2102348: Deciphering Tectonic Controls on Fluvial Sedimentation within the Barmer Basin, India: the Lower Cretaceous Ghaggar-Hakra Formation.

Hazel Beaumont[1*], Stuart M. Clarke[1], Stuart D. Burley[1 & 3], Andrew Taylor[2], Thomas Gould[2], and Pinakadhar Mohapatra[4]

[1] Basin Dynamics Research Group, Geography, Geology and the Environment, Keele University, UK
[2] Ichron, part of the RPS Group, Northwich, Cheshire, UK
[3] Murphy Oil Company Limited, Petronas Twin Towers, 50088, Kuala Lumpur
[4] Cairn India Limited, Gurgaon, India
* h.beaumont@keele.ac.uk

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The Cretaceous sedimentary succession of north-western India has received comparatively little academic attention, despite the fact that it represents part of the fill of hydrocarbon prospective basins within the West Indian Rift System. This Mesozoic onshore rift system (600 km long by 800 km wide), comprises the Kachhch (Kutch), Cambay, Narmada and Barmer basins (Figure 1a). The Barmer Basin is a 200 km long, 40 km wide and ≤6 km deep (Figure 1b), extensional rift, active predominantly from the latest Cretaceous through to Paleogene periods. The basin fill is largely of Paleogene age; however, the Lathi and Ghaggar-Hakra formations were deposited within the Mesozoic Era.

In this work, we describe the stratigraphy, sedimentology and petrography of outcrops of the Cretaceous Ghaggar-Hakra Formation situated in rotational fault blocks on the eastern margin (the Sarnoo Hills) of the Barmer Basin (Figure 1b & c). The Ghaggar-Hakra Formation exposed at outcrop comprises three fluvial sandstone successions with coeval floodplain deposits (Figure 2). We use these outcrop data to constrain interpretation of correlative subsurface core data within the distal extent of the Barmer Basin.

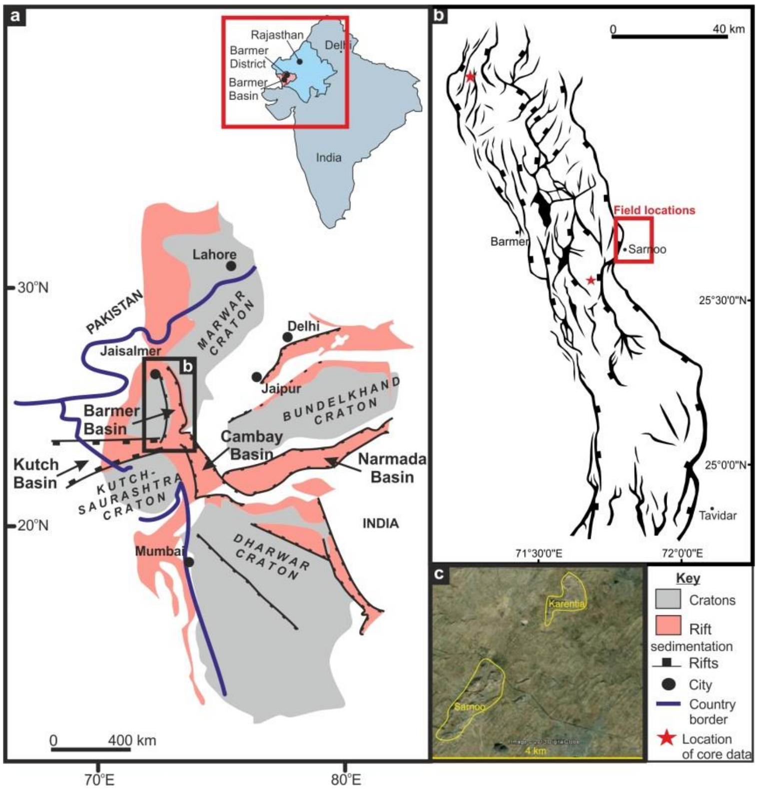


Figure 1: *(a) North-western India, displaying the regional framework and the basin layout. The Barmer basin and extent of the map shown in (b) are highlighted. Adapted from Balakrishnan et al., (2009); (b) Extensional fault network that defines the Barmer Basin, with field and subsurface data locations shown, adapted from Dolson et al., (2015) and (c) field locations of the Ghaggar-Hakra Formation.*

Sedimentology

At outcrop, the Ghaggar-Hakra Formation comprises three sandstone-dominant successions of varying fluvial style, with interbedded floodplain deposits. The base of the formation comprises mud- to very fine-grained, pedogenic sand and unconformably overlies the Precambrian Malani Igneous Suite (750Ma, Dolson *et al.,* 2015) or, in

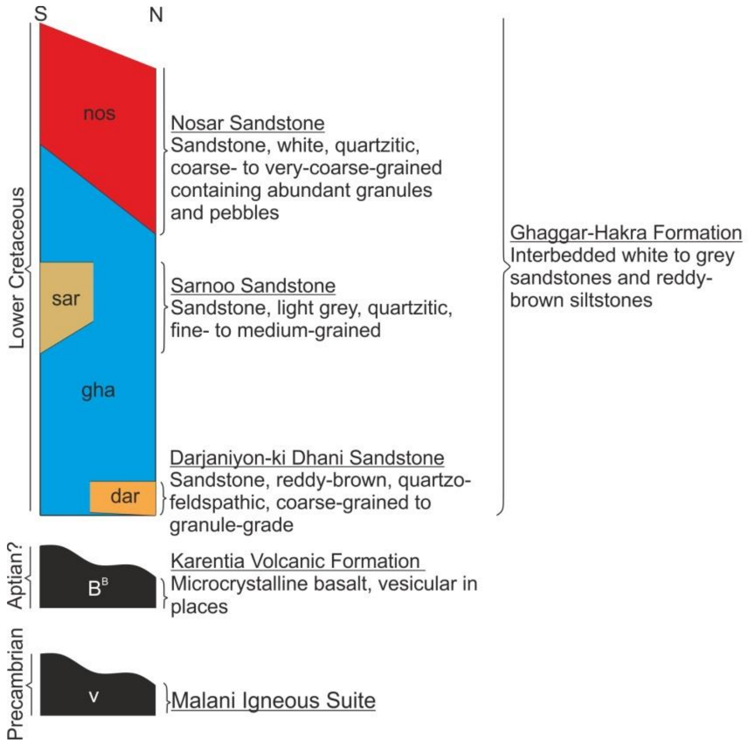


Figure 2: *General vertical section of the Ghaggar-Hakra Formation, displaying each sandstone succession and the background sedimentation of the formation (adapted from Bladon et al., 2015).*

places, the Lower Cretaceous Karentia Volcanic Formation (120Ma, Sharma 2007). The Ghaggar-Hakra Formation has been dated to the Upper Jurassic – Lower Cretaceous periods based on preserved specimens of *Phlebopteris athgarhensi, Ptilophyllum acutifolium* and *? Sphenopteris* (Baksi and Naskar 1981).

The lowermost fluvial sandstone succession - the Darjaniyon-ki Dhani Sandstone (Figure 2) - comprises granule- to large pebble-grade quartzitic and basaltic conglomerates that are the product of migrating braid bars (2 m high and ≤50 m long), overlain by coarse-grained quartz-arenites in planar and trough cross-bedded sets (95 cm high) representing the amalgamated fill of channels which are ≤2 m high and ≥5 m wide. Finally, the succession is capped with silt to fine-grained sands which are heavily bioturbated and form a floodplain element (≥30 m thick).

The middle sandstone succession – the Sarnoo Sandstone (Figure 2) – is variable in sedimentology. The base of the succession contains granule-grade conglomerates with erosive beds and crude planar sets (≤30 cm high) formed from the migration of coarse braid bars (braid bar size: 1.5 m high and up to 25 m long). Above this, medium- to very coarse-grained quartz-arenites in cosets of planar cross-bedding (90 cm high) represent the amalgamated channel fill element of in-channel migrating bar forms (10 m high and 15 m wide). The succession then passes upwards into fine-grained rippled-laminated sandstones which are laterally extensive (≤1.5 m high and ≤2 km long) and formed through sheetfloods. These are overlain by, fine- to medium-grained quartz-arenites that form low-angle cross-bedded sets (≤75 cm high), arranged into geometrically consistent cosets but commonly truncated by third- and fourth-order bounding surfaces (Figure 3, Brookfield 1977 and Miall 1985) and represent the deposits of point bars (4 m high and 20 m long). These deposits are overlain by bioturbated silt of the floodplain (≥1 m high and ≤2 km long).

Capping the formation at outcrop, the Nosar Sandstone (Figure 2) comprises medium- to very coarse-grained quartz-arenites, arranged in planar and trough cross-bedded cosets (25 cm high), and representing the amalgamated fill of channels at least 10 m high and 25 m wide. Interbedded with the channel fill are granule-grade quartz conglomerates arranged into localised planar coset packages (≤30 cm high) and representing braid bars (≤4 m high and ≤25 m long). These elements display bounding surfaces between the first and fourth order (Figure 4) suggesting amalgamation and stacking of channels and braid bars. The top of the exposed Nosar Sandstone displays fine- to medium-grained quartz-arenites with ripple lamination, formed in a sheetflood environment (3 m high and ≤2 km in lateral extent). There are small (0.2 m high and 1 m long) packages of bioturbated silt-throughout the Nosar Sandstone which represent intermittently preserved floodplain deposits.

The sediments between major sandstone successions (Ghaggar-Hakra Undivided, Figure 2) comprise dominantly parallel laminated clay to fine-grained sandstones in packages up to 30 m thick that are laterally continuous and very extensive (2 km) throughout the field areas. The sediments are pedogenic in nature, with rhizoliths, soil slickensides, fractures, nodules and mottled textures that formed in a vegetated floodplain.

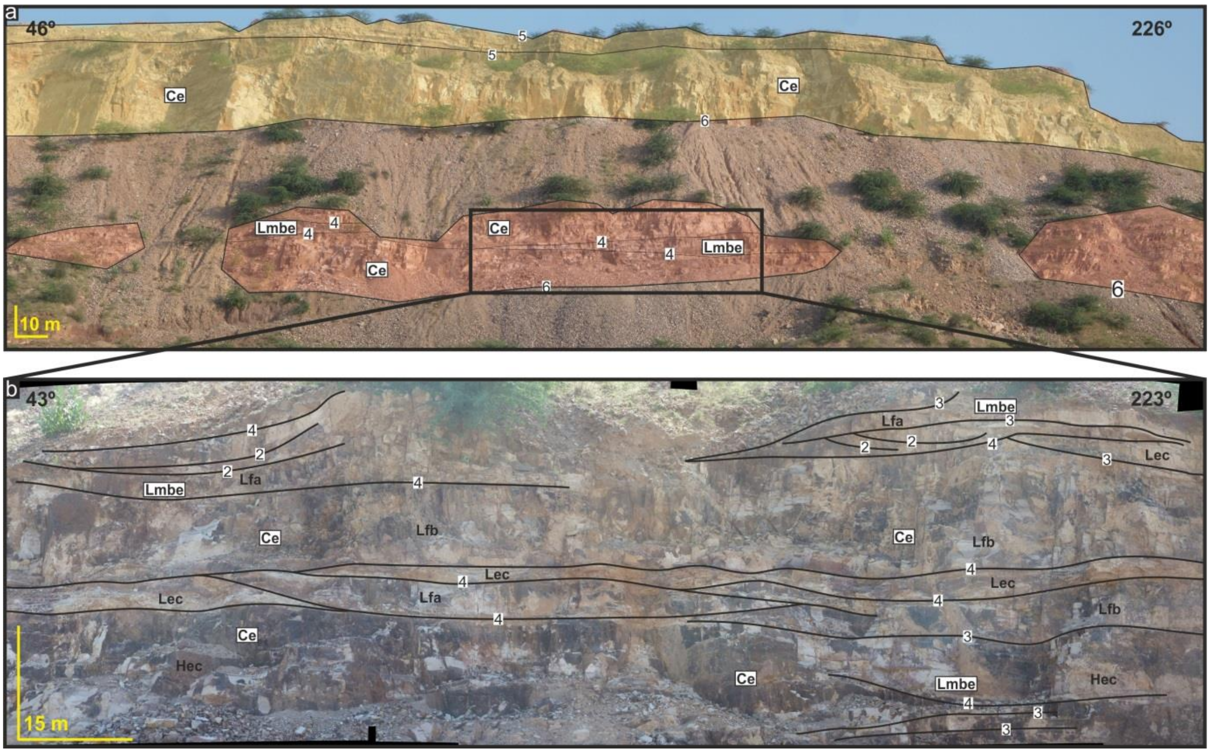


Figure 3: *Outcrop of Ghaggar-Hakra Formation in the Sarnoo Hills displaying examples of bounding surfaces one to six, (a) red areas indicate exposures of the Sarnoo Sandstone and the yellow area indicates exposure of theNosar Sandstone, (b) detailed view of the Sarnoo Sandstone interpreted for bounding surfaces within the channel (F1) and point bar elements (F5).*

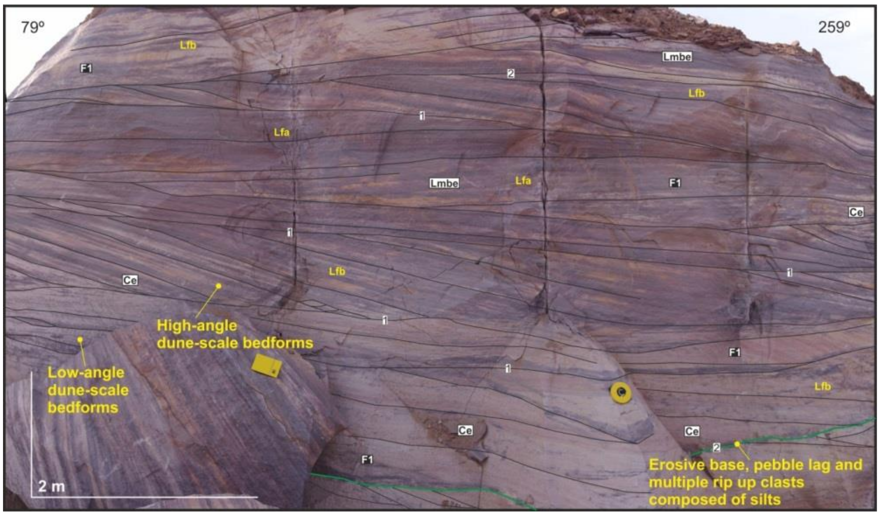


Figure 4: *Bounding surfaces relationships within the Nosar Sandstone displaying 1st order bounding surfaces truncating against the 2nd order bounding surfaces. There are numerous sets displayed here in multiple orientations displaying a variation in the palaeoflow.*

Petrography

The textural characteristics of each sandstone succession (Table 1) demonstrate that the Sarnoo Sandstone is finer grained, is more rounded, displays greater porosity, and is generally more mature than the Darjaniyon-ki Dhani and Nosar sandstones.

Compositionally (Table 2), all three sandstone successions are mature but the Sarnoo Sandstone displays slightly higher compositional maturity. The detrital grains are similar throughout all samples analysed and comprise: monocrystalline and polycrystalline quartz (66%), occasionally displaying undulose extinction; lithic fragments (5.2%) of chert, igneous lithic fragments displaying intergrown quartz and muscovite mica, and metamorphic lithic fragments exhibiting a schistose fabric; heavy minerals (0.5%); optically non-resolvable clays (10.1%) that infill intergranular areas; and ductile muscovite micas which are buckled between rigid detrital grains (1.9%).

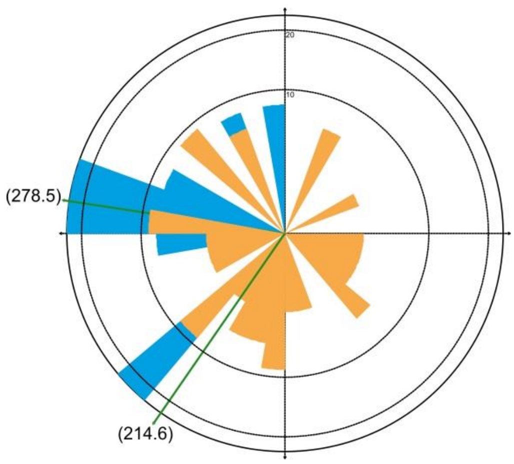
	Average grainsize	Average sorting	Average roundness	Average porosity
Darjaniyon-ki Dhani Sandstone	0.594 mm	Moderately sorted	Subrounded	5.5%
Sarnoo Sandstone	0.297 mm	Moderately well sorted	Rounded	8.2%
Nosar Sandstone	0.401 mm	Moderately sorted	Rounded	4.5%

Table 1: *Textural characteristics of the Darjaniyon-ki Dhani, Sarnoo and Nosar sandstones within the Ghaggar-Hakra Formation. Data based upon fifty samples in total.*

The authigenic minerals consist of thin (2 – 3 µm) syntaxial quartz overgrowths (1.7%) that are discontinuous around their host grains, haematite cement (4.3%) locally replacing detrital grains, secondary (post-depositional) calcite cement (3%), anatase (Tr) and kaolinite booklets infilling intergranular areas (1.4%).

The macroporosity (7.7% at outcrop) consists of primary intergranular porosity (6.4%) that varies from well-interconnected to isolated pore spaces, secondary intergranular porosity (0.5%), and secondary ‘oversized’ porosity (0.8%). Secondary porosity occurs after unstable grain dissolution and can be connected to primary pores.

Palaeocurrent Data



Palaeocurrent data were collected from planar and tough cross-bedded sets of all three sandstone successions and corrected for the shallow regional southeast tilt on the basin at the margin. In general, all sandstones indicate a palaeoflow towards the west to southwest. The Darjaniyon-ki Dhani Sandstone is orientated to the south, with a mean of 181°.

The Sarnoo Sandstone indicates palaeoflow orientated dominantly to the west (Figure 5) with a mean direction of 278.5° and a standard deviation of 18.25. The Nosar Sandstone is orientated predominantly to the southwest (Figure 5), with a mean direction of 214.6° and a standard deviation of 17.39.

Figure 5: *Palaeocurrent for the Sarnoo Sandstone (blue), is orientated generally towards the west, and for the Nosar Sandstone (orange) it is dominantly to the southwest. The green lines display the average palaeocurrent for each sandstone; Sarnoo Sandstone (278.5), Nosar Sandstone (214.6). The change in direction may be attributed to the onset of an active extensional regime. Thirty-two measurements from the Nosar Sandstone and twenty-six measurements from the Sarnoo Sandstone.*

Palaeoenvironment of the Ghaggar-Hakra Formation

The outcrop of the Ghaggar-Hakra Formation displays three separate fluvial sandstone successions of varying sedimentology, petrography and three-dimensional nature. The evolving fluvial system starts at the base of the formation with a bedload dominated, low-sinuosity fluvial system with variable

	Darjaniyon-ki Dhani Sandstone			Sarnoo Sandstone			Nosar Sandstone		
	Average	**St. De.**	**St. Er.**	**Average**	**St. De.**	**St. Er.**	**Average**	**St. De.**	**St. Er.**
Detrital Mineralogy									
Quartz	64.46	9.18	2.54	75.89	5.94	1.36	81.64	6.11	1.44
Rigid rock fragments									
igneous	0.50			1.17	0.96	0.28	0.75	0.26	0.08
metamorphic	2.94	2.54	0.85	2.25	2.14	0.62	2.85	2.36	0.75
sedimentary	3.85	3.13	0.99	1.35	0.85	0.24	1.54	0.78	0.22
Heavy Minerals	0.50			0.70	0.27	0.12	0.50		
Undifferentiated	3.43	5.56	2.10	0.63	0.25	0.13	4.25	7.17	3.59
Muscovite Mica							0.80	0.67	0.30
Non-resolvable clay	10.31	11.32	3.14	3.24	3.62	0.88	5.33	4.07	0.96
Undifferentiated	1.50			1.36	0.89	0.24	5.65	3.96	0.96
Detrital pore-filling	2.67	4.20	1.21						
Pseudomatrix	14.36	10.99	4.15	2.40	3.22	0.83			
Authigenic Mineralogy									
Quartz Overgrowths	1.62	0.87	0.24	2.28	1.52	0.36	1.29	0.70	0.19
Calcite cement	2.90	2.72	1.22	1.94	0.68	0.24	5.00		
Dolomite cement	0.67	0.29	0.17	0.83	0.29	0.17	1.93	1.46	0.55
Haematite	8.62	7.23	2.00	4.69	4.43	1.04	0.92	0.66	0.27
pore-filling	8.62	7.23	2.00	5.28	4.35	1.09	1.00	0.65	0.24
Kaolinite	1.42	1.39	0.57	1.00	0.91	0.35	1.90	1.49	0.38
Undifferentiated	1.33	1.04	0.60	0.50			0.50		
Non-resolvable clay							1.50		
Marcoporosity									
primary intergranular porosity	5.54	3.57	0.99	8.17	5.22	1.23	4.50	2.17	0.53
secondary intragranular porosity	0.67	0.29	0.17	0.50			0.50		
secondary 'oversized' porosity	1.50			0.50			1.08	0.49	0.20

Table 2: *Average mineralogical composition of each sandstone unit. Total data set of fifty samples with standard deviations (St. De.) and standard errors (St. Er.) shown. All values given in percent.*

discharge (the Darjaniyon-ki Dhani Sandstone - Figure 6) and evolved into a well-developed, mixed load, high-sinuosity fluvial system (the Sarnoo Sandstone), with an accompanying slight increase in textural and compositional maturity. The frequency of third to fifth order bounding surfaces within the Sarnoo Sandstone attests to variability in bedform and barform migration (and therefore flow) within,

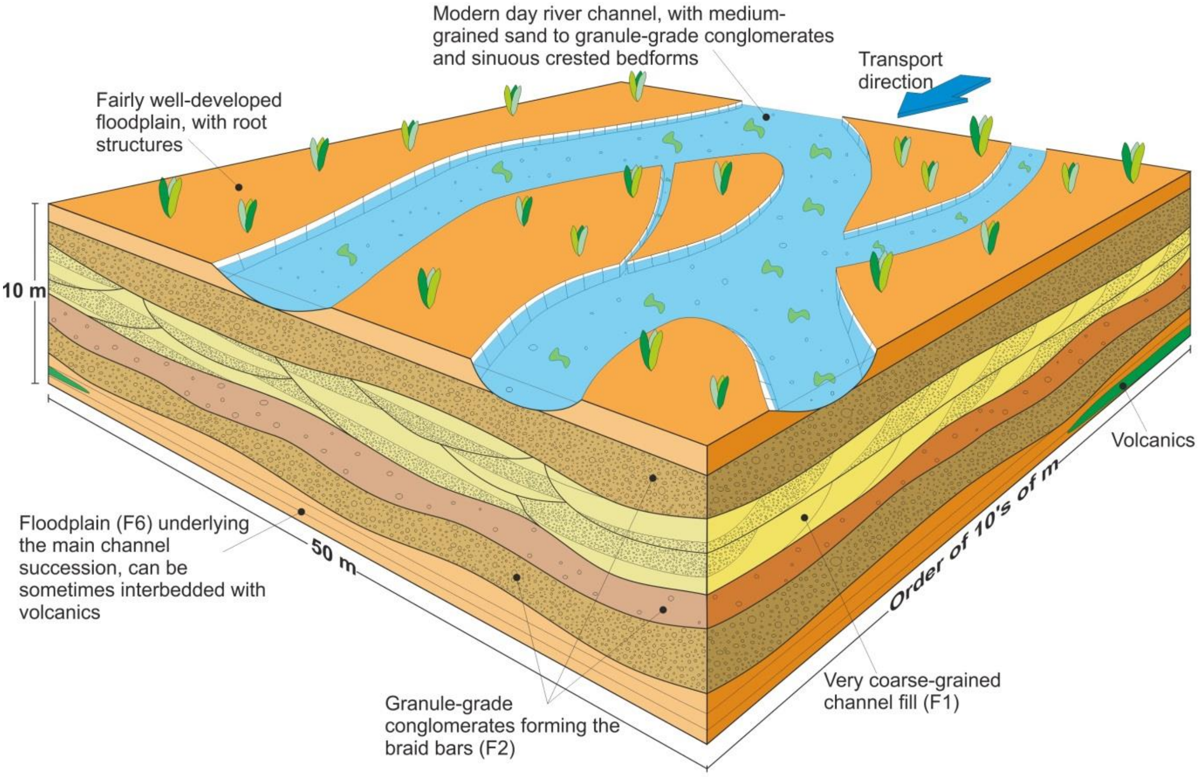


Figure 6: *Darjaniyon-ki Dhani Sandstone which is a bedload dominant low sinuosity fluvial system, which had a variable discharge and is dominantly composed of braid bar elements.*

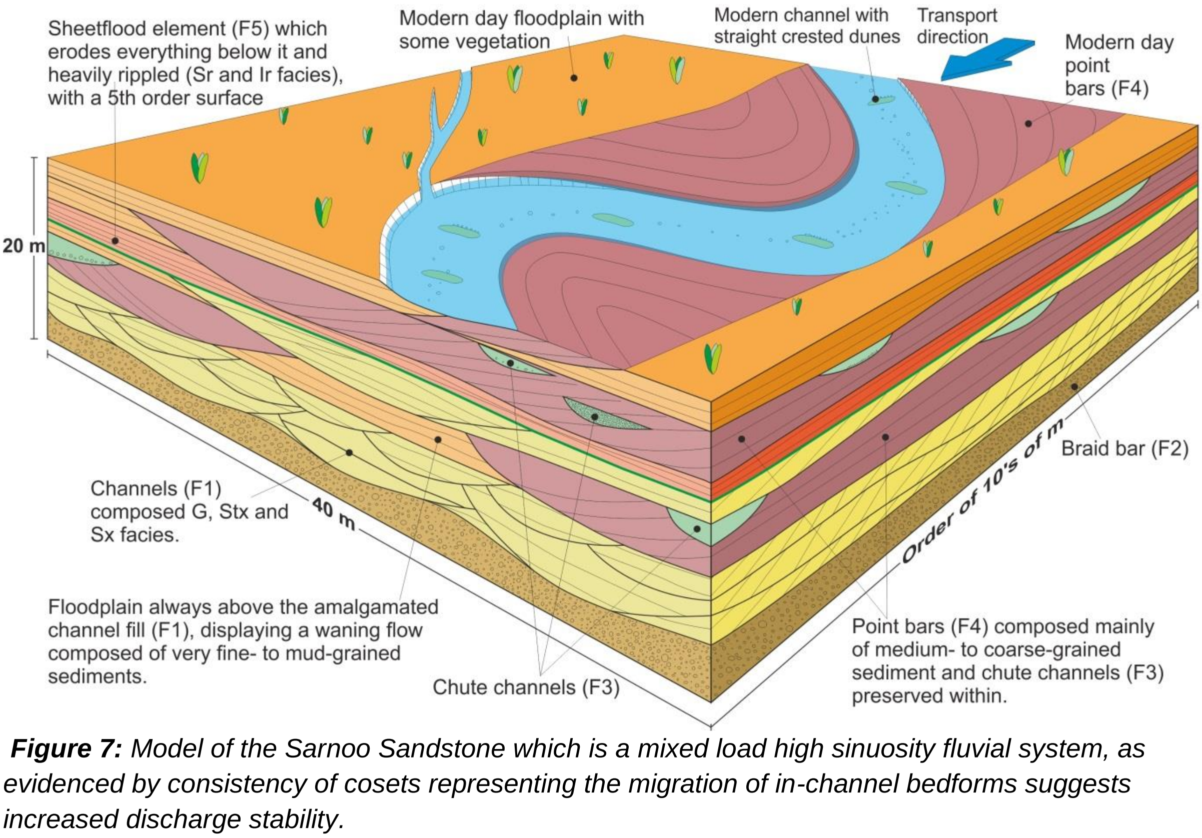


Figure 7: *Model of the Sarnoo Sandstone which is a mixed load high sinuosity fluvial system, as evidenced by consistency of cosets representing the migration of in-channel bedforms suggests increased discharge stability.*

or adjacent to, the fluvial channels of a highly sinuous system. The consistency of cosets representing the migration of in-channel bedforms suggests increased discharge stability.

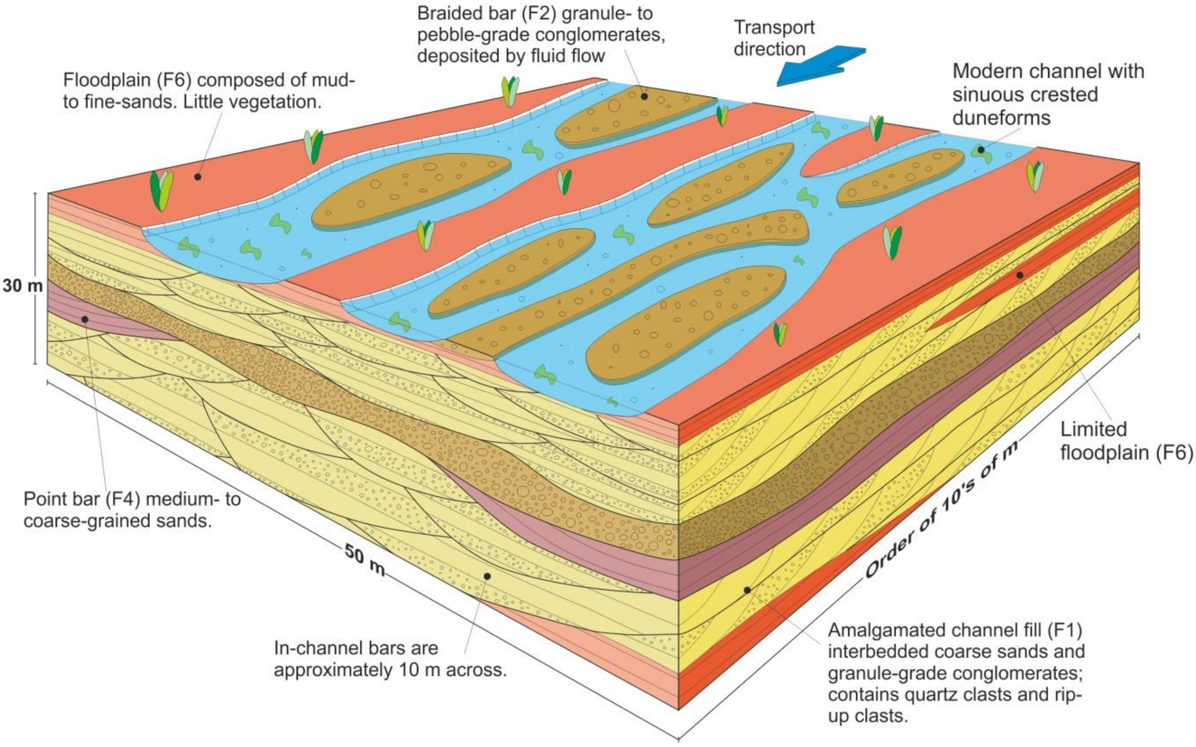


Figure 8: *Three-dimensional model of the Nosar Sandstone, which is a bedload dominant low sinuosity fluvial system, where there was discharge irregularity and a high level of channel migration as evidenced by the first and second order surfaces.*

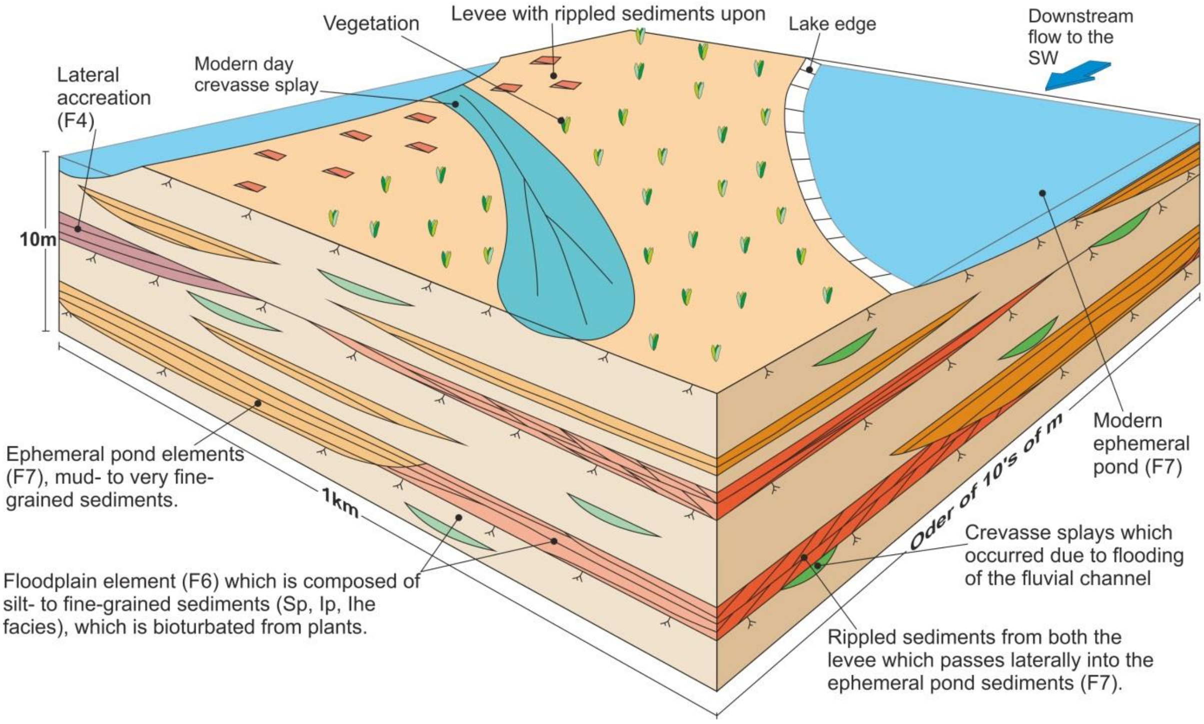


Figure 9: *Three-dimensional model of the siltstone successions, displaying thick and well vegetated floodplains and ephemeral ponds, suggesting tectonic stability during their deposition.*

The highly erosive nature, the dominantly coarser grain size, the increased amounts of lithic fragments and a lower porosity within the Nosar Sandstone (Figure 8) suggest rejuvenation of the fluvial system, back to a bedload-dominant, low-sinuosity fluvial style. The channel-forms are amalgamated and stacked. This, coupled with the lack of consistent cosets from the migration of in-channel bedforms, suggests high levels of channel migration and discharge irregularity.

The thick and the extensively vegetated floodplain deposits (Figure 9) associated with the Sarnoo Sandstone may suggest localised tectonic stability (Arguden and Rodolfo 1986) at the start of the Ghaggar-Hakra deposition. The rejuvenation of the fluvial system coupled with a switch in fluvial style and palaeoflow by Nosar Sandstone times may be attributed to renewed localised tectonic activity at the basin margin.

Application

The core data for this work have been collected from the subsurface adjacent to the outcrop localities (Figure 1b) but representing a generally more distal setting towards the basin centre. Subsurface cored sections display three distinct facies assemblages, one of which correlates well with outcrop data.

The lowermost facies assemblage represents the Pushka Member (Dolson et al., 2015) of the Ghaggar-Hakra and comprises three distinct associations that correlate with outcrop data. The associations represent in-channel deposition, braid bars and floodplain. The in-channel association comprises fine- to medium-grained sandstone in planar cross-bedded sets and cosets (90 cm in height) alternating with medium- to coarse-grained trough cross-bedded sets (25 cm high). Units of granule-grade conglomerates are also present. The braid bar association constitutes coarse-grained sand to granule-grade conglomerates with crude trough cross-bedded sets (20 cm high), and granule- to pebble-grade, matrix-supported conglomerates along with units of medium- to very coarse-grained massive sandstones. The floodplain association contains clay to fine-grained sand in crude laminations, some of which have been destroyed due to bioturbation, along with mottled patches, roots and siderite nodules.

These three facies associations correlate well with the low sinuosity, fluvial system and associated floodplain deposits of the Nosar Sandstone at outcrop. It follows that the contacts in core between separate facies of the in-channel association, and between facies of the braid bar association, are likely to represent third order bounding surfaces at outcrop. The contact at the base of the floodplain association is most likely a forth order surface and again correlates with similar fourth order surfaces visible within the outcrop. By drawing parallels between facies assemblages and bounding surface relationships between outcrop and subsurface data we suggest that the Pushka Member in the subsurface represents a low sinuosity fluvial system with channel sizes up to 15 m to 25 m wide and 10 m high. It is likely that the braid bars are 1.5 m to 4 m long and 20 m wide and are interbedded with the in-channel association. The proportion of floodplain material preserved within the system is likely to be limited to 1 m thick packages that are laterally discontinuous.

The second facies assemblage evident in core represents the Kamyaka Member (Dolson *et al.,* 2015) of the Ghaggar-Hakra Formation. It is composed of fine-grained sandstone with symmetrical and asymmetrical ripple lamination at the base followed by soft-sediment deformation from load and flame structures (up to 3.5 cm thick) and slumps, containing fine-grained sands. Next there are very fine- to fine-grained, horizontally laminated sandstones which can contain a little soft deformation from bioturbation (roots and organisms). At the top of the sedimentary package there are clay- to very fine-grained sands which are massive but contain siderite nodules (1 – 3 mm) and occasional Lockeia burrows. This assemblage represents a lacustrine facies association that does not collate to the outcrop data.

The third facies assemblage comprises in-channel and floodplain associations. The in-channel association contains medium- to coarse-grained planar cross-bedded sets (20 cm high), interbedded within medium-grained, parallel-bedded sandstones. The floodplain association contains very fine- to fine-grained sands with asymmetrical ripple laminations and soft-sediment deformation due to bioturbation from plant roots. There are also very fine-grained sands with siderite nodules and siderite-filled fractures. This facies assemblage forms a bedload dominant, low-sinuosity, fluvial system within the subsurface of the Barmer Basin that cannot be correlated directly to the outcrop.

Discussion

Comparisons between outcrop of the basin margin and core data from the more distal subsurface suggest that the Ghaggar-Hakra represents deposition in a dominantly fluvial environment draining from the basin margin highs to the basin centre and into a lacustrine system. At the basin margin, the fluvial system evolves with time from a low sinuosity, fluvial system to a high sinuosity system and this is accompanied by a slight but significant variation in general palaeocurrent. We suggest that variations in fluvial style, particularly rejuvenation and increased instability of the fluvial system from Sarnoo to Nosar sandstones, along with the switch in palaeocurrent, may be attributable to renewed localised tectonic activity at the basin margin.

We are able to attribute the Pushka Member of the subsurface Ghaggar-Hakra to a low sinuosity, fluvial system comparable to the Nosar Sandstone, by drawing comparisons with the channel fill and braid bar sedimentology and third and fourth order bounding surfaces. Above this are the lacustrine deposits (Kamyaka Member), overlain by a second low sinuosity fluvial system. The interbedded nature of fluvial and lacustrine deposits suggests migration of the lacustrine shoreline through time. It is possible that migration of the lacustrine shoreline may have resulted from renewed tectonic activity and therefore may correlate to the change in fluvial style in the proximal setting. However, a climatic control on the lacustrine system and the position of the shoreline cannot be ruled out, and the variation in fluvial system within the deposits of the subsurface does not favour one model over the other.

The palaeoflow of the fluvial system at outcrop is generally parallel to the axis of the rotational fault blocks that form the basin margin. However, the main extensional phase within the Barmer Basin was superimposed upon a pre-existing extensional tectonic framework (Bladon *et al.,* in press), and palaeoflow directions, along with variations in time, may be attributable to movement during the earlier phase and under a transtensional regime. Changes in structural style within the Barmer Basin have been attributed to the separation of the Greater Indian and Madagascan plates during Gondwanan fragmentation (Bladon *et al.,* in press) and therefore Ghaggar-Hakra sedimentation may record this.

Conclusions

The Ghaggar-Hakra was deposited within a maturing upwards fluvial system rejuvenated as a result of tectonic instability. Core data from the equivalent distal setting demonstrates lacustrine and fluvial environments controlled and constrained by a migrating lacustrine shoreline. Correlations can be made between sedimentology of the core and the outcrop that allow the fluvial succession of the subsurface to be better characterised, and that suggest that the migrating lacustrine shoreline may be controlled by the same tectonic instabilities interpreted from proximal deposits. Ultimately, this work improves understanding of the role of regional tectonics upon the depositional systems preserved at surface and subsurface successions of the Barmer Basin during the Lower Cretaceous Period.

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