1 **Sedimentology and the facies architecture of the Ghaggar-Hakra Formation, Barmer Basin,**

2 **India: Implications for early Cretaceous deposition on the north-western Indian Plate**

3 **margin**

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

5 Mohapatra[4]

6 [1] Basin Dynamics Research Group, School of Geography, Geology and the Environment, Keele University,

7   Staffordshire, UK

8 [2] Orient Petroleum Limited, PTET House, Mauve Area, G-10/4, Islamabad, Pakistan

9 [3] Skolithos Ltd., The White House, Higher Banks, Mellor, Lancashire, UK

10 [4] Cairn India Ltd., DLF Atria, Jacaranda Marg, Gurgaon, India

11

12 *Current address: Department of Geography and Environmental Management, University of the West of

13 England Bristol, Bristol, UK

14 hazel.beaumont@uwe.ac.uk

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16 **ABSTRACT**

17 Fluvial strata of the Lower Cretaceous Ghaggar-Hakra Formation are exposed in fault blocks

18 on the central-eastern margin of the Barmer Basin, Rajasthan. The sedimentology of these

19 outcrops is described from 114 logs (thicknesses up to 100 m) and 53 two-dimensional

20 correlation panels. The formation comprises three distinct channel-belt sandstone packages

21 defined as the Darjaniyon-ki Dhani, Sarnoo and Nosar sandstones separated by thick

22 siltstone-dominated floodplain successions. The sediments were deposited in a sub-tropical,

23 low sinuosity fluvial system that matures into a highly sinuous fluvial system. The Nosar

24 Sandstone, the youngest of the three packages, exhibits a significant increase in energy and

25 erosive power compared to those underlying it. This distinct change in fluvial style is

26 interpreted to be rejuvenation due to an actively developing rift network forming

27 accommodation space, rather than climatic controls acting on part of the depositional

28 system. Consequently, the Ghaggar-Hakra Formation at outcrop represents Lower

29 Cretaceous syn-rift deposition within the Barmer Basin with active localised fault movement

30　　from Nosar Sandstone times onward. These findings provide sedimentological evidence in

31　　support of pre-Palaeogene northwest-southeast extension in the Barmer Basin. Moreover,

32　　they imply Cretaceous extension took place widely along the northern extremity of the West

33　　Indian Rift System consistent with plate tectonic models of the break-up of Gondwana and

34　　evolution of the Indian Ocean. Outcrops of Lower Cretaceous strata are patchy across India

35　　and Pakistan. This study provides valuable material which, when combined with the

36　　available published data, facilitates a re-evaluation of Lower Cretaceous palaeogeography

37　　for the northwest Indian Plate. The reconstruction demonstrates a complex fluvial system,

38　　where the sediments are preserved sporadically as early syn-rift strata. The findings imply a

39　　high preservation potential for early Cretaceous fluvial successions within rifted fault blocks

40　　near Saraswati and Ashiwarya of the Barmer Basin beneath the Palaeogene fill that likely

41　　have significant potential for further hydrocarbon exploration.

42　　**Key words**: Barmer Basin, fluvial, Ghaggar-Hakra Formation, palaeogeography, tectonics.

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Introduction

The Barmer Basin is the northern most basin of a series of rifts that comprise the West Indian Rift System (WIRS; Fig. 1A), and hosts large hydrocarbon reserves within continental sediments of the basin fill (Dolson *et al.,* 2015). However, the early geological history of the basin, and the nature of the Mesozoic sedimentary fill, remain poorly understood. This lack of knowledge stems mostly from the limited surface exposure which restricts outcrop studies and thereby constrains interpretations of subsurface well and seismic data.

The Barmer Basin was considered to have developed in response to passage of the Indian Plate over the Reunion hotspot, giving rise to a syn- and post-rift Palaeogene to Eocene sedimentary fill, overlying Precambrian rocks of the Malani Igneous Suite (Fig. 2A, Crawford & Compton, 1969) and pre-rift Mesozoic sediments (Sisodia & Singh, 2000; Compton, 2009). Recently, an important earlier northwest – southeast extensional event has been recognised, preserved in structural geometries exposed on the basin margins and overprinted by the perceived main Palaeogene rifting (Bladon *et al.,* 2015b; Dasgupta & Mukerjee, 2017). Fluvial sediments preserved on the rift margin are ascribed to the Lower Cretaceous Ghaggar-Hakra Formation and rift-margin geometries suggest that they were deposited contemporaneously with the pre-Palaeogene normal faulting (Bladon *et al.,* 2015a, b). Although the Ghaggar-Hakra Formation occurs in relatively small outcrops around Sarnoo, they are regionally significant as they provide excellent exposures of the early Cretaceous sediments which document intra-plate continental deposition during the early break-up of India from Gondwana. It follows that the Ghaggar-Hakra Formation is likely to be the time and depositional-equivalent of the Lower Cretaceous fluvial Himatnagar Sandstone of the Cambay Basin (Bhatt *et al.,* 2016; Mohan, 1995; Mukherjee, 1983), the fluvial to marine

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75   Nimar Sandstone of the Narmada Basin (Ahmad, 1988), the fluvial to coastal and deltaic Bhuj

76   Formation of the Kachchh Basin (Biswas, 1987; Desai & Desai, 1989; Akhtar & Ahmad, 1991),

77   the predominantly fluvial Dhrangadhra Group of the Than Basin in Saurasthra (Casshyap &

78   Aslam, 1992) and the fluvial Lumshiwal and Goru and marine-coastal Sembar successions of

79   the Central and Southern Indus basins of Pakistan (Ahmad *et al.,* 2012; Ahmad & Khan, 2012;

80   Khalid *et al.,* 2014; Zaigham & Mallick, 2000). These basin margin early Cretaceous

81   sediments are likely to be contemporary with rifting between Madagascar and India (Bastia

82   *et al.,* 2010; Reeves, 2014; Torsvik *et al.,* 2000) and separation of the Seychelles micro-

83   continent from Greater India (Eagles & Hoang, 2014).

84   Therefore, the Ghaggar-Hakra Formation and these isolated occurrences of fluvial sediments

85   are important in reconstructing the Lower Cretaceous depositional palaeogeography of the

86   north-western Indian Plate. Identification and detailed characterisation of a well-preserved

87   fluvial succession of Lower Cretaceous age in the Barmer Basin not only has significant

88   implications for the evolution of the basin, but also for potential reservoir distribution and

89   hydrocarbon potential of early Cretaceous sediments in the subsurface across the northern

90   Indian Plate.

91   Here, a comprehensive description and interpretation of the Lower Cretaceous Ghaggar-

92   Hakra Formation exposed in the Sarnoo and adjacent hills close to the settlements of Sarnoo

93   (also known as Sarnu or Saranu), Karentia and Nosar, Rajasthan (Fig. 1B) is presented as a

94   basis for re-evaluating the early Cretaceous palaeogeography of the northern Indian Plate

95   margin. Detailed sedimentary logging, combined with geometrical analysis of large-scale,

96   two-dimensional inclined exposures, are used to characterise and interpret the evolution of

97   the fluvial succession. Variations in fluvial style and the controls upon them are discussed,

98   along with the implications for the evolution of the Barmer Basin and its palaeogeographical

99   setting in the early Cretaceous Period during the early separation of India Plate from

100   Gondwana.

101   **Geological setting**

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103   The WIRS (Fig. 1A) includes, from south to north, the Narmada, Cambay, Kachchh (Kutch)

104   and Barmer basins (Akhtar & Ahmad, 1991; Biswas, 1987; Pandey *et al.,* 2009; Rai *et al.,*

105   2013). The formation of the WIRS was initiated in the mid to late Jurassic Period by the

106   break-up of Gondwana as the eastern part, including the terranes of Greater India,

107   Madagascar and Antarctica, separated from West Gondwana (Africa) in response to the

108   development of the Mozambique and Somali proto-oceans west and north of Madagascar

109   and India (Reeves & DeWit, 2000; Reeves, 2014). Strike-slip reactivation of pre-existing

110   Proterozoic structures (from tectonic inheritance: Misra & Mukherjee, 2015) in the Jurassic

111   produced the Kachchh Basin (Biswas, 1982, 1999). By early Cretaceous times, development

112   of the Mozambique and Somali proto-oceans gave way to sea-floor spreading between the

113   Greater Indian and Antarctic continents (Eagles & Hoang, 2014; fig. 3 of Bladon *et al.,*

114   2015b). Consequently, the northward movement and anticlockwise rotation of the Greater

115   Indian continent occurred as break-up progressed (Chatterjee *et al.,* 2013; Storey *et al.,*

116   1995; Torsvik *et al.,* 2000) forming a series of interlinked failed rifts that constitute the WIRS.

117   Although the Jaisalmer and Indus basins are well known to have a late Gondwanan origin,

118   the relationship between the Cretaceous sediments of the WIRS, the Jaisalmer and Indus

119   basins remains obscure as it is patchily preserved across the northern margin of the Indian

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120   Plate below the Deccan Traps (Ahmed & Amad, 1991; Akhtar & Ahmad, 1991; Chowdhary,

121   1975; Jaitly & Ajane, 2013; Misra & Mukherjee, 2017; Khosla *et al.,* 2003; Raju, 1968;

122   Sharma, 2007; Sheth, 2007) and the geometry and extent of the associated rifts are poorly

123   documented. That said, preservation of isolated fluvial Lower Cretaceous sediments clearly

124   suggests the presence of an established rift system through the north-western Indian Plate

125   prior to the onset of the main Deccan eruptions around 64 Ma in the Danian (Mukherjee *et*

126   *al.,* 2017). Regional palaeogeographical reconstructions (Biswas, 1999; Chatterjee *et al.,*

127   2013) also include continental rift basins between India, Madagascar and the Seychelles

128   microcontinent, although the geometry of these rifts and their sedimentary fills are very

129   poorly described (see Plummer & Belle, 1995).

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131   The Barmer and Cambay basins, together with the Sanchor sub-Basin that separates them,

132   form a present day generally north-northwest tending rift 'arm' of the WIRS extending up to

133   600 km into northwestern India from the Gulf of Khambhat (Fig. 1A). The Barmer Basin is a

134   200 km long, <40 km wide, 6 km deep, failed continental rift (Bladon *et al.,* 2015a; Biswas,

135   1982; Compton, 2009; Dolson *et al.,* 2015) (Fig. 1B) containing continental sediments (Fig.

136   2A; Compton, 2009; Dolson *et al.,* 2015; Sisodia & Singh, 2000). A comparable rift system,

137   generally known as the Thar or 'Lower Indus' rift (Ahmed & Ahmad, 1991; Zaigham &

138   Mallick, 2000; Zaigham *et al.,* 2012) and specifically including the Panno-Aqil Graben,

139   extends northwards into Pakistan south of the Mari-Kandkot High and east of the Jacobabad

140   High (Ahmed & Ahmed, 1991) and probably represents the continuation of the WIRS.

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142   Subsidence and sedimentation along the WIRS presumably continued contemporaneously

143   with rifting of the Seychelles microcontinent and eruption of the Deccan volcanics at the

144   Cretaceous-Palaeogene boundary ~65 Ma (Collier *et al.,* 2008; Eagles & Hoang, 2014;

145   Ganerød *et al.,* 2011; Plummer *et al.,* 1998). The exact causes of this extension remain

146   equivocal, with many authors citing the migration of the western margin of India over the

147   Reunion Plume (Morgan, 1971; Plummer & Belle, 1995; Simonetti *et al.,* 1995), even though

148   the present-day Reunion Plume impinges on a remnant of continental crust (Torsvik *et al.,*

149   2013).

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151   Post-Deccan subsidence was concentrated along the Cambay-Barmer rift where some 6 km

152   of alluvial through to lacustrine environments of Palaeogene and Neogene age have

153   accumulated (Roy & Jokhar, 2002; Sisodia & Singh, 2000; Tabaei & Singh, 2002; Tripathi *et*

154   *al.,* 2009). These sediments have developed under a tropical to sub-tropical climate (Ali &

155   Aitchison, 2014; Chatterjee *et al.,* 2013; Hallam, 1985) as the Indian Plate migrated

156   northwards to its present-day position.

157   <u>The Barmer Basin</u>

158   Rifting in the Barmer Basin resulted from two distinct non-coaxial extensional events (Bladon

159   *et al.,* 2015b; Dasgupta & Mukherjee, 2017). An earlier northwest to southeast extensional

160   phase, oblique to the present orientation of the basin, was followed by dominantly

161   Palaeogene northeast to southwest extension (Bladon *et al.,* 2015b). Together, these two rift

162   events produced an asymmetrical half-graben in the north and a more symmetrical graben

163   in the south. Seismic data from the Barmer Basin indicates that pre-Deccan rifting is present

164   along the full extent of the basin with stratigraphical thickening being pronounced on the

165   present-day eastern margin (Dolson *et al.,* 2015).

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167   Basement rocks of the Precambrian Malani Igneous Suite are unconformably overlain by

168   clastic fluvial sediments of the Jurassic Lathi Formation and the Lower Cretaceous Ghaggar-

169   Hakra Formation (Fig. 2A). Eastwards the Ghaggar-Hakra Formation onlaps the Karentia

170   Volcanic Formation (Fig. 2A), consisting predominantly of microcrystalline and plagioclase-

171   phyric basalts (Roy & Jokhar, 2002) which erupted in response to initial rifting between east

172   and west Gondwana (Bladon *et al.,* 2015a; Storey *et al.,* 1995; Reeves & DeWit, 2000).

173   Previous authors have ascribed all three of these formations to a 'pre-rift succession'

174   (Biswas, 1987; Compton, 2009; Roy & Jokhar, 2002).

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176   Syn-rift strata are ascribed to the Palaeogene Mallinath Group and the early part of the

177   Eocene Jagmal Group (Fig. 2A). Earliest syn-rift strata of the Mallinath Group comprise acidic

178   pyroclastics and basaltic lavas of the Raageshwari Volcanic Formation erupted

179   predominantly in the centre of the basin (Compton, 2009), whilst contemporary alluvial fan

180   sediments (the Dhandlawas Formation) were deposited along the western margin, adjacent

181   to major fault scarps (Dolson *et al.,* 2015). From Maastrichtian to Thanetian times, braid-

182   plain fluvial and alluvial systems of the Fatehgarh and Barmer Hill formations dominated

183   with alluvial fan deposition (Jogmaya Formation) along the western faulted margin and

184   flanking horsts within. Regional uplift removed the youngest Barmer Hill strata to produce a

185   widespread unconformity across the basin before deposition resumed in Ypesian times

186   (Jagmal Group). Lacustrine systems (Dharvi Dungar Formation) dominated during the early

187   Jagmal Group giving way to swamp clastics of the Thumbli and Akli formations by Lutetian

188   times exhibiting minor marine incursions.

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190   Post-rift subsidence and in-fill began in Lutetian times with lacustrine sediments of the

191   Nagarka Formation (Dolson *et al.,* 2015). A period of uplift coincident with collision of the

192   Indian and Eurasian plates developed the regional base Miocene unconformity, before

193   deposition of the fluvial and alluvial Neogene Jagadia and Uttarlia formations of the Rawal-

194   Umed Group (Najman *et al.,* 2018).

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196   The Ghaggar-Hakra Formation

197   In the Sarnoo Hills, a succession of fluvial sediments unconformably overlay volcanic rocks of

198   the Karentia Volcanic Formation and, in places, the Malani Igneous Suite (Fig. 2B; Baksi &

199   Naskar, 1981; Compton, 2009; Mishra *et al.,* 1993; Sisodia & Singh, 2000). The formation is

200   ~100 m thick at outcrop (Mishra *et al.,* 1993) and comprises three distinct, quartz-rich, fluvial

201   channel belt sandstone packages separated by ~30 m of variegated white and red coloured,

202   horizontally-laminated and cross-laminated sands, with rhizoliths and soft-sediment

203   deformation structures (Bladon *et al.,* 2015a), attributed to deposition on a fluvial floodplain

204   (Bladon *et al.,* 2015a, b). The sandstone packages have been assigned informal

205   lithostratigraphical status and named (in ascending order): the Darjaniyon-ki Dhani, Sarnoo

206   and Nosar sandstones (Fig. 2B; Bladon *et al.,* 2015a, b).

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208   The Darjaniyon-ki Dhani Sandstone comprises poorly sorted and clast-supported lithic

209   arenites along with coarse sand to pebble-grade conglomerates attributed to deposition in

210   an immature, braided system with a high sediment load (Bladon *et al.,* 2015a). The Sarnoo

211   Sandstone comprises cyclic, well-sorted, fine to medium-grained, quartz arenites with

212   regular cross-bedded sets (Sisodia & Singh, 2000) and deposited in a mobile meandering

213   system (Bladon *et al.,* 2015a). The Nosar Sandstone caps the formation at outcrop and

214   comprises medium to coarse-grained sands and granule-grade conglomerates with cross-

215   bedded sets and channel geometries with erosive bases, typical of deposition in an actively

216   migrating braided fluvial system (Bladon *et al.,* 2015a).

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218   Plant leaves (*Phlebopteris athgarhensis Jain, Ptilophyllum acutifolium Morris* and

219   *?Sphenopteris sp.*; Baksi & Naskar, 1981; Compton, 2009; Rajanikanth & Chinnappa, 2016)

220   are present within the formation and are characteristic of the *Dictyozamites – Pterophllum –*

221   *Anomozamites* Assemblage (8th) zone (Dev, 1987; Rajanikanth & Chinnappa, 2016). Together

222   with trisaccate pollen (Podocarp *Microcachrydites* spp., *Cyclusphaera* spp.), they date the

223   Ghaggar-Hakra Formation to the Lower Cretaceous. Further constraints on the earliest age

224   of the formation are provided by an Aptian (120 Ma) date for the underlying basalts of the

225   Karentia Volcanic Formation (Sharma, 2007) and basaltic intrusions of Deccan age (68.57 ±

226   0.08 Ma; Basu *et al.,* 1993) constrain the youngest age of these sediments; indicating the

227   formation is Aptian to Albian age.

228   **Dataset, methods and field area**

229   The Ghaggar-Hakra Formation is exposed in a series of three low-lying, fault-bounded hills

230   separated by a peneplained surface covered in modern desert deposits near the village of

231   Sarnoo. Progressive down-stepping of the faulted blocks toward the west and north provides

232   excellent exposures that can be correlated providing continuous, composite vertical

233   sections. Extensive quarrying provides continuous lateral exposure of the sediments in the

234   scarp slopes of these hills. The dataset consists of 114 detailed sedimentary logs (Fig. 3) and

235   53 detailed two-dimensional panels providing correlation and geometries between the logs.

236 **Sedimentology of the Ghaggar-Hakra Formation**

237 The details of lithofacies are given in Table 1 and Fig. 3. Eight architectural elements (Table 2

238 and Figs 4, 5 and 6) are identified and summarised below with the bounding surface

239 terminology of Miall (1985, 1988).

240 Channel element – **Ch**

241 *Description*

242 These 'U'-shaped elements (Table 2) – laterally up to ~25 m and ~7 m thick – are bound by

243 sharp, sometimes erosional, convex-down 5th order surfaces at their bases, and generally

244 planar and concordant 4th order surfaces at their tops. The basal 5th order bounding surface

245 erodes other elements of this type (Ch), overbank (Ob), or channel margin (Cm) elements

246 but the 4th order surface, where preserved, is gradational over approximately 2 m into

247 overlying point bar (Pb) or overbank (Ob) elements. Typically, the full geometry is not

248 preserved, eroded by younger channels (Ch), channel margins (Cm), gravel bars (Gb), point

249 bars (Pb) or sheet flows (Sf; Figs 4A, 5A and 6A).

250 The 5th order surface is immediately overlain by the pebble-grade quartz clasts of grain-

251 supported conglomerate (G) characterised by indistinct cross-bedding. The conglomerate is

252 typically overlain by cross-bedded sandstone (Stx, Sx) in sets (30 cm thick) and co-sets (50 –

253 95 cm thick) bound by 1st to 3rd order surfaces. The contact between the basal conglomerate

254 and sandstone is sharp, generally with pebble-grade lenses within the toe-sets of the

255 lowermost cross-bedded sets. Sporadically, convolute bedding, tree stumps and rip-up clasts

256 are preserved, and packages of structureless sand (Sm) occur between sets of cross-bedded

257   sandstone (Stx, Sx). Where preserved, the upper half of the element comprises horizontally-

258   laminated sandstone (Sh) and cross-laminated sandstone (Scl) in sets climbing at 5°. These

259   sediments are overlain by mottled, bioturbated, very fine-grained pedogenic sands (Sp; Fig.

260   6A).

261   *Interpretation*

262   These elements are interpreted to represent small-scale, erosively based, fluvial channels.

263   The initial conglomeratic deposits overlying the channel base indicate high-energy flow with

264   significant bedload transport. Pebble lenses are concentrated in areas marking the thalweg,

265   indicating unsteady flow with localised periods of scour and fill (Froude *et al.,* 2017). Cross-

266   bedded sandstone (Stx, Sx) sets record the development and migration of lower flow regime

267   bedform trains and barforms, generally migrating towards the south-west. The irregular

268   nature of the sets and the range of bounding surfaces (along with convolute bedding, tree

269   stumps and rip-up clasts where preserved) suggests flow variability and reactivation of

270   bedforms and barforms.

271   Above this, the sediments (Scl, Sr, Sp) represent a decrease in energy as the flow wanes and

272   ripple-scale bedforms develop in trains and migrate. Bioturbation and structureless sands

273   below the 4th order surface most likely represents the final stages of sedimentation within

274   shallow, largely stagnant waters, followed by pedogenesis.

275   <u>Channel margin element – **Cm**</u>

276   *Description*

277   These tabular to wedge-shaped elements – up to 5 m high and 10 m long – are bound by

278   planar 5th order surfaces at their bases and planar 4th order surfaces at their tops (Table 2).

279   5th order surfaces are sharp and typically concordant with the underlying and overlying

280   sediments. Typically, they merge laterally with 5th order surfaces of channel elements and

281   become erosional. Sporadically, basal surfaces are replaced by a slightly gradational contact

282   from the underlying channel elements (Ch). Upper 4th order surfaces are sharp with the

283   overlying sediments of gravel bar (Gb), point bar (Pb), sheet flow (Sf) or overbank (Ob)

284   elements.

285   Bases are overlain by stacked, sub-critically climbing sets (30 cm) and co-sets (95 cm) of

286   planar cross-bedded sandstone (Sx) bounded by 1st to 3rd order surfaces. Above these, sets

287   of cross-laminated sandstone (Scl) climb sub-critically at 5°. Capping the elements are

288   deposits of fine-grained, horizontally-laminated sandstone (Sh) and pedogenic facies (Sp, Ip;

289   Figs 4B, 5B and 6B).

290   *Interpretation*

291   These elements are interpreted to represent the deposition of sediments on the channel

292   margin as flooding occurs. Sets of cross-bedded sandstone (Sx) and cross-laminated

293   sandstone (Scl) represent the development and migration of dune- and ripple-scale

294   bedforms as the flow overtops the channel on to the floodplain and wanes (O'Conner *et al.,*

295   2003; Wakefield *et al.,* 2015). The presence of horizontally-laminated sandstone suggests

296   periodic episodes of upper flow regime conditions as water moves from the restricted

297   channel to an unrestricted floodplain (Brierley *et al.,* 1997). Mottled sands and silts with

298   poorly preserved bedding possibly indicate destruction of primary depositional fabrics by

299   vegetation.

300   Gravel bar element – **Gb**

301   *Description*

302   These lenticular elements – up to 75 m long and 4 m thick – are bound by sharp and erosive

303   5th order surfaces at their bases, eroding into channel (Ch) or overbank (Ob) elements, and

304   sharp or gradational 4th order surfaces into the channel, point bar or overbank elements (Ch,

305   Pb, Ob; Figs 4C, 5C and 6C, Table 2). 5th order surfaces are laterally extensive and can

306   transition laterally into 5th order surfaces at the base of channel elements (Ch).

307   Matrix-supported conglomerates (M) and / or clast-supported conglomerates (G)

308   immediately overly the bases. Matrix-supported conglomerates (M) comprise rounded

309   quartz clasts and extraformational lithics, supported in a matrix of very fine to fine-grained

310   sandstone. Sporadically, indistinct foresets of cross-bedding are present. Clast-supported

311   conglomerates (G) comprise poorly sorted but rounded pebbles of quartz and

312   extraformational lithic clasts with sporadic and indistinct cross-beds.

313   The upper third comprises either massive sandstone (Sm) or horizontally-laminated

314   sandstone (Sh) facies (Fig. 6C), exhibiting sharp contacts with the underlying sediments. The

315   massive sandstone is moderately to poorly sorted with numerous quartz clasts. The clasts

316   are typically distributed randomly, but sporadically form indistinct horizontal layers. The

317   horizontally-laminated sands are up to 9 mm thick but thin upwards. The full succession is

318   rarely preserved and conglomerates (M, G) dominate.

319   *Interpretation*

320   Highly erosional 5th order surfaces typically contiguous with those of channels and

321   conglomeratic sediments indicate gravel bar deposition primarily by bedload transport

322   under high-energy conditions (Froude *et al.,* 2017). This is likely to have occurred along the

323   bases of developing channels with long axes of bars parallel to the channel. Grainsize is not

324   conducive to producing bedforms, and a high sediment load promotes rapid deposition that

325   further supresses their development (Bridge & Best, 1988). Where sediment load is reduced,

326   deposits grade from matrix to clast- supported with sporadic and poorly developed cross-

327   bedding indicating some migrating bedforms (Blair & McPherson, 1994) and implying

328   transient gravel bar movement (Figs 4C, 5C and 6C; c.f. Bridge 1993).

329

330   Massive and horizontally-laminated sandstone represents deposition in shallow water on

331   top of the developing barforms. Horizontally-laminated sandstone was deposited under

332   upper flow regime conditions (Ghazi & Mountney, 2009) when the gravel bars were fully

333   submerged. Massive sandstone represents deposition when the top of the bar was at

334   surface or slightly emergent, and stationary waters allow suspension fall out (Banham &

335   Mountney, 2013; Jones & Rust, 1982).

336   Chute channel element – **Cc**

337   *Description*

338   These small, symmetrical 'U'-shaped elements are up to 70 cm in height and no more than

339   2 m wide (Table 2). Their lower 5th order bounding surfaces are convex-down and erosional

340   into either point bar (Pb) or overbank (Ob) elements. Upper 4th order surfaces are generally

341   gradational into the overbank elements (Ob) over a thickness of 50 cm (Figs 4D, 5D and 6D).

342   Internally, the succession fines upwards from grain-supported conglomerates (G) composed

343   of quartz clasts, through massive sands and silts (Sm, Im) containing quartz clasts up to

344   5 mm. This succession culminates in parallel-bedded sands and silts forming ~50 cm thick

345   packages with individual beds ranging between 10 cm and 15 cm thick and the horizontally-

346   laminated sandstone (Sh) with packages up to 80 mm with laminations up to 9 mm thick.

347   Capping this element are bioturbated, rooted, pedogenically modified fine-grained sands

348   and silts (Sp, Ip). Typically, the succession is fully preserved, but sporadically, granule-grade

349   conglomerates (G) pass straight into pedogenically modified sands and silts (Sp / Ip)

350   producing a strongly bimodal grainsize profile.

351   *Interpretation*

352   The 'U'-shaped geometries and their erosional lower bounding surfaces are indicative of

353   small-scale channels. Conglomerates (G) consisting of locally reworked material immediately

354   overlying 5th order surfaces suggest initial deposition of sediments in a high-energy flow

355   cutting channels (Bordy *et al.,* 2004). Subsequently, flow waned rapidly to stagnant

356   conditions with a high sediment load promoting deposition of massive sands and silts (Sm,

357   Im; Martin & Turner, 1998). Where present, parallel-bedded and horizontally-laminated

358   sandstone (Sb, Sh) may suggest periods of extended and fluctuating upper flow regime

359   conditions prior to rapid waning (Wakefield *et al.,* 2015). In other examples, flow waned

360   rapidly to stagnant water, depositing a strongly bimodal grainsize (Martin & Turner, 1998).

361   The strong spatial association between these elements and point bar elements (Pb), coupled

362   with palaeocurrents that are generally perpendicular to the main channel system, suggest

363   small-scale, high-energy chute channels formed during flood conditions (Ghinassi, 2010;

364   Wakefield *et al.,* 2015). During flooding, sediment load is high, increased discharge promotes

365   'short-cutting' of the system across meanders, and energy levels wane rapidly to promote

366   rapid and structureless deposition (Wakefield *et al.,* 2015). Further evidence for this

367   interpretation is provided by the presence of locally reworked quartz clasts most likely

368   derived directly from the main channel system. Pedogenic sands and silts (Sp, Ip) represent

369   bioturbation and reworking of later stage sedimentation. The geometries of these elements

370   suggest 'low sinuosity' chute channels comparable to the 'type 1' chute channel of Ghinassi

371   (2010).

372   <u>Point bar element – **Pb**</u>

373   *Description*

374   These wedge-shaped elements (Table 2), up to 4 m thick and a maximum of 15 m wide, are

375   bound by lower 5th order surfaces that are sporadically slightly erosional but are generally

376   concordant with underlying strata and typically extend laterally into the base of a channel

377   (Ch). Upper 4th order surfaces, where preserved, are concordant with sediments of overbank

378   (Ob) and / or channel margin (Cm) elements. Typically, the upper parts of these elements are

379   not preserved because of erosional down-cutting by chute channel (Cc), channel (Ch) or

380   sheet flow (Sf) elements (Figs 4E, 5E and 6E).

381   Overlying the 5th order surfaces are co-sets (95 cm thick) of planar cross-bedded sandstone

382   (Sx) comprising sets of up to 30 cm thick that are interbedded with 2 m thick co-sets of low-

383   angle cross-bedded sandstone (Sla). This succession generally fines upward. Sets of both

384   facies are bound by 1st or 2nd order surfaces and sporadically truncated by 3rd order surfaces.

385   Capping the elements is cross-laminated sandstone (Scl) forming individual sets up to 5 cm

386   thick with internal structures disrupted by meniscate trace fossils of *Taenidium* or *Beaconites*

387   (Gowland *et al.,* 2018).

388   *Interpretation*

389   Elements of this type are interpreted to represent the deposits of laterally accreting point

390   bars. Multiple sets and co-sets of cross-strata decreasing in size from dune to ripple scale

391   (Sx, Sla, Scl) are the product of migrating bedforms within the lower flow regime (Ghazi &

392   Mountney, 2009; Jackson, 1976), this, combined with the reduction of grainsize indicates a

393   waning flow. The complex and varied geometry of sets and co-sets and numerous bounding

394   surfaces of varying scales suggest dominantly lateral but slightly down-stream migrating

395   barforms. 3rd order surfaces suggest frequent reactivation and meniscate trace fossils

396   towards the top suggest calm, possibly emergent, conditions with ripple-lamination

397   representing wash-over of the bar (Bridge *et al.,* 1995). 5th order bounding surfaces grading

398   laterally into the bases of channel elements (Ch) and the spatial association of these two

399   elements demonstrate an evolutionary relationship between them suggesting attachment of

400   the bar to the channel.

401   <u>Sheet flow element – **Sf**</u>

402   *Description*

403   These sheet-like tabular elements (Table 2), with a thickness of ~0.5 m, are bound by lower

404   5th order surfaces that are convex-down and erosive. Where the elements are fully

405   preserved, 4th order surfaces bound their tops and separate them from the overlying

406   overbank (Ob) elements. However, the tops of the elements are typically marked by erosive

407   surfaces at the bases of successive elements of sheet flow (Sf), or at the bases of channel

408   (Ch), chute channel (Cc) or point bar (Pb) elements (Figs 4F, 5F and 6F).

409   Facies of these elements form an ordered succession. Beds up to 30 cm thick of parallel-

410   bedded sandstone (Sb) fine and thin upward into beds of horizontally-laminated sandstone

411   (Sh). Overlying these are sets (10 cm) of rippled sandstone (Srha), climbing super-critically up

412   to 30°, and stacked 30 cm cosets of cross-laminated sandstone (Scl) climbing sub-critically at

413   5°. Pedogenic sandstone and siltstone (Sp, Ip) display mottled textures, and contain fossil

414   leaf imprints along with meniscate trace fossils typical of *Taenidium* or *Beaconites* (Gowland

415   *et al.,* 2018).

416   *Interpretation*

417   Deposition of subaqueous facies above 5th order surfaces with sheet-like geometries

418   indicates a largely unconfined flow (Blair, 2000). Upper flow regime conditions initially

19

419   prevailed, depositing parallel-bedded sandstone and horizontally-laminated sandstone (Sb,

420   Sh). Waning occurred rapidly to lower flow regime conditions depositing rippled sandstones

421   (Srha, Scl; Hjellbakk, 1997) indicating bedform development and migration. Variations in

422   climbing angle suggest variations in sediment load, flow competency and capacity (Blair,

423   2000; Hampton & Horton, 2007; Hunter 1977a, b). Pedogenic facies with high levels of

424   bioturbation and abundant plant remains implies times of depositional quiescence (Bromley

425   & Asgaard, 1979, 1991; Buatois & Mangano, 2002).

426   The relationships between sheet flows, channels and bars (Sf, Ch, Pb and Gb) suggest that,

427   whilst largely 'unconfined' (Banham & Mountney, 2013), the sheet flows may be restricted

428   to the lateral extent of active channel belts and most probably represent times of high

429   discharge when channels were filled to capacity.

430   <u>Overbank element – **Ob**</u>

431   *Description*

432   These elements are dominantly tabular (Table 2), up to 1.5 m thick and 2 km in lateral extent

433   and bound at their tops and bottoms by planar 4th order surfaces except where tops are

434   eroded by overlying channel (Ch) or gravel bar (Gb) elements. Lower boundaries can be

435   sharp where overbank elements overlay gravel bars (Gb), or gradational where they overlay

436   point bar or sheet flood (Pb, Sh) elements (Figs 4G, 5G and 6G).

437   The facies occur in any order, but when massive sandstone and siltstone (Sm, Im) and / or

438   horizontally-laminated sandstone (Sh) are present they typically overlay the 4th order

439   surface, interbedded in an apparently random manner by individual sets of cross-laminated

440   sandstone (Scl). When present, together these facies account for no more than 15% of the

441   element with the remainder comprising pedogenic facies (Sp, Ip, Ihe). Pedogenic facies are

442   dominantly red, and contain abundant granular peds (Retallack, 1988) between 2 cm and 3

443   cm long, along with grey to white patches of generally coarser grain. Abundant orange

444   goethite-rich rhizoliths reach lengths of 15 cm (Fig. 7), and carbonate cemented rhizoliths

445   reach lengths of 1 m (Fig. 4G) along one particular horizon. All facies are remarkably fissile,

446   and rare root structures and soils slickensides can be found throughout.

447   *Interpretation*

448   The physical dimensions and particularly the lateral extents indicate sediments of

449   unconfined overbank floods. The facies indicate sub-aqueous upper (Sh Sm) and lower flow

450   regime conditions with limited bedform development or migration (Scl) and occasional

451   suspension settlement (Sm, lm). Facies displaying granular peds and extensive colour

452   mottling indicate significant bioturbation (Sp, Ip, Ihe; Retallack, 1988; Tennvassås, 2018),

453   subaerial exposure and palaeosol formation (Retallack, 1988; 1990).

454   Elements of this type typically overlie one-another, with little to no erosion, and likely

455   represent cumulative soil growth on a floodplain supplied regularly with sediment from

456   flooding (Kraus, 1999; Kraus & Aslan, 1999). The rhizoliths indicate floodplain areas were

457   imperfectly to poorly drained soils (Kraus & Hasoitis 2006) suggesting they were seasonally

458   wet (Retallack 1990).

459   Pond element – **Po**

460   *Description*

461   These elements form lenticular bodies – up to 2 m thick and 50 m wide (Table 2). The lower

462   and upper boundaries are both 4th order surfaces and this element grades into the overbank

463   (Ob) element over ~30 cm.

464   Facies do not form regular definable successions, but where present cross and horizontally-

465   laminated sandstones (Scl, Sh) are typically preserved near element bases, followed by

466   massive fine-grained sandstone and siltstone (Sm, lm), with pedogenic (Ip) and haematitic

467   siltstone (lhe) dominating.

468   *Interpretation*

469   Elements of this type are interpreted as small ponds of limited lateral extent developed on

470   the overbank areas. Horizontally-laminated sandstone, massive sandstone and massive

471   siltstone (Sh, Sm, lm) indicate that sediment deposition was dominated by suspension

472   settlement. Sporadic cross-lamination (Scl) indicates development and migration of small

473   ripple-scale bedforms when pond levels were recharged by overbank flooding. Wind shear

474   on standing water combined with localised current turbulence formed symmetrical,

475   asymmetrical and interference ripple patterns (Sr; Wilson, 1993). The development of soils

476   (Sp, Ip, lhe) as ponds dried-out obliterated many primary bedding structures.

477 **Depositional Model for the Ghaggar-Hakra Formation**

478 All the field observations support the presence of a fluvial system where the transport and

479 deposition of sediment takes place within erosive channels by the development of in-

480 channel barforms (Ch), accompanied by bedload transport (Gb). The fluvial channels are

481 accompanied by laterally accreting bars (Pb) with chute channels (Cc), channel-margin

482 sediments (Cm) and sheet flows (Sf). The elements are arranged to form distinct 'channel

483 belt' depositional elements (terminology of Grotzinger *et al.,* 2005; Posamentier & Kolla,

484 2003). Each belt is separated by 'floodplain' depositional elements dominated by fine-

485 grained sediments deposited in bodies of standing water (Po) or by unconfined flooding

486 (Ob). Three channel belt depositional elements are recognised that correspond to the

487 informal lithostratigraphical subdivisions of Bladon et al. (2015a, b): the Darjaniyon-ki Dhani,

488 Sarnoo and Nosar sandstones. Conceptual facies models for these depositional elements are

489 presented in Figures 8, 9 and 10 along with a description of the key features and element

490 relationships that define them. An interpretation of each is given below.

491 The Darjaniyon-ki Dhani Sandstone is dominated by stacked and amalgamated channels and

492 gravel bars indicating a highly mobile, bedload-dominated system where barform migration

493 was transient (Best *et al.,* 2003; Bridge, 1993). Transient bars, coupled with a scarcity of

494 completely preserved elements, a range of grainsizes and rare preservation of overbank

495 suggests a highly avulsive system perhaps controlled by frequent changes in energy (Cant &

496 Walker, 1978). The dominance of gravel bar elements (Gb) comprising sediments of debris-

497 driven processes (Tables 1 and 2) indicates a high sediment load (Gulliford *et al.,* 2014; Lowe,

498 1988; Mather *et al.,* 2008) representing a bedload-dominated, low sinuosity fluvial system

499 (fig. 8 of Miall, 1985).

500   The sediments of the Sarnoo Sandstone are dominated of stacked and amalgamated

501   transient gravel bars in the initial deposits indicating a significant degree of channel avulsion.

502   Sinuosity and stability increase up section to develop channels of stable flow with associated

503   point bars and chute channels (Ielpi & Ghinassi, 2014; fig. 13 of Miall, 1985). However,

504   discharge is still sufficiently irregular to cause sheet flows (Sf) and support ponding on the

505   floodplain; overall this system represents a mixed load, high sinuosity fluvial system (fig. 11

506   of Miall, 1985).

507   The Nosar Sandstone displays channels with some degree of stability but separated by

508   transient bars. The system was influenced by avulsion and flooding (Best *et al.,* 2003; Bridge,

509   1993). Sparse preservation of the overbank may indicate limited and patchy development, or

510   poor preservation because of frequent fluvial avulsion. All features indicate a bedload

511   dominant, low sinuosity fluvial system (fig. 9 of Miall, 1985).

512   Channel belt elements are separated by significant sections of floodplain sediments (Fig. 2B),

513   that formed through cumulative soil growth and were likely imperfectly to poorly drained

514   due to being seasonally wet. Cyclicity suggests regular flooding which supplied the

515   floodplains with new sediment and recharged ponds, probably a consequence of channel

516   instability caused by variations in discharge and sediment load. The thickness of preserved

517   floodplain suggests that the channel belts themselves were reasonably stable for significant

518   periods.

519   The change in fluvial style from the Darjaniyon-ki Dhani to the Sarnoo sandstones,

520   particularly the increase in sinuosity and the decrease in the dominance of bedload

521   transport, indicates progressive maturing of the Ghaggar-Hakra fluvial system through time

522   (Schumm, 1981). This interpretation is supported by evidence for less flooding and fewer

523   floodplain ponds up-section. However, a decrease in sinuosity from the Sarnoo to Nosar

524   sandstones, coupled with an increase in the proportion of bedload, an increase in bedform

525   and barform migration, and stacking at all scales is atypical of increasing fluvial maturity (Fig.

526   11) and indicates rejuvenation of the whole system.

527   **Discussion**

528   <u>The Ghaggar-Hakra succession</u>

529   The Ghaggar-Hakra Formation records the maturing evolution of an early Cretaceous fluvial

530   system, followed by a sudden rejuvenation, preserved on an atypical relay ramp on the

531   margin of the Barmer Basin. Dating indicates the succession is of Aptian-Albian age.

532   Deposition of fluvial sediments always represents the complex interplay between the

533   intrinsic processes of sediment transport and deposition and allogenic-controls acting at a

534   variety of spatial and temporal scales (Leeder, 1993). Notwithstanding the constraints of the

535   limited spatial extent of the outcrop available in this study, the relative dominance of broad-

536   scale allocyclic-controls of climate and tectonics (Gawthorpe & Leeder, 2000; Robinson &

537   McCabe, 2012) and the implications for the evolution of the Barmer Basin, warrant some

538   discussion as presented below.

539   During deposition of the Ghaggar-Hakra Formation initial rifting between India and

540   Madagascar had started but India and Madagascar remained a single island continent

541   (Biswas, 1987; Bladon *et al.,* 2015b). The WIRS was located ~40° south of the equator with

542 the Indo-Tethyan Ocean to the north, and the Aravalli Mountain Range and continental India

543 to the south, in a position between the subtropical arid and temperate climatic belts

544 (Acharyya & Lahiri, 1991; Chatterjee *et al.,* 2013). The abundance of plant remains in the

545 Ghaggar-Hakra Formation indicates that the floodplains were extensive and highly

546 vegetated, with abundant palms and conifers.

547 Studies and models from other fluvial systems evolving under well vegetated subtropical

548 regimes (Fielding *et al.,* 2009) display a range of characteristics that are like many of those

549 observed in the Ghaggar-Hakra, including stacked and amalgamated channels with

550 convolute bedding, tree stumps, imperfectly to poorly drained palaeosols (Kraus & Hasoitis

551 2006) and variable but significant amounts of floodplain deposition.

552 However, preserved floodplain thicknesses predicted from fluvial models for subtropical

553 conditions are notably thinner than those observed in the Ghaggar-Hakra (Fielding *et al.,*

554 2009), and the thick cyclic floodplain successions formed are attributed to periodic flooding,

555 the result of channel instability caused by temporal variations in discharge and sediment

556 load.

557 Changes in discharge and load may relate to local and / or regional controls of either

558 tectonics or climate. Given that the floodplain is very uniform, with a lack of internal

559 variation in its pedogenic nature, and that the Indian Plate was within the subtropical arid

560 and temperate climate belt (Chatterjee *et al.,* 2013; Scotese *et al.,* 2007; Scotese, 2011)

561 throughout the time of deposition; it is argued that climatic variation is unlikely to have had

562 a significant influence upon the fluvial rejuvenation. However, the climate did influence

563   overbank conditions and soil growth. Based on the palaeosol profile exhibited by overbank

564   elements, the floodplain likely formed oxiosols that imply it received at least 100 mm per

565   month of rain over 7 months of the year (Cecil & Dulong, 2013).

566   In the absence of climate control upon the rejuvenation of the fluvial system during Nosar

567   times, local or regional tectonics are the most likely influence on accommodation space and

568   sedimentation. Recent studies indicate a Mesozoic section is preserved in the subsurface up

569   to 6 km deep, in the centre of the Barmer Basin (Bladon *et al.,* 2015b; Kothari *et al.,* 2015)

570   and recognise a west-striking, pre-Palaeogene tectonic grain on the eastern margin (termed

571   the Saraswati Terrace Bladon *et al.,* 2015b) that is overprinted by the younger Palaeogene

572   extensional event. Bladon *et al.* (2015b) conclude that early northwest-southeast rifting is a

573   consequence of the trans-tensional structural regime that existed between Greater India

574   and Madagascar prior to their separation and the main phase of Deccan volcanic eruption.

575   The sedimentological work on the Ghaggar-Hakra presented herein indicates that this early

576   rift event did indeed influence depositional style and architecture as many of the

577   sedimentary characteristics of the Nosar Sandstone, and rejuvenation of the system, can be

578   explained by deposition on a tectonically subsiding continental alluvial plain.

579   However, there is no direct evidence from outcrop for stratal growth patterns in the

580   Ghaggar-Hakra, or for a strong relationship between fluvial drainage patterns and fault

581   geometry in the Darjaniyon-ki Dhani to Sarnoo sandstones, which is atypical as these

582   features are generally common in fluvial systems strongly controlled by contemporaneous

583   rifting (Gawthorpe & Leeder, 2000). Apart from the high-energy system recorded in the

584   initial deposits of the Darjaniyon-ki Dhani Sandstone, the succession through to the base of

585   the Nosar Sandstone exhibits progressive fluvial maturation suggesting stability and

586   quiescence. It is only during Nosar times that significant rejuvenation of the fluvial system

587   occurs and that can be attributed to tectonically induced changes in fluvial gradient (Bridge

588   & Leeder, 1979; Leeder, 1993; Schumm, 1993). Consequently, it is tempting to conclude that

589   the base of the Nosar Sandstone, rather than the base of the Ghaggar-Hakra, represents the

590   onset of active rifting in the Barmer Basin during the early northwest-southeast phase of

591   extension recognised by Bladon et al. (2015b). Alternatively, rift flank uplift accelerated

592   significantly at the base of the Nosar Sandstone, indicating syn-rift deposition during Early

593   Cretaceous times. This in turn implies high preservation potential for thick Early Cretaceous

594   fluvial successions within rifted fault blocks beneath the Palaeogene fill that likely have

595   significant potential for further hydrocarbon exploration.

596   <u>Implications for Palaeogeography of the northwest Indian Plate in the Lower Cretaceous</u>
597   <u>Epoch</u>

598

599   During Early Cretaceous times, clastic deposition across the northwest Indian Plate was

600   dominated by fluvial systems carrying sediment to coastal plains and deltas forming along

601   the edge of the Indo-Tethyan Ocean. In the Kachchh and the Middle and Lower Indus basins

602   the Lower Cretaceous Bhuj and Lower Goru formations are established reservoirs for

603   hydrocarbons (Ahmad *et al.,* 2012; Biswas, 1999; Mukherjee, 1983). However, Cretaceous

604   sediments are rarely exposed at outcrop across the Indian Plate, being preserved only within

605   rift basins or at basin margins, where they have been downfaulted and protected from the

606   effects of Palaeogene and Neogene uplift and erosion. Therefore, reconstructing even local

607   Cretaceous palaeogeography is difficult because of limited outcrop, and collation of

608   descriptions of the Lower Cretaceous sediments is required.

609   In addition to the Ghaggar-Hakra, Lower Cretaceous fluvial deposits are present in the

610   Kachchh (Aslam, 1992; Casshyap & Aslam, 1992) Cambay (Bhatt *et al.,* 2016; Mukherjee,

611   1983; Jana *et al.,* 2013) and Narmada (Akhtar & Ahmed, 1991; Racey *et al.,* 2016) basins and

612   shallow marine sedimentation occurred within the Kachchh (Racey *et al.,* 2016; Rai, 2006),

613   Jaisalmer (Singh, 2006), and Indus (Ahmad *et al.,* 2004; 2012) basins. There is also evidence

614   for ~1 km of Mesozoic sediments beneath the main Deccan volcanic pile as indicated by

615   geophysical mapping (Rajaram *et al.,* 2016; Rao *et al.,* 2015). Therefore, it is pertinent to ask

616   the following question, initially posed by Biswas (1999): was the Ghaggar-Hakra Formation

617   only deposited in the rift systems or was it widespread across the northwest Indian Plate?

618   The depth to top basement map for north-west India of Kothari et al. (2015) is used to

619   establish a detailed structural framework to depict the early Cretaceous rift systems which in

620   turn define the depositional systems and their distribution (Fig. 12). The extent, type and

621   distribution of the depositional systems are initially established from the Sarnoo Hills work,

622   together with published accounts of early Cretaceous outcrop and subsurface sediments,

623   before speculatively extrapolating facies following Walther's Law.

624   During Cretaceous times, the Indian Plate was rotated 90° clockwise with respect to its

625   present orientation (Fig. 12; Chatterjee *et al.,* 2013) so its leading edge comprised much of

626   present day Pakistan where the Lower Cretaceous sediments were deposited in coastal

627   embayments, deltas and shorefaces (Ahmad *et al.,* 2012; Smewing *et al.,* 2002). As India was

628   within the subtropical arid and temperate climate belt, the overall precipitation across India

629   was low to medium (1.5 – 12 cm/month; Chatterjee *et al.,* 2013). The FOAM palaeoclimate

630   simulations (Goswami, 2011; Scotese *et al.,* 2007; Scotese, 2011) indicate that the WIRS and

631   surrounding areas were comparatively dry and warm (17 °C) when compared to the east of

632   the India which is separated from them by the 600 km long Aravalli Mountain Range.

633   Along the northern leading edge of the Indian Plate, the coastal Sembar Formation

634   siliciclastics were deposited on top of an extensive carbonate platform (Khalid *et al.,* 2014).

635   This resulted from a gradual and long-term base-level rise leading to high-stand shedding

636   with the formation of a westerly prograding delta (the 'Goru Fan Delta'). An active longshore

637   drift and tidal influence restricted these sands to the east of the shelf where they formed a

638   ramp ~200 km wide (Ahmad *et al.,* 2004) that gradually deepened to the west and north (fig.

639   9 of Khalid *et al.,* 2014). The Goru Fan Delta fed by fluvial systems draining the northwest

640   Indian Plate built out into the marine embayment, across the Jaiasalmer Basin and the

641   Punjab Platform and is imaged on regional 2D seismic data (Fig. 12; Khalid *et al.,* 2014).

642   Consequently, the Lower Cretaceous shoreline, shelf edge positions and lateral shifts are

643   reasonably well-known across the north-west Indian Plate in south-central Pakistan (Khalid

644   *et al.,* 2014). Fluvial palaeocurrent directions across the Lower Goru Fan Delta are from the

645   east and southeast consistent with sources on the Indian Plate (Ahmad *et al.,* 2004). The

646   Ghaggar-Hakra Formation palaeocurrent directions, present day, are to the south-west (Figs.

647   7, 8, 9; Sisodia and Singh, 2000; Bladon *et al.,* 2015a) into the Barmer Basin reflecting their

648   location on a feeder relay ramp (Saraswati Terrace) into the rift and directed towards the

649   Cambay Basin. Therefore, it is possible to speculate that these sediments actually fed the

650   southerly part of the WIRS and potentially drained into a poorly known early Cretaceous rift

651   basin beneath the present-day Gulf of Khambhat. Early Cretaceous rivers draining the

652   Devikot High and the northern Aravalli Range likely supplied the Lower Goru and Sembar

653   formations across the Punjab Platform (Fig. 12).

654   This palaeogeographical reconstruction suggests a much more complex drainage system

655   than has previously been envisaged for the northern leading edge of the Indian Plate.

656   Upland deposits had a very low preservation potential which, compounded with later uplift

657   and widespread erosion preceding the Deccan volcanism, resulted in the disparate

658   preservation of fluvial early Cretaceous sediments. Along with Biswas (1999), it is proposed

659   here that most of the early Cretaceous sediments preserved in the WIRS are indeed

660   remnants of a syn-rift continental succession. By contrast, the coastal plain and deltaic

661   deposits of the Sembar-Lower Goru succession were much more regionally extensive at

662   deposition and accumulated along the Indo-Tethyan leading edge in coastal plain, deltaic

663   and shallow marine shoreface settings.

664   **Conclusions**

665   The outcrops at Sarnoo, Karentia and Nosar provide continuous sections and significant

666   insight through Lower Cretaceous fluvial strata of the Ghaggar-Hakra Formation. The

667   sedimentary succession includes channels, bars, sheet floods and overbank deposits in

668   varied proportions that typify a fluvial system deposited under subtropical climate

669   conditions. The immature, low sinuosity system of the Darjaniyon-ki Dhani Sandstone,

670   dominated by gravel bars and isolated channels, along with its frequently flooded and

671   poorly-drained floodplain, matures upward into the laterally migrating channel system of the

672   highly sinuous Sarnoo Sandstone. The Nosar Sandstone completes the formation at outcrop

673   and comprises stacked and amalgamated channels and gravel bars indicating fluvial

674   rejuvenation.

675   Fluvial rejuvenation is most likely a response to faulting and it is concluded tentatively that

676   the Nosar Sandstone may represent the onset or acceleration of rifting and development of

677   the eastern margin of the Barmer Basin. Consequently, the Nosar Sandstone, along with

678   contemporaneous and later sediments of the Ghaggar-Hakra Formation, is syn-rift in nature.

679   This conclusion supports that of Bladon et al. (2015a) derived from structural analysis and

680   provides further evidence that extension in the Barmer area of northwest India was probably

681   established prior to the start of the Palaeogene Period. Given this interpretation, well

682   developed successions of Cretaceous fluvial strata may be preserved in Mesozoic sections of

683   the subsurface of the WIRS, offering hydrocarbon potential below the presently explored

684   Palaeogene succession of the Barmer and related basins.

685   Early Cretaceous sediments are rarely exposed at outcrop across the northwest Indian Plate.

686   Comparisons between the Ghaggar-Hakra Formation and other successions of comparable

687   age, between their relative positions in a plate tectonic framework, and with regional

688   structural data, allow for a reconstruction of a detailed palaeogeographical map for this part

689   of the north-west Indian Plate for the early Cretaceous. The reconstruction suggests a more

690   complex fluvial drainage system than previously envisaged, with continental early

691   Cretaceous sediments preserved only within contemporaneous rifts.

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1026   the Yorkshire Geological Society, 49, 171-188.

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1027   **Zaigham, N.A. Ahmad, M.** and **Hisam, N.** 2012. Thar Rift and its significance for

1028   hydrocarbons. American Association of Petroleum Geology Search and Discovery Article,
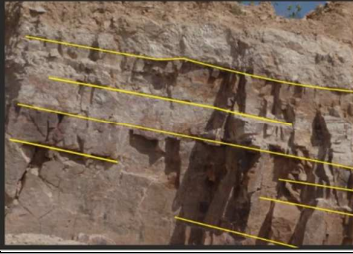
1029   2014, conference paper.

1030   **Zaigham, N.A.** and **Mallick, K.A.** 2000. Prospect of hydrocarbon associated with fossil-rift

1031   structures of the southern Indus basin, Pakistan. American Association of Petroleum

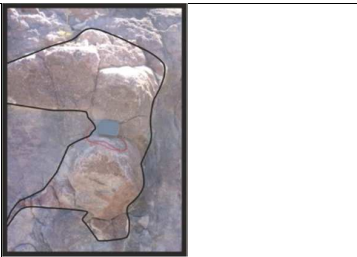1032   Geology Bulletin, 84, 1833-1848.

1033   **Table captions**

1034   Table 1: Fluid, debris and subaerial facies of the Ghaggar-Hakra Formation developed from

1035   the logged and panelled data of the formation.

1036   Table 2: Architectural elements of the Ghaggar-Hakra Formation.

Lithofacies	Texture	Structures	Interpretation	GPS Location	Figure
Fluid flow facies					
G (clast supported conglomerate)	Sub-rounded pebble-grade quartz and lithic clasts (2 – 52 mm), poorly sorted.	Erosional surfaces, grading of the clasts and indistinct cross-beds	Confined lower flow regime, potential migration of dune-scale bedforms	UTM 0777247, 2841083	
Stx (Trough cross-bedded sandstone)	Fine- to coarse-grained sands, moderately sorted, sub-rounded with rounded pebbles of quartz (22 mm)	Trough cross-bedding and erosional surfaces	Migration of sinuous crested dune-scale bedforms in the lower-flow regime	UTM 0778735, 2842021	
Sx (Planar cross-bedded sandstone)	Fine- to coarse-grained, well sorted, sub-rounded, with rounded pebbles of quartz (50 mm)	Planar cross-bedding, u-shape structures, reactivation and erosional surfaces	Migration of straight crested dune-scale bedforms in the lower-flow regime	UTM 0782621, 2853326	

Sb (Parallel bedded sandstone)	Very fine- to coarse-grained, moderately sorted, sub-rounded, clasts (22 mm).	Parallel bedding, erosional surfaces, silt bands, with very occasional cross-beds.	Non- or partially-confined flow events with bedload dominant transport and sporadic dune bedforms	UTM 0782621, 2853326
Sla (Low-angle cross-bedded sandstone)	Fine- to coarse-grained sands, moderately sorted, sub-rounded	Low angle cross-bedding	Sediments likely deposited due to helical flow during lateral migration	UTM 0777898, 2840794
Sr (Rippled sandstone)	Very fine- to medium-grained, well sorted, sub-rounded	Symmetrical and asymmetrical ripples upon laminated and bedded sediments	Ripple-scale bedforms in the lower flow regime	UTM 0777801, 2841812
Srha (Rippled sandstone with supercritical climbing)	Very fine- to medium-grained, well sorted, sub-rounded	Fully preserved symmetrical and asymmetrical ripples	Ripple-scale bedforms in the lower flow regime; high sediment output	
Scl (Cross-lamination sandstone)	Fine-grained sands, well sorted, sub-angular	Cross-lamination	Ripple-scale bedforms in the lower-flow regime	UTM 0783859, 2853121

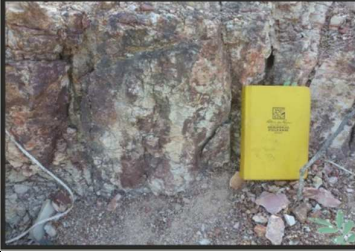| Sh (Horizontally-laminated)	Fine- to medium-grained sands, moderately sorted, sub-angular	Laminations	Low amplitude, long wavelength bedforms of the upper flow regime	UTM 0783727, 2853017	
Sm (Massive sandstone)	Fine- to coarse-grained, on occasion there are clasts up to 19 mm.	Massive	Material deposition from suspension, in very low slow moving or stationary waters	UTM 0777107, 2840577	
Im (Massive siltstone)	Siltstone	Massive	Material deposition from suspension, in stationary waters	UTM 0777181, 2841039	
Debris flow facies					
M (Matrix-supported conglomerate)	<27 cm boulders, where the matrix is granule-grade conglomerates; the material is matrix-supported	Indistinct cross-bedding	Non-Newtonian flow resulting from high sediment load suppression of bedforms	UTM 0777865, 2841891	
Subaerial facies					

Sp (Pedogenic sandstone)	Mottled red and white very fine-grained sands	Occasional laminations, soft sediment deformation and indistinct bedding and laminations	Bioturbation from plants and organisms and a pedogenic nature equalling soil formation	UTM 0778635, 2842386
Ip (Pedogenic siltstone)	Mottled red and white, muds and silts	Occasional laminations, soft sediment deformation and indistinct bedding and laminations	Pedogenic nature, soil slickenlines, fractures and bioturbation from root traces and organisms allowing for soil formation	UTM 0778640, 2842381
Ihe (Haematitic siltstone)	Mottled red and white, muds and silts	Haematitic horizons with occasional laminations, soft sediment deformation and indistinct bedding and laminations	Bioturbation from plants and organisms, haematitic and a pedogenic nature equalling soil formation	UTM 0778635, 2842386

Table 1

AE	Litho-facies	Description	Interpretation
Ch	G, Stx, Sx, Scl, Sh, Sp	Geometry: Tabular and sheet-like geometries Size: up to 6 m thick External boundaries: Lower fifth order surfaces are erosional and the upper fourth boundaries are gradational where seen	Packages of sediment represent in-channel deposits.

		Internal boundaries: First to third order bounding surfaces	
Cm	Sx, Sh, Scl, Sp, Ip	Geometry: Wedged and tabular Size: Up to 5 m thick and 10 wide External boundaries: Lower fifth order surface is sharp and the upper fourth order surface is gradational. Internal boundaries: First to third order bounding surfaces	Deposited due to flow migrating from a confined to an unconfined setting.
Gb	G, M, Sm, Sh	Geometry: Lenticular to wedge shaped Size: <6 m high and 300 m in lateral extension External boundaries: Lower fifth order boundaries are erosion and the upper fourth order boundaries are gradational. Internal boundaries: First to third order surfaces	Transient braid bars, with deposition by migrating bedforms.
Cc	G, Sm, Im, Sh, Sp, Ip	Geometry: Lenticular and wedged shaped Size: Channels are <70 cm in height and 2 m wide External boundaries: Lower fifth order boundaries are erosional and the upper fourth order boundaries are gradational Internal boundaries: No internal bounding surfaces, generally structureless, can contain normal grading	Flooding of the river system by cutting off the point bar.
Pb	Sla, Sx, Scl	Geometry: Wedge Size: <3 m in height, and 20 m in length External boundaries: Lower order fifth order bounding surface and the fourth order bounding surface are gradational Internal boundaries: First and second order bounding surface which truncate against third and fourth order bounding surfaces where the sets and cosets are perpendicular to one another	Laterally migrating bars
Sf	Sr, Sh, Srha, Sb, Scl, Sp, Ip	Geometry: Sheet-like and tabular Size: laterally extensive (< 2 km) and 2 m high External boundaries: Lower fifth order bounding surface is concave-down and concordant and the upper fourth order bounding surface is gradational Internal boundaries: Interbedded laminations and ripples with first and second order bounding surfaces	Formed through the flooding of the fluvial system.
Ob	Sh, Sm, Im, Sr, Scl,	Geometry: Tabular and sheet-like Size: up to 150 cm in thickness and 2 km in lateral extension External boundaries: Lower sixth order bounding surface is sharp and the upper fourth order bounding surface is sharp	Formed from cyclic flooding from the fluvial system, with palaeosol evident.

	Sp, Ip, Ihe	Internal boundaries: First to fifth order surfaces are present; the first to third order surfaces are from ripples, fourth order surfaces are sharp and form from the pond element. The fifth order surfaces are regional quiescence periods.	
Po	Scl, Sm, Im, Sr, Sh, Ip, Ihe	Geometry: Sheet-like and tabular Size: <0.5 m high and 20 m in length External boundaries: both the lower and upper fourth order boundaries are gradational into the floodplain element Internal boundaries: First and second order surfaces present with boundaries removed due to bioturbation.	Slight coarsening upwards successions, capped with palaeosols.

Table 2
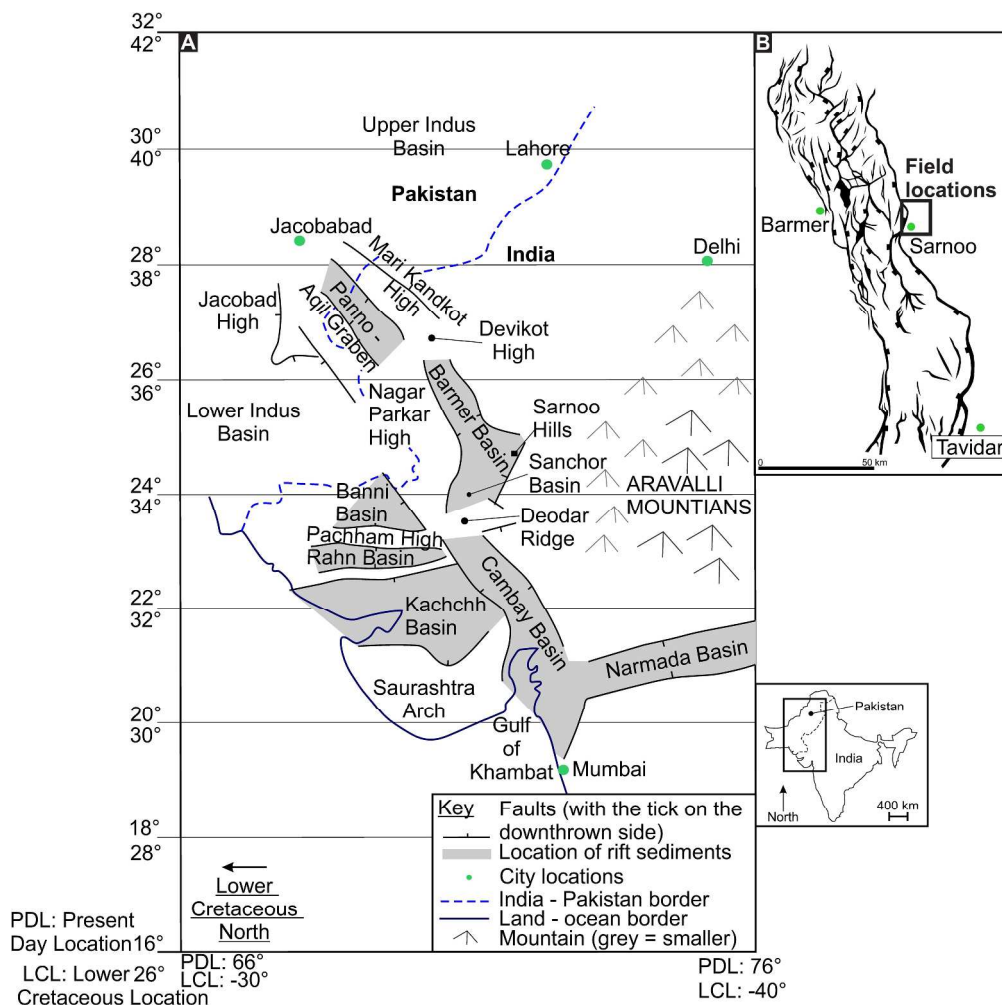
Figure 1: (A) Onshore rift basins within the WIRS (adapted from Balakrishnan et al., 2009) and various locations mentioned in the text: Insert gives the location of the Barmer Basin indicated by the solid black line within the Barmer District; (B) Principal extensional faults that define the geometry and limits of the Barmer Basin (adapted from Dolson et al., 2015), displaying the field locations for this study on the eastern, central margin. The settlement of Sarnoo is shown.

301x299mm (300 x 300 DPI)
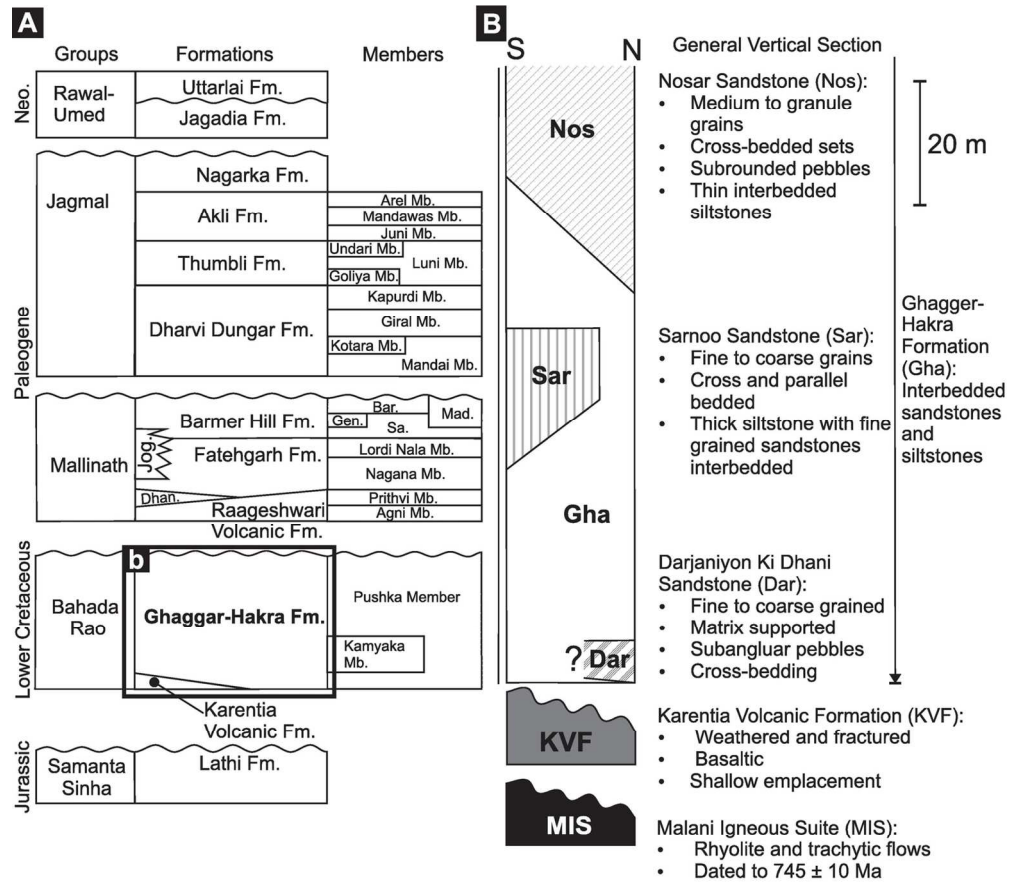
Figure 2: (A) Generalised vertical section of the Barmer Basin, displaying currently accepted group formations and members; Dhan. = Dhandlawas Formation, Jog. = Jogmaya Mandir Formation, Sa. = Sarovar Member, Gen. = Genhu hill Member, Mad. = Madpura Member, Bar. = Bariyada Member (Compton, 2009; Dolson et al., 2015 Sisodia & Singh, 2000; Tabaei & Singh, 2002; Tripath et al., 2009); (B) generalised vertical section of the Ghaggar-Hakra Formation, displaying the separate lithostratigraphically informal sandstone units recognised by previous authors (adapted from Bladon et al., 2015a).

134x124mm (300 x 300 DPI)

Figure 3: Simplified representative logs from the Ghaggar-Hakra Formation. Three logs displaying the typical facies from (A) the Darjaniyon-ki Dhani Sandstone, (B) the Sarnoo Sandstone and (C) the Nosar Sandstone. The facies codes stated on the logs are denoted in Table 1, the arrows represent the palaeoflow orientation and logs are in metres.

160x106mm (300 x 300 DPI)

160x109mm (300 x 300 DPI)

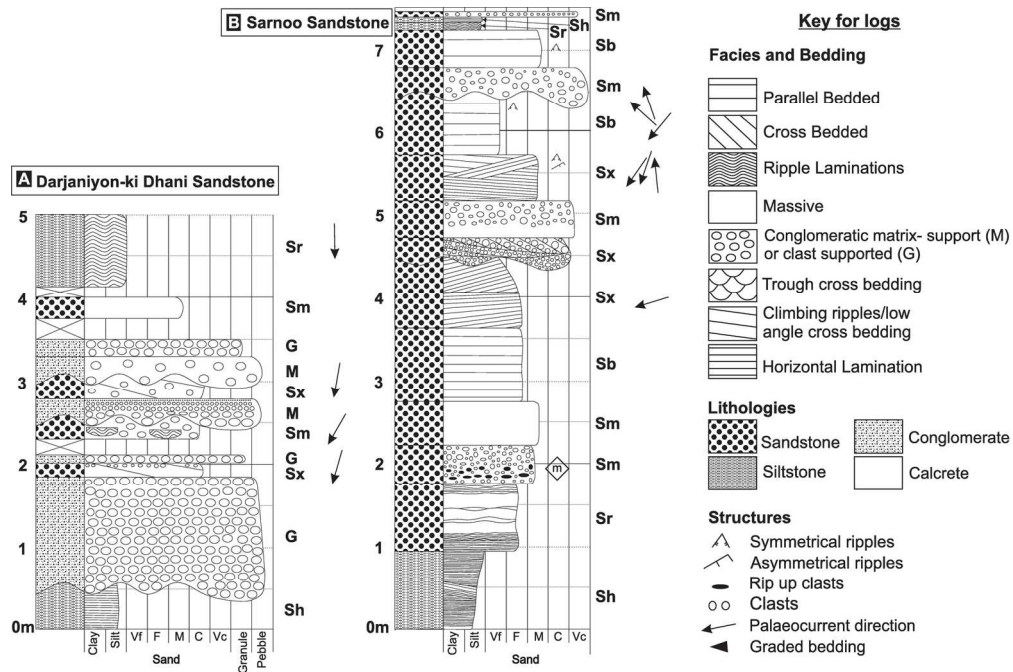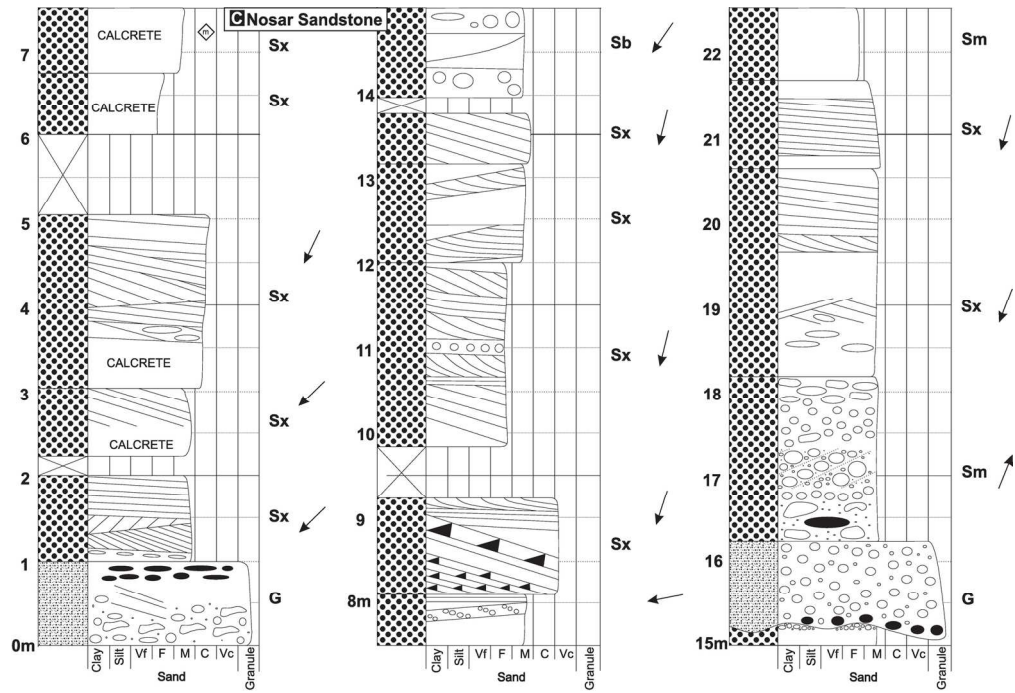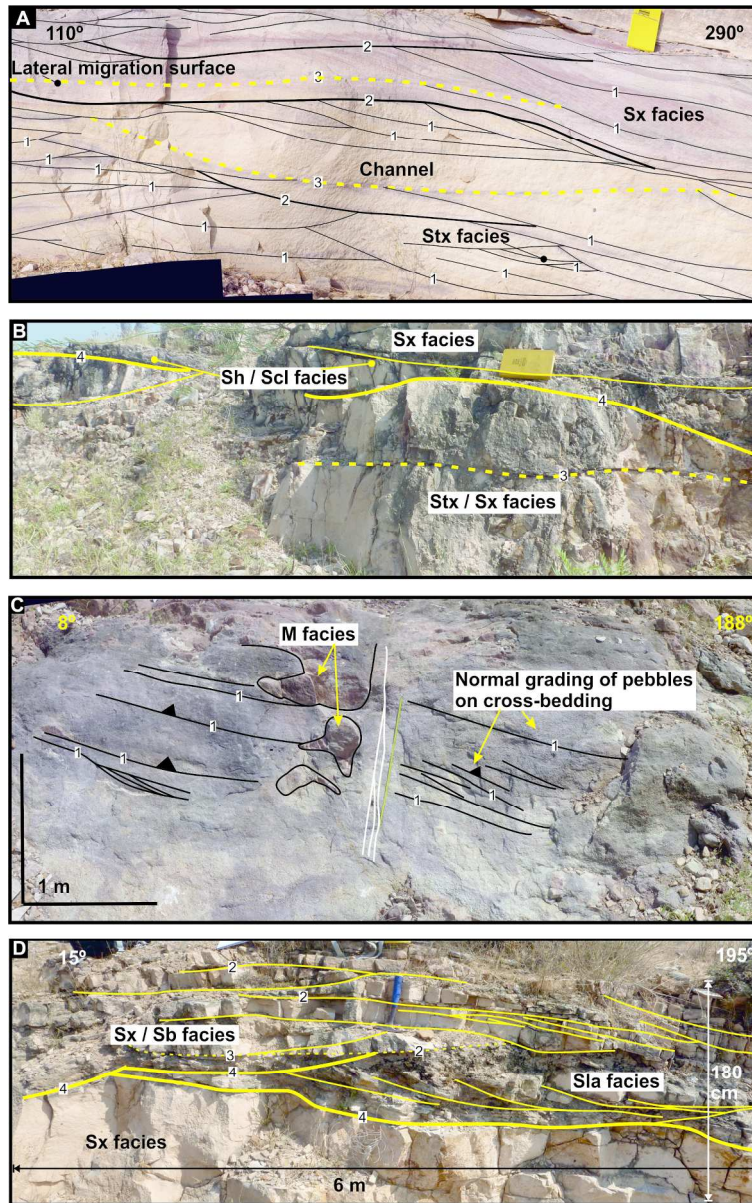Figure 4: Interpreted photographs of the architectural elements (A) Channel element (Ch) displaying 1st – 3rd order bounding surfaces with the trough and planar cross-bedded sandstone facies; (B) Channel margin element (Cm) displaying the gradational change from the cross-bedded facies (Stx / Sx) into the cross / horizonal-lamination facies (Sh / Scl) overlain by an erosional surface and the planar cross-bedded facies; (C) Gravel bar element (Gb) displaying the conglomerate facies (M & G) with indistinct cross-bedding and upon some of the cross-beds there are graded clasts; (D) Chute channel element (Cc) this image depicts the channel element indicated by the planar cross-bedded facies (Sx), the Point bar element indicated by the low-angle cross-bedded facies (Sla) and the chute channel indicated by the thick, thin solid lines and the planar cross-bedded and planar horizontally bedded facies (Sx / Sb); (E) Point bar element (Pb) Low-angle cross-bedded facies (Sla) with 2nd and 4th order bounding surfaces laterally migrating into the channel element (Ch); (F) Sheet flow element (Sf), here the element displays the horizonal-laminated and cross-lamination facies (Sh / Scl) with various types of ripples; (G) Overbank element (Ob) indicated by the rhizoliths and the pedogenic facies (Sp / Ip / Ihe), and; (H) Pond element (Po) indicated by the horizonal-

laminated and cross-lamination facies (Sh / Scl).

155x247mm (300 x 300 DPI)
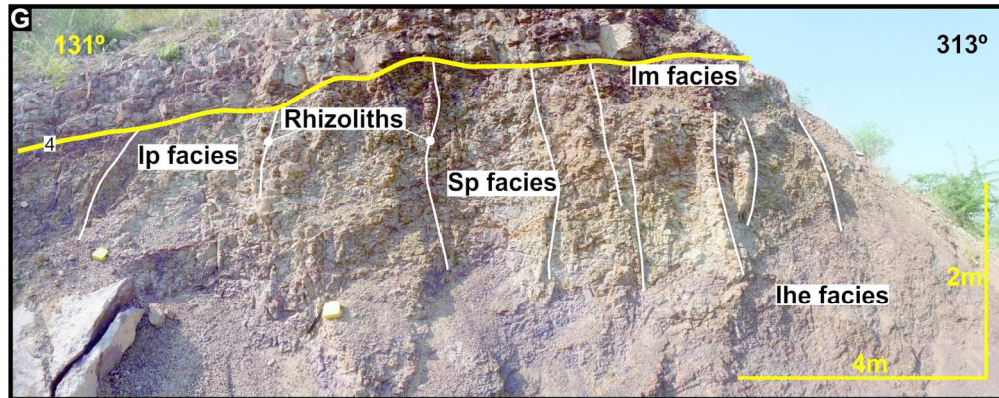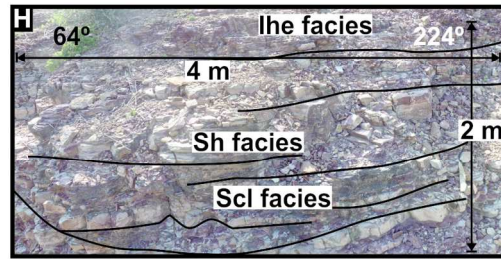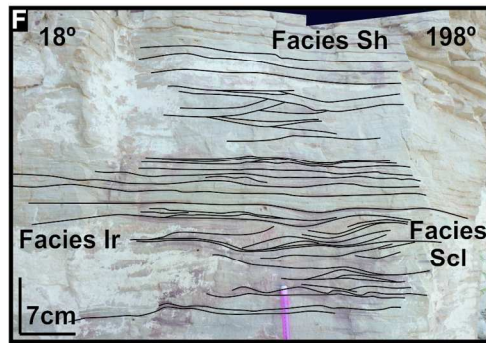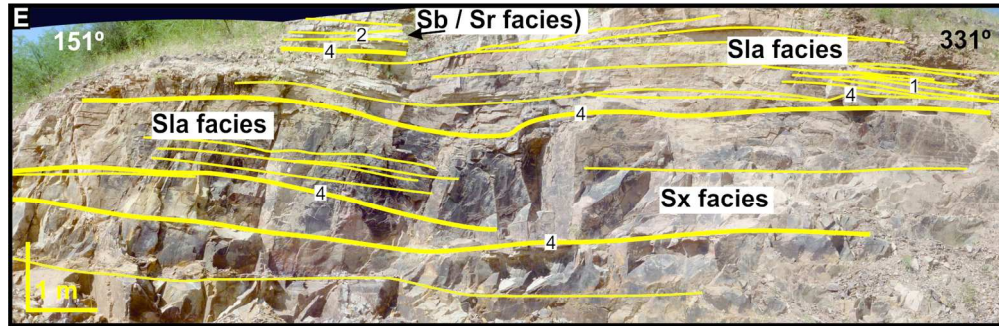
155x170mm (300 x 300 DPI)
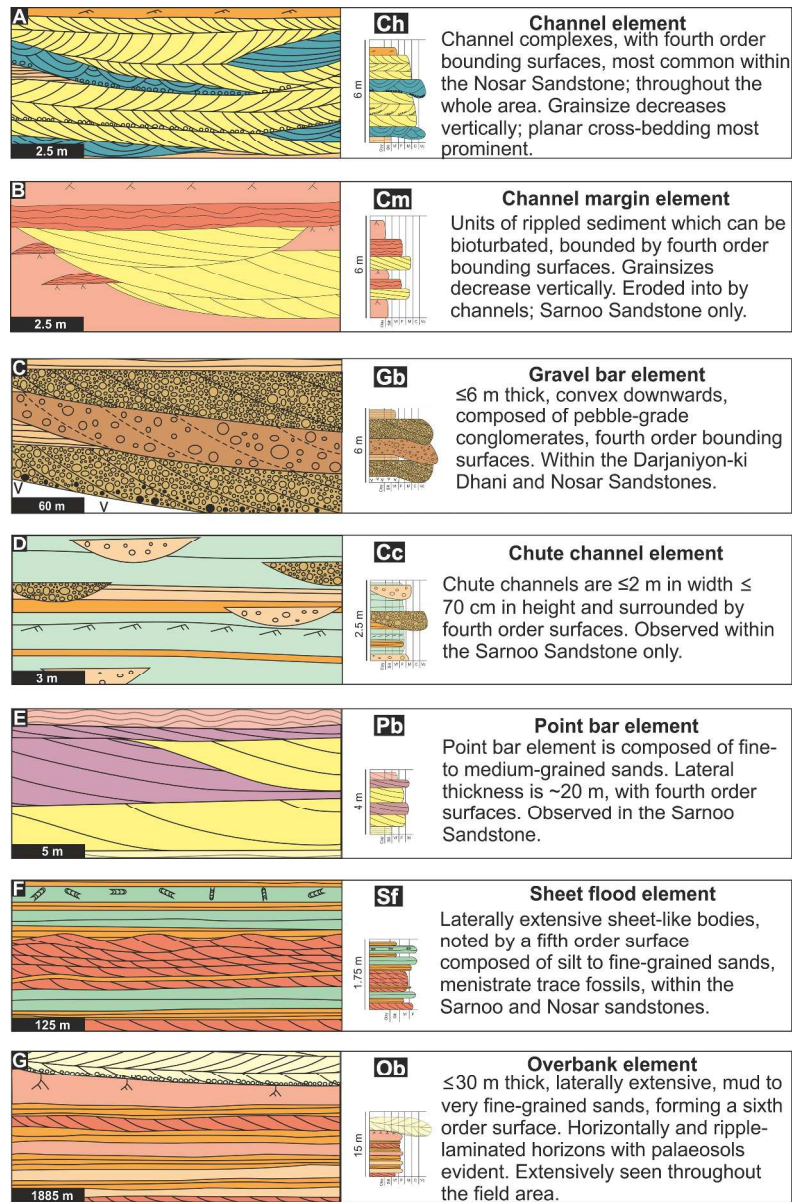
Figure 5: Two-dimensional sketches and logs that typify the architectural elements observed in the Ghaggar-Hakra Formation (A) Channel, Ch; (B) Channel margin, Cm; (C) Gravel bar, Gb; (D) Chute channel, Cc; (E) Point bar, Pb; (F) Sheet flow, Sf; (G) Overbank, Ob, and; (H) Pond, Po.

237x360mm (300 x 300 DPI)

H

5 m

Po

0.4 m

Pond element

Thin units which can be laterally extensive, within the overbank (Ob), composed of muds to fine-grained sands. Observed within the siltstone succession only.
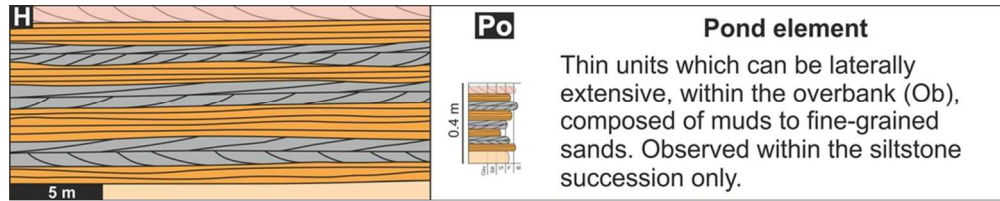
Grain-supported conglomerate (G)

Trough cross-bedd sandstone (Stx)

Cross-bedded sandstone (Sx)

Parallel bedded sandstone (Sb)

Massive sandstone (Sm)

Low-angle cross-bedded sandstone (Sla)

Rippled sandstone (Sr)

Cross-laminated sandstone (Scl)

Horizontally-laminated sandstone / siltstone (Sh)

Matrix-supported conglomerate (M)

Pedogenic sandstone (Sp) / Pedogenic siltstone (Ip) / Haematitic pedogenic siltstone (Ihe)

Volcanics

Roots   Current ripples   Trace fossils

90x52mm (300 x 300 DPI)
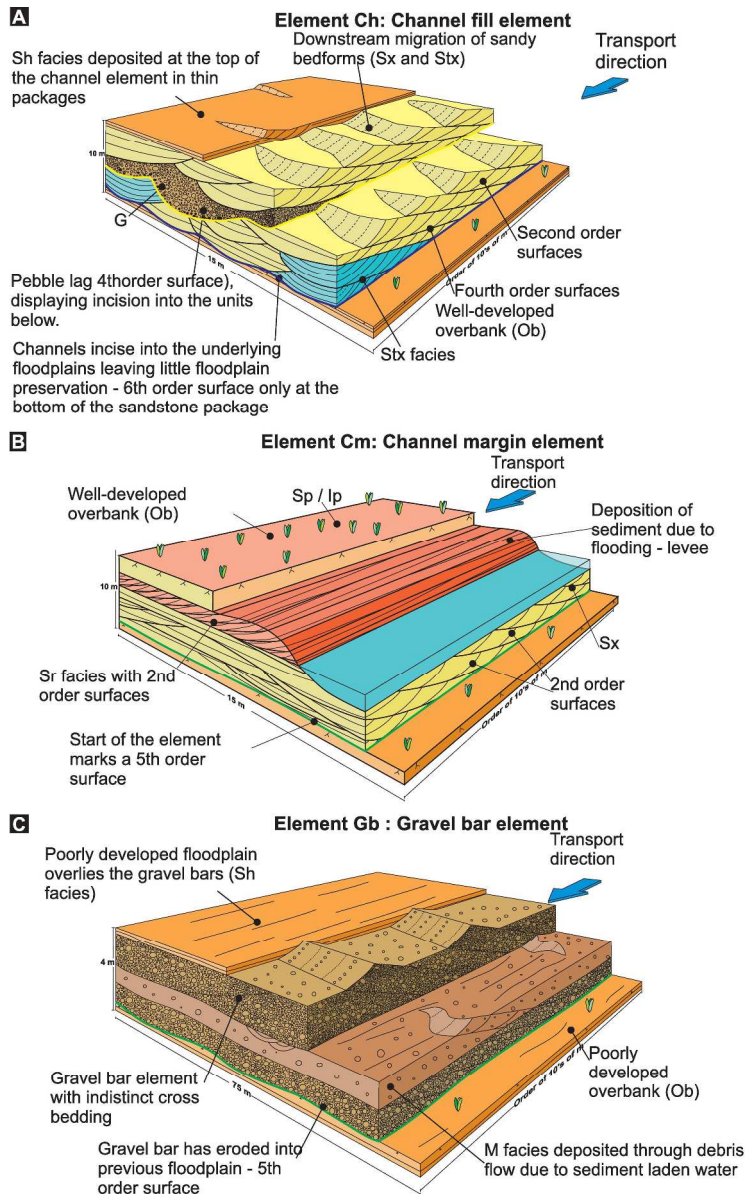
Figure 6: Three-dimensional facies models of the architectural elements; (A) The channel element (Ch) with an erosive lower base contains 1st to 3rd order surfaces internally; (B) The channel margin (Cm) element with an erosive lower base and 1st to 3rd order surfaces internally, the succession grades into the overbank; (C) The gravel bar (Gb) element with an erosive lower boundary and 1st to 2nd order surfaces within; (D) The chute channel (Cc) element with an erosive lower boundary and occasional first order boundaries within; (E) The point bar (Pb) element with an erosive 4th order boundary with 1st to 3rd order surfaces internally. This succession grades into the overbank; () The sheet flow (Sf) element starting with a lower 4th order bounding surface with 1st to 3rd order surfaces within. There are quiescent periods here evidenced by trace fossils; (G) The overbank (Ob) element with 1st, 2nd and 4th order surfaces within; (H) The pond (Po) element has a 4th order base and 1st to 2nd order surfaces internally.

244x390mm (300 x 300 DPI)

D

Element Cc: Chute channel element

Poorly developed overbank (Ob) with little vegetation - marked by palaeosol development from mottling - Sh / Sp

Transport direction

1 m

Few trace fossils representative of quiescent periods

10 m

Order of 10s of m

5th order surfaces

Chute element is combined of both the Sm and G.

Chute channel incises into the Sb facies, overbank muds (Ob), sheet flood (Sf) and point bar (Pb) elements

E

Element Pb: Point bar element

Migrating sandy bedforms

Transport direction

Sla and Sx facies are interbedded.

4 m

Sr facies is always deposited at the upper boundary of the point bar as the flow wanes representing the overbank (Ob) and occasionally sheet floods (Sf).

20 m

Order of the 10s of m

5th order surfaces

Generally deposited vertically or laterally to the channel element (Ch)

Poorly developed overbank (Ob)

F

Element Sf: Sheet flow element

Trace fossils are suggestive of a quiescent period within the flow events.

Transport direction

2nd. 3rd and 4th order surfaces

1.5 - 2 m

5th order surface

Poorly developed overbank (Ob), due to a high flood events there is limited root growth, however the mottled colour is suggestive of a root fabric.

Order of 10's of m

Channel element (Ch)

Main deposition of the sheet flood from Sb, Sr and Sh facies displaying varying turbulence within an unconfined flow.

262x429mm (300 x 300 DPI)

G

Element Ob: Overbank element

The element is capped by the start of fluvial channel incision (Ch), 6th order surface

Downstream mirgration of sandy bedforms

Transport direction

Channel element (Ch)

15 m

Heavily vegetated unit suggestive of a well-developed overbank, Sp, Ip and Ihe facies

2 km

Order of 10s of m

Downstream mirgration of sandy bedforms due to flooding (Sr)

Sediments deposited from stationary flood waters

H

Element Po: Pond element

Sr

Sh

Transport direction

2 m

Non-erosive - fourth order surface

20 m

The pond element occurs within the overbank (Ob)

Order of m's

Sm and Sp

Scl facies is indicative of the pond element.

187x207mm (300 x 300 DPI)

Figure 7: Rhizoliths within the floodplain (Ob) sediments (A) and (B) orange rhizoliths within the formation; (C) white reduction zones due to the organic mater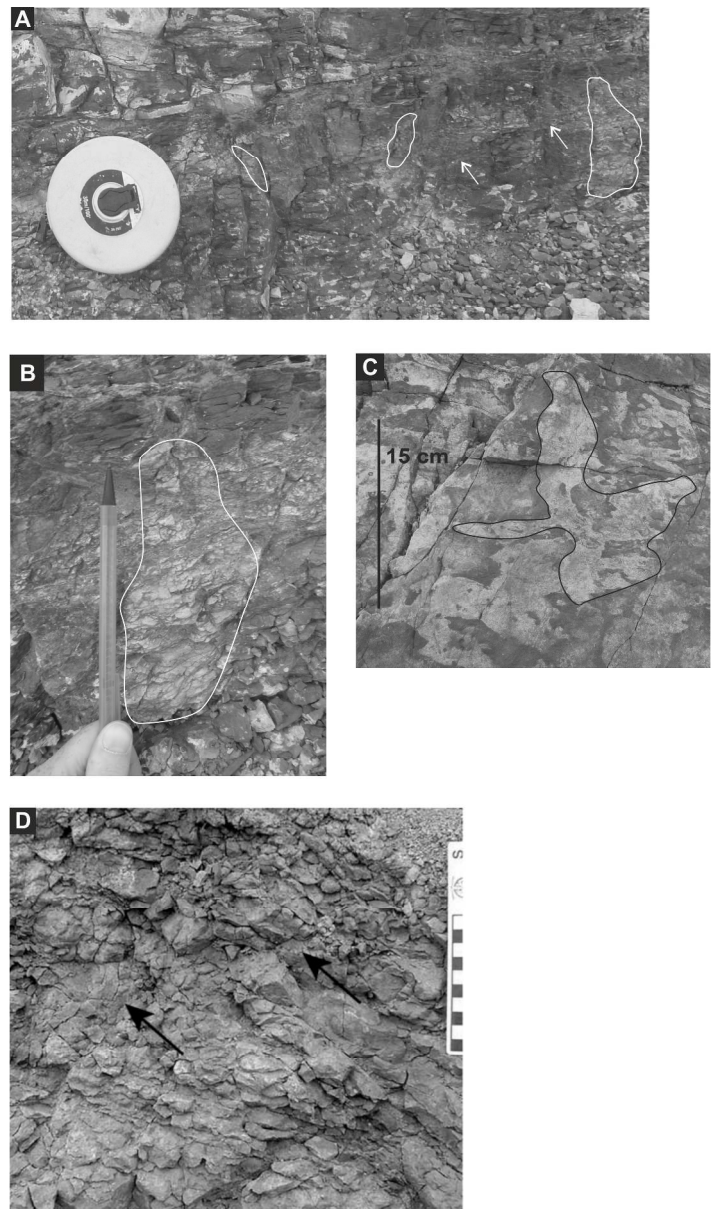ial within the roots and rhizoliths, and; (D) the orange rhizoliths from Kraus and Hasiotis (2006), to allow for an easy comparison.

208x357mm (300 x 300 DPI)

Modern day river channel, with medium-grained sand to granule-grade conglomerates and sinuous crested bedforms

Transport direction

Very coarse-grained channel fill (Ch)

Modern day braid and gravel bars

10 m

Volcanics

Overbank (Ob) underlying the main channel succession, erosively overlying the volcanics

50 m

Order of 10's of m

Granule-grade conglomerates forming the gravel bars (Gb) which are stacked and amalgamated bar-froms, there are very occasion cross-bedded foresets noted within the M and G facies here.

There are very occasional cross-bedded foresets (Ch) that are stacked and amalgamated into the with the pebble-grade clasts here gravel bars (Gb).

Bedload dominant, highly avulsive, low sinuous fluvialsystem

Number of measurements: 22
Mean: 191.42°
Dispersion of ±53.60°.

Figure 8: Facies model of the gravel bedload dominant low sinuosity fluvial system, the Darjaniyon-ki Dhani Sandstone, which contains the channel (Ch), gravel bar (Gb) and the overbank (Ob) architectural elements. There are 4th to 6th order bounding surfaces within. The sets and cosets within are inconsistent suggesting the gravel bars are transient, suggesting fluvial immaturity. The proportion of channels to floodplain is 90% to 10%, respectively.

179x134mm (300 x 300 DPI)
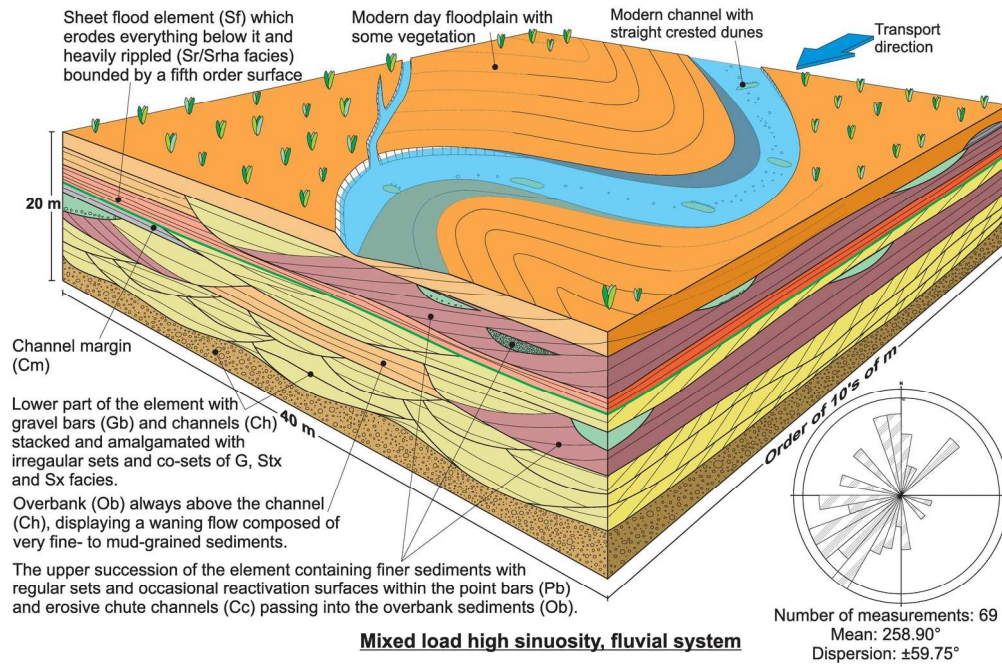
Figure 9: Facies model of the mixed load high sinuosity fluvial system, the Sarnoo Sandstone, as evidenced by the channels (Ch), channel margin (Cm), gravel bars (Gb), chute channels (Cc) sheet flows (Sf) and overbank (Ob) elements. The consistency of sets and cosets representing the migration of in-channel bedforms suggests discharge stability. The proportion of sand to mud increases from 80% sand and 20% mud to 60% sand and 40% mud vertically throughout the facies model.

169x114mm (300 x 300 DPI)

Gravel bar (Gb) granule- to pebble-grade conglomerates, deposited by fluid flow

Transport direction

Modern channel with sinuous crested duneforms

Overbank (Ob) composed of mud- to fine-sands. Little vegetation.

Rarely preserved overbank (Ob) accounting for 5% of the model

30 m

50 m

Order of 10's of m

Sheet flood (Sf) medium- to very fined -grained sands which is laterally extensive throughout the field area.

Channel fill (Ch) bound with erosive 5th order surfaces interbedded with coarse sands and granule-grade conglomerates; containing quartz clasts and rip-up clasts with irregular sets and cosets. The channels approx. 10m across and stacked and amalgamated with gravel bars (Gb) forming tabular geometries.

Bedload dominant, low sinuosity fluvial system

Number of measurements: 62
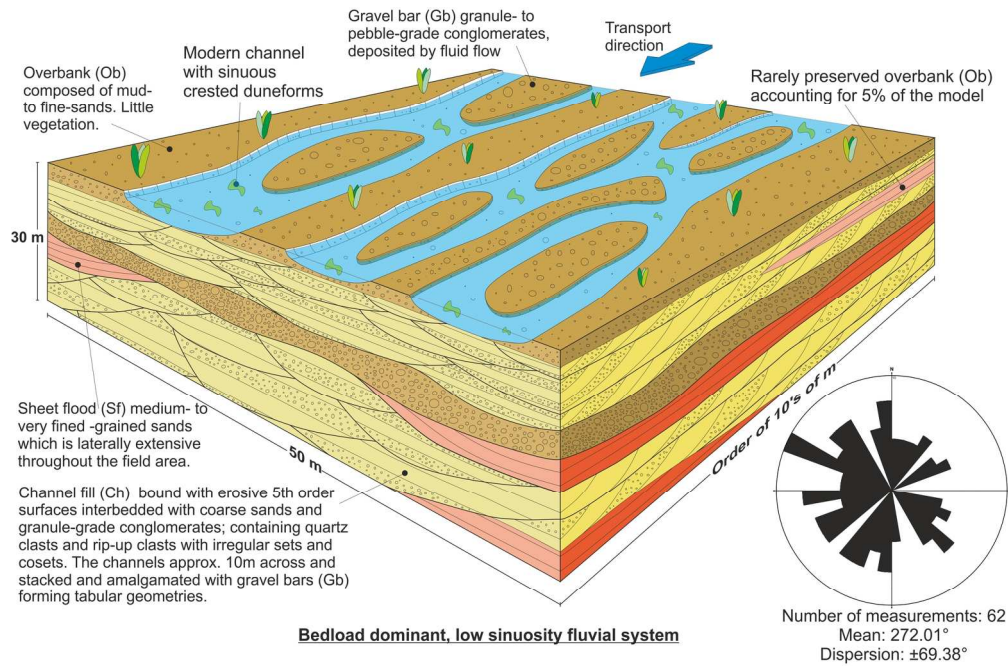Mean: 272.01°
Dispersion: ±69.38°

Figure 10: Facies model of a well-developed, bedload dominant, low sinuosity fluvial system, the Nosar Sandstone, displays channel (Ch), floodplain (Ob), gravel bars (Gb) and sheetflow (F6) elements. There are all six types of bounding surfaces within indicating erratic surfaces and multiple truncations. This suggests discharge irregularity and a high level of channel migration. The proportion of sand to mud is at 90:10.

169x115mm (300 x 300 DPI)

Bedload dominant, well-developed low sinuosity fluvial system - Nosar Sandstone

Transport direction

Siltstone succession - Sarnoo Floodplain

100 m

Siltstone succession - Darjaniyon-ki Dhani Floodplain

50 m

Order of 10's of m

Mixed load, high sinuosity fluvial system - Sarnoo Sandstone

Bedload dominant, low sinuosity fluvial system - Darjaniyon-ki Dhani Sandstone

Key

Channel element (F1)

Channel levee element (F2)

Braid bar element (F3)

Chute channel element (F4)

Point bar element (F5)

Sheetflood element (F6)

Floodplain element (F7)

Pond element (F8)

Fourth order surface

Fifth order surface

Sixth order surface

PDL: Present Day Location 16°
LCL: Lower Cretaceous Location 26°

18° 20° 22° 24° 26° 28° 30° 32°
28° 30° 32° 34° 36° 38° 40° 42°

PDL: 66° LCL: -30°

Lower Cretaceous North

INDO-TETHYS OCEAN

SM

Pakistan

Lower Indus Basin

Jacobad High

Madagascar

Upper Indus Basin
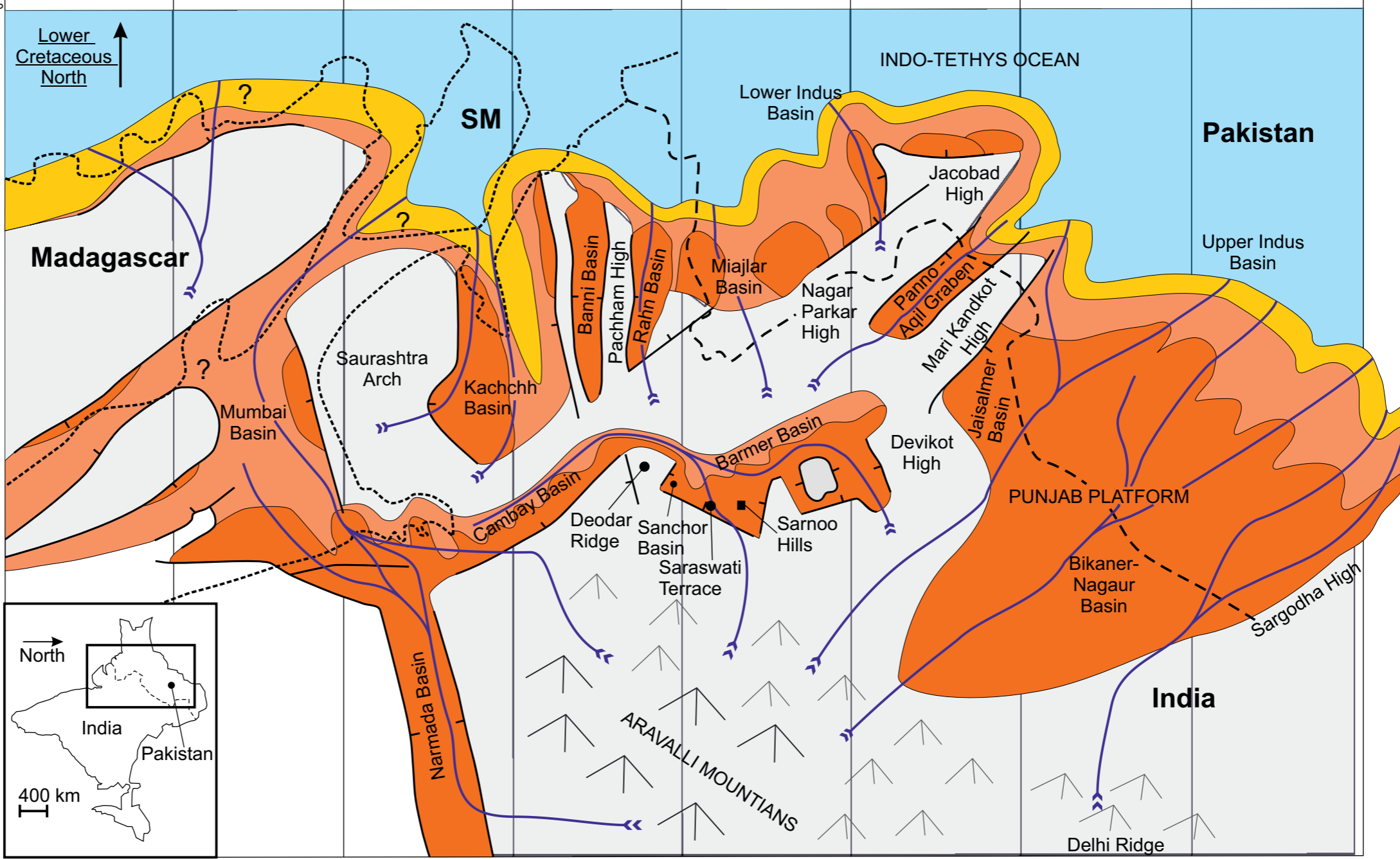
Key

Faults (with the tick on the downthrown side)

SM Seychelles Microcontinent

India - Pakistan border

Land - ocean border

Boundary between different sedimentary environments

? Limited or no data available

Mountain (grey = smaller)

Rivers; arrows indicate the direction of flow

High lands

Alluvial / proximal deposits

Fluvial systems

Shoreface / Deltaic

Open marine

Banni Basin

Pachham High

Rahn Basin

Miajlar Basin

Nagar Parkar High

Panno - I Aqil Graben

Mari Kandkot High

Jaisalmer Basin

Saurashtra Arch

Kachchh Basin

Mumbai Basin

Barmer Basin

Devikot High

PUNJAB PLATFORM

Cambay Basin

Deodar Ridge

Sanchor Basin

Saraswati Terrace

Sarnoo Hills

Bikaner- Nagaur Basin

India

Sargodha High

North

India

Pakistan

400 km

Narmada Basin

ARAVALLI MOUNTIANS

Delhi Ridge

PDL: 76° LCL: -40°