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The Ordovician record of North and West Africa: unravelling sea-level variations, Gondwana tectonics, and the glacial impact

Jean-François Ghienne^{1*}, Hussein Abdallah², Rémy Deschamps³, Michel Guiraud⁴, Juan Carlos Gutiérrez-Marco⁵, Moussa Konaté⁶, Guido Meinhold⁷, Abderamane Moussa⁸ and Jean-Loup Rubino⁹

¹Institut Terre et Environnement de Strasbourg (ITES, UMR 7063), CNRS-Université de Strasbourg, 5 rue R. Descartes, 67000 Strasbourg, France

²Calle Sacerdote Isidro Albert 20, Esc. 2, piso 2 C, Alicante 03010, Spain

³IFPEN, 1-4 avenue de Bois-Préau, 92852 Rueil-Malmaison, France

⁴Biogéosciences, UMR 6282, Université de Bourgogne Franche-Comté, 21 000 Dijon, France


⁵Instituto de Geociencias (CSIC, UCM), and Área de Paleontología, Departamento GEODESPAL; Facultad de Ciencias Geológicas, 28040 Madrid, Spain

⁶Département de Géologie, Université Abdou Moumouni, Faculté des Sciences et Techniques, BP 10662 Niamey, Niger

⁷TU Bergakademie Freiberg, Institut für Geologie, Bernhard-von-Cotta-Straße 2, D-09599 Freiberg, Germany

⁸Laboratoire Hydro-Géosciences et Réservoirs, Département de Géologie et Paléontologie, Université de N'Djamena, BP 1027 N'Djamena, Chad

⁹ISTeP-Sorbonne Université (UMR 7193), 4 place Jussieu, 75005 Paris, France

 J-FG, 0000-0002-9448-5285; RD, 0000-0002-0888-3456; MG, 0000-0003-3125-8947; JCG-M, 0000-0003-4213-6144; GM, 0000-0001-8375-8375; J-LR, 0000-0003-4101-6327

*Correspondence: ghienne@unistra.fr

Abstract: The Ordovician of North and West Africa comprises three main transgressive–regressive sequences understood as ‘second-order’ cycles of 10–15 myr duration. Tide- to wave-dominated shallow-marine clastic successions, preserving incidental bryozoan carbonates to the north, include fluvial deposits over the most proximal southern stretches of the platform. The boundary with Cambrian strata remains unclear but the latter are progressively less represented to the south in the undifferentiated ‘Cambro-Ordovician’. To the north, graptolites, brachiopods and trilobites combined with palynomorphs provide a robust biostratigraphic frame. Maximum flooding intervals occurred in the early to middle Tremadocian, middle Darriwilian and middle to late Katian. Two events interfered with an overall long-term transgressive trend. The ‘intra-Arenig’ (late Floian?) tectonic event highlighted palaeohighs coinciding with Paleoproterozoic basements. Gondwanan drainage basins were reorganized, which had an impact on sediment sourcing and distribution of detrital material (e.g. zircons) feeding the pre-Variscan Europe. The second event is the end-Ordovician glaciation. The domain supported the greatest part of the Hirnantian glaciers and may also have preserved pre-Hirnantian glacial archives. It is not until the very latest Ordovician that offshore conditions developed far inland; it is however suspected that this inundation benefited from a transient postglacial isostatic flexure.

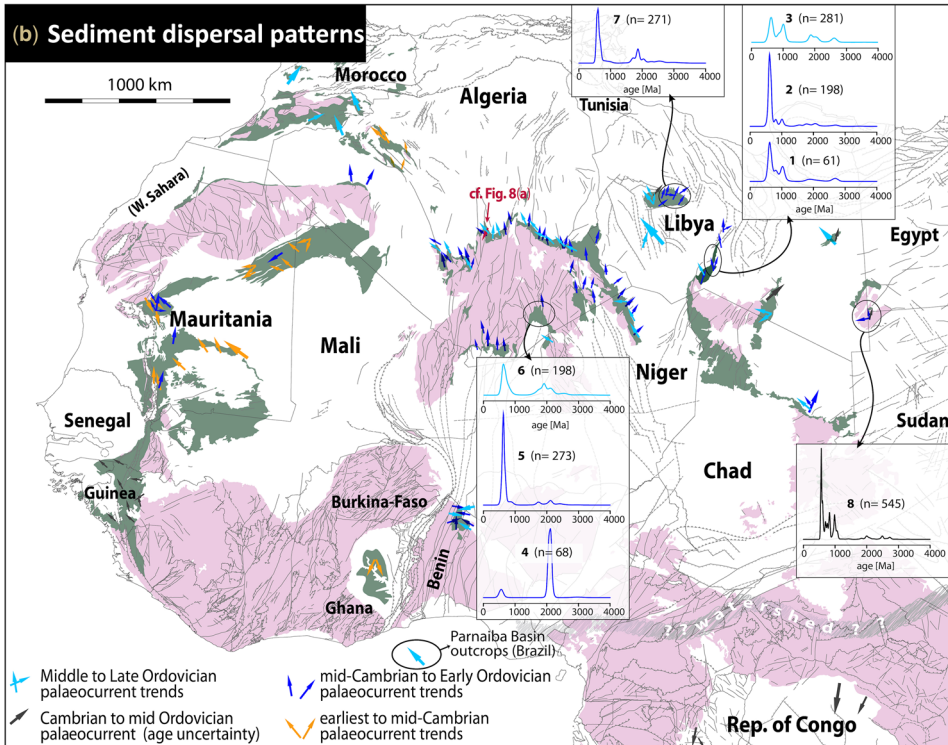
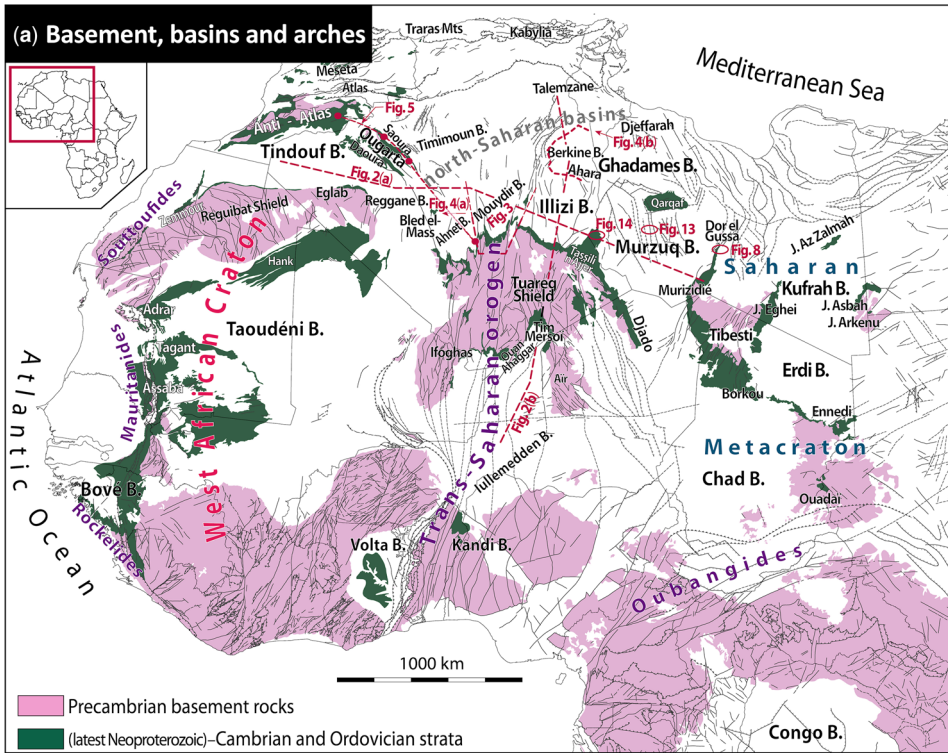
Ordovician strata of North and West Africa were first thought to be an inverted Devonian succession overlying a metamorphic Silurian basement – in order to match a Caledonian geological framework – and conformably ‘overlain’ by Silurian shales. The age of the latter was established at the very beginning of the twentieth century owing to several discoveries

of graptolites north of the Tuareg Shield (Ahnet-Mouydir), then in the Ougarta and in northern Algeria (Willefert 1997; Legrand 2003). It was not until a few decades later that (1) the so-called Devonian strata were attributed to the Silurian *sensu lato*, at a time when the Ordovician system had not yet been established as such (Lower Sandstones of Kilian

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The Ordovician record of North and West Africa

1922, 1924) and (2) Tremadocian graptolites were discovered, and the ‘Silurian’ Lower Sandstones were finally understood to be a succession comprising Cambrian and Ordovician rock units (Poueyto 1952). The latter, which are often referred to as an undifferentiated ‘Cambro-Ordovician’ unit wherever no clear (bio)stratigraphic boundary can be recognized, rest upon the Precambrian basement or Ediacaran volcanics along the infra-Tassilian Unconformity that was identified all over the central and eastern Sahara (Furon 1964; Arbey and Cabyl 1966; Beuf *et al.* 1971; Eschard *et al.* 2005). This scheme, which was then expanded only with minor variations from Mauritania (where the Cambrian strata rest upon virtually undeformed Neoproterozoic sediment) to Chad (where Silurian shales are frequently missing), was popularized by the geological map printed on the occasion of the 19th International Geological Congress of Algiers in 1952.

After the pioneering studies, our knowledge of the Ordovician of North and West Africa has greatly benefited from numerous studies launched from the 1950s to the 1970s by the petroleum industry and in the frame of geological mapping projects (e.g. Wacrenier *et al.* 1958; Borocco and Nyssen 1959; Joulia 1959; Plauchut and Faure 1959; Dubois 1961; Morange *et al.* 1992). It allowed basin by basin regional (litho)stratigraphies to be established supported, at that time, by fragmentary biostratigraphic frames (e.g. B.R.P. 1964; Legrand 2002 and references therein). It soon became apparent that efforts to integrate datasets would be needed,

addressing issues such as links between lithostratigraphy and chronostratigraphy, links between subsurface (primarily wells, the first one reaching the Ordovician in the Sahara dating back to 1953) and outcrop belts, and links between basins that are adjacent but separated by distinctive ‘highs’ or arches (e.g. Legrand 1962). This was addressed generally on a country-by-country basis (e.g. De Lestang 1965; Greigert and Pougnet 1967; Whiteman 1971; Legrand 1974a; Bellini and Massa 1980; Trompette 1983; Takherist 1990). Studies in Algeria and Libya were ahead of schedule, since both regions remained the main targets of the oil and gas industry (Askri *et al.* 1995; Boote *et al.* 1998; Fekirine and Abdallah 1998; Echikh and Sola 2000; Combaz 2002; Hallett 2002). In parallel, research programmes linked to doctoral and habilitation theses added substantial pieces of knowledge to the Ordovician stratigraphy, as part of regional-scale stratigraphic studies most often encompassing the entire Paleozoic development (e.g. Gevin 1960; Sougy 1964; Klitzsch 1970; Beuf *et al.* 1971; Trompette 1973). Shortly after, the first platform-scale stratigraphic syntheses were published in the academic literature (e.g. Fabre 1976, 1988; Klitzsch 1981; Deynoux *et al.* 1985). In the late twentieth and early twenty-first centuries, a renewed interest in oil and gas resources of the Sahara has allowed for joint development of industrial research (e.g. acquisition of 3D seismic datasets, high-resolution well logs and Formation-Micro-Imager data) and academic projects (Biteau *et al.* 2016). Often funded by the

Fig. 1. Location maps, including place names cited in the text (B, basin). (a) Distribution of exposed Ordovician strata in North and West Africa. Ordovician strata are also almost systematically recognized in the subsurface of sedimentary basins, which are bounded by basement uplifts (large shield areas and less extensive arches or ‘highs’; see also Figs 2–4). The Ordovician is not differentiated from the Cambrian in most places (constituting the so-called ‘Cambro-Ordovician’), since its lower bounding surface is frequently debated, at least in the southern part of the considered domain (Taoudeni Basin, northern and southern Hoggar, Murzuq, Kufrah and Erdi basins, etc.). Red dashed lines refer to regional-scale cross-sections of Figure 2; red dots (Anti-Atlas, Ougarta Range and Ahnet Basin) refer to the locations of the four logs shown in Figure 5. (b) Sediment dispersal patterns in the Cambro-Ordovician of North and West Africa, compiled from unpublished data and from Bamulezi *et al.* (2014), Beuf *et al.* (1971), Burollet and Byramjee (1969), Carney *et al.* (2010), Dia (1984), Ghiene *et al.* (2013, 2023), Gil-Ortiz *et al.* (2022), Konaté *et al.* (2003, 2006), Le Heron and Howard (2012), Le Heron *et al.* (2015), Linol *et al.* (2016), Medaouri (2004), Ramos *et al.* (2006), Razin *et al.* (2003), Seilacher *et al.* (2002), Villeneuve and Komara (1991) and Vos (1981) (Brazilian outcrops: cf. Assis *et al.* 2019). The significance of the red arrow (Ahnet Basin) is highlighted in Figure 8. The southern watershed location should be considered only as a working hypothesis. 1–7, Detrital zircon U–Pb age spectra of Cambrian–Ordovician sandstones from Algeria and Libya. Data taken from Meinhold *et al.* (2011) (1–3), Linnemann *et al.* (2011) (4–6) and Altumi *et al.* (2013) (7) are shown in kernel density estimate (KDE, area normalized) plots produced using the R-package Provenance (Vermeesch *et al.* 2016): 1, basal Hasawnah Formation (sample P5890); 2, Hasawnah Formation, Upper Cambrian–Lower Ordovician (P5889, P5876, W5207); 3, Hawaz Formation, Middle Ordovician (H6063, H6048, P5880); 4, basal Grès des Ajers Formation (sample HOG1); 5, Grès des Ajers Formation, Upper Cambrian–Lower Ordovician (HOG2, HOG3, HOG4); 6, Middle–Upper Ordovician strata (HOG-5, HOG 6); 7, Hasawnah Formation, Cambrian (all samples, except basal sandstones). 8, Detrital zircon ages from a Neoproterozoic metasedimentary rock of the Arkenu area on the eastern margin of the Kufrah Basin (Le Heron *et al.* 2009b, sample H2519) and from the southern areas of the Saharan Metacraton (Blades *et al.* 2021) are shown as a reference. The data were filtered following criteria outlined in Lewin *et al.* (2020). Only zircon ages with 90–110% concordance are shown in the diagrams.

industry, the latter focus on particular aspects of Ordovician stratigraphy (e.g. micropalaeontology, facies models, the end-Ordovician glaciation, source-to-sink approaches, diagenesis and petrophysics). However, synoptic works have not dealt specifically with the Ordovician (Schandelmeier and Reynolds 1997; Boote *et al.* 1998; Carr 2002; Guiraud *et al.* 2005; Craig *et al.* 2008; Nedjari *et al.* 2011; Hallett and Clark-Lowes 2016), with the exception of Riché and de Charpal (1998) and Fabre and Kazi-Tani (2005).

This paper outlines the Ordovician of North and West Africa, which characterized a major segment of the north-facing south-polar Gondwana platform – sometimes referred to as the so-called ‘North-Gondwana platform’. Morocco, that exposes from the Anti-Atlas to the Meseta domains one of the major strips of Ordovician strata in Africa

(Destombes *et al.* 1985; Michard *et al.* 2010), is however excluded from this paper. Its undisputed biostratigraphic record is the subject of several recent studies (among others: Gutiérrez-Marco *et al.* 2014, 2017, 2022a; Jiménez-Sánchez *et al.* 2015; Van Roy *et al.* 2015; Gutiérrez-Marco and Martin 2016; Lefebvre *et al.* 2018, 2022; Álvaro *et al.* 2022; Colmenar *et al.* 2022). The Ordovician strata that will be featured here are well exposed from the Variscan front of the Mauritanides and Souttoufides belts to the west, to Libya and Chad to the east, generally along extensive cuesta systems running along shield contours (Reguibat, Tuareg and Tibesti–Ouadaï), more sporadically owing to fault-bounded uplifts and/or windows beneath the upper Paleozoic to Mesozoic cover (Figs 1a & 2). The Ordovician is even better developed in the subsurface, where it is recognized within virtually all the intervening

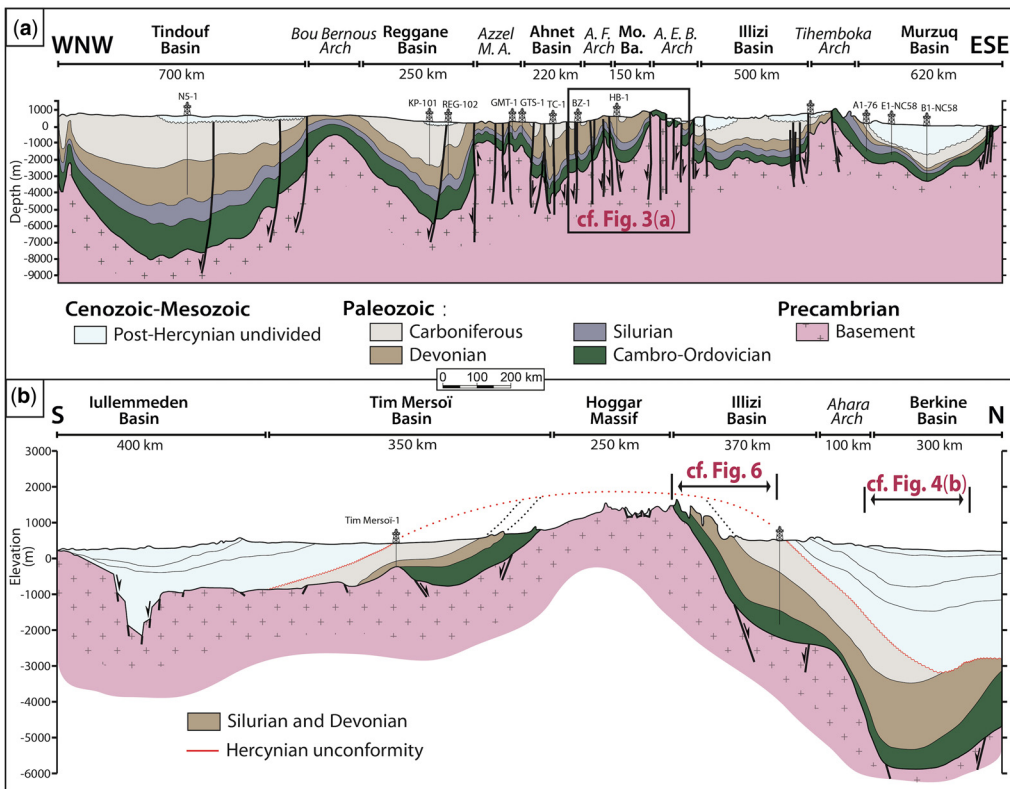


Fig. 2. Regional cross-sections showing the Ordovician record in its current configuration (location in Fig. 1). (a) This west–east-oriented profile illustrates the configuration of the Ordovician strata preserved in the suite of north-Saharan basins, which display a typical tectono-stratigraphic architecture in basins and arches resulting from differential subsidence patterns acquired during the entire Paleozoic development (modified from Craig *et al.* 2008 and Perron *et al.* 2018). Mo. Ba., Mouydir Basin (cf. Fig. 3); Azel M. A., Azzel Matti Arch; A.F. Arch, Arak-Foum Belrem Arch; A.E.B., Amguid El Biod Arch. (b) This submeridian profile illustrates the configuration of the Ordovician record on both sides of Tuareg Shield corresponding to an extensive swell formed in the Cenozoic (modified from English *et al.* 2017b and Perron *et al.* 2018).

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sedimentary basins, principally the train of north-Saharan basins, which has been the focus of diverse and considerable research (Boote *et al.* 1998; Craig *et al.* 2008; Galeazzi *et al.* 2010; Perron *et al.* 2018; Fig. 2). To the east, we arbitrarily limit the domain at the western margin of the large north-south-oriented basement uplift running from Egypt to Sudan (Semtner and Klitzsch 1994; Guiraud *et al.* 2005; for further information on the Ordovician record of both countries see Klitzsch 1981; Keeley 1989; Wanas 2011, with issues regarding age attributions discussed by Weissbrod 2004). To the south, strata attributed to the Ordovician, sometimes with uncertainty, are followed more discontinuously from Chad to Mauritania and Guinea. In addition, spottier areas are identified in particular tectonic settings tied to basement lineaments (Konaté *et al.* 2003, 2006), and potentially up to the Congo Basin in Central Africa (Linol *et al.* 2016; Delvaux *et al.* 2021). All the considered domain is in the back of what would become Variscan and Alpine Europe (Torsvik and Cocks 2013; Stephan *et al.* 2019; Martínez-Catalán *et al.* 2021; Oriolo *et al.* 2021; Tabaud *et al.* 2021).

It is not the intention to review here the Ordovician successions basin by basin, or even country by country, since the earlier studies by R. Chudeau, J. Tilho, C. Kilian, A. Desio, N. Menchikoff, M. Dalloni, T. Monod, J.-M. Freulon and others (see, for instance, Klitzsch 1994; Legrand 2002; Taquet 2007 for historical perspectives). Up-to-date lithostratigraphic correlation tables can be found in Craig *et al.* (2008) and Askri *et al.* (1995) or Perron *et al.* (2018) for Algeria. As with so many other platform systems across time and space on Earth, Ordovician strata are paradoxically relatively uniform throughout North and West Africa, but nevertheless, they systematically display particular successions making distant correlations sometimes challenging. We aim at presenting first a platform-scale overview of the Ordovician stratigraphy in its structural and biostratigraphic contexts (*c.* 4000 × 2500 km²), then an idealized succession and, afterwards, the reasons explaining the unexpected variety of Ordovician successions throughout such a so-called tectonically stable domain. To achieve this, the paper describes the succession of stratigraphic cycles through time, as it may be preserved in northern basinal areas (northern Algeria, western Libya) where stratigraphic breaks appear or at least should appear as minimal. Second, for each cycle, variation along-dip (SSE–NNW) will be examined, in an attempt to separate Ordovician strata from the undifferentiated ‘Cambro-Ordovician’ strata recognized in the proximal, southeastern reaches of the platform (southern Algeria, Niger, southeastern Libya, Chad and Sudan). The Ordovician from the west (western Algeria, Mauritania, Guinea) must be treated

separately. The end-Ordovician glacial archive, a large part of which emerged from the study of North and West African basins, is outlined and its relationship with the proposed frame of stratigraphic cycles is discussed. Finally, tectonic controls on the Ordovician accommodation space and related depositional environments are addressed, and the relationship between the Ordovician of Africa and coeval records of the European peri-Gondwana domains is emphasized through the lens of sediment dispersal patterns. Overall, we pay attention to citing the most recent literature, with the bias of not dwelling on the older literature (before 1990). The reader should find in the bibliography of the most recent papers the prolific works which, after a century of research, have given a comprehensive understanding of the Ordovician stratigraphy of the vast area considered here.

The Gondwana platform of North and West Africa

The basement architecture

The basement of the study area comprises a juxtaposition of distinct crustal domains accreted to each other during the late Neoproterozoic Era (Pan-African orogenic event; Liégeois 2019). Three main crustal domains are recognized (Fig. 1a): (1) to the west, the West African Craton (WAC; e.g. Jessell *et al.* 2016), assembled during the Paleoproterozoic Era, preserving a paraconformable succession of Mesoproterozoic to Cambrian strata (Bertrand-Sarfati *et al.* 1990; Waters and Schofield 2004; Deynoux *et al.* 2006; Lahondère *et al.* 2008); (2) in the middle, the Trans-Saharan Belt, one of the main Pan-African accretional domains, 1000–1500 km-wide, itself including several submeridian cratonic to juvenile terranes accreted before the Cambrian Period (Bertrand and Caby 1978; Black *et al.* 1994; Amara *et al.* 2017; Brahimi *et al.* 2018; Perron *et al.* 2021); and (3) to the east, the Saharan Metacraton, a Meso- to Neoproterozoic assemblages of subdomains including at least three cratonic nuclei, and variously reactivated during the Pan-African event (Abdelsalam *et al.* 2002; Liégeois *et al.* 2013; Blades *et al.* 2021). These domains are surrounded by a suite of more or less connected Pan-African belts, amongst which are the Anti-Atlas, Mauritanides and Rockelides belts around the West African Craton, and the Oubangides Belt separating the Saharan Metacraton from the Congo Craton in Central Africa (Trompette 1994; Villeneuve 2005; Ngako *et al.* 2008; Villeneuve *et al.* 2014, 2015a, b; Soulimani *et al.* 2018). All of these basement units had contrasted behaviours during the Paleozoic plate-tectonic development and frame the depositional setting of the

overlying Cambrian and Ordovician stratal (Coward and Ries 2003; Craig *et al.* 2008; Brahim *et al.* 2018; Perron *et al.* 2018, 2021).

Foreland basins were associated with these large collisional systems, which became inactive during the early Cambrian (Fabre *et al.* 1988; Fabre 2005; Deynoux *et al.* 2006), and by the middle Cambrian, the platform configuration became effective, with quartz-dominated sources now prevailing over arkosic compositions (Trompette 1973; Avigad *et al.* 2005; Sabaou *et al.* 2009; Bassis *et al.* 2016). Note that the overall platform was even larger, extending from northern South America up to the Middle East (Sharland *et al.* 2001; Ghienne *et al.* 2010; Bassis *et al.* 2016; Assis *et al.* 2019), forming one of the largest sandstone-dominated sedimentary domains of all time (Burke *et al.* 2003). However, the present-day physiography alternating vast uplifted Proterozoic shields and large subcircular sedimentary basins mainly inherited from late Paleozoic to Cenozoic developments has little to do with the original configuration of the Ordovician landscape (Beuf *et al.* 1971; Askri *et al.* 1995; Haddoum *et al.* 2001; Rougier *et al.* 2013; Carruba *et al.* 2014; Leprêtre *et al.* 2014; English *et al.* 2017b; Perron *et al.* 2018). Outcrops and subsurface data can be viewed as distributed windows into an originally highly uniform sedimentary system, which at first order comprised: (1) a distal marine-dominated depositional domain behind a distant Gondwana margin positioned more to the north and NNW, providing most of the biostratigraphic framework as far as the Ordovician is concerned; (2) an intermediate mixed marine and continental depositional domain – coinciding approximately to the present-day Sahara – where the robustness of biostratigraphic controls rapidly decreases to the south, and where few restricted and temporary basement exposures may constitute local sediment sources; and (3) to the south and SSE, an exhuming basement linked to remote, long-term sediment source areas progressively narrowing in the context of a Paleozoic continental encroachment megacycle. Deeply weathered profiles including rubefaction processes are preserved in the later area (Germann *et al.* 1993; Ghienne *et al.* 2023), in agreement with the composition of exported sediments (Sabaou *et al.* 2009). The occurrence of a significant population of Archean zircon grains in Ordovician sandstone deposited in southern Algeria and southern Libya on the one hand (Linnemann *et al.* 2011; Meinhold *et al.* 2011) and on the other southward-oriented Paleozoic palaeocurrent trends in the Congo Basin (Bamulezi *et al.* 2014; Linol *et al.* 2016), suggest that the watershed of the North and West African platform expanded far south with a water divide tentatively positioned in Central Africa (Fig. 1b). As shown below, the stratigraphic record derived from this somewhat basic organization has been greatly

complicated by the permanent interference of tectonic, eustatic and climatic signals, throughout the Paleozoic in general, and during the Ordovician in particular.

Tectono-stratigraphic development

In North and West Africa, the Ordovician sedimentary pile most often displays thicknesses in the 200–1000 m range, corresponding to rather limited averaged accumulation rates (5–25 m/myr; Perron *et al.* 2018). A typical tectono-stratigraphic architecture in basins and arches – the latter also often referred to as palaeohighs – is acknowledged (Fig. 2a; Klitzsch 1981; Abugares 2003; Coward and Ries 2003; Sikander 2003; Gabtni *et al.* 2006; Craig *et al.* 2008; Eschard *et al.* 2010). Owing to recent flexural uplift (Fig. 2b; Rougier *et al.* 2013; English *et al.* 2017b), the northern Hoggar shows one of the rare well-documented examples of intracratonic basins in the world where the architecture of both the Precambrian basement and the overlying North Saharan basins are cropping out (Figs 2 & 3a; Craig *et al.* 2008). It allows the architecture of Paleozoic basins to be detailed as simple syncline-shaped basins or as more tectonized, complex-shaped basins (Perron *et al.* 2018). The first-order syncline-shaped pattern is best illustrated by the Mouydir Basin (Fig. 3a). The Tim Mersoi Basin of northern Niger is another example. Second-order interbasin/intrabasin secondary arches are observed in the Ahnet Basin (Fig. 2a). During the Paleozoic, the structural development of these basins was mainly controlled by submeridian, high-dip (>60°) normal faults forming horst and graben networks associated with forced folds, weakly inverted and/or reactivated through time (Perron *et al.* 2018). This structural framework is preferentially nucleated on the basement structures (Zazoun 2001; Haddoum 2009), which are characterized by lithospheric shear zones with predominantly high dips (Bouزيد *et al.* 2008; Brahim *et al.* 2018).

Maximum subsidence is recorded in basinal areas, while minimum rates typified either the intervening arches or the most proximal, i.e. southern reaches of the platform (Figs 1a, 2, 4 & 5). In both cases, Ordovician shallow-marine to fluvial sandstones prevail, indicating sediment oversupply through time. This conforms to palaeocurrent trends persistently oblique relative to the structural fabrics, but consistent at the platform scale (Fig. 1b). In these conditions, where accumulation can be used as a proxy for total accommodation and considering an Ordovician global sea-level rise of c. 100 m (e.g. Haq and Schutter 2008), virtually no active tectonic subsidence occurred over large proximal areas of the platform. Accumulated thicknesses preserved outside the basinal, tectonically driven depocentres

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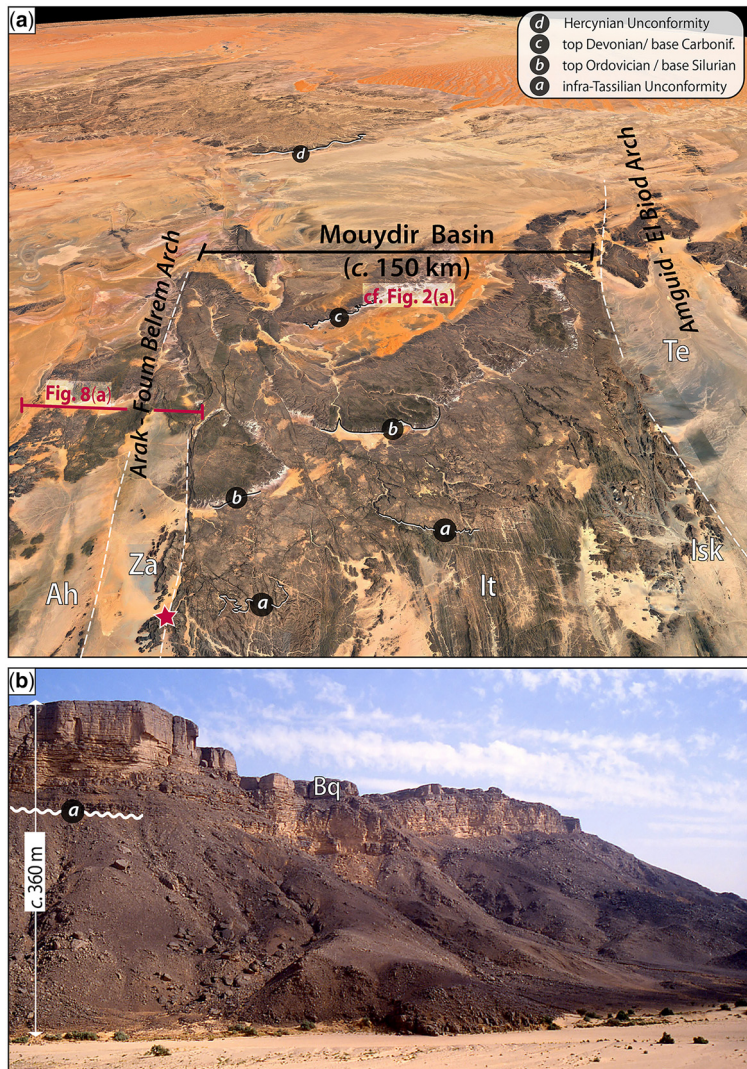


Fig. 3. The north African Ordovician record in its basin-scale context. **(a)** The example of the syncline-shaped Mouydir Basin, in northwestern Hoggar (location in Fig. 1; oblique satellite view looking north, from GoogleEarth), which rests over a Meso- to Neoproterozoic basement (It-In Teideni and Isk-Iskel terranes) and is bounded by the Arak-Foum Belrem and Amguid-El Abiod arches, cored by terranes essentially Paleoproterozoic in age (Ah-Ahnet and Za-In Zaouatene to the west; Te-Tefedest to the east). Pan-African shear zones (the Tuareg Shield (terrane sutures) can be prolonged in the deformed north-Saharan cover series; some have been highlighted (white dotted lines). See Perron *et al.* (2018) and references therein for more details. **(b)** The Cambro-Ordovician Grès des Ajjers Formation near the Arak Pass (red star in a), bounded at its base by the infra-Tassilian Unconformity (a) and displaying at its top the upper Lower to Middle Ordovician Banquette Member (Bq; cf. Fig. 8).

would essentially result, from a conservative perspective, in a combination of eustasy-driven increases in accommodation space, ‘transgressive’ deposition and subsequent isostatic compensation. It is argued that the impact of global eustasy across the entire platform domain has been substantial and that global eustasy is responsible for the second-order

cycles described below and their internal organization including landward extent of the flooding events, shoreline migrations, distribution of depositional facies and ichnofacies belts, among others; in other words, the palaeolandscape evolution. Tectonics is, however, instrumental for long-term accumulation and preservation patterns, sediment thicknesses,

angular stratal relationships at the outcrop to map scales, and basin and arch individualization, just to name a few. In such a context, most of the timing and significance of erosion processes tied to the unconformities are controlled by eustasy – or climate when considering the end-Ordovician glaciation – while their map-scale expression and amplitudes of the resulting stratigraphic hiatuses are linked to and highlight earlier inherited differential subsidence patterns controlled by tectonics (Ghienne *et al.* 2007a, 2013; Eschard *et al.* 2010; Perron *et al.* 2021). Note that the unconformities usually correspond to marine ravinement surfaces, with little evidence for subaerial exposures and fluvial incisions. It is suspected that the shorelines were generally not significantly deflected by tectonic structures, the time scale of the sedimentary dynamics – regarding both erosion and deposition processes – being faster by one or two orders than deformation rates. As a consequence, isopach maps emphasizing depocentres are a poor reflection of potential shoreline circumvolutions. This scheme of course suffered exceptions of limited extent, where and when tectonic was temporarily active and/or where and when true uplifts occurred, for instance during the ‘intra-Arenig’ deformation phase (Beuf and Montadert 1962) and/or in fault-bounded basins where centripetal flow clearly points to a structural control (e.g. the Kandi Basin, Fig. 1; Konaté *et al.* 2003, 2006).

Temporal controls in the Ordovician stratal record

The published biostratigraphic dataset on the Ordovician of North and West Africa is sparse with respect to the extent of the considered domain. This is due to (1) sandstone-dominated lithologies prevailing in outcrop belts, while (2) favourable depositional facies belts principally lie in basinal areas and (3) unpublished biostratigraphic data, a great part of which was acquired by petroleum companies. The latter is however available from confidential reports (e.g. Robertson reports) and PhD theses (e.g. Massa 1988; Legrand 1999) or is sometimes detailed, or at least outlined, some decades after coring or sample collection (Vecoli *et al.* 2003; Videt *et al.* 2010; Popov *et al.* 2019). This is in contrast to Morocco and its extensive biostratigraphic record from the adjacent Anti-Atlas, which have been the source of a large number of publications in academic journals (see above).

Macrofauna and conodonts

The Anti-Atlas record can be prolonged southward along a ‘pathway’ that appears to be positioned east of the WAC and across the western Tuareg

Shield, and within which transgressive events preferentially and recurrently penetrated far inside the platform during the Ordovician Period. They left behind a rich and diverse faunal record including mainly brachiopods, trilobites and echinoderms, but also graptolites and conodonts (Ougarta Range, Daoura and Saoura: Legrand 1964a, c, 1966; Destombes 1983; Belhadj *et al.* 2004; Ghienne *et al.* 2007a; Makhlouf *et al.* 2018; Popov *et al.* 2019 and references therein; Bled el-Mass area: Legrand *et al.* 1959; Beuf *et al.* 1968; Adrar des Ifoghas Massif: Gatinskiy *et al.* 1966; see also Legrand 1985). Further south, fauna is lacking, yet in the fault-bounded Kandi Basin, and apparently coinciding with the southward continuation of the same ‘pathway’, a Middle–Late Ordovician ichnofauna is still preserved in one of the more proximal segments of the platform (Seilacher and Alidou 1988; Alidou *et al.* 1991; Konaté *et al.* 2003).

Other places displaying valuable Ordovician macrofauna relate to: the graptolite-bearing shales mainly obtained from cores (e.g. Legrand 1960, 1963, 1964a, 1974b, 1985, 1999; Legrand and Nabos 1962; Blain 1963; B.R.P. 1964; Kichou-Braïk *et al.* 2006), from which brachiopods have also been recovered in places (north-Saharan basins, Mélou *et al.* 1999); the Lower Ordovician strata of western Mauritania (Destombes *et al.* 1969) that should however be revisited; lingulid shell beds, most often showing endemic species (e.g. Legrand *et al.* 1959; Legrand 1964b, 1969, 1971, 1973); and the Upper Ordovician shelly fossils of the Murzuq Basin (Prokop 1973; Massa 1988; Becq-Giraudon and Massa 1997). Graptolites and a diverse benthic fauna have also been known for a long time in the Darriwilian strata of allochthonous units in northern Algeria (Great Kabylia: Termier and Termier 1950; Makhlouf *et al.* 2017) and the subsurface of the Djefarah–Ghadames Basin of southeastern Tunisia and northwestern Libya (Massa *et al.* 1977; Cocks and Fortey 1988; Massa 1988). Katian benthic assemblages have also been described from the Great Kabylia (Termier and Termier 1950; Botquelen *et al.* 2006). These Ordovician macrofaunas from North and West Africa have been extensively reviewed in a series of publications tracking palaeogeographic affinities between this domain and other parts of the ‘Mediterranean Province’ (e.g. Havlíček 1989; Makhlouf 2022), considering in particular themes such as (1) graptolites of the Ordovician Lagerstätten (Gutiérrez-Marco and Martin 2016; Gutiérrez-Marco *et al.* 2022a), (2) characterization of the Dapingian Stage in south Gondwana (Gutiérrez-Marco *et al.* 2014) or (3) the merits of a regional ‘Bohemian-Iberian’ chronostratigraphic scale which might help better identify regional correlations (Gutiérrez-Marco *et al.* 2017). We also note a variety of contexts linked to the end-Ordovician

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glaciation: a *Hirnantia* Fauna generally linked to the late- to post-glacial developments (Massa *et al.* 1977; Mergl 1983; Legrand 1988; Massa 1988; Popov *et al.* 2019), more rarely found within the glaciogenic deposits (Sutcliffe *et al.* 2001) or below (Destombes 1983); latest Ordovician graptolites specifically found far south on the platform most often in post-glacial seas (Underwood *et al.* 1998; Legrand 2000, 2001, 2009, 2011; Page *et al.* 2013; Sachanski *et al.* 2018), more rarely within the glaciogenic succession (Denis *et al.* 2007a; Legrand 2011); and fossil reworked as clasts in glaciomarine strata, most often Late Ordovician in age (Ghienne *et al.* 2007b; Gutiérrez-Marco *et al.* 2017, 2022b). The latter indicate that the southern extent of the coeval faunal record was originally more developed than usually envisioned.

A great part of the shelly faunal record is preserved as concentrations in major transgressive horizons from Mauritania to Libya, generally linked to storm or condensation processes. The original distribution was most likely greater considering the abundance of the *Cruziana* record – in southern Algeria, Niger, Libya and Chad, up to Benin – but shells suffered preservation issues during early diagenesis in such a sand(stone)-dominated record. The same is true considering for instance conodonts. They only occur in diagenetic limy nodules or in rare limy sandstones (e.g. Beuf *et al.* 1968; reassessed by Lehnert *et al.* 2016 as a Floian assemblage), with, however, the notable exception of the conodonts of the bryozoan mud mounds of the Djefarah Basin in NW Libya (Bergström and Massa 1991; Buttler *et al.* 2007). Considering the latter carbonate strata, relationships with the Late Ordovician ‘Boda event’ have been proposed (Boucot *et al.* 2003; Armstrong *et al.* 2009), but are still debatable (Cherns and Wheeley 2007).

Palynomorphs

Palynomorph distribution in North and West Africa has been the subject of considerable research since the 1960s, mainly on the basis of chitinozoan and acritarch assemblages. The microfossil record had generally suffered preservation issues in outcrops exposed once to tropical or arid weathering conditions. The best assemblages are from the cores of the oil industry, yet their release in the literature has been fragmentary for a long time (e.g. Paris 1990; Oulebsir and Paris 1995; Vecoli *et al.* 1995, 2003; Belhaj 1996; Servais *et al.* 2004) prior to the publication of synoptic works constantly improving the related biostratigraphic frameworks (Paris *et al.* 2004; Vecoli and Le Hérisse 2004; Videt *et al.* 2010; Kroeck *et al.* 2020). A revision of the Lower Ordovician assemblages is however pending, considering that some of the chitinozoan assemblages

initially pointing to an early Arenig/early Floian time interval now appear to record the late Tremadocian (Lefebvre *et al.* 2018; Achab and Maletz 2021). Lower Ordovician acritarch assemblages have also been reported from basement inliers of northern Algeria (Great and Lesser Kabylia; Baudelot and Géry 1979; Baudelot *et al.* 1981). Darriwilian assemblages are, however, the most widespread, from outcrops (Great Kabylia, Baudelot and Géry 1979; Traras Mountains, Benachour *et al.* 2020) and the subsurface of Algeria (Oulebsir and Paris 1995; Videt *et al.* 2010), Tunisia (Kilani *et al.* 2015) and Libya (Abuhmda and Wellman 2017). The latter also include cryptospore assemblages that provide rare evidence for Middle Ordovician terrestrial vegetation at this very early stage in its development. Palynomorphs are also frequent in glaciation-related strata, especially in post-glacial successions from Mauritania to Chad where they also frequently include a cryptospore record (Paris *et al.* 1998, 2000; Vandembroucke *et al.* 2010; Le Hérisse *et al.* 2013; Thusu *et al.* 2013; Spina 2014), but also within the glaciogenic strata (Paris *et al.* 2000; Vecoli *et al.* 2009). Palynomorph studies from wells have emphasized significant (>5 myr) stratigraphic hiatuses even in the shale-prone successions of north-Saharan basins (Oulebsir and Paris 1995; Vecoli *et al.* 2003).

In spite of some endemism issues (e.g. Legrand 1985, 2009; Vecoli and Le Hérisse 2004; Gutiérrez-Marco *et al.* 2017; Popov *et al.* 2019), the biostratigraphic record of North and West Africa correlates fairly well with that of other areas of the Mediterranean Province (southern Europe, Middle East), which in turn are well integrated into global stratigraphic frameworks (Webby *et al.* 2004; Achab and Paris 2007; Bergström *et al.* 2009; Gutiérrez-Marco *et al.* 2017). For example, the middle Darriwilian to earliest Sandbian brachiopod fauna described by Mélou *et al.* (1999) in the northeastern Algerian Sahara correlates very precisely with identical late Oretanian to earliest Beronian brachiopod assemblages from the Ibero-Armorican domain (Gutiérrez-Marco *et al.* 2017). Overall, the temporal distribution of this biostratigraphic record is principally linked to transgressive episodes of various significance (Videt *et al.* 2010), which together point to three major flooding events across the platform: they form the basis for the subdivision into three major stratigraphic cycles described below.

Ordovician stratigraphic cycles in North and West Africa

The Ordovician succession of North and West Africa has long been subdivided into stratigraphic cycles (e.g. sub-systems of Legrand 1974a; Fekirine and

Abdallah 1998). They are evidenced by: (1) alternating tens to hundreds of metres-thick mud- and sand-dominated depositional intervals, usually showing archetypal retrogradational to progradational stacking patterns; (2) extensive erosional surfaces, which in fact frequently relate to transgressive marine ravinement surfaces – with, however, the notable exception of end-Ordovician glacial erosion surfaces; and (3) recurrent ‘flooding’ or ‘re-flooding’ of southern proximal areas or of adjacent ‘uplifted’ – or, at least, less subsided – areas

(Figs 4–7). An Early Ordovician ‘intra-Arenig’ or ‘Arenigian’ tectonic event is frequently identified (Figs 4 & 8), from northern basinal areas (Galeazzi *et al.* 2010; Gharsalli and Bédir 2020) to southern, more proximal outcrop belts (Ghienne *et al.* 2013); a subordinate Middle–Late Ordovician deformation event is inferred in places – improperly linked to a ‘Taconic’ event (Beuf *et al.* 1971). The resulting unconformity is often superimposed by the end-Ordovician glacial erosion surfaces (Fig. 5). Moreover, localized deformations tied to events of

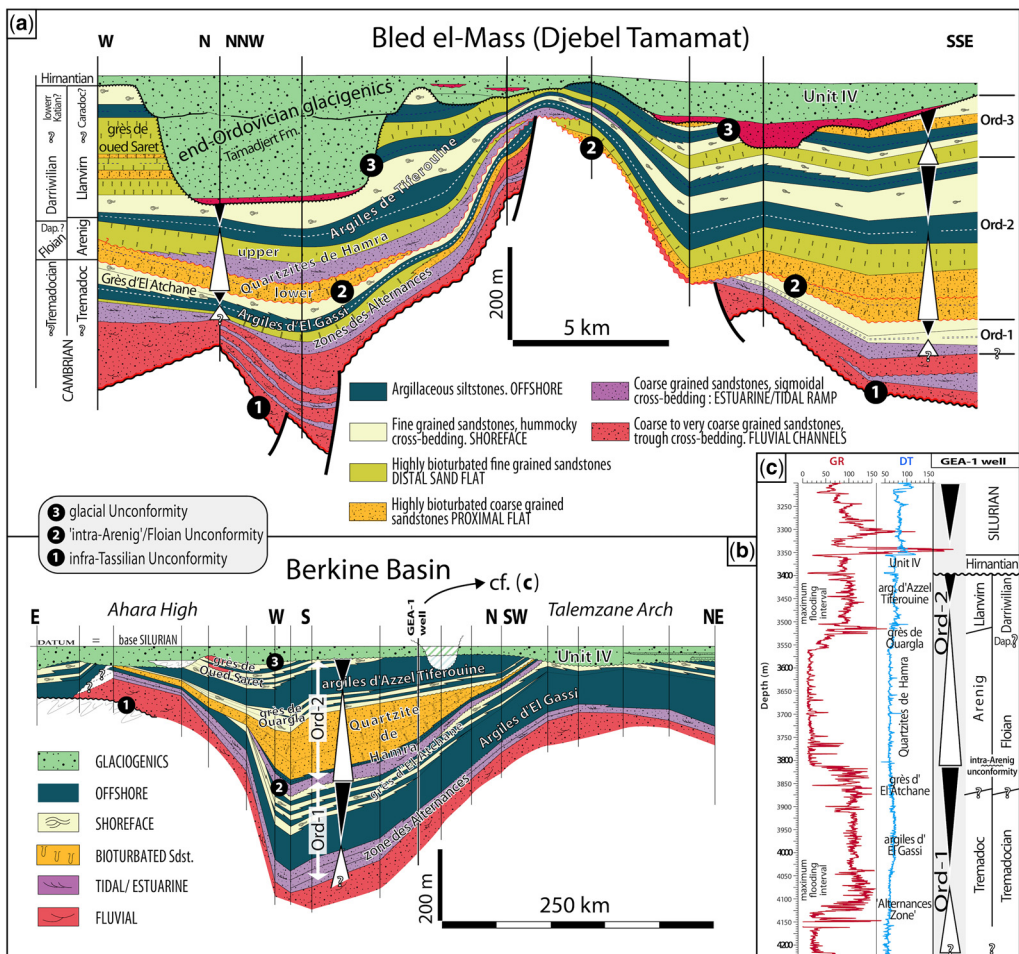


Fig. 4. Perspectives on the Ordovician succession of Algeria. **(a)** From the Bled el-Mass area (location Fig. 1), based on correlation of sedimentary logs from both sides of a palaeohigh (modified from Eschard *et al.* 2010). **(b)** From the Berkine Basin (location Fig. 1), based on a long-range correlation of well logs. West–east palaeohighs, to the south (Ahara) and the north (Talemzane), limit the basin, showing truncation (e.g. Ord-1 Cycle) and/or thinning (e.g. Ord-2 Cycle) of the Ordovician units. **(c)** A representative well log from the Berkine Basin (location in b). The Hamra Quartzites Formation (sharp-base, a blocky pattern, a transitional, fining-upward, upper contact) constitutes a marker in most basins of the northern Sahara Platform. For other well log examples, see for instance Gharsalli and Bédir (2020).

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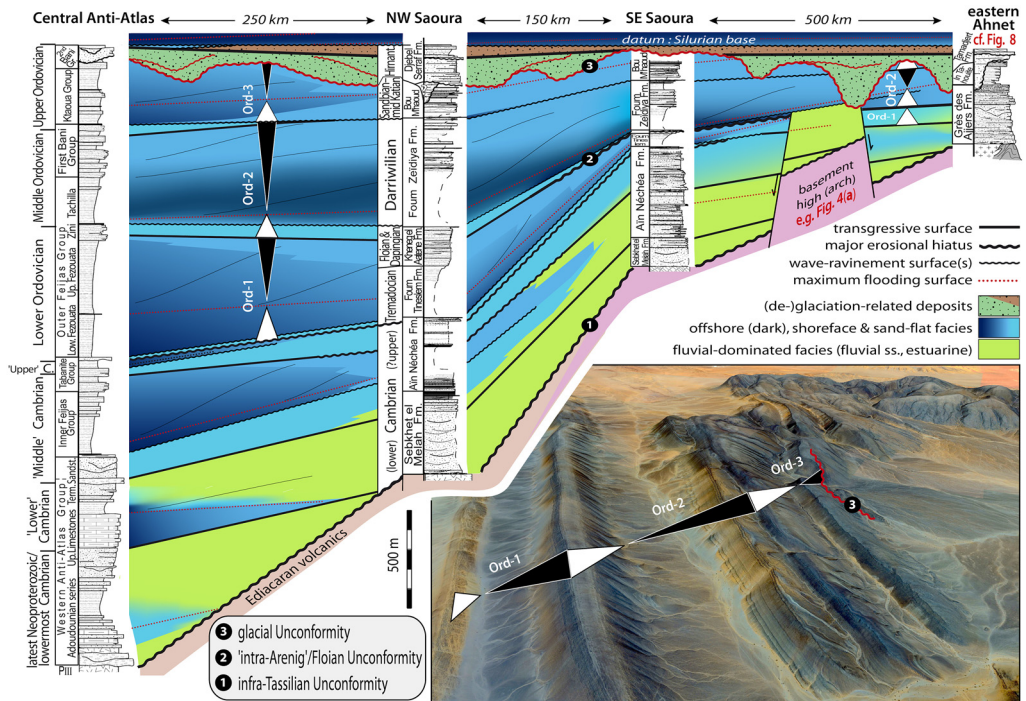


Fig. 5. The Ordovician succession of the Ougarta Range (Saoura, NW Algeria), with tentative correlations proposed towards both the more distal Anti-Atlas in Morocco and the more proximal Ahnet Basin in northwestern Hoggar (red circles in Fig. 1a; modified from Ghienne *et al.* 2007a). The Ordovician stratigraphy might be distinct, including significant hiatuses (e.g. the ‘intra-Arenig’ Unconformity), in areas located over ‘highs’ such as the Bled el-Mass in between the southern Saoura and the Ahnet Basin (see Fig. 4a). Note that the envelope of the end-Ordovician glacial erosion surfaces cut through older strata from NW (Hirnantian in the Anti-Atlas) to SE (Middle Ordovician to Cambrian north of the Hoggar), not because of deeper downcuttings but because of a combination of a thinner pre-glaciation stratal record and tectonic inheritance (cf. also Fig. 16). In the northeastern Ougarta Range, the younger Ordovician pre-glaciation strata are middle Katian in age according to Popov *et al.* (2019) and Legrand and Bouterfa (2021). Lower right, Oblique satellite image of the Ordovician succession in the northern Saoura (Ougarta Range, from GoogleEarth, looking to the NNW). The 3.3 km-long, NE dipping section displays three extensive soft talus corresponding to the three main maximum flooding intervals of the transgressive–regressive cycles.

glacio-isostatic readjustment have been postulated (Ghienne *et al.* 2003; Le Heron *et al.* 2006; Perron *et al.* 2018).

Here below, we report on three main Ordovician cycles, which correspond to three ‘second-order’ transgressive–regressive sequences (Figs 4 & 5). Each of them lasted 15 ± 3 myr. From the older to the younger, the three cycles are referred to as cycles Ord-1 (Early Ordovician), Ord-2 (late Early to Middle Ordovician) and Ord-3 (Late Ordovician). They constitute the upper part of the transgressive wedge of a larger-scale, first-order ‘Lower Gondwana Sequence’ (Middle Cambrian to Lower Devonian), itself belonging to the Paleozoic ‘Gondwana Super-Cycle’ *sensu* Boote *et al.* (1998) (see also in Galeazzi *et al.* 2010; Perron *et al.* 2018). The subsequent Silurian to Devonian regressive package is well characterized (Bellini and Massa 1980;

Eschard *et al.* 2005; Djouder *et al.* 2018; Jabir *et al.* 2021). A subdivision in cycles of higher frequency, e.g. 1–3 myr-long cycles, understood as ‘third-order’ cycles of the conventional cyclostratigraphy, has also been proposed for the entire Ordovician (Videt *et al.* 2010), or parts of it, the applicability of which is waiting for confirmation at the platform scale. Some of individual third-order cycles appear to have considerable extent throughout large stretches of the domain (e.g. the individual cycles constituting the Lower Ordovician of Tunisia, Gharsalli and Bédir 2020; Middle Ordovician Hawaz Formation in the Murzuq Basin, Anfray and Rubino 2003; Fig. 7) and such high-frequency cycles are very useful at the local scale because these elementary units allow basin-scale stacking patterns to be deciphered, either at outcrop or in wells (e.g. Kichou-Braïk *et al.* 2006; Ghienne

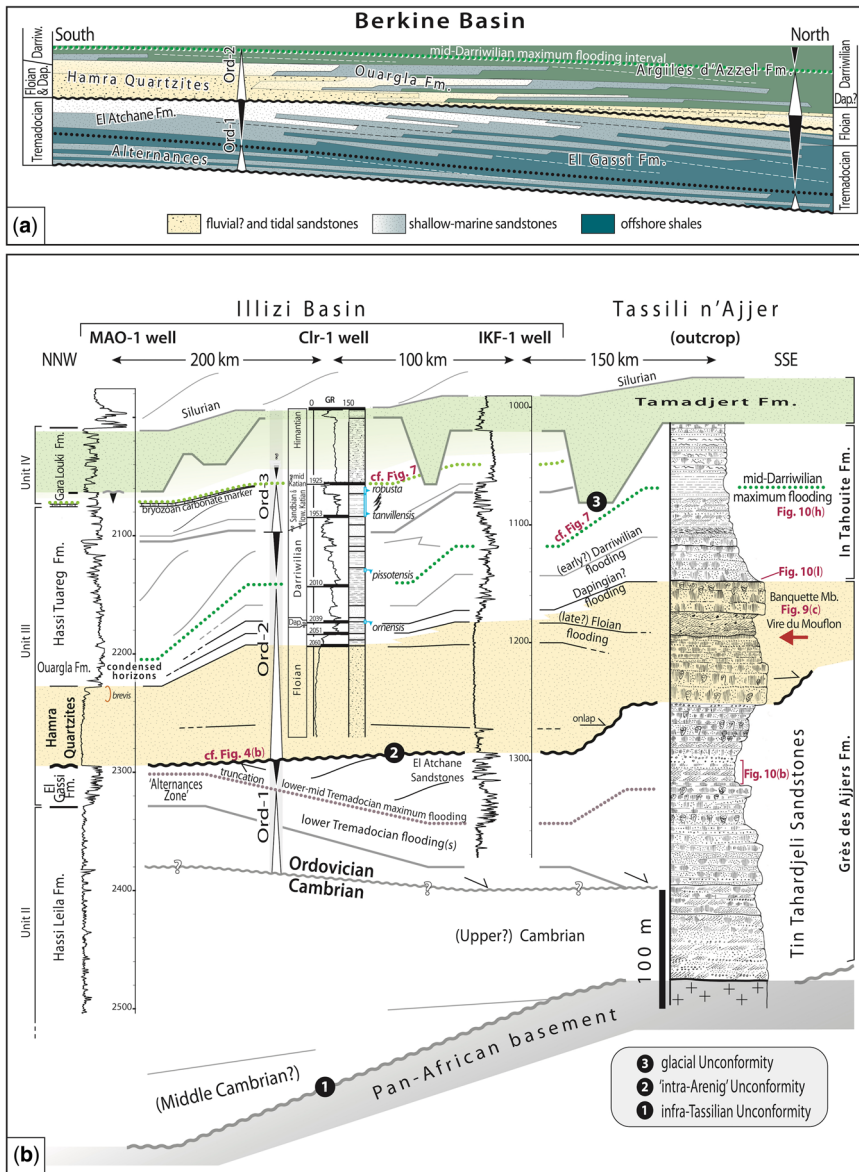


Fig. 6. Lower to Middle Ordovician lithostratigraphy and age assignments in the Illizi and Berkine basins. **(a)** Model accounting for a ramp-style depositional architecture that includes prograding and retrograding trends (not to scale; length c. 400 km). Formations are regarded as time-transgressive at the regional scale (modified from Galeazzi *et al.* 2010; stratigraphic ages are only indicative). **(b)** Illustrative correlation scheme from the subsurface (Illizi Basin) to the Tassili n'Ajjer exposures (southern Algeria), with the nearest well dataset not less than 150 km from the outcrops. The 'intra-Arenig' Unconformity truncates Ord-1 deposits in basinal area (see also Fig. 4b) and is positioned at outcrop according to the scheme depicted in Figure 8a. Considering the unconformity as a time marker, the underlying, unfossiliferous sandstones of the upper part of the Tin Tahardjeli Member are assigned to the Tremadocian, not to the Cambrian (red arrow, base of the Cambrian according to Askri *et al.* 1995). The sandstones of the 'Hamra Quartzites Formation (Ord-2) are not considered the distal counterpart of the only Banquette Member despite a strong facies similarity. The latter may include Dapingian deposits, which essentially correspond to condensed horizons to the north. Indicated late Floian to early Darriwilian subordinate flooding surfaces are only shown as working hypotheses. Biostratigraphic data for the Clr-1 well are from Oulebsir and Paris (1995) and Kichou-Braïk *et al.* (2006). Sedimentary log modified from Beuf *et al.* (1971).

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et al. 2007a; Eschard *et al.* 2010; Kracha 2011; Gil-Ortiz *et al.* 2022).

Ord-1 Cycle in the north-Saharan basins

The transgressive–regressive Early Ordovician Ord-1 Cycle typically includes an erosion-based lower interval dominated by shallow-marine (tidal) sandstones, the lower part of which is potentially included in the Cambrian units of the lithostratigraphic correlation schemes (Figs 4 & 5). These Tremadocian sandstones bear lingulid shell beds at their top, which are usually understood as a marker level across the northern Saharan Platform (Legrand 1985). Above the basal Tremadocian sandstones (Vecoli *et al.* 1995), an active retrogradation is noted (lower Tremadocian; ‘Alternances Zone’, e.g. Askri *et al.* 1995; Gharsalli and Bédir 2020), including more or less developed and amalgamated transgressive wave ravinement surfaces and some glauconitic beds. Then, a 75–300 m-thick, relatively monotonous fine-grained, graptolite-bearing, offshore to outer-shelf succession forms the bulk of the Lower Ordovician record in the northern Saharan Platform (at outcrops: in the Ougarta Range, with incursion up to the Bled el-Mass area, Figs 4a & 5; El Gassi shales of the north-Saharan basins, e.g. the Berkine–Ghadames Basin and Tunisia, Fig. 4c; Vecoli *et al.* 2003; Galeazzi *et al.* 2010; Kilani *et al.* 2015). Early Ordovician graptolite faunas of NW Africa, recently reviewed by Gutiérrez-Marco and Martín (2016), are consistent with relatively deep shelfal environments. The Ord-1 maximum flooding interval is not biostratigraphically characterized in the Murzuq and Kufrah basins, although finer-grained intervals within the Cambro-Ordovician strata are potential candidates (Bellini and Massa 1980; Turner 1980; Lüning *et al.* 2010).

The regressive wedge of the Ord-1 Cycle (e.g. Gharsalli and Bédir 2020) was dated early Floian mainly on the basis of chitinozoans (Videt *et al.* 2010), but recent findings in the framework of the studies linked to Moroccan Lagerstätten (Lefebvre *et al.* 2018) now suggest that the corresponding biozones rather indicate the upper Tremadocian. The latter is most often truncated by a severe erosion surface underlining the abrupt base of Ord-2 Cycle (see below), suggesting at first glance that the regressive wedge of Cycle Ord-1 might have been entirely included within the Tremadocian and, accordingly, a significant hiatus is characterized throughout large segments of the Saharan Platform (Oulebsir and Paris 1995; Belhaj 1996; Vecoli *et al.* 2003; Kilani *et al.* 2015; Jabir *et al.* 2021). However, in the distal stratal record of the Anti-Atlas, the regressive trend demonstrably pertains to the Upper Floian (Vaucher *et al.* 2017), as recorded by prograding sandstones (Zini Formation) that have in part

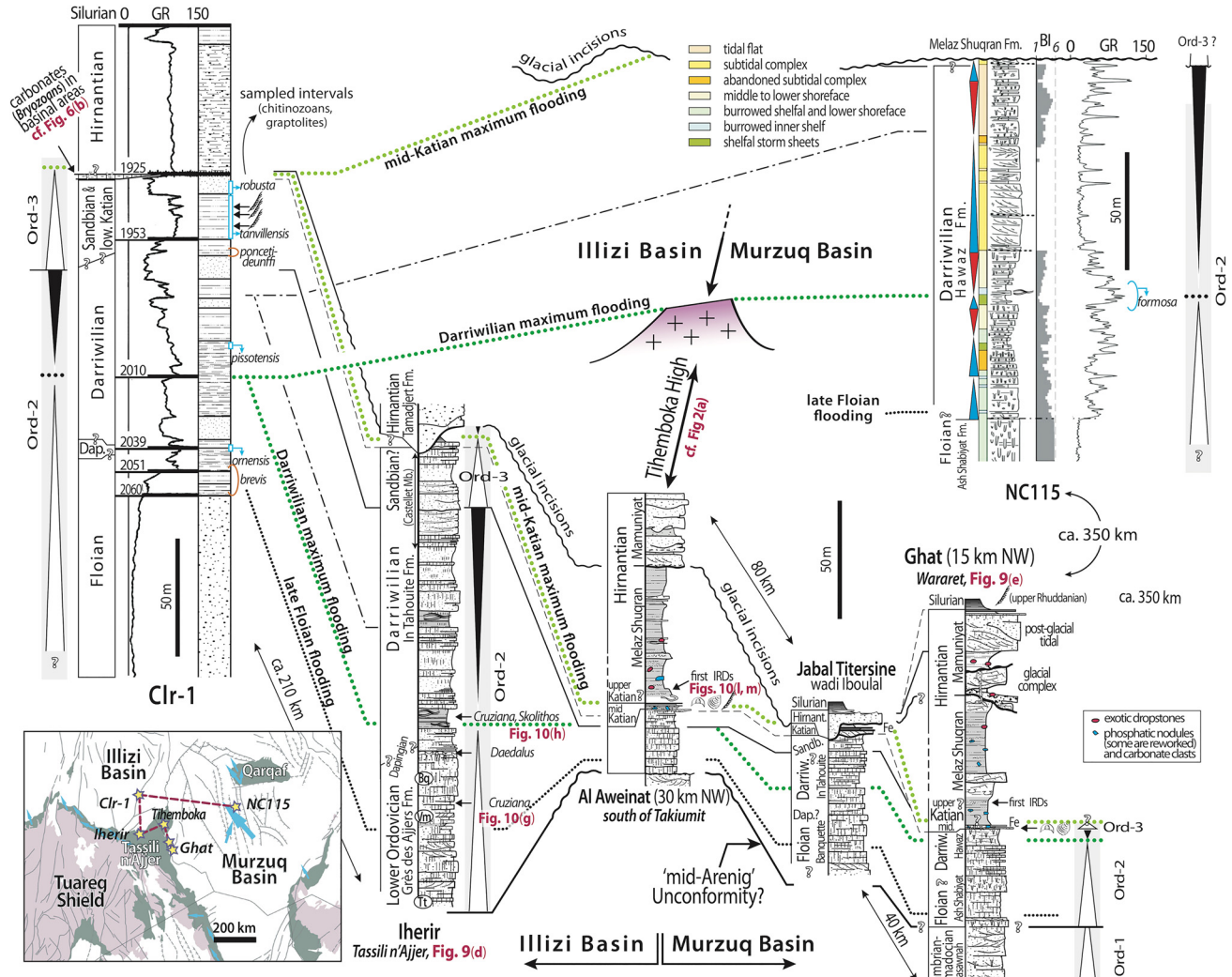
escaped erosion in this distal, basinal domain (Fig. 6a; Destombes *et al.* 1985).

Ord-2 Cycle in the north Saharan basins

The base of the late Early to Middle Ordovician Ord-2 Cycle is positioned at the abrupt base of a thick and sandstone-dominated unit known as the Hamra Quartzites in Algeria (intensively burrowed tidal ramp deposits), which is a marker horizon throughout the north-Saharan basins (Fekirine and Abdallah 1998; Eschard *et al.* 2010; Galeazzi *et al.* 2010). At outcrop (Figs 4a & 5), in well correlations (Figs 4b, c & 6) and seismic profiles, the erosional base of the Hamra Quartzites is sometimes referred to as the ‘mid-Arenig’ Unconformity (Galeazzi *et al.* 2010; Perron *et al.* 2018) that might in fact essentially correspond to a late Floian unconformity, as the immediately overlying, transgressive deposits are latest Floian in age (Oulebsir and Paris 1995). Note that the prominence of the unconformity does not straightforwardly increase towards proximal segments. Instead, related hiatuses are documented over basin-bounding tectonic ‘highs’ that are positioned adjacent to, but also beyond the basin in the distal direction, displaying north–south and west–east orientations, respectively. In the latter case, the highs are roughly perpendicular to sediment dispersal patterns and more or less parallel to a putative and remote continental margin. Severe hiatuses are therefore recorded in the more distal reaches of North Africa, e.g. from the Talemzane Arch at the northern margin of the Berkine–Ghadames Basin (Fig. 4b; Galeazzi *et al.* 2010; Soua 2014; Kilani *et al.* 2015).

The Hamra Quartzites generally include an intermediate finer-grained interval and in some areas corresponds to a double, more or less amalgamated package (Fig. 4). Patterns of sandstone thickness changes include paradoxically both (1) limited thickness variations in relatively stable areas and (2) rapid wedging-out, or to the contrary, thickening trends close to some tectonic structures. This suggests that they were deposited as a transgressive ramp during the development and/or the fading out of the tectonic perturbation linked to the basal unconformity of Ord-2 Cycle. This interval is thus regarded as representative of essentially early transgressive conditions, although late lowstand, aggrading strata may still constitute its very base in some distal segments of the platform (Fig. 6a; Fekirine and Abdallah 1998; Galeazzi *et al.* 2010; Gharsalli and Bédir 2020). Note that, in these cases, part of the Hamra Quartzites represents the latest and regressive deposits of the Ord-1 Cycle rather than the earlier deposits of the Ord-2 Cycle.

The overlying strata show a typical retrograding to prograding succession, usually subdivided into distinct lithostratigraphic subunits (e.g. Perron



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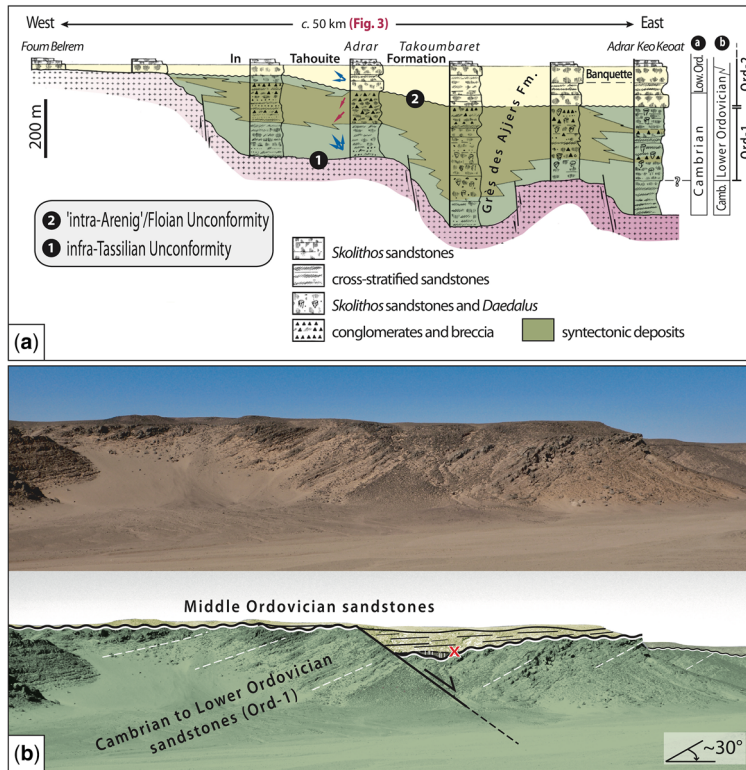


Fig. 8. Aspects of the ‘intra-Arenig’ (Floian) tectonic event and related unconformity. (a) In the Ahnet Basin, modified from [Beuf *et al.* \(1971\)](#) (location in [Fig. 3](#)). The mid-Darriwilian flooding is used as a datum (base of the In Tahouite Formation). The base of the Ordovician is often positioned high in the Grès des Ajjers Formation (column a), resulting in a scheme with prevailing Cambrian strata for this essentially shallow-marine highly bioturbated rock unit, but lacking biostratigraphic data. Interpreting the body of syntectonic deposits – conglomerates, breccia and inverted palaeocurrents: red arrows, see also [Figure 1b](#) – as the signature of the ‘intra-Arenig’ deformation phase identified in basinal areas (e.g. [Figs 4 & 5](#)) suggests a Cambrian–Ordovician boundary at a significantly lower level (column b) and a reduced thickness of Cambrian deposits around the Hoggar (see also [Fig. 6b](#)). (b) In the Dor el Gussa area, eastern Murzuq Basin (location in [Fig. 1](#)). The angular unconformity is understood as the ‘intra-Arenig’ Unconformity. The underlying deposits include Lower Ordovician sandstones ([Meinhold *et al.* 2011](#); [Ghienne *et al.* 2013](#)). The unconformity, which is dissected by subsequent normal faults, is sealed by a thin, lenticular sandstone body potentially representing upper Lower Ordovician deposits (red cross) and a fault-bounded wedge of fine-grained sediments. The overlying deposits are essentially *Skolithos* sandstones, including a horizon yielding abundant *Cruziana* and *Arthropycus*, as yet of unknown age (late Floian, Dapingian or early Darriwilian?). Note that the fine-grained wedge overlying the unconformity was attributed to the Late Ordovician in former interpretations (e.g. [El-Hawat *et al.* 2003](#)).

Fig. 7. Connecting the Middle–Upper Ordovician succession of the Illizi and Murzuq basins. Upper left, Clr-1 well in the Illizi Basin, chitinozoans from [Oulebsir and Paris \(1995\)](#) and graptolites from [Kichou-Braïk *et al.* 2006](#). Upper right, NC115 wells in the Murzuq Basin, chitinozoans from [Abuhmida and Wellman \(2017\)](#). In the latter area, the Middle Ordovician strata comprise a number of subordinate long-range ‘parasequences’ (blue and red triangles) displaying a layer-cake stratigraphy (from [Gil-Ortiz *et al.* 2022](#); see also [Anfray and Rubino 2003](#)). Lower right, three outcrop logs from the southwestern Murzuq Basin (Ghat–Al Aweinat area), an area from which a mid-Katian trilobite fauna is available ([Gutiérrez-Marco *et al.* 2022b](#); [Fig. 9e](#)). The outcrop log of the Iherir valley (Tassili n’Ajjer, Illizi Basin, see also [Fig. 9d](#)) is used as a link between the outcrop of the Murzuq Basin and the well logs, overpassing the Tihemboka arch (Tt, Tin Taharadjeli Sandstones; Vm, Vire du Mouflon; Bq, Banquette; cf. [Fig. 9c](#)). Mid-Darriwilian (Ord-2) and mid-Katian (Ord-3) maximum flooding intervals are depicted (dotted green lines, see also [Fig. 9](#)). The middle Katian condensed horizons of the SW Murzuq Basin are paralleled with a widespread carbonate marker bed bearing bryozoans in the Illizi Basin ([Kichou-Braïk *et al.* 2006](#)).

et al. 2018). A single or a few subordinate, higher-order transgressive–regressive sub-sequences are frequently reported above the basal Hamra Quartzites (Fig. 6b). An overlying subsequence as old as the latest Floian is recognized in the relatively distal area while a younger subsequence, Dapingian in age, characterizes the more proximal area (e.g. wells Gd1-bis and Clr-1, respectively; Oulebsir and Paris 1995; Figs 4c & 6b). This diachronous configuration illustrates quite well a retrogradational trend (Fig. 6). In more distal areas, shoreline retrogradations correlate to iron-rich condensed horizons, oolitic in places (Chauvel and Massa 1981), which might be hypothesized to be coeval with the Dapingian hiatus noted more distally (Gutiérrez-Marco *et al.* 2014; Álvaro *et al.* 2022). The maximum flooding interval is reached in the mid-Darriwilian with deposition of outer-shelf fine-grained successions (Figs 4–7; Vecoli *et al.* 2003; Videt *et al.* 2010; Kilani *et al.* 2015), more likely during the *formosa* chitinozoan Biozone in the Murzuq Basin (Abuhmida and Wellman 2017; Gil-Ortiz *et al.* 2022). The shallowing-upward regressive wedge of Ord-2 Cycle is well expressed in basinal areas – at least where it has not been truncated by glacial erosion – and shows a superimposition of well-defined higher-order sub-cycles (‘parasequences’) alternating storm- and tide-dominated deposits (Figs 6b & 7) deposited from the middle to upper Darriwilian (Kichou-Braïk *et al.* 2006; Ghienne *et al.* 2007a; Videt *et al.* 2010).

Ord-1 and Ord-2 cycles in southern proximal outcrops

While Cambro-Ordovician outcrops outline both the northern margin of the Tuareg Shield and the entire Murzuq Basin, up to the Djado (Figs 1 & 9b–d), correlations with well data documenting their nearby subsurface counterpart are not straightforward and have long been debated (Beuf *et al.* 1971; Legrand 1985, 2002; Eschard *et al.* 2005; Fabre and Kazitani 2005; Ghienne *et al.* 2013; Hammache 2019). Indeed, related sandstone-dominated successions display a virtually absent faunal record, in spite of recurrent pipe-rock ichnofacies and abundant tracks characterizing the *Cruziana* ichnofacies (Fig. 10), yet indicating favourable, shallow-marine, palaeoecological conditions. Greigert and Pognet (1967, updated ichnotaxa names) reported on the following association in the Djado (Niger): *Cruziana rouaulti*, *C. furcifera*, *Arthropycus alleghaniensis* (cited as *A. harlani*) and *Skolithos linearis* (see also, Seilacher 1970, 2007; Beuf *et al.* 1971; Alidou *et al.* 1991; Le Heron *et al.* 2010; de Gibert *et al.* 2011; Ghienne *et al.* 2013, 2023). Only the characterization and correlation of the Ord-2 Cycle are relatively robust owing to easy identification of the related mid-

Darriwilian maximum flooding interval (Figs 7 & 9d; In Tahouite Formation of the Tassili n’Ajjer, Eschard *et al.* 2005; Hawaz Formation of the Al Qarqaf Arch; Anfray and Rubino 2003; Ramos *et al.* 2006; Gil-Ortiz *et al.* 2022), including shoreface to fine-grained upper offshore depositional facies (Figs 7 & 10h). The underlying initial flooding is marked by a conspicuous horizon bearing *Daedalus* in the Tassili n’Ajjer (Figs 6b & 10i). These markers progressively disappear towards the south and east. Towards more proximal areas (e.g. in Niger), sandstones of Ord-2 Cycle grade into an unconformable fluvial-dominated sandstone wedge, which is a distinctive unit in the southern Sahara Platform, yet lacking age information (In Azaoua sandstones of Joulia 1959; Greigert and Pognet 1967). Its transgressive and/or regressive nature is yet to be established.

Nevertheless, identifying the boundary between Ord-1 and Ord-2 cycles remains challenging. There is a consensus to place it within the Grès des Ajers Formation, which is representative of the ‘Cambro-Ordovician’ in the Tassili n’Ajjer and all around the Tuareg Shield (Figs 6b & 8a). On lithostratigraphic grounds, the Hamra Quartzites Formation of the basins has often been paralleled with the Banquette Member, the uppermost subdivision of the Grès des Ajers Formation (Figs 6b & 9c). According to this facies-based correlation – *Skolithos* sandstones, with a blocky pattern considering gamma-ray logs (Figs 4c & 6b) and appearing as a massive unit in exposures (Banquette Member, Figs 3b & 9c) – the immediately underlying distinctive finer-grained, heterolithic, *Cruziana*-bearing interval (Vire du Mouflon Member, Fig. 9c and 10g) is usually assigned to the Tremadocian (Askri *et al.* 1995; Eschard *et al.* 2010; Videt *et al.* 2010; Perron *et al.* 2018). As a consequence, it is correlated with the coeval shaly successions of the basins (El Gassi Shales, Figs 4 & 6) and most of the underlying fluvial to tidal sandstones – known as the Tin Taharadjeli Sandstones (c. 300 m thick; Eschard *et al.* 2005) – are regarded as Cambrian in age. However, assuming the ‘intra-Arenig’ Unconformity and related features (breccia and conglomerates, growth strata and deviated palaeocurrents; Beuf *et al.* 1971) can be valorized as a stratigraphic proxy, it appears that the syntectonic strata north of the Hoggar are positioned below the *Cruziana*-bearing heterolithic interval, rather than above (Fig. 8a). Postdating the ‘intra-Arenig’ Unconformity, the *Cruziana*-bearing heterolithic interval would in fact be better assigned to the Floian rather than to the Tremadocian. In this case, the Grès des Ajers Formation would significantly comprise Lower Ordovician sandstones and the Tremadocian flooding is to be found within, and not at the top of the Tin Taharadjeli Sandstones (Figs 6b & 9c) as suggested by

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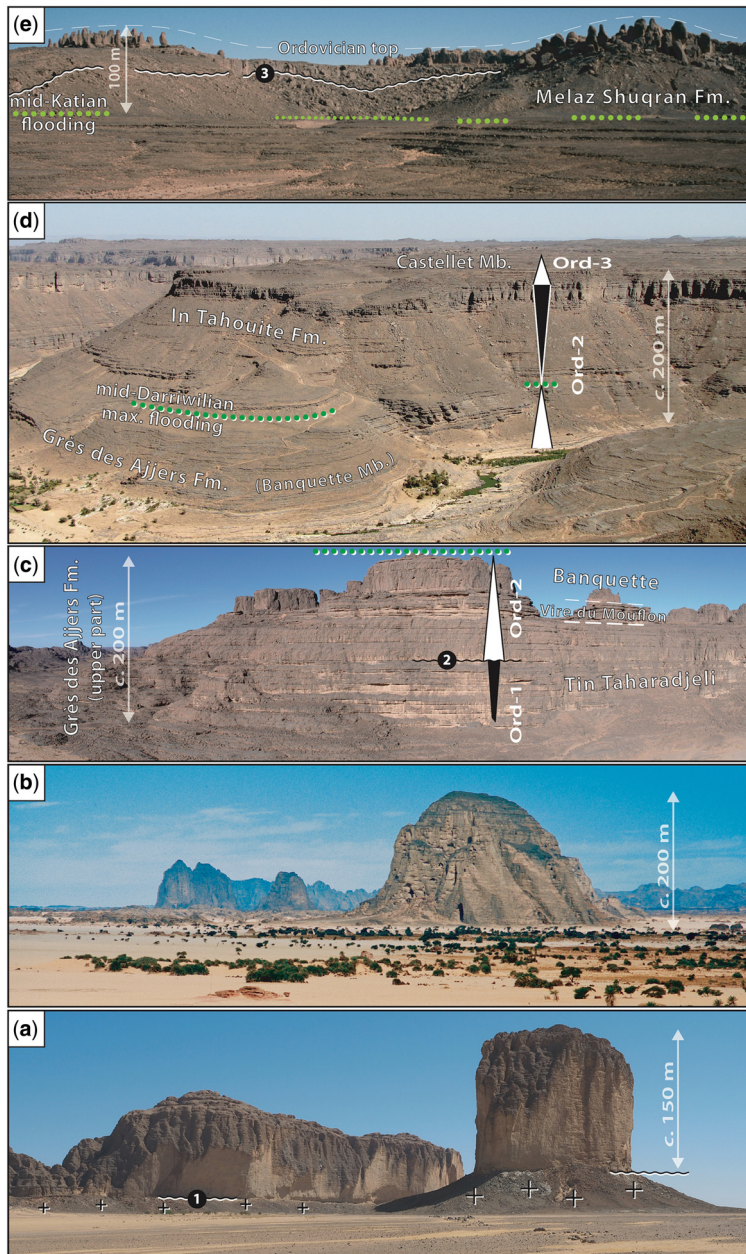


Fig. 9. The Ordovician sandstones from base to top, in the central and eastern Sahara. (a) The ‘Cambro-Ordovician’ Lower Sandstones at Deli-Borototou, Ennedi (NE Chad); in this proximal area, Cambrian strata may be of restricted thickness or even absent above the infra-Tassilian Unconformity (‘1’; see [Ghienne et al. 2023](#)). (b) The Lower Sandstones, or Grès des Ajjers Formation in the Orida Mountains, Djado (northern Niger); background – the Cambro-Ordovician strata form an extensive cuesta running all around the Tuareg Shield ([Fig. 1a](#)). (c) The upper part of the Grès des Ajjers Formation in the Djebel Assar (Dider area, Tassili n’Ajjer, SE Algeria; [Eschard et al. 2005](#)). The Cambrian–Ordovician contact is often positioned at the base of the Vire du Mouflon Member (in this case, considered as a Tremadocian interval), while the sandstones of the Banquette Member are paralleled with the Hamra Quartzites Formation of the north-Saharan basins ([Figs 4 & 6](#)). Here, we favour a lower position of the Cambrian–Ordovician boundary (within the Tin Taharadjeli Sandstones) and consider that the uppermost part of the Tin

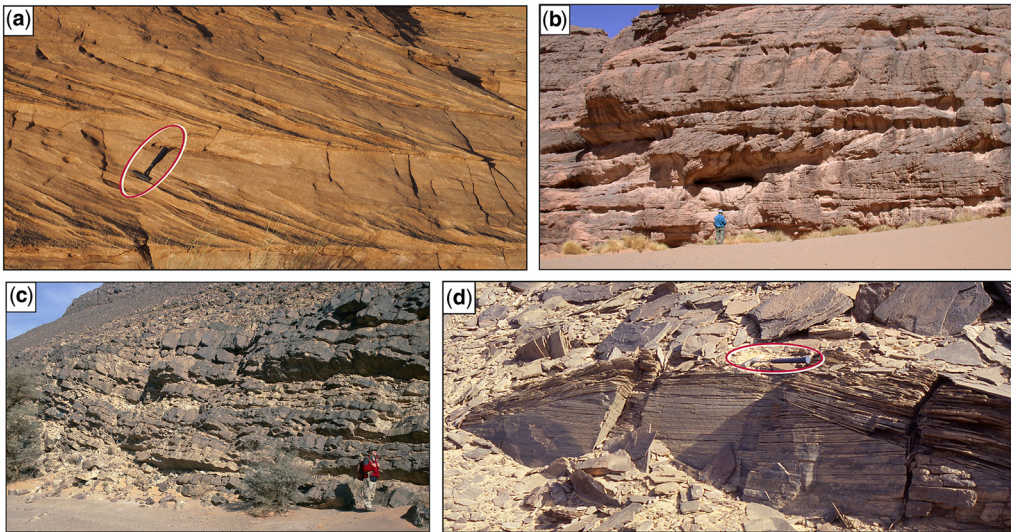


Fig. 10. Representative sandstone facies and ichnofacies of Ordovician units in North and West Africa. (a) Very coarse-grained, cross-laminated, fluvial sandstones of the Ennedi (Lower or Middle Ordovician, Chad; encircled hammer for scale). (b) Coarse-grained, estuarine bars and channels of the Tin Taharadjeli Sandstones (Lower Ordovician – or Cambrian?, see Fig. 9c; Algeria). (c) Coarse- to medium-grained, shallow-marine sandstones including tidal channels and *Daedalus* (Darrivilian of the Ougarta, Kheneg el Aatène section, Algeria; Fig. 10j). (d) Medium- to fine-grained shoreface sandstones with large-scale hummocky-cross stratification (Tremadocian of the Ougarta, Foug Zeidiya section, Algeria; encircled hammer for scale).

Riché and de Charpal (1998) and Fabre and Kazi-Tani 2005). A particular horizon, again displaying a transgressive assemblage of ichnofacies characterized by *Daedalus*, can be taken as a marker of the Tremadocian flooding and, finally, only the lower part of the ‘Cambro-Ordovician’ might represent an (Upper?) Cambrian record (Fig. 6b). This correlation accounts for a high degree of diachroneity of the Hamra Quartzites Formation/Banquette Member, the latter being substantially younger (including Dapingian strata) than the former (upper Floian), yet displaying very similar depositional patterns.

Similar conclusions also arise from the adjacent Murzuq Basin. The recognition of a true angular (<30°) unconformity in the Dor el Gussa area of

the eastern Murzuq Basin (Klitzsch 1963; Klitzsch and Ziegert 2000; Le Heron *et al.* 2013a) also helps to revise the stratigraphic scheme, provided it is coeval with the ‘mid-Arenig’ Unconformity of the north-Saharan basins (Fig. 8b). Truncated strata (Hasawnah Formation; Hallett 2002) have usually been assigned to the Cambrian by comparison with the Al Qarqaf Arch and Ghadames Basin, yet their upper part is now preferentially attributed to the Lower Ordovician as far as the proximal sectors of the Murzuq Basin are considered (Ghienne *et al.* 2013; Gil-Ortiz *et al.* 2022). This revised age assignment considering proximal successions is independently supported by detrital zircon geochronology. Tremadocian zircon grains at 484 ± 10 and $478 \pm$

Fig. 9. Continued. Taharadjeli Sandstones might belong to the Ord-2 Cycle, its base corresponding to the ‘intra-Arenig’ Unconformity (‘2’; see text for more details and Fig. 8a). (d) The mid-Ordovician In Tahouite Formation in the Edarene wadi (Iherir valley, Tassili n’Ajjer, SE Algeria; synoptic section in Fig. 7). The mid-Darrivilian maximum flooding interval is positioned at the base of the formation. In its upper part, a renewed transgressive trend is recorded at the very top of the Castellet Sandstones, which is interpreted as the signature of the Late Ordovician transgression. (e) The top part of the Ordovician in Wararet, Ghat area (SW Libya; section in Fig. 7). A flooding surface, with a well-developed condensed interval that yielded mid-Katian fauna (Gutiérrez-Marco *et al.* 2022b), marks the base of the Melaz Shuqran Formation. This contact is overlain by (para?) conformable, glaciomarine, fine-grained deposits (soft talus) that pre-date the first glaciation-related glacial incisions (glacial Unconformity, ‘3’). The uppermost sandstones cropping out as pinnacles are relicts of the post-glacial transgressive tidal wedge (Moreau 2011). The middle Katian condensed horizon, paralleled with a bryozoan-rich carbonate level in basinal area (Fig. 7, Clr-1 well), is only preserved in interfluvial areas of the glacial erosion surfaces (see Fig. 13).

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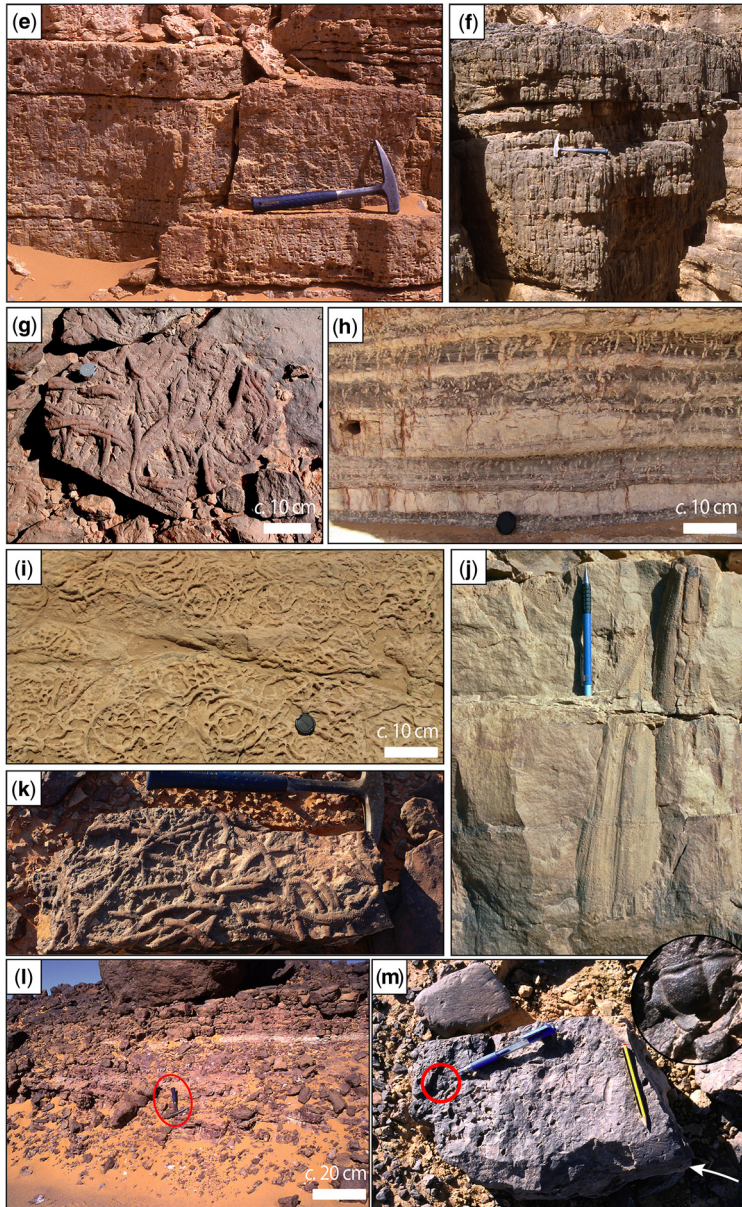


Fig. 10. *Continued.* (e) *Skolithos* sandstone (burrow diameter *c.* 5 mm) of the Darriwilian Hawaz Formation (Al Qarqaf, Libya). (f) *Skolithos* sandstone (burrow diameter *c.* 10 mm); this piperock facies is typical for the Lower Ordovician Banquette Member (Arak pass, Ahnet, Algeria). (g) *Cruziana* trails from the Lower Ordovician Vire du Mouflon (Tassili n'Ajjer, Algeria, Figs 6 & 9c). (h) Intensively burrowed upper offshore deposits in the lower part of the In Tahouite Formation and considered as the marker of the mid-Darriwilian flooding in the Iherir area (Tassili n'Ajjer, Algeria, Figs 7 & 9d). (i) *Daedalus* (bed top) from the Banquette Member (Iherir guelta, Tassili n'Ajjer, Algeria; see also Figs 6 & 9c). (j) *Daedalus* (cross-section) from the Darriwilian Fom Zeïdiya Formation (Ougarta, Algeria; Fig. 10c). (k) *Arthropycus linearis* from the Lower (or Middle?) Ordovician sandstones of the Ennedi (Fada area, Chad). (l) 2 m-thick condensed horizon (coarse-grained bioturbated sandstones, phosphatic nodules, oolites, iron crusts, etc.) that yield a mid-Katian (upper Berounian) trilobite fauna (Tihemboka high, Al Awainat area, SW Libya; location in Fig. 7). (m) Reworked carbonate shell bed including Katian trilobites (inset zoom) from the Melaz Shuqran Formation (Tihemboka high, Al Awainat area, SW Libya; cf. Fig. 7). This lithology is only found as dropstones in the end-Ordovician glaciomarine facies; the white arrow points a relict striated surface.

10 Ma have been reported from the Hasawnah Formation sandstones, which thus must include an Ordovician record (Meinhold *et al.* 2011). Above tilted and truncated Cambrian to Lower Ordovician strata, a shaly interval and an overlying intensively burrowed interval with *Cruziana* trails is better attributed to the Ord-2 Cycle (Ghienne *et al.* 2013), which is in contrast to previous, Late Ordovician age assignments (Klitzsch 1981). A similar *Cruziana* interval, Early to Middle Ordovician in age, is also recognized farther east from the eastern Tibesti in the ‘Cambrian’ Hasawnah sandstones of the Kufrah Basin (Seilacher *et al.* 2002). Other *Cruziana* levels all around the Kufrah Basin (Turner 1980; Le Heron *et al.* 2010; Lüning *et al.* 2010; Le Heron and Howard 2012) suggest as well that a (?) significant part of the ‘Cambrian’ Hasawnah Formation sandstones would be best assigned to the Early to Middle Ordovician.

Age revisions in both Algeria and Libya conform to an overall depositional architecture with a progressive pinchout of the Cambrian strata beneath the Ordovician strata towards the south and east (Ouan Ahaggar of southern Algeria, Djado in Niger, Kufrah Basin of SE Libya), where Cambro-Ordovician sandstones may ultimately comprise almost exclusively Ordovician deposits (Legrand 1974a; Fabre and Kazi-Tani 2005; Ghienne *et al.* 2023; Fig. 9a). This Ordovician onlapping trend, associated with the wedging out of the underlying Cambrian strata, reflects the larger-scale lower Paleozoic encroachment cycle (Boote *et al.* 1998; Sharland *et al.* 2001). The same interpretation in fact more directly emerges from the overall Paleozoic basin-scale onlap relationships onto progressively buried basement rocks, as shown by the Tim Mersoï strata progressively overstepping the Aïr basement in northern Niger (Zanguina *et al.* 1998; Fig. 2b), or on the Anti-Atlas to Ahnet correlation profile featured in Figure 5 (see also Fig. 11b).

The two above-mentioned Tremadocian zircons grains, several other grains from the Silurian-Devonian strata (491 ± 16 Ma, 485 ± 10 Ma, 481 ± 14 Ma; Meinhold *et al.* 2011) and two others from the Ordovician strata of the Ouan Ahaggar (477 ± 11 and 480 ± 13 Ma; Linnemann *et al.* 2011) suggest that the occurrence of a restricted Lower Ordovician source in the southern drainage basins feeding the central Sahara. Age consistency would further suggest early Tremadocian volcanoes, which however remain to be identified. The alkaline plutons of the Aïr in northern Niger relate to a younger, late Silurian–Early Devonian volcanism (Moreau *et al.* 1994; Ngako *et al.* 2006) and no Ordovician magmatism is recognized in the area postdating the Neoproterozoic events (Henry *et al.* 2009; Fezaa *et al.* 2010). Middle Ordovician zircons (464 ± 17 , 461 ± 23 Ma) are recovered as well

from Darrivilian strata of the eastern Murzuq Basin (Meinhold *et al.* 2011). These grains have more or less the same age as K-bentonites that have been found interstratified in the Middle Ordovician sandstones of the northern Murzuq Basin (Al Qarqaf Arch; Ramos *et al.* 2003). K-bentonite layers suggest remote explosive volcanism at the margins of Gondwana, or beyond. Note that a remote origin for the few Tremadocian zircon grains might also be invoked considering coeval widespread Late Cambrian to Early Ordovician magmatism characterizing Morocco (Letsch *et al.* 2018; Ouabid *et al.* 2021) and more generally the entire adjacent Gondwana margin (Martínez-Catalán *et al.* 2021).

Ord-1 and Ord-2 cycles across the West African Craton

Paleozoic strata overlying the WAC and its Mesoproterozoic to lower Cambrian sedimentary cover are well characterized along its northern margin from the Zemmour to the NW to the Ougarta Range to the NE, and within the Taoudéni and Bové basins (Fig. 1; Deynoux 1983; Villeneuve 2005).

The Ougarta Range (Daoura and Saoura) is positioned over the metacratonic margin of the craton (Brahimi *et al.* 2018; Melouah *et al.* 2021), which accommodated a thick and comprehensive Ordovician succession (Belhadj *et al.* 2004; Ghienne *et al.* 2007a; Hamdidouche 2009; Popov *et al.* 2019) in the prolongation of the Moroccan Anti-Atlas (Destombes *et al.* 1985) and in continuity with the Tindouf Basin (Deynoux 1983; Boote *et al.* 1998; Medaouri 2004; Craig *et al.* 2008; Kettouche 2009; Figs 2, 5 and 11). Middle Ordovician strata of the Ord-2 Cycle in the Ougarta Range are in particular evidenced by the fossiliferous Fom Zeïdiya Formation (Fig. 5), which ranges from the early to late Darrivilian (late Arenigian to late Dobrotivian), according to the chitinozoans (*bullia* Biozone; Videt *et al.* 2010) and graptolites (*Corymbograptus retroflexus*: cited as ‘*Corymbograptus v-fractus wieli*’ by Legrand 1964c) recorded from its base together with the brachiopod ?*Sivorthis fraterna*. Higher up, graptolites (*Didymograptus purchisoni*), trilobites (*Neseuretus* gr. *tristani*, *Crozonaspis*, asaphids) and brachiopods (*Tissintia convergens*) show close affinities with late Oretanian and Dobrotivian ‘Mediterranean’ faunas (Popov *et al.* 2019).

In the Tindouf Basin, the Ord-1 and Ord-2 cycles are comparable with those of the Ougarta and Morocco (e.g. HMA-1 well in Fig. 11c). A general onlap of the Cambrian to Ordovician strata from the north to the south is highlighted by basin-scale cross-sections (Fig. 11b; Hollart and Choubert 1985; Boote *et al.* 1998; Kettouche 2009). The

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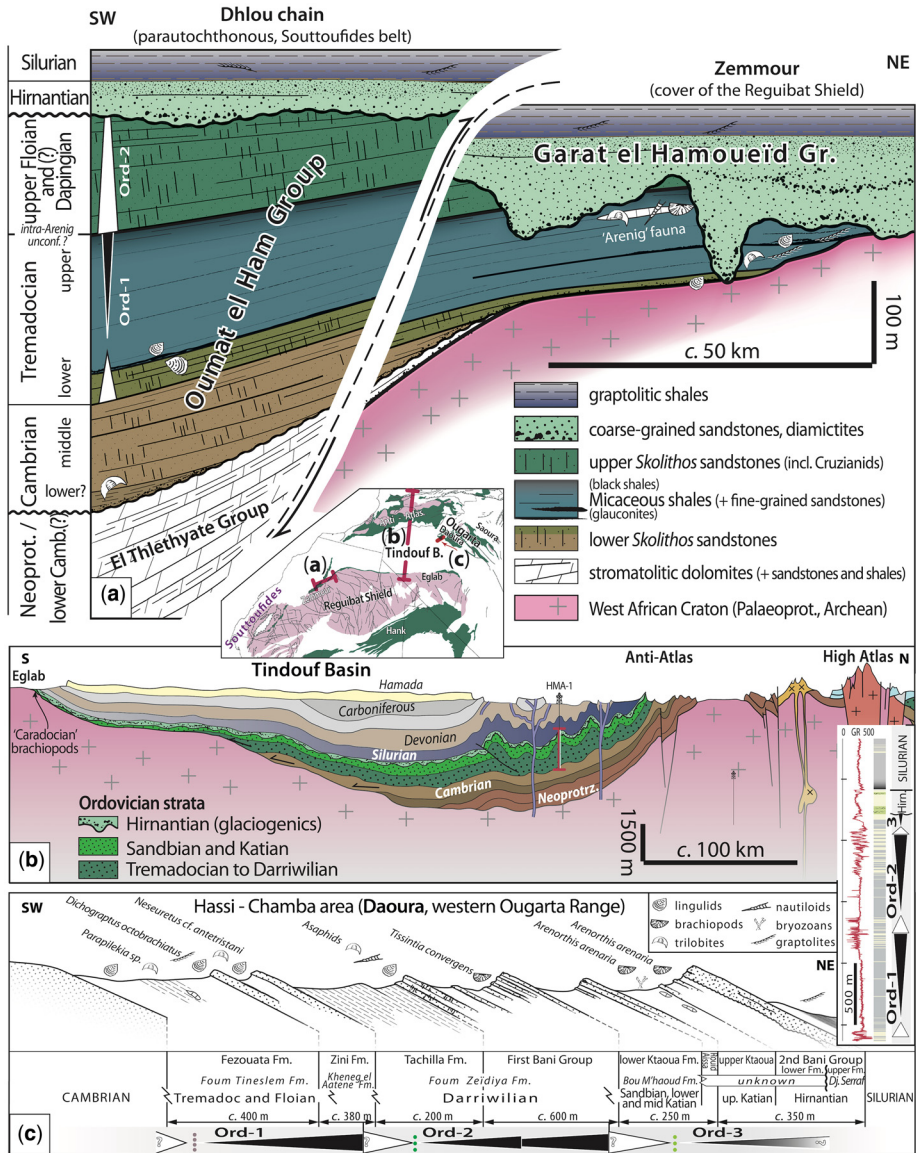


Fig. 11. The Ordovician succession on the northern West African Craton. (a) In the Zemmour area (northern Mauritania and Western Sahara), where the Ordovician succession of the allochthonous to paraautochthonous units of the Souttoufides Variscan Belt (left hand side) are comparable with the autochthonous succession onlapping the Reguibat Shield (right-hand side); compiled from Sougy 1964; Destombes *et al.* 1969; Deynoux 1980; Villeneuve *et al.* 2015a; Gärtner *et al.* 2017). The so-called ‘Arenig’ fauna of Destombes *et al.* (1969) must now be considered as upper Tremadocian (Lefebvre *et al.* 2018). (b) In the Tindouf Basin, according to a submeridian cross-profile from the Atlas and Anti-Atlas in Morocco to the Reguibat Shield in Algeria (modified from Hollart and Choubert 1985; seismic sections shown in Kettouche 2009). Towards the south, the entire lower Paleozoic succession is shown progressively onlapping the basement of the WAC. The location for ‘Caradocian’ brachiopods (Dourthe and Serra 1961) is projected from the Eglab area. The HMA-1 well (projected from the east; inset on the lower right) shows an Ord-3 Cycle truncated by relatively thick glaciogenic-related deposits (c. 200 m), but a comprehensive record of the Ord-1 and Ord-2 cycles. (c) The Ordovician record of the Daoura (western Ougarta Range), according to Poueyto (1952) and Destombes (1983). This is probably the most complete Ordovician succession cropping out in Algeria. Lithostratigraphy is ‘imported’ from the Anti-Atlas area (see Fig. 5). Formation names in italics refer to the lithostratigraphy of the Saoura (eastern Ougarta Range, see Fig. 5).

pre-glaciation Ordovician is absent or very thin along most of the northern fringe of the Reguibat Shield (Gevin 1960). Only a thin Upper Ordovician interval separates glaciogenic deposits and basement rocks of the NE Reguibat Shield in the Eglab area (Fig. 1; Beuf *et al.* 1971), where, coming from the Ougarta or Bled el-Mass areas, Cambrian, Ord-1 and Ord-2 strata have progressively pinched out from the east to the west. Along the NW fringe of the Reguibat Shield, i.e. in the Zemmour area, 'transgressive' Tremadocian sandstones, shales and glauconitic horizons progressively reappear, directly onlapping the Proterozoic to Archean basement (Fig. 11a; Destombes *et al.* 1969). The latter strata connect more to the west to the foreland of the Variscan Souttoufides Belt, the thrust units of which preserved a comparable, yet thicker, Ordovician stratal record (Villeneuve *et al.* 2015b; Gärtner *et al.* 2017). Sharp-based *Skolithos* sandstones of the autochthonous and parautochthonous units, which

are themselves truncated by end-Ordovician glacial surfaces, are reminiscent of the Hamra Quartzites/Banquette Member of north-Saharan basins and central Sahara, their basal unconformity being tentatively paralleled with the 'mid-Arenig' Unconformity (Fig. 11a).

In the Taoudéni Basin, no firm biostratigraphic data are available to discriminate Ordovician from Cambrian strata. Two distinct lingulid shell beds in the upper part of the undifferentiated Cambro-Ordovician succession led first to the suggestion that *Skolithos* sandstones underlying the end-Ordovician glaciogenic deposits might be assigned to the upper Cambrian or Lower Ordovician (Monod 1962; Dia *et al.* 1969; Trompette 1973; Lafrance 1996). A facies correlation with the Upper *Skolithos* sandstones of the Zemmour area (Fig. 11a) has then favoured a slightly younger age ('Arenig', following Deynoux 1983; column 'a' in Fig. 12). Mapping projects (Lahondère *et al.* 2008) considering a basin-

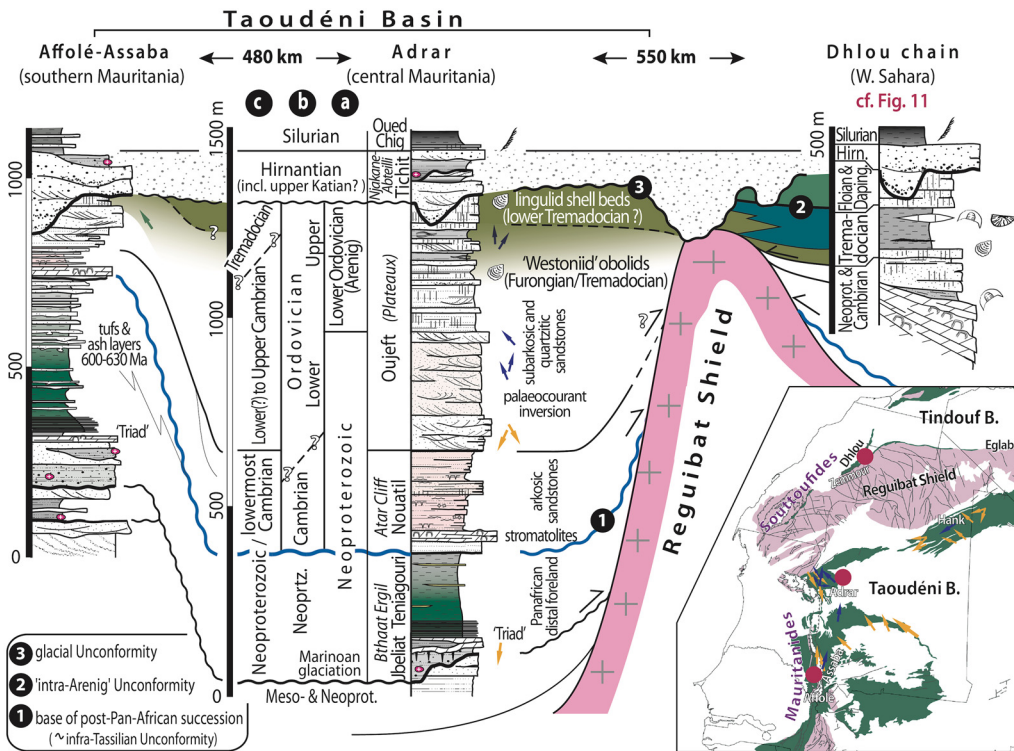


Fig. 12. Status of the Ordovician strata in the Taoudéni Basin (Mauritania) and proposed correlation with the Zemmour area (see Fig. 11). Age assignments remain a challenge and three distinct temporal frameworks are shown: 'a' following Deynoux (1983); 'b' following Lahondère *et al.* (2008); and 'c' this study (see text for details). The pre-glaciation Ordovician stratal record from the Taoudéni Basin is probably limited to a Tremadocian succession and may pinch out southward. Arrows (central log and inset map) represent palaeocurrent trends: see Figure 1b for the colour code. Compiled from Destombes *et al.* (1969), Trompette (1973), Deynoux (1980, 1983), Waters and Schofield (2004), Shields *et al.* (2007), Lahondère *et al.* (2008) and Gasquet *et al.* (2008).

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scale petrographical boundary – feldspar-rich below, less arkosic above, Figure 12 – that is positioned well below the lingulid shell beds suggested more recently that a thicker Ordovician succession would be in fact preserved in the Taoudéni Basin, which might have expanded up to the Middle or Upper Ordovician in the Tagant and Adrar (column ‘b’ in Fig. 13). However, recent palaeoecological studies confirm that the type of low-diversity fauna (‘Westoniid’ obolids) described in the lower lingulid shell bed of the Adrar (Legrand 1969) proliferated in the Furongian and rapidly declined in the Tremadocian (Mergl *et al.* 2018). This suggests that the original age assignment close to a Cambrian–Ordovician boundary is finally most likely (see also Waters and Schofield 2004; column ‘c’ in Fig. 12). A similar conclusion arises comparing the upper faunal assemblage of the Adrar of Mauritania with that of the Bled el-Mass (Beuf *et al.* 1968) and Zemmour areas (Desbambes *et al.* 1969), both characterizing the

Tremadocian transgression of the Ord-1 Cycle. In brief: (1) the pre-glacial Ordovician succession of the Taoudéni Basin is potentially restricted to a less than 250 m-thick Tremadocian (to Lower Floian?) succession of *Skolithos* sandstones; (2) only glaciogenic infills might represent the Ordovician throughout southern areas of the Taoudéni Basin; and (3) the ‘intra-Arenig’ tectonic phase might be hypothesized to be responsible for ending sediment accumulation throughout the Taoudéni Basin. After having initially displayed southeastward and southwestward centripetal palaeoflows in the Adrar and Hank area, respectively (Figs 1b & 12; Lahondère *et al.* 2008), dispersal patterns show afterwards NW-oriented trends, indicating that the Reguibat Shield was then no more an obstacle in the Early Ordovician (according to the revised time frame). At that time, the WAC was therefore included in the overall platform system feed from the south. Tremadocian sandstones of the Adrar

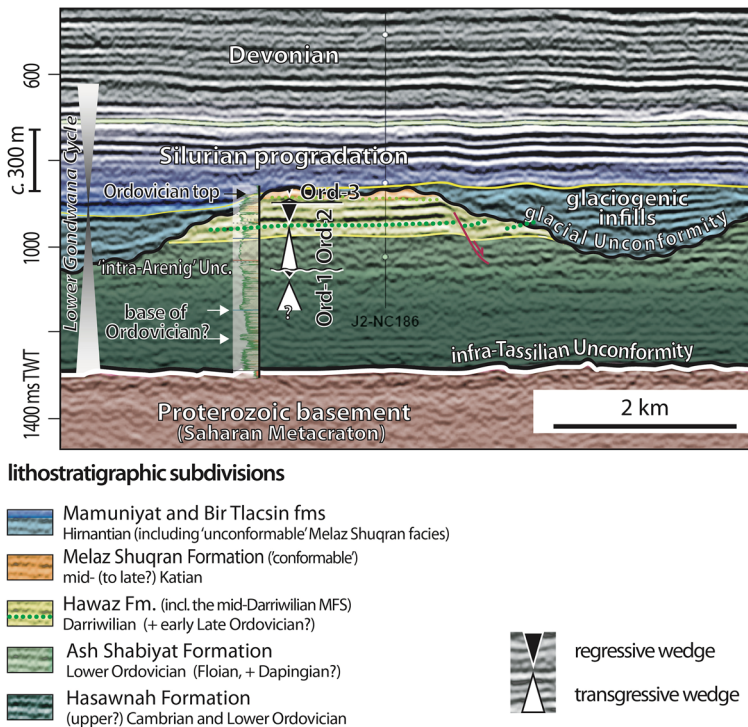


Fig. 13. Representative seismic cross-section within the Murzuq Basin (NC-186 C Concession; location in Fig. 1), showing that a comprehensive Ordovician succession is only preserved in interfluvial areas bounding end-Ordovician glacial incisions. Glaciomarine Melaz Shuqran-type facies are identified both over interfluvial areas – where they rest (para?) conformably on older Ordovician deposits (e.g. Gil-Ortiz *et al.* 2022) – and as deposits infilling the lower part of glacial incisions (e.g. McDougall and Martin 2000; Bataller *et al.* 2021). Sandstones of the Hasawnah Formation have long been considered Cambrian in age, although they must include a Lower Ordovician record. The Cambrian–Ordovician boundary, however, remains unknown: two alternative positions are shown within the lower part of the Hasawnah Formation (see also Fig. 6 for a comparable case study in Algeria). The two large triangles on the left side feature the transgressive and regressive wedges of the Lower Gondwana cycle *sensu* Boote *et al.* (1998).

can be best understood as the proximal counterpart of the shaly succession of the Zemmour (Fig. 11a), considering that Ord-1 transgressive strata originally overstepped the Reguibat Shield (Fig. 12a). Eastward, via northernmost Mali, *Skolithos* sandstones (known as the upper part of the Erg Chech Group; Deynoux 1983; Lahondère *et al.* 2008) are followed up to the Tremadocian interval of the Bled el-Mass area (B.R.P. 1964; Fabre 1976; Fig. 4a). Activated by the ‘intra-Arenig’ tectonic event (Beuf *et al.* 1971), the Paleoproterozoic Reguibat Shield possibly worked as a ‘giga-arch’ during most of the Middle and Late Ordovician, but it is not known if it corresponded to a real uplifted area – and to a potential first-cycle sedimentary source at that time – or to a domain enduring restricted subsidence with resulting thin successions subsequently remobilized, and erased by the end-Ordovician ice sheets.

Beyond the Taoudéni Basin to the south, the Lower Paleozoic stratal record expands again in the Bové Basin (Guinea; Fig. 1a), where a fluvial-dominated, 250–1000 m-thick cross-stratified Cambro-Ordovician succession (Youkounkoun and Pita groups) rests unconformably above a >1000 m-thick deformed sandstone pile that was assigned to the Cambrian (Mali Group; Villeneuve and Komara 1991; Villeneuve 2005). The Cambro-Ordovician sequence is unfossiliferous, yet a significant part of it was long attributed to the Ordovician. Roman’ko (1974) only reported some ‘problematica’, representing possible trace fossils that would suggest marine influences in the upper part of the succession (Pita Group). The latter significantly thins to the north of the basin (150 m), where it directly onlaps basement highs. Geochronological data (U–Pb) have however suggested that the Mali Group could be in fact younger than 493 ± 8 Ma (Brinckmann and Meinhold 2007; Villeneuve *et al.* 2014). If true, the main part the ‘Cambrian’ succession must be uppermost Cambrian to Early Ordovician in age, the base of which includes a conglomerate of possible glacial origin (Villeneuve *et al.* 2014). In this scheme, the overlying Cambro-Ordovician strata should essentially represent a transgressive Lower(?) to Upper Ordovician succession (Brinckmann and Meinhold 2007), the unconformity bounding the two units being potentially reminiscent of the ‘mid-Arenig’ unconformity. A consequence of these revised age assignments would also be the significant and rapid northward thinning of the Ordovician succession from the Bové to the Taoudéni basins.

Our understanding of the stratigraphy of this area, and in particular relationships to tectonic events and orogenic belts, has drastically changed in the last decade (Fullgraf *et al.* 2013; Villeneuve *et al.* 2014, 2015a), and its formal revision is pending. If the fluvial-dominated succession and related

palaeocurrents appear in line with other eastern equivalents of the central and eastern Sahara (Fig. 1b), the outflow of the Bové Basin once faced North American/Avalonian terranes and potential volcanic arcs localized initially west of the WAC, which is in stark contrast with the other segments of the Saharan Platform.

In the Volta Basin (Ghana, SE of the WAC; Fig. 1a), the occurrence of Ordovician strata has never been formally demonstrated in the higher part of the section. Although the latter potentially expands into the lower Paleozoic (Affaton 1990; Villeneuve 2005), no strata younger than the lower Cambrian are to be expected in the Volta Basin following Carney *et al.* (2010). However, from Senegal to Ghana, significant changes in stratigraphic attributions might be expected in the future because of the aforementioned current age revisions. This may result in younger age assignments for some so-called Neoproterozoic to Cambrian units, the ordering of which principally relied on a succession of in fact poorly dated glacial episodes (Deynoux *et al.* 2006; Villeneuve 2006). In particular, it will be critical if some glacial intervals attributed to the lower Cambrian might finally feature late Cambrian to Early Ordovician events (Villeneuve *et al.* 2014).

Ord-3 Cycle in the north-Saharan basins

In the Saoura (eastern Ougarta Range), the Ord-3 Cycle is represented by the Bou M’Haoud Formation (Fig. 5; Legrand and Bouterfa 2021). At its base, a striking conglomeratic lag can be interpreted as a transgressive ravinement surface superimposing a subaerial erosion surface (Ghienne *et al.* 2007a; Fig. 5). The lower half of Ord-3 Cycle yields an upper Sandbian to lower Katian (middle Berounian) brachiopod fauna (*Tafialtia destombesi*, *Drabovia* cf. *tenuiseptata*, *Drabovinella regia*, *Hirnantia?*, *Rostricellula ambigena*) – which recalls the Lower Ktaoua Formation of the Moroccan Anti-Atlas – as well as some widespread Berounian trilobites (*Klouckia taouzensis*, *Calymenella* aff. *boisseli*, *Mucronaspis*). Above, a middle Katian (late Berounian) brachiopod assemblage (*Svobodaina* cf. *havliceki*, *Drabovinella maxima*, *Drabovia*, *Hirnantia?*) has been recognized (Popov *et al.* 2019). The youngest Ord-3 strata appear to be preferentially preserved to the west of the Saoura below the end-Ordovician glacial erosion surface (Legrand and Bouterfa 2021). This observation appears to be in line with the relatively thick (>400 m) Ord-3 Cycle preserved more to the west in the Daoura (western Ougarta Range; Fig. 11c). Including a storm-dominated upper to uppermost Katian record (Destombes 1983; Metatla *et al.* 2022), Ord-3 strata of the Daoura appear in full continuity with the Moroccan Anti-Atlas record of the ‘Zagora Trough’ that includes a

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comparable Upper Ordovician record (Destombes *et al.* 1985; Loi *et al.* 2010; Ghienne *et al.* 2014). Incisions filled in by sandstones have been recognized in the northwestern Saoura (Legrand and Bouterfa 2021); such occurrences of such pre-Hirnantian incisions are another feature shared with coeval Moroccan strata (Tafilalt area; Razin *et al.* 2020).

Elsewhere in North and West Africa, strata of Ord-3 Cycle are discontinuously identified beneath what is usually ascribed to the envelope of the aggregated, locally deep, Hirnantian glacial erosion surfaces, which together constitute the Ordovician glacial Unconformity (Figs 4–7 & 13). To the SW of the Ougarta, in the Eglab, ‘Caradocian’ brachiopods have been reported from the thin (<100 m), residual – and glaciotectionized in places (Beuf *et al.* 1971) – sandstone succession directly onlapping basement rocks of the Reguibat Shield (Dourthe and Serra 1961). In the Tindouf Basin, the Ord-3 Cycle is progressively truncated to the west by the glacial Unconformity (Destombes *et al.* 1985; compare also the HMA-1 well of Fig. 11b with the Daoura cross-section of Fig. 11c). It is no longer identified in the western Anti-Atlas and Zemmour and, more generally, is probably not recorded at all more to the south across the WAC (Fig. 12; see above). South of the Ougarta, the Ord-3 Cycle is well characterized in the Bled el-Mass area where it is still highlighted by a shaly interval (Fig. 4a). Its lower bounding surface is tentatively positioned within a compound shallow-marine sandstone succession. In the latter area, a localized yet significant tectonically controlled thickening of the transgressive sandstones has been observed, which suggests a Late Ordovician tectonic pulse (Eschard *et al.* 2010), also suggested from the Tassili n’Ajjjer outcrops (Zazoun and Mahdjoub 2011). In contrast, in some wells in a relatively distal position, no sandstones are cored that could have highlighted maximum regressive conditions of the Ord-2 Cycle or transgressive deposits of the Ord-3 Cycle. Instead, a single horizon with iron oolites is identified, which separates Middle and paraconformable Upper Ordovician offshore deposits (NI-2 well in Oulebsir and Paris 1995).

In the north-Saharan basins and up to the Murzuq Basin, the pre-glaciation Upper Ordovician strata only appear in restricted ‘windows’ preserved in interfluvial position beneath the glacial Unconformity that locally extends down to Ord-2 strata (Figs 5 & 13; Galeazzi *et al.* 2010; Mohamed *et al.* 2016; Hammache 2019; Bataller *et al.* 2021; Gil-Ortiz *et al.* 2022). If the transgressive surface corresponding to the lower bounding surface of Ord-3 Cycle might be debatable (see above), the overlying transgressive wedge is still well characterized in places by relatively thick Sandbian to lower Katian, graptolite- and chitinozoan-bearing shale intervals (e.g. in the

Illizi Basin, Fig. 6b: Kichou-Braïk *et al.* 2006; Videt *et al.* 2010; in the Djefarah Basin, Massa 1988). Above, sedimentary condensation is evidenced locally by a marker level displaying carbonates (including the bryozoan genus *Polyteichus* and a few echinoderm plates), iron oolites and phosphates (B.R.P. 1964; Chauvel and Massa 1981; Kichou-Braïk *et al.* 2006; Nardin and Paris 2009; Legrand 2011). This horizon reflects a significant southward shift of the Upper Ordovician facies belts and the maximum flooding interval of the Ord-3 Cycle might be expected immediately above (Figs 6b, 7 & 14). No published biostratigraphic record of strata younger than the mid-Katian and older than the first glaciation-related deposits is available (Videt *et al.* 2010). The status of potential glaciation-related deposits conformably or paraconformably overlying the condensed horizon is further discussed below. Note that a number of published Ashgillian, i.e. late Katian, palynomorph records (e.g. Molyneux and Paris 1985), which would have emphasized an upper (regressive?) wedge, seem to have been in fact mostly cored in strata clearly Hirnantian in age (Vandenbroucke *et al.* 2010), usually including a few reworked taxa (Paris *et al.* 2000, 2015; Vecoli and Le Hérissé 2004; Vecoli *et al.* 2009).

Ord-3 Cycle in southeastern proximal outcrops

The Ord-3 transgression is also well characterized at outcrop across more proximal segments of the platform. In the Tassili n’Ajjjer, sharp-based estuarine sandstones grading into shallow-marine deposits – themselves including at least one subordinate transgressive–regressive sub-sequence – are taken as a signature of the Ord-3 transgression (Fig. 7, Iherir section and Fig. 9d). The latter culminates with iron-rich sandstone and overlying offshore shales, which have escaped subsequent glacial erosion only locally. The same stratigraphic interval can be followed from place to place eastward across the whole Tassili n’Ajjjer, up to Libyan outcrops of the SW Murzuq Basin (Fig. 7). Here, a macrofauna including numerous trilobite species – as well as the ‘Bohemian’ bryozoan genus *Polyteichus* – indicates a middle Katian age (late Berounian) for the condensed horizons marking the base of a fine-grained shaly unit (Melaz Shuqran Formation; Massa 1988; Gutiérrez-Marco *et al.* 2017, 2022b), the significance of which is further discussed below (Fig. 7, Al Aweinat and Ghat sections). This intriguing horizon (Fig. 10l), displaying fossiliferous carbonate nodules and oolites, is probably correlated with the carbonate marker of the more distal reaches of the platform in north-Saharan basins (e.g. Clr-1 well; Figs 7 & 14). The Ord-3 transgression is also indirectly evidenced by the reworking of representatives of a Katian fauna in younger end-Ordovician

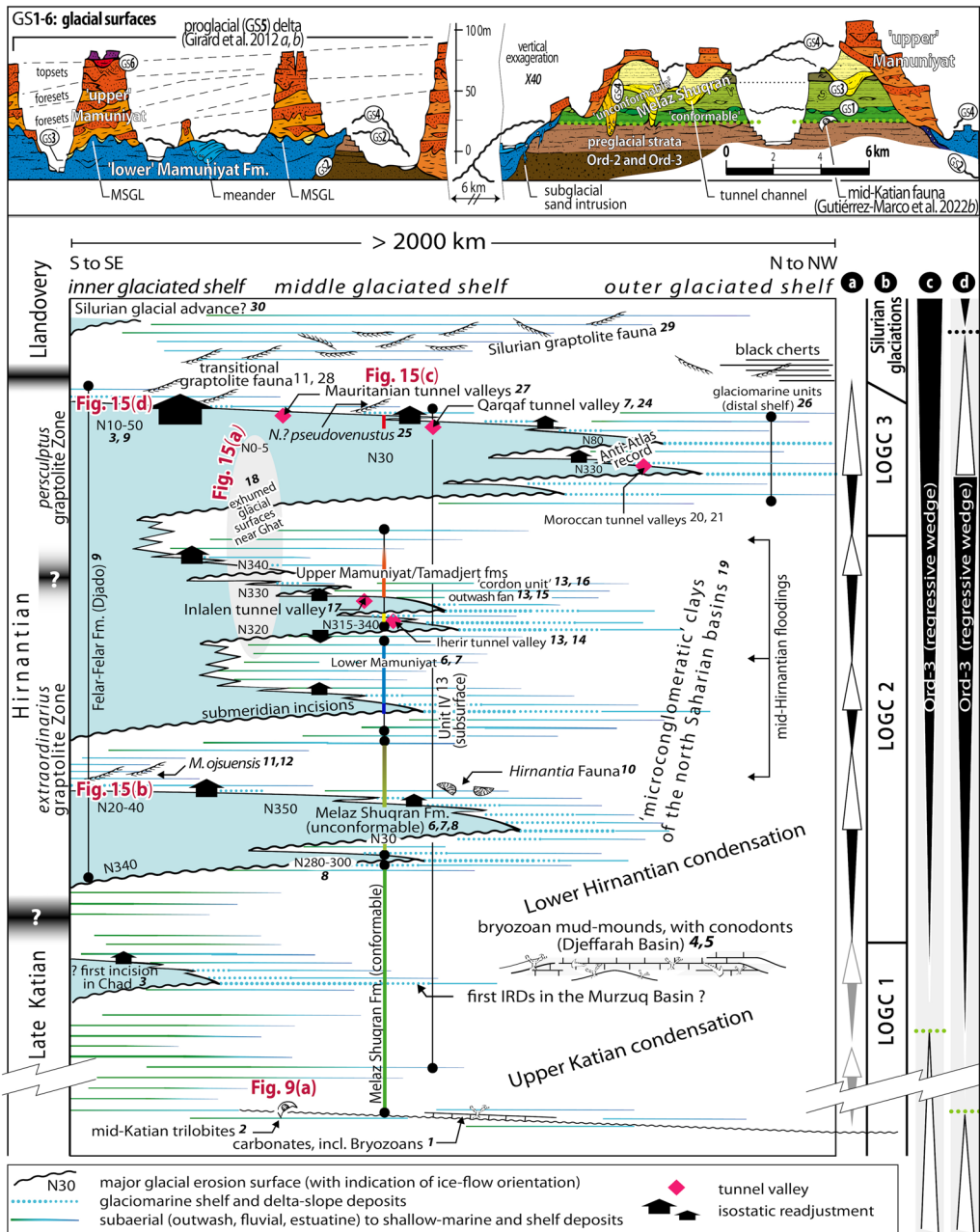


Fig. 14. Glacial cycles representing Late Ordovician waxing and waning ice sheets. Upper panel, from a field perspective, as understood from a 40 km-long cross profile in the Tihemboka area (location in Fig. 1a), where up to six successive glacial surfaces (GS) have been recognized (Murzuq Basin, SW Libya; to be compared with Fig. 13); lower panel, tentative chronostratigraphic chart, individualizing four main cycles within the Hirnantian (column 'a'). The scenario is primarily based on the stratigraphic record of Central Sahara. The coloured line in the middle part of the chart refers stratigraphic units shown in the upper panel. A correlation with the Late Ordovician Glacial Cycles (LOGC 1–3, Ghienne *et al.* 2014) defined in Morocco is proposed (column 'b'), but only as a working hypothesis. Columns 'c' and 'd': two interpretations of the significance of the end-Ordovician glaciation within the framework of second-order transgressive–regressive cycles described in this study (see text). Note that the final deglaciation stratigraphy is here represented for a suite of underfilled glacial incisions, not for intervening depositional highs –

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glaciomarine successions (Ghienne *et al.* 2007b; Legrand 2011; Gutiérrez-Marco *et al.* 2017, 2022b). Striated limestones made up of sandy shell beds that include trilobites have also been found (Fig. 10m). Both demonstrates an ancient, yet unknown extension of fossiliferous Ord-3 transgressive deposits farther south. Reworked in glaciogenic deposits, the same Katian fauna was once used to argue for a Caradocian glaciation (Beuf *et al.* 1971; Bellini and Massa 1980).

Owing to subsequent glacial erosion(s), the signature of the Late Ordovician transgression is more and more fragmentary further south and east. In northern Mali (Ifoghas Adrar), a diversified middle Katian (upper Berounian) fauna is, however, available (Gatinskiy *et al.* 1966; revision in Gutiérrez-Marco *et al.* 2017). This exception allows us to catch a glimpse of the southward retrogradation of the Late Ordovician transgressive deposits across the cratonic platform. More to the east (e.g. Djado), the occurrence of relatively fine-grained *Skolithos* sandstones that rest over coarse-grained fluvial-dominated sandstones might also be time-equivalent with Ord-3 Cycle, possibly representing shallow-marine sand flats emplaced during transgressive or highstand conditions. Middle to Upper Ordovician *Cruziana* ichnofacies (including *C. petraea*), found from beneath the Silurian strata as far as Benin (Kandi Basin, Konaté *et al.* 2003), SE Libya (Kufrah Basin, Lüning *et al.* 1999) and Chad (Ennedi, Seilacher 2000, 2007), can also be understood as representatives of an Ord-3 transgressive interval. All of these horizons from Mali to Chad highlight the continuous trend of continental encroachment with tidal-estuarine conditions reaching the most proximal segments of the platform by the early to middle Late Ordovician.

Impact of the end-Ordovician glaciation

Most of the Ord-3 deposits described above are linked to a relatively well-defined, transgressive depositional trend that culminated with an episode of mid-Katian sedimentary condensation (Figs 9d, 10l & 14). The status of the regressive wedge of Ord-3

Cycle is largely debatable as the corresponding stratal record interferes with glaciation forcing. This issue is further discussed below.

Transition from preglacial to glacial records

Where glacial erosion has preserved Ordovician strata younger than the Ord-3 transgressive succession, distinct configurations are reported. Only in the Daoura (western Ougarta Range), a relatively thick, Upper Katian to preglacial Hirnantian record is reported (Fig. 11c; Destombes 1983), which connects to the storm-dominated succession of the Moroccan Anti-Atlas to the north (Loi *et al.* 2010). It possibly extends southward to the Bled el-Mass (Fig. 4a). In the Illizi, Murzuq and Ghadames basins, another configuration is documented. The preserved, intervening succession essentially shows inner-shelf shaly deposits, yet including glaciomarine intervals and striated dropstones just a few decimetres to metres above the middle Katian condensed horizon. These conformable, or at least paraconformable deposits characterize the uppermost part of the preglacial Ordovician succession and rest atop interfluvial areas beneath the deep glaciation-related erosions, as identified both in outcrops and in the subsurface (Figs 7 & 13; Gil-Ortiz *et al.* 2022). Cropping out in the Tihemboka and on the back of the eastern Tassili n'Ajjer (SW Murzuq Basin; Fig. 7), and recognized in the subsurface of the Illizi Basin (e.g. MAO-1 well in Fig. 6b), such fine-grained sediments represent the earliest glacially influenced record ('conformable Melaz Shuqran Formation' in the Murzuq Basin, Fig. 14), which is older than the first, major, glacial erosion surface. However, no direct biostratigraphic data may help to decipher if the age of this early glacial record is late Katian (e.g. middle 'Ashgill'), latest Katian or early Hirnantian. In Figure 14, it has been tentatively assigned to the first Late Ordovician Glacial Cycle (LOGC 1) of Ghienne *et al.* (2014), thus assuming a latest Katian age.

A third configuration characterizes the northern Ghadames Basin (and the adjacent Djefarah Basin), where up to 100 m-thick bryozoan mud-

Fig. 14. *Continued.* interfluvial areas or top of outwash fans – that are re-shaped by tidal activity during and after the final glacio-isostatic readjustment (Lüning *et al.* 2000; Le Heron *et al.* 2006; Moreau 2011; Hirst 2016; Girard *et al.* 2019). References corresponding to available biostratigraphic data points and some prominent glacial depositional features (numbers in bold italics): 1, Kichou-Braïk *et al.* (2006); 2, Gutiérrez-Marco *et al.* (2022b); 3, Ghienne *et al.* (2023); 4, Bergström and Massa (1991); 5, Buttler *et al.* (2007); 6, Sutcliffe *et al.* (2000); 7, Ghienne *et al.* (2003); 8, Bataller *et al.* (2021); 9, Denis *et al.* (2010); 10, Sutcliffe *et al.* (2001); 11, Legrand (2009); 12, Denis *et al.* (2007a); 13, Deschamps *et al.* (2013); 14, Hirst (2012); 15, Girard *et al.* (2012a); 16, Girard *et al.* (2012b); 17, Girard *et al.* (2015); 18, Moreau *et al.* (2005); 19, Paris *et al.* (2000); 20, Loi *et al.* (2010); 21, Ravier *et al.* (2015); 22, Le Heron (2007); 23, Dietrich *et al.* (2019); 24, Le Heron *et al.* (2004); 25, Sachanski *et al.* (2018); 26, Le Heron *et al.* (2007); 27, Ghienne and Deynoux (1998); 28, Page *et al.* (2013); 29, Štorch and Massa (2006); and 30, Semtner and Klitzsch (1994). See Ghienne *et al.* (2007b) for a definition of the inner, middle and outer glaciated shelf segments.

mounds yielding a diversified Upper Ordovician conodont fauna are reported (Fig. 14; upper Djefarah Formation of Bergström and Massa 1991; El-Hawat *et al.* 2003; Buttler *et al.* 2007). This limestone interval, the palaeoclimatic significance of which is questionable (Cherns and Wheeley 2007), directly underlies Hirnantian glaciomarine deposits. Its depositional age is usually ascribed to the late/latest Katian (Kralodvorian; e.g. Gutiérrez-Marco *et al.* 2017), yet an early Hirnantian age cannot be partially excluded at its top (Paris 1990). In Figure 14, these limestones are understood as a transgressive unit marking a stage of starved detrital sedimentation at the end of LOGC 1.

The end-Ordovician glaciation-related deposits

The end-Ordovician glaciation left behind a meaningful record in North and West Africa, which constitutes one of the main archives documenting this global, palaeoclimatic event (Beuf *et al.* 1971; Deynoux 1980, 1985; Hambrey and Harland 1981; Khoja *et al.* 1998; McDougall and Martin 2000; Sutcliffe *et al.* 2000; El-Hawat *et al.* 2003; Ghienne 2003; Ghienne *et al.* 2003; 2007b; Le Heron *et al.* 2006, 2010, 2018; Denis *et al.* 2007a, 2010; McDougall and Gruenwald 2011; Moreau 2011; Zazoun and Mahdjoub 2011; Deschamps *et al.* 2013; Girard *et al.* 2015; Bataller *et al.* 2021). Related exposed and sub-surface records have been found from the Variscan Mauritanides along the Atlantic Coast to the Kufrah Basin and Ennedi (SE Libya and NE Chad), and from Djado (Niger) to northern Morocco. Filling the fault-bounded Kandi Basin of northern Benin, a thick (c. 500 m), syntectonic Late Ordovician glacial record has been published (Konaté *et al.* 2006). However, the occurrence of Late Ordovician cruzianids in the overlying strata suggests that this archive is most likely older (Lower Ordovician? or Cambrian?). Echoing some other potential indications for a pre-Late Ordovician glacial event, it could be younger than the Neoproterozoic to early Cambrian glaciations (Villeneuve *et al.* 2015b; Ghienne *et al.* 2023). Note that the restricted Ordovician strata cropping out more southward along the Atlantic coast (the Ghana basins of Villeneuve 2005) essentially comprise end-Ordovician (de-)glaciation-related deposits (Talbot 1981; Asiedu *et al.* 2010). They correspond to remnants of the South American Parnaíba Basin (Grahn and Caputo 1994), where older Cambrian–Ordovician successions are restricted to fault-bounded troughs underlining the Trans-Brazilian Lineament in the direct prolongation of the Kandi Basin (Assis *et al.* 2019), a situation reminiscent of the revised stratigraphy proposed above for the Kandi Basin.

Subaerial to glaciomarine outwash fans (Le Heron *et al.* 2010; Girard *et al.* 2012a, b; Deschamps *et al.* 2013; Dowdeswell *et al.* 2015; Le Heron 2016), jökulhlaup flow conditions (climbing-dune cross-stratification of Ghienne *et al.* 2010; Girard *et al.* 2012a; Hirst 2012; Lang *et al.* 2021), subglacial shear zones (Deynoux and Ghienne 2004; Le Heron *et al.* 2005; Denis *et al.* 2006), fields of glacial lineations (Moreau *et al.* 2005, 2007; Denis *et al.* 2007a, 2010; Moreau and Ghienne 2016) and underfilled large-scale incisions (Ghienne *et al.* 2007a; Le Heron and Craig 2008; Deschamps *et al.* 2013) both related to ice streaming, tunnel valleys (Ghienne and Deynoux 1998; Hirst *et al.* 2002; Ghienne *et al.* 2003; Le Heron *et al.* 2004; Ghienne 2009; Hirst 2012; van der Vegt *et al.* 2012; Deschamps *et al.* 2013; Ravier *et al.* 2015), glaciotectonic fold-and-thrust belts (Ghienne 2003; Le Heron *et al.* 2005, 2010; Girard *et al.* 2015) and subglacial sediment injections (Denis *et al.* 2007b; Girard *et al.* 2015), among other features, have been described. Glaciers were responsible for repeated and severe erosion and subsequent sediment remobilization (Hirst 2012; Ghienne *et al.* 2018; Sachanski *et al.* 2018).

Wherever the glaciogenic deposits are bounded by a disconformity or an unconformity, which is the most common situation, the hiatus is demonstrative (Figs 13 & 15c), yet it can be variously understood as a consequence of (1) the end-Ordovician glaciation alone (glacial erosion and/or lowstand, subaerial conditions), (2) Late Ordovician tectonics (sometimes referred to as the ‘Taconic phase’; Echikh 1998; Eschard *et al.* 2010; Gharsalli and Bédir 2020; Nedjari *et al.* 2021) or (3) a combination of both (McDougall *et al.* 2003). Tectonics may also locally interfere with glaciotectonic deformation (Zazoun and Mahdjoub 2011). Deep glacial erosion superimposing earlier erosion surfaces – for instance related to the ‘intra-Arenig’ event – and basin-scale growth-structures (Perron *et al.* 2021) have inevitably generated striking unconformable stratal relationships between pre- and syn-glacial strata, the former being in places much older than the latter (Fig. 16; Echikh and Sola 2000; Ghienne *et al.* 2007a, 2013; Lahondère *et al.* 2008; Eschard *et al.* 2010). Moreover, reduced thicknesses of upper Katian strata in the proximal segments of the platform have enhanced the stratigraphic hiatus, whatever its fundamental origin (Figs 4, 5 & 13). These stratal relationships are especially emphasized in the vicinity of structural highs, above which glacial erosion may have truncated Lower Ordovician to Cambrian strata, sometimes down to the basement (Ahnet Basin, Beuf *et al.* 1971; Perron *et al.* 2018; eastern Illizi Basin, Hirst 2012; Murizidié area, Ghienne *et al.* 2013).

The glaciation is at the origin of a prolific petroleum play, especially in Algeria and Libya,

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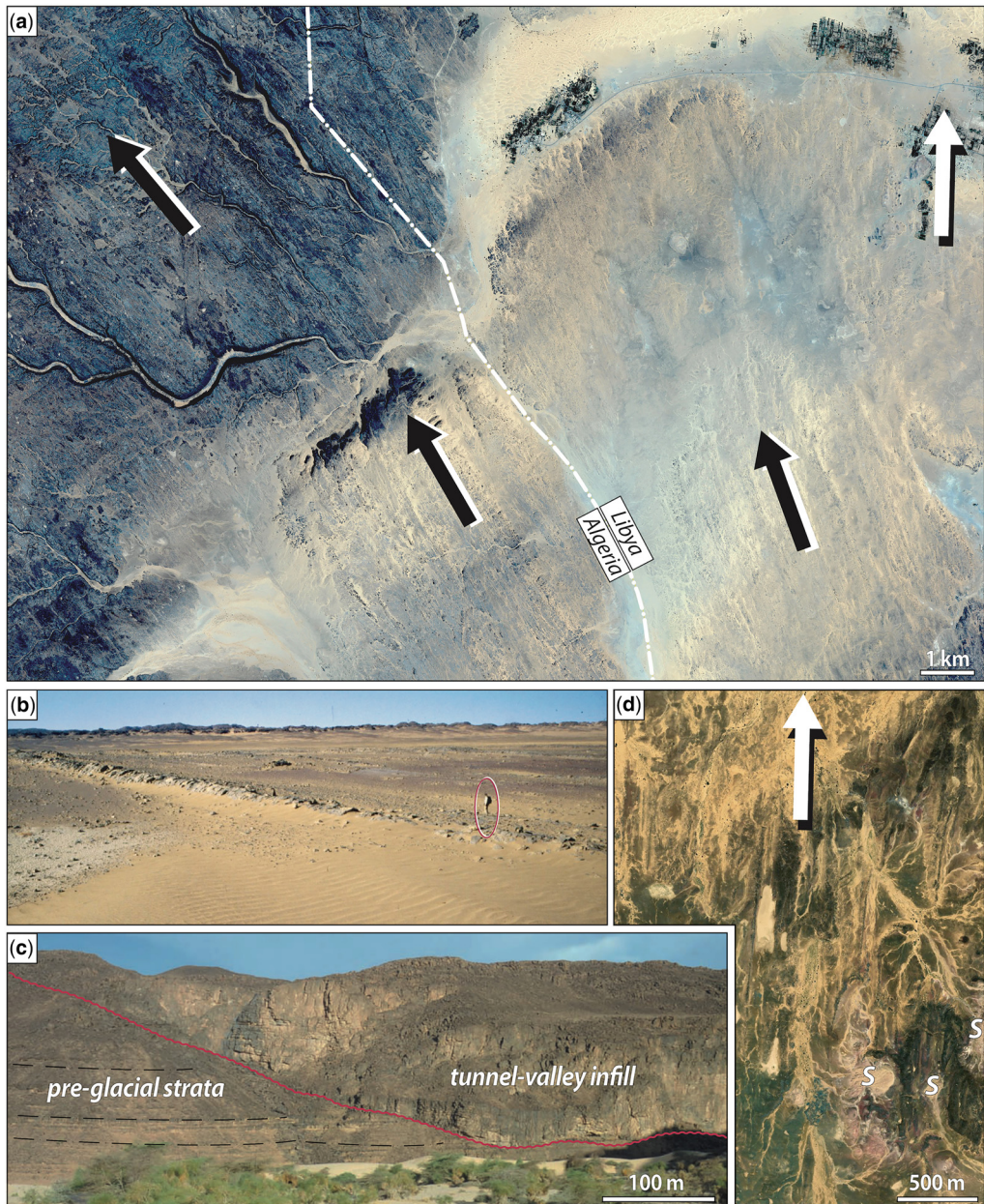


Fig. 15. Ordovician glacial surfaces throughout the Sahara. (a) Four, superimposed, exhumed glacial surfaces across the Algeria–Libya boundary, near the town of Ghat (SW Murzuq Basin; [Moreau *et al.* 2005](#)). The youngest one (white arrow) was buried by uppermost Ordovician to Lower Silurian shales ([Moreau 2011](#)), including hot shales ([Fello *et al.* 2006](#)). (b) An individual glacial lineation exhumed in Djado, northern Niger ([Denis *et al.* 2010](#)). (c) The margin of a tunnel valley in the Adrar of Mauritania ([Ghienne and Deynoux 1998](#)). (d) A set of exhumed, north-trending, glacial lineations in the Ennedi (NE Chad, satellite view), which might be one of the innermost glacial surfaces in North and West Africa. It was overlapped by inner-shelf, shale-dominated deposits (marked S) highlighting a maximum retrogradation of the Ordovician shorelines south of the Ennedi ([Ghienne *et al.* 2023](#)). For relative age assignments of these glacial surfaces, see the lower panel of [Figure 14](#).

associating glaciation-related reservoirs ('buried hills' consisting of preglacial strata, Khoja *et al.* 2000; glaciogenic infills and postglacial tidal sands) and late- to post-glacial lower Silurian source rocks (Lüning *et al.* 2000; 2009a; El-ghali *et al.* 2006; Fello *et al.* 2006; Le Heron *et al.* 2006; Vecoli *et al.* 2009; Tournier *et al.* 2010; Hirst 2012, 2016; Wells *et al.* 2015; English *et al.* 2017a; Bataller *et al.* 2019, 2021). Lithostratigraphy has been proved to be inefficient in deciphering the end-Ordovician glacial record, the stacking pattern of individual subsequences consisting of vertically superimposed and laterally juxtaposed allostratigraphic units displaying comparable facies assemblages (Fig. 14, upper panel; Ghienne 2003; Ghienne *et al.* 2003, 2007b; Moreau *et al.* 2005; Le Heron *et al.* 2006, 2010; Moreau 2011; Deschamps *et al.* 2013; Bataller *et al.* 2021). Nowhere can the glacial record be regarded as complete owing to the superimposition of glacial erosion surfaces through time. In addition, glacio-isostasy has been interpreted to interfere with eustatic signals. Lithospheric flexures might have driven relative sea-level rise during some of the ice-advance phases (Sutcliffe *et al.* 2001). On the contrary, isostatic readjustment and out-of-phase relative sea-level fall during ice-retreat phases have been inferred (Ghienne 2003; Le Heron *et al.* 2006; Ghienne *et al.* 2007b, 2023; Hirst 2016; Girard *et al.* 2019). Moreover, glaciation-induced lithospheric deformation has been suspected to have induced fault reactivations on a local scale (Ghienne *et al.* 2003; Kichou-Braïk *et al.* 2006; Le Heron *et al.* 2006; Perron *et al.* 2018). With the exception of such restricted areas where long-term and fault-controlled subsidence has been generated, virtually no accommodation space was available for glacial depositional systems that represented too-short events relative to subsidence patterns. At each time, deposition and preservation of the glacial archive only benefited from antecedent overdeepenings (e.g. Girard *et al.* 2015). Over interfluvial areas, just a few metres of generally transgressive and post-glacial sandstones may separate the preglacial deposits from the Silurian prograding wedge (Fig. 13).

Ice-sheet reconstructions: a perspective from North and West Africa

Currently regarded as an event bracketed within the Hirnantian (Sutcliffe *et al.* 2000), the spatial and temporal development of the end-Ordovician ice sheets in North and West Africa remains in fact poorly understood. Late to latest Katian events might have occurred before the Hirnantian (Loi *et al.* 2010; Ghienne *et al.* 2014), and it is tempting, as suggested above, to associate them with the early,

yet poorly defined glaciomarine record of the Illizi and Murzuq basins (LOGC 1, 'conformable' Melaz Shuqran Formation; Fig. 14). Specifically for the Hirnantian, previous reconstructions recognized a relatively simple development consisting of one or two cycles driven by the waxing and waning of the end-Ordovician ice sheets (Blanpied *et al.* 2000; Sutcliffe *et al.* 2000; El-ghali 2005). Scenarios with up to four cycles were subsequently proposed (Ghienne 2003; Ghienne *et al.* 2003, 2007b; Le Heron *et al.* 2006; Lang *et al.* 2012; Deschamps *et al.* 2013), and now a hierarchy of glacial cycles is most commonly acknowledged (Denis *et al.* 2010; Moreau 2011; Ghienne *et al.* 2014; Bataller *et al.* 2021). Figure 14 is a tentative proposal for a multicycle reconstruction based primarily on records from the Central Sahara (Djado in Niger; Tassili n'Ajjer in SE Algeria; Ghat and Tihemboka areas in SW Libya), where up to six glacial erosion surfaces are superimposed in places (Fig. 14, upper panel). It includes four main Hirnantian glacial cycles of unknown relative temporal significance (column 'a' of Fig. 14), and lower rank, shorter-term events, some of the latter potentially just corresponding in some cases to the dynamics of superimposed grounding-zone wedges (Fig. 15a).

It is not easy to establish a correspondence with the Moroccan, ice-distal but comprehensive record, from which three Late Ordovician Glacial Cycles (LOGC 1–3) of global significance have been postulated (Ghienne *et al.* 2014), which appear correlated with low-latitude records (Desrochers *et al.* 2010; Kiipli and Kiipli 2020; Mauviel *et al.* 2020; Calner *et al.* 2021; Li *et al.* 2021). As a working hypothesis, Figure 14 proposes a tentative correlation between the Saharan record and the LOGC suite (Fig. 14, column 'b'), in which: (1) LOGC 1 is not one of the four cycles recognized in Central Sahara, but it may have a record in Chad; (2) LOGC 2 comprises three of the four Saharan cycles; (3) the glaciation climax occurred within the *persculptus* graptolite Zone and only gave a restricted glacial record in the Central Sahara, but left behind deep underfilled depressions later filled in by Silurian strata; and (4) the flooding event separating LOGC 2 and 3 could be of lesser significance than one of the earlier 'mid-Hirnantian flooding events' that was responsible for the deposition up to northern Niger (Djado) of inner-shelf deposits. The latter, yielding a graptolitic fauna, has long been considered as latest Katian by Legrand (2009, 2011), an age that might have allowed the immediately underlying glacial record to be correlated with LOGC 1. However, the same fauna (*M. ojsuensis*) more likely characterizes the *extraordinarius* graptolite Zone (P. Štorch in Denis *et al.* 2007a). The isostatic flexure that permitted such a marine incursion far into the platform must have been associated with an earlier significant ice-

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sheet advance. The latter is here correlated with the first glacial advance that reached the north-Saharan basins, which is Hirnantian in age (*elongata* chitinozoan Biozone; Paris *et al.* 2000). This first cycle deposited the ‘unconformable’ Melaz Shuqran Formation of the Murzuq Basin (Fig. 14). In the Al Qarqaf area, the condensed horizon concluding the deglacial record of the first Hirnantian ice-sheet retreat yields a *Hirnantia* fauna (Sutcliffe *et al.* 2000, 2001), that is here correlated with the graptolite-rich interval of the Djado.

Ice-flow orientations usually vary from ESE–WNW to SW–NW. The dominant flow orientation is from the SSE to the NNW (Beuf *et al.* 1971; Ghienne *et al.* 2007b; Moreau *et al.* 2007; Deschamps *et al.* 2013), which seems reminiscent of the preglacial sediment dispersal pattern (Fig. 1a). Rotations of ice-flow orientations through time might suggest in places occurrences of either convergent flow patterns (ice-stream onset zones?) or divergent flow patterns (ice lobes?). Another interpretation would be the possibility of multidome ice sheets, the domes and related ice divides not being positioned in the same place from one cycle to another. The latter interpretation would suggest that the size of the apparent giant ice sheet, which would have aggregated the maximum extents of several individual, potentially diachronous ice domes (Legrand 2000, 2011), might be overestimated. The recent recognition of northward-orientated ice-flow patterns in eastern Libya (Kufrah Basin; Le Heron and Howard 2012), NE Chad (Ennedi, Fig. 15d; Ghienne *et al.* 2023) and up to northeastern Africa (Ethiopia and Eritrea: Kumpulainen 2007; Lewin *et al.* 2020) – and southern Saudi Arabia (Moscariello *et al.* 2009) – strongly suggests that at one time or another at least one vast ice sheet covered the whole platform from Mauritania to Arabia. Whether this ice sheet developed during LOGC 3 – and was precisely the one that reached Morocco and Brazil (cf. Assis *et al.* 2019) – or earlier in the Hirnantian remains unresolved, however. It should be noted that ice sheet developments also occurred within the Silurian (Davies *et al.* 2016; Sproson *et al.* 2022), primarily in South America (Díaz-Martínez and Grahn 2007) but also possibly in Africa (Semtner and Klitzsch 1994; Le Heron *et al.* 2013b). As a result, the Hirnantian glaciation should be considered the period of maximum ice extents within an expanded Early Paleozoic Ice Age (Ghienne *et al.* 2007b; Page *et al.* 2007).

In the literature, end-Ordovician ice sheets are generally considered as ranging between the minimum and maximum configurations of Ghienne *et al.* (2007b), respectively characterized by no or full connections of the Saharan ice sheet(s) with South African and South American ice caps (Schönian and Egenhoff 2007; Le Heron and Dowdeswell 2009; Le Heron *et al.* 2018; Assis *et al.* 2019). It is

particularly striking that there is no evidence of a significant impact of glaciation on the Congo Basin (Delvaux *et al.* 2021). The Late Ordovician ice sheet(s) may have occupied the broad, high-latitude, crescent-shaped area fringing the Gondwana land mass that faced open-marine, moisture-feeding domains, while the envelope of the glacierized zone circumvented the innermost, and most likely drier, part of the continent. Note that the ice sheet (s) – and more or less penecontemporaneous periglacial features – can all be positioned at palaeolatitudes everywhere greater than 45° S provided the geographic South Pole was located over north-central Africa (Nutz *et al.* 2013) rather than over northwestern Africa as usually proposed (e.g. Cocks and Torsvik 2021).

The Ordovician record at the platform scale

Ordovician transgressions across North and West Africa

Three Ordovician transgressive–regressive cycles and a glaciation-related wedge have been described, which respectively display maximum flooding intervals in the early to middle Tremadocian (Ord-1 Cycle, duration 10–15 myr), in the mid-Darriwilian (Ord-2 Cycle, duration 12–14 myr), in the mid or late Katian (Ord-3 Cycle, duration >12 myr) and in the very latest Ordovician (postglacial inundation). Within such a scheme mainly based on second-order stratigraphic cycles, the meaning of the glaciogenic strata is however puzzling and might be understood in two distinct ways. If mostly restricted to the Hirnantian, the entire glaciation-related strata only relate to a short-term, climate-controlled, ‘third-order’ cycle, rather than to a second-order cycle. Because the duration of the Hirnantian is <1.4 myr (according to the last chronostratigraphic chart, Cohen *et al.* 2022), the glaciation-related development should be viewed as superimposed on, and interfering with the second-order subdivision scheme based on c. 10–15 myr-long cycles. The latest Ordovician age for the maximum retrogradation of the Ordovician shorelines (Fig. 15d) is partly due to a temporary glacio-isostatic flexure and/or rapid post-glacial sea-level rise. These ‘maximum flooding’ conditions are just an artifice and the latest Hirnantian/earliest Silurian ‘post-glacial’ flooding can be considered the restoration of the preglaciation, late and latest Katian sea-levels. The second-order regressive wedge of the Ord-3 Cycle might then expand within the early Silurian (Fig. 14, column ‘c’; Bellini and Massa 1980; Klitzsch 1981; Gindre *et al.* 2012). Alternatively, it is possible to interpret a longer-term end-Ordovician glaciation, which in this case was responsible for a

comprehensive Ord-3 regressive wedge, yet largely dominated across the considered domain by the Hirnantian stratal record (Fig. 14, column 'd'). In this second model, a mid-Katian age is preferred for the Ord-3 maximum flooding conditions. Although belonging to a (long-term) second-order regressive wedge, each of the subsequent (short-term) mid- to late Katian transgressions associated with high rates of post-glacial sea-level rises (Loi *et al.* 2010) might have flooded significant portions of the North and West African platform (greyed-out cycles in Fig. 14, column 'a'). The same platform would not have been submerged in the absence of a glacio-eustatic forcing that drove platform drowning and efficient retrogradations of the facies belts. In the latter interpretation, the climax of the glaciation would correspond to the maximum regressive conditions of Ord-3 Cycle (Fig. 14, column 'a'), with inevitable confusions arising from glacio-isostatic interferences (e.g. Nutz *et al.* 2015; Dietrich *et al.* 2017, 2019 for Quaternary analogues) when deciphering the stacking pattern of successive glacial cycles (McDougall and Martin 2000; Sutcliffe *et al.* 2000; Le Heron *et al.* 2006; Ghienne *et al.* 2007b). A transgressive surface within the glacial strata should be defined, which would bound a last subsequent second-order transgressive–regressive cycle. Starting in the latest Ordovician and expanding into the early Silurian, its maximum flooding interval might be positioned in the Aeronian (Djouder *et al.* 2018; Girard *et al.* 2019). Note that the second model better conforms to established global sea-level curves (Haq and Schutter 2008; Embry *et al.* 2019). Both models highlight a glaciation inception during second-order high sea-level conditions. Occurrences of high-latitude, inundated, shallow shelf areas might have favoured ice-sheet growth phases from sea-ice covers.

Whatever the favoured interpretation, the three (or four) second-order cycles show an overall retrogradational trend throughout North and West Africa, which is essentially in the continuity of the Cambrian evolution (Boote *et al.* 1998; Eschard *et al.* 2005; Ghienne *et al.* 2007a; Fig. 5). From the base to the top of the Ordovician, inner-shelf facies belts have migrated from the north-Saharan basins to central and southern Sahara – but were subsequently eroded by end-Ordovician ice sheets. Ord-3 Cycle and related high-frequency intervals of fine-grained deposits are thin relatively to Ord-1 and Ord-2 equivalents, possibly as an expression of sedimentary condensation since shorelines were shifted at that time far to the south. In contrast, lowstand wedges might have been fully detached, reaching the northernmost part of the basin areas (Morocco, southern Europe) in the case of control by high-frequency and high-amplitude glacio-eustatic cycles (Loi *et al.* 2010). The most transgressive event, associated

with offshore shales deposited farthest south, definitely occurred at the very end of the Ordovician as a manifestation of post-glacial seas owing to glacio-isostatic flexures (Le Hérisse *et al.* 2013; Page *et al.* 2013; Ghienne *et al.* 2023), even if ice caps might have temporarily subsisted over central parts of the Gondwana or in South America. Such interferences owing to long-wavelength flexures and unusual long-range migrations of the sediment source points clearly do not facilitate the inclusion of the potential late Katian and Hirnantian Ordovician records in a conventional sequential stratigraphic scheme. For this reason, and with the exception of Figure 14 (columns 'c' and 'd'), the iconography of the present contribution does not incorporate glaciation-related strata in the second-order sequence stratigraphic scheme.

Building an Ordovician stratal record: the impact of the basement structures

Despite the overall stable tectonic setting, the Paleozoic basins throughout North and West Africa exhibit from place-to-place patterns of differential subsidence that largely distorted the stratal record (Figs 2–4). Their origin has long been a matter of debate in such an intracratonic setting, at least with respect to the post-Pan-African evolution. It rapidly appeared that the Saharan Paleozoic stratigraphy, even when considering the centre of larger sedimentary basins, was complexified by the network of arches or 'palaeohighs', which are typified by a reduced or missing Ordovician pile and adjacent depocentres preserving thicker and finer-grained successions (see the section 'Tectono-stratigraphic development'). The role of inherited faults or lineaments was previously emphasized, although more recent seismic lines and well-documented profiles rather display large-scale 'growth structures' including thickening trends towards the basins and progressive thinning, onlap and truncations towards the highs (Galeazzi *et al.* 2010; Eschard *et al.* 2010; Perron *et al.* 2018, 2021; Figs 2, 3 and 8), with a subordinate role attributed to inherited faults. All of these observations document the control by the Precambrian structural inheritance on the architecture of the Paleozoic sedimentary succession. This is best expressed around the Tuareg Shield (Fig. 2), where geological and geophysical observations of the exhumed and exposed terrane structures characterize subvertical sutures and shear zones at the lithospheric scale between terranes of different nature and ages (Bouزيد *et al.* 2008; Brahimi *et al.* 2018; Perron *et al.* 2018). Over arches are thin sedimentary successions resting upon 'old' Archean- and Paleoproterozoic-aged terranes while the Paleozoic depocentres are preferentially distributed on younger Neoproterozoic domains (Fig. 3; Perron *et al.* 2021).

The Ordovician record of North and West Africa

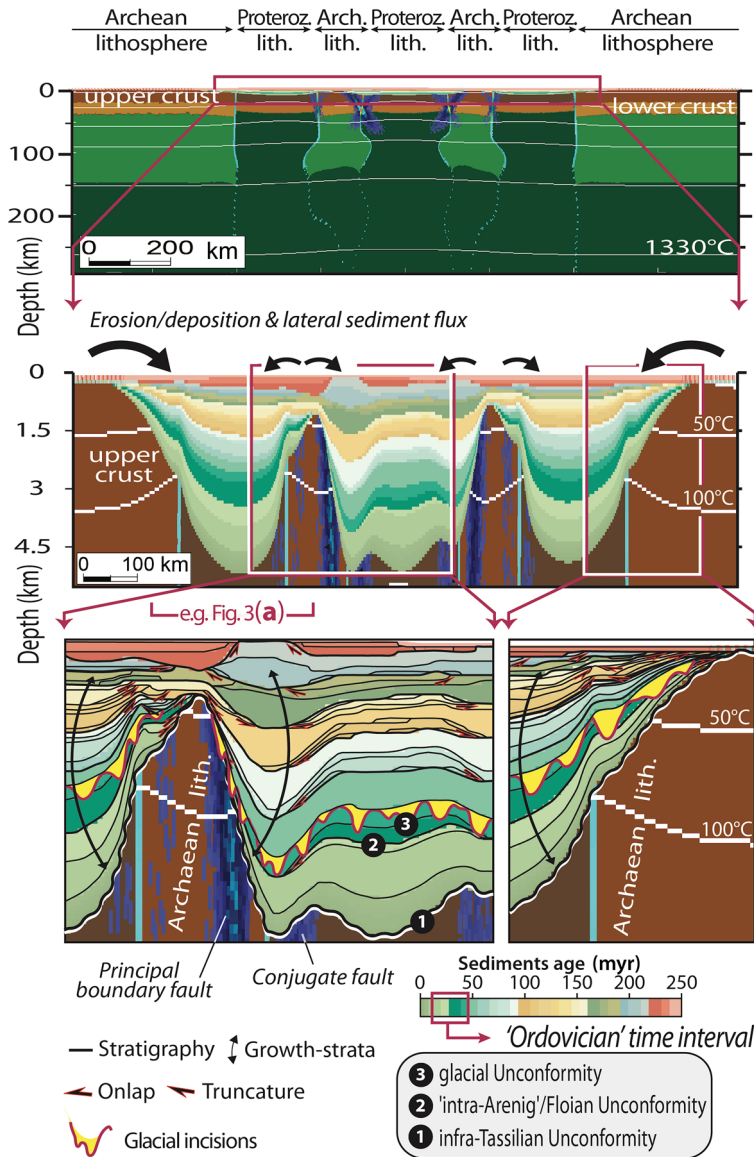


Fig. 16. Thermo-mechanical modelling of depositional architecture after 250 myr of subsidence controlled by density heterogeneities differentiating cratonic and Pan-African terrane basements (upper panel). Subsidence is minimal over Archean lithospheres (cratons and metacratons) and maximal across Proterozoic Pan-African basement units (see also Figs 2 & 3). Basin-scale growth structures, onlaps and truncations are depicted (see Perron *et al.* 2021 for more details). The ‘Ordovician’ time interval and the ‘intra-Arenig’ Unconformity are figured, yet they have not been specifically modelled. In addition, glacial incisions (c. 150 m deep) have been added manually and are only illustrative. The significance of associated stratigraphic hiatuses depends on both the glacial incision depth and the pre-glaciation development controlling the thickness of the underlying ‘Cambro-Ordovician’ sedimentary pile.

More generally, the subsidence in the context of giant continental platforms – sometimes referred to as intracratonic sag basins – remains an open question because usual tectonic processes (flexure, stretching then cooling) do not allow the

reproduction of relatively restricted depositional thicknesses with respect to the longevity that characterizes such domains (e.g. Burke *et al.* 2003; Pinet *et al.* 2013; Perron *et al.* 2021 and reference therein). Holt *et al.* (2010) suggested that the cooling of an

originally thin accretionary lithosphere may explain the subsidence pattern of the Ghadames and Kufrah basins. However, building on the well-characterized spatial coincidence between ‘sedimentary basins’ and the underlying Pan-African structures (Beuf *et al.* 1971; Boote *et al.* 1998; Coward and Ries 2003; Craig *et al.* 2008; Brahim *et al.* 2018; Perron *et al.* 2018), Perron *et al.* (2021) performed comprehensive modelling accounting for realistic, first-order and subtler stratigraphic patterns characterizing the Paleozoic succession all around the Tuareg Shield. The thermo-mechanical modelling considers first a heterogeneous basement made up of the juxtaposition of terranes displaying contrasted strengths and crustal thicknesses according to the relative contribution of Archean, Paleoproterozoic or Meso- and Neo-Proterozoic components to their lithospheric frame. Second, by imposing far-field perturbations and testing scenarios of sediment supply across the platform, Perron *et al.* (2021) show the extent to which the resulting stratigraphic architecture is controlled by slowly dissipating lateral density variations that forced differential isostatic re-equilibration in the long term (Fig. 16). They reproduced well the stratal geometries over the arches usually linked to Archean-dominated terranes as well as basin geometries – displaying large-scale growth structures – that prevailed over Proterozoic-dominated terranes (Fig. 3). Synsedimentary faults nucleate above weakness zones corresponding to Pan-African megashear zones bounding the terranes. It is also shown that covering the arches by reduced but existing sediment piles required a long-term sediment flux from remote, i.e. southern areas, which is well illustrated by palaeocurrent datasets and provenance studies (Fig. 1b); all these features, if superimposed by deep, undulating glacial erosion surfaces, mimic an unconformity tied to a compressional tectonic event (Fig. 16).

More interestingly and surprisingly, the model explains how reduced accommodation may have occurred in some basinal areas, which echoes the poorly understood significant stratigraphic gaps observed in north-Saharan basins. It also describes asymmetrical developments including short-term uplift phases and longer-term subsidence phases. Finally, it allows some diachronous patterns to be understood considering sediment dispersal patterns that may be oblique to the structural fabrics, the two latter model consequences probably being applicable to the ‘intra-Arenig’ tectonic phase.

Ordovician sedimentary systems

Sediment transport throughout the vast North and West African platforms has long been intriguing in the context of low-gradient depositional profiles showing poorly differentiated shallow-marine facies

belts grading from the outer shelf to tidal flats over distances >1000 km. Indeed, most of the Ordovician record is shallow marine, from offshore shales – including condensed horizons – to estuarine sandflats (e.g. Figs 4 & 5). Fluvial deposits are frequently absent from the Ordovician succession although they widely occurred (1) in the Cambrian stratal record, (2) within the most proximal reaches of the Ordovician platform (Guinea, Niger, Chad, SE Libya and Sudan), where they interfinger with estuarine/tidal sandstones, and (3) in the overlying Devonian strata. Also, extensive ‘estuarine’ or ‘deltaic’ depositional environments, generally showing widely bioturbated tide-influenced fluvial systems, are recognized down to the north-Saharan basins. Altogether, lower Paleozoic fluvial systems, including Ordovician ones, were most likely instrumental in patterns of sediment dispersal, even if rarely preserved as such in the large (several hundreds of kilometres) intermediate buffer zone that separated entirely marine deposits and purely continental stretches; the former preferentially preserved in the subsiding area and the latter primarily characterized areas with virtually no subsidence as far as the Ordovician is concerned. The Ordovician fluvial record is usually interpreted as braided stream deposits (Beuf *et al.* 1971; Turner 1980; Ghienne *et al.* 2023), usually lacking floodplain facies and possibly representing megafan or super-fan systems (Meinhold *et al.* 2013) in contexts where vegetation is absent or nascent. Exceptions are known from the glaciation-related fluvial deposits where sandy floodplains (the ‘cordons’ of Girard *et al.* 2012b) and large meandering systems (Rubino *et al.* 2003) have been described. Systems of Ordovician lowstand ‘incised valleys’ have, to our knowledge, never been characterized prior to the end-Ordovician glaciation. Palaeosol horizons are rare and poorly developed and aeolian deposits are unknown (or only suspected). In contrast, marine ravinement surfaces are frequent, characterizing both high-frequency sequences and second-order cycles, from the north (north-Saharan basins) to the south (e.g. Chad). Transgressive ravinement processes linked to tides and waves over very low-gradient depositional profiles (in the order of 100 m/1000 km, by comparison with the largest, present-day river systems) might well explain the absence of fluvial strata to the north, where they were first deposited as veneers, and later remobilized during ensuing transgressive trends. Subaerial erosion surfaces, if developed, were almost systematically superimposed by marine ravinement surfaces forming a Shoreline Unconformity *sensu* Embry (2009). More to the south, nearby the continental encroachment, aggradation of only fluvial strata – i.e. totally devoid of marine incursions – usually form relatively thin, 5–30 m-thick intervals inevitably bracketed in between bioturbated strata

The Ordovician record of North and West Africa

representing ‘estuarine’ facies belts. The latter directly seal in places the basal infra-Tassilian unconformity or are identified just a few decimetres or metres above. The fluvial coarse-grained and cross-stratified strata were usually preserved owing to the aggradation component of second-order transgressive wedges, as indicated by the progressive increasing-upward development of marine, bioturbated horizons within them. Whether they have been preferentially deposited during multiple, successive, high-frequency highstands or transgressive intervals, or a combination of both, remains unclear.

In this context, Ordovician strata are dominated by shallow-marine clastic facies, for which specific non-actualistic models have been recently proposed. Associations of tidal flats and tide-influenced shorefacies have been well described from the Murzuq Basin (Ramos *et al.* 2006; Abouessa and Morad 2009; Gil-Ortiz *et al.* 2019, 2022) and in the Tassili area (Eschard *et al.* 2005), within which bioturbation is intense and diversified in places, showing *Skolithos* and *Diplocraterion*, *Daedalus*, *Arthropycus*, *Cruziana*, *Teichichnus*, *Planolites* and rarer *Asterosoma*, among a few others (de Gibert *et al.* 2011; Fig. 10e–k). In contrast, less-bioturbated, storm-dominated deposits organized in prograding ‘parasequences’ seem to prevail in distal areas (Fig. 10d), with tidal-dominated deposits restricted to relatively thin transgressive wedges (Fig. 10c; Ghienne *et al.* 2007a). The detailed distribution through time and space of the Ordovician ichnofacies throughout the platform is the subject of ongoing projects (e.g. Meischner *et al.* 2020; Elicki and Magnus 2021). The contribution of facies partitioning within a stratigraphic cycle (e.g. storm deposits during regression v. tide deposits during transgression) relative to the impact of physiographic patterns (storm deposits along exposed shorelines v. tide deposits in protected embayments) is still to be established in the context of this giant Paleozoic Gondwanan platform. In addition, no true large-scale river-dominated deltaic depocentres including mouth-bar systems have ever been characterized across the considered domain during the Ordovician and a ‘braidplain delta’ setting with multiple sediment-input points might be envisioned. Larger-scale delta systems possibly developed and were preserved more to the north as lowstand wedges, especially in the late Darriwilian and, later, in response to Late Ordovician glacio-eustatic lowstand events (e.g. Morocco, Razin *et al.* 2020).

Sediment dispersal patterns: palaeocurrent trends

Ordovician sediment dispersal patterns over North and West Africa can be identified by continental-scale palaeocurrent distribution and provenance

studies, mainly on the basis of the U–Pb geochronology of detrital zircon grains (conventional heavy mineral studies seem to be less informative, e.g. Morton *et al.* 2011). Numerous publications, PhD theses and unpublished data are available for constructing a map of palaeocurrents from the west (Guinea, Mauritania, Benin) to the east (Chad, SE Libya) (Fig. 1b). A significant change in current orientation has been noted in several places from the base to the top of the pre-glaciation Cambrian–Ordovician succession, especially in the Tassili area (de Charpal *et al.* 1962; Beuf *et al.* 1971; synthesized in Perron *et al.* 2018). Subtler changes, yet in the same direction, are observed in other areas (e.g. southern Libya, Ghienne *et al.* 2013; Ennedi, Ghienne *et al.* 2023). To the east of the Tuareg Shield and over the Saharan Metacraton, it appears that palaeocurrent orientation has changed from a NNE to NE sector to a NNW to NW sector within a Lower to Middle Ordovician time interval (Fig. 1b). Integrating into this scheme palaeocurrent data from the base of the undifferentiated Cambro-Ordovician pile remains problematic. Currents from so-called ‘Cambrian’ strata exposed to the south might in most cases characterize (latest?) Cambrian to Lower Ordovician sandstones in southern central and eastern Sahara (Fig. 6; see description of Ord-1 and Ord-2 cycles). Very localized and temporary changes in sediment sources have also been recognized linked to the ‘intra-Arenig’/Floian deformation event (Beuf *et al.* 1971; Fig. 8 and red arrow in Fig. 1b). They are however not significant at the platform scale.

The situation is different to the west, in the Taoudéni Basin, within which the Cambrian–Ordovician boundary, and even the occurrence of Middle to Upper Ordovician strata, is questioned over a large part of the WAC (Fig. 12). Beuf *et al.* (1971) considered the ‘intra-Arenig’ phase as a widespread uplift event of the Reguibat Shield, disconnecting the Tindouf from the Taoudéni basins. Whether the Reguibat Shield was, or was not, a sediment source area during the Late Ordovician is an open question (see above).

As a consequence of the continuous trend of continental encroachment, Ordovician sediment sources were progressively shifted farther southward. Neither the present-day Tuareg Shield nor the northern part of the Saharan Metacraton, largely buried under the upper Cambrian to Lower Ordovician sandstones, can be considered as a direct significant sediment source as far as the middle to upper Ordovician record is concerned. During the ‘intra-Arenig’ phase, sediment recycling of the Cambrian cover, the latter having been originally sourced from the Tuareg Shield and the Sahara Metacraton, is however likely – particularly above arches separating the basins.

Insights from and consequences for zircon provenance from North and West Africa

The above proposed scenario is consistent with the detrital zircon record, which is essentially available from central Sahara (Fig. 1b): Tassili Ouan Ahaggar, south of the Tuareg Shield (Linnemann *et al.* 2011), and Dor el Gussa area, southern Libya (Meinhold *et al.* 2011). Other studies have mainly focused on the Cambrian, indicating that the lowermost Cambrian strata were largely fed from local sourcing (Avigad *et al.* 2012; El Houicha *et al.* 2018; Wang *et al.* 2020). A zircon record is also available from the middle? Cambrian strata of the Al Qarqaf Arch in western Libya (Altumi *et al.* 2013; diagram '7' in Fig. 1b). In this area located on the Sahara Metacraton, most of the zircon grains have a source compatible with the Pan-African Trans-Saharan Belt, and more precisely – when accounting for palaeocurrent distribution (towards the NNE in both the Tassili n'Ajjer and Al Qarqaf, Fig. 1b) – from the southern reaches of this orogen (Air basement including Paleoproterozoic/Orosirian metacratonic units, or more southern equivalents units beneath the present-day sedimentary cover; cf. Brahimi *et al.* 2018). This is representative of the configuration expected to characterize the time interval preceding the change in palaeocurrent distribution. In southern Libya, the Cambrian–Ordovician zircon record (Meinhold *et al.* 2011) basically shows three stages, from base to top: (1) zircon grains from the lowermost part of the Cambro-Ordovician succession are characterized by a source typifying the Sahara Metacraton, which is best understood as the signature of local sources (diagram '1' in Fig. 1b); (2) upper Cambrian to Lower Ordovician samples from the middle part of the succession progressively lost this early signal, suggesting a sourcing dominated by the recycling of Pan-African belts and again, according to palaeocurrent trends, from the Trans-Saharan Belt (diagram '2'); and (3) the zircon record changes drastically in the Ordovician strata that post-date the 'intra-Arenig' unconformity by the massive arrival of *c.* 1 Ga zircon grains associated with a subordinate Neoproterozoic sourcing (diagram '3'), a combination that pertained up to the Upper Paleozoic. This change is in line with local and regional-scale palaeocurrents depicting a re-organized north-northwestward to northwestward dispersal pattern. After the 'mid-Arenig' event, the source area must now be found in an area expanding from the southern Sahara Metacraton (e.g. Blades *et al.* 2021) or the Central African Fold Belt (Kalsbeek *et al.* 2013), and most likely up to the Congo Craton (Linol *et al.* 2016) when accounting for the Archean detrital components. The super-fan system suggested by Meinhold *et al.* (2013) would have become active only in the course of the Ordovician.

In southern Algeria (diagrams 4–6 in Fig. 1b), the zircon record also interestingly includes a comparable tipping point in source ages (Linnemann *et al.* 2011), although the stratigraphic context is uncertain owing to a poorly differentiated Cambro-Ordovician succession. In this area characterized at that time by north-flowing fluvial systems, the lowermost sample has logically a zircon record dominated by Paleoproterozoic/Rhyacian ages, i.e. sourced from the immediately underlying basement that is known to expand further south (Brahimi *et al.* 2018; Perron *et al.* 2018). This local signal rapidly disappeared upward, replaced by a more usual combination of a Pan-African signal linked with a large-range but subordinate and decreasing Paleoproterozoic population of zircon grains, testifying to the enlargement and southward extension of the southern drainage basins. Then, sediment sourcing changed as shown by a significant arrival of Cryogenian grains and a renewed Paleoproterozoic population. Although of unknown origin, these new age spectra appear coeval with a palaeocurrent change in the nearby Tim Merso Basin, suggesting a sourcing from the SE (rather than from the south). The two overlying samples from the glaciogenic succession show two distinct signals: one, with an 'exotic' source including an Archean component, and a second with a more 'autochthonous' signature only suggesting the working of the underlying Cambrian–Ordovician strata by glacial erosion. Here also, a change in the zircon population is associated with a palaeocurrent reorganization, which seems to have occurred, abruptly or progressively, within the Early Ordovician.

The role of the (southern) Trans-Saharan Belt as a sediment source thus tends to diminish over time, replaced – or overprinted – by a supply from more eastern sources appearing or increasingly contributing in the course of the Ordovician (Fig. 17). It is here argued that the perennial platform-scale sediment source re-organization was linked in some way to the 'intra-Arenig' tectonic event. The lower Paleozoic continental encroachment and a profound, tectonic-driven change in the distribution of drainage basins indicate that North and West Africa cannot be considered an unchanging sediment source through time, which might have consequences for provenance studies linking Africa and the pre-Variscan Europe (e.g. Shaw *et al.* 2014; Dabard *et al.* 2021). One of the far-field signatures of this change in sediment sourcing is possibly illustrated by the relatively unexpected appearance of *c.* 1 Ga zircons in the Ordovician strata of Morocco (Perez *et al.* 2019; Accotto *et al.* 2021), in an area generally understood as specifically fed by West Africa where 1 Ga sources are insignificant. With westward rotating palaeocurrent trends by 50–80° (Fig. 17), any palaeogeographical scheme 'averaging' the Cambrian to

The Ordovician record of North and West Africa

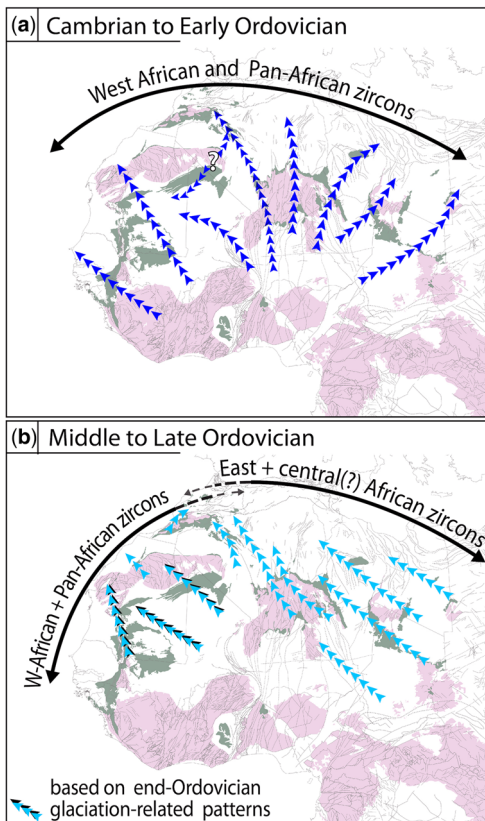


Fig. 17. Contrasting Ordovician dispersal sediment patterns. (a) West Africa and the Pan-African Trans-Saharan Belt were the main clastic source during the Cambrian to Early Ordovician. (b) During the Middle and Late Ordovician, a more eastern and southeastern sourcing, including a significant contribution of the Saharan Metacraton, replaced West African sources when considering the eastern part of the domain. In (b), reconstruction over the West African Craton essentially relies on end-Ordovician glaciation-related dispersal patterns as the preglacial Middle to Late Ordovician stratal record is restricted.

Late Ordovician configuration into a perennial and submeridian south to north dispersal pattern (e.g. [Stephan et al. 2019](#); [Tabaud et al. 2021](#)) might be oversimplified. Accounting for the aforementioned palaeocurrent change offers an alternative interpretation for reconstructions inferring margin-parallel strike-slip displacements on the basis of changes in zircon sourcing ([Azor et al. 2021](#)); the change in Gondwanan dispersal patterns precisely results in the same apparent signature as strike-slip displacements. Note that this is true whatever the origin of this change, either as a consequence of Early Ordovician tectonics (our preferred interpretation) or as

a consequence of the re-organization of the depositional systems after shallow-marine processes, especially tides, penetrated farther south in the course of the Ordovician.

Conclusions

The Ordovician of North and West Africa illustrates a pattern of sustained continental encroachment. Three main transgressive–regressive stratigraphic sequences are individualized, which are understood as second-order, eustasy-controlled cycles. Related maximum flooding intervals occurred in the early to middle Tremadocian, the mid-Darriwilian and the mid to late Katian. In spite of apparent facies consistencies through long-range cross-profiles, progradation and retrogradation trends over the low gradient continental platform are suspected to have resulted in highly diachronous depositional schemes. Moving southward or southeastward, Cambrian strata are suspected to be less and less represented in the poorly differentiated ‘Cambro-Ordovician’ successions. Most records are of shallow-marine clastic depositional systems, preserving fluvial strata only over the most proximal, southern stretches of the platform and some incidental carbonate strata bearing bryozoans (condensed horizons, mud-mounds) in rare locations to the north.

Two events interfered with the long-term Ordovician transgression. An ‘intra-Arenig’ (late Floian?) tectonic event first had a profound impact on basin-scale depositional geometries, resulting in hiatuses or at least reduced thicknesses characterizing palaeohighs or arches, generally coinciding with the extent of Paleoproterozoic basement units. At the same time, active accumulation had probably ended throughout most of the West Africa Craton, with the exception of its northern and southern margins. The same tectonic event drastically modified the Gondwanan watersheds in the most internal segment of the platform, a re-organization that impacted sediment sourcing and especially the age distribution of the detrital zircons feeding the pre-Variscan Europe. This tectonic perturbation is probably the far-field manifestation of one or several tectonic events affecting the Gondwana margin beyond the domain considered here, as it is the case in Turkey ([Ghienne et al. 2010](#)). However, structural relationships with for instance the compressional Sardinian Phase, rift basins tied to the ‘Armorican Quartzite’ and/or opening of the Rheic Ocean remain to be substantiated ([Ballèvre et al. 2012](#); [Ouanaimi et al. 2016](#); [Pouclot et al. 2017](#); [Álvarez et al. 2018](#); [Stephan et al. 2019](#); [Oriolo et al. 2021](#); [Cocco et al. 2022](#)).

The second main event impacting North and West Africa during the Ordovician is the end-

Ordovician glaciation. The domain has supported the greatest part of the Hirnantian ice masses and may have preserved archives of pre-Hirnantian glacial events. Glacial erosion and related significant sediment remobilization have been associated with glacio-eustasy and instrumental glacio-isostatic flexures – and subsequent re-adjustments. It is not until the latest Ordovician that offshore conditions developed far inland into the shallow-marine platform but it is largely suspected that part of this inundation benefited from a glacio-isostatically flexured Gondwana lithosphere. As a consequence, deciphering and dating the Ordovician maximum flooding interval remains a challenge. The latter might have occurred during the mid-Katian. After a short-term but successive glacial advance and retreat phases, high sea-levels were restored in the very latest Ordovician after major deglaciation.

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