B (~1370 Ma) and 24VG2A (~1270 Ma). All samples contain abundant Stenian to early Tonian zircons (1200–900 Ma), with distinct peaks between 1170 and 960 Ma.

Only 20 of 678 concordant analyses in Type-2 samples fall within the Terreneuvian to end-Cryogenian range that dominates the Type-1 samples. Type-2 samples also include a notable Paleozoic component (n = 38), mainly spanning the Late Ordovician to the Llandovery Epoch of the Silurian (458–433 Ma). Only one concordant grain, from the Givetian Příčná Hora Quartzite (24VG1), yielded a Devonian age (389 ± 12 Ma) approximating the inferred stratigraphic age.

4.2 Lu-Hf isotopic data

Zircons from ten representative samples were further studied using Lu–Hf isotopic analyses. These samples cover a diverse range of facies domains and stratigraphic ages. In total, 241 spot analyses were performed. Notably, the Type-2 samples are characterized by small (20–50 µm), often fractured zircons, which limited the available material for the 45 µm laser spot size required in Lu–Hf isotopic analysis.

In each of the Type-1 samples, late Neoproterozoic zircons predominantly yield positive $\varepsilon_{Hf(t)}$ values, mostly within the range of +4 to +10 (Fig. 7). The main exception is sample 24VG4A, which contains a cluster of six analyses with $\varepsilon_{Hf(t)}$ values between −7.5 and −10. However, the majority of data from this sample (n = 22) share positive $\varepsilon_{Hf(t)}$ values consistent with other type-1 samples. Additionally, single Late Neoproterozoic zircons in both 24BR1 and UD53 show overlapping negative εHf(t) values with the outliers from 24VG4A. Sample UD53 is notable for its higher abundance of late Ediacaran (560–550 Ma) zircons compared to other samples, but these late Ediacaran zircons exhibit a similar range of positive $\varepsilon_{Hf(t)}$ values as earlier Ediacaran zircons.

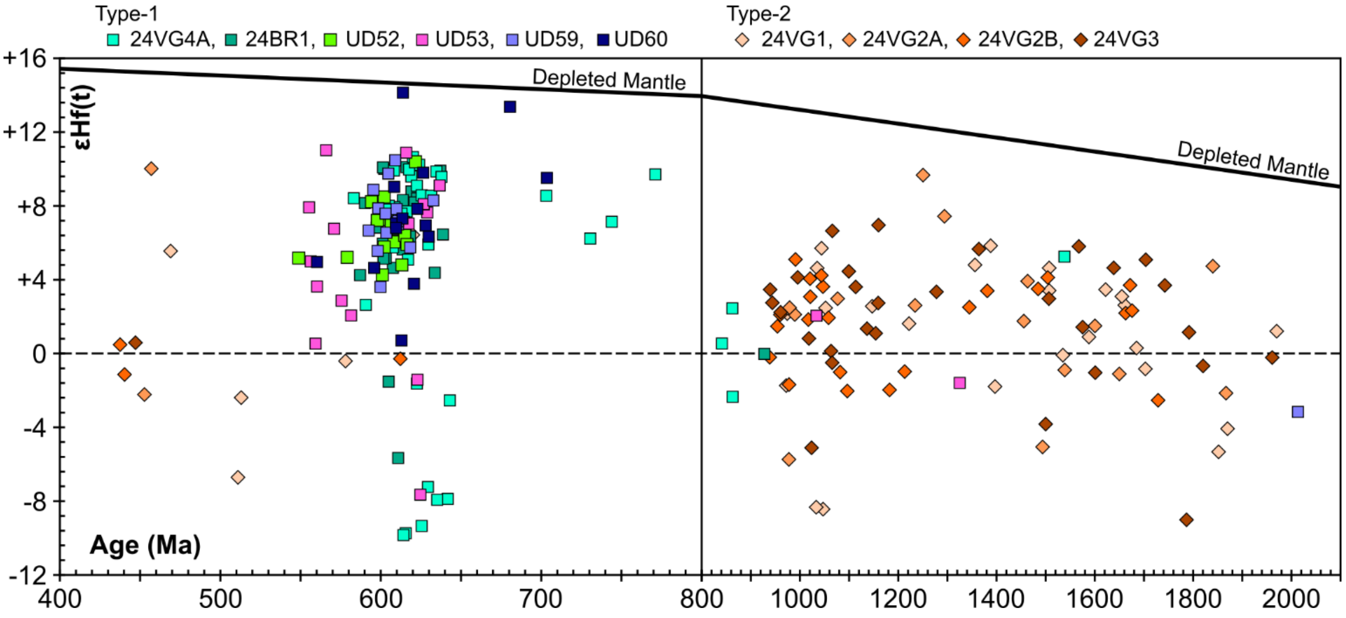

Figure 7: Age versus $\varepsilon_{Hf(t)}$ plot for the studied zircons from the Brunia Devonian clastics.

Cryogenian zircons in sample UD60 exhibit highly positive $\varepsilon_{Hf(t)}$ values (+9.3 and +13.1), as do Cryogenian and Late Tonian zircons (n = 4) in 24VG4A (+6 to +9.5). In contrast, mid-Tonian zircons in 24VG4A (~850 Ma, n=3) plot on either side of the

Chondritic Uniform Reservoir (CHUR) line, while a single early Tonian (~930 Ma) zircon in 24BR1 has a similar $\varepsilon_{Hf(t)}$ value of −0.2. Older scattered data points from the Type-1 samples cluster near and on both sides of the CHUR line.

In the Type-2 samples, approximately 70 % of zircons aged between 2000 and 900 Ma yield positive $\varepsilon_{Hf(t)}$ values within a range of −8.9 to +9.6. The distribution forms a slight crescent shape, with the oldest and youngest zircons showing the most negative $\varepsilon_{Hf(t)}$ values, and the highest positive values observed in intermediate-aged zircons (1300–1250 Ma).

Two Neoarchean data points (not shown in Fig. 7) yield CHUR-like $\varepsilon_{Hf(t)}$ values (−0.2 and −0.5). Among three late Neoproterozoic zircons, one has a positive $\varepsilon_{Hf(t)}$ value (+6.1) similar to the Type-1 strata, while the other two show CHUR-like values (−0.6 and −0.7). Two Cambrian (~510 Ma) zircons display negative $\varepsilon_{Hf(t)}$ values (−2.7 and −7), two Middle Ordovician zircons exhibit positive values (+5.2 and +9.7), and four Late Ordovician to Silurian zircons present CHUR-like values ranging from −2.5 to +0.3.

5. Discussion

5.1 Sources and significance of Type-1 zircon spectra

The Type-1 zircon spectra display a nearly unimodal population centred in the late Neoproterozoic, with Hf-in-zircon isotopic compositions clustered at positive εHf(t)values. While a few older zircons appear scattered across the early Neoproterozoic, Mesoproterozoic, Paleoproterozoic, and Archean, these populations are statistically insignificant. This distribution suggests that the zircon source is relatively local, with limited mixing from external sources.

The late Neoproterozoic zircon ages correspond well with granitoids and their metamorphosed equivalents widespread in the Slavkov and Thaya domains, as well as the Moravian and Silesian nappes. However, the narrow age range and consistently positive $\varepsilon_{Hf(t)}$ values strongly point to the Slavkov Domain and Desná Dome (par-autochthonous part of Silesian nappes) as the most plausible sources. This is supported by the juvenile isotopic signatures of (meta-)granitoids in these areas ($^{87}Sr/^{86}Sr_{(580Ma)}$ = 0.703–0.705; $\varepsilon_{Nd(580Ma)}$ = −1 to +4; Finger et al., 2000; Hanžl et al., 2007; Krmíčková et al., 2025).

In contrast, granitoids of the Thaya Terrane show more mature crustal signatures ($^{87}Sr/^{86}Sr_{(580Ma)}$ = 0.708–0.712; $\varepsilon_{Nd(580Ma)}$ = −1 to −7; Finger et al., 2000; Soejono et al., 2017), making them less likely sources. Similarly, allochthonous meta-granitoids in the Moravian and Silesian nappes exhibit mature crustal signatures ($^{87}Sr/^{86}Sr_{(580Ma)} \approx 0.7101$; $\varepsilon_{Nd(580Ma)}$ = −5 to −11) and contain significant xenocrystic Mesoproterozoic zircon components (Hegner and Kröner, 2000; Friedl et al., 2004; Soejono et al., 2017), further excluding them as contributors.

5.1.1 Discriminating Ediacaran and Devonian clastics

Surface clastic strata of the pre-Variscan Brunia units have traditionally been assigned to Devonian basal clastics, based on limited faunal evidence and stratigraphic continuity with Devonian limestones (Zukalová and Chlupáč, 1982). However, the discovery of marine Ediacaran to early Cambrian acritarchs in borehole-derived clastics suggests some may be older (Mikuláš et al., 2008; Vavrdová and Dašková, 2011). Recent detrital zircon studies have revisited this issue. Jastrzębski et al. (2021), Soejono et al. (2022), and Timmerman et al. (2023) presented zircon age spectra from Brunia, including samples from confirmed Ediacaran units and clastics previously mapped as Devonian. Jastrzębski et al. (2021) studied samples from the Silesian nappes, while Timmerman et al. (2023) focused on the Moravian Karst Facies Domain. In both cases, mapped Devonian clastics were reinterpreted as Ediacaran based on the absence of Paleozoic zircons and similarity to Ediacaran age spectra also citing earlier findings by Košler et al. (2014), who reported Cambrian zircons from a single sample. Timmerman et al. (2023) further supported their interpretation with ash layers dated to ~550 Ma, though these were limited to basal part of the clastic succession in areas east of the Slavkov granitoids.

Our new data contest these reinterpretations. Paleontologically constrained Devonian clastics and interbeds within Devonian limestones consistently show unimodal zircon age spectra peaking in the late Ediacaran. To assess the reliability of distinguishing Ediacaran–Cambrian from Devonian units via zircon geochronology, we compiled and compared all published Brunia detrital zircon datasets (Fig. 8).

Figure 8: Compiled detrital zircon data in the 700–500 Ma range from Brunia strata that exhibit a near unimodal late Neoproterozoic age peak. N value represents the number of concordant (concordia distance <5) zircons in the 700–500 Ma range versus total number of concordant grains. The data used in the construction of this figure was compiled in Collett (2025).

The compiled data clearly show that both Ediacaran and Devonian strata are characterized by nearly identical unimodal zircon age spectra, with peaks in the late Neoproterozoic. While true Ediacaran samples typically exhibit broader age distributions and a slightly higher proportion of older zircons, these differences are minor and insufficient for reliable stratigraphic differentiation. Some variation in peak ages exists. For example, sample Ceská1 (Timmerman et al., 2023) peaks near ~650 Ma, likely reflecting proximity to ~650 Ma meta-igneous rocks (Hanžl et al., 2019). Sample Jabl1 shows a distinct ~550 Ma peak, but its interpretation is uncertain, as Timmerman et al. (2023) did not examine hand specimens or thin sections. But, otherwise it appears the U–Pb detrital zircon isotopic data alone is not able to discriminate between Ediacaran–early Cambrian and Devonian strata.

Nonetheless, there are potential subtle differences from Hf-in-zircon isotopic data (Fig. 9a). Ediacaran strata (Soejono et al., 2022) include ~600 Ma zircons with both positive and slightly negative (centred around –2) $\varepsilon_{Hf(t)}$ values, while Devonian strata analyzed here generally lack this slightly negative component. The group of c.600 Ma zircons with even more negative $\varepsilon_{Hf(t)}$ values in sample 24VG4A are also not represented in the data from Ediacaran strata. Tentatively, the former finding may indicate that both Slavkov and Thaya terrane granitoids (or isotopically similar sources) were exposed to erosion during the Ediacaran, with only Slavkov sources contributing detritus during the Devonian. However, further Hf isotope data are needed to test this hypothesis.

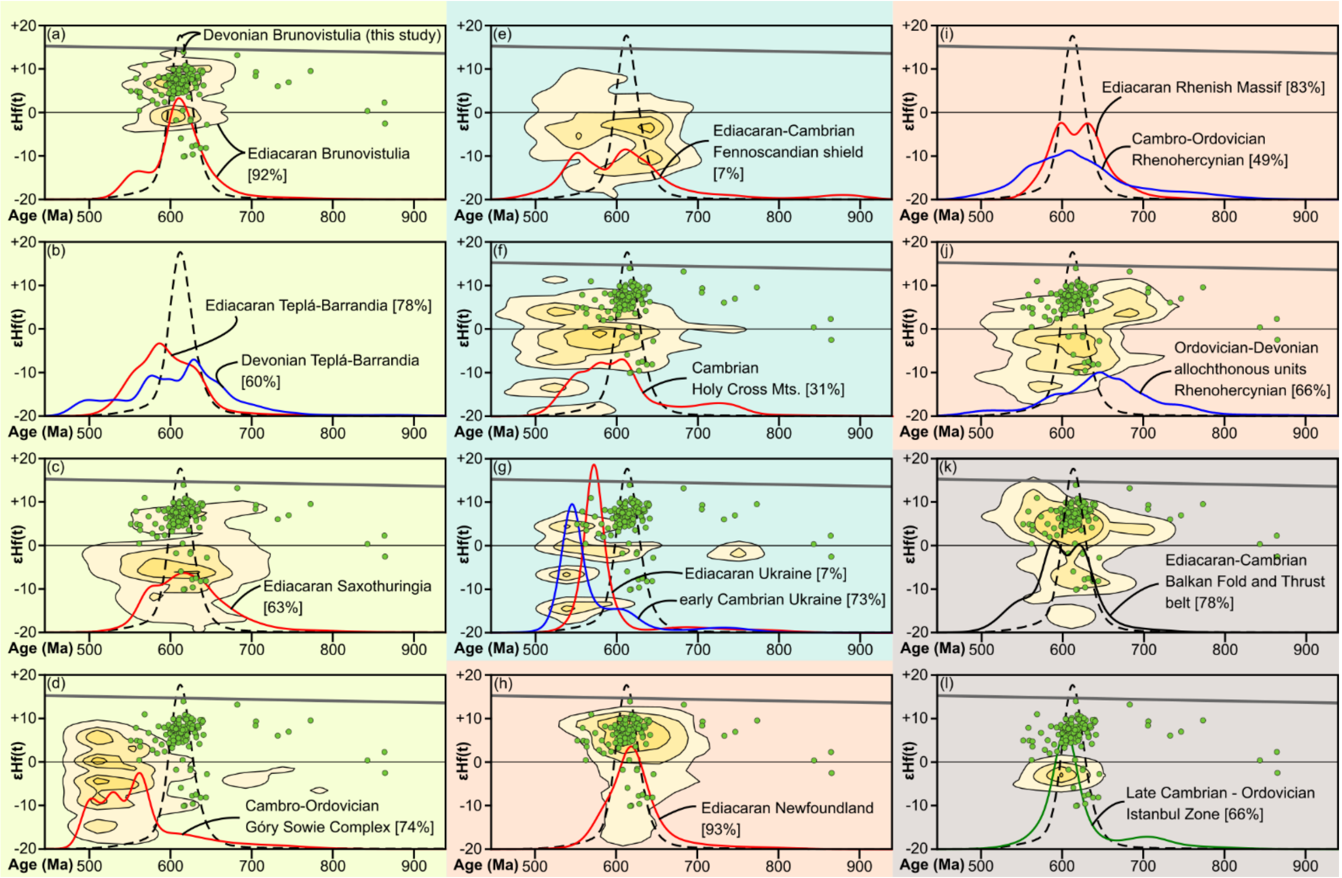

Figure 9: Compiled U–Pb and Lu–Hf isotopic data from Neoproterozoic–early Paleozoic zircons in the Bohemian Massif (a–d), SW marginal Baltica (e–g) and Avalonian (h–j) and Far-East Avalonia (k,l) Ediacaran – Devonian strata. Number in percentages equals the percentage of all concordant zircon analyses in the range 900–485 Ma. Compiled data used to construct this figure are from the detrital zircon database in Collett (2025), a full list of data sources is provided in Section S3.

5.1.2 Wider paleogeographic significance

With the Type-1 zircon spectra predominantly reflecting erosion of local sources within the Slavkov Domain (or isotopically equivalent units), these data provide limited direct constraints on the Devonian paleogeography of Brunia. Nonetheless, the detrital zircon record offers insights into Neoproterozoic correlations with other terranes, particularly the internal Bohemian Massif, Baltica's SW margin, and Avalonian terranes (see Sect. 1).

Previous studies (e.g., Košler et al., 2014; Soejono et al., 2022) have suggested links between late Neoproterozoic magmatism in Brunia and thick Ediacaran to early Cambrian successions within the internal Bohemian Massif, known for their abundance of late Neoproterozoic zircons. However, when comparing detrital zircon data from Brunia to other Bohemian Massif strata (Fig. 9b–d), a key distinction arises: Ediacaran to Cambrian strata elsewhere in the Bohemian Massif exhibit more diverse detrital sources, characterized by broader Neoproterozoic age maxima and significant (>20%) contributions of Paleoproterozoic zircons. Where hafnium isotopic data exist; for example, from Ediacaran strata in Saxo-Thuringia (Linnemann et al., 2014, 2018) and Cambro–Ordovician strata of the Góry Sowie Metamorphic Complex (Tabaud et al., 2020), a wider range of $\varepsilon_{Hf(t)}$ values is observed, including abundant zircons with negative $\varepsilon_{Hf(t)}$ signatures. This contrasts with the more restricted and generally positive $\varepsilon_{Hf(t)}$ values observed in Brunia strata.

These differences suggest that, while Brunia may have contributed some late Neoproterozoic detrital material to Saxo-Thuringia or Teplá-Barrandia, these regions also received detritus from additional sources beyond the Brunia catchment. Consequently, and in contrast to the model proposed by Soejono et al. (2022), if Brunia and the internal Bohemian Massif domains (Teplá-Barrandia, Saxo-Thuringia) shared a Neoproterozoic relationship, it is more plausible that Brunia occupied an oceanward (fore-arc) position relative to the cratonward (back-arc) position of Teplá-Barrandia and Saxo-Thuringia.

Alternatively, recent U–Pb zircon data from southwestern Baltica indicate a significant input from a source region characterized by late Neoproterozoic primitive magmatism, with Brunia considered one of the more plausible candidates. However, these late Neoproterozoic zircons; identified across a broad region from the Fennoscandian Shield (Sláma, 2016; Fig. 9e), through the Holy Cross Mountains in Poland (Callegari et al., 2025; Fig. 9f), to the western margin of the Ukrainian Shield (Paszkowski et al., 2021; Fig. 9g), show more diverse sources than those found in either the Ediacaran or Devonian strata of Brunia. In particular, Baltica's marginal strata contain a significant component of latest Ediacaran to Cambrian zircons with varied $\varepsilon_{Hf(t)}$ signatures notably absent in Brunia strata. The isotopic and age similarities between these zircons and those from the Góry Sowie Metamorphic Complex in the Bohemian Massif (Fig. 9d) led Collett et al. (2022a) to propose a paleogeographic link between these regions.

Recent chronological and isotopic work on the Neoproterozoic Brunia basement has led to discussion on the similarity between arc magmatism in Brunia and West Avalonia (e.g. Krmíčková et al., 2025). This correlation is re-emphasized by comparison of our detrital zircon data with both U–Pb and Lu–Hf detrital zircon data from late Neoproterozoic strata of the Avalon Peninsula, Newfoundland (e.g., Beranek et al., 2023; Gómez et al., 2025). The West Avalonia late Neoproterozoic strata exhibit strikingly similar detrital zircon spectra to Brunia's, with over 90 % of all zircons in the 900–485 Ma range and dominance of positive $\varepsilon_{Hf(t)}$ values within these zircons (Fig. 9h).

Within East Avalonian terranes in Central Europe Ediacaran strata are rare, but detrital zircon data from a single occurrence in the Rhenish Massif exhibit a concentrated ~600 Ma maxima (Fig. 9i) resembling the data from Brunia. However, Cambrian–Ordovician strata differ in that they display a broader range of Neoproterozoic ages and considerably greater proportion of older than Neoproterozoic zircons. Autochthonous Devonian strata from the Rhenohercynian zone yield spectra comparable to Brunia's Type-2 Devonian strata and are discussed in the next section (5.2.). No Hf-in-zircon isotopic data is available for autochthonous Rhenohercynian strata. Data is available from allochthonous Ordovician–Devonian units (in Mende et al., 2019), however, these reveal isotopic diversity similar to Saxo-Thuringia (Fig. 9j), suggesting Brunia is unlikely to be a source for these strata.

Avalonian-associated terranes are thought to also continue SE from Brunia around the Moesian Platform and in the Istanbul Zone in NW Turkey. Recent U–Pb and Lu–Hf zircon isotopic data (in Žák et al., 2026) from the Balkan Fold and Thrust Belt (southern margin of the Moesian Platform) reveal similar c.600 Ma maxima and positive $\varepsilon_{Hf(t)}$ values to those observed in Brunia (Fig. 9k). In the Dobrogea region (north-eastern part of the Moesian Platform) late Neoproterozoic–early Cambrian turbidites with ~600 Ma maxima are also present, but these also contain significant proportions (>75 %) of older detrital components (not depicted in Fig. 9). Nonetheless, some Paleozoic strata with unimodal ~600 Ma maxima have also been identified in boreholes in this region (e.g., GM-087 in Balintoni and Balica, 2016), though the stratigraphic age of this sample is poorly constrained. In the Istanbul Zone, late Cambrian–Ordovician strata also show ~600 Ma maxima, but Hf isotopic data (in Yılmazer et al., 2025) cluster near slightly negative $\varepsilon_{Hf(t)}$ values (Fig. 9l), contrasting with the positive values in the Brunia Devonian strata. Nonetheless, these data overlap with the slightly negative $\varepsilon_{Hf(t)}$ values in Brunia's Ediacaran strata, which may suggest an isotopic equivalent of the Thaya Terrane was exposed near the Istanbul Zone in the early Paleozoic.

Overall, these comparisons support Brunia as a segment of the Neoproterozoic Avalonian arc, fragments of which are today scattered along Baltica's southwestern margin. While Avalonia's Neoproterozoic provenance is debated (Baltica vs. Amazonian Gondwana affinity; see Murphy, 2023 or Beranek et al., 2023), its Paleozoic drift from Gondwana and accretion to Baltica/Laurentia are better constrained. Thus, if there was a Neoproterozoic link between Brunia and West Avalonia this was likely already broken by the early Cambrian since faunal and paleomagnetic data suggest that Brunia was already accreted to Baltica by this time (Belka et al., 2002; Nawrocki et al., 2004, 2021). Nonetheless, it is important to highlight that Brunia was probably not the primary source of late Neoproterozoic and early Cambrian detrital zircons found in Baltica's Cambrian strata as previously suggested in Collett et al. (2022a).

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5.2 Sources and significance of Type-2 zircon spectra

5.2.1 An internal Brunia-derived source?

The Type-2 zircon spectra are dominated by zircons with isotopic ages between 1800 and 900 Ma, with minor contributions of Neoarchean (~2600 Ma), Ediacaran (~600 Ma), and Late Ordovician–Silurian (460–430 Ma) zircons. Strata with similar abundances of late Paleoproterozoic to early Neoproterozoic zircons have previously been documented from Brunia (e.g., Soejono et al., 2022). These include the host rocks of the Thaya Domain granitoids, which must predate the early Ediacaran emplacement of these granitoids, as well as the Bílý Potok Group of uncertain age, exposed above the Dřínová Thrust in the Moravian Nappes. This thrust separates the Devonian cover (Tišnov Facies Domain, sample UD52, this study) of the Neoproterozoic basement from the allochthonous Moravian nappes.

Additional samples rich in 1800–900 Ma zircons include a mica-schist from the Velké Vrbno Dome, the westernmost nappe of the Silesian Domain (Jastrzębski et al., 2021), and a paragneiss from the Drosendorf Unit in Lower Austria (Sorger et al., 2020). While the Drosendorf Unit lies in the hanging wall of the Moldanubian Thrust, Sorger et al. (2020) consider it an underthrust segment of Brunia and notably, it also contains exotic Mesoproterozoic (~1400 Ma) meta-igneous rocks (Lindner et al., 2021). Clasts rich in 1800–900 Ma zircons are also documented by Timmerman et al. (2023) within their Basal Clastics, and similar-aged zircons occur as xenocrysts in Ediacaran meta-igneous rocks, most prominently within the Bíteš orthogneiss (Soejono et al., 2017). Though a minor component, 1800–900 Ma zircons are also present in the Ediacaran strata and in Type-1 Devonian samples analyzed in this study.

Crucially, the distribution of these 1800–900 Ma zircons is not uniform across all samples, enabling the identification of three distinct provenance signatures. This classification was first proposed by Collett (2025) and is further refined here using Multi-Dimensional Scaling (MDS), a statistical technique that visualizes similarities in age distributions by plotting samples with similar spectra closer together and dissimilar ones further apart (Vermeesch, 2013).

In the resulting MDS plot (Fig. 10), the combined >800 Ma components of the Type-1 strata and the Ediacaran strata cluster closely with the Bílý Potok Group (sample UD11) and a clast from Timmerman et al.'s Basal Clastics (Hády-1), collectively referred to as Cluster-1. A second cluster (Cluster-2) includes the host rocks of the Thaya Domain granitoids (UD16 and UD23), the Velké Vrbno Dome sample (SUD42/3), the Drosendorf Unit (DR), xenocrystic components in the Bíteš orthogneiss, and a second clast from Timmerman et al.'s Basal Clastics (Bil-4). Notably, the Type-2 strata analyzed in this study form a distinct third cluster (Cluster-3), spatially isolated from the other two groups in MDS space.

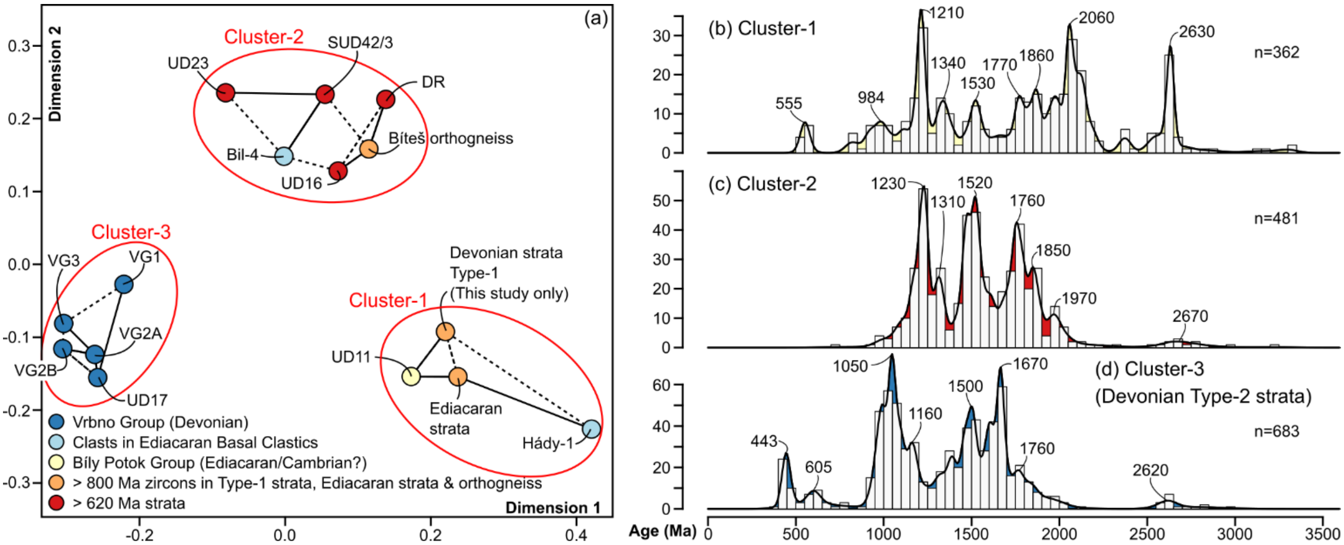

Figure 10: (a) MDS plot for selected samples from Brunia as well as compiled data from >800 Ma zircons from Type-1 strata, Ediacaran strata and the Bíteš orthogneiss. Note that only >800 Ma zircons are used so as not to overwhelm the statistical comparison with late Neoproterozoic zircons that are minor component in other samples. (b–d) Representative histograms and KDE plots of the data included in each cluster. Data used in construction of this figure was compiled in Collett (2025).

To further explore intra-cluster differences, KDE plots of the compiled data from each cluster were generated. Cluster-1 (Fig. 10b) is notable for significant peaks at ~2630 and 2060 Ma, features that are relatively minor in the other clusters, as well as a prominent maximum at ~1210 Ma, which coincides with a relative minimum in the Type-2 Devonian strata (Cluster-3). Cluster-2 (Fig. 10c) is characterized by a three-pronged maximum at ~1800, 1500, and 1230 Ma. Notably, the late Mesoproterozoic to early Neoproterozoic zircons that dominate the Type-2 Devonian spectra are largely absent in Cluster-2. Additionally, the significant ~1600 Ma maximum in the Type-2 Devonian strata (Cluster-3, Fig. 10d) corresponds to a general minimum in Cluster-2 samples.

Given the geological context of each sample, it may be speculated that Cluster-1 represents the provenance signature of the Slavkov Domain basement, whereas Cluster-2 reflects a provenance signal from the Thaya Domain and the Moravian and Silesian Nappes. Regardless, the distinctiveness of Cluster-3 suggests that our Type-2 zircon spectra do not represent a provenance signal sourced from within Brunia. As such, it is necessary to look beyond Brunia to identify the likely sources of these zircons.

5.2.2 Similar sources in the Devonian of the Bohemian Massif

As a first-order comparison, data from the Type-2 strata are evaluated against published zircon data from the Bohemian Massif (Fig. 11). Although data from the crucial Early Devonian time interval remain relatively sparse, an increasing number of datasets are now available for Middle to Upper Devonian strata. Samples from Famennian strata of the Bardo Basin and Frasnian(?) strata of the Kłodzko Complex (both from Jastrzębski et al., 2025), as well as Givetian strata from the Prague Basin (Strnad and Mihaljevič, 2005; Drost et al., 2011) and the Sedlčany–Krásná hora roof pendant (Žák and Sláma, 2018);

all belonging to Teplá-Barrandia or its Sudetes equivalent, are highly dissimilar to the Type-2 spectra. These samples also show limited resemblance to the Type-1 spectra, primarily due to either significant Paleozoic zircon components or a greater abundance of Paleoproterozoic zircons.

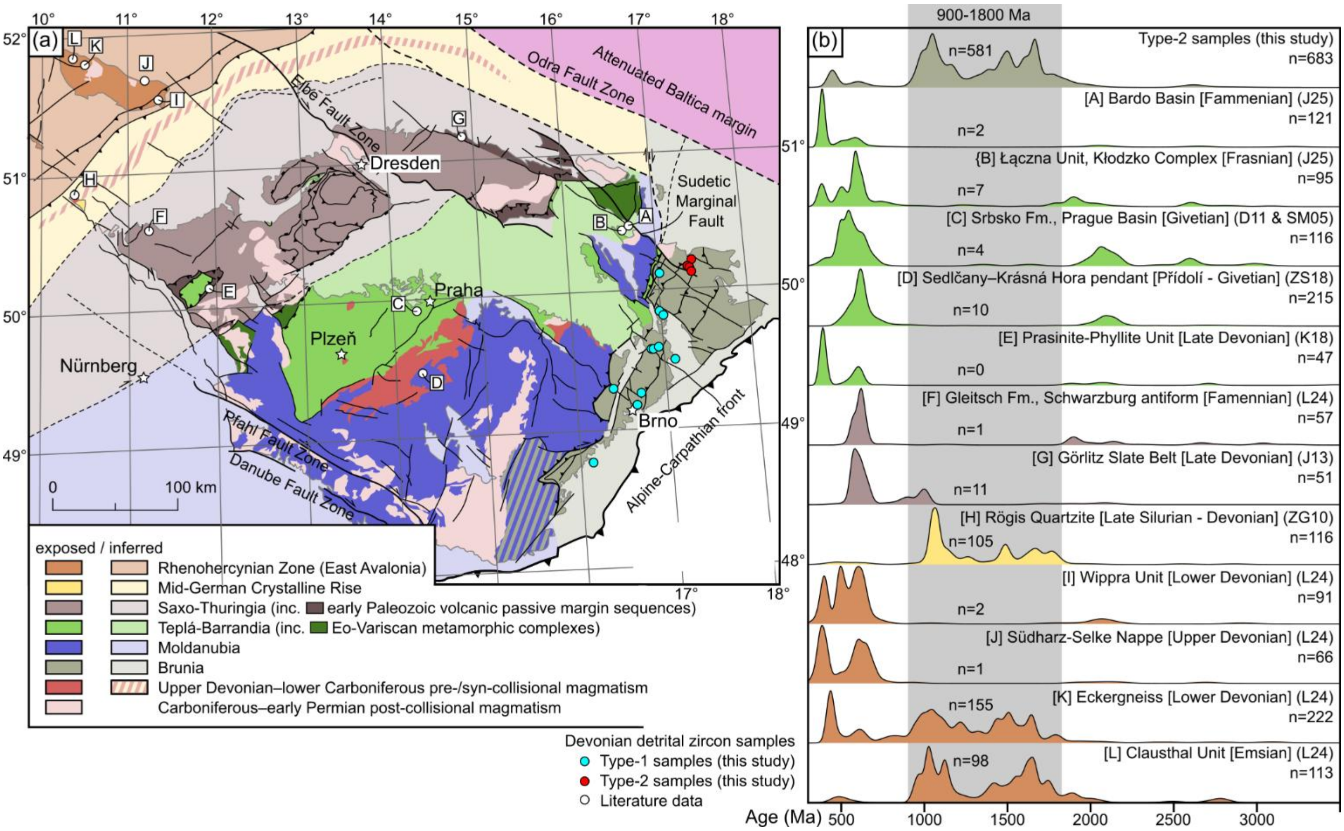

Figure 11: Comparison of published zircon U–Pb data from Devonian strata in the Bohemian Massif. J25: Jastrzębski et al. (2025); D11: Drost et al. (2011); SM05: Strnad and Mihaljevič (2005); ZS: Žák and Sláma (2018); Koglin et al. (2018); L24: Linnemann et al. (2024); J13: Jähne et al. (2013); ZG10: Zeh and Gerdes (2010).

Upper Devonian strata of Saxo-Thuringia also show strong dissimilarity to the Type-2 spectra. Although a sample from the Görlitz Slate Belt (Jähne et al., 2013) contains a significant population of Stenian zircons, these are interpreted to differ from the Stenian zircons characteristic of the Type-2 spectra; a point elaborated upon later (see sect. 5.2.4). A more promising correlation is found with the Late Silurian to Lower Devonian Rögis quartzite from the Mid-German Crystalline Rise (Zeh and Gerdes, 2010), which contains similar abundances of 1800–900 Ma zircons and overlapping (though not always proportionally identical) maxima with the Type-2 spectra. The tectonic relationship of the Rögis quartzite and the wider Mid-German Crystalline Rise to Saxo-Thuringia is uncertain but it is generally considered to represent the northern extension of Saxo-Thuringia (e.g. Linnemann et al., 2025).

More robust correlations emerge from recent data published by Linnemann et al. (2024) on Devonian strata in the Harz Mountains, part of the Rhenohercynian Zone north of the Mid-German Crystalline Rise. Here, the upper allochthonous strata in the south (Wippra Unit, Sudharz Selke Nappe) bear no resemblance to the Type-2 spectra; instead, their zircon age distributions more closely resemble those of Teplá-Barrandia. In contrast, autochthonous Lower Devonian strata in the north (Clausthal Unit) and the lowermost nappe unit (Ecker Gneiss) exhibit an almost identical distribution of 1800–900 Ma zircons to that found in the Type-2 spectra. The main differences lie in the relative abundances of late Neoproterozoic and early Paleozoic zircons, which are more abundant in the Ecker Gneiss and less abundant in the Clausthal Unit compared to the Type-2 spectra.

5.2.3 A vast Caledonian fan?

Linnemann et al. (2024) argue that the source of the 1800–900 Ma zircons in the Lower Devonian strata of the Harz Mountains is uplifted Baltica crust within the Caledonian Mountains. Zeh and Gerdes (2010) reached a similar conclusion for the Rögis Quartzite. While both studies equivocate regarding the source of Late Ordovician and Silurian zircons, they are generally assumed to have been derived from local arc magmatism associated with the closure of the Rheic Ocean.

A potential original source for the 1800–900 Ma zircons in Brunia Type-2 strata within Fennoscandia is supported by the close similarity in detrital zircon spectra and Hf-in-zircon isotopic data between Brunia Type-2 samples and Late Ordovician–Silurian strata from the Oslo Rift (Kristofferson et al., 2014; Sláma, 2016). The only age population in the Brunia Type-2 samples not well represented in the Fennoscandian strata are late Neoproterozoic zircons (Fig. 12a), which may indicate some admixture from the Brunia basement in the Type-2 strata. Notably, Ordovician–Silurian zircons of broadly similar isotopic composition are well represented in Fennoscandian strata, suggesting even these may potentially have originated from Fennoscandia.

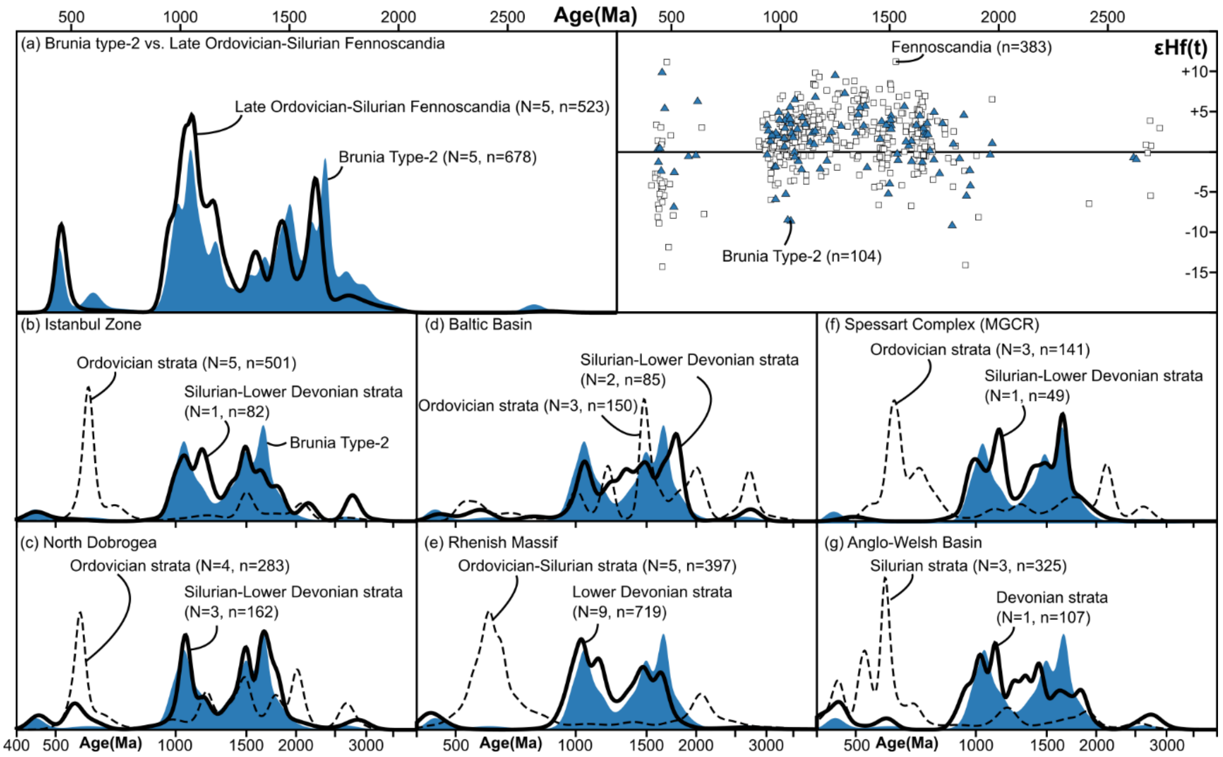

Figure 12: Comparison of Brunia Type-2 detrital zircon data with compiled published data from Late Ordovician–Silurian strata of Fennoscandia (a) as well as Late Silurian – Lower Devonian strata from the (b) Istanbul Zone (Akdoğan et al., 2021), (c) North Dobrogea region (Beștepe and Cerna formations in Balintoni and Balica, 2016), (d) Baltic Basin in Estonia (Põldvere et al., 2014), (e) Rhenish Massif (Eckelmann et al., 2014; Linnemann et al., 2024; Dörr et al., 2025), (f) Spessart Complex in the Mid-German Crystalline Rise (Kirchner and Albert, 2021), and (g) Anglo-Welsh Basin (Waldron et al., 2025). Data used in the construction of this figure is compiled in Collett (2025).

On a broader scale, Upper Silurian to Lower Devonian strata with strikingly similar detrital zircon spectra are documented across diverse terranes in northern and central Europe, extending into Anatolia. Examples depicted in Fig. 12 include the Istanbul Zone (Akdoğan et al., 2021); the North Dobrogea region (Beștepe and Cerna formations in Balintoni and Balica, 2016); the Baltic Basin in Estonia (Põldvere et al., 2014); the Rhenish Massif (Eckelmann et al., 2014; Dörr et al., 2025); the Spessart Complex of the Mid-German Crystalline Rise (Kirchner and Albert, 2021); and the Anglo-Welsh Basin (Waldron et al., 2025). In each of these regions, the detrital zircon spectra of Upper Silurian–Devonian strata represent a marked shift from those recorded in older units (Fig. 12).

At an even greater scale, similar spectra are also reported from the Orcadian Basin in NE Scotland (Strachan et al., 2021); Givetian–Famennian strata in East Greenland (Sláma et al., 2011); Silurian–Devonian Sandstones from Svalbard (Beranek et al., 2020; Anfinson et al., 2022) and northern Novaya Zemlya (Lorenz et al., 2013); and the Devonian parts of the Acadian foreland basin in North America (Bradley and Sullivan, 2017; Perrot et al., 2025). This should not be taken to imply a single vast interconnected basin, but rather a network of detrital pathways likely reflecting multiple erosional–depositional cycles with limited in-transit mixing, and originally derived from a relatively restricted source region; most likely in Baltica-derived crust within the Caledonian Mts. (Fig. 13).

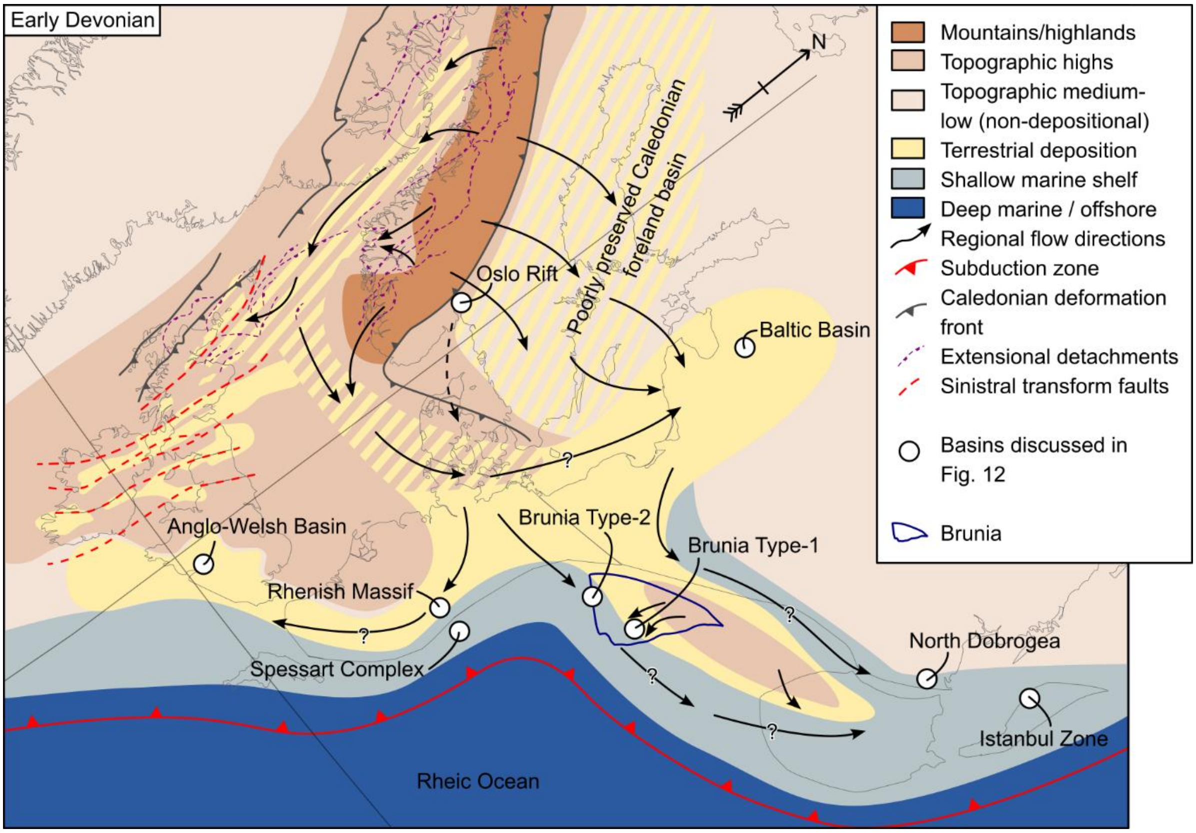

Figure 13: Conceptual paleogeographic map for the Lower Devonian indicating the distribution pattern of detritus from the Scandinavian Caledonian Mountains into Devonian terrestrial and shallow marine basins discussed in this work. Also highlighted is the exposed Slavkov Terrane basement in the east of Brunia that fed the Type-1 samples. Figure influenced by Cederbom et al. (2000); Fossen (2010); and Davies et al. (2024).

The preference for a Baltica rather than a Laurentia source is reflected in the relative proportions of early versus late Mesoproterozoic zircon populations. In all examples cited above these two populations are broadly balanced. In contrast, Ordovician–Silurian strata within the Acadian foreland basin are dominated by late Mesoproterozoic zircons (Bradley and Sullivan, 2017; Perrot et al., 2025). Waldron et al. (2014) likewise reported late Mesoproterozoic dominance in Laurentian-derived Ordovician–Silurian strata of the Southern Uplands Terrane in Scotland. Compare also the late Neoproterozoic strata of East Greenland (Sláma et al., 2011) with those of Fennoscandia (Sláma, 2016); the former is dominated by late Mesoproterozoic zircon and the latter exhibits a more balanced distribution of early and late Mesoproterozoic zircons. This distinction is illustrated in Fig. 14, which displays the geographic distribution of detrital zircon data from Late Ordovician to Late Devonian strata in the database of Collett (2025), classified into six provenance types based on the positions and relative abundances of zircon age maxima.

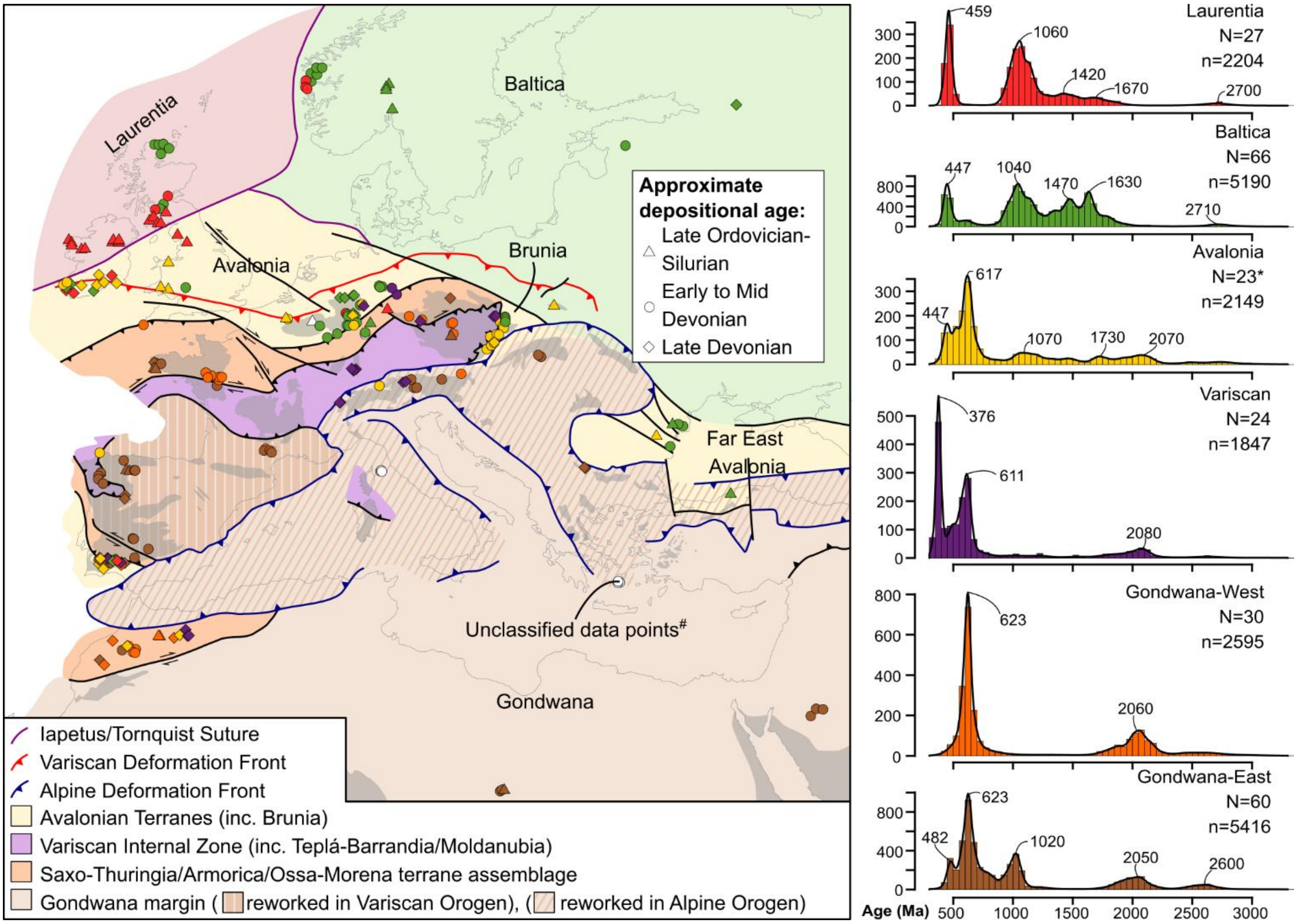

Figure 14: Distribution of Late Ordovician–Devonian strata with published U–Pb zircon isotopic data in the database of Collett (2025). Samples with high proportion of Mesoproterozoic zircons and low proportion of late Neoproterozoic are classified as either 'Laurentian' or 'Baltican' based on relative abundance of early versus late Mesoproterozoic zircons and by analogy to the Late Ordovician–Silurian strata of the Southern Uplands (Laurentia) and Oslo Rift (Baltica). 'Avalonian' samples have Late Neoproterozoic maxima and scattered presence of Meso- and Paleoproterozoic zircons. *Brunia type-1 strata of this study technically belong to this provenance but are not included in the compiled histogram due to extreme low abundance of older than Neoproterozoic zircons that would mask the presence of these zircons in other compiled data. 'Variscan' provenance are attributed to samples with prominent Devonian zircon population (min. 10%). 'Gondwana-East' and 'Gondwana-West' spectra are discriminated by the relative abundance of Stenian–Tonian maxima and the typical association of late Neoproterozoic and Paleoproterozoic maxima. #Unclassified samples in the Cyclades, on Elba island and in the Rhenish Massif have singular Ordovician or Silurian maxima. The basemap is modified from Mazur et al. (2025).

5.2.4 Implications for continuation of the Rheic Ocean in the Devonian

Not depicted in Figs. 11–14 are data from Lower Devonian strata of Saxo-Thuringia recently reported by Linnemann et al. (2025). These preliminary results, published without supporting raw data, show abundant Stenian (1200–1000 Ma) zircons. Linnemann et al. (2025) suggest that these zircons derive from a source region similar to that of the Stenian zircons found in the Lower Devonian Harz Mountains strata and the Rögis Quartzite. Their interpretation is based on a paleogeographic model assuming the complete closure of the Rheic Ocean during the late Silurian–Early Devonian and a Laurussian provenance for the Stenian zircons. It is hard to evaluate this properly without the supporting raw data; however, we are sceptical of this conclusion. Notably, the Lower Devonian Saxo-Thuringian strata appear to contain virtually no zircons in the 1700–1500 Ma range but do include appreciable Neoproterozoic (900–550 Ma) and Paleoproterozoic (2100–1800 Ma) components, with no detectable Ordovician or Silurian zircons. In these respects, the Lower Devonian Saxo-Thuringian strata differ from either the Baltica or Laurentia detrital signals depicted in Fig. 13. Instead, the influx of Stenian zircons more closely resembles that reported from Gondwanan regions, including Iberia, Armorica, the Alps, and the Western Carpathians, that are included in the Gondwana-East provenance signal in Fig. 13 (see more detailed discussions on this topic in Soejono et al., 2024; Collett, 2025).

A potential test of this hypothesis lies in Hf-in-zircon isotopic data. Stenian zircons in this study, as well as those from the Rögis Quartzite and Fennoscandia, exhibit a relatively limited spread in Hf isotopic values clustering near or above chondritic values ($\varepsilon_{Hf(t)}$ = –8 to +6). In contrast, Stenian zircons from Devonian strata in Iberia, Armorica, and the Western Carpathians (as well as recent Nile River sands) show a much wider range of Hf isotopic values ($\varepsilon_{Hf(t)}$ = –25 to +10), with a tendency toward more negative εHf(t) values (see figures in Soejono et al., 2024 and references therein).

If our interpretation is correct; that the Stenian zircons in Saxo-Thuringia derive from Gondwana, while the 1800–900 Ma zircons in the Type-2 Brunia strata originate from Laurussia, then the apparent lack of mixing between these two provenance signals in Devonian strata of the Bohemian Massif (Fig. 11) strongly suggests that the Rheic Ocean remained open as a barrier to detritus throughout the Devonian. In this scenario, Brunia would have been situated on the northern margin of the Rheic Ocean, with Saxo-Thuringia (and possibly also Teplá-Barrandia; although the influx of Stenian zircons is not well-documented here) lying to its south. This interpretation aligns with paleogeographic models proposed by Collett et al. (2022b), but leaves two principal unresolved questions.

The first concerns the tectonic relationship of the Rögis Quartzite, and by extension the entire Mid-German Crystalline Rise, to Saxo-Thuringia. Although often considered a northern continuation of Saxo-Thuringia (e.g., Linnemann et al., 2025), other models propose that the Mid-German Crystalline Rise internally hosts the Rheic Suture (e.g., Zeh and Gerdes, 2010).

The second issue concerns the position of the Rheic Suture within the Bohemian Massif. It is unlikely to coincide strictly with the Moldanubian Thrust, the traditional western boundary of Brunia, because the Drosendorf Unit within the Moldanubian Thrust hanging wall has a demonstrably Brunia-derived character (e.g., Sorger et al., 2020). Recent reports of Mesoproterozoic (~1.3 Ga) crustal material deeper within Moldanubia (Soejono et al., in review) further challenge the long-held assumption of a purely Gondwanan provenance for this domain. Consequently, the Rheic Suture may lie internally within Moldanubia, at the Moldanubia–Teplá-Barrandia boundary (now largely obscured by the Central Bohemian Plutonic Complex), or may yet equate to the Saxothuringian Suture. Resolving this question will require carefully targeted provenance analyses of the complex, high-grade metamorphic rocks that constitute the Moldanubian basement.

6 Conclusions

- Detrital zircon isotopic data from Devonian (pre-orogenic) strata of Brunia (easternmost European Variscides) reveal two distinctly contrasting provenance signatures. Most samples exhibit unimodal populations of late Neoproterozoic zircons with positive $\varepsilon_{Hf(t)}$ values (Type-1 spectra), indicating erosion from a local source within the Brunia basement. In contrast, a subset of samples from northern Brunia (Type-2 spectra) display broader age distributions, with prominent peaks spanning the late Paleoproterozoic to early Neoproterozoic (c. 1800–900 Ma), alongside minor populations of Neoarchean, Ediacaran, and Ordovician–Silurian zircons.
- The Type-1 spectra closely resemble detrital zircon populations from Ediacaran strata in Brunia. The stratigraphic (Ediacaran vs. Devonian) age of some clastic strata remains uncertain and zircon U–Pb data alone cannot fully resolve these age relationships. However, differences in Hf-in-zircon isotopic signatures may provide additional potential for stratigraphic discrimination.
- When combined, the Devonian and Ediacaran zircon datasets from Brunia show striking similarities to those from Ediacaran strata in West Avalonia supporting a shared Late Neoproterozoic provenance. Our findings do not support a shared Neoproterozoic history with other parts of the Bohemian Massif, nor do they suggest that Brunia was the primary source of Late Neoproterozoic zircon grains found in southwestern Baltica.
- The Type-2 spectra differ significantly from all previously reported detrital zircon datasets from Brunia, instead exhibiting strong similarity to Lower Devonian strata across Laurussia. The most plausible source for these zircons is erosion of the Caledonian mountains in Fennoscandia.
- This Caledonian-derived detritus was dispersed widely, covering regions of the modern Arctic Ocean, eastern Greenland, Atlantic North America, and extensive parts of Northern and Central Europe, extending into Anatolia. Notably, this spectral signature has not been credibly identified within the internal domains of the European Variscides, implying that the Rheic Ocean remained an effective barrier to such detrital material well into the Devonian.
- Consequently, the Rheic Suture must lie within the Bohemian Massif, although its precise location remains unresolved. A renewed focus on the provenance of high-grade rocks in the Moldanubian Zone is therefore essential to better constrain the position and nature of this suture.

Author contributions

SC: Conceptualization, Data curation, Investigation, Visualization, Writing (original draft preparation). IS: Conceptualization, Investigation, Writing (review and editing). TK: Resources, Investigation, Writing (review and editing). PH: Resources, Investigation, Writing (review and editing). JM: Methodology, Formal analysis. NN: Formal analysis. JS: Methodology, Formal analysis.

Competing interests

The authors declare that they have no conflict of interest.

Disclaimer

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