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RESEARCH PAPER

# Sandstone mounds from the Ordovician of the Central Iberian Zone, Spain

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## Abstract

Sandstone mounds (*sensu* Bradshaw in Sedimentology 7:149–154, 1966) are sedimentary structures formed by fluid erosion of sands consisting of systems of variously shaped mounds, ridges and gullies preserved on the upper surface of sandstone beds. Sandstone mounds are here reported from the Armorican Quartzite Formation and Marjaliza beds, Extremadura, and the Pochico Formation of Ciudad Real. These are the first reports of this sedimentary structure from the Ordovician of the Central Iberian Zone, southwest Spain, adding to the scarce global record of this sedimentary structure. A literature review reveals no reports of sandstone mounds from rocks younger than the Devonian Period, with the majority coming from Ordovician rocks located on the Gondwanan margin of the Rheic Ocean. It is probable that sandstone mounds exist in younger rocks but secular changes in sediment properties and favourable shelf configuration are alternative explanations for this pattern.


**Keywords** Sandstone mounds · Ordovician · Spain · *Skolithos* · Sedimentology

### "Sandstone mounds" del Ordovícico de la Zona Centroibérica, España


## Resumen

Los "sandstone mounds" o monticulos arenosos (*sensu* Bradshaw en Sedimentology 7:149–154, 1966) son estructuras sedimentarias formadas por erosión de fluidos sobre arenas. Consisten en sistemas de montículos, crestas y depresiones de forma variada, preservados en la parte superior de las capas de arenisca. En este estudio se describen "sandstone mounds" en la Formación Cuarcita Armoricana y en las Capas de Marjaliza, Extremadura, y en la Formación Pochico de Ciudad Real. Son las primeras citas de estas estructuras en el Ordovícico de la Zona Centroibérica, suroeste de España, añadiéndose al escaso registro global de estas estructuras sedimentaria. Una revisión bibliográfica revela que no existen citas de "sandstone mounds" en rocas más modernas que el Devónico y que la mayoría proceden de rocas ordovícicas situadas en el margen gondwánico del Océano Reico. Es probable que existan "sandstone mounds" en rocas más modernas, aunque cambios seculares en las propiedades de los sedimentos y una configuración favorable de la plataforma podrían ser explicaciones alternativas para este patrón.


**Palabras clave** Sandstone mounds · ordovícico · España · *Skolithos* · sedimentología

## 1 Introduction

Sandstone mounds (*sensu* Bradshaw, 1966) are erosional relics preserved on the upper surface of sandstone beds, formed by fluid erosion of sand generating gullies defining variously shaped mounds and ridges (e.g., Baldwin & Johnson, 1977). In the French language, they are known as "pains de grès" (sand breads; Macar & Ek, 1965) or, more commonly, "brioches" (a type of bun; e.g., Durand, 1985), terms that well describe the morphology of the mounds. Sandstone mounds have been interpreted as formed by current-induced erosion during subaerial emergence in a tidal environment (e.g., Baldwin & Johnson, 1977; Durand, 1985), but also by storm-related erosion (Goldring & Langenstrassen, 1979;

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Hiscott, 1982). In both scenarios, undercuts in the sides of the mounds suggest that the sand was sufficiently cohesive at the time of erosion to prevent collapse.

Documentation of sandstone mounds is rare, but includes reports from the upper Cryogenian of northern Norway (Baldwin & Johnson, 1977), the Ordovician of France (Bradshaw, 1966; Durand, 1985), and northern Spain (Baldwin & Johnson, 1977), and the Devonian of France (Macar & Ek, 1965).

In the present paper sandstone mounds are documented for the first time from Ordovician rocks of the Central Iberian Zone, southern Spain. Sandstone mounds from the Lower Ordovician Armorican Quartzite Formation, near Guadalupe, Extremadura, are described in detail, and additional occurrences from the Middle Ordovician Marjaliza beds, Extremadura, and the Pochico Formation, Ciudad Real, are briefly described. The global record of sandstone mounds is tabulated and the temporal and palaeogeographical patterns are briefly discussed.

## 2 Sandstone mounds in the Armorican Quartzite Formation near Guadalupe, Extremadura

### 2.1 Geological setting and stratigraphy

Sandstone mounds were found on bed surfaces of the Armorican Quartzite Formation near Guadalupe, Extremadura, Spain (Fig. 1a). The study area is located in the southern part of the Central Iberian Zone (Fig. 1b), within a Variscan topography of tight synclines and open anticlines. The Armorican Quartzite Formation consists of thin- to thick-bedded fine- to coarse-grained quartzarenite with minor shale, which formed on a passive margin of Gondwana affinity in the Rheic Ocean. This type of facies is widely distributed in Spain, Portugal and France, where it is known as Armorican Quartzite Formation, Grés Armoricain Formation, Armorican Sandstone Formation, Penha Garcia Formation, Barrios Formation, and many other regionally named units (e.g., Bayet-Goll & Neto de Carvalho, 2020; Gutiérrez-Marco et al., 2019; Hamman et al., 1982). Within the Central Iberian Zone thickness ranges from 5 to 500 m. In many areas of Spain and France the Armorican Quartzite Formation can be divided into sandstone-dominated lower and upper parts, separated by a muddier heterolithic middle part (e.g., Dabard et al., 2009; Durand, 1985; Julivert & Truyols, 1983; Rey & Hidalgo, 2004). Rey and Hidalgo (2004) interpreted the sandstone-dominated parts of the Armorican Quartzite, with thick-bedded (metre–decametre) planar to trough cross-bedding as proximal shoreface deposits, and the muddier parts with well developed Cruziana ichnofacies trace fossils as distal shoreface and inner shelf. Bayet-Goll and Neto de Carvalho (2020) interpreted the Armorican Quartzite facies in the Penha Garcia area of Portugal as comprising different wave and river-dominated deltaic facies with strong storm influence.

Based on *Cruziana* ichnostratigraphy, and age constraints from fossils in overlying units the Armorican Quartzite within the Central Iberian Zone has been assigned to the

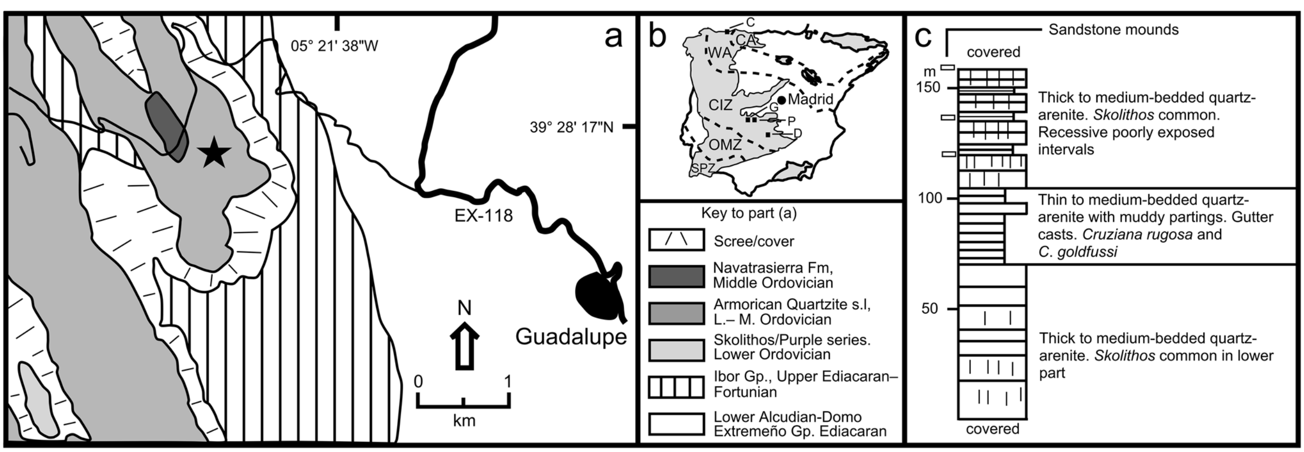


**Fig. 1** Geographical and geological context of Ordovician sandstone mounds in Spain. **a** Geology of study area near Guadalupe, Extremadura, simplified from IGME (1985a). The location of sandstone mounds in the northern flank of the Río Viejas syncline is indicated by a star. Location of the study area within the Iberian Peninsula is indicated by a G in **b**. **b** Map of the Iberian Peninsula showing tectonostratigraphic zonation and the Iberian Massif (grey shading). Localities with sandstone mounds (black boxes) in the Central Iberian Zone (CIZ) are; Guadalupe (G), Puerto de San Vicente (P), and Puebla de Don Rodrigo (D). Sandstone mounds in the West-Asturian Leonese Zone (WA) of northern Spain (C) from Baldwin and Johnson (1977). *CA* Cantabrian Zone, *OMZ* Ossa-Morena Zone, *SPZ* South Portugues Zone. **c** Schematic measured section of the Armorican Quartzite Formation, in the study area. Levels with sandstone mounds are indicated by bars

Arenigian regional scale, which is upper Floian to lower Dapingian (Lower to Middle Ordovician) in global chronostratigraphy (Gutiérrez-Marco et al., 2017, 2019).

Within the study area the Armorican Quartzite rests disconformably on the late Ediacaran to basal Cambrian Ibor Group or, conformably or paraconformably, on a Lower Ordovician micaceous siliciclastic sequence of conglomerate, sandstone and shale characterized by abundant *Skolithos*.

The transition from the Armorican Quartzite Formation into the overlying shaly and locally highly fossiliferous Middle Ordovician Navatrassiera Formation, is gradational and represented by thin-bedded siliciclastics of the Marjaliza beds. In the study area the Marjaliza beds are poorly exposed and are not differentiated on the 1:50,000 geological map (IGME, 1985a).

## 2.2 Material and section studied

Bedding surfaces with sandstone mounds were found on the northern flank of the NW–SE trending Río Viejas syncline, about 5 km NWW of Guadalupe (Fig. 1a). Sandstone mounds were not found in the western continuation of the northern flank of the Río Viejas syncline. Small-scale faults are abundant and the outcrop is not continuous but approximately 150 m of Armorican Quartzite Formation was logged (Fig. 1c), having scree-covered contacts with both under- and overlying rocks.

The lower 60 m of the section consists of thick to medium bedded quartzarenite with *Skolithos* abundant particularly in the lower part. This is followed by approximately 30 m of thin-bedded sandstone with shaly partings (Fig. 2a), with thicker sandstone beds towards the top. Sedimentary structures in the lower part of this interval include gutter casts. Trace fossils are generally well preserved and include *Cruziana rugosa* (Fig. 2d) and *C. goldfussi*. This interval is in turn followed by about 40 m of mostly thick- to-medium bedded quartzarenite with abundant *Skolithos* (Fig. 2b, c, e, f). Finer grained and thinner bedded intervals generally show recessive weathering, are not well exposed and are largely covered in soil and vegetation.

Seven sites with sandstone mounds were identified (Supplementary Fig. 1), all from the upper to uppermost part of the Armorican Quartzite Formation (Fig. 1c). Exact stratigraphic placement is complicated by faults and covered parts of the section but the principal sandstone mound surfaces are assigned to three horizons, located at 120, 135 and 160 m in the measured section, in all cases being surfaces

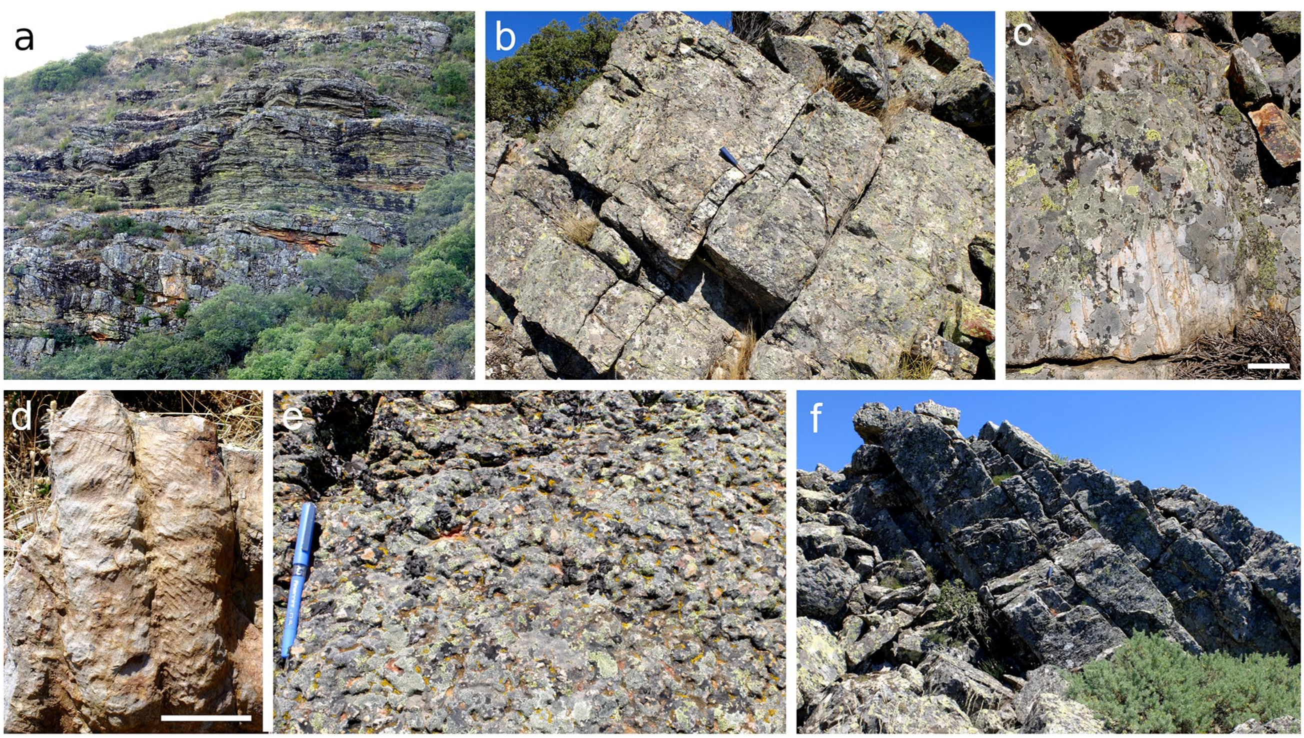

**Fig. 2** Outcrops and trace fossils in the Armorican Quartzite Formation. Locations refer to Supplementary Fig. 1. **a** Transition from thick-bedded to thin-bedded sandstone in the southern end of the syncline, corresponding to approximately 50–100 m in measured section. **b**, **c** Thick-bedded *Skolithos*-rich facies from 110 m at location 7. Hammer in **b** is 28 cm, scale in **c** is 5 cm. **d** *Cruziana rugosa* in loose block at about 90 m. **e** Upper surface of sandstone bed densely covered with *Skolithos* from locality 7. Pen is 13.5 cm. **f** Thick-bedded facies at about 150 m

that culminate thick-bedded intervals and are followed by a recessive interval.

The sandstone mounds did not undergo significant post-Ordovician deformation and retain their bedding parallel configuration. This can be inferred from the lack of distortion of trace fossils, such as *Cruziana* (Fig. 2d), in the section studied.

## 2.3 Description

Sandstone mounds range from nearly circular (Fig. 3c) to highly elongated in plan view (Fig. 4c). They have a relief of up to 10 cm, with sides that are vertical, or may be over-steepened (Fig. 3b) and be undercut (Fig. 5d). The sandstone mounds are located within broad shallow depressions, parallel in orientation to the long axes of elongate mounds (Figs. 4a, 5b). The base of the recessed area is approximately 20 cm lower with respect to the top of the bed on the 120 m surface. On the 120 m surface the long-axis orientation of the mounds has an approximately N–S strike. Sandstone lamination is seen along the margins of mounds due to differential resistance to weathering (Fig. 4b), and sandstone mounds may have a flat top where the sandstone has split along lamination (Figs. 4b, 5d).

The vertically oriented tubular trace fossils *Skolithos* is common on some of the mound-bearing beds. On the 120 m level surface *Skolithos* typically form depressions on the upper bed surface (Fig. 2e), whereas *Skolithos* associated with sandstone mounds on the same bed typically rises above the surface of the sandstone mounds (Fig. 5a). This suggests that tubes were filled with sediment and somewhat stabilized prior to the erosive event that generated the mounds, which is also indicated by rare tubular trace fossils in the gullies (Fig. 3c), interpreted as eroded and reworked *Skolithos*.

The sandstone mound-bearing beds are sharply overlain and draped by finer-grained sandstone (Fig. 3d, Supplementary Figs. 2 and 3). Although contacts are rarely exposed due to weathering and soil and lichen cover, they are important in providing conclusive evidence for a primary origin of the sandstone mounds.

The salient features of the sandstone mounds in the Guadalupe area are shown schematically in Fig. 6.

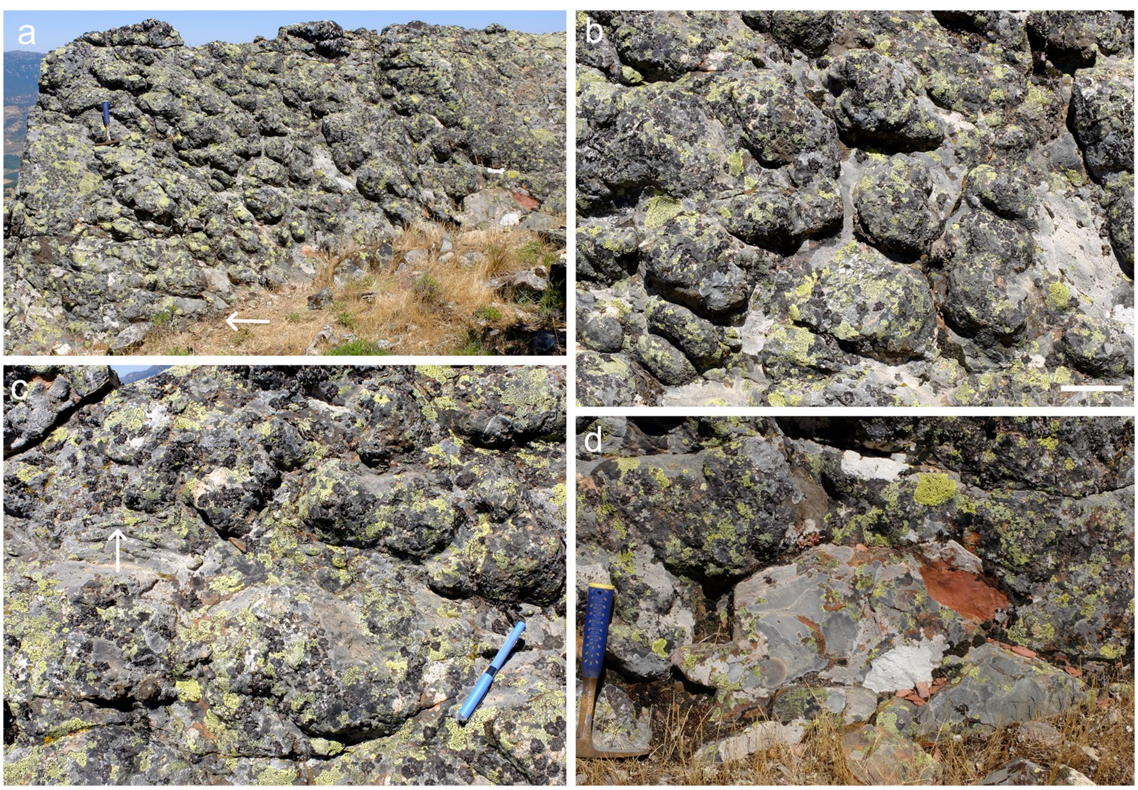


**Fig. 3** Sandstone mounds from 120 m at location 6 (see Supplementary Fig. 1). **a** General view. The contact of the sandstone mound-bearing surface with overlying, finer-grained, sediment is largely covered but exposed near the right margin of image. See part **d** for close-up. Another contact, indicated by an arrow, is shown in Supplementary Fig. 2. Hammer for scale is 28 cm. **b** Close-up of central part of **a** to illustrate the range of sizes and shapes of the sandstone mounds. Scale bar is 10 cm. **c** Close-up of upper left-hand portion of **a**. Note trace fossils interpreted as reworked *Skolithos* in the gullies, one of which is indicated by a white arrow. Pen is 13.5 cm. **d** Close-up of lower-right part in **a** showing fine-grained sandstone immediately overlying and draping the sandstone mounds. Hammer is 28 cm

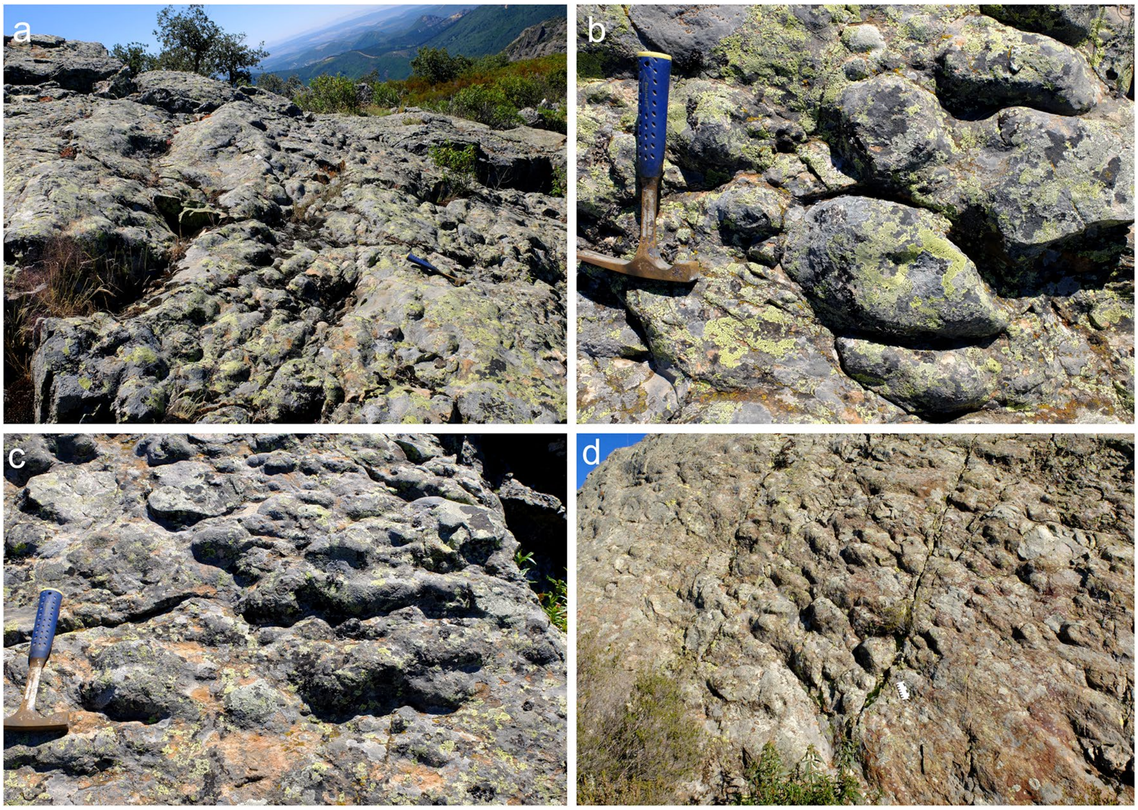


**Fig. 4** Sandstone mounds. See Supplementary Fig. 1 for locations. **a**–**c** Location 2, approximating 160 m. **a** General view. Hammer for scale is 28 cm. **b** Nearly circular, tear-shaped and irregular mounds. **c** Area with irregularly developed ridges. **d** Large surface with well-developed sandstone mounds, which become more diffuse in the lower part. Location 3, 160 m. Scale at lower centre is 13 cm

## 3 Other locations with sandstone mounds in the Central Iberian Zone

During the preparation of this manuscript, two other occurrences of sandstone mounds were discovered in Ordovician rocks of the Central Iberian Zone.

A small outcrop of sandstone mounds (Fig. 7d) is located in a road-cut along the EX-102 road, south of Puerto de San Vicente, in the northern flank of the Guadarranque syncline. This outcrop (UTM (WGS 84) 30 S 318070 E, 4375830 N) belongs to the lower part of the Middle Ordovician Marjaliza beds (IGME 1985b).

Well-developed sandstone mounds are exposed along the N-430 road, SE of Puebla de Don Rodrigo, Ciudad Real (Fig. 7a–c). This outcrop (approximate centre at UTM (WGS 84) 30 S 363883 E, 4323690 N), is mapped (ITGE, 1986) as the Pochico Formation, which is a Middle Ordovician lateral equivalent of the Marjaliza beds (e.g., Gutiérrez-Marco et al., 2019). Remains of muddy rock in the gullies of these sandstone mounds demonstrate that these are not recently formed structures.

## 4 Discussion

Baldwin and Johnson (1977) interpreted sandstone mounds from the upper part of the Armorican Quartzite Formation in France as having formed intertidally during late stages of run-off erosion of sheet sandstone, which initiated the formation of gullies. Subsequently the ridges were truncated, resulting in the formation of mounds. This interpretation was based on the association with flat-topped ripples and mud-cracks, implying periodic emergence. Bidirectional currents, meandering channels and rapid vertical changes in heterolithic facies additionally indicated a tidal environment (Baldwin & Johnson, 1977; Durand, 1985). Other occurrences of sandstone mounds have been interpreted to have formed subaqueously. This includes Goldring (1971) and Goldring and Langenstrassen (1979) who argued that late Devonian examples from England and Belgium formed during a single erosional event at shallow water depth, but without emergence. Similarly, Long (2007) reported sandstone mounds associated with storm deposits. Hiscott (1982) interpreted sedimentary characteristics associated with sandstone mounds in the lower Cambrian Random Formation to indicate deposition on the inner part of a storm-dominated

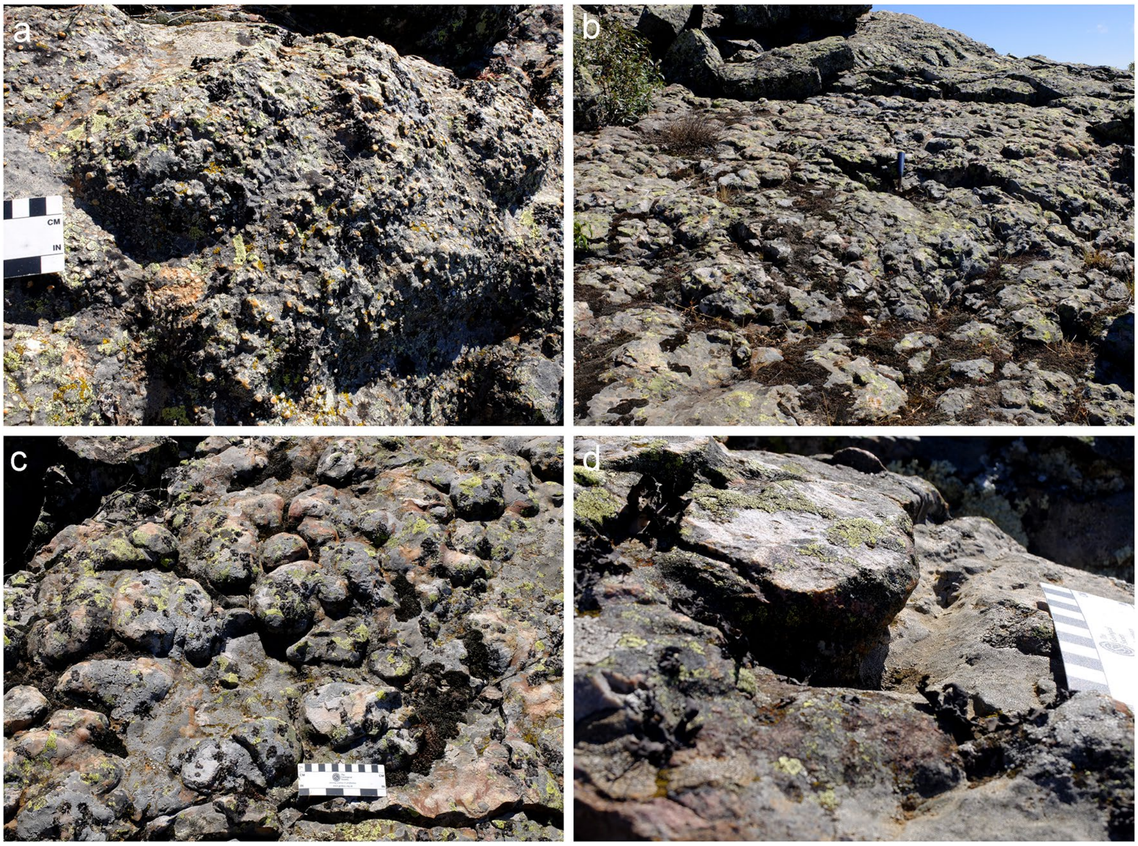


**Fig. 5** Sandstone mounds. See Supplementary Fig. 1 for locations. **a** Sandstone mounds with *Skolithos*, at location 7. **b–d**. Sandstone mounds at site 4. **b** General view. Note that the area of sandstone mounds is depressed with respect to the lateral continuation of the same bed. Hammer for scale is 28 cm. **c** Surface showing wide range of mound shapes. Scale divisions in cm. **d** Side view of sandstone mound with under-cut. Scale divisions in cm

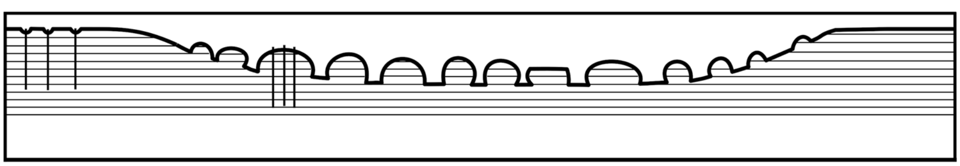

**Fig. 6** Cartoon showing, schematically and not to scale, sandstone mounds formed in shallow depressions eroded in sandstone beds of the Armorican Quartzite Formation. A selection of *Skolithos* are indicated by vertical black lines. Horizontal lines represent planar lamination and are only shown for part of the cartoon

sandy shelf. Hiscott (1982) further suggested that seaward facing rip-currents contributed to the formation of sandstone mounds. In the Random Formation this surface displays a phosphatic patina, suggesting a transgressive surface with slow sedimentation. In France, Bradshaw (1966) observed concentrations of lingulid fragments and coarse sand grains as part of the initial sedimentation that occurred after mound formation. However, Durand (1985, Fig. 38) recorded sandstone mounds from thin sandstone beds in a muddy interval, so sandstone mounds are not restricted to one type of succession.

As suggested by the above examples it is probable that sandstone mounds formed in different inner-shelf or shallower environments. The occurrences reported here from the Guadalupe area are found at the top of upward-thickening bed successions overlain by fine-grained sediment. Their association with abundant *Skolithos* is consistent with moderately shallow wave agitated settings, but there is no sedimentological evidence for subaerial emergence. They are more likely to have formed subaqueously on a marine flooding surface by storm-related erosion, and their concentration in shallow channel-like depressions suggests locally


**Fig. 7** Sandstone mounds from the Pochico Formation near Puebla Don Rodrigo, Ciudad Real (**a**–**c**), and Marjaliza beds near Puerto San Vicente, bordering Cáceres and Toledo (**d**). **a** Portion of large surface with variously developed sandstone mounds. Person for scale is 1.3 m. **b** Elongated sandstone mounds with evidence of smoothering erosion. Scale bar is 50 cm. **c** Sandstone mounds with partially preserved areas with draping mud, one of which is indicated by a white arrow. Scale bar is 10 cm. **d** Sandstone mounds on a small outcrop along EX-102. Hammer is 28 cm

concentrated higher current strengths (rip currents?) or parts of the sea-floor that was more susceptible to erosion.

The Armorican quartzite facies in Spain has a vast areal extension and formed on a wide shelf of low topography. Young (1990) remarked on the lack of evidence of coastal proximity in the Armorican Quartzite, and no evidence for subaerial exposure was reported by Rej and Hidalgo (1994), or in Bayet-Goll and Neto de Carvalho's (2020) study of the Armorican quartzite facies in the Penha Garcia area, Portugal. The Armorican Quartzite represents areas of storm and tide-distributed sheet sandstones reworked by strong currents. Brenchley et al. (1986) hypothesized that storm-related off-shore currents influenced sedimentation over vast areas of Iberia in the younger Monte da Sombadeira and Los Rasos formations, with wave reworking of the sands common in proximal areas, and a similar conditions can be envisaged for the Armorican Quartzite Formation.

Sandstone mounds represent one end of a spectrum of scour and fill structures made in mud and sand (Goldring & Aigner, 1982). Whilst gutter cast, sand-filled scours in mud, are moderately common, this does not appear to be the case for sandstone mounds, with a literature search generating less than 15 reports (Table 1). Notable in this list are: 1) the high proportion of reports from rocks bordering the Iapetus/Rheic Ocean, especially from the Armorican Quartzite facies s.l.; and 2) the lack of reports from post-Devonian rocks.

Although there are likely to be other occurrences, including from younger rocks, possible reasons for the patterns in Table 1 are speculated below. A possible younger occurrence is Homewood et al's. (2008) report of "brioches" from the Upper Cretaceous of Oman, with the scoured surfaces colonized by oysters, but the origin of these structures as primary or secondary appears to be unsettled.

Some of the more common documentation of sandstone mounds comes from the upper part of the Armorican Quartzite Formation of NW France and in particular from the Crozon Peninsula (Baldwin & Johnson, 1977; Bradshaw, 1966), where sandstone mounds are widespread and have been mentioned as a notable feature of the area's geodiversity (e.g., Plusquellec, 2010; Vidal, 2019). In northern France sandstone mounds have also been reported from the Upper Ordovician Grès de May Formation of Normandy (Lemosquet, 1970). In northern Spain, within the West-Asturian

**Table 1** Tabulation of reports of sandstone mounds

| Age | Unit | Geography | Primary reference | Environment, primary reference |
|---|---|---|---|---|
| Cryogenian | Stangeneset Fm | Finnmark, Norway | Baldwin and Johnson (1977) | Tidal/lagoonal mud flat |
| Cam., Age 2 | Random Fm | Newfoundland | Hiscott (1982) | Lower shoreface, macrotidal setting |
| Fur.-Trem | Los Cabos Group | Asturias, Spain | Smosna and Bruner (2016) | Subtidal nearshore |
| Ord., Early | Beach, Redmans fms | Newfoundland | Brenchley et al., (1993) | Inner shelf |
| Ord., Floian | Armorican Quartzite Fm | Crozon, France | Baldwin and Johnson (1977) | Mixed tidal flat |
| Ord., Floian | Armorican Quartzite Fm | Extremadura, Spain | This report | Subtidal |
| Ord., Floian | Los Cabos Group | Asturias, Spain | Baldwin and Johnson (1977) | Tidal lagoonal mud flat |
| Ord., Middle | Marjaliza beds | Extremadura, Spain | This report | Subtidal |
| Ord., Middle | Pochico Fm | Ciudad Real, Spain | This report | Subtidal |
| Ord., Late | Vauréal Fm | Anticosti, Canada | Long (2007) | Mid- to outer shelf |
| Ord., Late | Grès de May | Normandy, France | Lemosquet (1970) | Shallow, with subaerial episodes |
| Dev., Emsian | Grès de Vireux | Ardennes, France | Cibaj (1991) | Platform with storm facies |
| Dev., Famm | Condoz Group | Ardennes, Belgium | Macar and Ek (1965) | Tidal flat |
| Dev., Famm | Baggy Beds | Devon, England | Goldring (1971) | Shallow marine |

*Cam.* Cambrian, *Dev.* Devonian, *Ord.* Ordovician, *Famm.* Fammenian, *Fur.* Furongian, *Trem.* Tremadocian

Leonese Zone, Baldwin and Johnson (1977) described, but did not illustrate, sandstone mounds from the upper part of the Cabos Group, within the stratigraphic range of *Cruziana rugosa* (cf. Baldwin, 1977) in a facies similar to that of the Armorican Quartzite Formation. Mounds were reported to have a relief of up to 25 cm and occasionally to have vertical flanks. Baldwin and Johnson (1977) mentioned another 17 occurrences of sandstone mounds of lower relief from the Furongian-Tremadocian part of the Cabos Group (age according to Villas et al., 1995). A probable example of this type of sandstone mound has been figured by Smosna and Bruner (2016, Fig. 11d). Sandstone mounds from the Beach and Redmans formations of Newfoundland (Brenchley et al., 1993), also belong to a facies similar to that of the Armorican Quartzite.

The present study extends the record of sandstone mounds in the Armorican Quartzite facies to the Central Iberian Zone of southern Spain, and it is expected that more occurrence will be found over the wide area of exposure of this unit. The two localities of sandstone mounds in Extremadura are located within the Villuercas-Ibores-Jara UNESCO Global Geopark, contributing to the geodiversity of this geopark.

The fact that sandstone mounds are restricted to Devonian and older rocks (Table 1), raises the question of secular factors being relevant to their formation or preservation. The recessed margins of the mounds suggest that the sand must have had some cohesion and this is probably true whether the gullies remained open or were filled with sediment shortly after the time of erosion. Macar and Ek (1965) reported evidence of reworking and rotation of the mounds, further evidence of sediment cohesion. Bradshaw (1966) and Hiscott (1982) have suggested algal binding as a possible source of stabilization, and microbial communities are known to strongly influence the erosion and formation of bedforms in sands (e.g., Hagadorn & McDowell, 1982). Biofilms attached to sand grains may have been a food source for the producer of *Daedalus* (Noffke et al., 2022), a trace fossil common in the Armorican Quartzite. Although biofilms may have played a role in the formation of sandstone mounds, there is no physical evidence, such as mat-induced sedimentary structures, to suggest significant microbial stabilization in the section studies. The fact that sandstone mounds appear to be relatively rare suggests that additional factors were involved. That the vast majority of reports of sandstone mounds are found in rocks deposited on the Gondwana margin of the Rheic Ocean may therefore be due to a combination of favourable sedimentary characteristics, the specifics of which remain to be tested (grain size, sorting) and a wide shelf of low topography affected by storms and/or tidal currents for their formation. It can also be speculated that the relatively low levels of animal mediated reworking of the sediment increased the likelihood of preservation of surficially bedding features. Sandstone mounds may therefore be another example of a sedimentary structure with preferential formation and/or preservation in the Early Palaeozoic (cf. Tarhan, 2018).

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s41513-024-00246-w.

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## Declarations

**Conflict of interest** The author declares that he has no conflict of interest.



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