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The far-field interplay between peripheral Cenerian Orogeny and inner north Gondwanan hinterland: Cambro-Ordovician siliciclastic veneer and pre-Hirnantian unconformities (Sahara, central Libya)

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Dear Editor-in-Chief,

Please find enclosed the manuscript entitled "*The far-field interplay between peripheral Cenerian Orogeny and inner north Gondwanan hinterland: Cambro-Ordovician siliciclastic veneer and pre-Hirnantian unconformities (Sahara, central Libya)*" that we submit for the publication in *Earth-Science Reviews*.

The study provides the very first integration of the recently constrained "Cenerian" Ordovician event (orogeny) recognized in parts of central-southern Europe vs. imprints in its former North African hinterland. During the Lower Paleozoic time, there were two major paleogeographic and tectonic regions of north Gondwana. The first, embedded into the Variscan southern Europe, and second, the vast intracratonic area accommodating within North African Paleozoic basins.

We describe paleogeographic connection by providing a set of paleotectonic evidences connecting this important *pre*-Variscan or "Taconic" suture with the Sardic(Cenerian)-Sarabesse events depicted recently across southern Europe and Balkans. We additionally, include own field experience in the described areas.

The paper as an authentic study will have highest impact on the knowledge of the early evolution of the north Gondwanan Lower Paleozoic tectonics and paleogeography, and thus will attract researchers involved in the (i) Precambrian to Lower Paleozoic topics, as well as (ii) these involved in exploring prolific North African plays.

Thank you for your assistance,

Dr Darko Spahić

(Corresponding author)

In Belgrade,

02/11/2023

Highlights

- The north Gondwanan Ordovician Cenerian Orogeny, Sardic and Sarrabese tectonic phases imprinted into the southern Europe and Balkans, influenced the deposition, stratigraphic and structural setting of the Lower Paleozoic Formations deeply buried within several prolific North African basins, as well as a number of outcropping elevated heights;

- The widespread North African Lower Paleozoic clastic sequence records a number of angular unconformities, predating the major Upper Ordovician Hirnantian glacio-eustatic unconformity;

- Analysis of truncations, ironstones, detrital zircons spectra from the Lower Paleozoic Ordovician north Gondwanan clastic mega-sequences suggests the intra-Ordovician Cenerian-type interference uplift and unconformity;

- The "intra-Arenigian" unconformity which is disconnecting the Hassawnah and Hawaz Formations, contains basic-type volcanism and K-bentonites. These are correlative with the unconformity ascribed to the Sardic or Sarrabese tectonic phases recognized in the peri-Mediterranean Variscan terranes;

- The "intra-Arenigian" unconformity is consistent with Sardic and Sarabesse unconformities recognized in southern Europe, including Alps-Carpathian-Balkans.

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Abstract

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1. Introduction: Lower Paleozoic north(eastern) Gondwanan framework

There is a well-documented paleogeographic link between the transported exotic southern European basements and the (late Neoproterozoic)-Cambrian to Ordovician Gondwanan northern flank, often collectively referred to as the peri-Gondwanan terranes (e.g., Avigad et al., 2005, 2012, 2017, 2018; Kolodner et al., 2006; Murphy et al., 2006; Bahlburg et al., 2009; Balintoni et al., 2010a,b, 2014; Meinhold et al., 2011; Zulauf et al., 2015; Antić et al., 2016; Balintoni and Balica, 2016; Kroner and Römer, 2017; Žák and Sláma, 2018; Siegesmund et al., 2021; Žák et al., 2023; Fig. 1a,b). Most of the available reports provide important paleogeographic and tectonic linking of these Avalonian-Cadomian basement terranes with a north Gondwanan Neoproterozoic – Lower Paleozoic periphery (Fig. 1b; 2). The majority of the Lower Paleozoic reconstructions agree with a bipartite north Gondwanan margin characterized by the Cambrian-early Ordovician opening of the Rheic Ocean to the west (Murphy et al., 2006, 2008; Stampfli et al. 2013; von Raumer et al. 2015; Couzinié et al., 2023), whereby a convergent margin propagated towards the eastern flank (e.g., Zhao et al., 2017; Li et al., 2023; Moghadam et al., 2023; Hung et al., 2023; Wu et al., 2023). The Lower Paleozoic tectono-magmatic events associated with a north-eastern Gondwanan flank (from 490 Ma to 440 Ma), which affected Cambrian-Ordovician sedimentary cover are collectively referred to as the Cenerian Orogeny (Zurbriggen, 2015, 2017). During this period the northeastern Gondwana margin was affected by different tectonic phases, the most important of which are the so-called Sardic and Sarrabese phases (Martini et al., 1997; Oggiano and Mameli., 2006; Casas, 2010; Cocco and Funedda, 2019; Fig. 3a). However, the exact tectonic modes and the precise time and length of its interaction with the western (Moghadam et al., 2023) or rather an eastern Gondwanan periphery is still a matter of debate (Pavanetto et al., 2012; Stephan et al., 2019; Cocco et al., 2023; Spahić et al., 2023a). The unresolved controversies and tectonic mode of (i) the subsequent partitioning and (back-arc) rifting of the post-mid-Ordovician to Early Silurian northeastern Gondwanan periphery, and (ii) the precursory compression-related far-field tectonic interference on the cratonic interior (including its central North Africa branch) offer just a few contrasting explanations (Toljić et al., 2012; Hefferan et al., 2014; Zulauf et al., 2015; Stephan et al., 2019; Spahić et al., 2023a; for a discussion).

The protracted tectonic activity along the eastern Gondwanan convergent margin is preserved within some of the south European Variscan terranes and is marked by the Sardic and Sarrabese unconformities. These intra-Ordovician unconformities are related to outboard-driven crustal-scale compression resulting in a near-margin folding event affecting the Cambrian-Lower Ordovician succession (Martini et al., 1997; Leone et al., 2002; Oggiano and Mameli., 2006; Cocco et al., 2023). A dominant transgressive Lower Paleozoic trend (Ghienne et al., 2023), inclusive of the first passive margin northeastern Gondwana stage, fits into the major Cambrian - Lower Ordovician transgression and a shallow epeiric sea rise. The ancient Lower Paleozoic Proto-Tethyan Ocean spread across the shallow north Gondwanan periphery and the opposite southern Baltican craton (Baltoscandian Alum Shale Formation; Lindskog et al., 2017; Schulz et al., 2023). Such conditions allowed the widespread deposition of the Gondwanan Cambrian-Lower Ordovician clastic sequence on both, its North African hinterland (Meinhold et al., 2011) and ca. 1000 km elongated East–West flanking shelf. The clastic mega-sequence is stacked on top of the older Neoproterozoic Cadomian remnant basements (Cocco et al., 2018, 2023; Abbo et al., 2019; Cocco and Funedda, 2019; Stephan et al., 2019; Pereira et al., 2022; Loi et al., 2023; Fig. 2; Table 1). The clastic succession, which was deposited across the northeastern Gondwanan flank, was interrupted by the Middle - early Upper Ordovician outboard magmatic arc activity and the emplacement of numerous Ordovician granitoids (Zurbriggen, 2015, 2017, 2020). Such a convergent geodynamic setting, however, failed to reach a complete crustal collisional growth (Zurbriggen, 2015, 2017; Cocco and Funedda, 2019; Fig. 2). As a result, several Middle Ordovician unconformities, together with the aforementioned arc magmatism, are well-documented across southern Europe and the western Mediterranean (Casas, 2010; Cocco and Funedda, 2019; Avigad et al., 2022; Pereira et al., 2022). Recently, such pre-Variscan compressional imprints have also been documented within the Alpine sector, in particular within the Carpathian-Balkan fold-and-thrust belt (e.g., Balintoni et al., 2010a,b; Antić et al., 2016). However, documented intra-Ordovician imprints within Alps-Carpathian-Balkans have just recently been recognized as a separate tectonic event of Lower Paleozoic age (Balintoni et al., 2011; Spahić et al., 2021, 2023a; Finger and Riegler, 2023; Siegesmund et al., 2023; Starijaš-Mayer et al., 2023).

Similar to its Gondwanan paleocontinent northeastern periphery (Fig. 2, 3a,b,c,d), the subsiding large central-eastern Gondwanan intra-cratonic basins (modern-day North Africa/Algeria, Libya, Tunisia; Fig. 1a,b) experienced an increasingly active post-Pan African clastic deposition (eventually pilling up to ca. 1000–2000 m thick sequences; e.g., Ghienne et al., 2007, 2023; Abouessa and Morad, 2009; Morton et al., 2011; Le Heron et al., 2013, 2015; Aissaoui et al., 2016; Fig. 2). But unlike the pronounced intra-Ordovician deformation well-studied in southern Europe, there is a bundle of the overlapping largely underexplored pre-Hirnantian truncations widespread across the large North African cratonic interior (Crossley and Mcdougall, 1998; Ghienne et al., 2007, 2013, 2023; Toljić and El Mehdi, 2007; Sabau et al., 2009; Marović et al., 2012; Tawadros, 2012; Le Heron et al., 2013; Najem et al., 2015; Fig. 2, 3c, 4; Tables 1, 2). Despite these prolific Paleozoic basins of North Africa having global significance in petroleum geology and hydrocarbon production, these intra-Ordovician uplift markers are still poorly constrained. The presence of (angular) truncations provides first-order constraints suggesting that subsiding hinterland geodynamically interacted with some adjoining lithospheric-scale either peripheral or central Gondwanan/African tectonism. Taking into account a considerable distance from the outboard tectonically active cratonic periphery, it appears that continental-scale stress tensors would be required to produce a puzzling bundle of pre-Hirnantian unconformities (Ghienne et al., 2013; Fig. 2).

The investigated truncated Cambro-Ordovician dominantly clastic sequences are transgressively overlying the Precambrian basement or Ediacaran volcanics positioned on top of the "infra-Tassilian Unconformity" or "Pan-African unconformity" (Fig. 4). The oldest "infra-Tassilian Unconformity" is identified throughout the central and eastern Sahara (Ghienne et al., 2023). The postdating Cambrian-Ordovician successions experienced several tectonic perturbations, including those analogous to the "intra-Ordovician event" (Ghienne et al., 2013). Determination of these craton-interior inboard truncations, their age, and their correlation with the formerly flanking then detached outboard crustal-scale basement and cover sequences, is important for understanding the Ordovician geodynamic linkage between the accretion and dispersal of peri-Gondwanan terranes. However, the origin of pre-Hirnantian intracratonic tectonic perturbations as indicated by its stratigraphic record and associated compression-related truncations is far from being fully understood. The precise age span of the so-called, "intra-Ordovician" truncations is not constrained, mainly because of the absence of clear Ordovician (bio)stratigraphic markers. Available sequence stratigraphic interpretation assigned an "MRS" (Maximum Regressive Surface) event to the upper boundary of the Ash Shabiyat Formation (Tremadocian) transitioned to the onset of the Hawaz Formation (Darriwillian) (Gil-Ortiz et al., 2022). To make matters even more complicated, once truncations are present either in subsurface seismic data or at the surface, these have frequently been obscured by the imprints of the Hirnantian glaciation event (e.g., Tawadros, 2012; Marović et al., 2012; Carruba et al., 2014; Gil-Ortiz et al., 2022). Nevertheless, a number of these intra-Ordovician hinterland truncations (in particular those documented in Libya; Fig. 4) are consistent with the timing of the outboard flanking Ordovician tectonic phases which are well-documented across southern Europe (and some areas of Carpathian-Balkan fold-and-thrust belt).

Fig.1. Here

Table 1. Here

The primary goal of the following synthesis is an illustrative identification and the extent of the Ordovician peripheral north Gondwanan tectono-magmatic phases exposed within the amalgamated exotic peri-Gondwanan Variscan and Alpine basements, and correlation with their counterparts widespread across the truncated North African hinterland (focus on the Libyan sector; Fig. 1a). The Libyan central North African segment of the Gondwanan hinterland is chosen because of the spatial change in sediment feeding occurred during the Lower Paleozoic. The provenance or the exposed paleo sources that were formerly feeding this segment of Gondwana differentiate (i) the Cambrian–Ordovician sandstones of southern Algeria from those of (ii) central–southern Libya (Meinhold et al., 2013). The following synthesis offers a new interpretation based on a combination of the large volume of published data, filed mapping, including the information extracted on Cambro-Ordovician clastics crosscut by the exposed bundle of the Ordovician truncations (Fig. 4). The new geodynamic constraints also include the erosional-type low-stand equivalents or the scattered information describing available intra-Ordovician ironstone occurrences. The new interpretation additionally involves the important re-evaluation of the available detrital zircon datasets for provenance analysis (Meinhold et al., 2011, 2013; Linneman et al., 2011; Altumi et al., 2013; Antić et al., 2016; Avigad et al., 2018, 2022; Javier Álvaro et al., 2020, and references cited therein). The following synthesis initially shows why these Ordovician events/truncations seem to be left behind. The results further reveal the presence of different far-field compressional effects on the central-north Ordovician Gondwana interior (central Sahara; Libya). The correlated Ordovician peripheral and hinterland truncations attest to the hypothesis of the presence of Ordovician compression related to the northeast Gondwanan magmatic arc, further providing, for the first time, the newly mapped back-arc extensional mafic-type magmatic signals (Fig. 2a,b, 3c). The new constraints are also improving the knowledge of the main petroleum system of North Africa (e.g., Murzuq basin), and its principal reservoir play: Middle and Upper Ordovician sandstones (Hawaz and Mamuniyat reservoirs; Ramos et al., 2006; Najem et al., 2015; Gil-Ortiz et al., 2019, 2022). A similar intra-Ordovician interference can be correlated with the Berkine-Ghadames basin of North Africa, particularly with the Upper Ordovician Djeffara (and Silurian Acacus) reservoir sections (Aissaoui et al., 2016).

Fig.2. Here

Fig. 3. Here

2. Cenerian Orogeny, Sardic and Sarrabese mid-Ordovician peripheral north Gondwanan tectonic events: Definition and deformations documented in exotic peri-Gondwanan terranes

The Cenerian orogeny (480 – 460 Ma; Zurbriggen, 2015; Moghadam et al., 2023), inclusive of the associated dominant felsic magmatism at 480 Ma (Zurbriggen, 2017), represents a Lower Paleozoic peripheral structural adjustment of flanking eastern Gondwana terranes. The peri-Gondwanan terranes are comprised of Neoproterozoic Cadomian mainly metamorphic basements frequently overlain by the widespread Cambrian-Lower Ordovician clastic (mega)sequences (deposition spanning 550 to 470 Ma, Zurbriggen, 2017; Fig. 2). Defined as compressional deformations of the pre-Variscan age, mainly recorded in southern Variscan and partially within Alpine Europe (Fig. 1a,b), these have often been referred to as the Sardic and Sarrabese deformations (SW and SE Sardinia is the location with typical stratigraphic sections; Cocco et al., 2023; Fig. 3a). Alternatively, imprints of peri-Gondwanan mid-Ordovician deformations can be correlated with the "Caledonian North African orogen" (Balintoni et al. 2011a; Battaglia et al., 2012). To make the structural-tectonic interpretation even more difficult, there are some suggestions that these North African–South European Ordovician deformations are related to a distant Taconic orogenic system (e.g., Zazoun and Mahdjoub, 2011; Toljić et al., 2012; Hefferan et al., 2014; Najem et al., 2015).

2.1. From Cadomian to Cenerian north Gondwanan events: Main mechanisms

The mechanism of (Neoproterozoic)Cambro-Ordovician tectonic setting along the western and eastern north Gondwana flanks relied on the protracted southward-directed subduction of the Proto-Tethyan slab (consistent with the modern-day analogous Alaskan type setting; Zurbriggen, 2015). This precursor Cadomian magmatic arc setting was generated in response to mantle-derived bimodal dominant peraluminous magmas (anatexis) emplacement. The juvenile bimodal magmas were emplaced into the unconsolidated clastic matrix above the subduction zone (e.g., Zurbriggen, 2014, 2017; Pereira et al., 2022). This episodic upwards-directed emplacement of the rising magma into the overriding clastic detritus compensated for the ongoing southward-directed Proto-Tethyan slab and its underthrusting. Such a voluminous mainly clastic-type sourcing mode of ancient subducting trench allowed the lithospheric-scale mixing of magmas with incoming voluminous terrigenous detritus washed away from the Cadomian thickened crust (Zurbriggen, 2015; Spahić et al., 2021). Recently, such peripheral events have been subdivided depending on plate convergence rates into (i) advancing and (ii) retreating-type orogens (Oriolo et al., 2021).

Unlike the western flank, the eastern north Gondwana flank experienced the maximum activity during the mid-Ordovician: (i) compressional regional crustal-scale uplift and the formation of Sardic and Sarrabese angular unconformities (the main difference is the paleogeographic proximity to the arc itself), (ii) emplacement of widespread felsic magmatism supported by the postdating calc-alkaline extrusions (Cocco et al., 2023; Fig. 3a). The magmatic activity lasted from the Darriwilian to the middle Katian, followed by the onset of deposition of a new mainly clastic-type sedimentary succession on top of the Middle-Upper Ordovician volcanic arc (Table 1). In a number of cases documented across Europe and North Africa, the Lower Paleozoic mid-Ordovician, as well as the younger unconformities, are preserved and marked by a contemporary production of low-stand markers or ironstones (e.g., Guerrak, 1991; Young, 1992; Mücke, 2006; Baioumy et al., 2017; Abia et al., 2020; Ferretti et al., 2022; Spahić et al., 2023a, see later in the text; Fig. 3d).

Fig.4. Here

In summary, Zurbriggen (2017) ascribes these regionally significant active margin-related early Paleozoic events (spanning in age from the late Cambrian to the early Silurian) to the so-called, "Cenerian Orogeny". The author builds his case by probing the Strona-Ceneri Zone in the Southern Alps (Zurbriggen, 2015). Accordingly, the Ordovician peraluminous arc-type magmatism (similar to a Cadomian-type) developed within a subduction-accretion geodynamic setting (Zurbriggen, 2020). However, the evidence from the Occitan Domain, Pyrenees, and Sardinia, where the effects of the Variscan and Alpine orogenesis did not obscure these Ordovician features, suggests that the magmatism at the Cambrian-Ordovician and Ordovician-Silurian boundary cannot be considered as the early and late stages of the "Cenerian Orogeny" (or the "orogeny" sensu strictu characterized by a significant crustal thickening; also underlined by the author itself). The north Gondwanan stratigraphic evidence supports a passive margin stage lasting during the Lower Ordovician (up to the Floian) and the Upper Ordovician (restarting since the Katian). Thus, we provide the list of the bulk Ordovician geodynamic stages, recorded mainly within the southern European basements (Table 1):

(1) a magmatic event at the Cambrian-Ordovician boundary marked by intermediate and felsic transitional volcanic rocks (Oggiano et al., 2010; Pouclet et al., 2017; Couzinié et al., 2023); (2) similar 488 Ma metamorphism and rootles suture embedded into the Serbo-Macedonian Unit (Spahić et al., 2021); (3) compressional deformation and folding that affected only the pre-Middle Ordovician successions (Cambrian – Lower Ordovician; constrained on the basis of deformed brachiopods discovered within Lower Ordovician sequence, Krstić and Maslarević, 1998; also in Casas et al., 2010; Cocco and Funedda, 2019); (4) an angular unconformity between the Lower Ordovician (Floian) and late Middle or Upper Ordovician sedimentary rocks

(Krstić and Maslarević, 1998; Cocco et al., 2018; 2023; Casas et al. 2019; Fig. 1a, white rectangle); (5) an important erosional stage is indicated by the presence of conglomerates that rest on the unconformity itself (Hartevelt, 1970; Leone et al., 1991; Loi et al. 2023); (6) widespread Middle-Upper Ordovician acidic to calc-alkaline magmatism with intrusive and extrusive to explosive products (Ramos et al., 2003; Oggiano et al., 2010; Casas et al. 2023); (7) widespread Ordovician ironstones (Young, 1992) interpreted as unconformity and deformational markers (Spahić et al., 2023a); and (8) high-strain deformation such are augen-, and migmatite-bearing gneisses (e.g., Ordovician Strone-Ceneri zone in Alps, Franz and Romer, 2007; orthogneiss of Western Carpathian basement, Putiš et al 2008; amphibolite of basaltic protolith, orthogneisses with Ordovician protoliths, Balintoni et al., 2010a; Kroner and Romer, 2013, Zurbriggen, 2020).

The absence of the Alpine event among south European Variscides (excluding Alps/Central Europe/Carpathian-Balkans) allows unrestricted exposure of the Cambro-Ordovician succession and the structures related to the pre-Variscan geodynamics. In turn, because the Carpathian-Balkan Alpine exotic basement terranes experienced both Variscan and Alpine orogenic overprinting, the focal point of the synthesis is the Middle Ordovician compression reflected as the Sardic and Sarrabese unconformities.

2.2. South European basements

Much is known about the pre-Variscan evolution of south European peri-Mediterranean Variscan terranes like these in Pyrenees, Occitan Domain, Sardinia, Western Carpathians, Alps/Central Europe, inclusive a few recent hints on Alpine Carpathian-Balkan belt (e.g., Putiš et al., 2008; Balintoni et al., 2010a,b; Siegesmund et al., 2018, 2021; Spahić et al., 2021, 2023a; Mandl et al., 2022; Pereira et al., 2022; Casas et al., 2023; Cocco et al., 2023; Ferretti et al., 2023; Lefebvre et al., 2023; Loi et al., 2023; Starijaš-Mayer et al., 2023). The Ordovician tectonics in southern Europe is very complex, with different geodynamic settings that coexist along the north Gondwana margin, now recognizable in the terranes involved in the Variscan Orogeny.

The oldest evidence of Ordovician geodynamics, which is the Furongian–Lower Ordovician igneous activity (e.g., Cézarenque–Joyeuse gneiss complex of French Massif Central; Couzinié et al., 2023) is testified by intermediate and felsic transitional volcanism recorded in the Occitan Domain (Pouclet et al., 2017) and the Variscan Nappe Zone of Sardinia (Oggiano et al., 2010; Gaggero et al., 2012). Note that other areas, like the Pyrenees and the Variscan External Zone of Sardinia, lack any evidence of magmatism of this age. This magmatism is interpreted as related to a continental break-up in the Occitan Domain (Pouclet et al., 2017; Couzinié et al., 2023) and as a volcanic passive margin in Sardinia (Oggiano et al., 2010).

Structural data from SW (Cocco and Funedda, 2021; Cocco et al., 2022) SE Sardinia (Cocco and Funedda, 2019) and Pyrenees (Casas, 2010) demonstrate a pre-Variscan folding event affecting only the pre-Middle Ordovician stratigraphic succession. For the time being, this event solely has been related to the Sardic Phase in SW Sardinia (para-autochthonous External Variscan Zone) and Pyrenees, and to the Sarrabese Phase in SE Sardinia (allochthonous Variscan Nappe Zone). The Sardic and Sarrabese phases led to the formation of the Sardic and Sarrabese angular unconformities and denudation of the exposed basement areas having stratigraphic gaps of ca. 17 and 6 My, respectively (Cocco et al., 2023; Loi et al., 2023). The stratigraphic gap in the Pyrenees corresponds to that of SW-Sardinia (missing ca. 20 My, Javier Álvaro et al., 2020). In other areas, such as Occitan Domain and NE-Sardinia (Internal Variscan Nappe Zone), most probably because of the higher imprint of the superposed Variscan deformation, the Sardic and Sarrabese phases can be presumed. The assumption is based on a stratigraphic gap between the Lower and Middle Ordovician, which is sometimes marked by ironstones. As an example, the Upper Ordovician Argentiera diamictite is resting on the Arenigian slates (Sardic unconformity) and is capped by sandstones with Caradocian faunas (Oggiano and Mammeli, 2006). The Sardic and Sarrabese phases and related folds and unconformities are interpreted as developed either in a compressional (Cocco et al., 2023) or extensional (Puddu et al., 2018; Alvaro et al., 2023) tectonic setting.

2.3. Carpathian-Balkan basement terranes

Unlike the situation within the Occitan Domain, Pyrenees, and Sardinia, the Alpine orogeny reworked crustal segments affecting the eastern sector of the Variscan orogen: Central Europe including a Carpathian-Balkan-Rhodope-Hellenic sector (e.g., Dimitrijević, 1997; Żelaźniewicz et al., 2004, 2007; Seghedi et al., 2005; Zulauf et al., 2014; Zurbriggen, 2014; Antić et al., 2016, 2017; Franke et al., 2017; Plissart et al., 2018; Siegesmund et al., 2018, 2021; Spahić and Gaudenyi, 2018; Arboit et al., 2019; Burda et al., 2021; Žák et al., 2021; Ferretti et al., 2022; Gerdjikov et al., 2023). Thus, these tectonically-sliced Alpine Carpathian-Balkan basement inliers underwent several orogenic cycles or overprinting episodes that resulted in their different structural positions in time and space (*e.g.*, Kräutner and Krstić, 2002; von Räumer et al., 2003; Iancu et al., 2005; 2006; Krstić et al., 2008; Zulauf et al., 2014; Spahić and Gaudenyi, 2018; Fig. 3b).

2.3.1. Sedimentary imprints across the Ordovician sequences

As a result of multistage orogenic exposures, the Ordovician magmatism is traceable exclusively in protolith forms (ortho protolith; Iancu et al., 2005; Kräutner and Krstić, 2006;), or occasionally as Ordovician peak extracted from the scarce detrital zircon data (Balintoni et al., 2010a,b, Dobrescu et al., 2010; Bonev et al., 2013; Zagorchev et al., 2015; Antić et al., 2016; Spahić et al., 2021, 2023a; Table 2). In addition, much of these latest Neoproterozoic to Cambro-Ordovician inliers experienced either mild or more frequently high-strain deformations. The latter deformation often hides constantly varying ortho- and para-protoliths of Cambro-Ordovician age; e.g., Balintoni et al., 2010a,b, 2014; Spahić and Gaudenyi, 2018; Abbo et al., 2020; Spahić et al., 2021; Žák et al., 2023b). The Cambro-Ordovician sedimentary successions, once preserved, are exposing barely distinguishable intra-Cambro-Ordovician stratigraphic boundaries (e.g., Ordovician metasandstones of Kučaj Mt., Serbia; Krstić and Maslarević, 1998; Fig. 3d).

Table 2. Here

Some remnants of Cadomian metamorphic basements, in particular fragments exhumed across eastern Serbia and westernmost Bulgaria, are occasionally overlaid by preserved Ordovician to Devonian/Lower Carboniferous (meta)sedimentary piles (Krstić and Maslarević, 1998; Kräutner and Krstić, 2002, 2006; Krstić et al., 2008; Gerdjikov et al., 2023; Fig. 3b). These more internal nappe-stacked eastern Serbian basement terranes of Alpine relevance (Getic/Kučaj and Supragetic/Serbo-Macedonian; Fig. 3b) record a vertical and lateral facies change, exposing almost the overturned yet a complete Ordovician succession (Krstić and Maslarević, 1998; Krstić et al., 2008; Georgiev et al., 2021, 2022; Ferretti et al., 2022; Spahić et al., 2023a; Fig. 1a,b, 3b,d). Despite the Ordovician sequence experiencing a mild crustal reworking, the imprints of the investigated intra-Ordovician compressional episode are not visible in the field (Krstić and Maslarević, 1998). A most recent reassessment of the thrusted Ordovician sequence exposed as a dominantly clastic succession of Kučaj Mt. indicates the presence of ironstone-marked mid-Ordovician unconformity in this Carpathian-Balkan domain of the Alpine sector (Spahić et al., 2023a; Fig. 3b,d). Another evidence of the post-Lower Ordovician compression across the Alpine-Carpathian-Balkan sector can be found within Lower Ordovician clastic sequence of Kučaj Mt., wherein a set of highly-deformed brachiopods is discovered (Krstić and Maslarević, 1998). More evidence of the Ordovician activity is shown by the mapped ortho-protolith connecting Eastern Carpathians at the north, with Inner Hellenides at the south (Table 2; Fig. 1a). In addition to the identical stratigraphic age, a similar origin between peri-Gondwanan Cambro-Ordovician clastic deposits of both North African and south European and Alpine sectors, is characterized by a set of sterile monotonous largely washed-out sandstone-dominated (mega)sequences comprising first-cycle quartz-rich mature sandstones (e.g., Krstić and Maslarević, 1998; Avigad et al., 2005, 2018; Bahlburg et al., 2009; Linnemann et al., 2011; Fig. 3d, 4).

2.3.2. Ordovician magmatic imprints of Cenerian relevance

The typifying Cenerian-type peraluminous magmatism of Middle-Upper Ordovician age (of 470–459 Ma; Dapingian – Darriwilian), slightly postdates the comparable event in the Strona-Ceneri zone (Zurbriggen, 2017). As shown, such a magmatic event is also imprinted into the northern metamorphic analog unit in Apuseni Mts., Romania (Balintoni et al., 2010b). This event is consistent with the intra-Ordovician magmatism recorded in more southern basement units (Serbia, Bulgaria, North Macedonian and Greece), detected by the rarely available detrital zircons (Kavalcheva and Nedjalkov, 1978; also small Ordovician peaks within younger sediments in Greece, Meinhold and Kostopoulos, 2013; Abbo et al., 2020; Spahić et al., 2023a). A similar Ordovician, but the magmatic zircon peak (not detrital zircons extracted from sediments, but a younger magmatic body in Serbia) is observed in the nearby Jadar block basement (Löwe et al., 2023; Fig. 1a, 3b). The Jadar block was later displaced to the west during the Mesozoic-Paleogene (peri)Neotethyan collisional stage. Slightly towards the east within the Rhodopean massif (Fig. 1a), extracted from the amphibolite-facies system, the intrusive mixture of alkaline and felsic or meta-mafic rocks (ortho protoliths) were emplaced into the exposed clastic-carbonate metasedimentary protolith succession (Bonev et al., 2013). Detrital zircons revealed a mean age of 455 Ma (Sandbian) for the magmatic crystallization of the protoliths. The observed consistency depicting mid-Ordovician imprints, the subsequent back-arc extension, and the emplacement into the clastic-carbonate sequence (Boncheva et al., 2023) further attests to the presence of a complex intra-Ordovician interference. The intra-Ordovician magmatic signature is also observed within the Inner Hellenides (e.g., the southern limb of Serbo-Macedonian analog units or the Vertiskos terrane in Greece; Abbo et al., 2020; Table 2). In addition to a proven mid-Ordovician tectonomagmatic interference and well-documented shelf Gondwana-type Cambro-Ordovician (meta)clastic rocks, we further probe a paleogeographic connection between this southern European-Alpine-Carpathian-Balkan flank and North African Cambro-Ordovician hinterland successions.

3. North African Lower Paleozoic hinterland: Lithostratigraphy and truncations, synthesis

North African Saharan desert area extends for more than 6000 km from the Atlantic coast to the east coast of the Arabian Peninsula, thus being very sensitive to Phanerozoic orogenic events (e.g., Meinhold et al., 2011, 2013; Marović et al., 2012; Oun and Busrevil, 2012; Tawadros, 2012; Zazoun, 2023). This large area is consistent with the Cambrian-Ordovician back-arc position, largely comprising the vast cratonic area of north Gondwana (Fig. 1a,b, 2a,b; Ghienne et al., 2023). Underneath the Cambro-Ordovician transgressive hinterland interior succession (Fig. 3a,b,c,d) is the “Infra-Cambrian” or “infra-Tassilian Unconformity” (Ghienne et al., 2023), or Pan-African unconformity (Stern, 1994; Ramos et al., 2006; Morton et al., 2011; Fig. 3, 4). The underlying basement cratons are West African craton, Saharan metacraton (e.g., Cvetković et al., 2022), East African Orogenic belt, and Arabian-Nubian Shield built of the Precambrian igneous, sedimentary and metamorphic rocks (e.g., Abdelsalam et al., 2002; Ghienne et al., 2023; Fig. 2a).

The sedimentary section within these intracratonic basins ranges from Cambrian to present, having almost ca. 7000 m in thickness (e.g., Aissaoui et al., 2016). The surface and subsurface data expose, however, a bundle of the hiatuses/unconformities that could be either tectonically- or eustatically-driven depositional interruptions (Fig. 4, 5a). Several truncations are recorded between the upper Cambrian-Lower Ordovician Hasawnah Fm., the Tremadocian Ash Shabiyat Fm., the Darriwillian Hawaz Fm., and the Upper Ordovician (Caradocian-Ashgillian) Mamuniyat Formation. Such a complex internal architecture of the mainly transgressive Ordovician trend (Ghienne et al., 2023) and resulting succession deposited across differentiated north Gondwanan paleogeomorphological areas indicates a set of multiple rather confusing tectonically-driven erosional truncation events and toplaps (Ghienne et al., 2007, 2023; Najem et al., 2015; Aissaoui et al., 2016; Gil-Ortiz et al., 2022). Despite these central hinterland intraplate basins being largely explored during the last 50 years, there are several unresolved issues related to prolific petroleum system elements of the Lower Paleozoic age (*e.g.*, Crossley and Mc Dougal, 1998; Lüning et al., 2000; Abouessa and Morad, 2009; Sabau et al., 2009; Aissaoui et al., 2016; Mohamed et al., 2016; Gil-Ortiz et al., 2019, 2022). The important issue unresolved is the origin of mid-Ordovician unconformity and some evidence of contemporaneous slightly basaltic magmatism, which is in tight connection with the related reservoir play (Ramos et al., 2006; Sabau et al., 2009; Toljić et al., 2012).

The main reasons why Cambro-Ordovician clastic sequence contains unresolved issues are (i) the absence of biostratigraphic control among broadly similar clastic sequences and their truncations (for field photos of the mapped truncations see Toljić and El Mehdi, 2007; Žolnaj and Turki, 2007; Le Heron et al., 2005, 2013), (ii) general absence of Cambro-Ordovician truncating-type 2D or 3D subsurface seismic response (e.g., Fig. 2 of Carruba et al., 2014; Fig. 6 of Najem et al., 2015; Fig. 5 of Mohamad et al., 2016; Fig. 2c of Gil-Ortiz et al., 2022), whereby the large portions of the Middle Ordovician deposits were eroded by the major Hirnantian glacial event (Ghienne et al., 2013; Gil-Ortiz et al., 2022). In addition, (iii) the attractiveness of the Ashgilian Hirnantian glaciation itself and its relevance in the petroleum geology and the local plays surpassed the importance of the precursor mid-Ordovician truncation (*e.g.*, Najem et al., 2015; Mohamed et al., 2016; Benayad et al., 2019; Gil-Ortiz et al., 2022). Thus, in further text, synthesis of these Lower Paleozoic systems, including available subsurface data, is coupled with the recent field observations of the central-southern Libyan outcrops (e.g., Toljić and El Mehdi, 2007; Žolnaj and Turki, 2007; Marović et al., 2012; Toljić et al., 2012). It is noteworthy that, until this study, just a few reports speculated that these unconformities are marking the epeirogenic uplifting-type Cambro-Ordovician episodes (e.g., Crossley and Mcdougall, 1998; Tawadros, 2012; Le Heron et al., 2013; Altumi et al., 2013; Gheinne et al., 2013; Carruba et al., 2014; Benayad et al., 2019; Fig. 4). We use some of the recent field data collected during the Field Geological Mapping campaign of central and southern Libya in this study (e.g., Toljić and El Mehdi, 2007; Žolnaj and Turki, 2007). The field campaign lasted from 2005 up to 2010, carried out in cooperation between the Industrial Research Centre, Tripoli, Libya, and the Geological Survey of Serbia, former Geoinstitute, Belgrade, Serbia.

3.1. Pre-intra-Arenigian unconformity mega-sequence: Mourizidae, Hasawnah, and Ash Shabiyat Formations

3.1.1. Mourizidie Formation

The onset of post-Pan-African or post-orogenic extension, consistent across central Gondwana (Libya), is associated with the emplacement of Ben Ghnema granitic batholiths and stocks (Ghuma and Rogers, 1978; Oun and Busrevil, 2012; Fig. 1b, 2). The Lower Paleozoic extension allowed a transgressive-type deposition, overlaying the exposed Pan-African basement (including the granitic basement Ben Ghnema igneous province; Fig. 4). This latest Precambrian, rather mild subsidence onset, likely supported deposition of the alluvial "Infracambrian" or the (i) latest Neoproterozoic – early Cambrian Mourizidae Formation (Hallett, 2002; Toljić and El Mehdi, 2007; Benshati et al., 2009; Ghienne et al., 2013; Fig. 3b, 4). With progressing subsidence, in particular along broad areas of the north Gondwanan post-Archaean basement systems (Ghienne et al., 2023), the alluvial Mourizidie Formation was unconformably overlain by the clastic Cambro-Ordovician Qarqaf Group (Altumi et al., 2013, and references cited therein). The "Gargaf Group" comprises the middle Cambrian Hasawnah Formation (Altumi et al., 2013), succeeded by these four Ordovician sequences: Ash Shabiyat, Hawaz, Melaz Shuqran, and Mamuniyat Formations (e.g., Ramos et al., 2006; Toljić and El Mehdi, 2007; Altumi et al., 2013; Le Heron et al., 2013; Gil-Ortiz et al., 2022).

3.1.2. Hasawnah Formation

The lowest portion of the "Garqaf Group" comprises the Hasawnah Formation. The Hasawnah Formation has a broad extent in western, central, and eastern Libya (e.g., Tawadros, 2012; Altumi et al., 2013; see the cross-section of Najem et al., 2015; Fig. 5a, for the location of seismic section see Fig. 3c). The

Hasawnah Formation is also extending across Egypt, Algeria and Chad, where it can be identified under different names (Craig et al., 2008). The thickness of the Hasawnah Formation is reported to be 250–300 m in the west, reaching up to 1000 m in the subsurface of the Ghadames Basin, ca. 1150 m in the Al Kufrah Basin, and 1700 m in central Libya (Gindre et al. 2012). In the investigated central Saharan or Libyan sector, the lower and upper contacts of the Hasawnah Formation are angular unconformities (Fig. 4). The lowermost part of the Hasawnah Fm. consists of massive cross-bedded quartz sandstone of fluvial to deltaic/shallow-water environment and unconformably overlays the Precambrian basement and the Mourizidae Fm. (Altumi et al., 2013; Ghienne et al., 2013; Fig. 4). These clastic lower Paleozoic sediments are super-mature, fossil-bared, or with the recovered fauna usually damaged (e.g., Tawadros, 2012; Abuhmida and Wellman, 2017). The "super-maturity" indicates that these sedimentary sequences consist almost exclusively of quartz, further implying widespread chemical weathering and several episodes of clastic grain recycling (Linneman et al., 2011). Depending on its location, the upper boundary of the Hasawnah Formation, or the contact with the younger Ash Shabiyat Formation is mainly represented by an angular unconformity or disconformity (marine transgression).

Fig. 5. Here

The uplift and erosion (latest Cambrian) led to the subsequent deposition of silty marine (neritic) sandstones and mudstones (Carruba et al., 2014), or are characterized by a gradual transition into the Hawaz Formation (Tawadros, 2012; Fig. 3a,b). Depending on the position of the surface exposure, which can either be in proximity, or remote away from the uplifted Tibesti massif, the Hasawnah Formation can transgressively be overlaid by each of the inner-cratonic Ordovician sequences. For example, the Hasawnah Formation is often succeeded by the Lower Ordovician Ash Shabiyat sequence package (e.g., central Murzuq; Abouessa and Morad, 2009), or the Upper Ordovician Mamuniyat Formations, or even by the Silurian Tanezzuft Formation (Toljić and El Mehdi, 2007; Le Heron et al., 2013). Across the western part of the Tibesti/Mourizidie region, the Late Ordovician and Silurian strata (Mamuniyat and Tanezzuft–Akakus formations) are transgressively overlying the older Precambrian meta-sediments and granitoids. Spatially, the Mamuniyat and Tanezzuft–Akakus are consistent having the average dip-direction striking towards the west at a low angle, into the underlying Murzuq Basin.

3.1.3. Ash Shabiyat Formation

The Ash Shabiyat Formation consists dominantly of a sandstone sequence/quartzarenites with *Tigillites*. Ash Shabiyat Formation is of the Early Ordovician age (Ramos et al., 2006), cropping in near the

Gussa/Dūr al Quṣṣah basaltic area (Žolnaj and Turki, 2007; Ghienne et al., 2013; Fig. 3c, 4). There, this Lower Ordovician sensu lato unit (Ramos et al., 2006) overlays the terminal clastic sedimentary sequence of the Hasawnah Formation and ends in the Melaz Shuqrane Formation (Toljić et al., 2012). The basal contact of the Ash Shabyiat Formation, which transgressively overlies the older sandstones of the Hasawnah Formation is consistent with the observed angular unconformity (Žolnaj and Turki, 2007).

3.2. Post-intra-Arenigian unconformity mega-sequence: Hawaz, Melaz Shuqrān, and Mamuniyat Formations

3.2.1. Hawaz Formation

In the outcrop scale, the Hawaz formation mostly consists of quartzarenites with interlayered several volcanoclastic sequences (Ramos et al., 2006). The Hawaz formation is a well-known hydrocarbon reservoir play (e.g., Ramos et al., 2006; Mohamed et al., 2016; Ghienne et al., 2023). Once present, this rather scarce Middle Ordovician Hawaz Formation was deposited along a north-eastern cratonic margin of Gondwana (Abouessa and Morad, 2009; Gil-Ortiz et al., 2022). The analysis of palynofacies shows the stratigraphic shallowing towards more proximal marginal marine conditions (Abuhmida and Wellman, 2017), consistent with the vicinity of the Ordovician arc. Moreover, the Ordovician vicinity of the vast peripheral shelf is supported by the fact that the lower part of the Hawaz Formation is accumulated under lower oxygenation, exhibiting a shallow marine shelf. Thus, the Hawaz Formation considerably varies, ranging from <1 up to 150 m. In the Gussa/Dūr al Quṣṣah area, this formation is less than 50 m thick (see Fig. 1b for location, 5b), Acritarchs yield a more precisely Darriwilian sequence (Llanvirnian–Llandeilian) of the Hawaz formation. The palynofacies also suggest that this formation represents a major transgressive-regressive cycle, consistent with the observations in upper Arenig-lower Llanvirn sequences from the Hassi-R'Mel area of north-central Algeria.

Back to the Gargaf area (Fig. 1b), the following two unconformities are observed: (i) the first at the top of the Hasawnah Formation ("intra-Arenigian" unconformity); and (ii) the second underneath the posterior overlaying Melaz Shuqran and/or the Mamuniyat formations (Ramos et al., 2006). In the basin scale (Fig. 5a), the Hawaz Formation is subdivided into the five third-order depositional sequences, where no low-stand was mapped (Ramos et al., 2006). The observed "intra-Arenigian" unconformity is sealed by the Hawaz Formation (Middle Ordovician). This precise Ordovician time should be consistent with a low-stand period (Young, 1992), which can be corroborated by a transgressive Hawaz reservoir zone HWZ1 (see Gil-Ortiz et al., 2022, for details). These basal Ordovician sub-units are interpreted as the (sub)sequences having a poor reservoir quality (Mohamed et al., 2016). However, the seismic data outlined a mid-Ordovician "Taconian unconformity" in some segments of the northern Murzuq basin (including the Berkine-Ghadames basin; Aissaoui et al., 2016; Fig. 5a). The subsurface seismic data interpretation involved the seismically distinctive paleohights/paleovalleys (Figs. 10, 11 of Najem et al., 2015). Despite being interpreted as of "Taconian relevance" (Najem et al., 2015) or as a truncational feature produced by the margin-related tensor i.e., the Avalonian separation from mainland Gondwana (Ghienne et al., 2013), such a stacked geometry of unconformities represents a significant compressional and uplift marker. The compression and uplift are consistent with a proposed North African intraplate tectonic interference and cratonic wobbling. Importantly, there is a well-documented presence of K-bentonites as additional volcanic markers in the shoreface subenvironments of the lowermost Hawaz Fm. (Ramos et al., 2003, 2006).

3.2.2. Melaz Shuqrane and Mamuniyat Formations

On top of the Hawaz Fm. is a widespread Melaz Shuqrān (Upper Katian-Hirnantian) siliciclastic sequence. This sequence unconformably overlies a large area consisting of Proterozoic rocks, whereas the overlying sediments of the uppermost Ordovician Mamuniyat Formation. The unconformity between the Hawaz and Melaz Shuqran north Gondwanan formations (Fig. 5b) is coeval with the onset of a passive margin above the magmatic arc recorded in Sardinia, Pyrenees, and Occitan Domain. This event is marked by the Upper Ordovician siliciclastic succession (Cocco et al., 2023). Such a configuration indicates the end of the volcanic arc activity related to the Cenerian Orogeny. Thin sediments of the Melaz Shuqran Formation are embedded with very rare basaltic extrusions (Toljić et al., 2012; Fig. 5b) exposed within the wider Gussa/Dūr al Quṣṣah area. These limited basalts are much older than those extruded in the Al Haruj and Jebel Eghei area (Radivojević et al., 2015; Elshaafi and Gudmundsson, 2016). The Melaz Shuqran Formation discordantly overlies several sandstone packages that are consistent with the underlying Cambrian-Early Ordovician Hasawnah and Ash Shabyiat Formations (Toljić et al., 2012; Fig. 5b). The periglacial nature of the Melaz Shuqrān is indicated by dropstones, often exposing exotic rocks (Upper Katian-Hirnantian age; Toljić et al., 2012; Ghienne et al., 2023; Fig. 5b). The stratigraphic position of dropstones i.e., the Hirnantian glacial event and seal-level drop are consistent with the extensional faulting, likely accompanied with extrusion of basalts (Fig. 5b).

The overlying Upper Ordovician Mamuniyat Formation has a shallow marine character, whereas the Silurian Tanezzuft Formation is transgressively overlying clastic sediments of the Mamuniyat Formation (Fig. 4b).

4. Mid-Ordovician imprints across North African hinterland: Detrital zircons and ironstone perspectives

4.1. Detrital zircons and connection with the peripheral Mid-Ordovician compressional front

The pre-Paleozoic structural elements of the north Gondwana/North Africa were largely consolidated during the Neoproterozoic Pan-African stage (e.g., Ghuma and Rogers, 1978; Altumi et al., 2013). The Pan-African Cadomian orogen (or Mediterranean coastal orogen; Garfunkel, 2015) and other elevated areas of that particular time (e.g., Tibesti, Transgondwana supermountain), as well as the intra-Ordovician magmatism, have provided a continuous sediment paleo-sourcing and a constant supply of voluminous clastic material into abutting lowlands, transported exotic peri-Gondwanan terranes (e.g., Fig. 6a,b; Table 2), and inner- and peri-cratonic areas (Meinhold et al., 2011, 2013; Avigad et al., 2018; Fig. 2, 6c,d,e).

Principal detrital zircons ages in Cambrian-Ordovician sequences of the central Sahara are 2.7–2.5, 2.15–1.75, and 0.75–0.53 Ga (Meinhold et al., 2013). Massive clastic sequences with a similar provenance are documented across the amalgamated peripheral Gondwanan basements of the wider Mediterranean south-European area (Eastern and Western Mediterranean, NW Iberia, including Carpathian-Balkan basements). The pallet of detrital zircons ages narrowed the original position of the early Paleozoic (thermal) subsidence depocenter to be allocated in the proximity of the central-northern Africa Saharan Metacraton (Altumi et al., 2013; Fig. 1b, 2). However, a decreasing trend in Cadomian sourcing during the mid-Ordovician Hawaz deposition (Meinhold et al., 2013) was not explained until this study.

Fig.6. Here

The available zircon populations from the correlative Cambrian-Ordovician sequence spread across Algeria (missing 1.0–1.2 Ga old zircon; Linnemann et al., 2011), including that of the central-western Libya and Jordan (eastern Gondwana, Meinhold et al., 2011, 2013; Altumi et al., 2013; Wang et al., 2020) are consistent with the paleo-sourcing (elevated) areas. Such sourcing discloses a set of protracted long-distance transportation paths of detrital material eroded from the formerly exposed Pan-African orogen (e.g., Morag et al., 2011) and Transgondwana super-mountain (Meinhold et al., 2013; Fig. 2). The paleocurrent trends were to the NNE (Ghienne et al., 2013). Sandstones of the Hasawnah Formation in the sources Al Qarqaf Arch (Fig. 3c) type areas are sourced by the Neoproterozoic–early Cambrian Pan-African cycle (Trans-Saharan Belt) and by the peri-Gondwanan flanking terranes. However, the noticeable change of sourcing (decrease) of the Cadomian detrital zircon age population (zircon ages from 700 Ma to 525 Ma; Meinhold et al., 2011; Altumi et al., 2013) appears to be consistent with palaeogeographical, eustatic and tectonically-driven paleo-depositional changes. The Cambrian changes mirrored in a widespread transgression and submerging these peripheral north Gondwana sources (Fig. 6c,d,e,f,g).

Ordovician shifting of paleo sources is reflected as an increase in 920–1060 Ma-old zircons in the following Middle Ordovician Hawaz Formation (Meinhold et al., 2011). The shift is testifying to the uplift and exposure of the underlying central hinterland basement units. Such a mid-Ordovician paleogeographic configuration and paleotectonic arrangement are consistent with the proximity of the peripheral Cenerian deformation front, which affected the Cambrian-Lower Ordovician shelfal clastic sequence (e.g., Sardinia; Cocco et al., 2023). Considering the large size of the north-eastern Gondwanan shelf and the highly differentiated paleorelief of its hinterland, intra-Arenigian unconformity lasted from the Floian to the Darriwilian. More precisely, the pre-Middle Ordovician deformation affected the terminal stages of Ash Shabiyat lasting until the onset of the Darriwilian Hawaz Formation.

With regards to detrital zircons collected within the more distant interior (southern Libya), available detrital zircon age populations include Mesoproterozoic (Meinhold et al., 2011) and Neoarchean 2.7–2.5 as well as 2.15–1.75 Ga signatures (e.g., Kolodner et al., 2006; Altumi et al., 2013; Meinhold et al., 2011). Grains of the puzzling Mesoproterozoic age, documented also within the Hawaz Formation, indicate the recycling of the older crust that was likely exposed during the inner African Neoproterozoic events (Dor el Gussa/Dūr al Quṣṣah area; Fig. 2). The regression or MRS has the fit with the onset of Darriwilian Hawaz Formation, whereby a maximum deposition has been constrained for *ca.* 460 Ma or the Middle Ordovician (Meinhold et al., 2011; Gil-Ortiz et al., 2022). In addition, there is a group of Darriwilian zircons (Meinhold et al., 2011) that was probably sourced from the suggested middle (early upper) Ordovician volcanic arc. The presence and influence of the Ordovician magmatic arc is additionally documented by the mapped K-bentonite levels in the Darriwilian Hawaz Formation (Ramos et al., 2003, 2006). Middle Ordovician K-bentonites are present in Baltoscandia (Bergström et al., 1995), whereas an island arc calc-alkaline K-bentonite levels are additionally documented at the Ordovician – Silurian boundary, occurring along the easternmost Gondwanan flank (Xiong et al., 2023).

The third argumentation lies in the eastward increase of 1.1–0.95 Ga detrital zircons observed within the flanking early Paleozoic sandstones *s.l.* of the Saharan Metacraton (Meinhold et al., 2013). Far-field tectonics related to the Ordovician plate-tectonic reorganization along the northeastern Gondwanan flank lifted another unknown 1 Gy old crustal source (Meinhold et al., 2011). The new sourcing of 1.0 Ga detrital zircons and their inflow occurred during the Floian timeframe or uppermost Lower Ordovician. The suggested regional uplift of the Floian age of the remobilized Gondwanan interior is consistent with the Sardic and Sarrabese tectonic phases (see Cocco et al., 2023, for details).

In addition to discussion and reinterpretation of the available detrital zircon data, we also align a broadly similar phenomenon representing a relevant marker of depositional truncation or unconformity/hiatus. This marker represents an important low-stand biochemical sedimentary feature referred to as the ironstone. We show the available ironstone occurrences as supplementary mid-Ordovician truncation markers (e.g., Berendsen et al., 1992; Young, 1992; Fig. 7a,b). Such important ironstone events are observed in Sardinia and Kučaj Mt., eastern Serbia (Cocco et al., 2023; Spahić et al., 2023a), and across other segments of Variscan Europe (Fig. 7b).

Fig. 7. Here

4.2. Intra Cambro-Ordovician ironstones as auxiliary truncation markers

As a rule of thumb, the pre-Hirnantian angular unconformities across the north Gondwanan shelf (Algeria, Tunisia and Libya; Fig. 7a) are often consistent with a number of the North African ironstone layers (Guerrak, 1987; Chauvel and Guerrak, 1989; Guerrak, 1991; Crossley and McDougall, 1998; Žolnaj and Turki, 2007; Le Heron et al., 2013; Fig. 7b). The Cambro-Ordovician ironstone sequences are equally widespread across southern European basements, e.g., Sardinia, Kučaj/Getic in Serbia and Bulgaria, Prague basin in Czech Republic, Bavaria and Thuringia (Germany), S. Normandy (France), central and northern Portugal, Celtiberia (Spain) (e.g., Young, 1992; Fernandez et al., 1998; Krstić and Maslarević, 1998; Gutiérrez-Marco et al., 2003; Mücke, 2006; Yanev et al., 2006; Oggiano and Mameli 2006; Pufahl et al., 2020; Ferretti et al., 2022; Fig. 7b; Table 3). However, several Fe-bearing sequences outlining sequence stratigraphic low-stand/erosional event(s) (Young, 1992; Spahić et al., 2023a), in particular, these intervening the North African latest Cambrian Haswnah and overlaying Ordovician layers (Toljić and El Mehdi, 2007; Žolnaj and Turki, 2007; Le Heron et al., 2013) are not discussed as yet.

Fig 7. Here (ironstone production)

Table 3. Here

Ironstone is an enigmatic Phanerozoic biochemical sedimentary rock containing ≥15 wt% Fe. Younger Ordovician ironstones have several important differences relative to the Precambrian irons. Ordovician ironstone is characterized by a lesser content of aluminum, often occurring as a voluminous deposit, imprinted by a more complex array of Fe-bearing minerals. Ironstone is not a geologic curiosity, it is, however, a product of geosphere-biosphere-hydrosphere feedback processes that regulated the Ordovician Earth system during the Great Ordovician Biodiversification Event (GOBE, Pufahl et al., 2020, and references therein). Results by Dunn et al. (2021) support an emerging model for the Ordovician ironstone formation of North Wales, underpinned by a development of ferruginous bottom water periodically tapped by a coastal upwelling. Expanding, inconsistently oxygenated, semi-restricted seaways such as the Rheic Ocean (Dunn et al. 2021; Matheson et al., 2022) provided suitable conditions allowing the development of anoxic, hydrothermally enriched seawater.

The North African and southern-central Europe Lower Paleozoic ironstones have a similar mineral composition. A dominant iron-bearing mineral, which is present in a vast majority of the European and African locations, is chamosite (the Fe^{2+} end-member of the chlorite group; Deer et al., 2013; Table 3). Only occasionally, other chlorite varieties with a less Fe^{2+} component, such as clinochlore (Iberian Massif), ripidolite, and sheridanite (Kučaj Mt.), are dominant. Other determined iron-bearing minerals are siderite ($FeCO_3$), hematite (α-Fe_2O_3), goethite [α-FeO(OH)], magnetite (Fe_3O_4), maghemite (γ-Fe_2O_3) and lepidocrocite [γ-FeO(OH)]. It should be emphasized here that these phases are a function of the (paleo)locality and could be absent (Abia et al., 2020). Likely continental or crustal source of iron is recorded in older iron deposits of the West African craton such as those in Mauritania (Bronner and Chauvel, 1979). Weathering during sea-level lowlands could have leached SiO_2 out of the exposed rocks, leaving an iron oxide/hydroxide residue. Such a case is documented within the Murzuq area, Melaz Shuqrane Formation (Žolnaj and Turki, 2007; Fig. 7c). The transport of the iron as particulates was likely carried out by a fluviatile network coming from southward-positioned sources, to eventually reach the shallow marine domain. In the Anti-Atlas, for example, the iron was deposited in estuaries and shallow marine embayment. Such reducing conditions during early diagenesis would have converted the insoluble Fe^{3+} compounds to soluble Fe^{2+}, which then could be incorporated into berthierine clays, or reworked by waves, and transported back into the water column. Oceanic waves provide iron reoxidation to Fe^{3+} and allow precipitation of goethite ooliths. The berthierine clays could similarly be reworked by wave action and formed into ooliths. In this respect, clastic grains of Mourizidae, Hasáwnah, and Mamuniyat Formation are largely compacted by a ferruginous cement (Toljić and El Mehdi, 2007). A separate ferruginous interval is detected between the Hawaz and Melaz Shuqrān Formations (Jiuma, 2006; Le Heron et al., 2012; Jabir et al., 2020). In addition to the presence of angular unconformity (Ghienne et al., 2013; Le Heron et al., 2013), consistency of the ironstone occurrence within a post-unconformity interval (Young, 1992) provides second-order evidence allowing the separation of Cambrian-Ordovician, and intra-Ordovician clastic sequences. In addition, the mechanism of the suggested Ordovician ironstone production is consistent with the ironstone favorable setting of an epicontinental shallow sea of north Gondwana (Fig. 6a). Such a Paleozoic redox paleoenvironment lasted throughout the Silurian and Devonian paleo oceanic developments imprinted into the Carpathian-Balkan basements (Boncheva et al., 2023).

4.3. Palaeotectonic reconstruction of the Ordovician hinterland

The investigated northeast Gondwnana hinterland (Fig. 8a) exposed a block-wise epeirogenic-like vertical movement-controlled configuration affecting the Ordovician paleorelief-dependent hinterland deposition (in particular of the Hawaz Formation, which is mainly documented near paleo-depocenters; Fig. 7a, 8,b,c). The observed differences in the thickness of the Hawaz Formation represent a good marker outlining these paleo-depocenters and formerly elevated paleo-heights. Such a vertical differentiation was caused by a remote tectonically-induced compressional tensor/active margin/collision (Fig. 8a) that occurred along the continent periphery (Fig. 2). Another important observation allowing the correlation between the investigated eastern north Gondwanan tectonics and arc setting, involves a thin K-bentonite layer of the lowermost Middle Ordovician Hawaz Fm (Ramos et al., 2003; Fig. 8a). Despite its distance, the investigated Mid-Ordovician magmatic arc and associated explosive volcanism influenced deposition of the so-called, volcanoclastic ”Kb” sequence or HW.2 (sub)unit belonging the Hawaz Formation (max. 10–20 cm of thickness; Ramos et al., 2003, 2006). This thin package records occasionally a higher iron content, thus having a reddish color. In addition, such a sequence is frequently devoid of bioturbation (Ramos et al., 2006), which suggests slow subsidence of these far inland areas and their base-level downward motions (no more compressional uplift at the beginning of Hawaz Fm.).

In turn, the precursory 470 to 465 Ma very shallow to erosional near shelf flanking paleoenvironment, produced by the mid-Ordovician compression and arc-related regional-scale crustal uplift have induced the investigated truncating-type deformations of the Cambro-Lower Ordovician sequence (Fig. 8b,c). Despite other syntectonic deformations of sediments being absent in the Libyan sector, this area underwent significant regional uplift and erosion washing away several hundreds of meters of Lower Ordovician sequence (Ghienne et al., 2013). The intra-Ordovician peripheral north-eastern Gondwanan event further contributed to a regional tilting of its inboard craton interior, depicted by the observed yet scattered intra-Ordovician angular unconformity.

The mapped inner cratonic calk-alkaline-type magmatic event and associated extrusion of vesicular basalts into the Melaz Shuqrane Fm. (Fig. 5b) can be interpreted as a far-field back-arc extensional response as indicated by its stratigraphic position (Fig. 8c). The localized intracratonic magmatism as single evidence of such extension-related magmatism recorded in the hinterland (Fig. 8c), is moreover consistent with the magmatism recorded in Sardinia: 440+/-1.7 Ma and 439+/-6 Ma (Cocco et al., 2023).

Fig 8. Here

5. Concluding remarks

A review and synthesis of outcrop and subsurface information show that the investigated intra-Ordovician unconformities of central Libya are related to the contemporaneous tectonic events of the active northeastern Gondwanan margin. The deformation affecting the North African Cambro-Ordovician sequences is an intra-cratonic tectonics characterized by regional uplift, tilting, and erosion, as a consequence of the far-field effect of the northeastern Gondwana margin geodynamics. The peri-Gondwanan south European and Alpine basement systems recorded the main tectonic-magmatic events during the late Cambrian-Late Ordovician age, the same period of the main unconformities of North Africa. The northeastern Gondwana flank was affected by the Sardic and Sarrabese compressional stages, which marked the termination of a passive margin stage that lasted roughly until the Floian. This time is consistent with the "intra-Arenigian" unconformity of Ghienne et al. (2013, 2023) well marked in the hinterland paleo-hights.

In deeper hinterland basinal sectors, North African Saharan depocenters, e.g., within the Murzuq basin, Lower Paleozoic succession may record a conformable relationship connecting the Hasawnah, Ash Shabiyat, Mamuniyat, and Tanezuft Formations. The gradual transition is consistent with a locally intense Lower Paleozoic subsidence, not significantly affected by the investigated far-field tectonism. Consequently, the Cenerian Orogeny had a limited effect on deep basinal areas with sufficient extensional forces. The main conclusions are as follows:

- According to the synthesis involving some field data from the central Libyan hinterland, there was indeed a far-field response on the active compression related to the intra-Ordovician Sardic and Sarrabese phases. The compressional deformations are reflected within scattered regional Ordovician uplifts or structural heights, characterized by long-lasting stratigraphic gaps testified by the fact that in many places the Cambrian-Lower Ordovician Hasawnah Formation is transgressively overlain by different-age Ordovician clastic sequences (locally in the central part even by the Upper Ordovician sequences). The field mapping data also unravel the presence of important angular unconformity of 30° (Crossley and McDougal, 1998; Toljić and El Mehdi, 2007; Žolnaj and Turki, 2007). On the contrary, in deeper basinal sections the Cambrian – Ordovician succession shows only the stratigraphic gap related to the Hirnantian glacial erosion.

- The Darriwillian Hawaz Fm. records deposition of K-bentonite clays and Darriwillian zircons derived from peripheral volcanism. This setting fits into the proposed magmatic arc activity related to the Cenerian Orogeny;
- The North African – south European Lower Paleozoic synthesis also shows that the change of detrital zircon data extracted from the mid-Ordovician Hawaz hinterland sequence indicates minor sourcing from the peripheral Cadomian terranes or supply with 530 to 720 Ma zircons. The minor presence of these peripheral sources further corroborates the proximity of the vast submerged shelf that was in connection with the cratonic interior (erosion has not started yet). Furthermore, the zircons from an Early Silurian sequence show an abundance of Cadomian sources, which is consistent with the precursory Cenerian Orogeny and uplift affecting the regional rather localized elevation of the inner cratonic-interior;
- Up to now, the presence of any intra-Ordovician unconformity is regionally mapped as the MRS (Maximum Regressive Surface; Gil-Ortiz et al., 2022). However, this surface is often obscured by a Hirnantian glacial erosion that often truncates an older structure related to the Cenerian Orogeny. In addition to here provided palaeogeographic and tectonic connection between peri-Gondwana and its Ordovician pre-Hirnantian developments across the cratonic interior, a better understanding of the investigated far-field interference and the development of mid-Ordovician truncation may provide important additional input for the constraints on the prolific Hawaz reservoirs and their quality.

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Figures

Fig.1. a. Map of the Mediterranean/south European area, including the Carpathian-Balkan belt. The figure underscores North African relief and areas presented in a synopsis, including the positions of hitherto documented Cenerian edifices: Pyrenees, Sardinia, and Alpine domain of southern Europe, Serbia, Romania, Bulgaria, and North Macedonia. The position of Ordovician ironstones exposing Cambro-Ordovician unconformities across north Gondwana (North Africa). b. Overview of the main central Gondwanan basins (Ghadames, Murzuq, and Kufrah), including the position of surface outcrops exposing Cambro-Ordovician sequences (inset from Le Heron et al., 2013, modified).c. Geological map of the Mourizdae area, slightly modified after Toljić and El Mehdi, 2007, inset from Le Heron et al., 2013).

Fig.2. a. Distribution of the Sahara cratons and Neoproterozoic orogens (modified after Meinhold et al., 2011): MB- Mozambique belt, ANS – Arabian-Nubian Shield, CAFB – Central African fold belt; TSB – Trans-Saharan fold belt; SF – São Francisco craton; RP – Rio de la Plata craton; DB – Damara belt; IB – Irumide belt. b. Simplified geological map of North Gondwana showing the distribution of basement rocks and Paleozoic outcrops, including widespread clastic sediments (inset from Avigad et al., 2017, and references cited therein, significantly modified).

Fig.3.a. Sardic unconformity in a typical section (Sardinia, Italy; after Cocco et al., 2023). The pre-Sardic unconformity succession includes the Nebida, Gonnesa, Campo Pisano, and Cabitza Formations from the bottom to the top. The post-Sardic unconformity succession comprises the Monte Argentu, Monte Orri, Portixeddu, Domusnovas, Rio San Marco, Genna Muxerru, Fluminimaggiore and Pala Manna Formations from bottom to the top (Battaglia, et al., 2012; Cocco and Funedda, 2023). b. Main tectonic units of east Serbian Carpathian-Balkan basement units (after Kräutner and Krstić, 2002), with Peri-Gondwanan inheritance taken from Spahić et al. (2023). c. A synthetic stratigraphic column of the Kučaj Ordovician sequence, taken from Spahić et al., (2023a), modified. d. Overview of the main central Gondwanan basins (Ghadames, Murzuq, and Kufrah), including the position of surface outcrops exposing Cambro-Ordovician sequences (inset from Le Heron et al., 2013, modified).

Fig. 4. Chronostratigraphic (or Wheeler) diagram representing the Cambrian to Middle Devonian development in the eastern Murzuq Basin, and comparison with more distal Al Qarqaf Arch (Ghienne et al., 2013, slightly modified). The first sequence is extracted from the tectonic-driven base-level changes: a Middle Cambrian to Lower Ordovician mega-sequence, bounded by the infra-Tassilian surface and the intra-Ordovician unconformity. The intra-Ordovician unconformity, in its key sections, is obscured by both, the Taconian and the pronounced Hirnantian glacial erosion surface. The second mega-sequence includes the Upper Ordovician glaciogenic deposits.

Fig.5. a. Seismic data unraveling the Lower Paleozoic subsurface architecture, including the gamma-ray signature of the Hawaz Formation within the Murzuq basin (inset taken from Gil-Ortiz et al., 2022, slightly modified and reinterpreted). For 2D seismic line details and their position see the aforementioned paper. The seismic section indicates the subsurface Ash-Shabiat-Hawaz paleo topography shaped by the Late Ordovician glaciation and erosion. The thick black horizon represents the major Hirnantian truncation, whereby the normal faults bound many of the paleohighs and the paleovalleys, indicating extensional activity during the Cambro-Ordovician. The red question mark shows the missing interpretation of the Middle Ordovician compressional event, or "Taconic unconformity", described in Najem et al. (2015) or Aissaoui et al., (2016). b. Geologic column of the volcano-sedimentary succession of the Melaz Shuqrān Formation in the Dor el Gussa/Dūr al Quṣṣah area (after Toljić et al., 2012, modified). Field mapping uncovered the important basic type of extrusive magmatism embedded into the Upper Katian-Hirnantian sequence. The sequence is reinterpreted as a far-field effect of the Cenerian Orogeny

Fig.6. Comparison of the detrital zircons from the two separated north Gondwanan segments, important age groups are shown in grey bands. a,b, are from the Serbo-Macedonian (basement) unit of central Serbia, and its southern analog unit "Eastern Veles Series" of North Macedonia (data taken from Antić et al., 2016). c,d and f are from the North African domain, different Cambro-

Ordovician systems, Arabian-Nubian Shield, Dor el Gussa/Dūr al Quṣṣah, and Anti-Atlas belt (data from Menhold et al., 2011). g. Detrital zircon data from Hasawnah and Hawaz Formations (after Meinhod et al., 2011, modified). The new interpretation shows a decrease in Cadomian and an increase in basement cratonic zircons in the Hawaz Formation, accounting for the Cenerian Orogeny compression and rearrangement of cratonic sources in the hinterland. For further details about detrital zircon data from the Balkans, see Spahić and Gaudenyi, (2018), Žak et al. (2023b), Western Europe detrital zircon data from e.g., Javier Álvaro et al. (2020), Avidag et al., (2022).

Fig.7. a. Model of ironstone formation in shelf and epicontinental sea conditions (modified after Matheson et al., 2022). b. Locations of the Ordovician ooidal ironstones in North Africa, southern and central Europe (modified after Young, 1992).c. The photo was taken during fieldwork on the Majdul geological map of Libya on a scale of 1:250,000 (Žolnaj and Turki, 2007). The significant presence of ironstone layers beneath the Melaz Shuqrane Formation provides the important validation of the passive margin stage or the pre-Katian low stand.

Fig. 8. a. Middle Ordovician paleogeography of north Gondwana, which includes an active margin along the eastern shelf, above the major North African basement provinces (thick white-red dotted line with red arrow): Saharan craton, and West African craton (thin white dotted line) (after Pufahl et al., 2019; significantly modified). The green line approximates the position of back-arc mafic volcanism. Line A-A' indicates an approximate crustal 2D cross sections illustrated in Figure 8b and 8c. b. The initial stage of active magmatic arc tectonic model at 475 Ma. Notably, the arc was developed across Cadomian vestiges distributed along the margin. Stage is characterized by the onset of folding. Yellow arrows show detrital sources supplying the submerged hinterland. Main source is Trans-Saharan belt, whereby small amount of zircons arrived from peripheral uplift c. Tectonic model of north Gondwana margin during 465 Ma, with a low stand condition across North African intra-cratonic area. The extrusive explosion-type magmatism affected the formation of K-bentonites in lowermost Hawaz Fm.

Tables

Table 1. Ordovician tectonic stages recorded in southern Europe and hypothesized across North Africa. Data sources are in the text.

Table 2. Table showing Late Cambrian-Ordovician ages in the basement of the Carpathian-Balkans and Inner Hellenides, and Romanian Carpathians. Data compiled from Balintoni et al. (2011), Antić et al. (2016), and Abbo et al. (2020).

Table 3. Summary of iron-bearing mineral phases within the oolitic ironstone occurrences among studied locations. Abbreviations: Chl–chlorite; Chm–chamosite; Rip–ripidolite; Clc–clinochlore; She–sheridanite; H–hematite; M–magnetite; MH–maghemite; G–goethite; L–lepidocrocite; S–siderite. Data compiled from: 1) Abia et al. (2020); 2) Young (1992); 3) Guerrak (1988); 4) Guerrak (1992); 5) Spahić et al. (2023a); 6) Mücke and Farshad (2005); 7) Mücke (2006); 8) Dunn et al. (2021); 9) Young (1989); 10) Pufahl et al. (2020); 11) Trela (2008); 12) Yanev et al. (2006).

Figure 1

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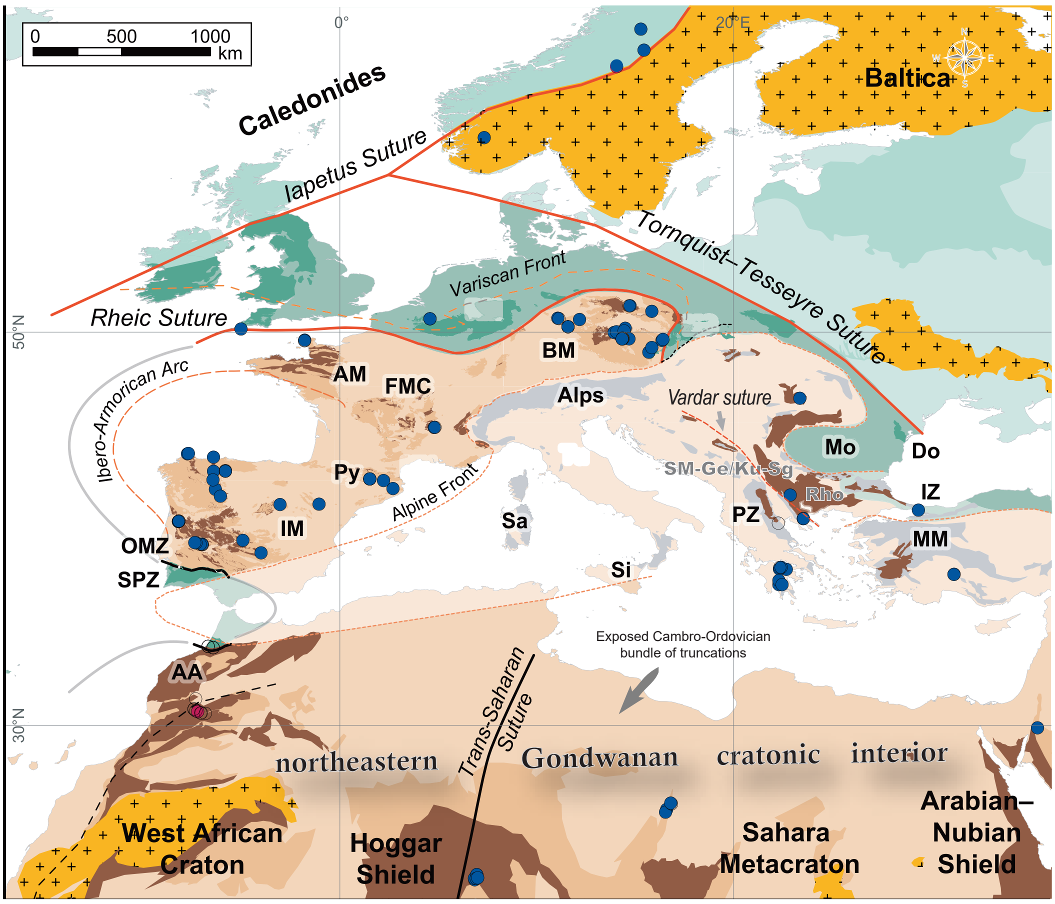
Relief map exposing major crustal thickening mountain areas in southern Europe & North Africa

Simplified tectonic sketch map of Peri-Gondwanan terranes (inset from Stephan et al., 2018, modified)



Alpine overprint | Avalonia | Precambrian rocks | Presence of Ordovician zircons
Laurussia | mainland Gondwana, Cambro-Ordovician hinterland | Cratonic basement
Peri-Gondwanan terranes involved in Variscan and Alpine orogeny

Variscan Europe with no Cenerian/Sardic imprints

Abbreviations: AA – Anti-Atlas; AM – Armorican Massif; B –Bohemian Massif; Do – Dobrogea;FMC – French Massif Central; Si – Sicily; SPZ – South Portuguese Zone; IM – Iberian Massif; IZ – Istanbul Zone; MM – Menderes Massif; M - Moesia; OMZ – Ossa-Morena Zone; PZ – Pelagonian Zone;

Variscan Europe with Cenerian/Sardic imprints

Sa – Sardinia; Py – Pyrenees;

Alpine basement terranes with Cenerian/Sardic imprints

SM-Ge/Ku-Sg - Serbo-Macedonian Unit/Getic or Kucaj/Supragetic; Rho - Rhodopean massif

Figure 2 Click here to access/download;Figure;Fig 2 Lib-ii.pdf

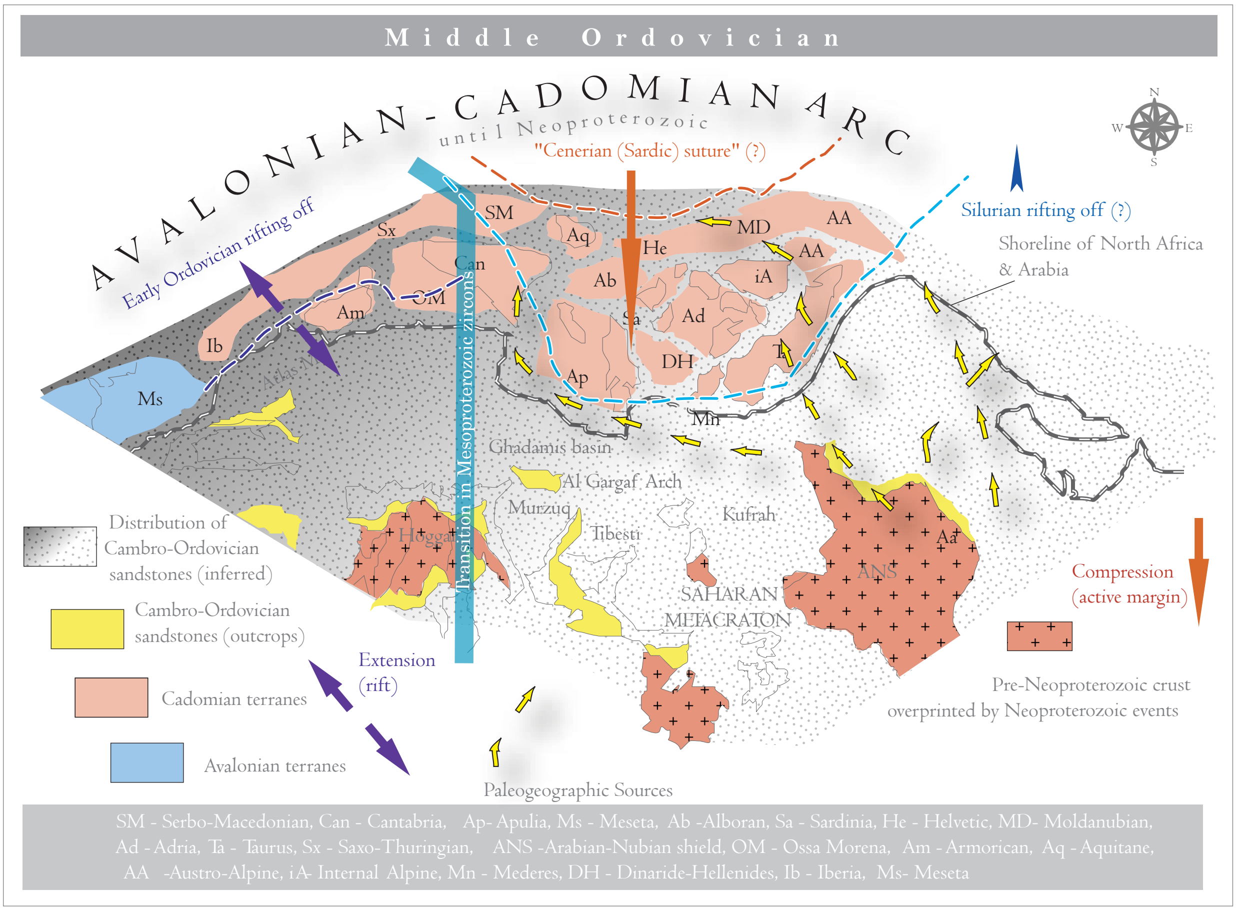


Figure 3

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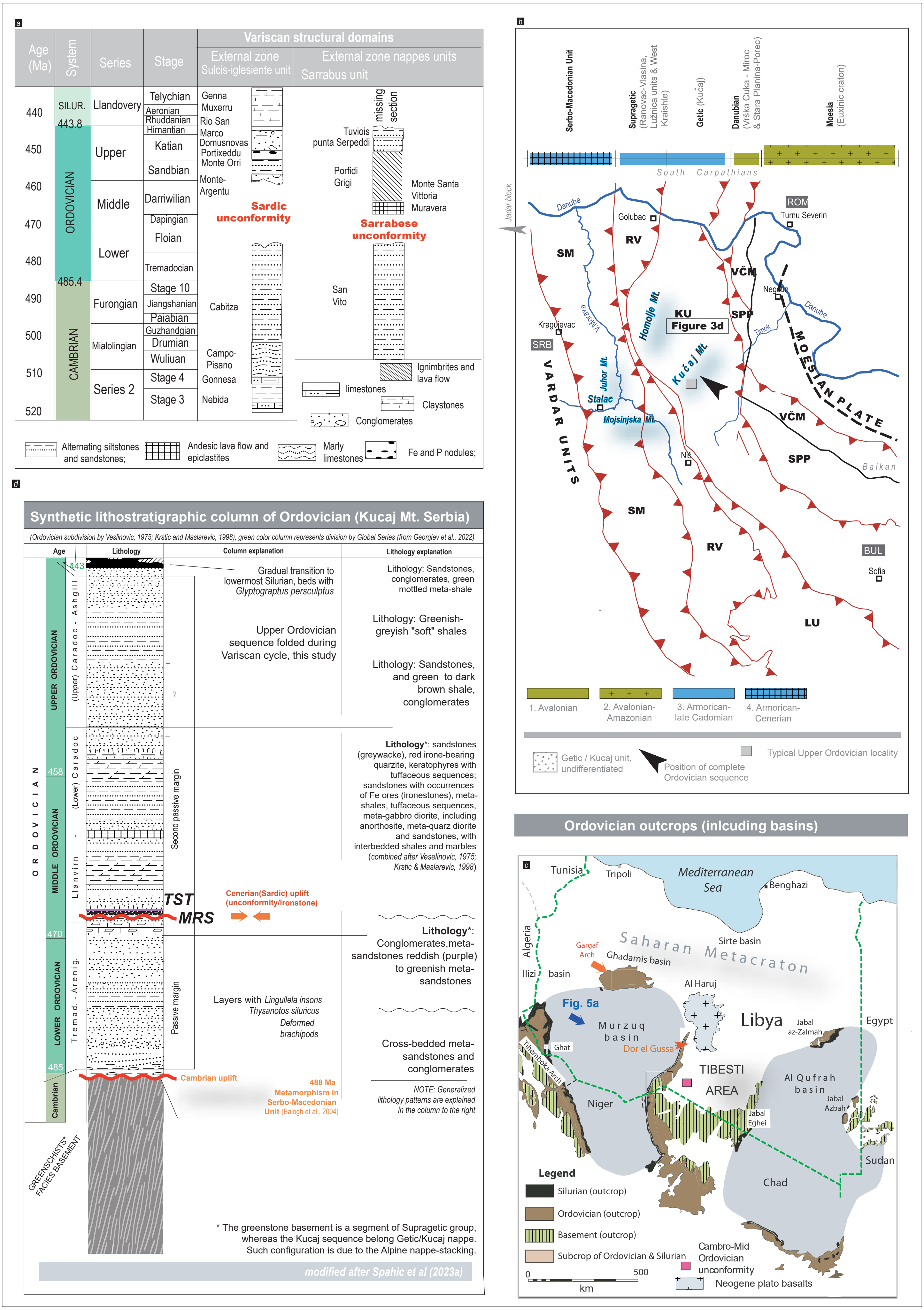

Figure 4

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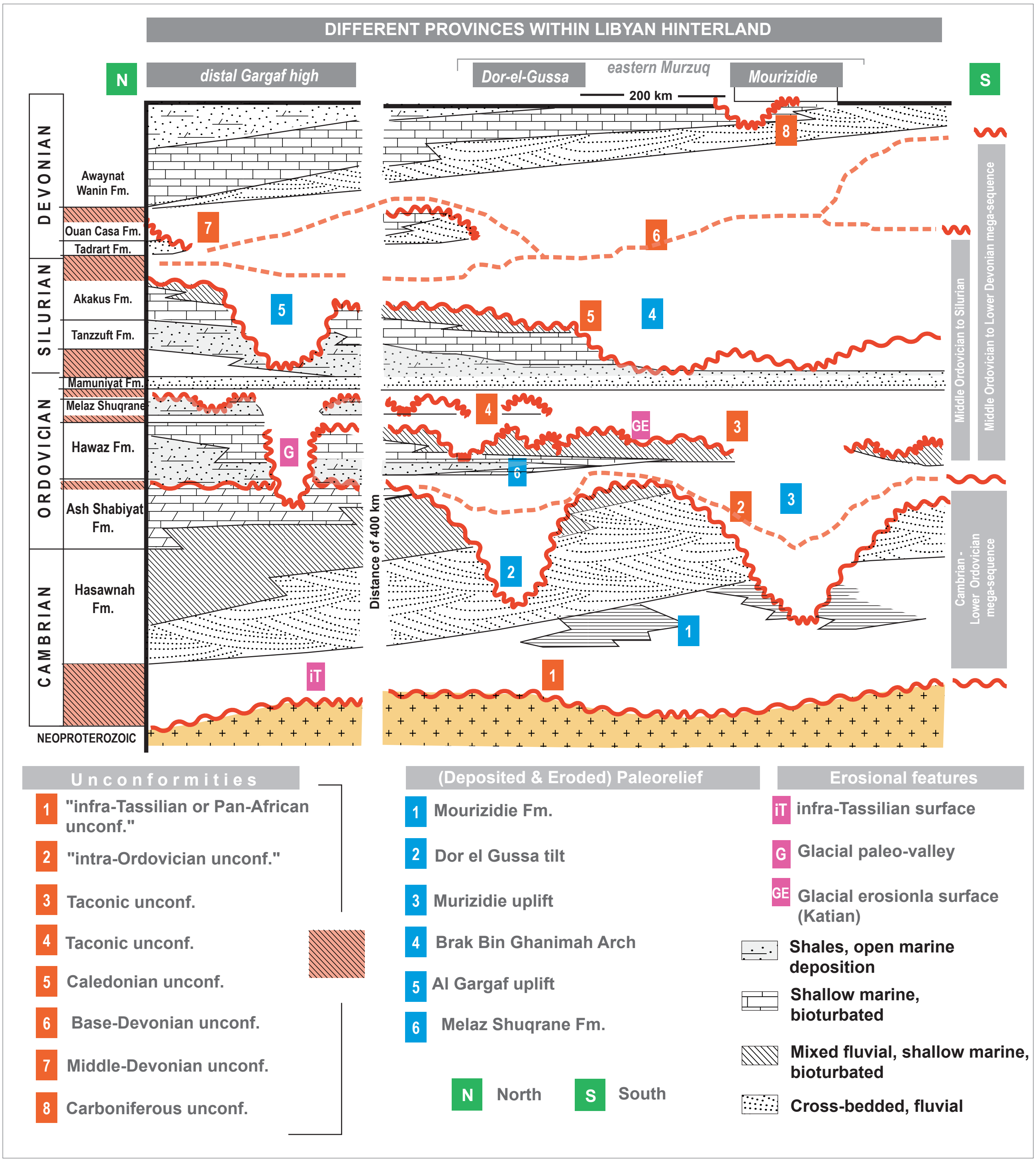

Figure 5

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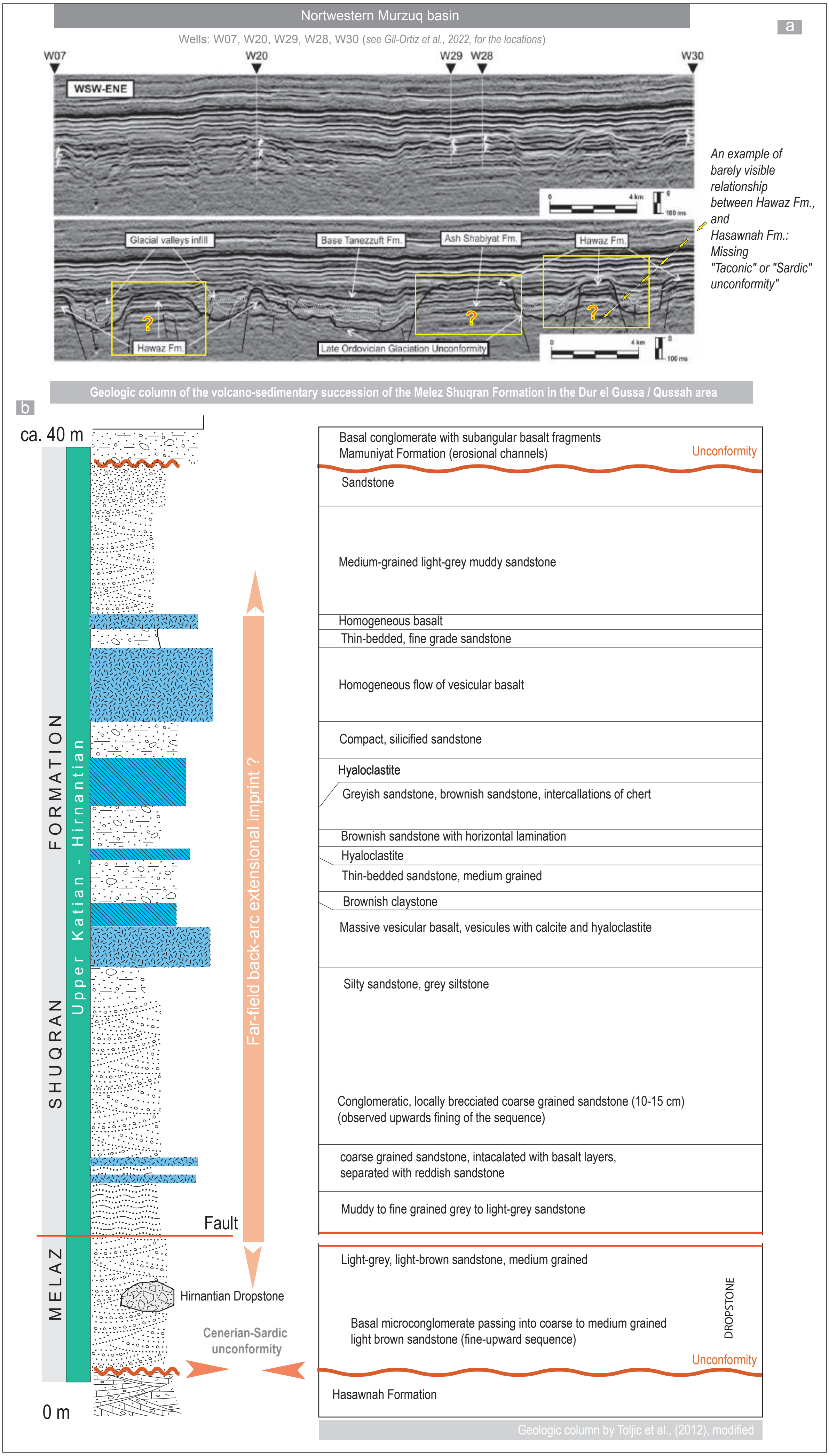
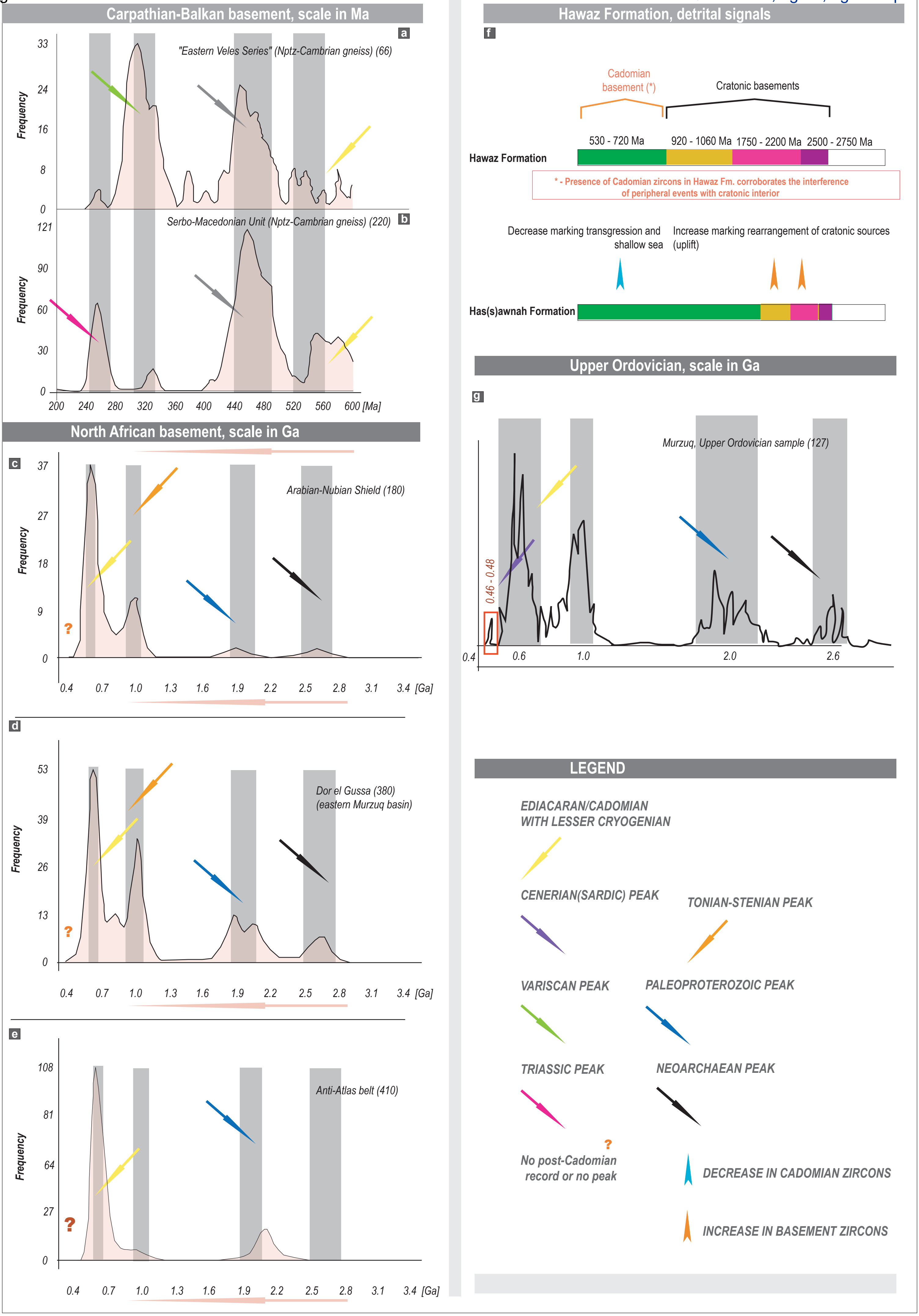


Figure 6



Carpathian-Balkan basement, scale in Ma
a
"Eastern Veles Series" (Nptz-Cambrian gneiss) (66)
b
Serbo-Macedonian Unit (Nptz-Cambrian gneiss) (220)
Frequency
200 240 280 320 360 400 440 480 520 560 600 [Ma]
North African basement, scale in Ga
c
Arabian-Nubian Shield (180)
d
Dor el Gussa (380)
(eastern Murzuq basin)
e
Anti-Atlas belt (410)
0.4 0.7 1.0 1.3 1.6 1.9 2.2 2.5 2.8 3.1 3.4 [Ga]
Hawaz Formation, detrital signals
f
Cadomian basement (*)
Cratonic basements
530 - 720 Ma
920 - 1060 Ma
1750 - 2200 Ma
2500 - 2750 Ma
Hawaz Formation
* - Presence of Cadomian zircons in Hawaz Fm. corroborates the interference of peripheral events with cratonic interior
Decrease marking transgression and shallow sea
Increase marking rearrangement of cratonic sources (uplift)
Has(s)awnah Formation
Upper Ordovician, scale in Ga
g
Murzuq, Upper Ordovician sample (127)
0.46 - 0.48
0.4 0.6 1.0 2.0 2.6
LEGEND
EDIACARAN/CADOMIAN WITH LESSER CRYOGENIAN
CENERIAN(SARDIC) PEAK
TONIAN-STENIAN PEAK
VARISCAN PEAK
PALEOPROTEROZOIC PEAK
TRIASSIC PEAK
NEOARCHAEAN PEAK
No post-Cadomian record or no peak
DECREASE IN CADOMIAN ZIRCONS
INCREASE IN BASEMENT ZIRCONS

Figure 7 Click here to access/download;Figure;Fig 7 Lib-iii.pdf

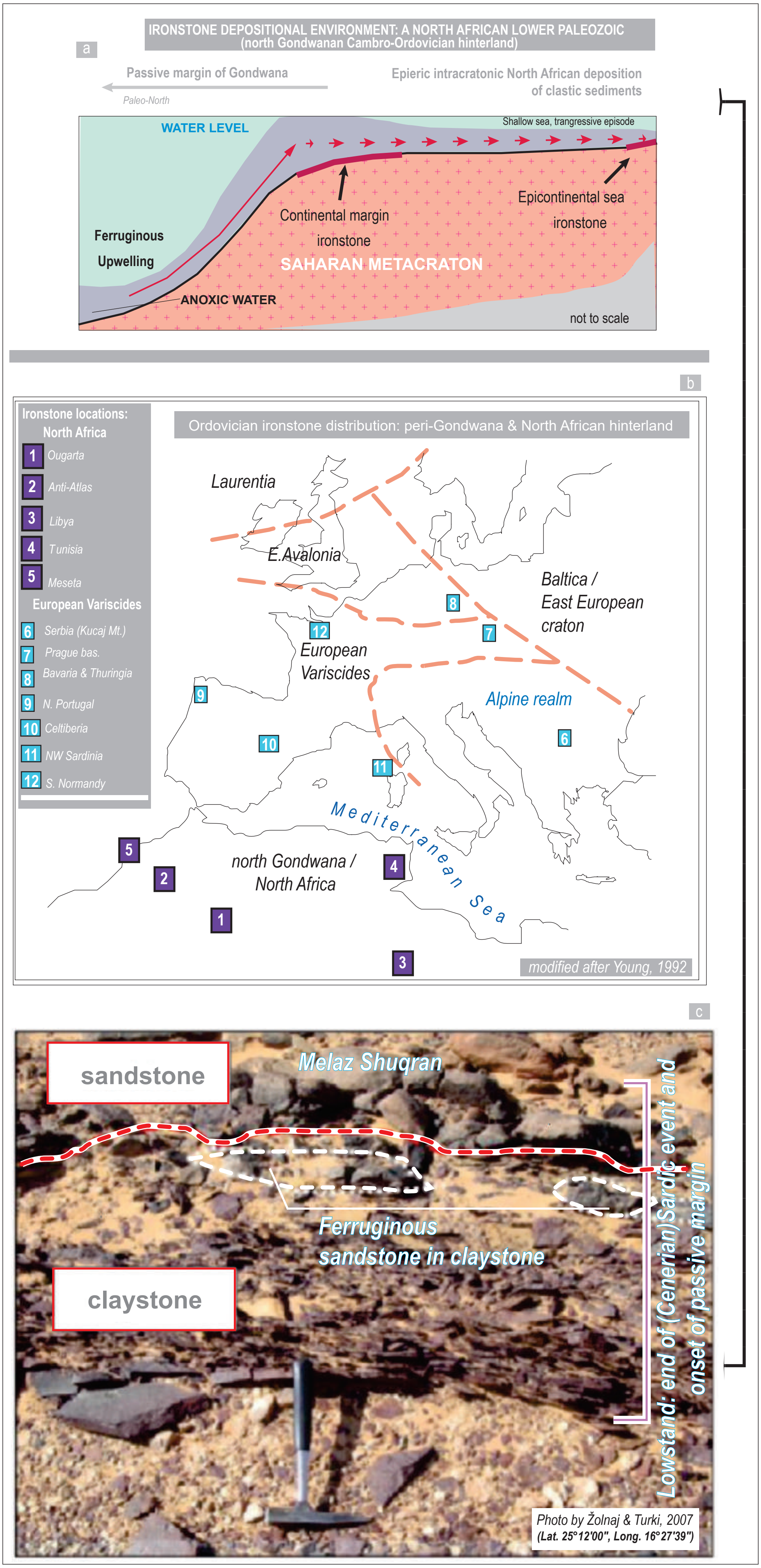
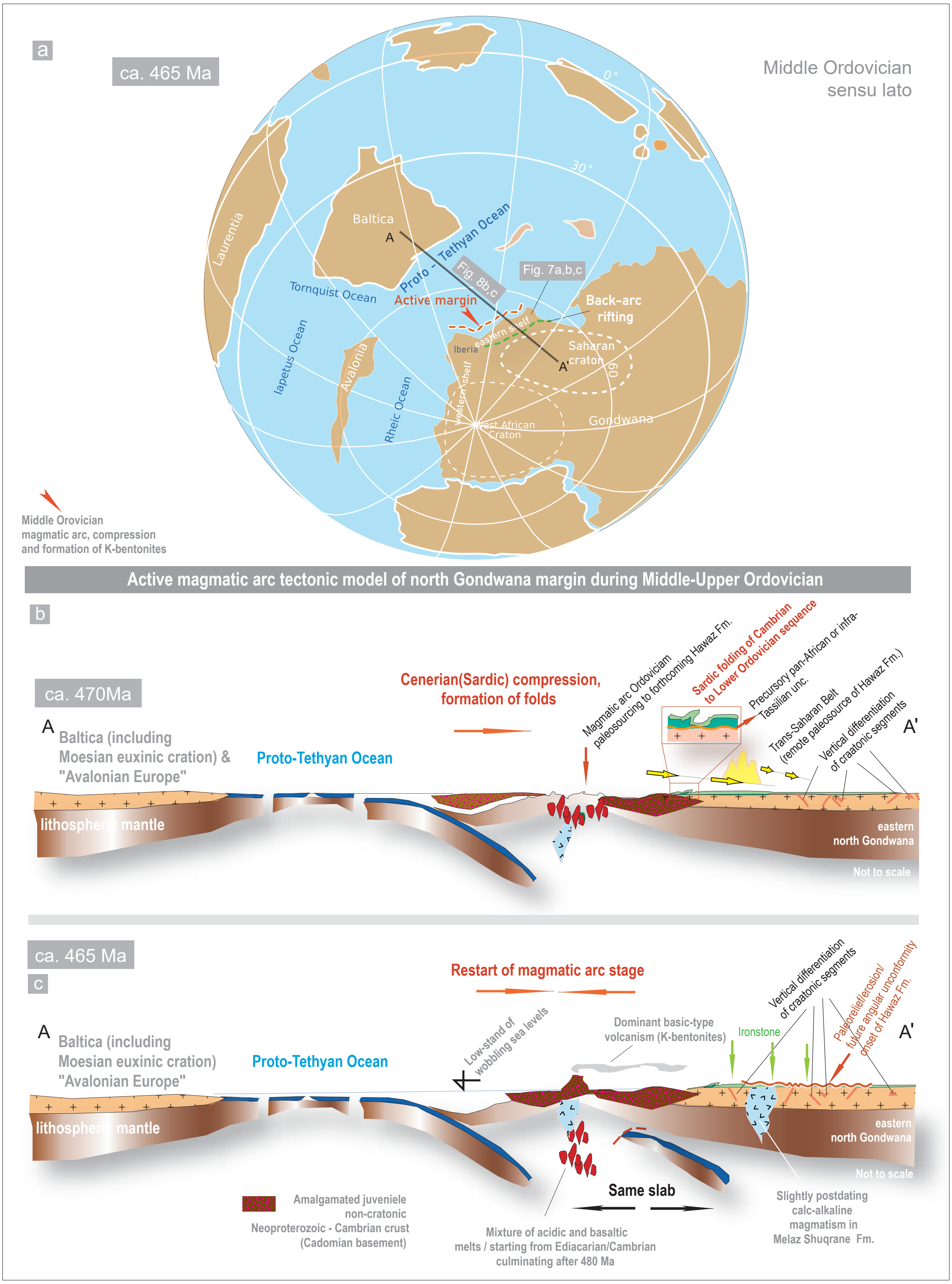


Figure 8


a
ca. 465 Ma
Middle Ordovician
sensu lato
0°
30°
Laurentia
Baltica
A
Proto - Tethyan Ocean
Fig. 8b,c
Fig. 7a,b,c
Tornquist Ocean
Active margin
Back-arc
rifting
eastern shelf
Iberia
Saharan
craton
A'
60
Iapetus Ocean
Avalonia
Rheic Ocean
western shelf
West African
Craton
Gondwana
Middle Orovician
magmatic arc, compression
and formation of K-bentonites
Active magmatic arc tectonic model of north Gondwana margin during Middle-Upper Ordovician
b
ca. 470Ma
Cenerian(Sardic) compression,
formation of folds
Magmatic arc Ordoviciam
paleosourcing to forthcoming Hawaz Fm.
Sardic folding of Cambrian
to Lower Ordovician sequence
Precursory pan-African or infra-
Tassilian unc.
Trans-Saharan Belt
(remote paleosource of Hawaz Fm.)
Vertical differentiation
of craatonic segments
A
Baltica (including
Moesian euxinic cration) &
"Avalonian Europe"
Proto-Tethyan Ocean
A'
lithospheric mantle
eastern
north Gondwana
Not to scale
ca. 465 Ma
c
Restart of magmatic arc stage
Low-stand of
wobbling sea levels
Dominant basic-type
volcanism (K-bentonites)
Ironstone
Vertical differentiation
of craatonic segments
Paleorelief/erosion/
future angular unconformity
onset of Hawaz Fm.
A
Baltica (including
Moesian euxinic cration)
"Avalonian Europe"
Proto-Tethyan Ocean
A'
lithospheric mantle
eastern
north Gondwana
Not to scale
Same slab
Amalgamated juveniele
non-cratonic
Neoproterozoic - Cambrian crust
(Cadomian basement)
Mixture of acidic and basaltic
melts / starting from Ediacarian/Cambrian
culminating after 480 Ma
Slightly postdating
calc-alkaline
magmatism in
Melaz Shuqrane Fm.

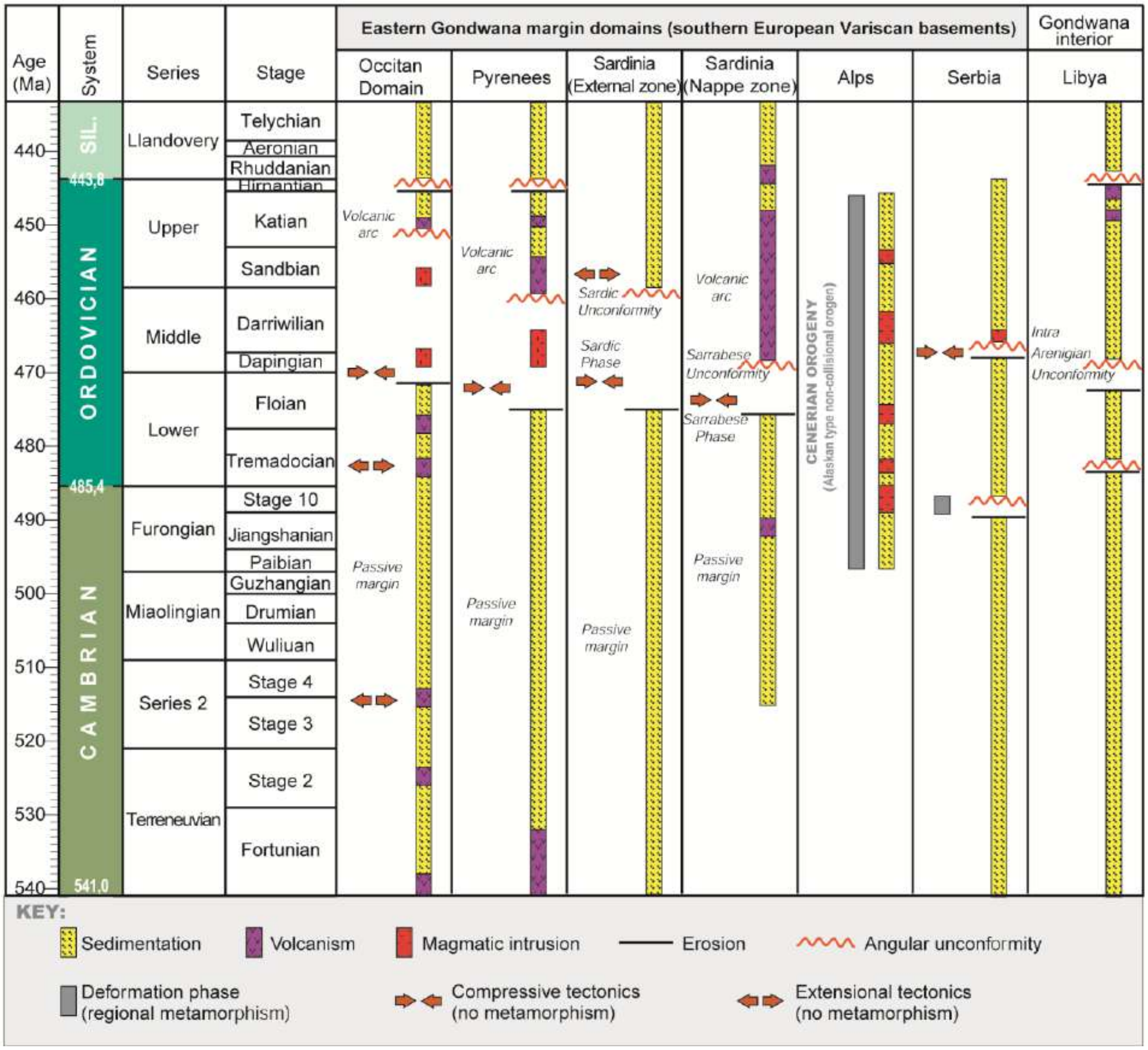


Table 1. Ordovician tectonic stages recorded in southern Europe and hypothesized across North Africa. Data sources are in the text.

Table 2. Table showing Late Cambrian-Ordovician ages in the basement of the Carpathian-Balkans and Inner Hellenides, and Romanian Carpathians. Data compiled from Balintoni et al. (2011), Antić et al. (2016), and Abbo et al. (2020).

Pre-Alpine basements and their metamorphic units (for positions see Fig.1a)	Protolith type	U/Pb age Or $^{206}Pb/^{238}U$	Method
Carpathian-Balkans			
Serbo-Macedonian Unit (segment of Supragetic/Getic nappe pile (Serbia)	Paragneiss, orthogneiss	From 490 ± 7 Ma to 472 ± 4 Ma	LA-ICP-MS
Serbo-Macedonian Unit, its analog “Eastern Veles Series” (North Macedonia)	Orthogneiss, leucocratic metagranite,	From 487 ± 17 Ma to 478 ± 3	
Inner Hellenides			
Vertiskos units (analog of Serbo-Macedonian Unit) (Greece)	Augen gneiss / ortho-protolith	466±2 Ma	- zircon U-Pb-Hf - rutile U\Pb data
	Granitic augen gneiss (two locations)	455±2 & 466±2 Ma	
	Biotite gneiss	468±2 Ma	
Southern Carpathians			
Sebes-Lotru terrane (presumable analog of Serbo-Macedonian Unit)			
Cumpana metamorphic unit	Capalna augen gneiss	458.9+/-3.5 Ma	LA-ICP-MS
	Latorita orthogneiss	Latorita orthogneiss 466.0+/-4.2 Ma	
Apuseni Mountains			
Somes terrane			
Somes metamorphic unit	Iara Valley orthogneiss	459.8+/-2.7 Ma	LA-ICP-MS
Baia de Aries metamorphic unit	Pociovalistea augen gneiss	470.8+/-5.0 Ma	
	Lupsa porphyroid	467.8+/-3.8 Ma	
	Mihoesti metagranite	467.8+/-4.7 Ma	
	Muncelu metagranite	467.1+/-3.9 Ma	
Biharia terrane			
Biharia metamorphic unit	Lunca Larga metagranites	495.0+/-2.1 Ma	LA-ICP-MS
	Metabasites 477.8+/-3.2 Ma	Metabasites 477.8+/-3.2 Ma	
Eastern Carpathians			
Rebra, Negrisoara, and Tulges terranes	Haghimas granitoid and Mandra granitoid	465 Ma and 468 Ma	TIMS
	Nichitas orthogneiss	460 Ma	
	Pietrosu orthogneiss	485 Ma	
	Brezuta orthogneiss	485 Ma	

Locations in north Africa	**Iron-bearing mineral phases**	**Ref.**
Anti-Atlas (Morocco)	Chm, H, M, MH, G, L, S	1, 2
Ougarta (Algeria)	H, Chm, G, S	2, 3
Tripolitania (Libya)	Chm, S, G	4
Locations in Europe	**Iron-bearing mineral phases**	**Ref.**
Kučaj (Serbia)	Chl (Rip, Chm?, She?), S	5
Welsh Basin (United Kingdom)	Chm, S, H, G, M	6, 7, 8
Prague Basin (Czech Republic)	Chm, S, G, H, M	2, 6, 7
Thuringian Basin (Germany)	Chm, S, G, H	2, 6, 7
Crozon Peninsula (South Normandy)	Chm, S	9
Cabril Formation (Central Portugal)	Chm, S	9
WALZ & CZ (Iberian Massif, Spain)	H, Chm/Clc, S, G, M	10
Holy Cross Mountains (Poland)	Chm, H, G, S	11
Western Balkanides (Bulgaria)	Chm	12

Table 3. Summary of iron-bearing mineral phases within the oolitic ironstone occurrences among studied locations. Abbreviations: Chl–chlorite; Chm–chamosite; Rip–ripidolite; Clc–clinochlore; She–sheridanite; H–hematite; M–magnetite; MH–maghemite; G–goethite; L–lepidocrocite; S–siderite. Data compiled from: 1) Abia et al. (2020); 2) Young (1992); 3) Guerrak (1988); 4) Guerrak (1992); 5) Spahić et al. (2023a); 6) Mücke and Farshad (2005); 7) Mücke (2006); 8) Dunn et al. (2021); 9) Young (1989); 10) Pufahl et al. (2020); 11) Trela (2008); 12) Yanev et al. (2006)

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: