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ORIGINAL PAPER

The zircon evidence of temporally changing sediment transport—the NW Gondwana margin during Cambrian to Devonian time (Aoucert and Smara areas, Moroccan Sahara)

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Abstract Detrital zircon provenance studies are an established tool to develop palaeogeographic models, mostly based on zircon of siliciclastic rocks and isotope data. But zircon is more than just istopes and features well definable morphological characteristics. The latter may indicate single grain transport histories independent of the individual grade of concordance. This additional tool for palaeogeoraphic reconstructions was tested on zircon from siliciclastic and carbonate sedimentary rocks of Palaeozoic age from the Aoucert and Smara areas of the Souttoufides, while findings of zircon in limestone generally open new archives for sedimentary provenance analysis. The morphologies—length, width, roundness, grain surfaces—of 834 detrital zircons from sediments of allochthonous Cambrian, and (par-)autochthonous Ordovician, and Devonian units were studied, while 772 of them were analysed for their U–Th–Pb isotopes by LA-ICP-MS. Mesoproterozoic zircon contents of more than 10% in the Cambrian sediments exclude the West African Craton (WAC) as exclusive source area. Thus, at least one additional external source is suggested. This is likely the western Adrar Souttouf Massif with its significant Mesoproterozoic zircon inheritance, or comparable, yet unknown sources. Decreasing Mesoproterozoic zircon age populations in Ordovician sediments are thought to be linked to the rifting of the terranes in the course of the Rheic Ocean opening and a predominant supply of WAC detritus. The Devonian sediments likely contain reworked material from the Cambrian siliciclastics, which is shown by the zircon age distribution pattern and the zircon morphologies. Therefore, multiple shifts in the direction of sedimentary transport are indicated.

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Introduction

The West African Craton (WAC) is subject of detailed research since the last 100 years and still is a wide field for numerous investigations (Jessel and Liégeois 2015). There are countless publications concerning the stratigraphy and fossil record of the early Palaeozoic sedimentary successions throughout the WAC (e.g. Beuf et al. 1971; Gevin 1960; Ghienne et al. 2007a; Sougy 1964; Trompette 1973; Wendt and Kaufmann 2006). Although sedimentary rocks of Ordovician to Devonian age occur widespread along the western margin of the WAC (Fig. 1), there is a significant lack of corresponding provenance studies. Comparable investigations in this area are either focussed on the (post-)Mesozoic (Pratt et al. 2015, 2016), or the (pre-)Cambrian (Abati et al. 2010; Avigad et al. 2012; Walsh et al. 2012; Blein et al. 2014), which applies even in adjacent regions like Libya (Altumi et al. 2013; Meinhold et al. 2013). Exceptions are given by Linnemann et al. (2011a) and Meinhold et al. (2014) who provide zircon data from the Ordovician and Devonian of Algeria and Lybia. Some provenance studies from the peri-Gondwanan terranes, e.g. Iberia, the Rhenohercynian Zone, and the Bohemian Massif, also include detrital zircon data from this period and suppose some input from the WAC or its vicinity (Drost et al. 2011; Eckelmann et al. 2014; Linnemann et al. 2008, 2011b; Shaw et al. 2014).

To unravel the sedimentary transport and provenance at the western margin of the WAC in post-Cambrian Palaeozoic times, five samples of Ordovician to Devonian sedimentary rocks were collected from the Smara-Zemmour Massif (D209, D211) and the Dhloat Ensour unit (MS11, MS12, MS13) of the Souttoufide belt sensu Villeneuve et al. (2015). One likely Cambrian sediment (MS15) from the westernmost Sebkha Matallah unit of the Adrar Souttouf Massif was sampled for comparison. The zircons of all samples were investigated with respect to their age distribution pattern and some morphological features. Therefore, the obtained data is thought to close a gap in the

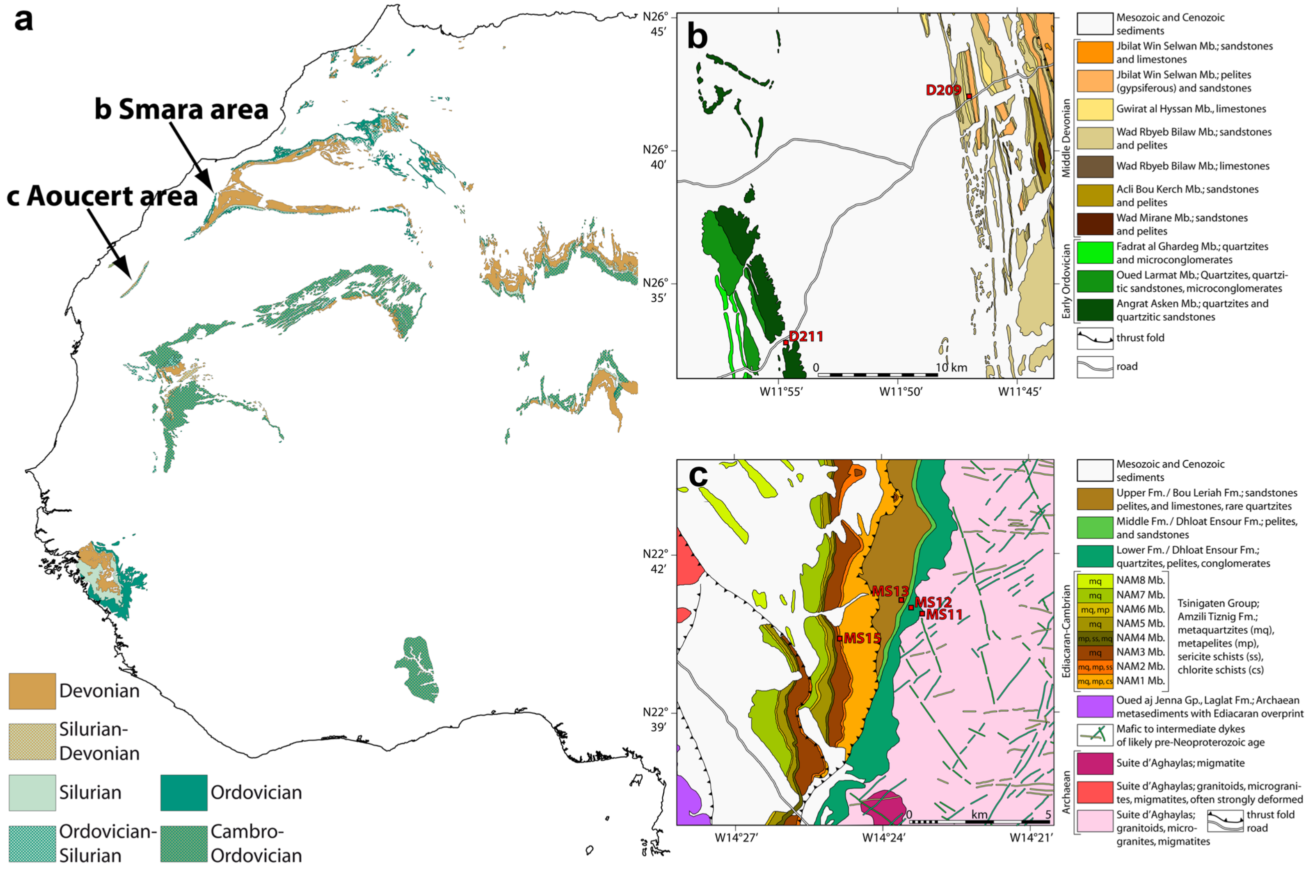


Fig. 1 **a** Overview of outcropping Cambro-Ordovician to Devonian sediments at the West African Craton (modified from Choubert and Faure-Muret 1988), **b** general geologic setting and sample localities at the Smara (modified from Rjimati et al. 2002c) and **c** Aoucert areas (modified from Rjimati et al. 2002a)

Ordovician to Devonian detrital zircon record of the northwest African realm of Gondwana. Finally, the zircon grains from the Dhloat Ensour unit might also give some information about geologic evolution of the polyphase and complex Adrar Souttouf Massif with its exotic units (Gärtner et al. 2013a, 2015a) during Ordovician to Devonian times.

Geological setting

Two areas in the Souttoufide belt (Villeneuve et al. 2015) were studied with respect to their Early to Mid-Palaeozoic sedimentary provenance. The Dhloat Ensour unit in the south is located between the Adrar Souttouf Massif, whose oldest yet detected rocks are of Neoproterozoic age (Gärtner et al. 2013a, 2016), and the Tiris Complex and Tasiast-Tijirit Terrane of the southwestern Reguibat Shield (Michard et al. 2010; Villeneuve et al. 2006). The latter is of Neo- to Mesoarchaean age (Chardon 1997; Gärtner et al. 2013a; Key et al. 2008; Montero et al. 2014; Schofield et al. 2012) and locally shows some Siderian intrusions (Bea et al. 2013, 2014). Situated in the northern part of the Souttoufide belt, the Smara Group is a part of the Zemmour-Smara Massif, which itself lies between the southern Neoproterozoic to Early Palaeozoic Tindouf basin, the Sfariat Region of the Reguibat Shield, and the Meso-Cenozoic Layoune coastal basin. In contrast to the Archaean Reguibat basement that forms the foreland of the Adrar Souttouf Massif, the igneous rocks of the Sfariat region are mostly of Rhyacian–Mid-Palaeoproterozoic-age (Meyer et al. 2006; Schofield et al. 2006) and were interpreted to be linked to the Eburnean orogeny (Schofield et al. 2006; Schofield and Gillespie 2007).

The Dhloat Ensour unit

The Palaeozoic sediments of the southern Souttoufide belt are termed the Dhloat Ensour unit (Villeneuve et al. 2006) and trend from SSW to NNE. They occur as a thin, 2–10 km width band over a distance of approximately 200 km. The units of the Adrar Souttouf Massif were thrusted onto the Dhloat Ensour unit, and therefore also onto the basement of the Reguibat Shield. This was first concluded by Sougy (1962), who also recognised an involvement of Devonian limestones and linked this thrusting to the Variscan orogeny. The hypothesis was corroborated by several studies (e.g. Bronner et al. 1983; Rjimati et al. 2002a; Sougy and Bronner 1969). Therefore, the Silurian and Devonian parts of this Palaeozoic sedimentary succession are interpreted as parautochthonous element between the allochthonous Adrar Souttouf Massif and the autochthonous basement of the Reguibat Shield. The Ordovician sediments are regarded as autochthonous cover sequence above the Adrar Souttouf Massif and the Reguibat basement. The Dhloat Ensour unit comprises the Dhloat Ensour Formation, including the Ordovician as well as the Silurian rocks, and the Devonian Bou Leriah Formation (Villeneuve et al. 2015). Rjimati et al. (2002a) introduced an alternative subdivision that distinguishes between the Dlo' al Koursiya Group in the south and the Zamlat al Foula Group in the north of the Awsard-Agalmin Twarta area. The Zamlat al Foula Group is made up of the "lower" (Ordovician), "middle" (Silurian), and "upper" (Devonian) formations, which are similar to the tripartite subdivision presented by Sougy (1962). Although there are no further partitions for the Dlo' al Koursiya Group, both groups show almost the same geologic structure. The rocks of the Dhloat Ensour unit are from base to top as follows (Fig. 2).

Ordovician

The base of these non-fossiliferous sediments consists of sandy conglomerates, that presumably represent the Hirnantian (Late Ordovician) tillite (Destombes et al. 1969; Lécorché et al. 1991; Michard et al. 2010; Rjimati et al. 2002a; Sougy 1969), which itself is covered by cross-bedded sandstones (Rjimati et al. 2002a; Sougy 1962). The succession's middle and upper parts mainly comprise quartzitic sandstones and whitish quartzites with some intercalated vesicular quartzites (Rjimati et al. 2002a). With thicknesses between 20 and 50 m the Ordovician sediments unconformably overly the crystalline basement rocks of the Tiris Complex and the Tasiast-Tijirit Terrane (Rjimati et al. 2002a) of the southern Reguibat Shield.

Silurian

The Silurian succession begins with greyish, ferruginous, bioturbidated sandstones (Rjimati et al. 2002a). They are overlain by intensively fractured pelitic rocks. The upper parts are made of bluish sandstones, whereas the topmost level consists of dark blue, locally bituminous, limestones (Rjimati et al. 2002a; Sougy 1962). Alia Medina (1950) was the first who described Gotlandian (Silurian) *Orthoceras*, which are supplemented by *Cardiola interrupta* and some crinoids (Rjimati et al. 2002a; Sougy 1962). Contrary to the map, the Silurian does not crop out between the Ordovician and Devonian rocks in several places. This is likely caused by a more pelitic composition of the local Silurian rocks, which therefore may have acted as potential surface of gliding during the Variscan thrusting processes (Michard et al. 2010). Thus, the recent maximum thickness of the Silurian deposits is about 100 m (Rjimati et al. 2002a) with a suggested pre-orogenic thickness of 50–150 m (A. Michard, pers. commun. Dec. 2016).

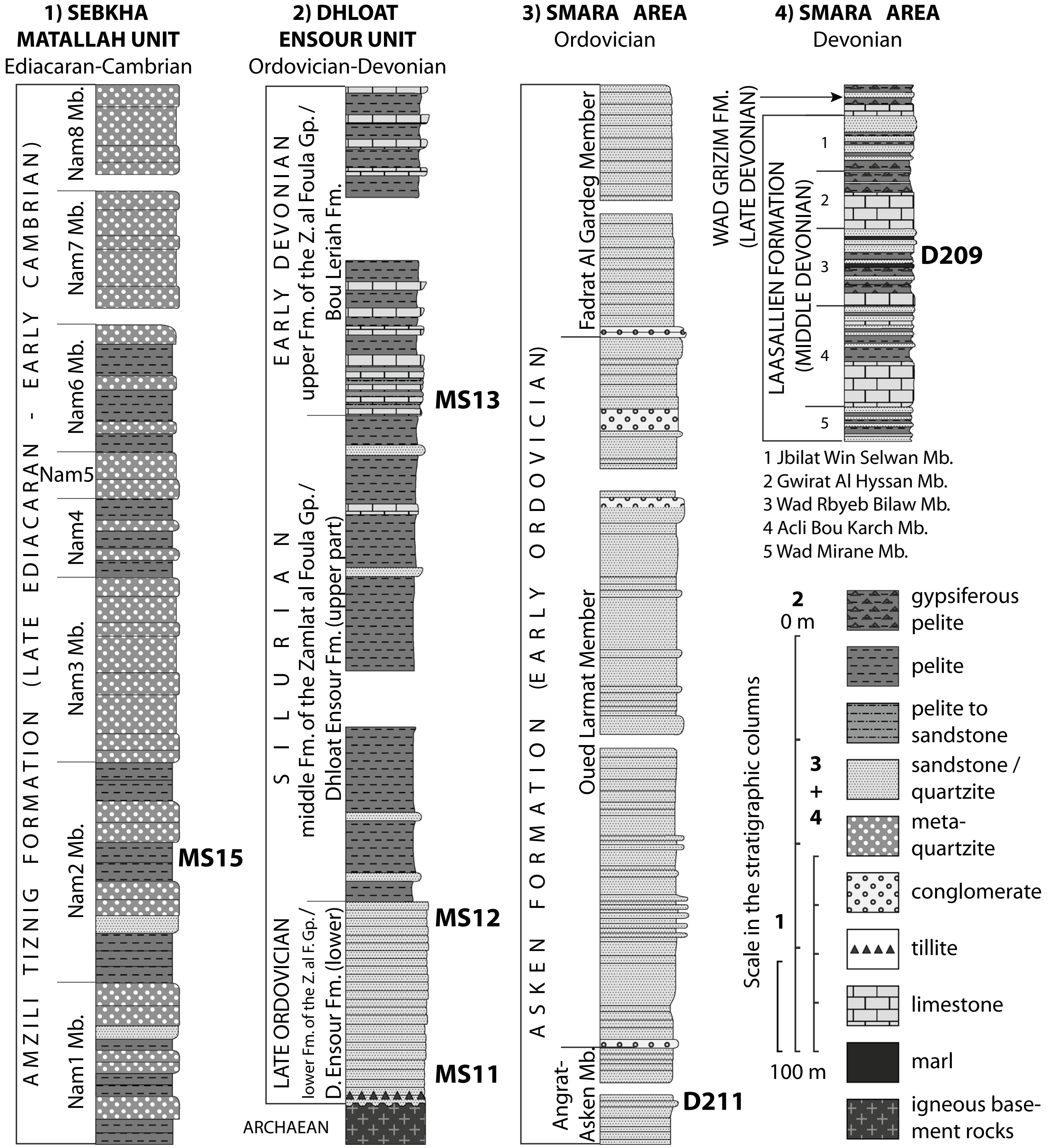


Fig. 2 Generalised stratigraphies of the Late Ediacaran to Early Cambrian sediments of the eastern Sebkha Matallah unit (compiled from Rjimati et al. 2002b and own data), the Late Ordovician to Mid-Devonian Dhloat Ensour unit (Rjimati et al. 2002b; Villeneuve et al. 2015), and the Ordovician (Rjimati et al. 2011b), as well as the Devonian sediments (Rjimati et al. 2011b; Wendt and Kaufmann 2006) of the Smara area. The *numbers* indicate the stratigraphic levels of the samples

Devonian

The base of the Devonian sediments comprises an intercalation of sandy pelites, banks of limestone, and quartzitic sandstone and is characterised by a N-S striking schistosity at its contact to the overlying upper part (Rjimati et al. 2002a). A tectonic doubling of both parts can not be excluded, as they have similar lithologies (Rjimati et al.

2002a). Fossil findings include brachiopods (*Acrospirifer, Tropidoleptus*), crinoids, and *Orthoceras*. Based on this biocenosis, Sougy (1962) attributed these rocks to the Lochkovian, which can be regarded as an analogy to the adjacent Zemmour (Sougy 1964), the Tindouf basin, or the eastern Anti-Atlas (Becker et al. 2004; Hollard 1967). These 100–200 m thick sediments are tectonically overlain by the likely Cambrian Tisnigaten Group sediments (Gärtner et al. unpublished data and sample MS15 of this work) of the eastern Sebkha Matallah unit (Rjimati et al. 2002a).

The easternmost Sebkha Matallah unit of the Adrar Souttouf Massif

The easternmost parts of the Sebkha Matallah unit sensu Villeneuve et al. (2006) are widely characterised by metamorphosed siliciclastic sediments that form the Amzili Tiznig Formation within the Tisnigaten Group (Rjimati et al. 2002a, b, 2011a). This more than 1000 m thick succession comprises eight members termed Nam1 to Nam8 (Rjimati et al. 2002a). They consist of alternating metaquartzites, metagreywackes, metapelites, and chlorite-sericite schists of variable thicknesses and frequencies (Fig. 2). Secondarily grown biotite, chlorite, and sericite in some schists are interpreted to result from the Variscan thrusting of the Sebkha Matallah unit over the Dhloat Ensour unit (Rjimati et al. 2002a). The lack of fossils led Rjimati et al. (2002b) to assume a Neoproterozoic age of these sediments. Preliminary data presented by Gärtner et al. (2015b) and data of sample MS15 indicate an Early Cambrian age (see Discussion below).

The Zemmour-Smara Massif

The Zemmour-Smara Massif is part of the northern Souttoufides (Villeneuve et al. 2015) and can be subdivided into the Zemmour (S) and the Smara (N) areas (Belfoul 2005). Palaeozoic sediments cover large areas and occur in a syncline with a Late Devonian core and Devonian to Ordovician flanks (Service géologique du Maroc 1985). The Palaeozoic realm of the massif itself can be devided into deformed and undeformed parts. The deformed SSW-NNE striking Dhlou-Sekkem belt is situated in the west (Villeneuve et al. 2015) and comprises six units that are separated from each other by thrust faults (Belfoul 2005; Dacheux 1967). Bordered by the Saguiet el Hamra River north of Smara and the Guelta Zemmour to the south, the approximately 600 km long belt, rarely exceeds 25 km in width. Its units form the western flank of the syncline and are interpreted to have been thrusted onto the core domain and the eastern flank of the syncline southeast and east of Smara during the Variscan orogeny (Lécorché et al. 1991; Michard et al. 2010; Villeneuve et al. 2015). The latter area and the Sfariat region of the Reguibat Shield represent the foreland of the Dhlou-Sekkem belt (Villeneuve et al. 2015). The well-exposed southern flank of the Tindouf basin represents the northern and northeastern border of the foreland units. Only few detailed studies about the Zemmour-Smara Massif (e.g. Dacheux 1967; Sougy 1961, 1964; Ratschiller 1971) are available. Rjimati et al. (2002c, 2011b) presented a new 1:100,000 geological map, which complements the earlier works. All following descriptions of the main geological characteristics refer to the northern Dhlou-Sekkem belt and the area around the city of Smara, where all Palaeozoic rocks belong to the Smara Group (Rjimati et al. 2002c). A more detailed description of the entire Zemmour-Smara Massif is given by Villeneuve et al. (2015).

Ordovician

All Ordovician sedimentary rocks in the investigated area belong to the up to 560 m thick Asken Formation of the Dhlou-Sekkem belt (Destombes et al. 1969; Rjimati et al. 2002c, 2011a, b). The lowermost part of the tripartite Asken Formation is the Angrat Asken Member, which is made of an alternating sequence of differently coloured massive and layered quartzites that are topped by a microconglomeratic layer (Rjimati et al. 2011b). The overlying Oued Larmat Member begins with massive greyish quartzites, followed by quartzitic schists, massive quartzites, and alternating layers of sandstones and pelites. In its middle and upper parts, this member comprises an intercalation of sandstones, quartzitic sandstones, quartzites, and locally occurring microconglomeratic layers (Rjimati et al. 2011b). Some of these rocks bear fossils, mostly brachiopodes. The Asken Formation terminates with the Fadrat Al Ghardeg Member, a thick succession of massive quartzites above thin layer of microconglomerates (Destombes et al. 1969; Rjimati et al. 2002c, 2011b).

Silurian

There are no Silurian outcrops in the area of the 1:100,000 geological map of Smara. However, they were found in a core drilled in the west of Smara (Rjimati et al. 2011b). In adjacent areas, the Silurian only occurs in some tens of metres thick layers of graptolite shales (Wendt and Kaufmann 2006).

Devonian

Up to 180 m thick Devonian rocks of the Smara area are subdivided into the Middle Devonian (Eifelian-Givetian) Laasallien and the Late Devonian (Frasnian-Fammenian) Wad Grizim Formations. From bottom to top, the first comprises five members: Wad Mirane, Acli Bou Karch, Wad

Rbyeb Bilaw, Gwirat Al Hyssan, and Jbilat Win Selwan (Rjimati et al. 2011b). Therein, Wendt and Kaufmann (2006) could indentify a sequence of up to six Givetian reef complexes. The Wad Mirane Member comprises alternating gypsiferous pelites and biotubidated sandstones with brachiopods. Coral reef deposits, including polyps, brachiopods, and crinoids form the base of the Acli Bou Karch Member. Its upper parts are composed of intercalated sandstones, pelites and limestones (Rjimati et al. 2011b). The Wad Rbyeb Bilaw Member begins with a thick layer of fosiliferous reddish limestones, similar to the underlying Acli Bou Karch Member. The following sequence is dominated by sandstones and marls. Again, a fossil coral reef, overlain by pelites, marks the base of the next member (Gwirat Al Hyssan). The Laasallien Formation terminates with the Jbilat Win Selwan Member, which is characterised by an intercalation of sandstones and pelites (Rjimati et al. 2011b). No subdivision has been made for the Wad Grizim Formation. The base of the latter consists of reddish limestones with goniatites and is covered by gypsiferous pelites (Rjimati et al. 2002c, 2011b).

Methods

Standard methods for detrital zircon separation and selection were employed for all samples. Detrital zircon ages were obtained by LA-ICP-MS dating at the GeoPlasma Lab at the Senckenberg Naturhistorische Sammlungen Dresden, Germany. Statistical analyses and data processing were done using an EXCEL® spread sheet and Isoplot/Ex 2.49 (Ludwig 2001). Frequency as well as relative probability plots were generated via AgeDisplay (Sircombe 2004). For zircons older than 1 Ga, $^{207}Pb/^{206}Pb$ ages were taken for interpretation, the $^{206}Pb/^{238}U$ ages for younger grains. For further details see paragraphs 3.1 and 3.2 in the supplementary data.

In order to separate zircon from the Devonian limestone sample MS13, 1011 kg of this rock was dissolved in acetic acid (25%). The residues total weight was 5 g, which were subsequently treated like the other samples of this study.

Results

Six sedimentary samples were studied for their detrital zircon record. Beside the radiogenic age determination of 772 grains, of which 417 yielded age values with a concordance between 90 and 110% (=concordant grains), a number of 834 zircons were also investigated with respect to their morphological features. This includes width, length, surface characteristics and roundness as introduced by Gärtner et al. (2013b; Figs. 3, 4, 5), but also the morphology according to Pupin (1980; Fig. 6). The Th–U values given below refer to concordant measurements. All values obtained by the U–Th–Pb LA-ICP-MS measurements including the morphological features of each grain can be found in supplementary table 1, while supplementary Fig. 1 shows examples of analysed zircon grains. Both are available from the journal homepage. A summary the main characteristics is given in Table 1. Results of age determination are depicted in Fig. 7.

D209, N26°41′48.72″, W11°47′04.80″, Middle Devonian red pelites, Smara Group, Laasalien Formation, Wad Rbyeb Belaw Member

A well sorted, red pelite (D209) exhibits parallel bedding and secondary calcite veinlets. The beds dip 75°E with an angle of 65°. The 145 zircon grains from this sample have

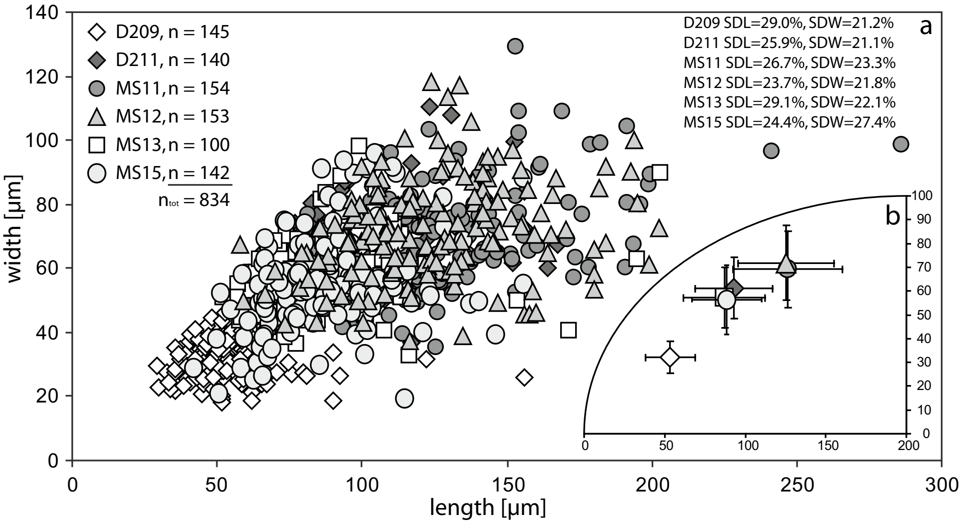


Fig. 3 **a** Length and width values of each zircon grain analysed in this study, **b** average zircon sizes and indication of the standard deviation *black crosses* of each sample (*SDL* standard deviation length, *SDW* standard deviation width)

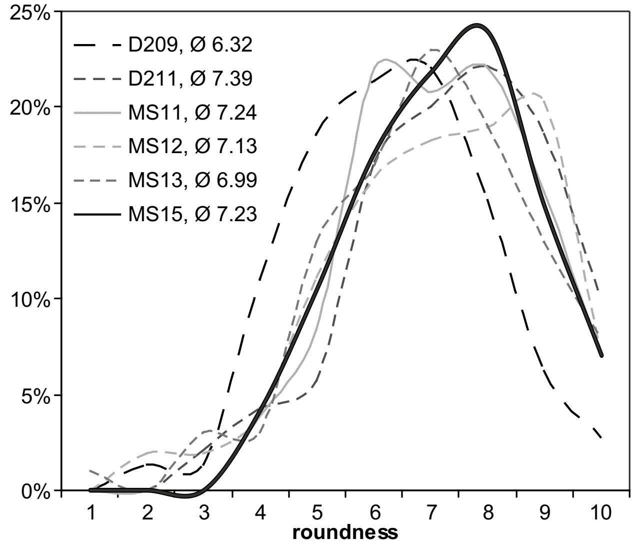


Fig. 4 Distribution and mean values of roundness classes in each sample

mean lengths and widths of 53 and 32 µm, respectively. About 77% of the grains are fairly to very well rounded, but the spectrum comprises all classes except 1. Crystal surfaces are mainly smooth and lack any grains which are totally covered by collision marks. Most of the 61 definable zircon morphotypes are S23, S24, and S25. Forty-one of 102 analysed zircon grains yielded concordant ages between 504 ± 13 and 2357 ± 48 Ma, with the largest group (37%) between 537 and 758 Ma. Eight zircons (~20%) show Mesoproterozoic ages, while 32% are older. Th–U values range from 0.01 to 1.15.

D211, N26°32′48.24″, W11°54′42.72″, Early Ordovician quartzitic sandstone, Smara Group, Asken Formation, Angrat Asken Member

The greyish, highly mature, well sorted quartzitic sandstone D211 shows imprints of brachiopods and remnants of parallel bedding. The 140 extracted zircons exhibit mean lengths and widths of 93 and 61 µm, respectively. Of all grains, 78% are rounded to almost completely rounded, while classes 3–10 were found. Abundance of collision marks grows with increasing roundness. Most of all grains have nearly smooth to scarcely pitted surfaces. Dominant morphotypes are S19 and S22–S25, comprising more than 60% of the 38 definable zircons. Of 128 zircons analysed for their U–Th–Pb isotopic composition, 59 gave concordant ages between 480 ± 14 and 3188 ± 14 Ma, with about 49% of them between 547 and 709 Ma. Four Mesoproterozoic grains could be obtained, while further subpeaks are at 1763–1866 and 1999–2211 Ma. Most Th–U elemental ratios are below 0.60 with seven zircons <0.10 but four grains >1.00.

MS11, N22°40′45.4″, W14°23′05.5″, Late Ordovician (Hirnantian) quartzite, Dhloat Ensour unit, Dhloat Ensour Formation/"lower" Formation, respectively

The brownish-grey, high mature quartzite MS11 lies above the Hirnantian tillite and partly shows cross-bedding, which hints to shallow marine environments. Other parts exhibit features of beach lamination. The beds dip 266°W with angle of 7°. The 154 separated zircos show mean lengths and widths of 126 and 69 µm, respectively. About 65% of the grains are rounded to very well-rounded within classes 4–10. Their surfaces are mainly smooth or show only few collision marks. Some more rounded grains have large numbers of collision marks. The most abundant morphotypes among the 64 definable zircons are S24, S23, and S19. Of 151 zircon grains analysed for their U–Th–Pb isotopic composition, 109 yielded concordant ages from 495 ± 10 to 2705 ± 21 Ma. About 65% of all concordant grains have ages between 536 and 727 Ma with a maximum around 633 ± 3 Ma. Three zircons show Mesoproterozoic ages, while two subpeaks can be found between 1726 and 1847 Ma, as well as in the range of 1968 and 2199 Ma. Th–U values range from 0.08 to 1.90 with a remarkable amount of almost 25% of those grains with values above 1.00.

MS12, N22°40′52.6″, W14°23′20.5″, Late Ordovician (Hirnantian) quartzite, Dhloat Ensour unit, Dhloat Ensour Formation/"lower" Formation, respectively

Quartzite MS12 from the uppermost part of the Ordovician sequence is very similar to MS 11. This rock is sheared but exhibits remnants of cross-bedding. Its beds dip 243°W with an angle of 4°. The 153 zircons show mean lengths and widths of 125 and 72 µm, respectively. Covering all classes of roundness from 2 to 10, 74% of the zircons are rounded to almost completely rounded. Most crystals show no or few collision marks on their surfaces, while more rounded grains generally tend to more pitted surfaces. Morphotypes defined on 59 crystals were mostly S19, S23, and S25. Of these 153 grains, 86 gave concordant ages in a range of 514 ± 11–3159 ± 46 Ma, with 56% of them between 530 and 725 Ma (maximum at 614 ± 4 Ma). Five zircons of Mesoproterozoic age were found. Most of the older grains are grouped around subpeaks between 1758 and 1839 Ma, as well as 1945 and 2178 Ma. Th–U elemental ratios are between 0.09 and 1.41 with only few grains >1.00 and <0.20.

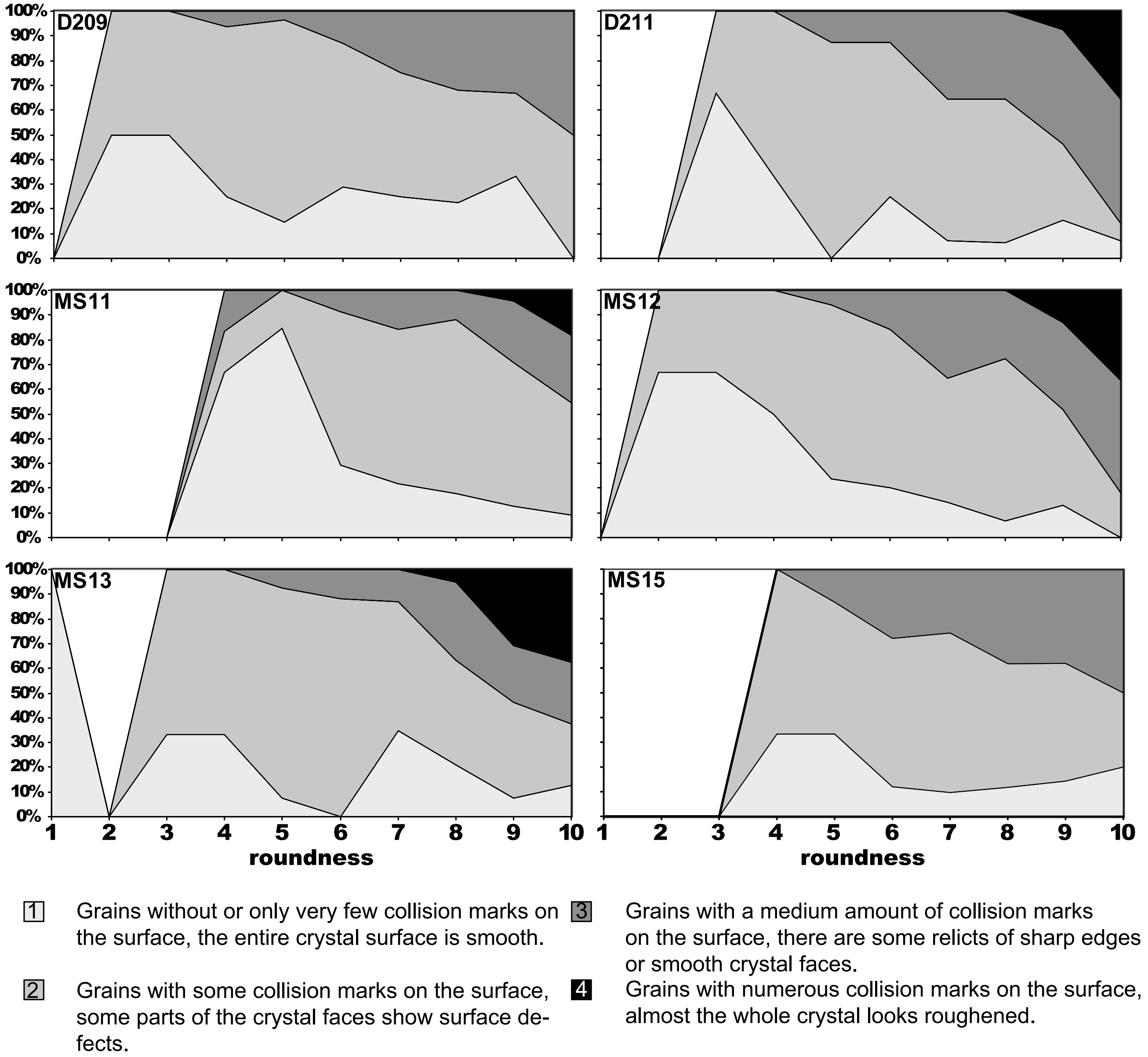
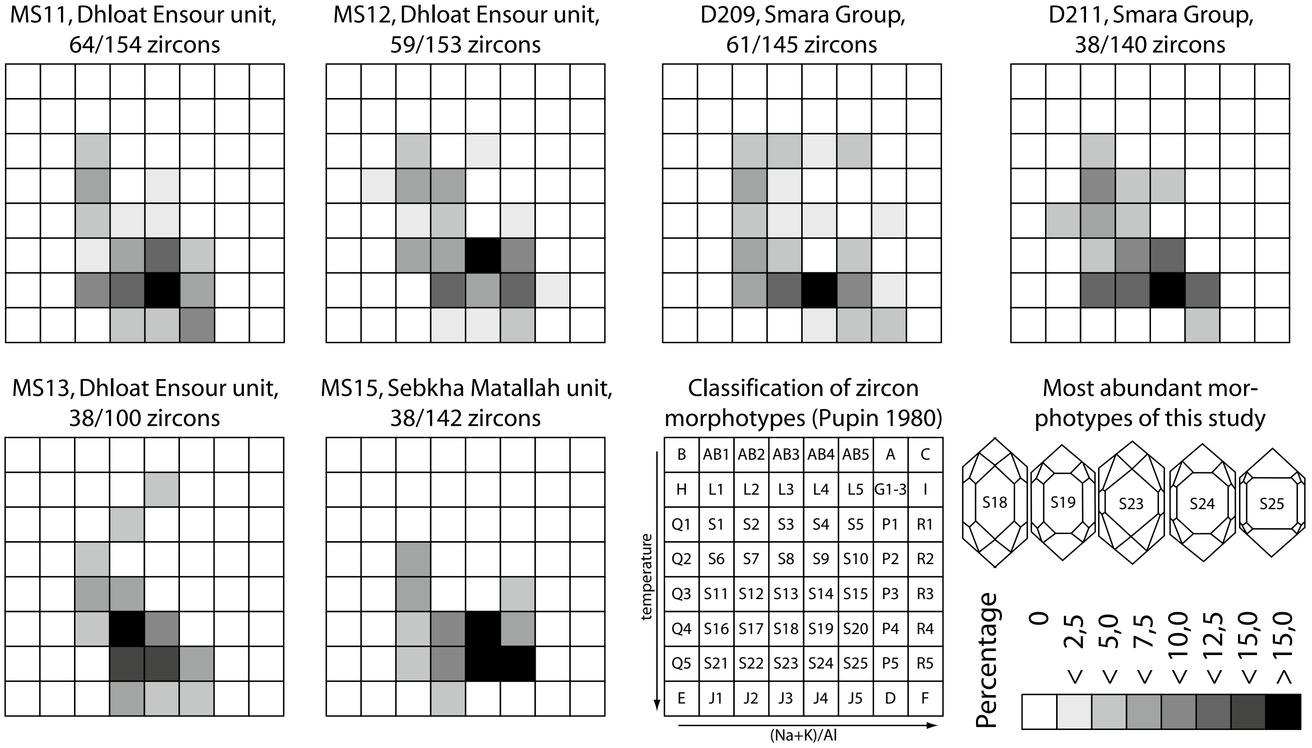


Fig. 5 Distribution of surficial collision marks versus the classes of roundness obtained for each sample

MS13, N22°40′57.8″, W14°23′30.7″, Early Devonian limestone (Lochkovian), Dhloat Ensour unit, Bou Leriah Formation/"upper" Formation, respectively

Reddish-grey limestone MS13 contains abundant fossils of orthoceras and shows irregular veinlets of secondary calcite. Residual material of the limestone is dominated by iron oxide particles, pyrite, few rounded quartz and zircon grains. The beds dip 239°W with an angle of 5°. The 100 zircos have mean lengths and widths of 87 and 57 µm, respectively. Of all grains, 59% belong to classes 6–8, which means rounded to well-rounded. Beside one zircon from class 1, all the other grains belong to classes 3–10. Abundance of surficial collision marks and pits is low, although increasing with proceeding roundness. Morphotypes were identified at 38 grains with S18, S23, and S24 as mainly occurring types. Sixty of 104 analyses resulted in concordant ages between 530 ± 13 and 2855 ± 53 Ma. The largest peak ranges from 530 to 711 Ma and comprises about 33% of the overall concordant zircon grains. Nine zircons (15%) yielded Mesoproterozoic ages, while most of the older ages cluster between 1950 and 2250 Ma. Higly variable Th–U ratios range from 0.15 to 3.82. A comparatively high number of 16 grains have values above 1.00, with nine of them dated between 560 and 671 Ma.



B	AB1	AB2	AB3	AB4	AB5	A	C
H	L1	L2	L3	L4	L5	G1-3	I
Q1	S1	S2	S3	S4	S5	P1	R1
Q2	S6	S7	S8	S9	S10	P2	R2
Q3	S11	S12	S13	S14	S15	P3	R3
Q4	S16	S17	S18	S19	S20	P4	R4
Q5	S21	S22	S23	S24	S25	P5	R5
E	J1	J2	J3	J4	J5	D	F

Fig. 6 Abundance of zircon morphotypes according to Pupin (1980) in each sample

MS15, N22°40′15.9″, W14°24′42.9″, Early Cambrian metapelite, Sebkha Matallah unit, Amzili Tiznig Formation, Nam2 Member

Greenish-grey chloritised metapelite MS15 is not as mature as the other samples, although feldspar is lacking and well-rounded quartz grains are abundant. Additionally, there are often microclasts composed of clay-size particles. The beds dip 292°W with an angle of 17°. Analysed zircons (142) have mean lengths and widths of 88 and 56 µm, respectively. About 63% of the zircons show roundness classes of 6–8, while the remaining grains are from classes 4–10. Any crystals with totally pitted surfaces are lacking. Similar to the other samples, the surficial roughness increases with the roundness. Morphotypes could be distinguished from 38 zircons, with S19, S24, and S25 as most abundant ones. Sixty-two of 134 grains gave concordant ages in a range between 530 ± 10 and 3059 ± 15 Ma. The main peak occurs between 530 and 723 Ma including ca. 37% of all concordant zircons. Nine (15%) Mesoproterozoic ages were found. The vast majority of the remaining grains yielded ages from 1993 to 2220 Ma. Th–U values vary from 0.05 to 0.95, with most of the grains in between 0.20 and 0.70.

Discussion

New U–Pb analyses on zircon indicate that the sediments of the easternmost Sebkha Matallah unit are not of Neoproterozoic age as proposed by Rjimati et al. (2002a, b). Instead, they seem to have been deposited in the Early Cambrian or slightly later, as indicated by their youngest zircons (530 ± 10 Ma). However, fossils have not yet been described from these rocks, which hamper any biostratigraphic correlation. The six Palaeozoic sediments collected from the Aoucert and Smara areas comprise 2.8–19.5% of Mesoproterozoic zircon (Fig. 8). Such ages are not yet known from zircon of igneous rocks within the WAC (Ennih and Liégeois 2008; Fig. 9) and imply an external source for those grains. The majority of the remaining zircon age populations belong either to a Cryogenian-Ediacaran (‘pan-African’) or to a Mid-Palaeoproterozoic (‘Eburnean’) peak. Beside the source of the Mesoproterozoic zircons, the origin of a sub-peak at around 1.8 Ga, an age which is also rare at the WAC, has to be identified. Aiming for a model of Palaeozoic sedimentary fluxes along the western margin of the WAC, a combination of isotopic and morphologic features of the analysed zircon grains, as well as a large zircon database of west and northwest Africa are applied. The use of morphological characteristics is

Table 1 Summary of the most important results of the detrital zircon analyses

Sample	Coordinates	Lithology and stratigraphic position	Age of deposition	Number of grains (total, U-Th-Pb analyses, 90–110% conc.)	Minimum, maximum, and mean width (µm)	Minimum, maximum, and mean length (µm)	Mean roundness (classes 1–10 according to Gärtner et al. 2013b)	Mean surface characteristics (classes 1–4 in % according to Gärtner et al. 2013b)	Most abundant zircon morphotypes according to Pupin (1980)	Youngest grain (90–110% conc.) (Ma)	Oldest grain (90–110% conc.) (Ma)
D209	N26°41′48.72″, W11°47′04.80″	Pelite; Smara Gp., Laasalien Fm., Wad Rbyeb Belaw Mb	Middle Devonian	145 102 41	18 52 32	30 156 53	6.32	24/58/18/0	S23, S24, S25	504 ± 13	2357 ± 48
D211	N26°32′48.24″, W11°54′42.72″	Quartzitic sandstone; Smara Gp., Asken Fm., Angrat Asken Mb	Early Ordovician	140 128 59	37 110 61	57 168 93	7.39	14/50/31/5	S19, S22–S25	480 ± 14	3188 ± 14
MS11	N22°40′45.4″, W14°23′05.5″	Quartzite; Dhloat Ensour unit, Dhloat Ensour Fm/“lower” Fm, respectively	Late Ordovician (Hirnantian)	154 151 109	35 129 69	60 286 126	7.24	27/57/14/2	S19, S23, S24	495 ± 10	2705 ± 21
MS12	N22°40′52.6″, W14°23′20.5″	Quartzite; Dhloat Ensour unit, Dhloat Ensour Fm/“lower” Fm, respectively	Late Ordovician (Hirnantian)	153 153 86	37 118 72	58 202 125	7.13	17/52/26/5	S19, S23, S25	514 ± 11	3159 ± 46
MS13	N22°40′57.8″, W14°23′30.7″	Limestone; Dhloat Ensour unit, Bou Leriah Fm./“upper” Fm., respectively	Early Devonian (Lochkovian)	100 104 (4 rims) 60	33 98 57	52 203 87	6.99	18/57/17/8	S18, S23, S24	530 ± 13	2855 ± 53
MS15	N22°40′15.9″, W14°24′42.9″	Metapelite; Sebkha Matallah unit, Amzili Tiznig Fm., Nam2 Mb	Early Cambrian or slightly younger	142 134 62	19 96 56	42 155 88	7.23	16/54/30/0	S19, S24, S25	530 ± 10	3059 ± 15

particularly useful to distinguish between multiply recycled sediments and newly input material.

As this study is limited to detrital zircon, all the interpretation refers to potential sedimentary fluxes derived from zircon bearing source rocks. Further possible source rocks depleted in zircon may not be detected. This is also valid for already eroded rock formations, which potentially provided material. The almost 46% discordant grains of all dated zircon grains are probably a result of the polyorogenic history of the potential source areas, which likely caused recurrent Pb-loss (Gärtner et al. 2013a; Bea et al. 2013, 2014; Montero et al. 2014; Schofield et al. 2012). However, this is not in conflict to the recommended number of detrital zircon—117 (Vermeesch 2004)—that should necessarily be dated to achieve a 95% certainty not to miss an age fraction ≥0.05 of the total sample, assuming that also discordant age populations bear some relevant information (Reimink et al. 2016). The latter seems to be valid when applied to large datasets as given in Fig. 9. Further, partly controversal discussion of the statistical side of this topic is given in several publications (e.g. Andersen 2005; Fedo et al. 2003; Vermeesch 2004). Additional effects, like sampling, zircon fertility of host rocks or naturally induced bias of the zircon record are discussed elsewhere (e.g. Cawood et al. 2003; Moecher and Samson 2006; Sláma and Košler 2012).

Detrital zircon morphologies and their significance to sedimentary provenance

Several parameters of detrital zircon surface texture are thought to have a significant meaning for provenance analyses (Gärtner 2011, 2013b, c; Mallik 1986; Moral Cardona et al. 2005; Tejan-Kella et al. 1991). In order to test this hypothesis, 834 zircons were analysed with respect to their morphological characteristics. Mean zircon sizes from the six samples show three clearly distinguishable groups (Fig. 3). Although showing different values, the standard deviations for length (23.7–29.1%) and width (21.1–27.4%) within the single samples are almost the same. This is interpreted as a result of well-defined clusters and relatively good sorting. With respect to the sample localities, there are significant differences in the grain size distribution. As the latter is dependent from the energy of the depositing medium (e.g. Allen 1971; McLaren and Bowles 1985; Watson et al. 2013), there seem to have been different environments of sedimentation. The smallest zircons were found in Middle Devonian red pelites (D209) of the Smara area which show mean lengths and widths of 58 and 32 µm, respectively. Those of the Early Cambrian metapelite MS15 of the easternmost Sebkha Matallah unit, the Early Ordovician quartzitic sandstone D211 from the Smara area, and the Devonian limestone from the Dhloat Ensour unit show similar mean lengths between 87 and 90 µm, while mean widths range from 56 to 61 µm. Both of the Latest Ordovician quartzites from the Dhloat Ensour unit are indistinguishable within the errors of their mean lengths of 125 and 126 µm as well as their mean widths of 69–72 µm. These similarities between particular samples are also present with respect to other morphological features.

The ten classes of zircon grain roundness in terms of Gärtner et al. (2013b) are thought to correlate with the energetic dimension that was present during the entire transport process (Köster 1964; Dietz 1973). Accordingly, the roundness of zircon grains is linked to the medium and the distance of their transport achieved during one or more sedimentary cycles (Gärtner et al. 2013b, c; Zoleikhaei et al. 2016). Notably, there are numerous possibilities of rounding independent of any transport. For example, physicochemical processes (Deer et al. 1997; Mager 1981; Tichomirowa et al. 2005), corrosion effects from transporting magmas prior to erosion (Gärtner et al. 2016, and references therein), or pre-rounded grains in S-type granitoids (Roger et al. 2004; Tichomirowa et al. 2001). However, the amount of such grains in sediments is regarded to be rather low (Gärtner et al. 2013b, and references therein). Average roundness values between 6.99 and 7.39 and the distribution of the single classes of roundness are more or less the same for all samples except for D209 (Fig. 4). The latter sample contains only few completely rounded grains and yielded an average roundness of 6.23. Therefore, it has to be assumed that major components of pelite D209 were derived from sources in a closer distance than those in the other samples.

Zircon shows a broad variety of surface characteristics (Gärtner et al. 2013b; Moral Cardona et al. 2005; and references therein). Nevertheless, there are only few studies considering such features (e.g. Tomaschek et al. 2003). Some of them, like collision marks, may have some significance with respect to the medium of transport (Gärtner 2011, 2013b). This applies in particular for zircon grains whose surfaces are almost completely roughened by numerous collision marks (class 4), and which occur preferentially in source areas with eroding glacial deposits (Gärtner 2011; supplement of; Gärtner et al. 2013c). Such features are present in samples D211, MS11, MS12, and MS13 (Fig. 5). All of them, except D211, occur stratigraphically above the Hirnantian tillite (Fig. 2), a fact that corroborates the hypothesis. All grains with extremely pitted surfaces from sample D211 may have been derived from some older—Ediacaran—glacigenic sediments (e.g. Deynoux et al. 2006; Trompette 1973; Vernhet et al. 2012), which likely were subsequently recycled or exposed during the Lower Ordovician. The distribution patterns follow the already mentioned trend. Thus, D209 is significantly different from D211, while MS11 and MS12 are very similar. Except for the extremely pitted grains, the distribution

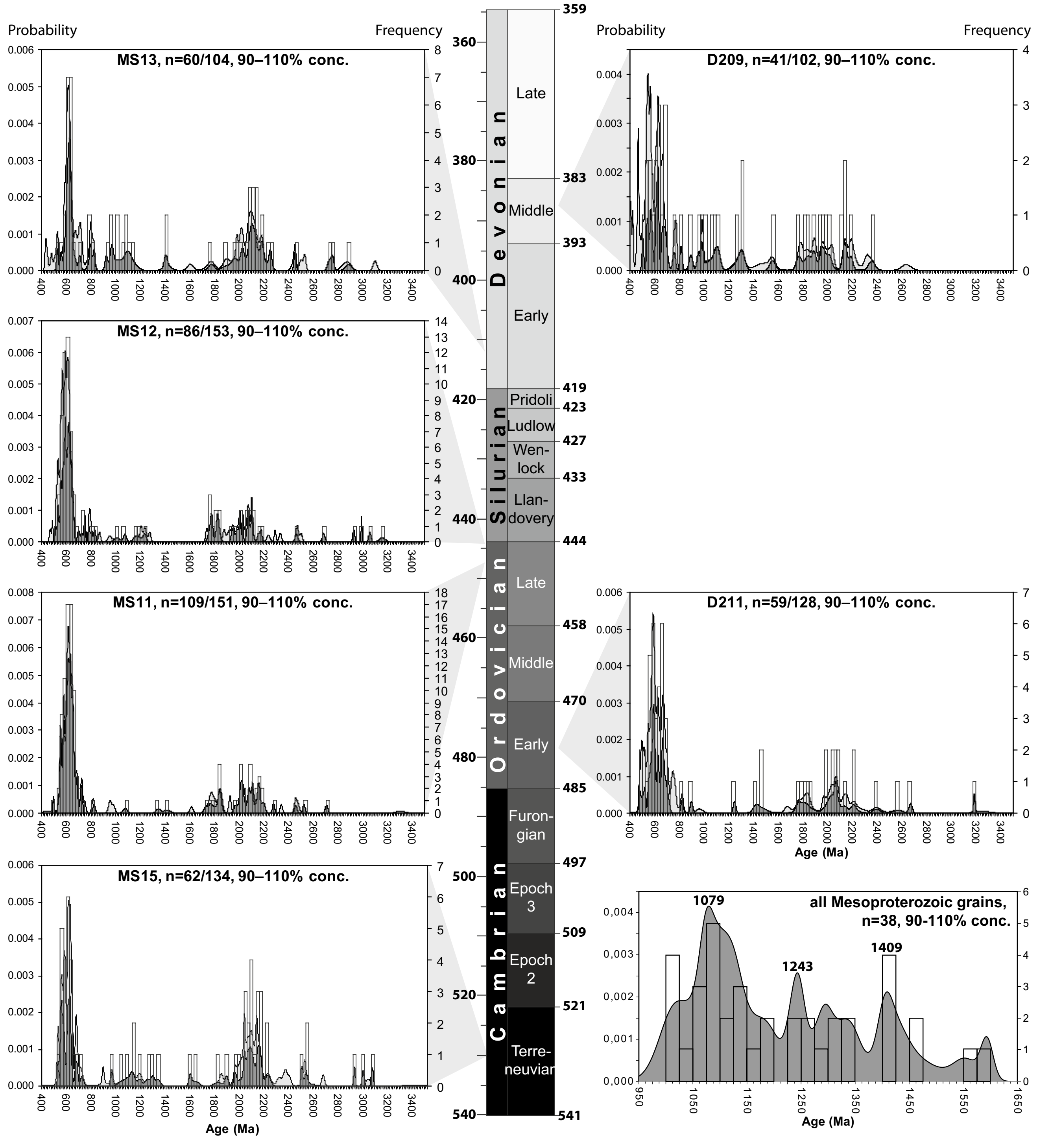


Fig. 7 Binned zircon age frequency distribution plots for all samples of this study (bin width = 25 Ma)

patterns of MS13 and MS15 are also the same (Fig. 5). The absence of grains with a very high number of pits or collision marks in sample MS15 is interpreted to be a result from its stratigraphic position below the Hirnantian tillite level, and lacking exposure or sedimentary input of older glacial sediments during the time of deposition.

Although the morphotypes according to Pupin (1980) are mostly used for the characterisation of igneous rocks (e.g. Siebel et al. 2006; Sturm 2010), there is a growing number of applications for detrital zircon (Anani et al. 2012; Dunkl et al. 2001; Gärtner et al. 2013c; Loi and Dabard 1997; Schäfer and Dörr 1997). Obtained distribution

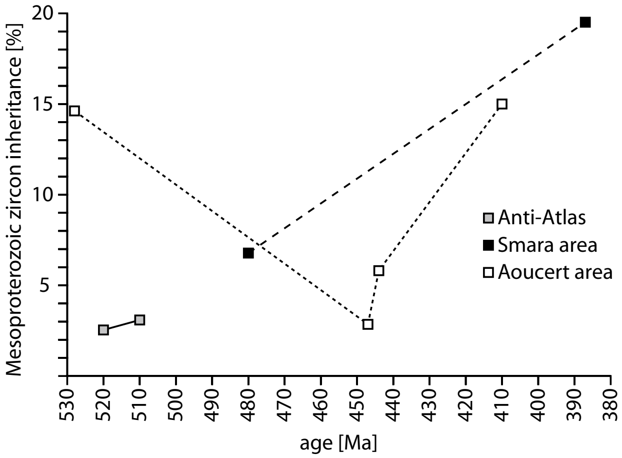


Fig. 8 Abundance of Mesoproterozoic zircon grains in sediments from the lower Middle Cambrian of the Anti-Atlas (Avigad et al. 2012) and the sedimentary rocks of this study

patterns of the morphotypes are comparable in all samples, with the S18, S19, S23, S24, and S25 types as most abundant variations (Fig. 6). Crystals exhibiting such shapes are assumed to be derived from orogenic granitoids of crustal and/or mantle origin (Belousova et al. 2006) and relatively hot melts with approximate temperatures between 800 and 850 °C (Pupin 1980). Zircon grains that are indicative for lower temperatures of crystallisation and mainly crustal origin, e.g. S2, S7, S8 (Belousova et al. 2006; Pupin 1980), were also found in all samples, although less abundant in MS15 (Fig. 6). If linked to the zircon ages, the morphotypes plot in three age-dependent fields (Fig. 10). Notably, the patterns characterised by very large spreads of morphotypes correlate quite well with the Eburnian and Neoproterozoic-Palaeozoic orogenic phases of the WAC. The third, Mesoproterozoic field is dominated by zircons that formed under high temperatures and some mantle contribution (Belousova et al. 2006). There are only few studies that suggest a connection between morphotype distribution pattern and age (Klötzli et al. 2004), but none of them gives data for sedimentary rocks. However, the present data lead to the assumption of at least three main sources: (1) a Neoproterozoic-Palaeozoic ('pan-African') orogenic realm, (2) a Mesoproterozoic source with significant mantle contribution, (3) a Palaeoproterozoic area, which likely was affected by the Eburnean orogeny.

Summarising the observations of surface textures and morphotypes, it has to be inferred that the samples D209 and D211 from the Smara area likely had partially different source rocks, whereas MS11 and MS12, as well as MS13 and MS15 are almost indistinguishable from each other. Nevertheless, the Late Ordovician samples of the Dhloat Ensour unit (MS11, MS12) are different from the Earliest Cambrian (MS15) and Devonian (MS13) samples. All of the studied sediments contain large amounts of very rounded and surficially pitted zircon grains, which indicate a recycling from older sediments with only minor input from freshly eroded igneous rocks.

Potential source areas for different zircon age populations

Based on the morphological studies of the detrital zircon grains (5.1), it is highly likely that the oldest samples of each working area represent recycled material from somewhat older sediments. Therefore, the following analysis of potential source areas does not reflect the sedimentary transport during the Cambrian to Devonian deposition of the investigated sediments, but gives hints to Precambrian source to sink dynamics at the western margin of the WAC. However, such Precambrian reconstructions cannot be part of the present study and will be discussed elsewhere.

Youngest obtained zircons are, with one exception at 480 ± 14 Ma (D211), from the Cambrian. Corresponding occurrences of magmatic rocks are known from the Anti-Atlas (e.g. Compston et al. 1992; Landing et al. 1998; Maloof et al. 2005, 2010) as well as from the Sebkha Matallah unit of the Adrar Souttouf Massif (Bea et al. 2016). Thus, the influence of Anti-Atlas material is suggested to be dominant in the Smara area, while the input from the Adrar Souttouf Massif is supposed as the main contribution in the Dhloat Ensour unit, assuming the existence of volcanic equivalents to the rift-related granitoids of the Sebkha Matallah unit described by Bea et al. (2016). With the beginning opening of the Rheic Ocean in Late Cambrian to Early Ordovician times (Nance and Linnemann 2008, Nance et al. 2010, 2012), the Oued Togba and Sebkha Gezmayet units are supposed to have started to rift away from the WAC (Gärtner et al. 2013a, 2016). Therefore, the plutonic rocks of these units that formed or underwent metamorphism during the Late Cambrian (Gärtner et al. 2013a) may have not provided any zircons for the sediments of this study, because they were likely not exposed at the surface at this time. Nevertheless, it cannot be excluded that some, not preserved, volcanic equivalents of the mentioned plutonic rocks may have contributed few zircons to the Cambrian sediments, e.g. via ash falls, etc.

The Neoproterozoic zircon record of the WAC shows at least two periods. Ediacaran to Mid-Cryogenian zircon ages from igneous and sedimentary rocks of almost all types are quite abundant along the western margin of the WAC (Fig. 9). Thus, they likely represent the preferential host rocks for such zircon grains in both of the studied areas. In contrast, Early Cryogenian to Tonian zircon ages around 800–1000 Ma are only known from some parts of the Anti-Atlas belt (e.g. Kouyaté et al. 2013; Fig. 9) and as detrital component in the Volta Basin (Kalsbeek et al.

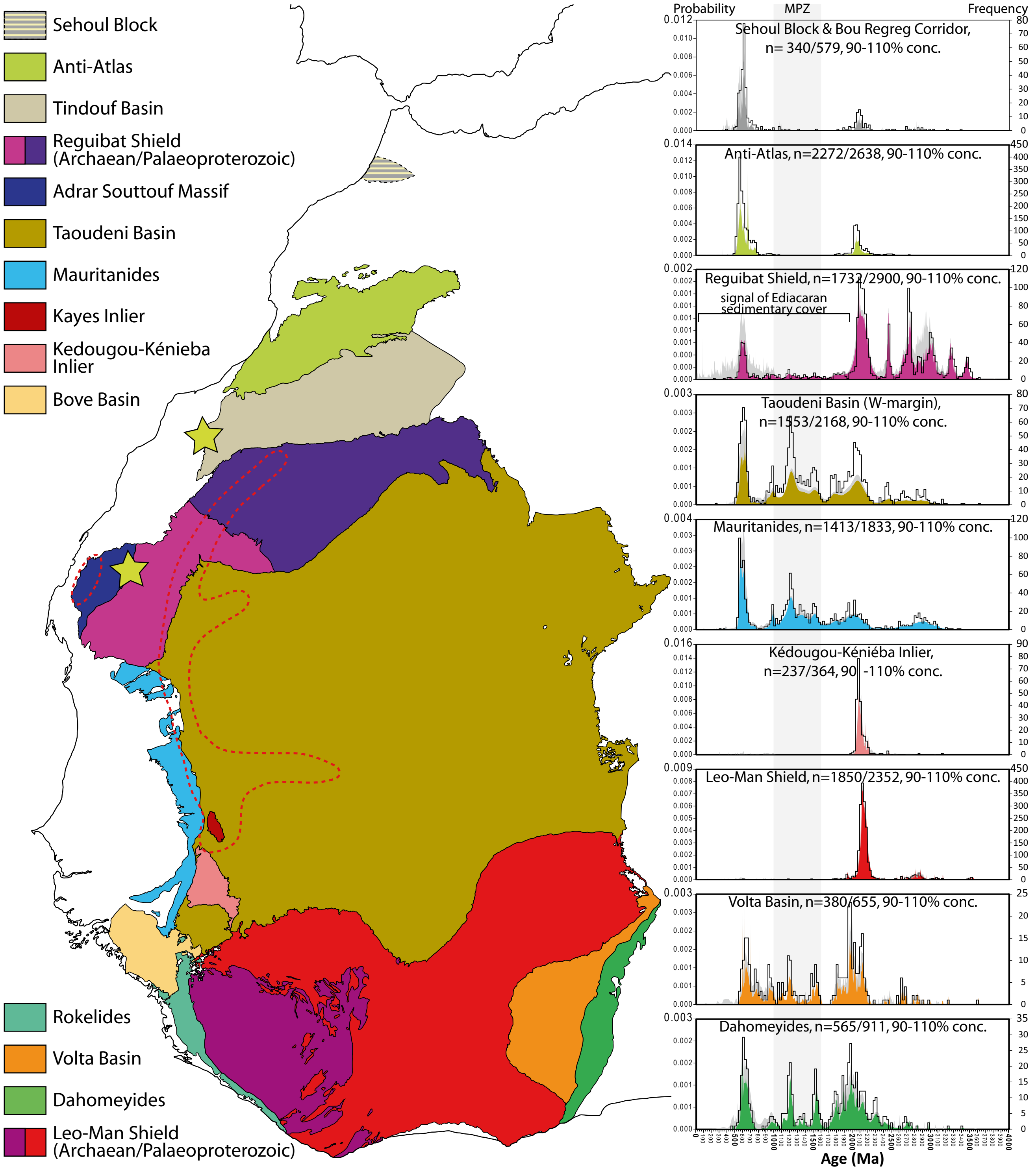


Fig. 9 Main geological components of the West African Craton and its available zircon record ($n = 14{,}400$, MPZ = Mesoproterozoic, *light grey curves* represent discordant analyses). The *stars* mark the working areas of this study, while *dashed lines* show the minimum areal distribution of Neoproterozoic sediment with significant Mesoproterozoic zircon populations inferred from Bradley et al. (2015), Gärtner et al. (2015b) and unpublished data. The cited literature for this compilation is given in the supplement

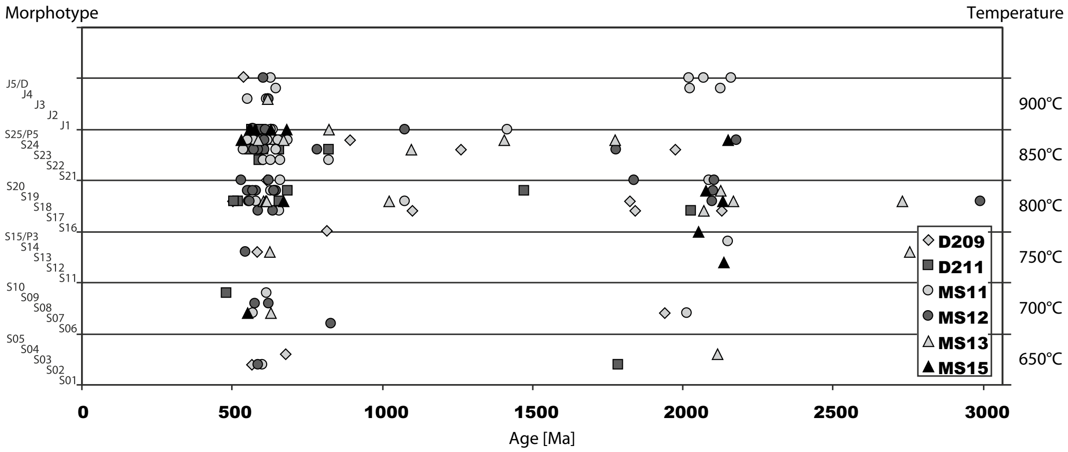


Fig. 10 Distribution of zircon morphotype groups of different temperature indication (Pupin 1980) versus the obtained zircon age

2008). Zircon grains of comparable age form also a very small subpopulation in the (meta-)igneous rocks of the Oued Togba unit of the Adrar Souttouf Massif (Gärtner et al. 2013a) and in the West Avalonian terranes in general (Gärtner et al. 2015a, and references therein).

Mesoproterozoic zircon is very rare at the WAC (Ennih and Liégeois 2008). However, some evidence for scarce magmatic or metamorphic activity was recently found in igneous rocks on other minerals than zircon (El Bahat et al. 2013; Gärtner et al. 2016; Söderlund et al. 2013) and other isotopic systems than U–Pb (Rooney et al. 2010) at some localities in and around the WAC. Several occurrences comprising some Mesoproterozoic zircon of highly variable abundance are known from the western parts of the Adrar Souttouf Massif (Gärtner et al. 2013a, 2015b, 2016), the Neoproterozoic of the Taoudeni Basin around Atar as well as the neighbouring parts of the Mauritanides (Bradley et al. 2015), the Bou-Regreg Corridor (Tahiri et al. 2010), and the lower Middle Cambrian of the Anti-Atlas (Avigad et al. 2012). Recent studies of Meso- and Cenozoic sediments in the Rif, the Middle Atlas, and the South Rifean Corridor gave evidence for further Mesoproterozoic zircon occurrences in northwest Africa (Pratt et al. 2015, 2016). Similar ages are also known from the southern parts of the craton, e.g. very sparsely from the Leo-Man Shield (De Waele et al. 2015; Kristinsdóttir 2013; Tapsoba et al. 2013) and, more abundant from Neoproterozoic sediments of the Volta Basin as well as the Dahomeyides (Kalsbeek et al. 2008). In both of the latter areas, the Mesoproterozoic zircons may are of potential Amazonian provenance (Kalsbeek et al. 2008, 2012). This is in contrast to the northern parts of the WAC, and the Adrar Souttouf Massif in particular. There, a Cryogenian-Ediacaran accretion of Avalonia-like terranes is proposed (Gärtner et al. 2013a, 2016). Furthermore, the West Avalonian terranes contain a significant amount of Mesoproterozoic zircon (e.g. Gärtner et al. 2015a, and references therein) and may have been derived from the peri-Baltica realm (Gärtner et al. 2015a; Henderson et al. 2015; Keppie and Keppie 2014; Thompson and Bowring 2000; Thompson et al. 2012). With respect to the assumed geotectonic evolution of the Adrar Souttouf Massif until the Cambrian, it is highly likely that the majority of the Mesoproterozoic zircon inheritance of the investigated sediments results from erosion of the Cryogenian-Ediacaran (‘pan-African’) orogen, which also included the Oued Togba unit with its significant Mesoproterozoic zircon population (Gärtner et al. 2013a, 2015b). A source for the sediments of the Smara area is very difficult to determine, whereas the lack of knowledge about the local Cambrian sediments as well as their zircon record hampers any comparison. Bradley et al. (2015; Fig. 9) describe likely Ediacaran sediments with remarkable amounts of Mesoproterozoic zircon that cover the Reguibat Shield. Therefore, these rocks are interpreted to be the potential source for at least the Mesoproterozoic zircon age population. A contribution from the Cambrian rocks of the Anti-Atlas is considered as not very likely. The latter have an average Mesoproterozoic zircon inheritance of ca. 2.8% (Avigad et al. 2012), which is only comparable to the value of 2.8% reported for the Late Ordovician sample MS11. However, these values are far away from the Cambrian one of 14.5% (MS15) of the Dhloat Ensour unit or the Ordovician value of 6.8% (D211) of the Smara area (Fig. 8). Nevertheless, the Cambrian sediments of the Anti-Atlas cannot fully be excluded as potential source for Mesoproterozoic zircon inheritance for the Smara area.

Late Palaeoproterozoic, i.e. Statherian zircon ages are as rare as Mesoproterozoic ones all over the WAC, except for the sediments of the Volta Basin and the Dahomeyides (Fig. 9). However, few zircons around 1.6 Ga are present in metapelite MS15, whereas ages at approximately 1.8 Ga occur in all samples of this study (Fig. 7). Few igneous bodies of that age have been found yet in the Anti-Atlas (Kouyaté et al. 2013; Youbi et al. 2013). But such ages are a typical component of the West Avalonian terranes as compiled by Gärtner et al. (2015a), and were found in the Oued Togba unit of the Adrar Souttouf Massif as well (Gärtner et al. 2013a). Therefore, the latter unit is the preferential source area for these Statherian grains, at least for the Aoucert area. A significant age peak at about 2.0–2.2 Ga was found in all investigated sediments and is mostly interpreted to be a result of the Eburnean orogeny, which affected large parts of the WAC (Baratoux et al. 2011; Egal et al. 2002; Schofield et al. 2006). Eburnean basement occurs at the eastern part of the Reguibat Shield (Peucat et al. 2005; Schofield et al. 2006) and in several of the Anti-Atlas inliers that are located south of the Anti-Atlas Major Fault (e.g. Gasquet et al. 2004; Kouyaté et al. 2013; Walsh et al. 2002). Further outcrops of this age are known in the Kédougou-Kéniéba Inlier (Dia et al. 1997; Hirdes and Davis 2002) and on large parts of the Leo-Man Shield (e.g. De Kock et al. 2011; Hirdes et al. 1996; Tapsoba et al. 2013), but not in the vicinity of the Adrar Souttouf Massif. Nevertheless, 'Eburnean' zircons were found in many sedimentary rocks around the studied areas, particularly in the Anti-Atlas (Fig. 9), as well as inherited component in the western units of the Adrar Souttouf Massif (Gärtner et al. 2013a). Accordingly, the 2.0–2.2 Ga zircon age population in the Smara area is interpreted to originate either from the neighbouring areas of the Reguibat Shield (Schofield et al. 2006) or from sediments containing detrital zircons from the 'Eburnean' Anti-Atlas Inliers (e.g. Gasquet et al. 2004; Walsh et al. 2002), while the source of such grains in the Aoucert area may have been additionally derived from the Western units of the Adrar Souttouf Massif (Gärtner et al. 2013a). All older zircon grains of the entire sample set are supposed to have a Reguibat Shield provenance. This is because of ages between 2.4 and 3.2 Ga that are well known from the neighbouring Tiris and Tasiast-Tijirit complexes (Bea et al. 2013, 2014; Gärtner et al. 2013a; Key et al. 2008; Montero et al. 2014; Schofield et al. 2012), but are not yet reported from the Anti-Atlas and other neighbouring regions of the study areas. Few of such zircon ages have been reported by Gärtner et al. (2013a) from the Oued Togba and Sebkha Gezmayet units of the Adrar Souttouf Massif and may also provide some minor contribution.

Implications for the Early and Mid-Palaeozoic palaeogeography and sedimentary transport processes

The morphological features of the zircon grains and the high maturity of the investigated rocks hint to a dominant reworking of sediments and only minor input from freshly weathered igneous sources. Striking similarities between the morphological features of detrital zircon in samples MS15 (Early Cambrian) and MS13 (Devonian), as well as MS11 (Late Ordovician) and MS12 (Latest Ordovician) led to the assumption of analogue provenance or reworking of the same material, respectively. Samples D209 (Mid-Devonian) and D211 (Early Ordovician) show some similarities, but not as distinct as the other ones. These relations were also found in the zircon age record and are expressed using the Kolmogorov–Smirnov (K–S) test, where a value of difference (*D*) is correlated to a value of sample size-dependent probability (*P*). If *P* is >0.05, it is assumed that the compared samples have more or less identical sources (Lovera et al. 2008; Shaw et al. 2014; Fig. 11). Except for the Tonian, Mesoproterozoic, and Statherian zircon grains, all the other age groups can be found in the vicinity of the studied areas (Fig. 9). However, the former mentioned age populations are interpreted to indicate some sedimentary input from the Oued Togba and Sebkha Gezmayet units of the Adrar Souttouf Massif, as they are very close. Other potential sorces for Mesoproterozoic zircon are the Toudeni basin around Atar, the Mauritanides, the Neoproterozoic cover of the Reguibat Shield (Bradley et al. 2015), or similar, yet unknown equivalents.

A general model of the early Palaeozoic sedimentary transport for the Aoucert area starts in the Early Cambrian (Fig. 12). At this time, erosion of the sedimentary cover of the Cryogenian-Ediacaran ('pan-African') orogen including the proto-Oued Togba and proto-Sebkha Gezmayet units likely provided significant Mesoproterozoic, but also considerable WAC zircon age populations (Gärtner et al. 2013a, 2015b) to the foreland basin represented by the Sebkha Matallah and Dhloat Ensour units. Ongoing erosion of the WAC, which may had a sedimentary cover comparable to the Taoudeni Basin (Bradley et al. 2015; Lahondère et al. 2003; Rooney et al. 2010; Trompette 1973), presumably delivered many of the characteristic zircon age groups older than 1.8 Ga (Figs. 7, 9). A result of this basin fill from at least two sources is an assumed

	D209	D211	MS13	MS12	MS11	MS15
D209		0.254	0.254	0.039	0.008	0.089
D211	0.254		0.096	0.768	0.451	0.101
MS13	0.254	0.096		0.026	0.001	0.894
MS12	0.039	0.768	0.026		0.823	0.026
MS11	0.008	0.451	0.001	0.823		0.002
MS15	0.089	0.101	0.894	0.026	0.002	

Fig. 11 *P* values of the Kolmogorov–Smirnov test for all studied samples. Note that $P < 0.001$ is characteristic for a statistically significant difference, $0.05 > P > 0.001$ identifies no statistically significant difference, while samples with $P > 0.05$ are interpreted to show a statistically significant similarity

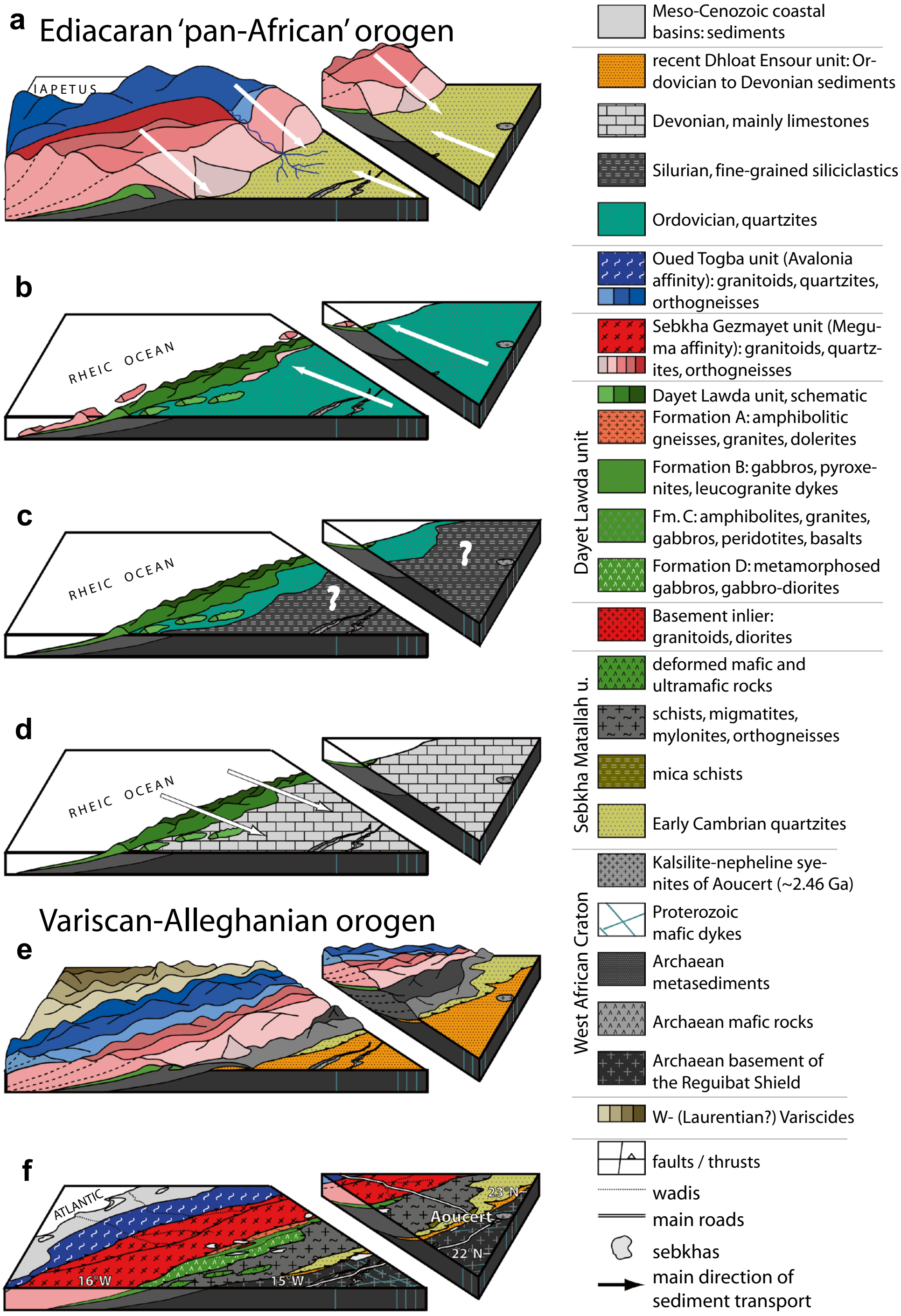


Fig. 12 Possible model for the Palaeozoic sedimentation in the Aoucert area: **a** Early Cambrian: erosion of the Ediacaran 'pan-African' orogeny and deposition of the Amzili Tiznig Formation on *top* of the Sebkha Matallah unit and likely further east. Initial rifting of the proto-Oued Togba and proto-Sebkha Gezmayet units took place in the Late Cambrian. **b** Ordovician: reworking of distal Cambrian sediments and accumulation of material from the West African Craton; erosion of potential remnants of the rifted precursor of the Sebkha Gezmayet and Oued Togba units. **c** Silurian: deposition of marine pelites and sandstones of yet not known provenance and areal distribution. **d** Early Devonian transgression onto the West African Craton, deposition of shallow marine limestones with detritus likely derived from reworked Cambrian sediments. **e** Variscan orogeny, thrusting of the Sebkha Matallah unit over the Dhloat Ensour unit. **f** Recent situation

decrease of Mesoproterozoic zircon inheritance in the Early Cambrian sediments towards the east, caused by increasing dominance of typical WAC detritus.

The proto-Oued Togba and proto-Sebkha Matallah units are supposed to have been already rifted away from the WAC margin during the opening of the Rheic Ocean (Gärtner et al. 2013a, 2016). Bea et al. (2016) do also report Late Cambrian rift-related magmatism in the Derraman complex of the Sebkha Matallah unit. Accordingly, the 511–517 Ma intrusions and potential metamorphic overprint at about 506 Ma (Bea et al. 2016; Gärtner et al. 2013a) on both sides of the Adrar Souttouf Massif narrow the time of rifting down to Late Cambrian times. This is in line with the general view of the post-pan-African geotectonic evolution of Avalonia and Meguma (Landing 2005; Murphy et al. 2010; Nance et al. 2012; Satkoski et al. 2010). Thus, the supply with material of these two units was terminated at this time. There are no known outcrops or drillings in the Smara area that indicate the presence of Cambrian sediments (Rjimati et al. 2011b; Villeneuve et al. 2015), and even in the vicinity there is no clear evidence for such rocks (Sougy 1964). The oldest Palaeozoic sediments belong to the Early Ordovician Angrat-Asken member (Figs. 1, 2). Therefore, an erosive event at the Early Ordovician is supposed for the Smara area. As its sediments directly overly the Archaean basement of the Reguibat Shield (Rjimati et al. 2002a, b), the Hirnantian glaciation (Delabroye and Vecoli 2010; Ghienne 2003, 2007b) may have abraded the (thin?) cover of older sediments in the Aoucert area. This is corroborated by the hypothesised direction of sedimentary transport during the glaciation, which was directed to the margins of the WAC and likely was caused by glacio-eustatic lowstand (Ghienne et al. 2007b; Saltzman and Young 2005). Under this assumption, the Ordovician sediments would have been derived from the interior of the WAC and recycled the Cambrian deposits, which were distal of the Adrar Souttouf Massif and depleted in Mesoproterozoic zircon. The Ediacaran cover sequence of the Reguibat Shield (Bradley et al. 2015) does not seem to have distributed major amounts of sediments at this time, as the amount of Mesoproterozoic zircon is comparatively low. Such a shift in provenance with respect to the Cambrian and Devonian sediments is also visible in the morphology (Figs. 3, 4, 5, 6) and the similarity of the zircon age distribution patterns (Figs. 7, 11).

As no absolutely certain Silurian rocks were identified during the fieldwork, we can not give any model approach for that interval of time. The Early and Middle Devonian is characterised by widespread transgression and deposition of shallow marine sediments in numerous places along WAC western margin (Guiraud et al. 2005; Wendt and Kaufmann 2006), and particularly in the investigated area. However, those areas that were affected by processes which led to platform dislocation during the Early-Middle Devonian were characterised by deeper marine sedimentary conditions (Baidder et al. 2008, 2016; Frizon de Lamotte et al. 2013; Michard et al. 2008; Wendt 1985). In the course of this transgression there likely was some reworking of the Cambrian sediments in the Aoucert area (Fig. 12), as well as some input of comparable material to the Smara area. This can be deduced from the very similar zircon morphological features and the extremely high conformity of the zircon age spectra in samples MS15 and MS13, and, with some more variation, even in sample D209. The recent situation with an overthrusting of the eastern Sebkha Matallah unit onto the Dhloat Ensour unit is a result of the Variscan-Alleghanian tectonics (Fig. 12).

Conclusion

The Palaeozoic sediments at the western margin of the WAC are a well preserved archive for geotectonic, palaeogeographic, and sedimentological processes. Therefore, morphological and isotopic investigations on detrital zircon from siliciclastic sediments and limestone of the Aoucert and Smara areas led to a model of sedimentary transport for the marginal regions of the northwestern part of Gondwana. In the Aoucert area, a significant amount of detrital zircon was likely transported from the western Oued Togba and Sebkha Gezmayet units as well as from the WAC to a basin in between both of the hypothesised main source areas during the Cambrian. Overlying Ordovician sediments clearly show the disappearance of the likely Avalonia and Meguma related terranes of the Adrar Souttouf Massif as detrital zircon source in the course of the proceeding opening of the Rheic Ocean. A reworking of the Cambrian sediments is suggested in the course of Devonian transgression onto the WAC. This is also a potential model for the Smara area. However, lacking Cambrian sediments with absence of any detrital zircon information hamper a more detailed reconstruction.

The present study shows that not only siliciclastic sediments are suitable for provenance studies. The Devonian limestones of the Dhlaot Ensour unit may represent an exception with respect to the concentration of detrital zircon. Nevertheless, the general feasibility of limestones for detrital zircon studies is obvious and opens many new possibilities for palaeogeographic and sedimentary flux reconstructions. Finally, the extension of zircon studies to morphological features of many individual grains is regarded as a valuable tool to obtain additional information on sedimentary provenance and recycling.

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