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REPLY

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A comment on overlooked storm sensitivity of the carbonate factory recorded in the Mississippian Mobarak Formation (Alborz Mountains, Iran)

Mehrdad Sardar Abadi[1] | Dennis F. A. E. Voeten[2,3] | Elena I. Kulagina[4] | Frédéric Boulvain[5] | Anne-Christine Da Silva[5]

[1]Rock Physics and Borehole Geophysics, LIAG, Leibniz Institute for Applied Geophysics, Hannover, Germany

[2]Department of Organismal Biology, Subdepartment of Evolution and Development, Uppsala University, Uppsala, Sweden

[3]Museum of Evolution, Uppsala University, Uppsala, Sweden

[4]Ufa Federal Research Center of the Russian Academy of Sciences, Institute of Geology, Ufa, Russia

[5]Laboratoire de Pétrologie Sédimentaire, Département de Géologie, Bat. B20, Université de Liège, Liège, Belgium

Correspondence
Mehrdad Sardar Abadi, LIAG, Leibniz Institute for Applied Geophysics, Stilleweg 2, Hannover 30655, Germany.
Email: mehrdad.sardarabadi@gmail.com

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Leibniz-Institut für Angewandte Geophysik

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New interpretations of depositional palaeoenvironments in the Mississippian (Lower Carboniferous) Mobarak Formation (Alborz Mountains, Iran) suggest a significant and persistent influence of storms. This deviates from previous conclusions that these deposits recorded mounds, patch reefs, and extensive lagoons deposited under stagnant environmental conditions. We here clarify and discuss the origin and nature of this misconception by explaining "unexpected" observations that are informed by outdated interpretations of the depositional environment of the Mobarak Formation. This evaluation offers the context required for appropriately interpreting and correlating Mississippian depositional records across the Alborz Basin.

KEYWORDS
depositional setting, Mississippian, Mobarak Formation, palaeoenvironment, storm deposits

1 | GEOLOGICAL SETTING AND HISTORY OF RESEARCH INTO THE MISSISSIPPIAN MOBARAK FORMATION OF THE ALBORZ MOUNTAINS

The Mississippian succession (359–323 Ma) that crops out in the central and eastern Alborz Mountains of northern Iran is one of the most complete Palaeozoic successions in Iran. Deposition of the Tournaisian–Visean Mobarak Formation recorded the development of an extensive carbonate factory along the northern margin of Gondwana following the opening of the Palaeo-Tethys Ocean. The Mobarak Formation consists of highly fossiliferous limestones and shales of a shallow marine origin (Mosaddegh, 2000). These carbonate intervals range from less than 100 m to well over 200 m in thickness that were described and dated using conodont and foraminiferal biostratigraphy. The conodont faunas from the Devonian–Mississippian Shahmirzad section in the Central Alborz Mountains span five biozones from the "*sulcata* Zone" up to the "Lower *typicus* – *anchoralis-latus* Interval" (Habibi, Corradini, & Yazdi, 2008). The Tournaisian–Visean foraminiferal assemblages in the Mississippian Mobarak Formation of the central and eastern Alborz reflect increasingly younger depositional ages from the central towards the eastern Alborz (Brenckle, Gaetani, Angiolini, & Bahrammanesh, 2009).

Preliminary work on Mississippian foraminifera in the Alborz Basin was conducted five decades ago (Bozorgnia, 1973). Twenty years later, the Mobarak Formation was interpreted to be depositionally analogous to carbonate sedimentation systems in the present-day southern Persian Gulf (Lasemi & Mahari, 1993). Subsequent

explorations of the Mississippian records of the Alborz Basin, such as in the PhD thesis of Mosaddegh (2000), proposed the ubiquitous presence of mud mounds in Middle Tournaisian intervals of the Mobarak Formation and compared them with Waulsortian mounds in Belgium. Lasemi and Mosaddegh (1999) and Mosaddegh (2000) furthermore described several coastal patch-reef complexes hosting oolite formation along tidal channels that were interpreted to reflect restricted environments in peritidal settings, such as extensive lagoonal systems and tidal flats. Slightly later, "The Geology of Iran" (Darvishzadeh, 1991 cf. Aghanabati, 2004 – page 164) suggested the Mobarak Formation was deposited across oxygen-poor and sulfur-rich stagnant water bodies, based on the elevated occurrence of organic matter in its Lower Tournaisian deposits. These studies have importantly contributed to current interpretations of the Mississippian Mobarak Formation and consolidated the perception that the presence of mud mounds and patch reefs in the Mobarak Formation (see Lasemi (2001) and Mosaddegh, Rahimi, and Aharipour (2006) for visual representations) was conclusively established. However, the referred model has led to multiple "surprising" or "unexpected" observations. For instance, Falahatgar and Mosaddeg (2012) state that: "Moreover, some sub-facies of open marine conditions which contain mud mounds and turbidite deposits that are dominant in eastern Alborz (Mosaddegh, 2000) have not been observed in the Kiyasar section." Nasiri, Moussavi-Harami, Mahboubi, and Mosaddegh (2019) did consider the role of storm activity and wave agitation in the formation of erosional surfaces, shell concentrations, and abraded carbonate grains across the Mobarak Formation along the eastern Alborz. Nevertheless, Nasiri et al. (2019) implicitly maintained the traditional depositional model for the Mobarak Formation (Lasemi & Mahari, 1993). Multiple environmental arguments, such as micritized grains, an abundance of bioclasts, and intraclasts in a grain-supported fabric (page 180, figure 5h,i,j in Nasiri et al., 2019), were presented in support of a semi-restricted lagoon environment in which high-energy events are "sporadic" rather than a structurally recurring influence on a largely unsheltered depositional system.

2 | REASSESSING DEPOSITIONAL MODELS FOR THE MOBARAK FORMATION BY ZANDKARIMI ET AL. (2019) AND OTHERS

Zandkarimi, Vachard, Najafian, Mosaddegh, and Ehteshami-Moinabadi (2019) recently presented new descriptions and interpretations of the Kalariz, Peyghambaran, Jaban, Naserabab, and Dozdehban sections that expose the Mississippian Mobarak Formation. By revisiting the sections originally described by Bozorgnia (1973) and revising Bozorgnia's biostratigraphic framework, they presented an updated subdivision of the Mississippian foraminiferal zones (MFZ) proposed by Poty, Devuyst, and Hance (2006). While Zandkarimi et al. (2019) have thus added valuable insight to the understanding of the lithological variation and spatial correlation across the Mobarak Formation, their work also reiterates a persistent misconception regarding the depositional nature of these Mississippian successions. Although sedimentological work conducted in the last decade has shed new light on the palaeoenvironmental context of these deposits (e.g., Falahatgar & Mosaddegh, 2012), the traditional essentially calm-water depositional model is maintained. Zandkarimi et al. (2019) cite Mosaddegh (2000) alongside an unpublished conference abstract of Lasemi and Mosaddegh (1999) that consider the presence and development of supposed mud mounds and patch reefs in a restricted lagoonal setting. This is followed by the erroneous statement that Sardar Abadi, Kulagina, Voeten, Boulvain, and Da Silva (2017) "confirmed" the "results" of such earlier literature on this subject (Zandkarimi et al., 2019—page 1487).

We have conducted extensive fieldwork in the Mobarak Formation and assessed numerous Mississippian sections across the Central Alborz (Sardar Abadi, Da Silva, Mossadegh, Spassov, & Boulvain, 2015; Sardar Abadi, Kulagina, Voeten, Boulvain, & Da Silva, 2017; Sardar Abadi, Kulagina, & Voeten, 2017). These include four highly representative sections: Jaban, Aroo, Shahmirzad, and Labnesar, from which 1,250 samples were collected and described with respect to lithology, sedimentology, facies, and fossil content (Sardar Abadi, Kulagina, Voeten, Boulvain, & Da Silva, 2017). To contextualize the retrieved facies sequences, we established a biostratigraphic framework that integrates foraminiferal and conodont records extracted from our samples and relevant literature (Habibi et al., 2008; Sardar Abadi, Kulagina, & Voeten, 2017; Sardar Abadi, Kulagina, Voeten, Boulvain, & Da Silva, 2017; Ueno, Watanabe, Igo, Kakuwa, & Matsumoto, 1997). These mutually consistent reconstructions resolved the spatial and temporal variation of carbonate facies along a broad W–E transect across the southern Central Alborz. Palynological observations revealed dry and warm climatic conditions in the hinterland (Sardar Abadi, Kulagina, Voeten, Boulvain, & Da Silva, 2017).

Contrary to earlier reports, evidence for mud mounds, patch reefs, and stagnant environmental conditions or extensive lagoons was not encountered. Instead, our results demonstrate that the Mississippian Mobarak Formation recorded the development of a storm-sensitive pervasive carbonate factory on the southern Palaeo-Tethyan passive margin (Sardar Abadi et. al, 2017; Sardar Abadi, Kulagina, & Voeten, 2017). This depositional system was activated by the opening of the Palaeo-Tethys Ocean into the Alborz Basin along the northern margin of Gondwana. Our work indicates that the cyclic pattern of carbonate deposition across the Tournaisian interval of the Mobarak Formation occurred under the indirect influence of climatic oscillations principally governed by the Devonian–Carboniferous glaciations and the subsequent decline in glaciation intensity during the late Tournaisian (Sardar Abadi, Kulagina, Voeten, Boulvain, & Da Silva, 2017).

Throughout the Shahmirzad section, the intense influence of storm activity is recorded as scoured surfaces (Figure 1) featuring concave-up laminae (storm layers; Figure 2), recurrent hummocky (swaley) cross-bedding, and abundant rip-up clasts containing marine fossils (Figure 3). Hummocky (swaley) cross-bedding occurs at multiple scales, reflecting cycles of moderate storm activity and incidental extreme events. Recurring storms scoured the bottom sediments,

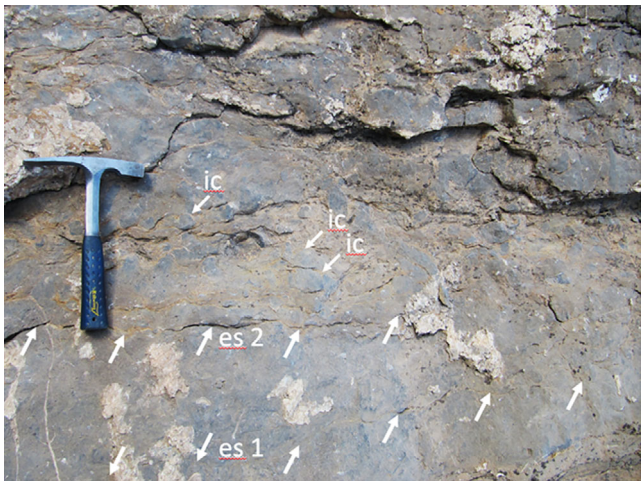

FIGURE 1 Irregular scoured surfaces (es) overlain by intrabasinal breccia/conglomerate, ("es" indicates two distinct erosional surfaces through white arrows and "ic" indicates three selected intrabasinal clasts). Scale: hammer 30 cm

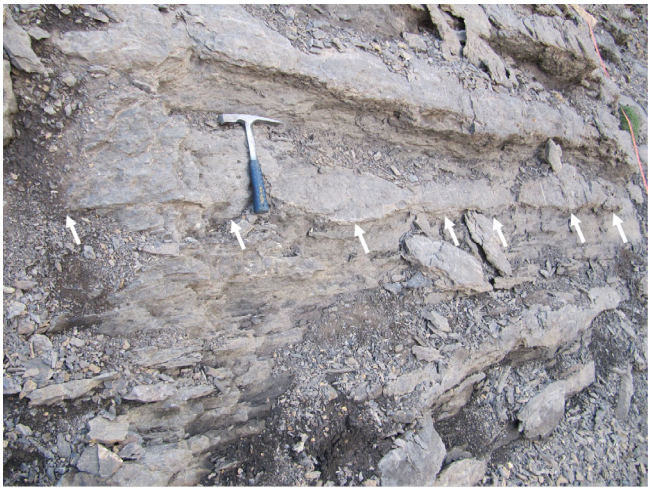

FIGURE 2 Recurring concave-up (white arrows) wavy laminar storm layers. Scale: hammer 30 cm

thereby fragmenting, winnowing, and sorting the grains according to density. This process generated skeletal and non-skeletal accumulations across the homoclinal ramps. Peloidal grainstones–packstones formed through storm-induced abrasion along the shoreline (e.g., figure 8c in Sardar Abadi, Kulagina, Voeten, Boulvain, & Da Silva, 2017). Although such deposits were presented as reflecting sheltered lagoonal environments (e.g., in Lasemi & Mahari, 1993), the described phenomena consistently confirm the absence of barrier reefs (Sardar Abadi et al., 2015) or significant sheltering by patch reefs in the recorded carbonate depositional environments. The sedimentological features indicative of persistent influence of storm activity (Figures 1–3) were here observed in the Shahmirzad section but are recorded throughout the Mobarak Formation (Sardar Abadi et al., 2015; Sardar Abadi, Kulagina, Voeten,

FIGURE 3 Abundant rip-up clasts composed of dark limestone (three of which are indicated by white arrows) containing haphazardly-oriented body fossils and surrounded by a fine-grained mud matrix. Scale: pen 15 cm

Boulvain, & Da Silva, 2017; Sardar Abadi, Kulagina, & Voeten, 2017).

The "mud mounds" described by Mosaddegh (2000) actually coincide with metre-scale channels featuring pronounced erosive bases that were filled in with massively bedded to discontinuously stratified limestones (figure 7f,g in Sardar Abadi, Kulagina, Voeten, Boulvain, & Da Silva, 2017). These channel-form deposits, rather than mounds (Figure 4), as well as distinct episodes of erosion or non-deposition occurring at the Hastarian–Ivorian boundary, all indicate a significant drop in relative sea level that affected the ramp system across a large part of the Central Alborz. Significant global sea-level fall and the coeval decline of foraminiferal diversity across the Kinderhookian–Osagean boundary (Hastarian–Ivorian boundary) in the Mobarak Formation was governed by extensive Middle Tournaisian continental glaciations, which also caused the development of the well-defined erosional hiatus at the base of the Ivorian in the Central Alborz (Sardar Abadi, Kulagina, & Voeten, 2017). Furthermore, sedimentological observations from the Middle Tournaisian of the Alborz support the hypothesis of eustasy at the Hastarian–Ivorian boundary, during which a global fall in sea level was followed by a relatively rapid recovery (Isaacson et al., 2008). Finally, fluctuations in the magnitude and expression of tectonic activity along the passive margin were demonstrated to explain the observed thickness variations of correlated carbonate intervals across the Tournaisian Alborz Basin (Sardar Abadi, Kulagina, Voeten, Boulvain, & Da Silva, 2017).

3 | SUMMARY AND RECOMMENDATIONS

Our observations cannot be reconciled with the persistent portrayal that sheltering patch reefs formed along the north-eastern margin of Gondwana (Alborz Basin) around the 30° palaeolatitude during Early

FIGURE 4 Incisive channel with pronounced erosive base (black dashed line) that was episodically filled in (black arrows indicate irregular erosional surfaces within the lower channel fill) with clast-bearing limestones topped by bioturbated fine-grained limestones. Recent water runoff locally evacuated the muddy matrix and dislodged dark limestone clasts, which caused vugs to remain where limestone clasts were originally present (white arrows). Scale: hammer 30 cm

Mississippian times, while the end-Devonian faunal extinction event had already eliminated most of the reef-building taxa (e.g., Shen & Qing, 2010). Although sedimentologic evidence of algal and mud mounds are frequently reported along carbonate platforms throughout the earliest Mississippian (e.g., Webb, 2005), evidence for such mounds is scant across the Mobarak Formation. The highly dynamic depositional history of the Alborz Basin during Early Mississippian times rendered these environments very sensitive to storm agitation, which has been extensively documented in the Mobarak Formation (Sardar Abadi et al., 2015; Sardar Abadi, Kulagina, Voeten, Boulvain, & Da Silva, 2017), including in the Jaban section also studied by Zandkarimi et al. (2019). The recorded storm-dominated depositional regimes are sedimentologically incompatible with the "sheltered depositional environment" and its inferred palaeoenvironmental phenomena, including mud mounds, patch reefs, and lagoonal facies that have been assumed since the 1970s. Rethinking the valuable research conducted on the Mississippian of the Alborz Basin will be required to appropriately reconstruct and interpret the depositional history of this rich sedimentologic archive. The Mobarak Formation represents a model record for palaeoenvironmental turnover following the end-Devonian faunal extinction. Revising the misapprehensions and refining the identifications of its depositional context is imperative for appropriately reconstructing the valuable spatial, temporal, and lithological records that it registered during this crucial stage of the geological history of north-eastern Gondwana.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

The data that supports our findings are included as figures in this article as well as provided by and available through the cited literature.

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