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Sedimentary dykes and genetically related features in the Upper Jurassic Jhuran Formation of the Kachchh Rift Basin, Western India

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In the Kimmeridgian–Tithonian Jhuran Formation of the Kachchh Rift Basin features such as sedimentary dykes, convolute bedding, and intraformational pillows are documented at several levels and localities. They are interpreted as having been produced by seismic events. Together with features, such as local intraformational unconformities and dying growth faults recorded earlier on in the literature they indicate that the basin was in a syn-rift stage until the end of the Jurassic. Interestingly, signs of seismic activity in the basin are far more conspicuous during the Oxfordian – Tithonian time interval than during the Middle Jurassic.

Key Words: Kachchh Rift Basin, soft-sediment deformation, Upper Jurassic, seismic activity.

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INTRODUCTION

The Mesozoic Kachchh Basin, situated at the western margin of the Indian craton (Fig. 1.1), is a rift basin, which according to Fürsich *et al.* (2020) was initiated in the Early Jurassic, according to Biswas (e.g., 1980, 1991, 2016a, b) in the early Middle Jurassic. The syn-rift phase continued to the end of the Jurassic period to be replaced by the post-rift phase in the Early Cretaceous (e.g., Biswas, 2016a). As one would expect, the associated tectonic activities are not only expressed by the formation of half-grabens bordered by faults and by corresponding changes in the thickness and facies of Jurassic strata normal to the long axis of the basin but also by several sedimentary features smaller in scale. These are particularly well-developed during the Late Jurassic, which corresponds to the late syn-rift phase. A well-known example is the soft-sediment deformation structures seen in the Kimmeridgian Jhuran Formation of the Khari River section north of Bhuj, which have been interpreted as seismites (Kale *et al.*, 2016). Similarly, sedimentary features such as dying growth faults, sand volcanoes, and frequent local intraformational unconformities in the same formation in more western parts of the basin, at the Keera and Jumara domes (Fig. 1.2), have been interpreted by Seth *et al.* (1990) as products of seismic shock waves. Here, we document sedimentary dykes and several sediment deformation features in the Jhuran Formation, which are related to ongoing tectonic activity during the late syn-rift stage of the basin.

GEOLOGICAL FRAMEWORK

The Jurassic and Lower Cretaceous sediment package in the Kachchh Rift Basin consists of three megacycles (Biswas, 2016a). The first of these records the transgression of the sea which culminated in the Oxfordian. During the second megacycle, starting in the Kimmeridgian and extending to the end of the Jurassic, the basin became gradually infilled by large delta systems that prograded from the east towards the west (e.g., Alberti *et al.*, 2019). Whereas the first two megacycles were formed during the Jurassic syn-rift stage, the Early Cretaceous megacycle recorded the final fill of the basin and is part of the post-rift stage (Biswas, 2016a). The sediments of the Late Jurassic megacycle have been accommodated in the Jhuran Formation, a nearly exclusively siliciclastic unit with a diminishing marine influence from west to east, which ranges in age from the late Early Kimmeridgian to the earliest Cretaceous (Fig. 2). The formation consists of several sandstone packages that are separated by argillaceous silt and silt units. Thick sandstone units are of delta-front origin (e.g., Desai and Biswas, 2018) or represent their offshore continuation as sand sheets. Thin sandstone beds commonly display hummocky cross-stratification or parallel lamination and are interpreted as recording the influence of storm waves or storm-induced flows. The fine-grained sediments are partly developed as bioturbated dark mudrocks (in some cases even as black shales; Arora *et al.*, 2015), and partly are interlayered with ripple cross-laminated sandstones

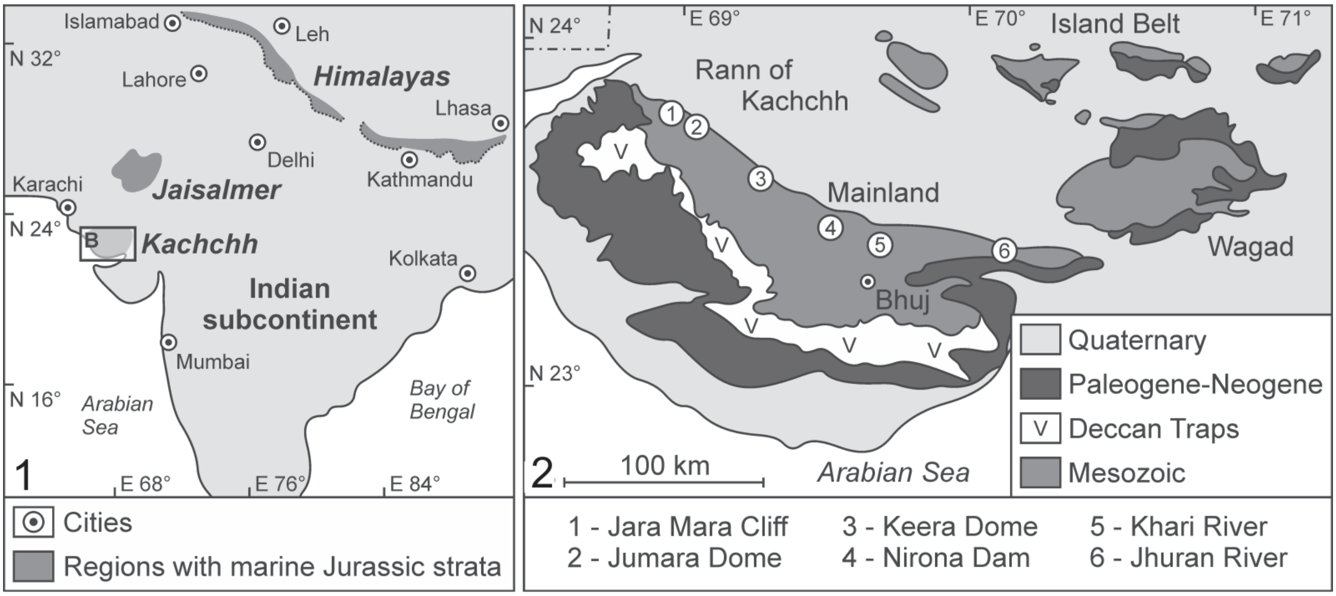


Fig. 1. 1. Schematic map of the Indian subcontinent showing areas with marine Jurassic strata including the Kachchh Rift Basin. 2. Simplified geological map of the Kachchh Rift Basin showing localities mentioned in the text.

or siltstones. Commonly, these sediments are arranged in highly asymmetric transgressive – regressive cycles (e.g., Fürsich and Pandey, 2003; Desai and Biswas, 2018; Pandey *et al.*, 2020; Fürsich *et al.,* 2021) and represent environments ranging from the foreshore above the fair-weather wave-base to offshore areas beyond the reach of storm-induced currents.

Lithostratigraphically, the Jhuran Formation of the Kachchh Mainland traditionally has been subdivided into four members, the Lower, Middle, Upper, and Katesar Member (Biswas, 1980, 2016a) ranging in age from the late Early Kimmeridgian to the Barremian. A new, more refined subdivision (Fürsich *et al.*, in prep.) recognizes in the western part of the basin the informal Lower member, followed by the Jara Sandstone Member, Green Ammonite Member, and Trigonia Sandstone Member, and in the eastern part the basal Jhuran River Member, followed by the Lothia Member and the Jhuran Sandstone Member (Fig. 2).

	Formation
Cretaceous	**Bhuj**
Tithonian–Kimmeridgian	**Jhuran**
Oxfordian–Callovian	**Jumara**
Bathonian–Bajocian	**Jhurio**

Member
Jhuran Sandstone *
Lothia *
Jhuran River *

Fig. 2. Lithostratigraphy of Jurassic rocks of the Kachchh Basin with the informal members of the Jhuran Formation in the eastern part of the basin. Asterisks denote the presence of soft-sediment deformation structures in the informal members of the formation.

LOCALITIES

Sedimentary dykes have been observed in the Kachchh Mainland at three localities (Fig. 1.2): (a) in the middle and at the eastern cliff of the Jhuran River (co-ordinates: N 23°21’36.9’’, E 69°59’40’’ and N 23° 21’32.7’’, E 69°59’51’’ respectively), (b) at the Nirona dam (N 23°26’30’’, E 69°29’06’’), and (c) in the Jara Mara cliff south of the village Jara (N 23°41’48.1’’, E 69°00’43.8’’). Additional sediment-deformation features are described from the Jhuran Sandstone Member of the Jhuran River (N23°21’10’’, E69°59’23’’).

RESULTS

Sedimentary dykes in the Lothia Member of the Jhuran River

The best example of sedimentary dykes in the Jhuran Formation can be seen south of Jawahar Nagar near the road to Kaniyabe. The described outcrops are found on both sides of a track leading westwards from this road to the bottom of the river bed and in a small outlier towards the centre of the river valley (Fig. 3.1). The near-vertical to slightly oblique dykes occur in dark-grey shaly fine-sandy argillaceous silt with cm-thick intercalations of ferruginous siltstone of the lower Upper Kimmeridgian Lothia Member (Intermedius Ammonite Zone) and usually are spaced several metres apart (Fig. 3). They are seen for a stratigraphic interval of at least 15 m and individual dykes can be followed for several metres up-section (Fig. 4.1). Commonly, the shaly sediment right next to the dykes is slightly upturned. Most of the dykes

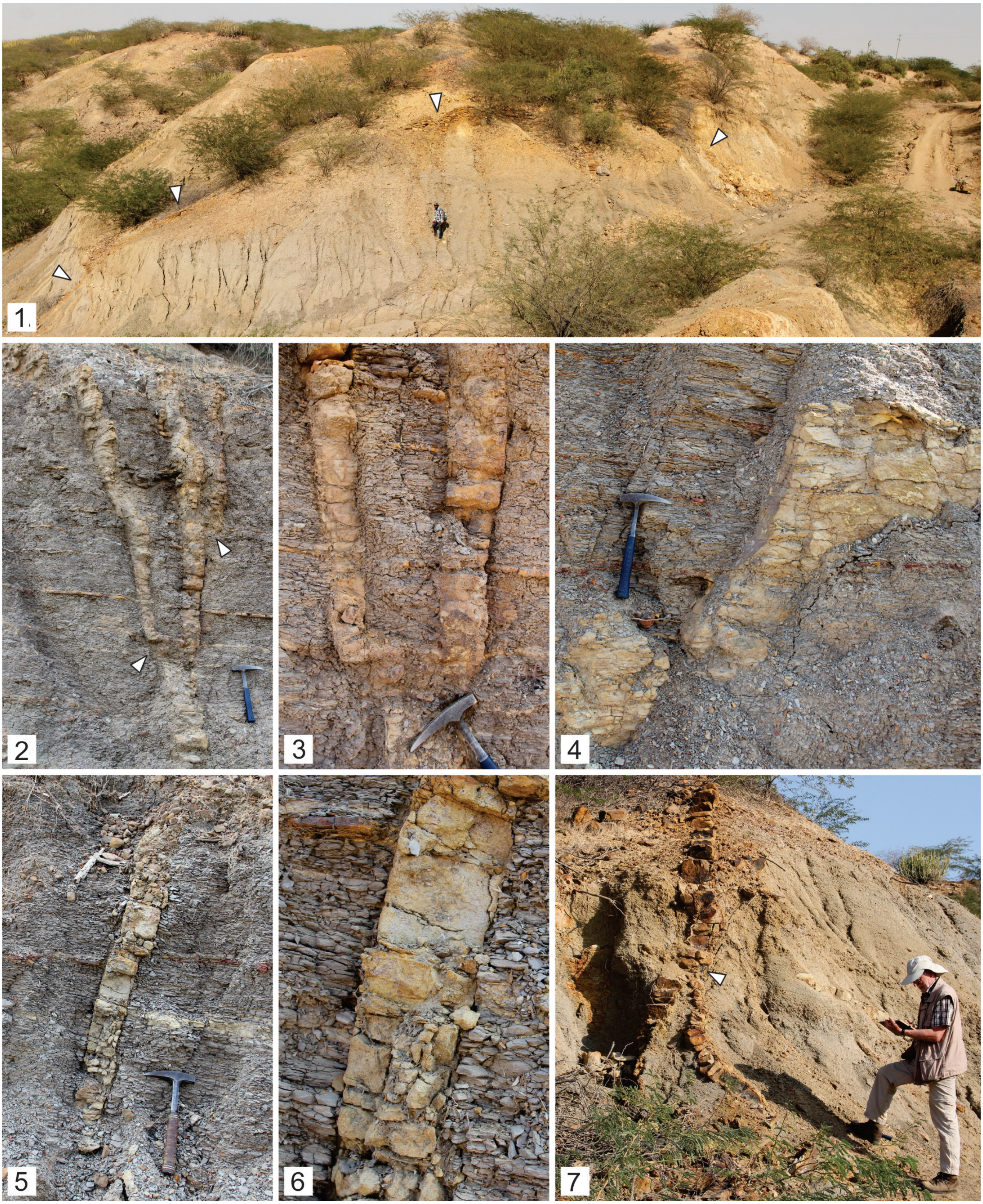


Fig. 3. Field photographs of the sedimentary dykes in the Lothia Member of the Jhuran River section. 1. Overview of the study area. Arrows indicate outcrops of a single sedimentary dyke (Dyke 9). 2, 3. Detailed view of Dyke 1 with arrows indicating branching points. 4. Lateral view of Dyke 2. 5, 6. Detailed views of Dyke 3 with a width of ca. 12 cm. Note the small-scale displacement of the intercalated siltstone band next to the dyke in (5). 7. Dyke 9 is characterized by the merging of two tortuous branches (arrow).

are sub-vertical with an inclination either to the east or W. Only two of the dykes are more strongly inclined (37° and 40°, respectively) (Fig. 5.1). In width, they range from 5 to 30 cm whereby the thickness may vary a bit. Most dykes are unbranched, but Dyke 1 splits up into three branches (Fig. 3.2, 3.3) and in Dyke 9 two tortuous branches merge up-section (Fig. 3.7). Although the strike direction of the dykes displays some scattering, there is a clear preference for the range 150°–180° with a second, albeit smaller, peak in the 90°–120° range (Fig. 5.1). Only a few measurements of joints occurring at the stratigraphic level of the dykes are available, but these also seem to show a slight preference for north-south and east-west directions (Fig. 5.2). All dykes are filled with sandstone, but the lithology varies from fine- to coarse-grained quartz arenite.

Sedimentary dykes and deformation features in the Jhuran River Member of the Nirona dam

In the Nirona dam section, two sedimentary dykes occur 31 m above the base of the Jhuran Formation in a black to beige shaly, fine-sandy argillaceous silt with cm-thick concretionary ferruginous bands (Fig. 4.2). The vertical dykes, which cross each other at a roughly right angle, are seen in the bedding plane view and represent two directions, 100° and 10° (Fig. 6). Their cross-section varies between 7 and 10 cm. The dykes consist of very poorly sorted, pinkish fine-grained sandstone with scattered coarse quartz grains. Another dyke seen at the base of the same shale unit has a direction of 154°. Three meters below the dyke level there is a fine-grained sandstone with convolute bedding and associated micro-faults. Finally, at around 23 m above the base of the formation, a rotated block of sandstone, 1 m in diameter, occurs within a 10.8-m-thick trough cross-bedded fine-grained sandstone (Fig. 4.2).

Sedimentary dyke in the Lower member of the Jara Mara cliff

Within the lower part of the Jara Mara cliff section there occurs a dyke near the base of a 40-m-thick argillaceous silt unit, which overlies a 3-m-thick package of fine-grained sandstone with scattered coarse quartz grains (Fig. 4.3). The dyke measures 15 cm across, its strike direction is 30°, and it consists of poorly sorted fine-grained sandstone with scattered coarse quartz grains (Fig. 7.1).

Soft sediment deformation features in the Jhuran Sandstone Member of the Jhuran River

The Jhuran Sandstone Member consists of thick packages of large-scale cross-bedded fine- to coarse-grained sandstones interpreted as delta-front deposits. Between these packages, there are thinner-bedded and finer-grained units, partly bioturbated, partly ripple or hummocky cross-laminated, or interlayered siltstone-sandstone beds. Close to the base of one of these finer-grained intervals, there is a 50-cm-thick bed consisting of subangular to subrounded blocks of beige bioturbated medium-grained sandstone separated from each other by grey-violet fine-grained sandstone (Fig. 7.3–7.4). The succession shown in Figure 4.4 depicts the top part of an 8.7-m-thick planar to trough cross-bedded fine- to medium-grained sandstone. The last 5–10 cm are ripple cross-laminated and contain dark silt intercalations.

The width of the sandstone slabs varies between 25 and 50 cm and some measure up to 120 cm across. Between the sandstone slabs, the material of the underlying bed has been pushed up, and thin interlayers of silt-/sandstone drape the slabs on top and fill depressions between them. The unit is followed by 30–40 cm of hummocky cross-stratified ferruginous fine-grained sandstone with oscillation ripples on top (Fig. 4.4). Within a distance of fewer than three meters, the sandstone slabs are tilted at various angles (Fig. 7.2).

DISCUSSION

The combination of soft-sediment deformation structures described above is best interpreted as having been caused by seismic shock waves (e.g., Lucchi, 1995; Rossetti and Góes, 2000; Owen and Moretti, 2011; Ghosh *et al.*, 2012). The sandstone fill of the sedimentary dykes in the Jhuran River section contrasts sharply with the surrounding dark-grey argillaceous silt. The upturned shaly layers in the immediate vicinity of the dykes confirm that the sandy material has been injected from a lower level. As the section in Fig. 4.1 shows, the most likely source of the sandy dykes is the top of the Jhuran River Member, approximately 15–20 m below the dyke level. Some of the dykes are filled with ferruginous fine-grained sandstone, others with coarse-grained sandstone. This documents that individual dykes became filled with sediment derived from different levels and may represent more than a single seismic event. The fill of the dykes observed in the Jara Mara cliff and near the Nirona dam again differ distinctly from the surrounding sediment but do not offer much additional information being isolated occurrences. The directions of the dyke near the Nirona dam are also represented by the dykes in the Jhuran River section (Fig. 5.1).

Convolute structures are generally interpreted as liquefaction features and may have various causes such as rapid deposition of a substantial layer of usually sandy sediment on top of the now disturbed layer, storm surges, and tsunamis (e.g., Molina *et al*., 1998; van Loon, 2009; Owen *et al*., 2011). Where layers indicative of rapid sedimentation or evidence of very high current velocities are lacking such as near the Nirona dam, the origin of the convolute structures more likely is related to seismic events.

The occurrences of large sandstone pillows, some of them oriented at different angles, in the Jhuran Sandstone Member of the Jhuran River section (Fig. 7.2–7.4) and the Jhuran River Member near the Nirona dam are also most easily explained by earthquakes. A layer of sand became disrupted by a seismic event and turned into isolated pillows. Between the pillows, the underlying still soft sediment was pushed upward to partially fill the space between them (Fig. 4.4). The remaining space was filled by interlayered siltstone/

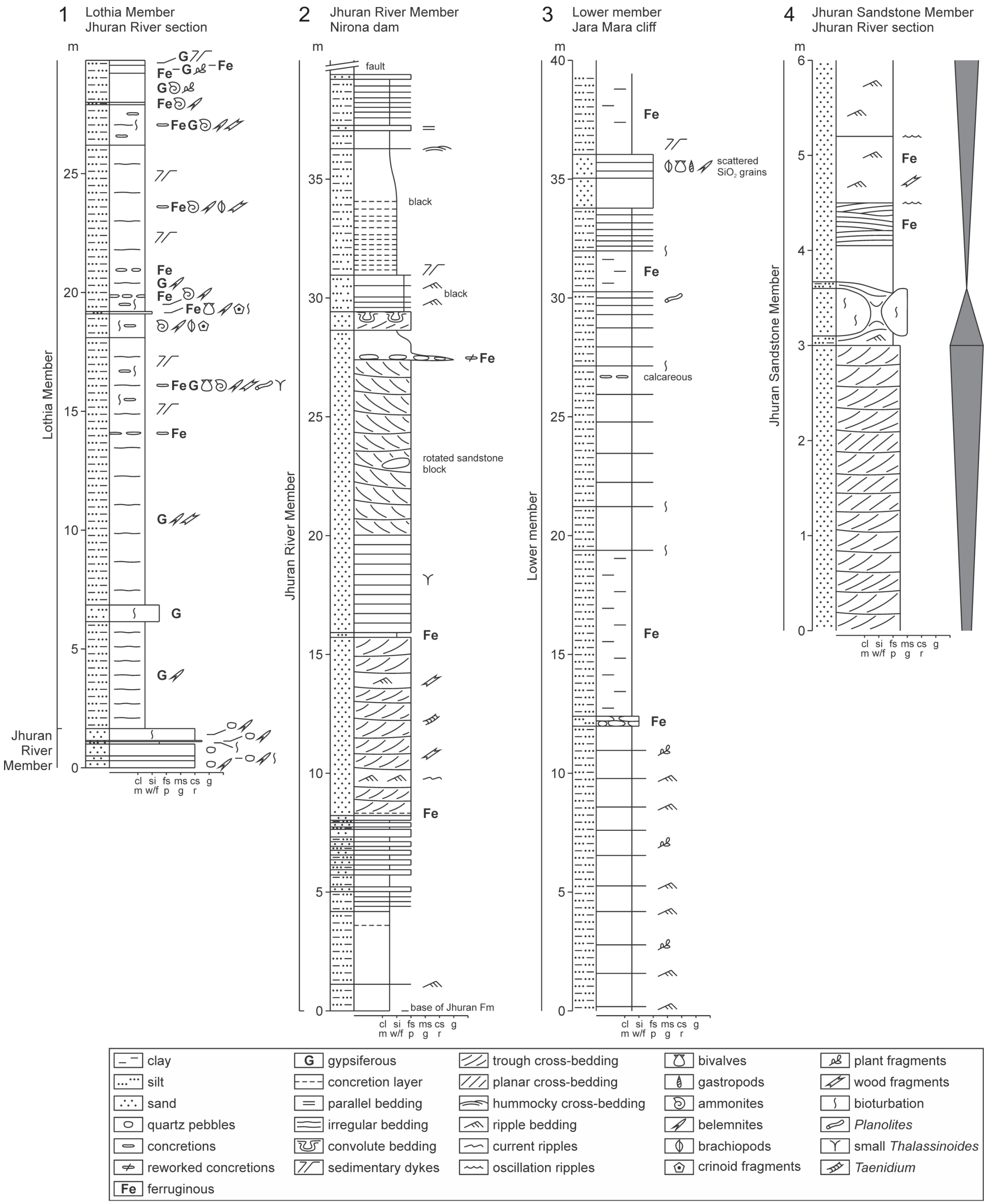
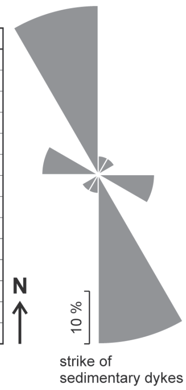


Fig. 4. Sections of parts of the Lothia Member at the Jhuran River section (1), of the Jhuran River Member at the Nirona dam (2), the Lower member at the Jara Mara cliff (3), and of the Jhuran Sandstone Member at the Jhuran River section (4).

1 Characteristics of sedimentary dykes

no.	strike	incl.	lithology	branch.	w. (cm)
1a	180°	10°E	coarse-gr. ss	yes	15
1b	5°	5°W	coarse-gr. ss	yes	5-7
1c	151°	5°E	coarse-gr. ss	yes	10
2	57°	0°	medium-gr. quartz ss	no	15
3	167°	13°E	coarse-gr. quartz ss	no	12
4	165°	12°E	medium-gr. ss	no	5
5	162°	3°E	fine-gr. ss	no	15
6	119°	13°W	medium-gr. ss	no	30
7	165°	0°	ferr. fine-gr. quartz ss	no	7-10
8	150°	5°W	ferr. fine-gr. quartz ss	no	20
9	100°	0°	poorly sorted medium-gr. ss	yes	20-30
10	170°	37°W	ferr. fine-gr. quartz ss	no	5
11	175°	40°W	poorly sorted ferr. fine-gr. ss	no	7
12	95°	5°N		no	20



2 Direction of joints

no.	strike	inclination
1	124°	10°SW
2	171°	0°
3	160°	0°
4	32°	0°
5	90°	0°
6	79°	0°
7	22°	50°NW
8	21°	0°
9	20°	0°
10	119°	0°
11	103°	0°

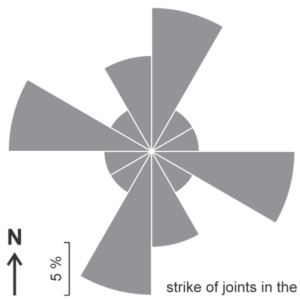


Fig. 5. Characteristics of sedimentary dykes (1) and joints (2) measured in the Lothia Member of the Jhuran River section. branch., branching; w, width; incl., inclination; gr., grained; ss, sandstone; ferr., ferruginous;

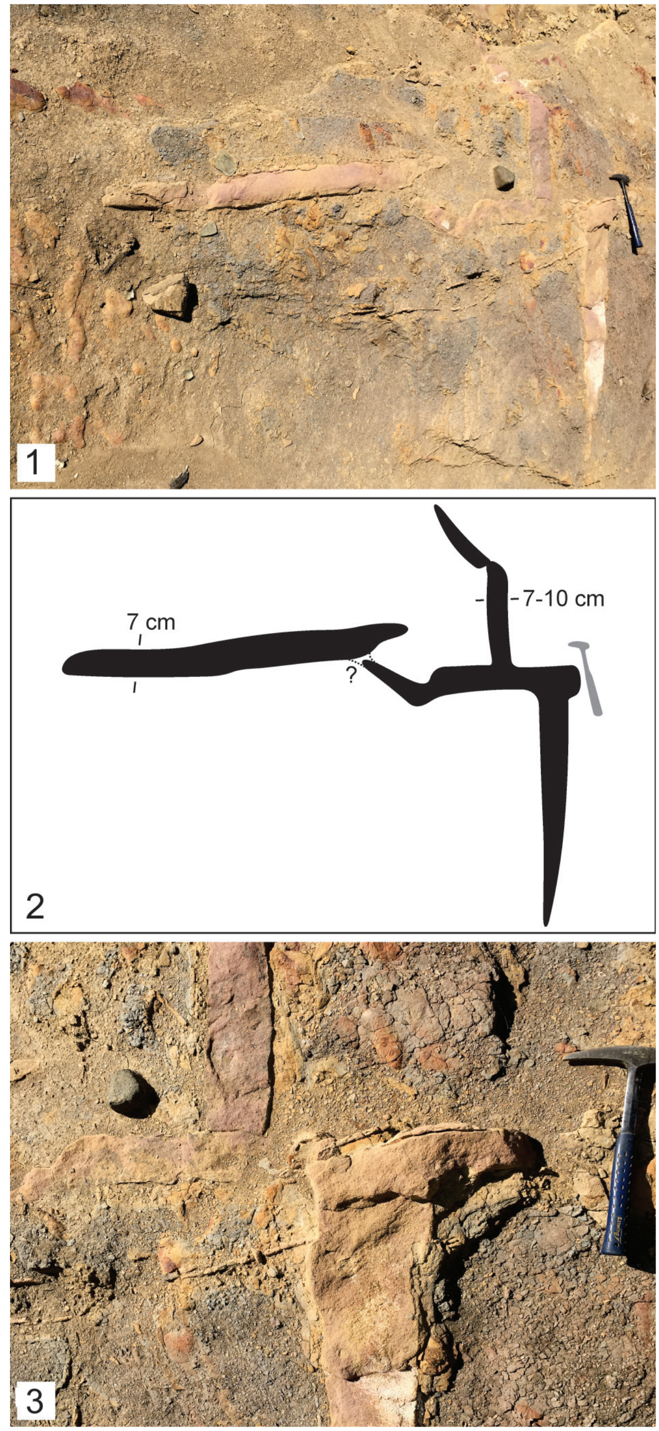


Fig. 6. Field photographs and explanatory sketch of the sedimentary dykes in the Jhuran River Member near the Nirona dam.

sandstone that otherwise forms a thin layer overlying the sandstone pillows. Apart from the local expansion of this layer, it appears to be undisturbed. There are no signs of significant lateral movements of the pillows. The pillows resemble ball and pillow structures described throughout the geological history and from numerous localities worldwide (e.g., Weaver and Jeffcoat, 1978; Rossetti, 1999; Boggs, 2006; Koç Taşgın *et al.*, 2011; Ghosh *et al.*, 2012; Ozcelik, 2016). They are interpreted as the result of physical shock, commonly earthquakes. Blocks tilted at different angles (Fig. 7.2) suggest that the sand unit, when mobilized, locally had already undergone early diagenetic initial lithification (concretion formation).

The pillows occur on top of a several metres-thick large-scale trough cross-bedded sandstone package, which is the top part of a coarsening- and shallowing-upward succession (highstand systems tract) interpreted to represent a delta-front environment. The bioturbated sandstone level, represented by the blocks/pillows, is interpreted as having been deposited during the ensuing transgression and is followed by another coarsening-upward package starting with hummocky cross-stratified and ripple-cross-laminated fine-grained sandstone (lower delta front) and turning into coarse-grained sandstone of the upper delta front (Fig. 4.4).

Sedimentary expressions of seismic activities are to be expected in a rift basin. So far, hardly any such features have been recorded from the Kachchh Basin before the Oxfordian. One of the few instances is large convoluted beds in the Bajocian thin-bedded Sadhara Coral Limestone Member of the Kaladongar Formation at the core of the Sadhara Dome (pers. obs.). They are most easily explained as having been caused by earthquakes. At several localities of the Dhosa Oolite Member of the Jumara Formation (particularly in the Jara and Jumara domes; compare Fig. 8.1) large isolated slabs of concretionary sandstone occur in the so-called Dhosa Conglomerate Bed, angled in different directions and floating in a pebbly micritic matrix (Fürsich *et al.*, 1992; Alberti *et al.*, 2013). This arrangement has been explained as a result of the liquefaction of the micritic matrix caused by seismic shock (Alberti *et al.*, 2013). In the overlying Jhuran Formation features such as dying growth faults, local intraformational angular unconformities, and shale beds with brecciated layers confined to their base have been described by Seth *et al.* (1990) and interpreted to reflect

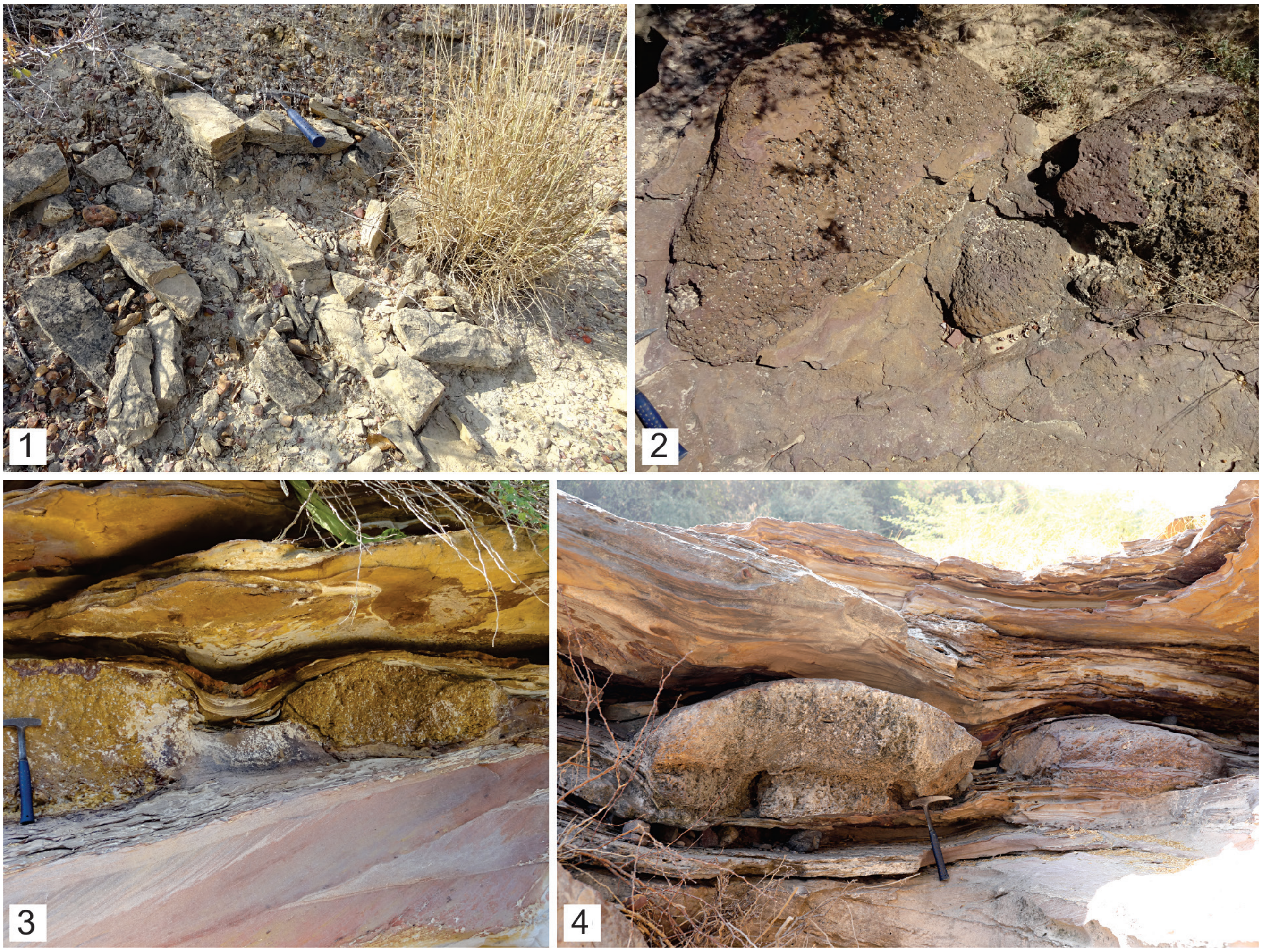


Fig. 7. Field photographs of the sedimentary dyke in the Lower member at the Jara Mara cliff (1) and of the sandstone pillows in the Jhuran Sandstone Member of the Jhuran River section (2–4).

seismic activity. Spectacular soft-sediment deformation structures from the Rudramata Member (= Lothia Member) of the Jhuran Formation have been described by Kale *et al.* (2016) in the Khari River section at the Rudramata Reservoir north of Bhuj. Apart from a small-scale clastic dyke, the authors document slump folds, convolute bedding, and small-scale synsedimentary faults restricted to particular horizons (compare Fig. 8.2–8.4). Excluding various other potential explanations of these features, Kale *et al.* (2016) interpreted the beds as seismites recording episodic seismic activity. The gravity flows documented by Desai and Biswas (2018) in the Jhuran delta succession exposed in the vertical cliff of the Jara Mara River (Jara Dome) are features that characteristically occur in a deltaic setting and may simply be the result of increased river discharge and a corresponding higher sedimentation rate. However, a seismic trigger of the observed debris flows and slumps cannot be excluded. Finally, Bandyobhadhyah (2004) described large convolute lamination and sedimentary clastic dykes from the Wagad Formation (time equivalent to the Jhuran Formation) of the Wagad Uplift in eastern Kachchh and related them to Late Jurassic tectonic activity in the area. Thus, it appears that in the Kachchh Basin earthquakes more commonly occurred during the Late Jurassic than during earlier Jurassic time intervals. This tectonic activity suggests that during the period represented by the Jhuran Formation the basin was still at the syn-rift stage and not at the post-rift stage as envisaged by Desai and Biswas (2018). In this context, the occurrence of a large slump in the Upper Jurassic of the neighbouring Jaisalmer Basin (Fig. 8.5, 8.6), interpreted as having been caused by seismic activity, is interesting since it might suggest stronger tectonic activity during the Late Jurassic at a regional scale along the western margin of the Indian craton than hitherto assumed (compare Alberti *et a*l., 2017).

CONCLUSIONS

The Kimmeridgian–Tithonian Jhuran Formation of the Kachchh Rift Basin displays several features indicative of soft-sediment deformation such as sedimentary dykes, convolute lamination, and pillow structures, which are interpreted to have been caused by earthquakes. They are recorded here

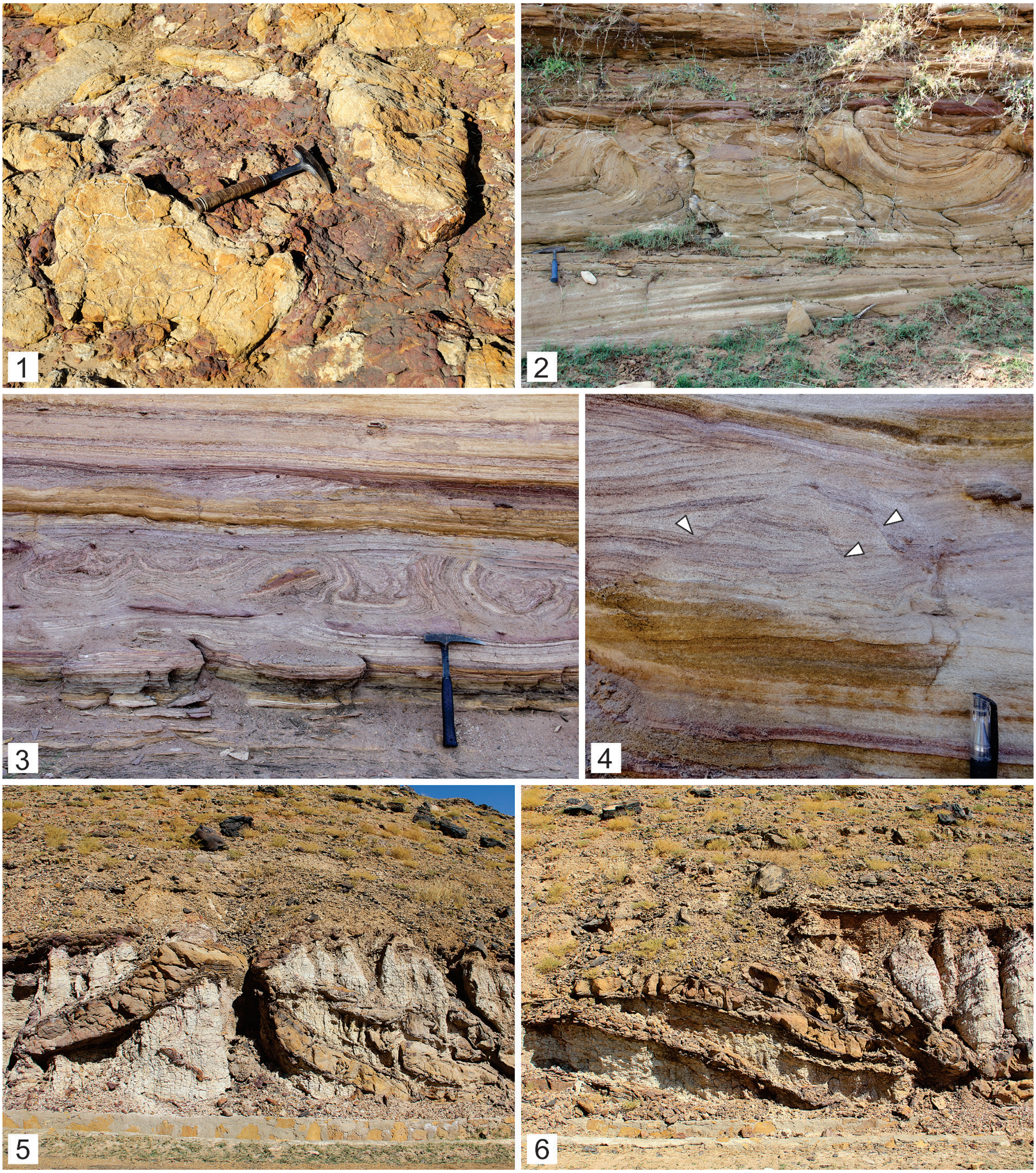


Fig. 8. Field photographs of additional sedimentary features in the Upper Jurassic of the Kachchh and Jaisalmer basins already previously connected to synsedimentary seismic activity. 1. Concretionary sandstone slabs oriented at various angles in the Oxfordian Dhosa Conglomerate Bed at Jara Dome (compare Alberti *et al*., 2013). 2-4. Soft-sediment deformation features in the Kimmeridgian Lothia Member at the Khari River section (compare Kale *et al*., 2016). 5-6. Large-scale slumping in the Upper Jurassic of the Jaisalmer Basin (compare Alberti *et al*., 2017). Width of pictures approximately 7 m.

from the type section of the formation, the Jhuran River, from the Jara Mara cliff, and the Nirona dam, occurring in both Kimmeridgian and Tithonian strata. Together with published records of synsedimentary deformation features in the formation, they support that the Kachchh Basin was still at the syn-rift stage during the Late Jurassic.

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