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Multi-origin of soft-sediment deformation structures

Slumping in the Upper Jurassic Baisakhi Formation of the Jaisalmer Basin, western India: Sign of synsedimentary tectonics?

Matthias Alberti [a,b,*], *Dhirendra K. Pandey* [c], *Jitendra K. Sharma* [b], *Narendra K. Swami* [b], *Alfred Uchman* [d]

[a] *Institut für Geowissenschaften, Christian-Albrechts-Universität zu Kiel, Ludewig-Meyn-Straße 10, 24118 Kiel, Germany*
[b] *Department of Geology, University of Rajasthan, Jaipur 302004, India*
[c] *Earth & Planetary Sciences Group/Palaeontology, Manipal Center for Natural Sciences, Manipal University, Manipal 576104, India*
[d] *Institute of Geological Sciences, Jagiellonian University, Oleandry 2a, 30-063 Kraków, Poland*

Abstract A spectacularly exposed slump is described from a 120-m-long road cut between the villages of Kanod and Deva in the northeastern Jaisalmer Basin of Rajasthan, India. The Upper Jurassic part of the sediments at the outcrop was formed in a near-shore setting and belongs to the Ludharwa Member of the Baisakhi Formation. The 3-m-thick unit shows a number of asymmetric folds and thrust faults leading to an imbrication of partly lithified sandstone beds. The deformation structures allow the reconstruction of a movement towards the northwest. This agrees well with the basin configuration that shows a deepening into this direction. Although the determination of a specific trigger mechanism is difficult for soft-sediment deformation structures, an earthquake caused by synsedimentary tectonics in the basin seems to be the most likely explanation.

Keywords Sedimentology, Mass movements, Slumping, Soft-sediment deformation structures, Jaisalmer Basin, Jurassic

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* Corresponding author.
E-mail address: matthias.alberti@ifg.uni-kiel.de (M. Alberti).
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1. Introduction

Soft-sediment deformation structures are ubiquitous features occurring within marine, lacustrine, fluvial, or terrestrial environments. Slumps (or slump sheets) are connected with the down-slope movement of a sediment mass and characterized by internal deformation (*e.g.*, reverse faults or folded beds; Allen, 1982; Owen *et al.*, 2011). Such movements of poorly consolidated sediments have been frequently described from the geological record (*e.g.*, Alsop *et al.*, 2016; Debacker *et al.*, 2001; Karlin *et al.*, 2004; Mastrogiacomo *et al.*, 2012; Ortner and Kilian, 2016; Shanmugam *et al.*, 1994) and can also be observed in the present (*e.g.*, Niemi and Ben-Avraham, 1994). Their formation is mostly attributed to a loss of shear strength of water-saturated, soft sediments due to sudden sedimentary overload, oversteepening of the slope gradient, sudden changes in wave action, or allogenic trigger mechanisms such as earthquakes or less commonly tsunamis and meteorite impacts (Allen, 1982; Chiarella *et al.*, 2016; Garcia-Tortosa *et al.*, 2011; Gladkov *et al.*, 2016; Moretti *et al.*, 2016; Obermeier, 1996; Owen and Moretti, 2011; Owen *et al.*, 2011; Shanmugam, 2016). Other possible processes leading to slumps are often confined to special circumstances (*e.g.*, glacial loading, salt tectonics, and volcanic activity; Shanmugam, 2016). Slumps generated by earthquakes are also commonly named seismites (Seilacher, 1969), although the validity of the term has been questioned recently (Shanmugam, 2016). While slumps have often been connected to comparatively steep slopes (*e.g.*, Kenyon *et al.*, 1978; Lewis, 1971), it is known that they can also occur at very weak gradients (<1°; Allen, 1982; Garcia-Tortosa *et al.*, 2011; Gibert *et al.*, 2005; Wells *et al.*, 1980). Once their mode of formation can be reconstructed, slumps can add valuable information to the depositional environment (*e.g.*, Strachan and Alsop, 2006).

The present study focuses on a slump spectacularly exposed along an approximately 120-m-long road cut in the northeastern part of the Jaisalmer Basin of western India. This outcrop of Upper Jurassic rocks was mentioned by Pandey *et al.* (2014: p. 101), but the detailed morphology and genesis of the slump are described here for the first time. Its analysis and interpretation can serve as a case study for deformational structures in slumps as well as further our knowledge on depositional conditions in the Jaisalmer Basin during its formation.

2. Geological overview

The Jaisalmer Basin in westernmost Rajasthan (Fig. 1) was formed due to the breakup of Gondwana (Pareek, 1981). It is a pericratonic basin located at the northwestern boundary of the Indian Subcontinent. During the Jurassic, it formed part of the southern Tethyan margin close to the Malagasy Gulf separating Africa from India (see Pandey *et al.*, 2014: fig. 14B). Geological research in the area started already more than a century ago (*e.g.*, Blanford, 1877; Carter, 1861; Oldham, 1886) and since then continued incessantly (for a complete and recent review of the literature see Pandey *et al.*, 2014). Today, the Jurassic succession is subdivided into four formations (Lathi, Jaisalmer, Baisakhi, and Bhadasar) and 14 members (Fig. 2; Das Gupta, 1975; Garg and Singh, 1983; Kachhara and Jodhawat, 1981; Pandey and Krishna, 1996; Pandey *et al.*, 2012, 2014; Sharma, 2016).

In comparison to the neighbouring Kachchh Basin (Fürsich *et al.*, 2013), the Jurassic succession of the Jaisalmer Basin is thinner, but also represents a variety of depositional environments. The landscape is characterized by flat plains with few low hills at the fringe of the Thar Desert. Consequently, the Mesozoic rocks are often covered by desert sand and outcrops are scattered. In general, the Jurassic succession starts with fluvial, deltaic, lacustrine, and marginal-marine sediments of the Lathi Formation (Early Jurassic to Bajocian; Bonde, 2010; Lukose, 1972; Pandey *et al.*, 2006; Pieńkowski *et al.*, 2015; Srivastava, 1966). Marine shallow-water deposits dominate the following Jaisalmer, Baisakhi, and Bhadasar Formations (Middle to Late Jurassic), but repeated phases of subaerial exposure are recorded in the sediments (*e.g.*, by fluvial conglomerates, caliche nodules, rootlet horizons, and potential insect burrows; Fürsich *et al.*, 1992; Mahendra and Banerji, 1989; Pandey *et al.*, 2005, 2010, 2014). For most of the time, the water depth was very low and even slight fluctuations in sea level led to distinct facies changes. Many of the lithostratigraphic members correspond to such small-scale variations. In addition, they commonly are present and/or preserved only in parts of the basin and their boundaries are diachronous (Pandey and Pooniya, 2015; Pooniya, 2013). These characteristics, together with the occasionally poor outcrop conditions, make intrabasinal correlations very difficult (Pandey *et al.*, 2009, 2014). Bed-by-bed collecting of ammonites has helped to clarify problems (for example the dating of certain litho-

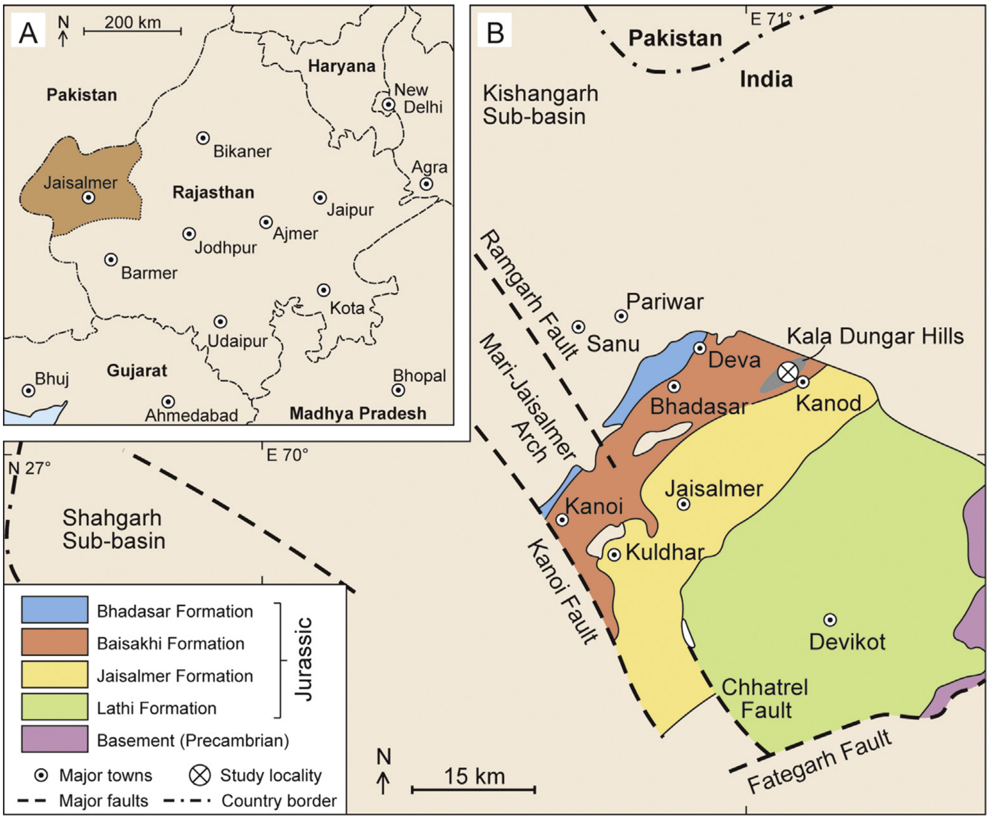

Fig. 1 A—Sketch map of Rajasthan in western India showing the major cities and the location of the Jaisalmer District; B—Geological sketch map of the Jurassic of the Jaisalmer Basin indicating the position of the study locality along the Kanod-Deva Road through the Kala Dungar Hills (modified after Das Gupta, 1975; Pandey *et al.*, 2014).

Age	Formation	Member	
?Early Cretaceous	Bhadasar	Mokal	
Tithonian		Kolar Dungar	
Tithonian –Oxfordian	**Baisakhi**	Lanela	Ludharwa
		Rupsi	
		Basal	
Oxfordian	Jaisalmer	Jajiya	
Callovian		Kuldhar	
Mid.–Late Bathonian		Bada Bag	
Early Bathonian –Bajocian		Fort	
		Joyan	
		Hamira	
Bajocian –Early Jurassic	Lathi	Thaiat	
		Odania	

Fig. 2 Lithostratigraphic framework of the Jurassic strata of the Jaisalmer Basin (modified after Sharma, 2016).

stratigraphic units or the identification of diachronous boundaries; *e.g.*, Sharma and Pandey, 2016), but many open questions exist especially regarding unfossiliferous units.

The Baisakhi Formation is Late Jurassic in age and consists of four lithostratigraphic members (Fig. 2). Their age, relationship, and stratigraphy have been recently reviewed by Pandey and Pooniya (2015). The rocks are exposed along an arc, approximately 8—10 km wide, stretching from the Kanoi Fault in the southwest to the area northeast of Kanod (Fig. 1). The Basal Member is characterized by carbonaceous, grey to black, silty clay. The sediment contains ammonites and belemnites, but no benthic fossils. The diversity of trace fossils is very low. Based on the fossil cephalopods, its age has been given as Middle to Late Oxfordian (Chatterjee, 1990; Pandey and Pooniya, 2015; Prasad, 2006). The following Rupsi Member consists mainly of occasionally-bioturbated silty clay with intercalations of partly cross-bedded, gypsiferous siltstones and fine-grained sandstones. Characteristic is the common occurrence of ferruginous concretions. The rocks contain ammonites and belemnites, as well as few trace fossils (*e.g.*, *Zoophycus*, *Planolites*, *Thalassinoides*; Pandey and Pooniya, 2015). A Kimmeridgian to Early Tithonian age has been assigned to the unit (Pandey and Krishna, 2000; Pandey and Pooniya, 2015). The Lanela Member consists of thinly-bedded, silty fine-grained sandstone interbedded with thin fine-grained sandstone beds and is Early Tithonian in age (Pandey and Pooniya, 2015). While the Basal, Rupsi, and Lanela members are dominated by fine-grained sediments, the Ludharwa Member is characterized by brown, cross-bedded, commonly-bioturbated, moderately-to well-cemented, fine- to medium-grained sandstones and occasionally conglomerates. The unit is fossiliferous with ammonites, plant fragments, and diverse trace fossils (*e.g.*, *Ancorichnus*, *Asterosoma*, *Gyrochorte*, *Gyrolithes*, *Palaeophycus*, *Phycosiphon*, *Polykladichnus*, *Taenidium*, *Thalassinoides*, *Skolithos*; Pandey and Pooniya, 2015). Its age has been given as Oxfordian to Early Tithonian (Pandey and Pooniya, 2015).

It should be noted that the lower boundary of the Baisakhi Formation as well as boundaries between its members are diachronous (Fig. 2; *e.g.*, parts of the Basal Member and the lowermost Ludharwa Member were deposited at the same time as the rud- and packstones of the upper Jajiya Member of the Jaisalmer Formation). The fine-grained Basal, Rupsi, and Lanela members are interpreted to represent conditions in the basin centre, while the Ludharwa Member formed under shallow-water conditions closer to the shoreline.

3. Study locality and depositional setting

The presently described slump is exposed along an approximately 120-m-long road cut between the villages Kanod and Deva in the Kala Dungar Hills, approximately 30 km northeast of Jaisalmer (N 27°08′09.0″, E 071°05′49.2″; Fig. 1). The succession measured across the hill side comprises around 39 m of siliciclastic sediments belonging to the Ludharwa Member (Fig. 3). It consists mainly of fine- to medium-grained sandstones with common ferruginous concretions in the lower half of the section. Towards the top cross-bedded sandstone beds occur as well as horizons with caliche nodules and rootlets. In the lower part, the beds are characterized by trace fossils including *Thalassinoides*, *Gyrolithes*, and unidentifiable burrows. Towards the top, the trace fossil *Ophiomorpha* appears. Due to a strong ferruginization of the sediments other sedimentary structures (*e.g.*, load or flame structures) are not visible.

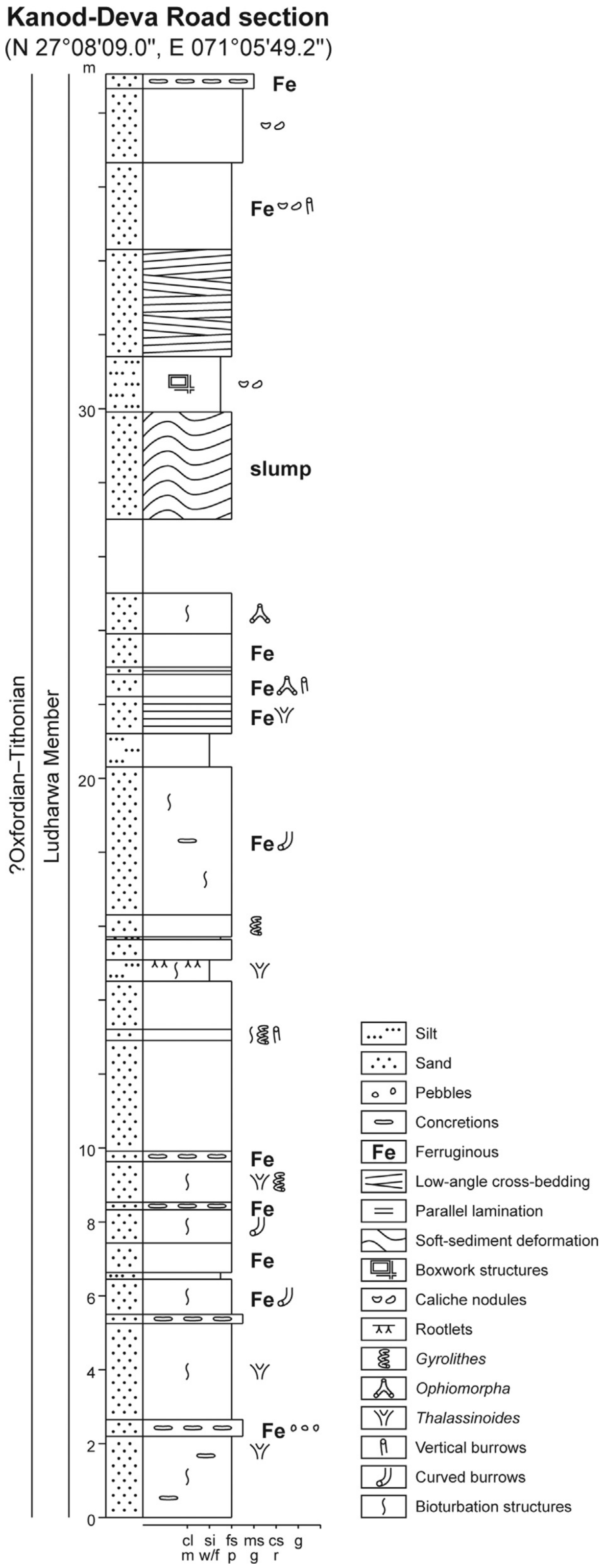

Fig. 3 Section through the Ludharwa Member of the Baisakhi Formation at the Kanod-Deva Road (N 27°08′09.0″, E 071°05′49.2″; modified after Pandey *et al.*, 2014). cl = clay; si = silt; fs = fine-grained sand; ms = medium-grained sand; cs = coarse-grained sand; g = gravel; m = mudstone; w/f = wacke-/floatstone; p = packstone; g = grainstone; r = rudstone.

In general, the Jaisalmer Basin was enclosed on three sides and opening towards the northwest (Pandey *et al.*, 2014). Most likely, the Ludharwa Member at the Kanod-Deva Road section represents a marginal-marine to terrestrial setting. The trace fossil *Gyrolithes* indicates very shallow and brackish water conditions (Fig. 4; Gernant, 1972; Netto *et al.*, 2007; Uchman and Hanken, 2013). Towards the top, the succession shows several beds with caliche nodules and rootlets which certainly formed above the sea level. The overall coarsening-upward trend in the Ludharwa Member reflects a shallowing, which is superimposed by small-scale fluctuations of relative sea-level leading to an alternation of sediments of a terrestrial, brackish, and marine origin. While few ammonites are present in the lower part of the unit, the higher energy conditions during the formation of the cross-bedded sandstones towards the top led to the destruction of hardparts and the absence of body fossils. Thereby, the succession at the Kanod-Deva Road closely resembles that of the better known Kahla Village section which has been studied and interpreted recently in detail (Pandey and Pooniya, 2015; Pandey *et al.*, 2014; Pooniya, 2013). The Ludharwa Member at this locality displays a series of depositional environments from fully marine to marginal-marine, brackish, deltaic, coastal-plain, and fluvial towards the top (Pandey *et al.*, 2014). Most of the basal beds were deposited in a setting below the fair-weather wave base (possibly lower shoreface; Pandey *et al.*, 2014) as evident by the occurrence of fine-grained sediment, marine organisms (*e.g.*, ammonites), and a diverse, well-preserved ichnofauna. Intervals with low-angle cross-stratification and vertical burrows (*e.g.*, *Skolithos*) have been interpreted to represent the upper to lower foreshore (Pandey *et al.*, 2014). The upper part shows trace fossils indicative of brackish water conditions (*e.g.*, *Polykladichnus*; Fürsich and Werner, 1986) and has been interpreted as a protected bay environment showing fluvial influence (Pandey *et al.*, 2014). The top of the Kahla Village section is then formed by a conglomerate of fluvial origin (Pandey *et al.*, 2014).

On a more regional scale, the Ludharwa Member represents near-shore deposits prograding into the basin. Deposition of the sediments started already in the Oxfordian, while in other parts of the basin sediments of the Jajiya Member (Jaisalmer Formation) formed. Due to the progradation of the Ludharwa Member, it commonly forms the top of successions and can be found overlying the Jajiya, Rupsi, and Lanela members further towards the basin centre.

4. Slump morphology

The unit exhibiting the deformation features consists of almost 3 m of poorly cemented, fine-grained sand with intercalated moderately-cemented, fine- to medium-grained sandstone beds (Figs. 5 and 6). Few thin horizons show higher clay and silt contents. The base of the unit is not exposed. The deformed sedimentary layers repeatedly change their strike and angle of dip. They exhibit an angular disconformity with the under- and overlying strata (Fig. 6A). Especially the harder sandstone beds show evidence of folding and faulting (Fig. 6B–G). Imbrication of beds can be seen repeatedly (Fig. 6C, F). The planes of the thrust faults dip towards southeast. The fold axes are directed northeast-southwest and the limbs directed southeast are generally longer and more gently inclined, while the northwestern flanks are steeper (Figs. 5 and 6D). The softer, more fine-grained

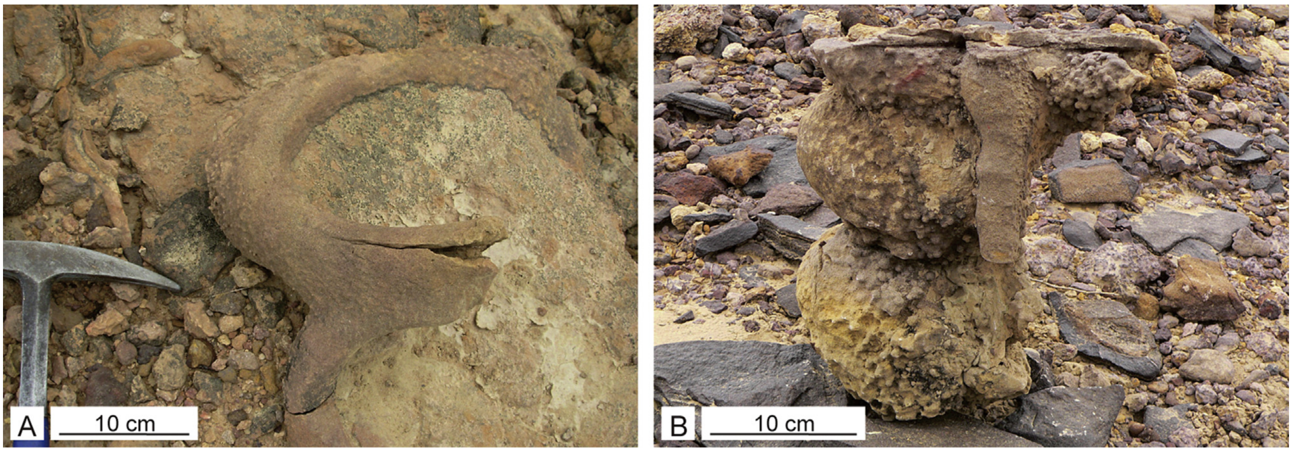

Fig. 4 The trace fossil *Gyrolithes* isp. in the Ludharwa Member of the Baisakhi Formation at the Kanod-Deva Road section (modified after Pandey *et al.*, 2014).

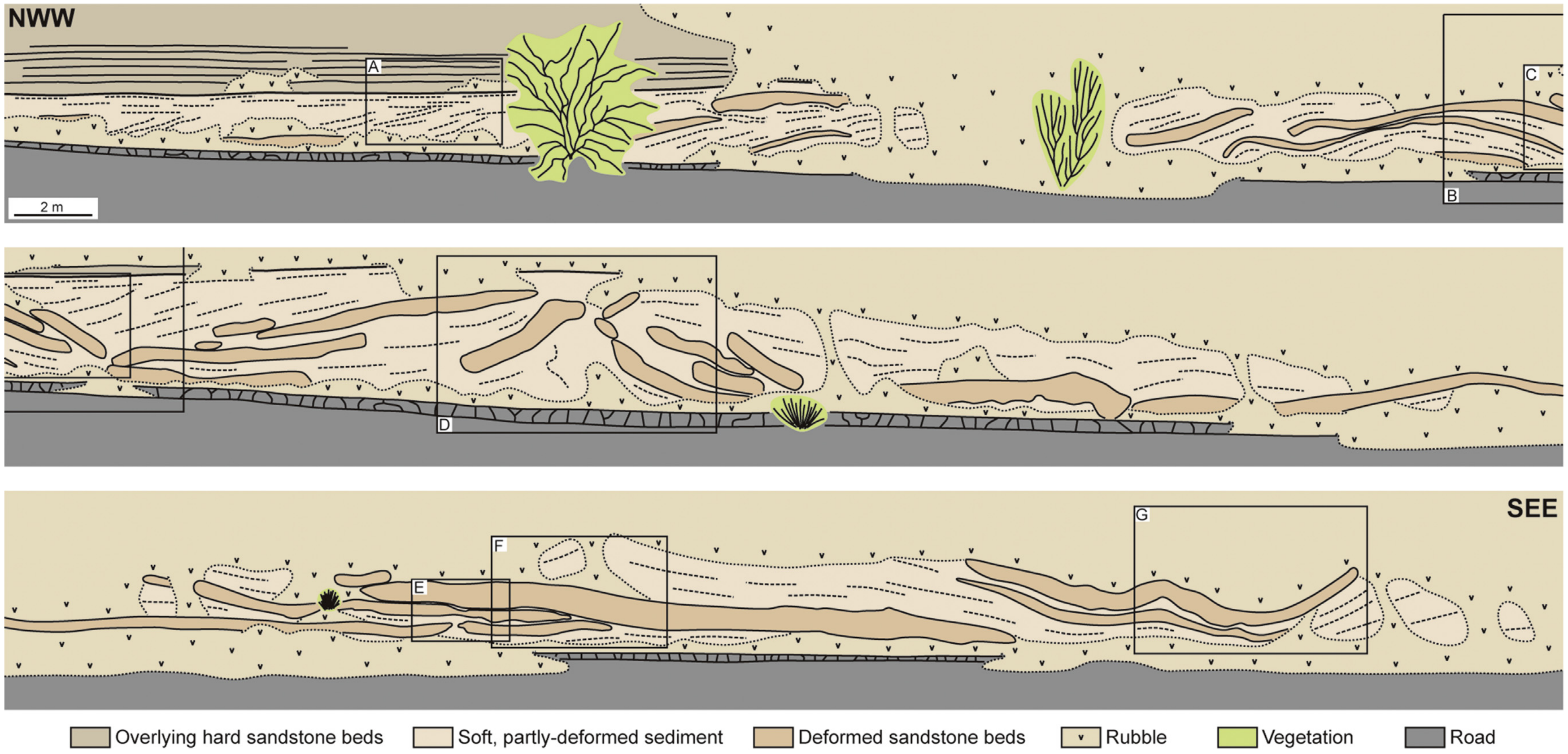

Fig. 5 Sketch of the approximately 3-m-thick slump along the 120-m-long road cut between Kanod and Deva. The road has a direction from SEE to NWW (100°) with the outcrop at its northern side. The boxes indicate the position of the photographs in Fig. 6.

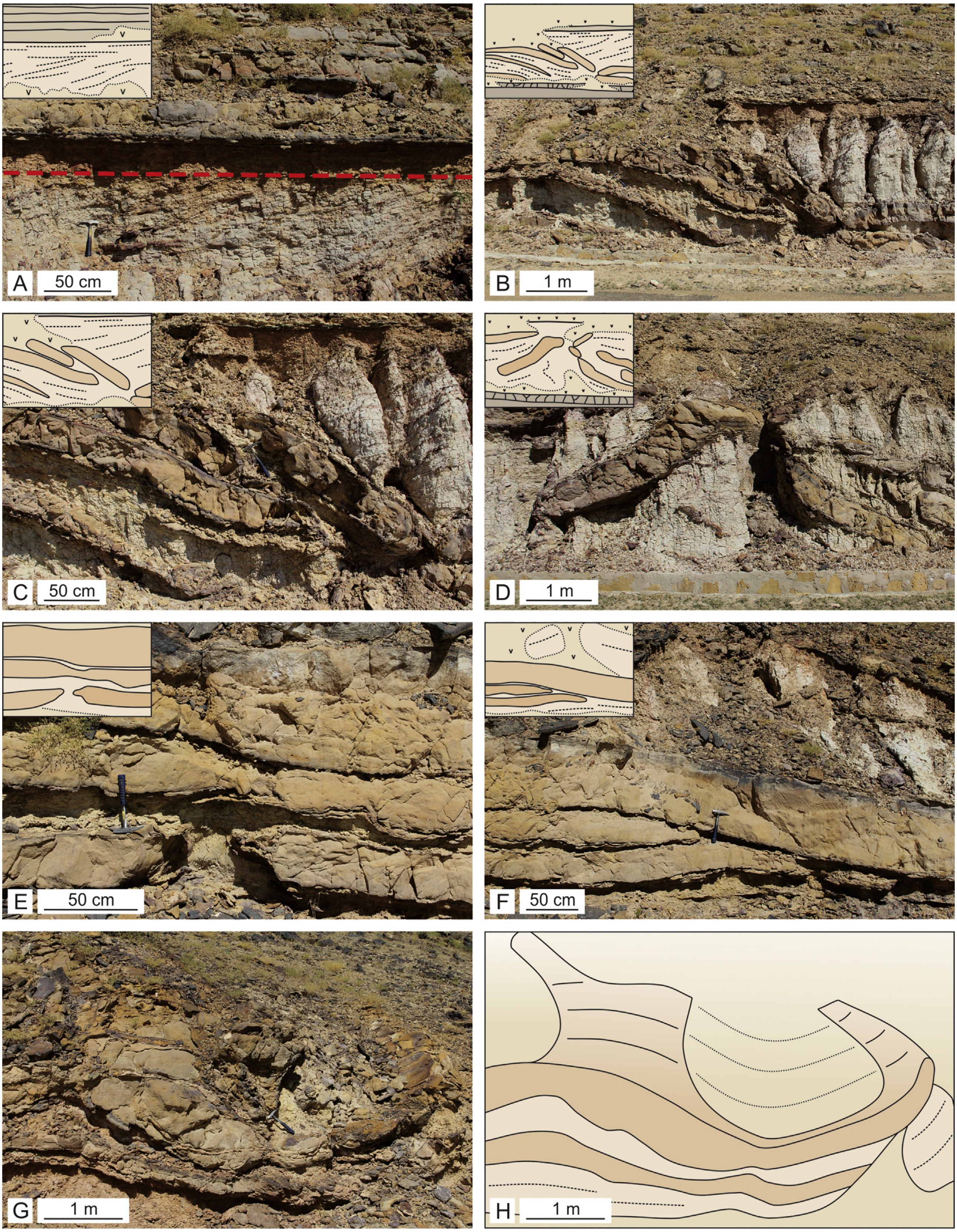

Fig. 6 Field photographs of the slump exposed along the Kanod-Deva Road. The exact positions of the photographed parts of the outcrop are illustrated in Fig. 5. A—Disconformity (shown as red dashed line) between tilted layers within the slump and horizontally-bedded, overlying sandstone beds; B, C—Sandstone beds showing imbrication due to thrust faults. The fault planes are dipping towards SEE (right) and the sediments moved towards NWW (left); D—Folded sandstone bed with a steeper flank towards NWW (left) and a more gently inclined limb towards SEE (right); E, F—Imbricated sandstone beds; G, H—Photograph and interpretative drawing of three-dimensionally exposed, folded sandstone beds.

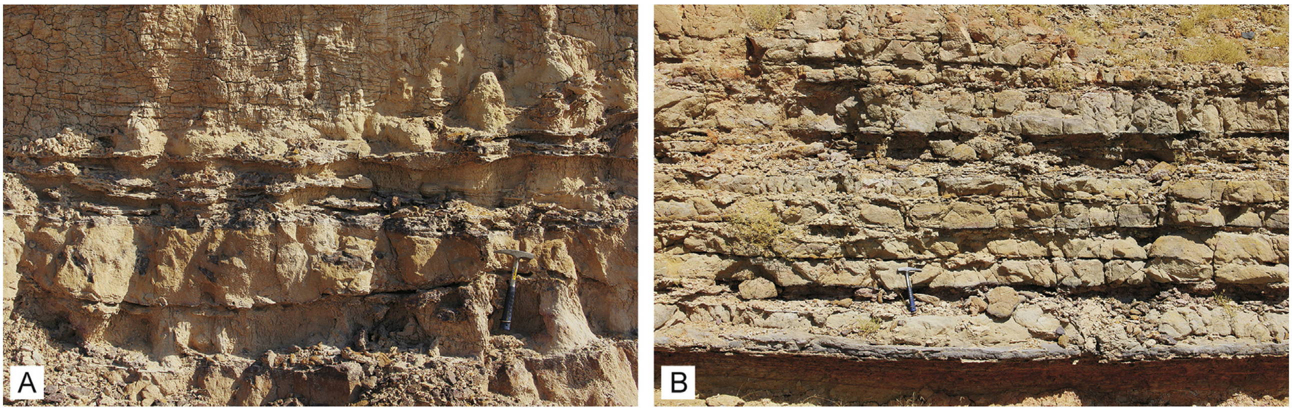

Fig. 7 A—Partly lenticular sandstones with irregular upper and lower surfaces exposed 200 m towards the southeast of the slump (N 27°08′09.3″, E 071°05′56.1″; 33-cm-long hammer for scale); B—Regularly bedded sandstones with sharp, even boundaries overlying the slump (33-cm-long hammer for scale).

sediment is occasionally more strongly deformed and lost all traces of primary lamination.

Following the road 200 m towards the southeast, the unit is first covered by scree, but again exposed beyond a curve (N 27°08′09.3″, E 071°05′56.1″). At this outcrop, the beds are less deformed and show a sub-horizontal bedding (Fig. 7A), but are often lenticular, showing sharp and irregular upper and lower surfaces.

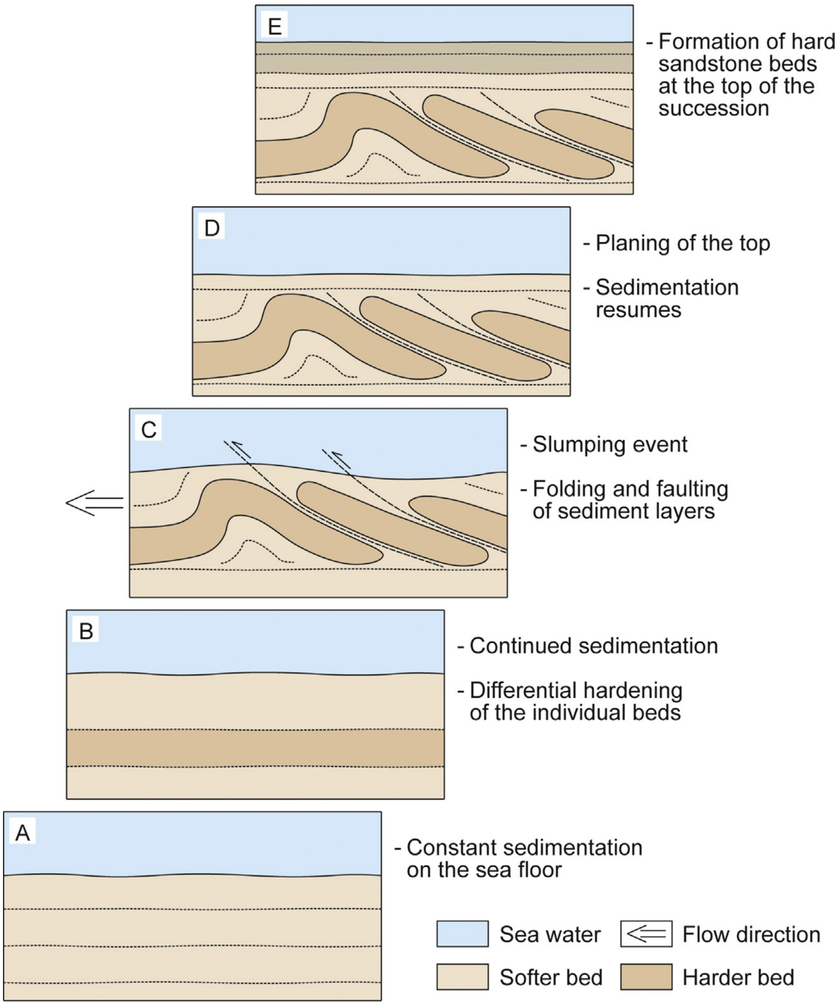

Fig. 8 Sketch summarizing the formation of the slump. For further explanation see text.

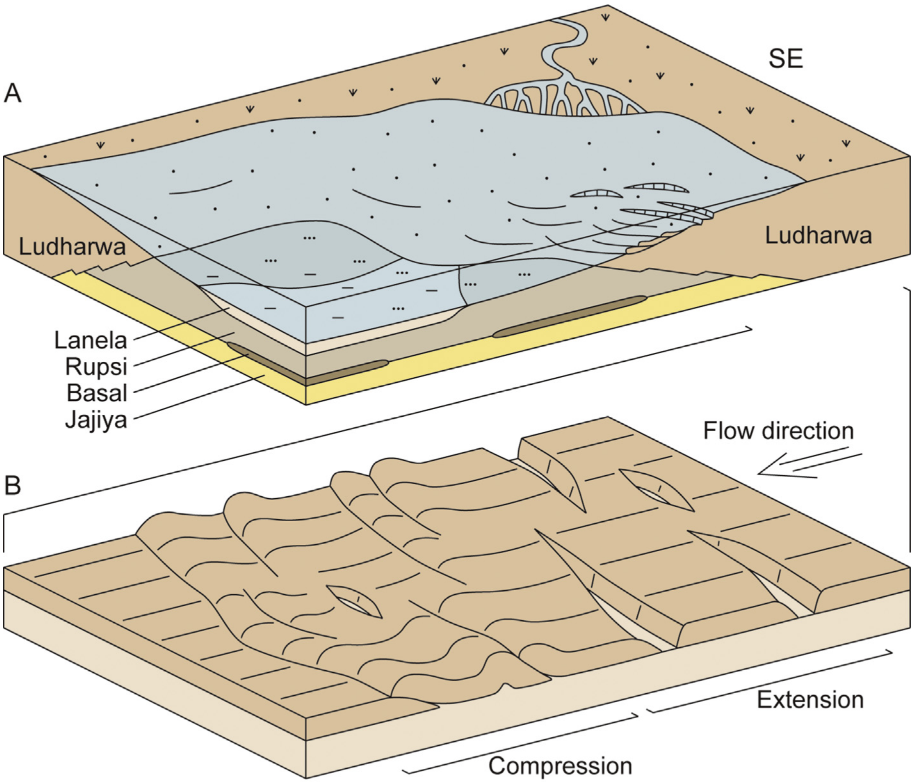

Fig. 9 A—Block diagram illustrating the distribution of the different members of the Baisakhi Formation in the northeastern half of the Jaisalmer Basin; B—Schematic model of a slump showing the zone of extension up-slope and the zone of compression down-slope (modified after Gibert *et al.*, 2005).

In contrast, the strata overlying the deformed unit are very regularly bedded sandstones with sharp, even boundaries (Fig. 7B).

5. Interpretation of the slump

The regular bedding of the under- and overlying strata points to a synsedimentary nature of the deformation. During normal background sedimentation, evenly-bedded sheets of sand were deposited (Fig. 8A). These underwent differential diagenesis with some beds cemented more than others (Fig. 8B). During the slumping event, the beds were deformed above a detachment plane, which is not visible in the outcrop. While the soft, not yet cemented fine-grained sand reacted ductile, the harder beds were folded and faulted. Asymmetrical folds formed with their steep side pointing towards the flow direction. Similarly, thrust faults led to the imbrication of sandstone beds (Fig. 8C; compare Allen, 1982; Alsop *et al.*, 2016). It can be assumed that the sea floor was very uneven and irregular directly after the slumping event (compare Gibert *et al.*, 2005). However, wave action most likely led to a planing of the surface. Background sedimentation continued leading to a disconformity with the irregularly inclined layers of the slump (Fig. 8D). Eventually, the sand at the top of the succession was deposited, which is now strongly lithified (Fig. 8E).

As evident by the deformation structures, the sediment moved down-slope into a northwestern direction. This fits very well with the general basin configuration which was deepening and opening towards the northwest (Fig. 9A; *e.g.*, Das Gupta, 1975; Pareek, 1984). In general, a slump is characterized by a zone of extension up-slope and a zone of compression down-slope (Fig. 9B; Alsop *et al.*, 2016; Gibert *et al.*, 2005; Ortner and Kilian, 2016). The first is characterized by extensional tectonics including normal faults. This zone is not well exposed along the Kanod-Deva Road. Possibly, the southeastern outcrops exhibiting subhorizontal sandstone beds with irregular boundaries often forming lenses represent this area (Fig. 7A). Although normal faults have not been recorded, continuous sandstone beds might have been divided into individual sand lenses by extensional forces (compare Alsop *et al.*, 2016; Martín-Chivelet *et al.*, 2011). In contrast, most of the deformational structures visible in the road cut (Fig. 5) can be attributed to compressional forces.

The determination of the trigger mechanism for soft-sediment deformation structures (or more particularly slumps) is generally a challenge and requires at least a detailed knowledge on the slump morphology as well as the depositional environment (*e.g.*, Martín-Chivelet *et al.*, 2011; Owen *et al.*, 2011; Shanmugam, 2016). A loss of shear strength of the water-saturated sediments can be caused by an increase of pore fluid pressure generated during rapid deposition or via seismic waves (Alsop *et al.*, 2016). The Jaisalmer Basin formed during the rifting of Gondwana which continued throughout the Jurassic (Pareek, 1981). It is bordered by major fault systems which can be expected to have repeatedly caused strong earthquakes in the region. This is important because earthquakes below a certain magnitude will not trigger slumping events (*e.g.*, depending on sediment conditions and potential seismic wave amplification due to specific geological structures; Alsop *et al.*, 2016; Obermeier, 1996). Since the Jaisalmer Basin was a tectonically active region during the Jurassic, a strong earthquake can be considered as a likely trigger mechanism of the observed slump. In contrast, there is no evidence for a sudden sedimentary overload (*e.g.*, fluid-escape structures) or an oversteepening of the slope gradient (also compare reasoning by Gladkov *et al.*, 2016). The sedimentation rate seems to have been relatively constant with the under- and overlying beds showing generally similar grain sizes and sedimentary structures. Endogenic trigger mechanisms, however, often lead to a repeated occurrence of deformation structures in several beds of the same facies types in contrast to the present case (compare Owen *et al.*, 2011). Similarly, there are no signs of sudden changes in wave action or tidal range influencing the sediments. The beds directly underneath or above the slump sheet do not show evidence of strong currents or storm waves, although the general depositional setting might have been marginal-marine. In addition, soft-sediment deformation structures caused by waves or currents reported in literature are also commonly smaller in scale (*e.g.*, Chiarella *et al.*, 2016). An oversteepening of the slope gradient could have been caused by a tectonic tilt of the beds. This would have resulted in a change in the dip of the otherwise undisturbed beds underlying the slump. In contrast, the sediment deposited after the formation of the slump would be horizontally bedded again. Since a resulting difference in dip between the beds under- and overlying the slump unit cannot be observed in the studied succession, this process can also be excluded as a potential trigger mechanism. Even if theoretically possible, it seems unlikely that a rare event, such as a meteorite impact or tsunami, caused the described slump (compare Shanmugam, 2016) without leaving any other trace within the sedimentary record.

6. Conclusions

During the Late Jurassic, the Jaisalmer Basin in western India experienced an overall shallowing from marine to partly terrestrial or fluvial conditions. The Ludharwa Member of the Baisakhi Formation consists of comparatively coarse-grained sediments which were deposited along the margin of the basin. The continuous shallowing caused a coarsening-upward trend within the unit as well as the appearance of trace fossils pointing to high-energy (*e.g.*, *Ophiomorpha*) or marginal-marine to brackish conditions (*e.g.*, *Gyrolithes*). Towards the top, evidence of terrestrial or fluvial influence can be found (*e.g.*, rootlets and caliche nodules).

The described outcrop in the Ludharwa Member of the Baisakhi Formation represents an impressive example of a slump in the geological record. Since its formation took place in a basin bordered by active fault systems, synsedimentary tectonics causing strong earthquakes in the region can be considered as a likely trigger mechanism. The asymmetric folds and orientation of thrust faults within the unit indicate a movement of the disturbed sediments towards the northwest, in the direction of the basin centre.

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