

Sequence stratigraphy of the Oxfordian to Tithonian sediments (Baisakhi Formation) in the Jaisalmer Basin

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Abstract. The Oxfordian to Tithonian sediments deposited along the southern Tethyan margin exhibit very diverse sedimentary facies. The Jaisalmer Basin, situated along the northwestern margin of the Indian peninsula, is a good example of those preserving these sediments (Baisakhi Formation). The scattered nature of the outcrops, due to peneplanation and desert sand cover, and the diversity in sedimentary facies, have led earlier workers to employ a confusing lithostratigraphy and lithostratigraphic correlations. New records of ammonites, more detailed facies description and the application of the sequence stratigraphic method helped to sort out the stratigraphical problems of these isolated outcrops. The complexity of the Oxfordian–Kimmeridgian–Tithonian sediments present in the Jaisalmer Basin, as evidenced by ammonite finds can be traced along an onshore – offshore transect. Within the Oxfordian–Tithonian strata of the Baisakhi Formation, Jaisalmer Basin, 35 parasequences grouped into three depositional sequences (TST–HST/FSST) have been recognized. In at least two cases, the maximum flooding surfaces (MFS) are superimposed on the transgressive surfaces within very condensed sections. The parasequences belong to a continuous succession representing shoreface (deepest part of the basin) to foreshore (shallowest part of the basin). During deposition of the Tithonian succession the southern part of the basin witnessed shallow, nearshore, or foreshore to fluvial depositional environments and, consequently, contains several depositional gaps and less distinct parasequences. The chronological order of the parasequences has been established on the basis of ammonites: Oxfordian – *Perisphinctes (Dichotomosphinctes)* sp. and *P. (Dichotomoceras)* sp.; Kimmeridgian – *Torquatisphinctes alterniplicatus* (Waagen) and *Pachysphinctes* aff. *major* Spath; Tithonian – *Aulacosphinctoides* sp., *Virgatosphinctinae* and other zonal ammonites recorded by earlier workers. The most logical facies correlation in conformity with Walther’s law was also used. Unfortunately, no marker beds have been recognized; however, the record of at least two brackish-water phases helped in the understanding of depositional settings along the onshore-offshore transects during these time intervals. In general, the Kimmeridgian–Tithonian part of Baisakhi Formation exhibits a general coarsening-upward trend and a change from lower shoreface zone to fluvial environments. The three sequence cycles interpreted within the Oxfordian–Tithonian sediments in the Jaisalmer Basin correspond to second-order sequence cycles.

INTRODUCTION

The Rajasthan shelf, broadly representing the southern Tethyan margin, located to the west of the Aravalli range (in the northwestern part of India), constitutes a vast, westerly and north-westerly gently dipping region, which formed the eastern most part of the “Indo-Arabian geological province”

(Rehman, 1963; Shrivastava, 1992; Pandey *et al.*, 2006). Its major part is occupied by the Thar Desert.

Tectonically, three sedimentary basins, viz. the Jaisalmer Basin, the Bikaner–Nagaur Basin and the Barmer–Sanchor Basin have been recognized in this part of the shelf (Misra *et al.*, 1993; Pandey, Dave, 1998, p. 7–10; Pandey *et al.*, 2014). The Jaisalmer Basin is a pericratonic basin with a well docu-

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mented Mesozoic and Cenozoic history, while the other two are intracratonic basins. All of them witnessed different geologic histories albeit they had some geological and structural similarity at some point of geological time.

JAISALMER BASIN

The sedimentary shelf basin of Jaisalmer is situated at the northwestern margin of the Rajasthan Shelf. The shelf deepens towards the northwest across the international boundary and merges into the Sui Basin of Pakistan in the west. The basin evolved at the beginning of the Triassic with the rifting of Gondwanaland (Biswas, 1982, 1991).

The areal extension of this basin is around 30,000 km² (Datta, 1983; Singh, 1984) to 50,000 km² (Awasthi, 2002)

and extends up to Mari in Pakistan and is controlled by a wrench fault system. The basin contains sediments ranging from Precambrian to Quaternary in age and exhibits rapid temporal changes in facies. Lithostratigraphically, the Jurassic sediments of the Jaisalmer Basin have been grouped into four formations; viz. the Lathi, Jaisalmer, Baisakhi and Bhadasar formations (Figs 1, 2). Tectonically, the Jaisalmer Basin is separated from the Nagaur – Bikaner basins by the Pokharan – Nachana high to the northeast and from the Barmer-Sanchor Basin by the Fatehgarh Fault in the south. The central part of the basin is traversed by a pronounced NW–SE-trending regional step-faulted high zone from Jaisalmer to Mari. The Jaisalmer Basin is divisible into four geostructural units (Rao, 1972; Sinha *et al.*, 1993; Singh *et al.*, 2005, Pandey *et al.*, 2014).

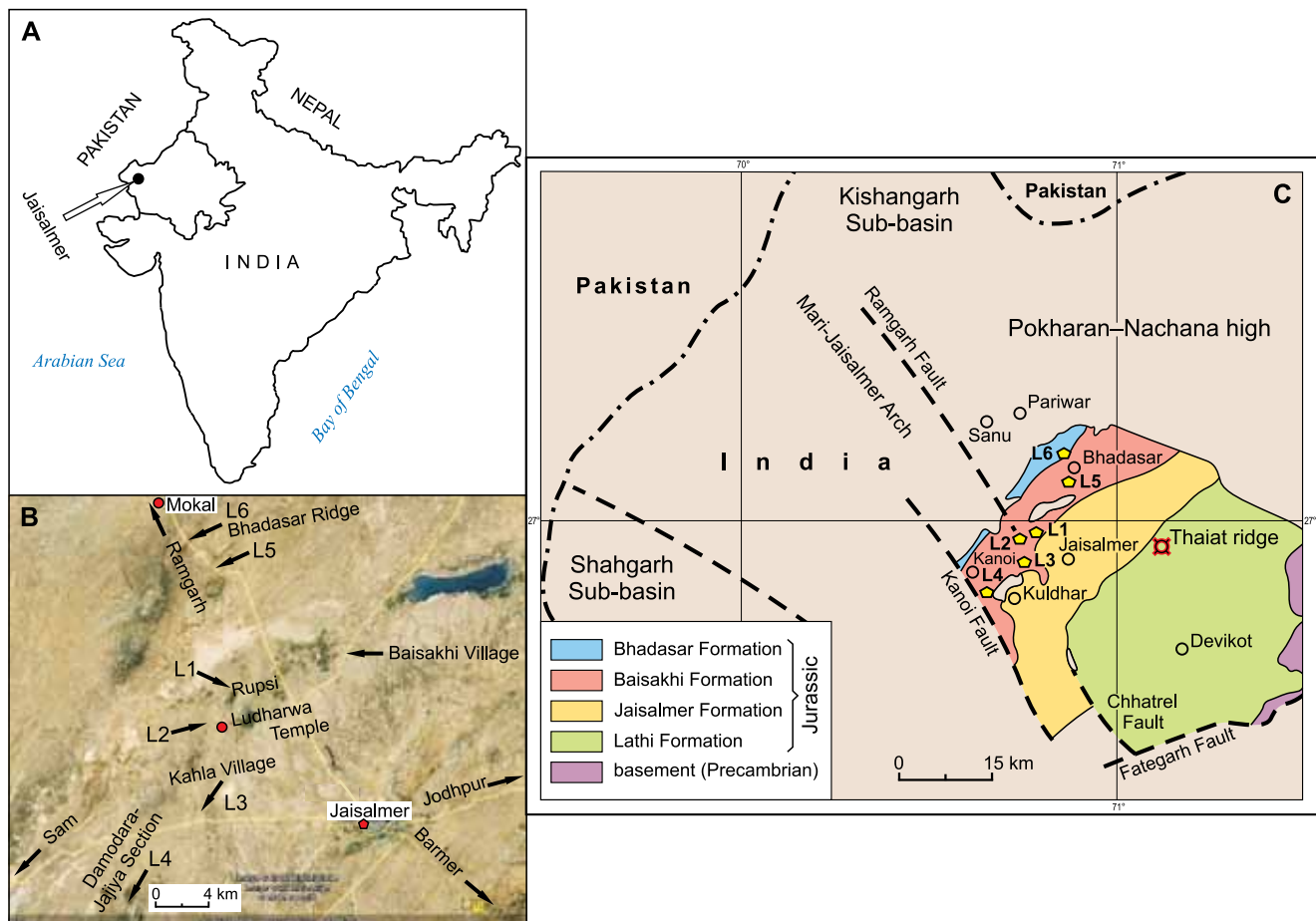


Fig. 1A. Outline map of India showing location of Jaisalmer. **B.** Satellite imagery showing locations of investigated sections (L1–L6). **C.** Geological map of the Jaisalmer Basin (modified after Das Gupta, 1975 and Pandey *et al.*, 2014) showing semi-arcuate outcrop of the Baisakhi Formation and outcrop locations of the investigated sections (L1–L6)

Fm	Das Gupta, 1975	Kachhara, Jodhawat, 1981	Garg, Singh, 1983	Pandey, Krishna, 1996	Modified after Pandey <i>et al.</i> , 2012	Age				
Bhadasar Fm	Mokal Member ²	Bhadasar Fm	Bhadasar Fm	Bhadasar Formation	Mokal Member	Mokal Member	? Lower Cretaceous			
	Kolar Dungar Mb ²				Bhadasar Member ⁵	Kolar Dungar Mb	Late Tithonian			
Baisakhi Fm	Rupsi Member ²	Baisakhi Fm	Formation	Bhadasar Formation	Baisakhi Fm	Lanela Mb ⁶ Rupsi Mb Basal Mb	Ludharwa Mb	Kimmeridgian–Early Tithonian		
	Ludharwa Mb ²								Rupsi Shale Member	Rupsi Member (includes Ludharwa Member)
	Baisakhi Mb ²								Baisakhi Mb	
..... unconformity										
Jaisalmer Formation	Kuldhar Mb ¹	Jaisalmer Formation	Jaisalmer	Jaisalmer Formation	Jaisalmer Formation	Kuldhar Member (includes carbonate succession exposed west of Baisakhi village earlier designated as Baisakhi Member)	Jaisalmer Fm	Jajiya Mb	Oxfordian	
								Kuldhar Mb	Callovian	
	Bada Bag Mb ¹							Bada Bag Mb	Bathonian	
	Fort Member ¹							Fort Member	Bathonian	
	Joyan Member ¹							Joyan Mb	Bajocian	
Hamira Member ²	Hamira Mb	Hamira Member	Lower Jurassic							
Thaiat Member ²	Lathi Formation	Lathi Formation		Lathi Formation	Lathi Fm	Thaiat Member				
Oдания Member ²			Oдания Member							

Fig. 2. A composite lithostratigraphic classification of Jurassic sediments of the Jaisalmer Basin (the corresponding age is based on the information available from the authors)

Additionally information from Krishna, 1979, 1987; Chatterjee, 1990; Pandey, Krishna, 2000; Prasad, 2006 and personal observation have also been incorporated); the members proposed by: 1 – Narayanan *et al.*, 1961; 2 – Das Gupta, 1975; 3 – Kachhara, Jodhawat, 1981; 4 – Garg, Singh, 1983; 5 – Pandey, Krishna, 1996; 6 – Prasad, 2006; 7 – Pooniya, 2013

OXFORDIAN-TITHONIAN SEDIMENTS

The Oxfordian to Tithonian sediments preserved in the Jaisalmer Basin exhibit very diverse sedimentary facies. Due to peneplanation and desert sand cover the outcrops of these sediments are scattered. Swaminathan *et al.* (1959) were the first to map these sediments and grouped them as the Baisakhi Formation. Previously, the sediments had been considered as a part of the “Jaisalmer Group” (see Pandey *et al.*, 2012). Swaminathan *et al.* (1959) did not discuss in detail the vertical as well as lateral lithological variations within the formation and also did not mention a suitable type section for this formation. Subsequently, Narayanan *et al.* (1961) and Das Gupta (1975) gave lithological accounts. The formation occurs in a semi-arcuate belt nearly 10 to 12 km wide south-southwest to northeast of Jaisalmer city. The thickness of this formation is 150–165 m on the surface (Narayanan *et al.*, 1961, Pandey, Dave, 1998).

The Baisakhi Formation consists predominantly of siltstones, fine-grained sandstones and shales. It is now evident that it unconformably overlies either the Bada Bag, Kuldhar or Jajiya members of the underlying Jaisalmer Formation, not just the Kuldhar Member (Das Gupta, 1975, also see Pandey *et al.*, 2012, 2014, Fig. 2), and it is overlain by the Bhadasar Formation. In the subsurface, the boundary between the Baisakhi and the underlying Jaisalmer Formation is marked by a glauconitic plastic clay, whereas in the subsurface it is difficult to demarcate the boundary between the Baisakhi and the overlying Bhadasar Formation (Swaminathan *et al.*, 1959). However, in the outcrop a more than 60 cm thick well cemented cross-bedded, coarse-grained, fossiliferous calcareous/ferruginous sandstone in the basal part of the Bhadasar Formation overlies this formation.

The outcrops of the Baisakhi Formation are rich in fossils. The biotic components include: ammonites, belemnites, brachiopods, bivalves, corals, trace fossils, silicified wood

trunks and other plant remains (Das Gupta, 1975; Misra *et al.*, 1993; Pandey *et al.*, 2014). Based on the sedimentary composition, sedimentary structures and fossils, on the whole a near-shore to shallow marine depositional environment has been inferred for this formation.

The records reveal that there has been no consistency in formalizing the members of the Baisakhi Formation. Previous attempts are shown in Fig. 2. Das Gupta (1975), on the basis of lithology, mentioned three members in the Baisakhi Formation: the Baisakhi, Ludharwa and Rupsi members in ascending order. Garg and Singh (1983) recognized only two members, namely the Baisakhi and Rupsi. Krishna (1983, 1987, p. 146) slightly modified the name of the members and called them the lower Baisakhi Member, middle Ludharwa Member and upper Rupsi Member (Fig. 2). Laul (in Pareek, 1984, p. 38) distinguishes three mappable units – A, B and C, corresponding to the Baisakhi, Ludharwa and Rupsi members of Das Gupta (1975).

Subsequently, Singh (1996) considered the Baisakhi and the overlying Bhadasar formations as a single formation. Pandey and Krishna (1996) considered only the Rupsi Member (including the Ludharwa Member) and included it in the Bhadasar Formation. Prasad (2006) changed the stratigraphic order of the members into the Rupsi, Ludharwa and Lanela members in ascending order.

During recent field surveys (2010–2013) it was observed that the poorly cemented and poorly bedded, marly, ferruginous, yellow, sandy siltstone sediments exposed in low mounds in the generally flat topography, west of Baisakhi village (originally assigned to the Baisakhi Member by Das Gupta, 1975) yield Middle Callovian ammonites. These sediments better correspond to the Kuldhar Member of the Jaisalmer Formation. The carbonaceous grey to black shales with rare plant remains recorded west of Baisakhi village by Das Gupta (1975, p. 80) then belong to the basal part, and were proposed as the newly defined Basal Member, of the Baisakhi Formation (Pandey *et al.*, 2014). In fact, due to poor outcrop condition earlier workers mixed two different horizons there.

The Basal Member is in fact best exposed at the base of the Rupsi scarp section, north of Rupsi village. In the Rupsi scarp section this member has yielded Middle Oxfordian ammonites (*Dhosaites*, *Epimayaites* and *Dichotomosphinctes*; compare Dave, Chatterjee, 1996; Prasad, 2006, p. 7). The ammonites recorded from this member suggest a horizon slightly younger than the Jajiya Member of the Jaisalmer Formation. The middle part of the Rupsi scarp section consists of silty shale to fine grained sandstone (Rupsi Member) and the top part is thick, mostly indurated cross bedded sandstones (Ludharwa Member). The middle and upper parts

of this section have yielded Kimmeridgian to Early Tithonian ammonites (Krishna, 1987; Chatterjee, 1990; Pandey, Krishna, 1996; Pandey, Krishna, 2000). The Rupsi scarp section is the classic section for the Rupsi Member. The Ludharwa sandstones outcrop westwards at Ludharwa village and form a thick succession in this type section of the Ludharwa Member. The last member of the Baisakhi Formation, the Lanela Member, predominantly siltstone and fine-grained sandstone beds, continues up to the base of coarse-grained calcareous sandstone, yielding Late Tithonian ammonites, of the Bhadasar Formation. These siltstone and fine-grained sandstone beds, best exposed along the Bhadasar Ridge, 14 km to the north of Lanela and Bhadasar villages, have been designated as the Lanela Member (Prasad, 2006, p. 9).

The Kimmeridgian age assigned to the Baisakhi Formation (Willm, 1964; Sigal *et al.*, 1970; Das Gupta, 1975; Laul, Kumar, 1994; Singh, 1996) was discounted by Pandey and Krishna (1996, 2000); instead they proposed a Tithonian age on the basis of the occurrence of the ammonites: *Aulacosphinctoides*, *Virgatosphinctes*, *Hildoglochiceras*, *Holcophyloceras*, *Haploceras* in the Rupsi Member (including the Ludharwa Member). Krishna (1987) has however recorded *Torquatisphinctes alterniplicatus* from the Rupsi Member and has assigned it a Late Kimmeridgian age. In addition, Chatterjee (1990); Dave, Chatterjee (1996) have recorded *Pachysphinctes major*, *P. bathyplocus*, *Katrolliceras depressum* and *Lithacoceras indicum* from the Rupsi scarp section and assigned it to the lower and upper Kimmeridgian. Prasad (2006) too has recorded *Katrolliceras* from the Baisakhi Formation. The basal part (Basal Member) of the Rupsi scarp section does contain *Dhosaites*, *Epimayaites* and *Dichotomosphinctes* of Oxfordian age (Dave, Chatterjee, 1996; Prasad, 2006). From the fossil records it seems that all the four members of the Baisakhi Formation are time transgressive from the Middle Oxfordian to the Lower Tithonian (Fig. 2). On the basis of the ammonite records mentioned above the possibility of the presence of Kimmeridgian sediments in the Jaisalmer Basin cannot be ruled out and the suggestion of Pandey and Krishna (2000) to discount the presence of the Kimmeridgian stage from the Jaisalmer Basin should be re-investigated.

BASAL MEMBER OF THE BAISAKHI FORMATION (Pandey *et al.*, 2014)

The member is best exposed at the base of the Rupsi scarp section, north of Rupsi village (N27°00', E70°49'). It consists of fossiliferous, carbonaceous grey to black shales. The fossils consist of ammonites and belemnites. The trace

fossil *Thalassinoides* has been recorded. We could not record even a single body-fossil of the benthic fauna. Chatterjee (1990) and Prasad (2006, p. 7) recorded Middle to Late Oxfordian ammonites (*Dhosaites*, *Epimayaites* and *Dichotomosphinctes*). This member is slightly younger than the Jajiya Member of the Jaisalmer Formation. In the other localities, such as west of Baisakhi village (Das Gupta, 1975, p. 80) and north of Baisakhi village (Prasad, 2006, p. 8), we could not trace the outcrops. Perhaps the low mound of this member is no longer exposed on the surface in these localities. On the basis of the ammonites: *Dhosaites*, *Epimayaites*, *Perisphinctes* (*Dichotomosphinctes*) sp., *P. (Dichotomoceras)* sp., *P. (Dichotomoceras)* cf. *dichotomus* (Buckman), this member has been assigned to Middle to Late Oxfordian age (also see Pandey *et al.*, 2012, 2014).

RUPSI MEMBER OF THE BAISAKHI FORMATION

This member is also best exposed in the Rupsi scarp section, north of Rupsi village (N27°00', E70°49'). In addition, it is also exposed north of Ludharwa village (Prasad, 2006, p. 8), south of Bhadasar Ridge (Fig. 1B) up to the base of Bhadasar Ridge scarp section – where it includes bed 8. Along this scarp section, the member is overlain by the Lanela Member (mentioned below). It consists of a more than 10 m thick succession of fossiliferous, occasionally bioturbated, gypsiferous siltstones and fine-grained sandstones with poorly developed current bedding. The fossils consist of ammonites and belemnites. Trace fossils such as *Zoophycos*, *Planolites* and *Thalassinoides* were observed during the field excursion for the 9th International Congress on the Jurassic System. Chatterjee (1990) recorded “*Pachysphinctes* assemblage zone” of earliest Kimmeridgian age. Prasad (2006) recorded *Torquatisphinctes* and assigned it to Kimmeridgian. In contrast, Pandey and Krishna (2000, p. 24) recognized three ammonite zones within the Rupsi Member: the *Virgatosphinctoides* Zone, the *Aulacosphinctoides natricoides* Zone and the *Virgatosphinctes communis* Zone – all Tithonian. The last zone continues upward into the Bhadasar Member of Pandey and Krishna (1996).

In the current study this member has yielded significant ammonites, viz. *Torquatisphinctes* sp. A, *Torquatisphinctes* aff. *alterneplicatus*, *Torquatisphinctes* sp., *Pachysphinctes* aff. *major* Spath, *Aulacosphinctoides* sp., *Virgatosphinctinae*, and a fragment of an ammonite referred to the Himalayitinae. Based on ammonites, the Rupsi Member has been assigned Kimmeridgian to Early Tithonian age. Surprisingly, in this member specimens of body fossils of a benthic macrofauna are rare.

LUDHARWA MEMBER OF THE BAISAKHI FORMATION

This member is exposed in the scarps around Ludharwa village (N26°59', E70°48') and up to the north-northeast at the top of the Rupsi scarp section. According to Prasad (2006), the best section is exposed 200 m west-southwest of Ludharwa Temple, where it overlies a silt-sandstone succession of the Rupsi Member. A good outcrop of the member has also been investigated 10 km to the southwest at the Kahla village section (Figs 1, 3). The thickness of the member decreases towards the northeast so much so that it is only 3 m thick in the Rupsi scarp section, and it is absent in the Bhadasar Ridge scarp section, where the Rupsi Member is overlain by the Lanela Member (Fig. 3). It is composed of brown, cross-bedded, occasionally bioturbated, moderately to well cemented fine- to medium-grained sandstones and an intraformational conglomerate. A *Sagenopteris* leaf has been identified by Dr M.N. Bose from Nibh Dungar (Pareek, 1984, p. 38).

On the basis of the ammonites *Perisphinctes* (*Dichotomoceras*) sp. and *Torquatisphinctes* cf. *alterneplicatus* recorded from the Kahla village section, and ammonites recorded from the beds in the Rupsi scarp section (mentioned above) this member has been assigned an Oxfordian to Early Tithonian age.

LANELA MEMBER OF THE BAISAKHI FORMATION

The Lanela Member is exposed from 3 km south of the village Lanela up to the Bhadasar Ridge (N27°06'05.7", E70°46'43.5"), north of Bhadasar village (Prasad, 2006). The member (beds nos 9–32) is best exposed along the Bhadasar Ridge scarp section below the basal bioturbated coarse calcareous sandstone beds of the Bhadasar Formation (Figs 1, 3). It consists of siltstones and fine-grained sandstones. The member has been assigned an Early Tithonian age (Fig. 3).

SECTIONS INVESTIGATED FOR OXFORDIAN-TITHONIAN SEDIMENTS

The scattered nature of the outcrops and the diversity in sedimentary facies have led earlier workers to a confusing lithostratigraphy and stratigraphic correlation. The records of ammonites by various workers mentioned above from these isolated outcrops without adequate knowledge of facies variation along the onshore-offshore transects also led to a perplexing chronostratigraphic correlation. Therefore, it is

necessary to investigate these sediments in sequence stratigraphy framework.

Five lithological successions of Oxfordian-Tithonian sediments in different localities (L1–L6) of the Baisakhi Formation in the Jaisalmer Basin (Figs 1, 3) were investigated. These successions have been correlated primarily on the bases of the ammonite horizons of earlier workers (Pandey, Krishna, 2000; Prasad, 2006) and those recorded in the present work (also Pandey *et al.*, 2014), and also on the basis of parasequences or stacking pattern and changes in lithology considering onshore-offshore directions. Consequently, the four members of the Baisakhi Formation (viz. Basal, Rupsi, Ludharwa and Lanela members) do not stack one upon each other, but are time transgressive and all range, in part or entirely, from Middle Oxfordian to Early Tithonian in age (Fig. 3).

Damodara-Jajiya road scarp section

(L4, co-ordinates N26°51'53.3", E70°44'00.6",

see Figs 1, 3)

The succession consists of thinly and sharp bedded, bioturbated, occasionally micaceous, poorly sorted, arkosic fine to coarse-grained, argillaceous and feebly calcareous sandstones in the lower part, and thinly cross bedded, occasionally bioturbated silty fine to coarse-grained, occasionally well sorted fine-grained sandstones in the upper part. The biotic elements consist of trace fossils: *Anchorichnus*, *Palaeophycus* and *Rhizocorallium jenense*. In general the succession shows a coarsening upward sequence deposited in a water environment which was low (lower part with *Cruziana* ichnofacies) to high energy (upper part beginning with *Rhizocorallium jenense* of *Skolithos* ichnofacies) (see also Fürsich, 1974; Worsley, Mørk, 2001). On the basis of the lithology recorded the succession has been assigned to the Ludharwa Member of the Baisakhi Formation. This succession compares well with the part of the succession exposed in the “Kahla village section” (see below), which is located further northeast. The stratigraphic correlation suggests that the sediments of this section range from Oxfordian to Early Tithonian.

Kahla village section

(L3, co-ordinates N26°55'17.5", E70°47'06.8",

see Figs 1, 3)

The successions recorded in the Kahla village section consist of thinly bedded moderately cemented fine-grained sandstone beds alternating with thin silty fine-grained sandstones, with abundant well preserved trace fossils of the

Cruziana ichnofacies (*Anchorichnus* (a), *Palaeophycus* (c), *Taenidium* (c), *Gyrochorte* (c) and *Asterosoma* (o)); see Pandey *et al.*, 2014, fig. 47A–F) in the lower part of the succession, representing marine comparatively low water energy conditions at the transition from the lower to middle shore face. In the middle part of the section, thick sandstone beds with *Skolithos* (o) are suggestive of an increased influx of sediments deposited in high energy conditions. In the upper part of the succession at two horizons the occurrence of *Polycladichnus* points to a brackish water depositional environment (see Pandey *et al.*, 2014, fig. 48A–C). The brackish water environment intervals have been interpreted only on the basis of the trace fossil *Polycladichnus* (see Fürsich, Werner, 1986). There is no other hard evidence from the sediments overlying these two *Polycladichnus* bearing horizons. From the intermediate horizons in the upper part large-sized *Thalassinoides* and *Ophiomorpha* are quite conspicuous. The uppermost *Polycladichnus* horizon is followed by a fluvial conglomerate (see Pandey *et al.*, 2014, fig. 48D, E). The conglomerate unit cuts across the underlying succession and is confined to the top of this section and is absent from the other adjacent hill tops which maintain a similar height.

Trace fossils are abundant but of low diversity. A benthic fauna in the section is absent. Two fragments of ammonites (*Perisphinctes* (*Dichotomoceras*) sp. and *Torquatisphinctes* cf. *alterneplicatus* (Waagen)) recorded from the lower part of the succession give Oxfordian and Kimmeridgian ages; however, the specimen assigned to *Torquatisphinctes* cf. *alterneplicatus* seems to be reworked. It should have come from a level in between bed nos 39 and 41. The stratigraphic correlation suggests that the sediments of this section range in age from Oxfordian to Early Tithonian.

Ludharwa village scarp section

(L2, co-ordinates N26°59'01.45", E70°47'46.46",

see Figs 1, 3)

The succession predominately consists of cross-bedded, partially bioturbated, well to moderately sorted, muscovite-bearing, medium-grained with occasional coarse-grained, calcareous, ferruginous sandstones. The lower part consists of silty fine-grained sandstone and poorly sorted, silty fine to coarse-grained sandstone beds. The upper part is characterized by cross-bedding and large spherical single or compound concretions (up to 20–100 cm diameter).

The moderately sorted thick sandstone beds with poorly matured sediments suggest a fast rate of influx of the sediments. Broadly two phases of increase of water energy can be interpreted on the basis of the stratigraphic order of deposition of the sediments. The formation of large spherical con-

cretions is considered only a diagenetic feature, however, these are a pervasive growth of concretion where cementation of the host sediments by infilling of its pore spaces by cementing material occurs simultaneously in large area during diagenesis.

Rupsi scarp section

(L1, co-ordinates N27°00'21.2", E70°48'48.8",
see Figs 1, 3)

This is the type-section of the Basal Member and Rupsi Member of the Baisakhi Formation. Stratigraphically, three members of the Baisakhi Formation viz. Basal, Rupsi and Ludharwa members (Oxfordian-Tithonian) are exposed in the Rupsi scarp section (Pandey *et al.*, 2014, fig. 39). The Basal Member is characterized by carbonaceous, occasionally bioturbated grey shales. It has yielded two specimens of *Perisphinctes* (*Dichotomosphinctes*) sp. and one specimen of *P.* (*Dichotomoceras*) sp. In addition two fragmentary specimens assigned to *P.* (*Dichotomoceras*) cf. *dichotomus* (Buckman) were collected loose from the outcrop of the Basal Member. These ammonites suggest Middle to Late Oxfordian age. The Rupsi Member is characterized by occasionally bioturbated, gypsiferous siltstone and fine-grained sandstone with poorly developed current bedding. The ammonite specimens collected from this member have been assigned to *Torquatisphinctes* sp. *Torquatisphinctes* aff. *alterneplicatus*, *Pachysphinctes* aff. *major* Spath, *Virgatosphinctinae*, *Aulacosphinctoides* sp. and *Himalayitinae*. These ammonites suggest a Kimmeridgian to Tithonian age. Based on the records of these ammonites and those recorded by the earlier workers (Pandey, Krishna, 2000; Prasad, 2006) the age boundary between the Oxfordian and the Kimmeridgian can be clearly marked in the upper portion of Bed no. 2 (Fig. 3) and between the Kimmeridgian and the Tithonian can be clearly marked between Bed nos 6 and 7 with the first occurrence of *Aulacosphinctoides* sp. in Bed no. 7. The top part of the Rupsi scarp section consists of brown, moderately to well cemented, fine- to medium-grained ferruginous sandstone. The sandstone is massive in appearance, only the upper part of the sandstone shows very faint cross bedding. This sandstone in the cliff of the scarp has been correlated with the bed in the lower part of the Ludharwa scarp section and has been assigned an Early Tithonian age (Fig. 3).

The fauna of ammonites and belemnites requires a marine depositional environment. The thinly laminated and rarely bioturbated siltstones suggest low water energy conditions below fair-weather wave base. The absence or rare occurrence of a benthic fauna and the carbonaceous nature of the basal beds are indicators of stress in terms oxygen and

nutrient supply. The occurrence of fine-grained or medium-grained sandstone beds suggests a little fluctuation in energy level.

The alternate stratigraphical arrangement of the two facies units (unit 1 – silty shale or siltstone, unit 2 – fine- to medium-grain sandstone) suggests of at least three episodes of increase of water energy level from very low water energy below fair-weather wave base to moderate energy above fair-weather wave base. In addition there is a general increase of water energy up in the section. The massive appearance of the sandstone at the top of Rupsi scarp section (Bed 23) suggests a rapid deposition from suspension, rarely interrupted with migration of incipient bedforms. The sandstone is probably allochthonous – *i.e.* it is redeposited by mass flows to a quite deep environment (G. Pieńkowski, personal comm., 2014).

Bhadasar Ridge scarp section

(L5, co-ordinates N27°05'07.2", E70°47'57.3"
& L6, co-ordinates N27°06'05.7", E70°46'43.5",
see Figs 1, 3)

The succession (L5) exposed along road side on the south of Bhadasar Ridge is stratigraphically underlain by the succession exposed in the Bhadasar Ridge scarp section (L6) (Pandey *et al.*, 2014, figs 41, 43). The successions in both the sections have been grouped into the Rupsi Member and the Lanala Member of the Baisakhi Formation and the Kolar Dungan Member of the Bhadasar Formation. The basal part exposed in the section (L5; Bed nos 1–5), included in the Rupsi Member, consists of thinly cross laminated, partially bioturbated, ferruginous siltstones, occasionally with rippled upper surface, intercalated with micaceous silty shales, which change into a thick shale facies upward (Bed no. 5). The trace fossils recorded from the lower part of this section are *Planolites*, *Thalassinoides*, *Anchorichnus*, *etc.* Based on the lithology and trace fossils it is comparable to the facies units 13 and 14 of Prasad (2006, p. 9, 145, fig. 13). Prasad (2006) recorded the Kimmeridgian ammonites *Hildoglochiceras latistrigatum* Uhlig, *Torquatisphinctes torquatus* Spath morph *mangnumbilocata* Prasad, *T. jurunensis* Spath and *T. acutiocostatus* Spath from facies unit 14 (Fig. 3). The trace fossils indicate the middle to lower *Cruziana* ichnofacies or impoverished *Cruziana* ichnofacies. The depth must have been around fair-weather wave base with low to moderate water energy conditions at shoreface.

The next overlying beds (nos 6 of L5 and 1–7 of L6), also included in the Rupsi Member, are thinly bedded silty fine-grained sandstones alternating with argillaceous siltstones. This suggests a little increase of energy level, however, still on the shoreface. These beds have been correlated

with unit no. 15 recorded by Prasad (2006, p. 9), which has yielded the “Middle Kimmeridgian” *Pachysphinctes symmetricus* Spath to him (Fig. 3).

The overlying bed (no. 8), forming the top part of the Rupsi Member, is exposed near the base of the Bhadasar Ridge scarp section. It consists of well sorted fine-grained sandstone with ferruginous concretions. The bed corresponds to unit 16 of Prasad (2006, p. 9), which has yielded the Late Kimmeridgian *Katrolicerias subkatrolense* Spath, *K. cf. depressum* Spath, *K. aff. katrolense* (Waagen), *K. aff. le-rense* Spath and *K. sp. juv. depressum* Spath to Prasad (2006; see Fig. 3).

The overlying succession of the Lanala Member (Beds nos 9–2) forming the central part of the Bhadasar Ridge scarp section, consists of thick, moderately sorted silty very fine grained micaceous calcareous sandstones alternated with thinly laminated moderately sorted fine-grained to medium-grained calcareous sandstones with a sharp base and ferruginous concretions. Bed no. 32 forming the top of the Lanala Member, is characterized by bioturbated (exhibiting large-sized *Thalassinoides*), well sorted coarse-grained ferruginous argillaceous calcareous sandstone with large iron concretions and sharp and uneven lower and upper surfaces. The sediments (Bed nos 9–32) show little fluctuating water energy level, but higher than that of the underlying sediments. The large-sized *Thalassinoides* suggests very shallow water depth conditions. This part of the succession of the Lanala Member has not hitherto yielded any ammonite. However, comparable beds in different sections have yielded Early Tithonian zonal ammonite fossils of the Communis Zone (Pandey, Krishna, 2000). The next bed (no. 33), forming the scarp the ridge-coarse quartz bearing fossiliferous, poorly sorted, thinly cross bedded, calcareous sandstones with pebbles has been grouped with Kolar Dungar Member of the Bhadasar Formation. The fossils recorded from this bed are poorly preserved *Virgatosphinctes densiplicatus* (Waagen), belemnites, terebratulids, gastropods, bivalves, *Trochocyathus*, wood fossils and *Thalassinoides*. According to Pandey and Krishna (2000), this bed represents the Late Tithonian *Densiplicatus* Zone (Fig. 3).

In general, the sediments show a coarsening upward sequence, hence the gradual increase of water energy level from shoreface to foreshore. The weathering profile of the Bhadasar Ridge scarp section suggests a different degree of cementation.

The Lanala Member represents a more offshore facies corresponding to the shoreface sediments recorded at the top of Rupsi scarp section (L1) north of the Rupsi village and Ludharwa scarp section (L2), upper part of the Kahla village section (L3) situated in a west-southwest direction near Ludharwa Temple and Kahla village, grouped with the Ludharwa Member.

SEQUENCE STRATIGRAPHIC FRAMEWORK

The six sections (L1–L6) on the semi-arcuate outcrops (Fig. 1) of the Baisakhi Formation were selected on the bases of their position along northwest–southeast trending onshore-offshore tracking, well exposed successions and scarp sections, including type-sections, studied by previous workers (Das Gupta, 1975; Pandey, Krishna, 1996; Prasad, 2006; Pandey *et al.*, 2012). The strata in these six sections can be grouped into four successions of a continuous sequence, which moves from lower shoreface to fluvial deposits:

1. Damodara-Jajiya road scarp section (L4) represents the foreshore, the most marginal section with several erosional gaps and less distinct parasequence.
2. The Kahla village section (L3) represents lower to middle shoreface during deposition of the earlier part of the sequence and fluvial during the deposition of the younger part of the sequence, with at least one interval of deposition in a foreshore depositional environment and two intervals of a brackish water depositional setting.
3. Rupsi-Ludharwa scarp section (L1, L2) represents shoreface during the deposition of the earlier part of the sequence. During the deposition of the upper part of the succession the area witnessed a similar depositional environment but with increased sediment delivery and re-deposition, marked by massive sandstone layers.
4. The Bhadasar Ridge scarp section (L5, L6) represents the deepest part in the study area of the basin.

In these four successions, which are located along an onshore-offshore track, 35 parasequences have been recognized. The chronological order and correlation of these parasequences have been established on the basis of their stratigraphic positions, record of ammonites and most logical facies correlation, keeping in mind the model that succession 1 (*i.e.* the Damodara-Jajiya road scarp section) represents the most near shore locality, whereas succession 4 (*i.e.* the Bhadasar Ridge scarp section) represents the most offshore locality.

Chronologically, the oldest parasequences are exposed only in the “Kahla village section” (L3). In general, the parasequences show coarsening (rarely fining) upward sequences with evidence of several erosional surfaces (sharp and uneven bedding surfaces, sudden change in grain size, *etc.*). These suggest at least 35 major fluctuations of water energy level influencing sediment supply and preservation of trace fossils. All these parasequences (nos 1–35) of the Baisakhi Formation are of lowest order (fourth order) and indicate an actual change in the depositional setting.

The occurrence of intervals with a brackish water environmental setting between two marine intervals, the packages of a fining upward sequence above a coarsening upward sequences demarcated by an abrupt change in the grain size

and erosional surfaces, and the long time span of more than five million years, inferred from the respective ammonite zones and the chronostratigraphical table, involved in the deposition of these thick siliciclastic sediments of the Baisakhi Formation, clearly indicate that these parasequences can be grouped in to three sequence cycles of third order TST-HST/FSST. Further, at least twice the Maximum Flooding Surface (MFS) has been observed superimposed on transgressive surfaces. Carbonate sediments are rarely preserved.

The lowermost sequence cycle, consisting of parasequence 1–22, represent HST, best exposed in the “Kahla village section” and partially exposed in the more distal “Rupsi-Ludharwa scarp section” and the more proximal “Damodara-Jajiya road scarp section”.

The second sequence cycle, consisting of seven parasequences (numbering 23–29), is again represented by HST. The transgressive surface superimposed by MFS can be traced by the sudden change from coarse to very fine sediments. This sequence cycle can be observed in all the four successions studied in the present work (Fig. 3). The third sequence cycle, consisting of 6 parasequences (numbering 30–35), is the most complete sequence cycle represented by TST, HST, FSST and fluvial deposits. It is also best exposed at “Kahla village section”. The TST (parasequence 30) is characterized by a fining upward succession. Bioturbation interpreted as low energy conditions prevailed between two successive transgressive peaks. The retrograding sequence of medium- to fine-grain sediments overlying brackish water sediments has been interpreted as a fresh inundation of marine water on the coastal area. Here once more the transgressive surface has been observed superimposed by the MFS, which can be traced by a sudden change of coarse to very fine sediment. The parasequences 32 and 33, characterized poorly sorted sandstone just above well sorted fine-grain sandstone of parasequence 31, can be best interpreted as FSST.

On a larger scale, there is a general trend of coarsening upwards sequence and change from lower shoreface to fluvial environment, crossing through middle/upper shoreface, foreshore and brackish water setting. This coarsening upward sequence, enclosing at least three sequence cycles, mentioned above, corresponds to the still higher (*i.e.* second) order sequence cycle. In a broad view, the Oxfordian to Tithonian sediments (Baisakhi Formation) in the Jaisalmer Basin, range from marine shales, clays, silts and sands to brackish to non-marine sandstones and conglomerates. The rapid change in facies of the Baisakhi Formation is explained mainly as the result of a change in the depositional environment due to changes in relative sea-level and climatic conditions. Development of sand bars during the deposition influenced the sedimentary architecture of parasequences.

CONCLUSIONS

The stratigraphic correlation based on sequence stratigraphy and records of Oxfordian-Early Tithonian ammonites from various levels of the studied sections of the Baisakhi Formation reveals that the sediments of the Ludharwa Member (Oxfordian to Early Tithonian), occupying the southwestern part of the basin, were deposited in nearshore conditions (as summarized in Fig. 3). The thickness of the member narrows towards the northeast so much that it is absent in the Bhadasar Ridge scarp section, where the Rupsi Member is directly overlain by the Lanala Member. The basal part (Oxfordian) of the Ludharwa Member corresponds to the Basal Member (Oxfordian) of the Baisakhi Formation, exposed at the base of the Rupsi scarp section. The carbonaceous sediments of the Basal Member were deposited in comparatively offshore low energy water condition. Similarly, the middle part (Kimmeridgian to Early Tithonian) of the Ludharwa Member corresponds to the Rupsi Member (Kimmeridgian to Early Tithonian). The latter represents again comparatively offshore low energy water conditions. The upper part (Early Tithonian) of the Ludharwa Member corresponds to the Lanala Member (Early Tithonian) of the Baisakhi Formation exposed more northeastwards at the Bhadasar Ridge section. Thus, the Ludharwa Member (Oxfordian to Early Tithonian) occupying the southwestern part of the basin corresponds to the offshore counterpart Basal, Rupsi and Lanala members.

Chronologically, the investigated sections along the onshore-offshore track show that there is a general coarsening upward sequence and change from marine shales, siltstones and sandstones to brackish and non-marine sandstones and conglomerates, which suggest a lowering of relative sea-level resulting in regression from the southeast to northwest, at least from the Early Kimmeridgian to Early Tithonian.

The Kimmeridgian sediments are better preserved in the more distal area. Towards the shore area, *e.g.* in the Rupsi scarp section, the thickness is reduced to 1.5 m and shows a condensed sequence with zonal species of *Torquatisphinctes*, *Pachysphinctes* and *Katroliceras* occurring together. Further southwest as is considered here the Kimmeridgian succession is still more poorly preserved.

The Basal Member (Middle to Late Oxfordian) of the Baisakhi Formation is chronologically younger than the Jajiya Member of the Jaisalmer Formation (Fig. 2).

The Oxfordian/Kimmeridgian and Kimmeridgian/Tithonian boundaries have been demarcated in the Jaisalmer Basin for the first time and are best seen in the Rupsi scarp section (Fig. 3).

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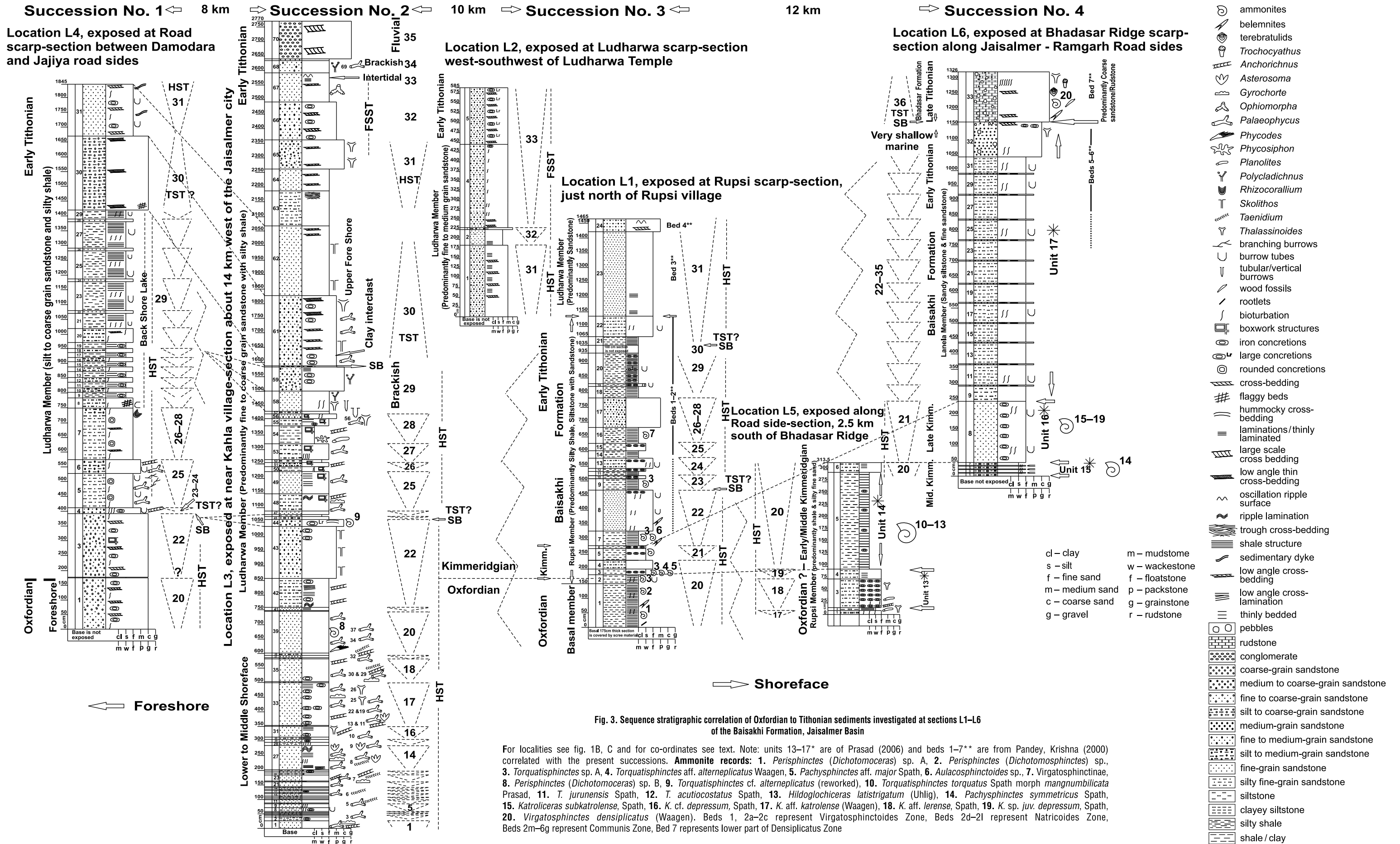


Fig. 3. Sequence stratigraphic correlation of Oxfordian to Tithonian sediments investigated at sections L1-L6 of the Baisakhi Formation, Jaisalmer Basin

For localities see fig. 1B, C and for co-ordinates see text. Note: units 13-17* are of Prasad (2006) and beds 1-7** are from Pandey, Krishna (2000) correlated with the present successions. **Ammonite records:** 1. *Perisphinctes* (*Dichotomoceras*) sp. A, 2. *Perisphinctes* (*Dichotomospinctes*) sp., 3. *Torquatisphinctes* sp. A, 4. *Torquatisphinctes* aff. *alterneplicatus* Waagen, 5. *Pachysphinctes* aff. *major* Spath, 6. *Aulacosphinctoides* sp., 7. *Virgatosphinctinae*, 8. *Perisphinctes* (*Dichotomoceras*) sp. B, 9. *Torquatisphinctes* cf. *alterneplicatus* (reworked), 10. *Torquatisphinctes torquatus* Spath morph *mangumbilicata* Prasad, 11. *T. jurunensis* Spath, 12. *T. acutiocostatus* Spath, 13. *Hildoglochiceras latistrigatum* (Uhlrig), 14. *Pachysphinctes symmetricus* Spath, 15. *Katrolceras subkatrolense*, Spath, 16. *K. cf. depressum*, Spath, 17. *K. aff. katrolense* (Waagen), 18. *K. aff. lerense*, Spath, 19. *K. sp. juv. depressum*, Spath, 20. *Virgatosphinctes densiplicatus* (Waagen). Beds 1, 2a-2c represent *Virgatosphinctoides* Zone, Beds 2d-2l represent *Natricoides* Zone, Beds 2m-6g represent *Communis* Zone, Bed 7 represents lower part of *Densiplicatus* Zone