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TIDE-DOMINATED DELTAS RESPONDING TO HIGH-FREQUENCY SEA-LEVEL CHANGES, PRE-MESSINIAN RIFIAN CORRIDOR, MOROCCO: REPLY

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INTRODUCTION

This comment is mostly concerned with upper Miocene sandstone layers at the locations of Ben Allou (BA) and El Adergha (EA) that formed in the Rifian Corridor. These sandstones were interpreted as deep-marine contourites by de Weger et al. (2020) following Capella et al. (2017, 2019), Miguez-Salas et al. (2020, 2021), Stow and Smilie (2020), and de Weger et al. (2021). These rocks were re-interpreted as shallow-marine tidal deposits by Beelen et al. (2020).

PRIMARY ARGUMENTS

The primary argument for our paleoenvironmental re-interpretations at BA and EA are the foraminiferal assemblages. We are fully aware that this type of analysis does not provide quantitative water depths with 100% accuracy, but we like to emphasize that the initial paleoenvironmental and paleo–water depth reconstruction of the BA and EA outcrops were based on foraminiferal data (Capella et al. 2017). This paleo–water depth analysis of Capella et al. (2017) is then relied on by other studies that further push and develop the deep-marine contourite interpretation. However, we demonstrate that the initial foraminiferal data by Capella et al. (2017) suffer from undersampling. Capella et al. (2017) state (regarding the deposits at Ben Allou):

> "*The water-depth of deposition has been inferred based on the benthic foraminifera assemblages contained in the hemipelagic marls of the studied sections*"…"*Sampling for biostratigraphy was carried out in the finer-grained muds/marls, interbedded with the sandstones*.
>
> —Capella et al. (2017).

Note that we refer to these "marls" as siltstones and "muds" as claystones.

Therefore, the main interval of interest (the sandstone layers) was never sampled and analyzed for paleo–water depth before our analysis, and the foraminifera in the sandstones are simply assumed to be the same for those in the interbedded fine grained siltstones and claystones. In Beelen et al. (2020), we showed that the foraminiferal assemblages in the sandstones are entirely different from those in the siltstone and claystone facies and constitute a shallow-marine assemblage. Because of this, we start one of our associated papers by saying:

> "*Our foraminiferal data were obtained directly from all facies. These more complete data show that, while the siltstone and claystone layers can be considered deep-marine, the sandstones are shallow-marine.*"
>
> —Beelen et al. (2021a)

Our foraminiferal data have been thoroughly double-checked by experts in a blind test. These experts had no information on our analysis or any other existing analysis and were given washed but unpicked, raw samples each of which contained thousands of individual microfossils. These experts (Michael Nault and Ardy Callendar) are highly experienced (> 100 years combined experience with describing and interpreting Neogene-age foraminifera, including experience in Mediterranean basins). They concluded that the assemblages in the BA and EA sandstones were deposited *in situ* due to their "swash polished" (Shroba 1993) yet intact nature and were not part of a resedimented assemblage. They stated that the sandstone foraminiferal assemblages formed in shallow inner-neritic water depth (estimated 0–30 m), while siltstone and claystone facies were formed in deep-middle to shallow-outer neritic water depths (estimated 60–140 m).

Another important reason for our re-interpretations is the paleogeography of the Rifian Corridor, which has been a debated topic for decades. This is partly because of its complex archipelago-like nature as a series of partially connected straits, islands, bays, and inlets and due to the limited availability of regional seismic data (e.g., Zizi et al. 1995; Capella et al. 2018). The equally intricate structural history of this area involves up-thrusted nappes and tectonic dissection of basins into subbasins, which further complicates paleogeographic reconstructions. Most researchers in this area have so far relied on the study of outcrop exposures, which are usually tens of meters in lateral extent (the larger outcrop at Ben Allou (BA) is an exception), and tens of kilometers apart. These factors make it impossible to confidently constrain any single outcrop's position within the entire Rifian Corridor depositional system. Paleoenvironmental reconstructions in this area should therefore be made independently for each outcrop. Like many authors before us, we also make independent paleoenvironmental reconstructions, including for the BA and EA outcrops, and then put these together in what is a schematic paleogeographic framework. This is clearly stated in our text and noted as "tentative

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paleogeographic reconstruction" in the caption of Figure 15 of Beelen et al. (2020). Minor differences between these interpretations and the geological map used by us (derived from Chenakeb 2004) and the earlier 1980 geological map (Suter 1980) used by Capella et al. (2017) and later de Weger et al. (2021) are of no relevance to our paleoenvironmental and paleo–water-depth interpretations of BA and EA. Minor age differences between EA and BA (16 kyr according to the biostratigraphy of Capella et al. 2017) are also not relevant to our depositional-environment interpretations for these outcrops.

As the geological setting remains poorly constrained, and the main argument for a deep-marine setting is forfeited due to undersampling by Capella et al. (2017), a complete paleoenvironmental re-interpretation becomes a possibility. Furthermore, if the authors of de Weger et al. (2021), comment to Beelen et al. (2020), wish to continue with their deep-marine sandy-contourite interpretations, they must come up with independent lines of argument to show that these deposits are deep marine. Instead, they continue to rely on the foraminiferal interpretations by Capella et al. (2017), without providing alternative lines of evidence.

That being said, do other factors that could be used to discern ancient processes and paleoenvironment, like sedimentary structures, discredit or corroborate our shallow-marine interpretations? An assemblage of rhythmic bedding, mud cracks, channels, mud drapes, symmetrical ripples, and reactivation surfaces strongly corroborates a shallow-marine, tide-dominated environment, with rapidly alternating and waxing and waning currents (e.g., Davis and Dalrymple 2011). None of these factors indicate that these rocks represent unique, never-before-seen deep-marine sandy contourites or deep-marine contourite channels. Also, the abundance of intact barnacles, scallops, *Psilonichnus* borings, and *Macaronichnus*–*Thalassinoides* burrows, further indicate a shallow-marine origin for these sediments. In fact, all types of relevant paleoenvironmental data that were collected (sedimentary structure, ichnological, macropaleontological, micropaleontological, stratigraphic, and geochemical) are in strong agreement, and point to a well-oxygenated, tide-dominated, shallow-marine environment for the sandstones, and a dysoxic, low-depositional-energy, deeper environment for the siltstone and claystone facies (Beelen et al. 2020, 2021a). We agree that some of these indicators are quite diminutive at BA and EA (for example, only a handful of wave indicators were found in the sandstones; Fig. 1). We also accept that some other indicators like the structures interpreted by us as herringbone cross strata and mud cracks are small and rare and may thus be open to interpretation, but these secondary arguments are not heavily relied on by us. It is the complete microfossil, macrofossil, ichnological, sedimentary-structure evidence that gives us confidence in our paleoenvironmental interpretations (Beelen et al. 2020, 2021a, 2021b).

To explain the apparent shallow sandstone to deeper siltstone and claystone facies changes, we infer 70–80 m amplitude (based on cycle thicknesses at BA), 100 kyr frequency (based on biostratigraphic indicators) glacioeustatic sea-level fluctuations (Beelen et al. 2020). We disagree with de Weger et al. (2021), comment to Beelen et al. (2020), that these inferred sea-level changes are not supported by existing studies. For example, in Mercer and Sutter (1982), it is stated:

> "*Cita and Ryan (1978, p. 1070) note that sedimentation associated with the late Miocene regression near Rabat on the Atlantic coast of Morocco was cyclical, and they suggest that this reflects fluctuations in sea-level related to repeated waxing and waning of the Antarctic Ice Sheet. At DSDP Site 397 off the coast of Morocco, three parameters—oxygen isotopes, grain size, and carbonate content—vary in unison in latest Miocene sediments at the same ca. 100,000-year frequency as during the Pleistocene glacial–interglacial cycles, but with about one third the amplitude for the 5180 signal. Cita and Ryan (1979, p. 455) believe that these cycles imply a strong glacial influence. Many of the estimates of the magnitude of the marine regression are quite similar: 40–70 m in New Zealand (Loutit and Kennet, 1979, p. 1199), 50–70 m in southeast Spain (Berggren and Haq 1976, p. 94), and about 80 m in Morocco (Cita and Ryan 1979, p. 455). Vail and Hardenbol (1979, p. 71), believe that sea-level dropped to about –100 m, as during Pleistocene glaciations.*"
>
> —Mercer and Sutter (1982)

Based on this evidence, we simply do not understand why de Weger et al. (2021), comment to Beelen et al. (2020), would consider our interpretations of 70–80 m, 100 kyr glacioeustatic fluctuations during the late Miocene as "*not supported by the literature*." The sharp, laterally extensive surfaces of marine erosion at the lower boundaries of the sandstones incise into the deeper siltstone and claystone facies, which corroborates our argument that the sandstones formed after an episode of regressive marine erosion, associated with a developing lowstand in sea level.

Despite our re-interpretations, we would like to emphasize that our work only concerns an aspect of the work by de Weger et al. (2021), comment to Beelen et al. (2020) (albeit an important aspect in some of their papers), and many of their insights remain valid and useful. Therefore, their contributions to our understanding of the Rifian Corridor, as well as contourites as a whole should not be understated. Notably, work by Capella et al. (2017, 2018a, 2018b) remains the most complete paleotectonic and paleogeographic work on the Rifian Corridor area, with implications for regional and larger-scale climate, tectonics, and paleoenvironment. Without their work, our work in this area would never have been possible in the first place.

In Miguel-Salas et al. (2020), however, the authors explain that the ichnology at BA resembles a proximal, shallow-marine assemblage, but then explain that this is a "*natural laboratory for* [deep-marine] *contourite ichnology*" based on the foraminiferal data by (Capella et al. 2017). They then go on to discredit those very data, by saying that foraminiferal interpretations regarding paleo–water depth may be wrong (de Weger et al. 2021, comment to Beelen et al. 2020). These authors are contradicting themselves regarding a central premise of their work, so their interpretations on the outcrops at BA probably require a re-interpretation.

EVIDENCE FOR WAVE ACTION

An absence of wave-related sedimentary structures certainly does not mean that the sediments formed below wave base (typically 5–15 m water depth) as was claimed by de Weger et al. (2021). Many ancient tidal environments (for example, Sego Canyon, Utah, USA; Willis and Gabel (2001) or Baronia Sandstone, Spain; Olariu et al. (2012)) look generally similar to BA in terms of sedimentary structures (e.g., large-scale cross strata and rhythmic bedding) and have little to no evidence for wave action, which can simply mean that tides were dominant here, overprinting any evidence for waves. Furthermore, dominance of a single paleocurrent direction is almost universal for tidal deposits, owing to tidal asymmetry (e.g., Davis and Dalrymple 2011). These factors are especially common in areas with amplified tides like sea straits (e.g., the Rifian Corridor).

That being said, rare indications for wave action in the form of hummocks, swales, and symmetrical ripples are in fact present at BA and EA (Fig. 1).

DRIOUATE OUTCROP

We agree that there is limited evidence to suggest that the Driouate outcrop is a direct lateral equivalent to BA, which is why we state:

> "*There is no direct evidence that the very course boulder-size material from the fluvial systems at Driouate reached the deltaic systems at Ben Allou or El Adergha, indicating that these deposits may not be part of the same depositional system. Nonetheless, since*

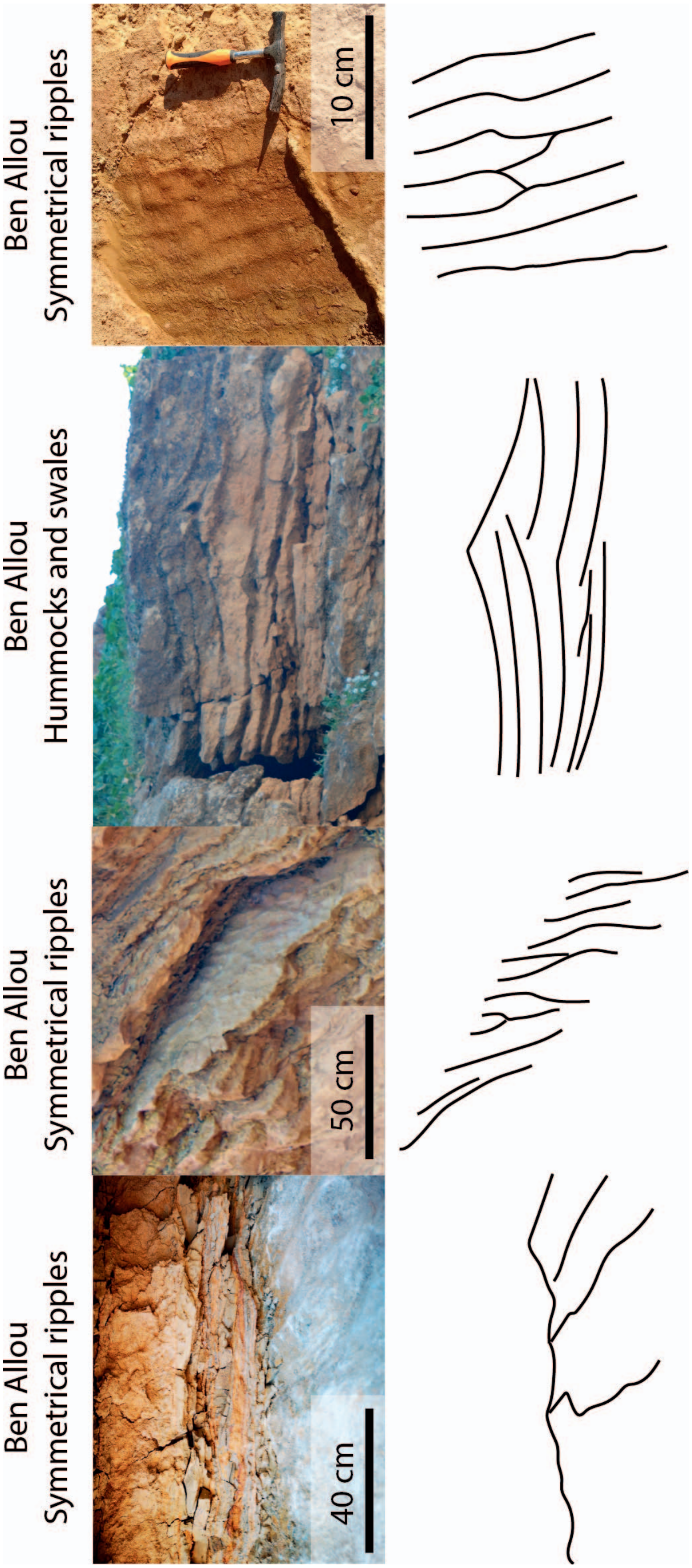

FIG. 1.—Evidence for wave-related processes found at the locations of EA (El Adergha) and BA (Ben Allou).

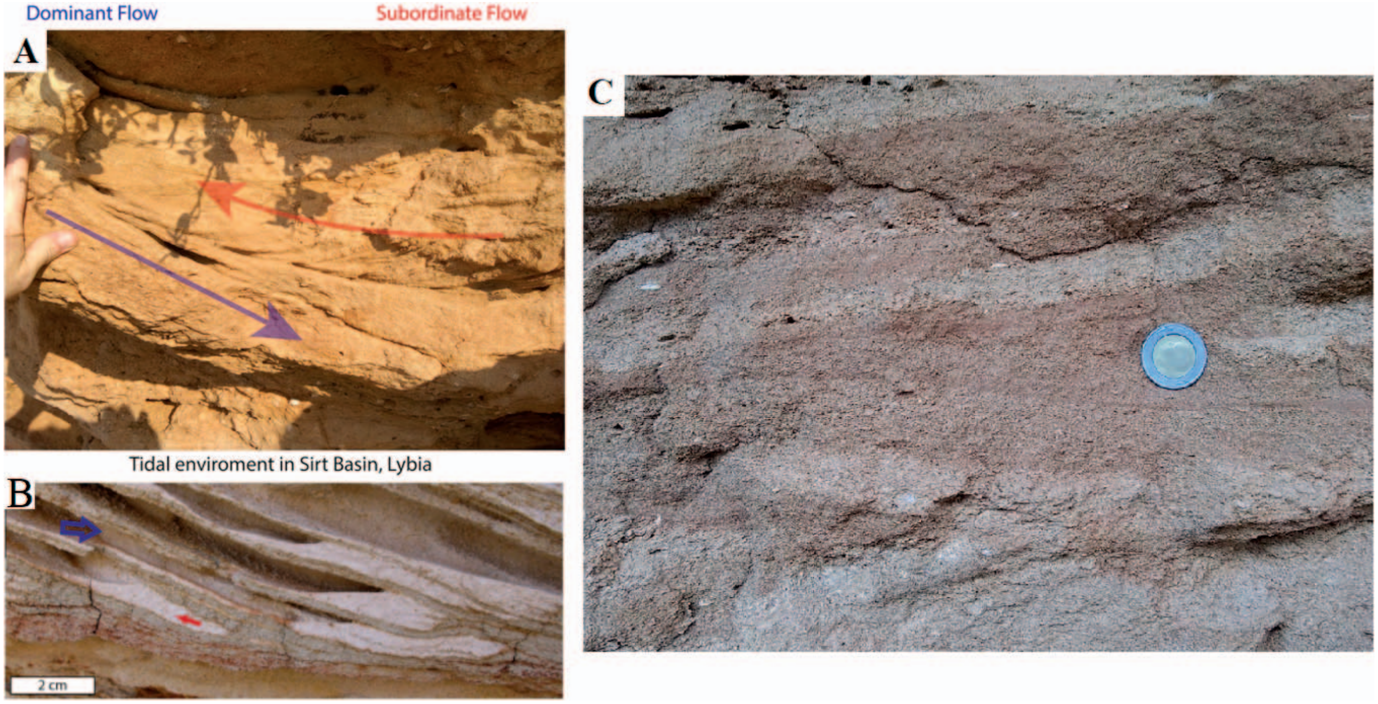

FIG. 2.—**A)** Bidirectional current structure in BA. **B)** Bidirectional current structure in Libya (Abouessa et al. 2014). **C)** Structure at BA that we interpreted as an example of true herringbone cross stratification.

> *some facies at Driouate were formed in a marine environment that was part of the same basin as the deposits at Ben Allou and El Adergha, the deposits at Driouate provide important context to the processes in and around the Rifian Corridor.*"
>
> —Beelen et al. (2020).

However, due to the presence of marine facies and fossils at Driouate, we believe that this outcrop cannot be younger than Messinian, since this is when the Rifian Corridor (and thus all marine influence) disappeared. Furthermore, the exposure at Driouate is man-made and likely postdates the construction of the geological map by Chekaneb (2004). This was confirmed to us by a local landowner, but due to the informal nature of this evidence we did not include it in our paper.

These things considered, we believe that this outcrop is unique because it showcases rapid alternations of marine and terrestrial facies that took place immediately before the disappearance of the Rifian Corridor. A very interesting part of the depositional history of this area is this recorded at Driouate, which are the geological events leading up to the Messinian salinity crisis.

Plant rootlets have been used to support the interpretation that the deposits have been subaerially exposed. We use this argument for the deposits at Driouate (not BA or EA). The plant rootlets found at Driouate are fossil rootlets because they are found at centimeters depth inside a rock outcrop that directly underlies younger rock strata. Driouate also contains abundant fossil plants and remains of bamboo or reed stalk imprints (Beelen et al. 2020).

OUT-OF-PLACE MICROFOSSILS

Rare abundance of *Dentalina* (a cosmopolitan genus with an abundance of 4%) and *Oolina* (2%) and very rare abundance of *Pullenia* (1%) in the deeper siltstone and claystone facies do not negate our broader depositional-environment interpretations, which are based on the larger, overall assemblages. For example, the 1% *Pullenia* foraminifera may have been transported here from deeper water by basinward-directed flood currents, which is common in tide-dominated environments like sea straits. A small number of Cretaceous-age foraminifera were also found in the sandstones at BA; species: *Globotruncana lapparenti* (1%). Like some of the deeper species, a small number of Cretaceous specimens does not define the overall interpretation. Large abundances of shallow-marine *Ammonia* (35%) and *Elphidium* (16%) as well as the abundant and diverse ostracods are the most important microfossil indicators for shallow water in the sandstones.

HERRINGBONES AND BIDIRECTIONAL CURRENT STRUCTURES

Some of the more contentious evidence presented to support our claims are the presence of herringbone cross strata and rare, small mudcracks. We like to emphasize that, although we continue to carry this as evidence, our interpretations do not heavily rely on these observations. Our main sedimentary-structure evidence for a tidal environment is the pervasive rhythmic bedding, reactivations surfaces, mud drapes, and the thick stacks of dune and channel-bearing sedimentary architectures.

De Weger et al. (2021), comment to Beelen et al. (2020) correctly point out that bidirectionally oriented cross strata are commonly "false herringbones" or simply the lateral interfingering of trough cross strata. However, the structures interpreted have no bounding surface in between both opposing herringbone cross strata, which suggests that these are true herringbones and not two adjacent 3D dunes (which are the original structures that generate trough cross strata; Fig. 2).

BA also contains bidirectional current structures, which are different from herringbone cross stratification. (Fig. 2; see Abouessa et al. 2014) This, in combination with pervasive reactivation structures caused by transient erosional episodes from opposing currents, are good indications of rapidly reversing tidal currents being the dominant depositional-processes regime. This evidence also goes against the contourite interpretation as it is hard to believe that a large, continuous-current process like Mediterranean Outflow Water would frequently periodically reverse. Instead, a more satisfying interpretation is that the rocks at BA and

FIG. 3.—Some small sand-filled mudcracks in the intertidal facies at BA. Mud drapes and flaser bedding are also visible and are classic indicators of tidal environments.

EA are not deep-marine sandstones formed by continuous, unidirectional bottom currents but instead are shallower tidal deposits that formed in a regime of rapidly alternating and reversing currents.

De Weger et al. (2021), comment to Beelen et al. (2020) have also expressed doubts that mud cracks in the sandstone layers exist at BA. Figure 3, shows some photographs of some of these mud cracks.

PALEOCURRENT DATA

Our independent paleocurrent data were not as numerous as those published by Capella et al. (2017) (n = 128 vs. n = 33); since our data agree with theirs but are less numerous, we decided to showcase their data in our work. To clarify, we never rejected any of the results by Capella et al. (2017), but we expand their data with our own data and then come to different interpretations.

ICHNOLOGY

Psilonichnus borings are very common in the upper sandstone layer at BA (Fig. 4). The reason that this ichnogenus is important is that it points to a tough (rigid) paleosubstrate texture (hence the borings). The ichnological expression of a rigid paleosubstrate is referred to as a *Glossifungites* Ichnofacies, which is associated with a shallow-marine environment. The rigidity here may be from occasional evaporation, since the lower, subtidal dune-bearing potions of the BA sandstones do not have this ichnofacies but rather a soft substrate *Cruziania* Ichnofacies (Beelen et al. 2021b).

SEDIMENT MATURITY

The sands at BA and EA are immature, having an angular texture with delicate carbonate structures left intact. Some of the quartz grains are perfectly euhedral. In some cases, scallop fossils were present with both valves still attached, and intact barnacle shells which are sometimes clustered, have upward-facing mouth scuta. Based on this, these are interpreted by us as being preserved in "life position." These barnacle clusters could have attached themselves directly onto the substrate if this substrate was indeed rigid, as is suggested by the ichnology (Coletti et al. 2018). Continuous currents like fluvial and contourite environments cause erosion of granular surface textures over time, leading to rounded, mature sediment grains and bioclasts composed of fragments of calcareous debris.

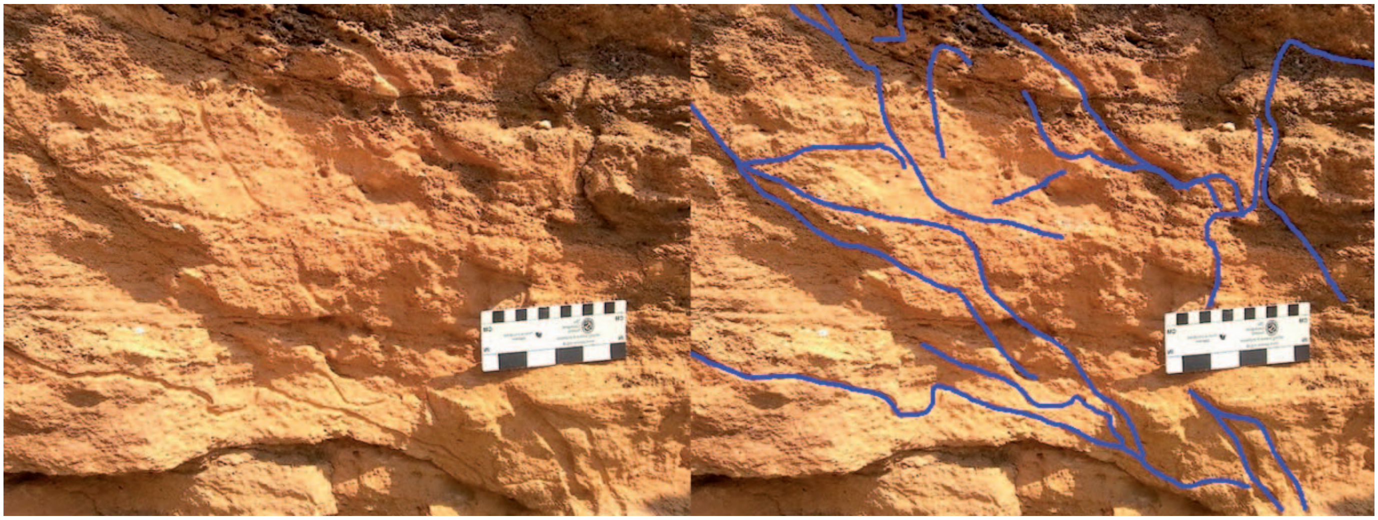

FIG. 4.—A photograph displaying at least six individual examples of *Psilonichnus* borings. This ichnogenus is very common in the upper parts of the BA sandstones and is associated with a hard-substrate *Glossifungites* Ichnofacies.

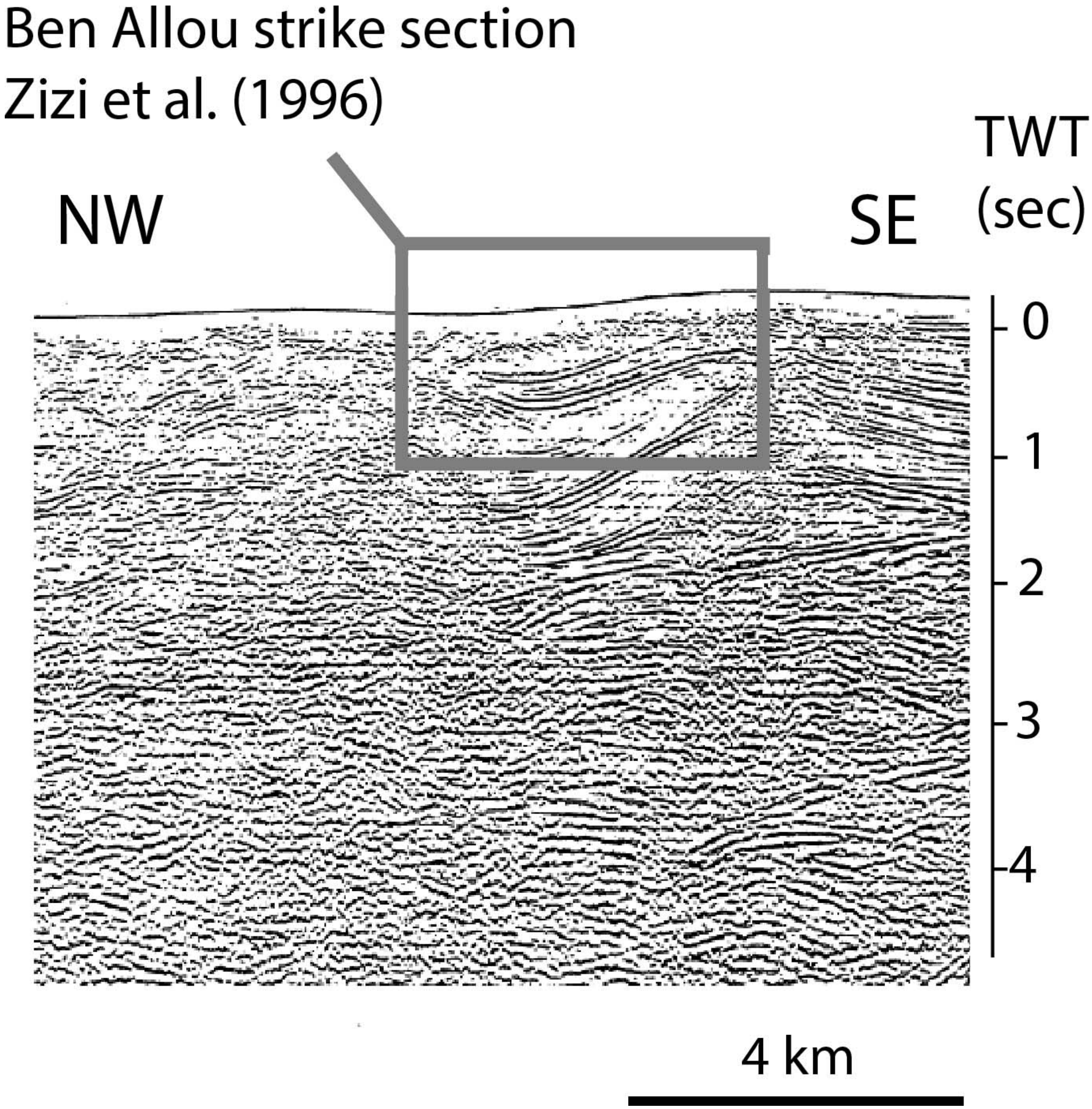

FIG. 5.—Seismic strike section of the BA outcrops showing that the strata here are structurally deformed in a gentle synform.

The immature textures at BA and EA containing euhedral grains and intact, delicate fossils are therefore more indicative of an intermediate-current, rapid-deposition environment like a tidal environment, instead of a continuous-current contourite environment.

"CONTOURITE CHANNELS"

De Weger et al. (2020) claim that the sandstone layers are unique outcrop examples of contourite channels. However, since the lateral fringes of the sandstone layers have not been preserved (neither at BA nor EA), it is not possible to confirm if these sandstone intervals thin out in any lateral direction based on the outcrops, and it is just as likely that these sandstone layers are roughly planar objects like ancient delta fronts. Furthermore, the sediments at BA are structurally deformed into a gentle syncline (Capella et al. 2017). The layers exposed here are therefore not depositionally convex upward, but instead planar layers that were structurally deformed after deposition. Seismic data from this area (published in for example Sani et al. 2007 and Zizi 2006) that trend along the depositional strike axis of the Ben Allou system confirm this; it shows synformal strata with no seismic-scale contourite channel geometries at BA (Fig. 5). The erosional surfaces below the sandstones are therefore more likely to represent regionally extensive surfaces of marine erosion from a drop in sea level before the deposition of the shallow-marine sandstones, rather than incision due to ancient, channelized contour currents.

RELEVANCE

The importance of the discussion raised by de Weger et al. 2020 regarding the conclusions of Beelen et al. (2020), should be emphasized. As the exploration for energy and critical mineral resources expands into ever deeper regions of the world's oceans, and ever deeper stratigraphically into older deposits, it is imperative that we distinguish between intermediate- to shallow-marine water depth current deposits and deepwater-current deposits. Outcropping examples of the latter are limited in occurrence (Stow et al. 1998), and non-ambiguous. We believe that deepwater contourite deposits should be well characterized with clear criteria for recognition, before using these interpretations to expound on global issues of the role of contourites in sea straits on larger problems like climate and ocean currents.

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