Palaeogeography, Palaeoclimatology, Palaeoecology 460 (2016) 50–61

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

Conodonts from the Lower Ordovician of Morocco — Contributions to age and faunal diversity of the Fezouata Lagerstätte and peri-Gondwana biogeography

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ARTICLE INFO

Article history:
Received 27 October 2015
Received in revised form 6 March 2016
Accepted 21 March 2016
Available online 31 March 2016

Keywords:
Morocco
Gondwana
Fezouata Formation
Conodonts
Lower Ordovician

ABSTRACT

This study documents conodont faunas of the Fezouata Formation, recovered from the AZ-1 borehole at Adrar Zouggar Mountain and from outcrops near Zagora in south-eastern Morocco. The Fezouata Formation was deposited on the peri-Gondwanan shelf near the South Pole during Early Ordovician times. It is composed of mostly fine-grained siliciclastics and is well known for including beds displaying the exceptionally well preserved Fezouata Biota. Studies on different microfossil groups, including conodonts, increase the diversity recorded from this exceptional ecosystem. Strongly recrystallised conodont elements were extracted from the fine-grained siliciclastic sediments by diluted hydrofluoric acid (HF), which was used for isolating palynomorphs. The material is dominated by simple cone taxa such as *Parapaltodus*, *Semiacontiodus*, *Scolopodus*, *Scalpellodus*, *Drepanoistodus*, *Acodus*, *Paltodus*, and *Cornuodus*. In addition, a few elements of early *Prioniodus* are recovered. This composition allows an estimation of uppermost Tremadocian through basal Floian ages for the fragmented elements because characteristic elements of younger assemblages, including ramiform (e.g., *Oepikodus*, *Baltoniodus*) or coniform (e.g., *Tropodus*, *Protopanderodus*) apparatuses, have not been recorded. The association is devoid of any warm/tropical and temperate water taxa and is typical for faunas in the cold water environments of the subpolar siliciclastic shelves during Early Ordovician times. The new term of 'subpolar faunal domain' is proposed for these conodont associations of low diversity that occur at high southern latitudes during the Early Ordovician. Ecological implications and palaeobiogeographical relationships of the conodont faunas are discussed.

1. Introduction

The Lower Ordovician Fezouata Formation of southeastern Morocco is famous for its records of Tremadocian to Floian faunas. The macrofossil record includes different groups such as cephalopods, echinoderms, brachiopods, trilobites and various other arthropods, graptolites, sponges, hyolithids and conularids (e.g., Van Roy et al., 2015a, and references therein; Martin et al., in press). The presence of exceptionally well preserved fossils with possibly a Burgess Shale-like mode of preservation marks a 'Konservat-Lagerstätte' (sensu Seilacher, 1970), which represents the only post-Cambrian Lagerstätte of this type on the open shelf at the transition between the lower shoreface and offshore environments (Van Roy et al., 2010, 2015a, 2015b; Gaines et al., 2012; Gaines, 2014; Martin et al., in press).

In the Fezouata Lagerstätte, soft-bodied biota typical of Cambrian Burgess Shale-type faunas co-occur with fossil groups typical for Sepkoski's (1984) Palaeozoic Evolutionary Fauna (Van Roy et al., 2015a), which started to flourish during the Great Ordovician Biodiversification Event (GOBE; e.g., Servais et al., 2010, with references therein). After five decades of documentation of different faunal groups from the Fezouata Formation, exceptionally well-preserved fossils were not documented before 2006 when within a short interval the papers by Van Roy and Tetlie (2006) on spinose arthropod appendages and by Lefebvre and Botting (2007) on well preserved echinodermata were published. In contrast to Van Roy et al. (2010) assuming that Lagerstätten levels occur in the upper Lower Fezouata Formation

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http://dx.doi.org/10.1016/j.palaeo.2016.03.023
0031-0182/

(Tremadocian) and Upper Fezouata Formation (Floian), Martin et al. (in press) suggest that the exceptional faunal preservation in the thick siliciclastic Fezouata Formation is occurring in only two main intervals in the upper Lower Fezouata Formation, comprising together an approximately 70 m thick interval. Since lens-like Lagerstätten bearing levels were recently also located in the Upper Fezouata Formation, the window for exceptional preservation now seems to range from the upper Tremadocian *A. murrayi* Zone into the middle Floian ?*Baltograptus jacksoni* Zone (Gutiérrez-Marco and Martin, 2016–in this issue).

Despite all faunal lists and abundant palaeontological literature (e.g., Van Roy et al., 2015a, with references therein), the timing of the formation of the Fezouata Konservat-Lagerstätte was not very well constrained. Graptolites and palynomorphs are important for dating the Lagerstätte.

Palynormorphs, specifically acritarchs, were described from the Fezouata Formation for the first time by Deunff (1968a, 1968b), and the literature on this group is summarized in Nowak et al. (2015, 2016–in this issue). *Lagenochitina destombesi*, described by Elaouad-Debbaj (1988) from this formation, is the index taxon of the lowermost chitinozoan biozone in the Ordovician (Paris, 1990). Most important for time constraints of the Fezouata Lagerstätte are the associated acritarchs belonging to the *messaoudensis–trifidum* assemblage (e.g., Servais and Molyneux, 1997, with references therein), which recently was documented by Nowak et al. (2015, 2016–in this issue) from the Fezouata Formation in the Adrar Zouggar Mountain (borehole AZ-1). This acritarch assemblage is indicative of the upper Tremadocian through lower Floian in many peri-Gondwanan successions in high southern latitudes (Servais et al., 2003; Molyneux et al., 2013).

Based on graptolites, the part of the Lower Fezouata Formation including exceptional preservation has been attributed by Martin et al. (in press) to the *A. murrayi* through basal *Hunnegraptus copiosus* zones (upper Tremadocian). The graptolite faunas in this critical interval are revised by Gutiérrez-Marco and Martin (2016–in this issue), indicating that exceptional preservation of the Fezouata biota extends into the Floian. A historical review of the research on the Fezouata Lagerstätte and its stratigraphic data has been compiled by Lefebvre et al. (2016–in this issue).

So far, Ordovician conodonts from Morocco have only been described by Bultynck and Sarmiento (2003) as reworked material (early Middle Ordovician) from a Siluro-Devonian succession in the Meseta (Khemis-n'Ga) and by El Bourkhissi and Sarmiento (1997) from the Middle Ordovician Taddrist and Izegguirene formations in the Anti-Atlas. The present study focuses on much older conodont material from an interval overlapping stratigraphically with the Lower Ordovician Fezouata Lagerstätte, with the goal to gain new biostratigraphic and palaeobiogeographic data based on collections from different areas.

2. Geological setting

During Early Ordovician times, Africa was an integral part of the Gondwana supercontinent, which occupied palaeolatitudes from the South Pole to the equator (e.g. Torsvik and Cocks, 2013a, 2013b). The shelf sequence studied in Morocco was deposited in cold water environments at extremely high latitudes close to the palaeo-south pole (Torsvik and Cocks, 2011, 2013a, 2013b). Plate-tectonic processes triggered rifting and subsidence in the latest Cambrian and earliest Ordovician, when the Rheic Ocean started to open up between Gondwana and Avalonia, with Avalonia being considered a well-constrained microcontinent (Servais and Sintubin, 2009, with references therein) that drifted north towards Baltica during the Ordovician (e.g. Cocks and Fortey, 2009), causing the subsequent closure of the Tornquist Sea and finally collided with Baltica during Late Ordovician times (e.g. Torsvik and Rehnström, 2003). At that point the study area in the Moroccan Anti-Atlas was covered by the large ice cap of the Hirnantian Gondwana glaciation (e.g. Le Heron et al., 2007; Le Heron and Craig, 2009).

The Lower Ordovician (Tremadocian to Floian) Fezouata Formation is widely distributed in the Anti-Atlas. The sedimentation of the thick succession of fine-grained siliciclastics (mud- and quartz-rich siltstones and sandstones) of about 900 m in maximum thickness took place in a vast but shallow epicontinental basin along the Gondwana margin (Destombes et al., 1985; Martin et al., in press; Vaucher et al., 2016–in this issue). This siliciclastic succession, which in the past has been subdivided into a Lower (Tremadocian) and Upper (Floian) Fezouata Formation, has its most important outcrops in the Draa Valley around Zagora (Destombes et al., 1985). However, the lithologic separation of its lower and upper part by a distinct horizon is not possible in certain regions such as the Zagora area (Destombes, 1962).

The Fezouata Formation is resting unconformably on the Guzhangian Tabanite Group (Geyer and Landing, 2006) and is in places covered by sandstones of the upper Floian Zini Formation. For the Fezouata and Zini formations, Vaucher et al. (2016–in this issue) present a first depositional model showing wave-dominated and tide-modulated deposition of sediments formed in foreshore to proximal offshore, with the deposition of sandstone lenses in lower shoreface environments under storm activity.

Both formations are separated by an unconformity from the overlying Darriwilian deposits of the Tachilla Formation. The three formations, the Fezouata, Zini, and Tachilla formations, constitute together the Lower through Middle Ordovician Outer Feijas Shale Group of Choubert (1942).

3. Materials and methods

Various localities in the Ternata plain near Zagora (Fig. 1) have been sampled in detail during several field campaigns, also for gaining biostratigraphic data based on palynomorphs (Nowak et al., 2016–in this issue). A detailed stratigraphic log for showing the position of palynomorphs (Fig. 2; Nowak et al., 2016–in this issue, Fig. 2). The displayed section corresponds to the interval ca. 240–330 m above the base of the Fezouata Formation in the compiled stratigraphic log by Vaucher et al. (2016–in this issue, Fig. 2). This includes the majority of strata bearing the exceptionally preserved biota of the Fezouata Lagerstätte (Martin et al., in press). A conspicuous approx. 20 m thick greyish blue and clayey interval (43 to 62 m in Fig. 2) serves as a local stratigraphic marker to correlate the different sections and also the sample positions (Fig. 2). 28 samples (prefix TZ-Paly) were taken at Jbel Tizagzaouine (30°31′04″N, 5°49′19″W, Fig. 1A) for palynomorph studies.

17 densely-spaced samples (prefix FZ1) were taken from the excavations of a ca. 4 m thick interval in three quarries at Bou Izargane (30°29′59″N, 5°51′00″W; Fig. 1A). Samples from each quarry, respectively encompassing samples from ca. 3–41, 66–89, and 341–418 cm above the base of the local section are compiled in the log shown in Fig. 2, where they are correlated approximately against the Tizigzaouine section. The sample material collected from the Bou Izargane excavations represents dark grey mudrocks that are much less altered than those exposed in other outcrop locations which are clearly affected by weathering processes (Nowak et al., 2016–in this issue).

In addition, subsurface material for palynological studies from the AZ-1 borehole (Fig. 1B; drilled in 1963 and 1964 at Adrar Zouggar Mountain, ca 300 km southwest of Zagora, by the petroleum company Petrofina for oil exploration) originates from cuttings sampled from the drillhole. This material is stored in the drill core repository of the ONHYM (Office National des Hydrocarbures et des Mines) at Rabat. The drilling stopped at a maximum depth of 3398.13 m. The interval between 624 m and 1134.8 m depth was assigned in the logging to the Fezouata Formation, based on lithological comparison with outcrop areas. This interval is overlain by 144 m of sediments assigned to the Zini Formation and subsequently by the Tachilla Formation (Destombes, 2006).

The conodont material studied in the present paper is derived from the siliciclastic palynomorph samples and was processed in the