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1 **Lower Permian fluvial cyclicity and stratigraphic evolution of the**
2 **northern margin of Gondwanaland: Warchha Sandstone, Salt**
3 **Range, Pakistan**

4

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10 **ABSTRACT**

11 During the early Permian (Artinskian), fluvial conditions prevailed in what is now the
12 Salt Range of northern Pakistan. Deposits of the Warchha Sandstone are
13 characterised by a range of fluvial facies and architectural elements that together
14 record both the proximal and distal parts of a meandering river system that drained
15 the northern margin of Gondwanaland. Stratigraphic units are arranged into vertically
16 stacked fining-upward cycles represented by thin accumulations of channel-lag
17 deposits at their bases, sandstone-dominated channel fill and thicker accumulations
18 of overbank mudstone at their tops. Sedimentary cyclicity records fluvial system
19 development on a variety of spatial and temporal scales. Overall, the Warchha
20 Sandstone preserves a series of three to ten vertically stacked fining-upward cycles
21 that form part of a larger-scale, third-order sequence that is itself bounded by
22 regionally extensive and laterally correlatable unconformities that were generated in
23 response to combined tectonic and eustatic changes. The sequence-stratigraphic
24 architecture reflects regional palaeogeographic development of the Salt Range
25 region. The small-scale fluvial cycles originated through autogenic mechanisms,
26 predominantly as a result of repeated channel avulsion processes that occurred
27 concurrently with on-going subsidence and the progressive generation of
28 accommodation. Each erosively based fining-upward fluvial cycle is divided into
29 three parts: a lower part of trough cross-bedded conglomerate and coarse
30 sandstone; a middle part of tabular cross-bedded, ripple cross-laminated and

31 horizontally laminated sandstone; an upper part of predominantly horizontally
32 laminated and massive mudstone. Overall, the Warchha Sandstone records the
33 progradation of a wedge of non-marine strata into a previously shallow-marine
34 depositional setting. The underlying marine Dandot Formation is terminated by a
35 major unconformity that represents a type-I sequence boundary associated with a
36 regional relative sea-level fall and a significant regression of the Tethyan shoreline.
37 The overlying Warchha Sandstone represents the onset of the subsequent lowstand
38 systems tract in which a northward-flowing meandering river system redistributed
39 clastic detritus derived from a tectonically-active source area (the Aravalli and Malani
40 ranges) that lay to the south. This episode of fluvial sedimentation was terminated by
41 a widespread marine transgression recorded by an abrupt upward transition to
42 estuarine and shallow-marine deposits of the overlying Sardhai Formation. This
43 change marks the transition from lowstand to a major transgressive system tract.

44 **KEYWORDS**

45 Fluvial, cyclicity, stratigraphic evolution, Gondwanaland, Lower Permian, Warchha
46 Sandstone, Salt Range

47 **INTRODUCTION**

48 The Salt Range of Pakistan forms part of the Sub-Himalayan Mountains, which
49 stretch for more than 180 km in an east-west orientation between the Jehlum and
50 Indus rivers, along the southern margin of the Potwar Basin (Fig. 1). Within the Salt
51 Range, a thick sedimentary cover, consisting of Precambrian to recent deposits,
52 unconformably overlies low-grade metamorphic and igneous rocks (Gee, 1989).
53 Within this cover succession the Lower Permian Nilawahan Group of the Gondwana
54 Realm is subdivided into the Tobra, Dandot, Warchha and Sardhai formations. The
55 Warchha Sandstone represents the deposits of a fluvial system that passed
56 northwards into a coastal plain and estuarine system at the margin of the Tethys Sea
57 (cf. Valdiya, 1997; Ghazi, 2009; Ghazi and Mountney, 2012a, 2012b). The Warchha
58 Sandstone forms a clastic wedge of fluvial strata bounded both below and above by
59 marine deposits of the Dandot and Sardhai formations, respectively (Ghazi and
60 Mountney, 2009, 2012a) and, as such records a major episode of non-marine
61 progradation. Overall, the Warchha Sandstone comprises a series of repeating
62 fining-upward cycles with capping palaeosols (Figs. 1 & 2), which comprise part of a

63 larger-scale depositional sequence. The Warchha Sandstone is one of many
64 palaeosol-bearing alluvial successions characterized by a hierarchical record of
65 depositional cycles that originated in response to the combined effect of autogenic
66 and allogenic processes (e.g. Shanley and McCabe, 1994; McCarthy and Plint,
67 1998; Kraus and Aslan, 1999; Kraus, 2002; Atchley et al., 2004; McLaurin and Steel,
68 2007).

69 The aim of this study is to account for the origins of the Warchha Sandstone in terms
70 of the wider palaeogeographic evolution of the Salt Range region during the early
71 Permian. Specific objectives are as follows: (i) to account for the style and nature of
72 deposition recorded within a succession of meandering fluvial facies; (ii) to assess
73 the origin of prominent decametre-scale depositional cycles within the Warchha
74 Sandstone; (iii) to identify and correlate key surfaces of sequence stratigraphic
75 significance at a larger-scale; (iv) to account for origin of the large-scale stratal
76 packages that accumulated during the early Permian in terms of the regional
77 palaeogeographic evolution of part of the northern margin of Gondwanaland.

78 **METHODOLOGY**

79 Sedimentological data were collected from eight measured stratigraphic sections of
80 the Lower Permian succession of the Salt Range (Figs. 1 & 2). In each section,
81 numerous depositional cycles and fluvial facies associations have been recognised
82 (Fig. 3). Lithofacies were identified in the present study (Table 1) based on the
83 widely adopted classification scheme of Miall (1996) and extended from that of Ghazi
84 and Mountney (2009). The cyclical arrangement of facies within the Warchha
85 Sandstone is herein described based on a modified version of the classification
86 scheme of Atchley et al. (2004).

87 **REGIONAL SEQUENCE STRATIGRAPHIC FRAMEWORK**

88 The regional stratigraphic framework and depositional setting of the non-marine
89 Warchha Sandstone provides a record of the history of base-level change and its
90 effects in governing sequence accumulation and preservation in a mixed terrestrial to
91 marginal-marine depositional system.

92 One of the first comprehensive and widely adopted sequence stratigraphic models
93 for prediction of stacking patterns in continental fluvial successions was that of
94 Shanley and McCabe (1994) who accounted for large-scale variations in

95 architectural style based on and systematic variations in controlling processes. Their
96 conceptual model is based on the notion of base-level fall and rise controlling fluvial
97 behaviour by adjusting the graded equilibrium profile of the fluvial system to generate
98 incised valleys during episodes of base-level fall and the subsequent filling of these
99 valleys with stacked fluvial channel complexes during episodes of subsequent base-
100 level rise. Ethridge et al. (1998) revised the model and discussed the complexity of
101 multiple feedbacks that govern processes known to influence fluvial sequence
102 development. Catuneanu (2002, 2006) emphasized the importance of stratigraphic
103 base-level as a mechanism for maintenance of an equilibrium between erosion and
104 deposition, whereby sediment accumulation occurs at sites where accommodation is
105 generated in response to base-level rise. The interplay between base-level change
106 and rate of sediment supply (sediment influx) controls whether a coastal fluvial
107 system experiences transgression or regression (Bhattacharya, 2011).

108 **Sequence stratigraphic framework of the Warchha Sandstone**

109 The application of sequence stratigraphic concepts to fluvial successions like the
110 Warchha Sandstone is not straightforward. The difficulty stems from the recognition
111 that sea-level change typically has limited or no effect on accommodation and
112 depositional patterns in continental environments that are more than a few tens of
113 kilometres from the shoreline (Shanley and McCabe, 1994; Ethridge et al., 1998). In
114 the Salt Range of Pakistan, the Warchha Sandstone is bounded at its base and top
115 by prominent erosion surfaces of broad regional extent that can be correlated
116 between outcrops and wells throughout the Salt Range and in the adjacent Potwar
117 Basin (Fig. 4). Distinct down-cutting and infilling is recorded along these erosional
118 surfaces (Ghazi and Mountney, 2009). No other significant and laterally correlatable
119 unconformities are identified in the Warchha Sandstone, though minor erosional
120 surfaces that define the bases of meandering channel sandstone cycles and which
121 are of limited local extent (< 1 to 2 km laterally) are numerous.

122 At a large scale, the Warchha Sandstone forms a wedge of strata that thins to the
123 north and which records an initially progradational and latterly retrogradational fluvial
124 system. This wedge of strata forms part of a larger sequence architecture that
125 records a major regressive and transgressive event at the shoreline of the northern
126 margin of Gondwanaland, the nature of which is herein reconstructed via the
127 analysis of lithofacies character and stacking patterns (Fig. 4). Variations in palaeo-

128 shoreline position in the Salt Range region are documented by the vertical and
129 lateral distribution of lithofacies belts; basinward-shift in lithofacies distributions
130 record regression, whereas landward-shifts record transgression (cf., Mukhopadhyay
131 et al., 2010).

132 **Sequence boundaries**

133 The 'Warchha-Sardhai' depositional sequence of the Nilawahan Group represents a
134 complete depositional sequence within which a thick lowstand system tract (LST) is
135 represented by the Warchha Sandstone. This sequence is bounded above and
136 below by erosional unconformities, SB I and SB II (Fig. 4; Ghazi, 2009; cf., Emery
137 and Myers, 1996; Catuneanu, 2006). SB I and SB II (discussed in detail below) are
138 both characterised by laterally extensive erosional truncation surfaces across which
139 a marked basinward shift in lithofacies occurs (cf. Catuneanu, 2002), as does an
140 increase in grain size and a change in sediment composition. An additional region-
141 wide unconformity is also present at the top of the Warchha Sandstone at its
142 boundary with the overlying Sardhai Formation: this is interpreted as a ravinement
143 surface associated with marine transgression (see below).

144 **Lower sequence boundary SB I**

145 The basal contact of the Warchha Sandstone represented by SBI is a sub-aerial
146 erosion surface that formed in response to relative sea-level fall (Fig. 5). This contact
147 between marine facies and overlying fluvial facies is traceable throughout the Salt
148 Range and represents a sequence boundary. This unconformity therefore marks the
149 base of a major sequence (Fig. 5) and its noticeable facies shift, is indicative of a
150 Type 1 sequence boundary (cf. Van Wagoner et al., 1988).

151 Below the sequence boundary, the Dandot Formation is characterized by estuarine
152 facies with tidal indicators in the eastern and central Salt Range and marine
153 mudstone in western Salt Range. The uppermost part of the Dandot Formation
154 records widespread marine deposition and is identified as a highstand systems tract
155 (HST) of an earlier sequence.

156 The widespread occurrence of fluvial channel-fill elements characterized by coarse-
157 grained lag deposits directly above the unconformity represents the base of the
158 lowstand system tract (LST) of the succeeding Warchha Sandstone. The uppermost
159 60 to 80 mm of marine mudstone, claystone and micaceous siltstone, directly below

160 the sequence boundary contains abundant broken bivalve remains, intense
161 burrowing and root traces, indicative of a protracted episode of sub-aerial exposure
162 prior to the onset of fluvial sedimentation. The relatively poor development of a
163 palaeosol on this surface may reflect the removal of such a profile by erosion
164 associated with fluvial channel scour. The appearance of a marine faunal
165 assemblage, including the bivalve *Eurydesma*, in the strata directly below SB I marks
166 an important change in climatic conditions from cold to less cold or relatively mild
167 climatic conditions (cf. Singh, 1987; Veevers and Tewari, 1995; Fielding et al., 2006;
168 Mukhopadhyay et al., 2010; Ghazi and Mountney, 2012a).

169 Evidence for the development of deeply incised valleys at the level of SB I is limited.
170 In low-relief shelf settings, like those of the Early Permian Salt Range region, the
171 equilibrium fluvial profile at positions close to the paleo-coastline likely had a low
172 slope, not much greater than that of the adjoining shallow shelf (e.g., Mukhopadhyay
173 et al., 2010). Thus, a lowering of stratigraphic base level would therefore have likely
174 resulted in only minor fluvial incision (Shanley and McCabe, 1994). Under such
175 conditions, fluvial profiles simply become extended, in some cases with a
176 concomitant change in fluvial channel pattern (Wescott, 1993). As such, deeply
177 incised valleys are not necessarily expected in such settings, even given significant
178 base-level fall (cf. Woolfe et al., 1998). Field observations suggest that the high
179 frequency of sea-level change (which likely limited the time available for fluvial
180 systems to adjust to a new base-level profile) and the inferred low gradient of the
181 lowstand coastal plain may have played a major role in determining the expression
182 of SB I by causing the fluvial channels to erosively sweep across a broad coastal
183 alluvial plain, rather than cut deep valleys.

184 **Upper sequence boundary SB II**

185 In the western Salt Range, SB II occupies a stratigraphic position between the top of
186 the Sardhai Formation and the base of the overlying Amb Formation (Fig. 5). In the
187 central Salt Range (east of the Nilawahana area) the Amb, Sardhai, and Warchha
188 formations are progressively cut out by a younger unconformity that has overlying
189 Palaeocene strata. Thus, the preserved expression of SB II is only present west of
190 Nilawahana (Fig. 5).

191 The SB II unconformity has up to 2 m of relief and three types of deposits are
192 identified above the unconformity surface: (i) a basal 20 to 30 mm-thick
193 conglomerate; (ii) dark-brown, dark-grey and white, medium- to fine-grained
194 sandstone and red to dark-brown and yellow bioturbated siltstone or claystone with
195 abundant pisolites; (iii) fossiliferous nodular limestone and dark-red mudstone. The
196 Amb Formation (Wordian) overlies sequence boundary SB II. It is composed of
197 sandy calcareous, interpreted as lowstand deposits (Mertmann, 2003). The basal 2
198 m of the Amb Formation consists of sandy bioclastic rudstone with abundant
199 brachiopods and fusulinids (cf. Wardlaw and Pogue, 1995; Mertmann, 2003).

200 **Systems tracts**

201 In the present study, the top of the Dandot Formation represents the early stages of
202 a regressive interval, and is identified as a late highstand system tract (HST) lying
203 below sequence boundary SB I (Figs. 6 and 7 ; cf., Posamentier and Vail, 1988;
204 Posamentier et al., 1988; Van Wagoner et al., 1988). Fluvial strata of the Warchha
205 Sandstone represent the overlying LST (Figs. 6 and 7). The lower part of the
206 overlying Sardhai Formation is the transgressive system tract (TST) and the
207 maximum flooding surface (MFS) is located somewhere in the middle part of this
208 formation (Figs. 6 and 7). The upper part of the Sardhai Formation represents the
209 subsequent HST.

210 **Highstand system tract (HST) of lower sequence**

211 Highstand system tract deposits of alternating shale, sandstone and mudstone with
212 abundant bivalves (e.g., *Eurydesma*) in the upper part of the Dandot Formation are
213 of shallow-marine and tidal origin, and are overlain by unconformity surface SB I
214 (Figs. 6 and 7). The progradational stacking pattern of these HST deposits records
215 regression in response to a progressively decreasing rate of base-level rise as the
216 highstand in relative sea level was approached (Fig. 7; cf. Catuneanu, 2006). The
217 well-developed exposure surface of SB I was generated in response to base-level
218 fall. In the western Salt Range, SB I grades into a correlative conformity marked by
219 the pinch-out of tidal and coastal facies and their gradual replacement by dark-grey
220 to dark-greenish grey mudstone of shallow-marine origin (Fig. 5), which likely
221 represent more offshore parts of the basin fill.

222 **Lowstand systems tract (LST)**

223 The Warchha Sandstone represents the lowstand systems tract (LST) of a major
224 depositional sequence that overlies SB I. This fluvial succession is arranged into a
225 series of upward-fining depositional cycles that record the accumulation and
226 preservation of multiple fluvial channel and floodplain elements (Fig. 6). The
227 succession records an incipient stage of base-level rise during an overall episode of
228 regression when the rate of sediment supply and accumulation was greater than the
229 rate of base-level rise. The fining-upward cycles of the Warchha Sandstone are
230 stacked in aggradational sets, demonstrating that each cycle was initiated by fluvial
231 incision associated with channel scour, most likely in response to autogenic channel
232 avulsion events that were intrinsic to the behaviour of the meandering fluvial system
233 (Ghazi and Mountney, 2009).

234 Multi-storey channel bodies in the lower part of the Warchha Sandstone suggest
235 stacked accumulation in response to a slow rate of net base-level rise. At this time
236 the rate of generation of accommodation to enable the preservation of vertically
237 stacked fluvial channel deposits was slow, resulting in fluvial channels that shifted
238 laterally and frequently and which led to an amalgamation of multi-lateral and multi-
239 storey channel elements. Single-storey channel deposits in the Warchha Sandstone
240 are more prevalent in the middle and upper parts of the succession and these record
241 accumulation and preservation at a time when rates of creation of accommodation
242 began to accelerate, likely in response to an increased rate of relative sea-level rise
243 in more distal parts of the basin. This acceleration in the rate of relative sea-level rise
244 ultimately caused the termination of non-marine fluvial sedimentation, and resulted in
245 the onset of deposition of tidal and estuarine sediments that form the topmost parts
246 of the Warchha Sandstone, as indicated by the presence of an ichnofacies
247 assemblage dominated by *Helminthopsis* and *Skolithos* (Bjerstedt, 1988; Amireh et
248 al., 2001; Fielding et al., 2006; Ghazi and Mountney, 2012b).

249 **Transgressive system tract (TST)**

250 The Warchha Sandstone passes upwards into overlying TST deposits of the
251 overlying Sardhai Formation, of predominantly shallow-marine origin (Figs. 6 and 7),
252 which is well exposed in parts of the western Salt Range. Continued relative sea-
253 level rise resulted in marine transgression over the fluvial deposits (Mukhopadhyay

254 et al., 2010), which led to the generation of a minor transgressive wave ravinement
255 surface, prior to the onset of deposition of the overlying Sardhai Formation (cf.
256 Catuneanu, 2006).

257 **Maximum flooding surface (MFS)**

258 A MFS marks the timing of maximum transgression of the palaeo-shoreline (Figs. 6
259 and 7; Posamentier et al., 1988; Van Wagoner et al., 1988). The middle part of the
260 Sardhai Formation is characterised by a shale-dominated interval above an interval
261 of thin, fine-grained sandstone beds (Figs. 4 and 7) and this likely represents the
262 MFS. The TST deposits below this surface are generally thinly developed as they
263 represent a condensed section. This MFS separates the TST of the lower part of the
264 Sardhai Formation from the overlying regressive highstand system tract (HST 2). At
265 the top of the Sardhai Formation (also the top of the Nilawahan Group), SB II marks
266 the end of the sequence (Wardlaw and Pogue, 1995; Mertmann, 2003).

267 **PRESERVED CYCLICITY IN THE WARCHHA SANDSTONE**

268 Preserved sedimentary cycles in fluvial deposits have been widely recognized (e.g.
269 Allen, 1964; Casshyap, 1970, 1975; Atchley et al., 2004; Hota and Maejima, 2004).
270 Ghazi et al. (2004) first recognized facies cyclicity in deposits of the Warchha
271 Sandstone from the Karuli area of the Salt Range, Pakistan. This present study
272 confirms a strong cyclic arrangement of facies across the Warchha Sandstone
273 outcrop belt (Figs. 1 & 2). Cycles are similar in thickness and internal composition to
274 those described for fluvial facies by Allen (1964), Casshyap (1970, 1975), Atchley et
275 al. (2004), Hota and Maejima (2004), Cleveland et al. (2007) and McLaurin and Steel
276 (2007). Cycles of the Warchha succession form small- and large-scale types (cf.
277 Atchley et al., 2004). Small-scale cycles are attributed to fluvial autogenic processes
278 of channel migration and avulsion (Atchley et al., 2004; Cleveland et al., 2007). By
279 contrast, large-scale cycles are generally attributed to allogenic processes (cf.
280 Posamentier and Allen, 1993; Kraus, 2002; Atchley et al., 2004; Cleveland et al.,
281 2007).

282 The large-scale regressive-transgressive cycle of the Sardhai and Warchha
283 formations represents a full depositional sequence (Emery and Myers, 1996;
284 Catuneanu, 2002; Folkestad and Satur, 2008; Ghazi, 2009). Biostratigraphic data
285 from the Dandot Formation in the Salt Range demonstrates accumulation of this

286 succession at a time of significant glacio-eustatic change during the Sakmarian (cf.
287 Visser, 1997b; Singh, 1987) and this can be used to estimate the duration of the
288 regressive-transgressive cycle (cf. Dickins, 1985; Visser, 1997b; Mack et al., 2003;
289 Veevers, 2006). The Permian sea-level history as a whole represents a second-
290 order cycle (Haq et al., 1988) with a total duration approximately 48 Myr (Wardlaw et
291 al., 2004). The Lower Permian large-scale cycle discussed herein represents a third-
292 order cycle, with a probable duration of 0.5 to 3 Myr, based on the fundamental units
293 of sequence stratigraphy (Haq et al., 1988) and the nature of inferred trends in
294 palaeo-shoreline shift (Catuneanu, 2006).

295 The number of small-scale cycles preserved in each vertical log measured through
296 the Warchha Sandstone varies from 3 to 10 across the Salt Range, in part reflecting
297 the changes in the preserved thickness of the formation itself, which varies from 30
298 to 155 m thick. However, many erosively based cycles are present and they are
299 laterally and partially vertically offset from neighbouring cycles. The average
300 thickness of each cycle is 8 to 9 m (Fig. 8). Although the Warchha Sandstone is
301 known to be of Artinskian age (Balme, 1970; Wensink, 1975; Wardlaw and Pogue,
302 1995), which has a total duration 8.8 Myr (cf. Wardlaw et al. 2004), the absence of
303 any diagnostic biostratigraphic age indicators means that the exact duration over
304 which the fluvial cycles accumulated cannot be determined. However, it is likely that
305 the maximum duration for each cycle within the Warchha Sandstone was probably
306 substantially less than 0.5 Myr.

307 **Large-scale cycles**

308 *Description:* The large-scale cycle represented by the Warchha Sandstone is a
309 regressive-transgressive phase of Permian sea-level change recorded in the
310 northeast part of Gondwanaland. The Warchha Sandstone succession represents a
311 wedge of non-marine strata bounded both below and above by marine deposits.
312 Both SB 1 and the transgressive surface of erosion, which bound the Warchha
313 Sandstone are traceable throughout the Salt Range (Ghazi, 2009; Ghazi and
314 Mountney, 2012a).

315 Channel-fill fluvial facies directly overlie SB I in a manner that is consistent with a
316 region-wide switch to a system characterised by non-marine fluvial sedimentation.
317 The erosion surface at the base of the Warchha Sandstone incises 1 to 2 m into the

318 underlying green to greenish-grey mudstone and siltstone marine deposits of the
319 underlying Dandot Formation. The lowermost part of the Warchha Sandstone is
320 composed of a 0.02 to 0.2 m-thick lag of pebble-size claystone and mudstone clasts
321 derived from the reworking of underlying strata.

322 The upper boundary of the regressive-transgressive cycle in the eastern Salt Range
323 is cut out, as is the uppermost part of the Warchha Sandstone, by the presence of
324 the major unconformity that juxtaposes the Permian succession against overlying
325 Palaeocene strata (Fig. 5). This major unconformity surface is overlain by the
326 presence of a 2 to 3 m-thick unit mainly composed of dark red claystone, dark brown
327 to reddish brown ferruginous nodules and 20 to 30 mm diameter carbonate nodules.
328 In central and western Salt Range, the deposits of the basal Amb Formation are
329 characterised by sandy bioclastic rudstone with abundant brachiopods and fusulinids
330 (Mertmann, 2003).

331 *Interpretation:* The origin of this 3rd-order depositional cycle is related to a region-wide
332 and significant variation in relative sea level that affected several depositional
333 systems (Ghazi, 2009). The basal part of cycle is marked by thin channel-lag
334 deposits that lie directly on the major SB I incision surface. This relationship records
335 the onset of a major regressive phase and a basinward shift of facies.

336 **Small-scale cycles**

337 A total of 54 small-scale cycles have been studied in detail in the Warchha
338 Sandstone. These upward-fining cycles are each 2 to 40 m (though mostly 3 to 10
339 m) thick. Complete examples of such cycles (Figs. 2 and 3) are characterised by
340 seven lithofacies (Table 1) that occur in a generally predictable order. Complete
341 sedimentary cycles carry no indicators to suggest the duration or frequency of their
342 development. Internally within each cycle, the thicknesses of component facies
343 varies in all measured sections (cf. Duff et al., 1967; Casshyap, 1970, 1975). As is
344 the case for the majority of cyclically arranged fluvial successions, most of the cycles
345 in the Warchha Sandstone are incompletely developed and many are truncated in
346 their upper part by the erosional bases of overlying cycles (Ghazi, 2009; Ghazi and
347 Mountney, 2009). A complete cycle is generally divided into three parts (Figs. 3 & 9):
348 a lower part consisting of facies Gt and St, a middle part consisting of facies Sp, Sr
349 and Sh, and an upper part consisting of facies Fl and Fm (see Table 1 for facies

350 descriptions). This tripartite succession of facies associations represents the
351 successive occurrence of different depositional sub-environments within the fluvial
352 system at a given point (Fig. 9; Ghazi and Mountney 2009, 2010, 2012b). The cross-
353 stratified conglomerates and sandstones represent sediments deposited in channel
354 as lags and a variety of types of mid-channel and point bars (Allen, 1964; Casshyap,
355 1970, 1975; Hota and Maejima, 2004). Ripple cross-laminated sandstones represent
356 predominantly levee and crevasse-splay elements (Casshyap 1970, 1975; Hota and
357 Maejima 2004; Ghazi, 2009). Horizontally bedded and solitary sets of cross-stratified
358 finer-grained sandstones were deposited by overbank sheet floods, and red
359 claystone with siltstone and fine-grained sandstone lenses represent vertical
360 aggradation of mud on the floodplain (Casshyap, 1970, 1975; Hota and Maejima,
361 2004; Ghazi and Mountney, 2009, 2011).

362 Analysis of the small-scale cycles reveals that only 25% are preserved in a complete
363 state, whereas all remaining incomplete cycles have one or more facies type missing
364 or are characterized by a facies succession that occurs in a non-standard order. In
365 most cases, the cycles terminate with claystone or mudstone deposits, which are
366 succeeded abruptly (erosionally) by the base of an overlying channel that signifies
367 the commencement of the next cycle. Many channel-sandstone units exhibit direct
368 evidence of incision of 1 to 2 m into underlying strata. The prominent erosion
369 surfaces at the base of channel elements are fifth-order surfaces (Miall, 1988; Halfar
370 et al., 1998; Mrinjek, 2006; Ghazi, 2009). On the basis of thickness and style of
371 occurrence, five types of small-scale fluvial fining-upward cycle have been identified
372 (Fig. 10).

373 **Type 1 cycles**

374 *Description:* Type 1 cycles are 2 to 5 m thick (Fig. 10) and constitute only 2% of the
375 Warchha Sandstone. These cycles are not completely developed and facies Sr, Sh
376 and Fl are typically missing. The facies Gt, St, Sp are typically thin, whereas facies
377 Fm is relatively thickly developed. Lithologically, Type 1 cycles can be divided into
378 two parts: a lower part that is 1 to 3 m thick and composed principally of
379 conglomerates and coarse-grained sandstones interbedded with millimetre-thick
380 lenses of siltstone and claystone; and upper part that is 1 to 2 m thick and composed
381 of massive claystone interbedded with millimeter-thick siltstone layers. Overall, these
382 cycles fine upwards, although locally they may show a coarsening-upward trend. The

383 upper surfaces of these cycles are mostly erosional due to channel incision at the
384 base of the overlying cycles.

385 *Interpretation:* The small thickness, only rare presence of channel sandstone bodies,
386 and the abundance of argillaceous deposits (Ghazi and Mountney, 2011), together
387 with the localized presence of coarsening-upward trends, indicates that these cycles
388 likely developed predominantly in settings away from major channels (cf. Stear,
389 1983), possibly in sub-environments prone to crevasse-splay development (Eberth
390 and Miall, 1991; Gani and Alam, 2004).

391 **Type 2 cycles**

392 *Description:* These cycles, which are 5 to 10 m thick, constitute 40% of the Warchha
393 Sandstone (Fig. 10). They are well developed in the Watli, Karuli, Matan, Nilawahan,
394 Amb, Sarin and Sanwans areas (Fig. 11), where they are composed predominantly
395 of 0.2 to 0.4 m-thick sandstone beds. Lithologically, these cycles comprise three
396 parts: a lower part that is 2 to 4 m thick and composed of conglomerate to very
397 coarse-grained sandstone interbedded with millimetre-thick laminae of fine
398 sandstone; a middle part that is 2 to 4 m thick and composed of interbedded
399 medium- to fine-grained sandstone and claystone beds; an upper part that is 1 to 2
400 m thick and mainly composed of very fine-grained sandstone, siltstone and
401 claystone/shale (Ghazi and Mountney, 2011). Within these upper parts of the cycles,
402 desiccation cracks, caliche nodules, disseminated carbonaceous matter, concentric
403 clay balls and rain imprints are all abundant, especially at their tops. Lower cycle
404 boundaries are usually marked by erosion with incised surfaces typically having
405 about 1 m of relief filled with channel-lag facies Gt (Ghazi and Mountney, 2009).
406 Upper cycle boundaries are also erosion surfaces and usually the uppermost parts of
407 the cycles (massive mudstone facies Fm) at the top of a cycle are missing. Large-
408 scale trough cross-bedding in beds of conglomerate and very coarse-grained
409 sandstone, and medium-scale, low-angle-inclined cross-bedding in coarse-grained
410 sandstone is abundant.

411 *Interpretation:* These cycles record significant channel incision and facies Gt, St,
412 Sp, Sr, Sh, Fl and Fm each record the progressive fill of these deeper channels. The
413 typical fining-upward succession and style of bedset development within these
414 cycles is indicative of the preservation of thalweg deposits overlain by the lower part

415 of multiple in-channel barforms (cf. McLaurin and Steel, 2007; Ghazi and Mountney,
416 2009). The presence of channel lag and very coarse-grained sandstone in the lower
417 parts of the cycles indicates a high-energy regime, whereas the finer-grained
418 sandstone in the middle part indicates a lower-energy bar later in the history of the
419 channel fill. By contrast the top parts of these cycles were deposited in an overbank
420 setting (cf. McLaurin and Steel, 2007). During their deposition, sediment-laden water
421 likely overtopped the channel banks during flood events, enabling sediments to be
422 deposited outside the channel confine (cf. Stear, 1983).

423 **Type 3 cycles**

424 *Description:* These cycles, which are 10 to 15 m thick, constitute 26% of the Warchha
425 Sandstone (Fig. 10). They preserve relatively thick fine-grained components and are
426 well developed in the Saloi, Watli, Karuli, Matan, Nilawahan and Sarin areas (Figs.
427 10 and 11). These cycles are divided into three parts: a lower part that is 4 to 6 m
428 thick and composed of Gt, and St facies, commonly with thin intervals of channel-lag
429 deposits in the form of sub-angular to sub-rounded intraformational claystone clasts;
430 a middle part that is 1 to 3 m thick and composed mainly of facies Sp with minor
431 contributions of Sr and Sh; an upper part that is 5 to 6 m thick and composed mainly
432 of siltstone and claystone (facies Fl and Fm). Both lower and upper boundaries of
433 these cycles are marked by erosional surfaces.

434 *Interpretation:* The vertical stacking of facies, the presence of channel lag deposits at
435 the base of the cycles and high degree of development of floodplain deposits at the
436 top of the cycles, is indicative of a single-storey channel-body origin (cf. Robinson
437 and McCabe, 1997) for which preservation likely occurred following abandonment of
438 a meander loop or reach of a channel belt (cf. Godin, 1991). Vertical facies variations
439 indicate a systematic transition from in-channel deposition, to point bar, to a
440 floodplain sub-environment (Ghazi and Mountney, 2011). Floodwater likely deposited
441 coarser sand and silt in areas close to the active channels, and finer-grained
442 sediments in more distal areas of the floodplain (cf. Hughes and Lewis, 1982). The
443 progressive increase up-section in relative proportions of overbank facies Fm and Fl,
444 likely records accumulation under the influence of a relatively rapid rate of
445 subsidence (Fig. 10; cf. Isbell and Collinson, 1991). The partial truncation of facies
446 Fm units in several of these cycles indicates erosion by an overlying channel and the
447 start of a new cycle.

448 **Type 4 cycles**

449 *Description:* These cycles, which are 15 to 20 m thick, constitute 20% of the Warchha
450 Sandstone (Fig. 10). They occur in the Karuli, Matan, Nilawahan, Amb, Sarin and
451 Sanwans areas (Fig. 11) but are usually not completely developed and facies are
452 commonly irregularly arranged within them. These cycles are divided into two parts.
453 Lower parts are 5 to 12 m thick and composed of conglomerate and coarse-grained
454 sandstone interbedded with millimetre- and centimetre-thick beds of fine sandstone,
455 siltstone and claystone. Facies Gt is predominantly developed in lower parts in
456 Matan and Nilawahan areas, whereas, in other areas, facies St is predominantly
457 developed. Facies Sp and Sh are either absent or only thinly developed. The upper
458 parts of these cycles are 8 to 10 m thick and are predominantly composed of
459 claystone and shale with interbedded centimetre-thick beds of fine-grained
460 sandstone (facies Fm and Fl). Ferruginous and carbonaceous matter caps the top of
461 the claystone intervals in many of these cycles. The basal and top boundaries of
462 these cycles are erosional.

463 *Interpretation:* These cycles are interpreted to represent channel-belt deposits
464 (e.g., McLaurin and Steel, 2007). The barform deposits within these cycles are poorly
465 to moderately preserved due to migration and avulsion within the channel belt (Ghazi
466 and Mountney, 2009). Overall, these cycles are interpreted to represent the deposits
467 of multi-storey channel bodies (cf. Rygel and Gibling, 2006). The local dominance of
468 coarse-grained strata in the lower parts of these cycles in the Matan and Nilawahan
469 areas (central Salt Range), might be attributed to the local tectonic uplift of the
470 eastern Salt Range area. The occurrence of thick floodplain deposits in these cycles
471 likely arose in response to a major regional avulsion of the channel belt and a
472 protracted period without channel activity within the area (cf. Heller and Paola,
473 1996). Following this avulsion process, and before the onset of renewed active in-
474 channel sedimentation, there was a significant thickness of floodplain aggradation
475 (Ghazi and Mountney, 2011). These cycles were likely deposited in a channel belt
476 system that was controlled by regional-scale avulsion (cf. McLaurin and Steel, 2007).

477 **Type 5 cycles**

478 *Description:* These cycles are > 20 m thick (Fig.10), but constitute only 12 % of the
479 Warchha Sandstone. The thickest observed cycle (from the Karuli area) is 42 m and

480 similarly thick cycles exist in the Nilawahan, Amb and Sanwans areas. The
481 uppermost 10 to 15 m of the uppermost cycles in the Sanwans area shows a
482 significant marine signature, with hummocky cross-bedding, flaser and wavy
483 bedding, cone-in-cone structures and trace fossils such as *Skolithos*. Marine
484 signatures are also present in cycles at the top of the formation in the Nilawahan
485 area, and these also include phosphatic nodules and the trace fossil *Helminthopsis*.
486 these cycles are divided into three parts: a lower part that is 6 to 12 m thick and
487 composed mainly of pebbly very coarse sandstone facies St with thinly developed
488 facies Gt as channel lag deposits (missing in Nilawahan area); a middle part that is
489 10 to 15 m thick and composed of facies Sp, Sr and Sh (the latter missing in the
490 Sarin area); an upper part that is 4 to 10 m thick and composed mainly of siltstone,
491 claystone and thin mudstone facies Fl and Fm, with associated desiccation cracks,
492 rain imprints, caliche nodules and rare bioturbation. Both upper and lower contacts of
493 these cycles are erosional.

494 *Interpretation:* These cycles record accumulation in a range of fluvial, estuarine and
495 marginal marine settings (cf. Bjerstedt, 1988; Ranger and Pemberton, 1997; Fielding
496 et al., 2006). The lower parts of these cycles are exclusively fluvial in nature,
497 whereas the upper parts exhibit characteristics indicative of deposition in estuarine
498 and marginal-marine environments, notably directly beneath the contact with the
499 overlying the Sardhai Formation (Ghazi, 2009; Ghazi and Mountney, 2012a). The
500 great thickness of these cycles, the dominance of sandstone assemblages and the
501 comparatively thin development of overbank mudstone facies likely reflects a rapid
502 avulsion process (Smith et al., 1989; Ghazi and Mountney, 2011, 2012b).

503 **Causes of cyclicity in the Warchha Sandstone**

504 Against a background of on-going basin subsidence, development of individual
505 cycles was probably controlled principally by autogenic channel migration and
506 avulsion (Casshyap, 1970; 1975; Ghazi et al., 2012a). Even after accounting for the
507 removal of the uppermost part of the Warchha Sandstone by the major unconformity
508 that separates the Permian from the Palaeocene succession in the eastern part of
509 the Salt Range, the number of preserved cycles present in the Warchha Sandstone
510 succession can be shown to systematically increase from east to west (Fig. 2). This
511 direct relationship between cycle thickness and number of cycles is consistent with
512 an origin driven by autogenic processes (cf. Hota and Pandya, 2002). If cycle

513 development had occurred in response to allogenic processes, such as widespread
514 diastrophic movements (Duff et al., 1967), climatic controls, or tectono-eustasy, then
515 the number of preserved cycles would be expected to have remained constant
516 throughout the basin (cf. Hota and Pandya, 2002). The absence of coal-bearing
517 strata in the uppermost parts of the fining-upward cycles could be due to rapid
518 avulsion (Allen, 1965) and high sedimentation rates, or alternatively (and more likely)
519 may reflect a lack of a suitable anoxic coal-forming environments and the poor
520 development of vegetation in a predominantly semi-arid climatic setting (cf. Nadon,
521 1994; Roberts, 2007). Both clay mineral analysis and sedimentary structures indicate
522 a warm to hot, semi-arid climate with short-term seasonal rainfall, which would not
523 have been conducive to coal accumulation (Ghazi and Mountney, 2011,2012b).

524 **AUTOGENIC VERSUS ALLOGENIC CONTROLS ON SEDIMENTATION**

525 Autogenic processes exercised very significant control on the pattern of
526 sedimentation during accumulation of the Warchha Sandstone. However, allocyclic
527 factors like tectonism, sea-level change and climate (which influenced the style of
528 weathering and the rate of generation of sediment supplied from the source area)
529 played an important additional role in the development of the larger sequence-scale
530 cycle during the Early Permian.

531 **Autocyclic controls**

532 The various cycles of the Warchha Sandstone identified in the eight localities studied
533 in detail cannot be correlated with each other directly. The nature of the small-scale
534 cycles is consistent with autogenic depositional mechanisms proposed by Kraus and
535 Aslan (1999), Atchley et al. (2004) and Cleveland et al. (2007): namely channel
536 avulsion and floodplain aggradation. During the avulsion process, sedimentation
537 rates were high and resulted in incomplete cycle development and generally only a
538 thin development of capping palaeosol facies (cf. Kraus and Aslan, 1999). Pebbly to
539 coarse-grained sandstone facies in channels are representative of downstream and
540 lateral accretion macroforms of gravel and sandy bars or, in few cases, of
541 progradational splay deposits (e.g. Type 1 cycles). The cause of channel avulsion
542 arises via a combination of complex processes: controls on avulsion frequency
543 include channel gradient, channel distribution, substrate composition and rate of
544 background basin subsidence (Törnqvist and Bridge, 2002; Bridge, 2006). Controls

545 on channel-element geometry (e.g. width and thickness of channel-belt deposits)
546 include the size of the formative channel, its rate of lateral migration across the
547 floodplain and the residence time of a channel on a given part of the floodplain –
548 itself a function of avulsion frequency (Bristow and Best, 1993). The style of stacking
549 of multiple cycles is a function of the freedom of the channel system to wander
550 across a broad alluvial plain, which itself determines the frequency with which
551 channels return to the same point on the plain, and the rate of subsidence, which
552 determines the nature of channel stacking to form either single- or multi-storey
553 channel complexes.

554 The fining-upward cycles reflect migration of channels across the alluvial plain
555 (Kraus and Aslan, 1999; Atchely et al., 2004). Thick floodplain deposits developed
556 and aggraded between avulsion events (cf. Cleveland et al., 2007). Flood-deposited
557 facies F1 and Fm were partially converted into soils during pedogenesis. The
558 presence of mature palaeosols in flood deposits of the Warchha Sandstone indicates
559 that they developed during periods of channel stabilization and low rates of
560 sedimentation (Ghazi, 2009; Ghazi and Mountney, 2010).

561 **Allocyclic controls**

562 Overall, the fluvial Warchha Sandstone succession is bounded by marine strata at its
563 base and top, and these major changes in facies are attributed to external drivers
564 including glacio-eustatic changes in global or regional sea levels and climatic
565 adjustments (cf. Dickins, 1985; Shanely and McCabe, 1994; Kraus and Aslan,
566 1999; Catuneanu, 2006; Fielding et al., 2006; Mukhopadhyay et al., 2010).

567 The climatic regime that prevailed during accumulation of sediment during the Early
568 Permian in the Salt Range region was apparently variable (Singh, 1987;
569 Mukhopadhyay et al., 2010). The glacio-fluvial deposits the Tobra Formation (cold)
570 pass into the coastal to shallow marine deposits of the Dandot Formation (cool to
571 sub-tropical). Within this formation, the abundance of the thick-shelled bivalves
572 *Eurydesma* (Wardlaw and Pogue, 1995; Mukhopadhyay et al., 2010), is widely
573 regarded as evidence of cold sea-floor conditions at this time (Singh, 1987; Fielding
574 et al., 2006). Based on evidence from sediment composition and sedimentary
575 structures, the overlying Warchha Sandstone appears to have accumulated under
576 the influence of a semi-arid to arid, monsoonal climate (Ghazi and Mountney, 2011).

577 Furthermore, the uniform composition and colour of each facies type present within
578 the Warchha Sandstone throughout its thickness indicates a static climatic regime
579 during the accumulation of the unit (Smith et al., 1998). However, the presence of
580 predominantly kaolinite clay minerals suggests a markedly different climate regime
581 for the source area that lay to the south, whereby a high rainfall in a hot to humid
582 climate resulted in severe chemical weathering of the source detritus (Ghazi and
583 Mountney, 2011).

584 During deposition of the Warchha Sandstone uplift of the source area caused
585 progradation of the Warchha fluvial system across the Salt Range area (cf. Steel and
586 Aasheim, 1978; Catuneanu, 2006; Ghazi, 2009). Although episodic tectonic uplift of
587 the headwater region of the drainage system would likely have acted to increase the
588 energy of the fluvial system, resulting in the deposition of coarse-grained facies in
589 downstream areas (cf. Fielding and Webb, 1996), it is unlikely that such effects
590 would be discerned in distal parts of the fluvial system that occupied a coastal plain
591 several hundred kilometres from the source area. That said, Lucas et al. (1997) have
592 described similar tectonically-controlled third-order cycles in the Chinle Formation of
593 New Mexico and Arizona and have attributed them to tectonic pulses. Although
594 Bridge (2003) has suggested that regional-scale tectonics can cause changes in
595 deposition rates and avulsion frequency on 10^6 -year time scales. Regardless,
596 sedimentological evidence demonstrates that the cyclicity in the Warchha Sandstone
597 arose from autocyclic channel avulsion, floodplain aggradation and channel
598 migration.

599 **DISCUSSION**

600 Sequence stratigraphic models for fluvial strata proposed by Wright and Marriot
601 (1993) and Shanley and McCabe (1994) are generally applicable to the lowstand
602 system tract deposits of the Warchha Sandstone. However, for this succession, it
603 multi-storey channel-fill complexes accumulated over a wide regional area during
604 LST times, rather than being confined within a series of incised valleys, as originally
605 envisaged in the early non-marine sequence stratigraphy models. This multi-storey
606 stacking of fluvial channel elements in the lower part of the Warchha Sandstone likely
607 reflects the slow rate of base-level rise during the initial part of the LST. Within the
608 succession, multi-storey channel bodies are progressively replaced by single-storey
609 bodies that are representative of high-sinuosity meandering fluvial channel behaviour

610 in the middle and upper parts of the formation (Ghazi and Mountney, 2009),
611 reflecting increased rates of base-level rise and an accelerating rate accommodation
612 generation. In particular, the presence of relatively thick floodplain elements within
613 cycles in the middle and upper parts of the formation can be related to an increase in
614 accommodation space and possibly to higher rates of sediment supply. The variation
615 in lithofacies, the range of sedimentary structures, and the presence of marine-
616 influenced lithofacies with diagnostic trace fossils in the uppermost part of the
617 Warchha Sandstone indicates the onset of a transgressive system tract (Fig. 12; cf.,
618 Mukhopadhyay et al., 2010) at a time when the rate of accommodation generation
619 was accelerating. Variations in rates of accommodation generation, sediment supply
620 and discharge likely all played major roles in controlling channel sand-body stacking
621 in this high-sinuosity meandering fluvial system.

622 The Warchha Sandstone represents a clastic wedge bounded on top and bottom by
623 marine strata (Fig. 12). The evolution of the depositional system can be broadly
624 divided into two phases (Fig. 7). The first phase was controlled by sea-level fall, and
625 the development of sequence boundary SB I (Fig. 7). Evidence for sub-aerial
626 exposure of former marine deposits abounds throughout the Salt Range. On the
627 basis of biostratigraphic data, this phase is dated as Sakmarian to Artinskian (cf.
628 Wardlaw and Pogue, 1995; Wardlaw et al., 2004; Fielding et al., 2006). The
629 cessation of Warchha sedimentation is marked by an abrupt termination of the fluvial
630 meandering system and its replacement by a shallow-marine depositional setting
631 represented by the overlying Sardhai Formation (Fig. 7). This second phase records
632 a relative sea-level rise and is marked by a regional development of a wave
633 ravinement surface at the top of the Warchha Sandstone (Fig. 12). This phase is
634 dated as Artinskian to Kungurian (Mukhopadhyay et al., 2010). The overlying
635 transgressive system tract is characterized by an upward transition to shale, and this
636 is indicative of a maximum flooding surface in the middle part of the Sardhai
637 Formation. This is followed by a highstand system tract in the upper Sardhai
638 Formation. A subsequent episode of relative sea-level fall occurred during the
639 Kungurian and this generated a second unconformity, SB II (Mertmann, 2003;
640 Mukhopadhyay et al., 2010). On the basis of biostratigraphic data (Mertmann 2003),
641 the strata below the unconformity representing SB II are Kungurian and those above
642 are of Wordian age (the absence of the Roadian stage indicates a break of ~2 Myr).

643 Wider results arising from this study contribute to our understanding of the regional
644 palaeogeographic evolution of the northern margin of Gondwanaland. The
645 occurrence of exclusively marine successions both below (the Dandot Formation)
646 and above (the Sardhai Formation) the continental deposits of the Warchha
647 Sandstone indicate a major regression and subsequent marine transgression
648 associated with the lowering and rising of the Tethys sea level during Early Permian
649 times (Ahmad 1970; Shah and Sastry 1973; Singh 1987; Ghazi and Mountney,
650 2012a,b). The major regression event can be shown to have occurred in response to
651 relative sea-level fall because the Warchha Sandstone accumulated directly above a
652 major region-wide sequence boundary (SB I). Transgression must have occurred in
653 association with a major episode of relative sea-level rise because the shoreline
654 apparently transgressed several hundred kilometres inland, despite the fluvial
655 systems of the Warchha Sandstone carrying a substantial sediment load to the
656 palaeo-coastline at this time. This detailed study of sequence development
657 demonstrates the sedimentary response of an alluvial plain and near coast shallow
658 marine succession to a major episode of relative sea-level change that was driven by
659 glacio-eustasy.

660 **CONCLUSIONS**

661 Sedimentary cyclicity in the Warchha Sandstone records fluvial system development
662 on a variety of spatial and temporal scales. Overall, the Warchha Sandstone exhibits
663 a series of vertically stacked fining-upward cycles, each bounded by fifth-order
664 erosional surfaces. These are nested within the lower part of a larger-scale third-
665 order sequence. Fifty-four small-scale cycles, each 2 to 40 m thick, have been
666 studied based on analysis at eight sites across the Salt Range. Completely
667 preserved cycles are divided into three parts: a lower part composed of an erosive
668 base with trough cross-bedded conglomerate- and coarse sandstone facies; a
669 middle part composed of tabular cross-bedded, ripple cross-laminated and
670 horizontally laminated sandstone facies; an upper part composed predominantly of
671 horizontally laminated and massive mudstone facies. The small-scale fluvial cycles
672 originated through autocyclic mechanisms, predominantly as a result of repeated
673 channel avulsion processes that occurred concurrently with on-going subsidence,
674 which generated the accommodation required for preservation.

675 The larger-scale third-order sequence is bounded by regionally extensive
676 unconformities that were themselves generated in response to a combination of
677 tectonic and eustatic changes that reflect the on-going regional palaeogeographic
678 development of the Salt Range region. Overall, the Warchha Sandstone records the
679 progradation of a wedge of non-marine strata into an otherwise shallow-marine
680 realm. The underlying marine Dandot Formation is terminated by a sequence
681 boundary (SB I) associated with a region-wide relative sea-level fall and a significant
682 regression of the Tethyan shoreline. The overlying Warchha Sandstone represents
683 the subsequent lowstand system tract. This episode of fluvial sedimentation was
684 terminated by a widespread marine transgression, as represented by an upward
685 transition indicative of a change from fluvial to estuarine channel fill, and to the
686 overlying Sardhai Formation of shallow-marine origin. This change is interpreted to
687 mark the transition from a lowstand to a transgressive systems tract. The maximum
688 flooding surface lies in the middle part of the Sardhai Formation, and the upper part
689 is representative of a highstand systems tract. The sequence is capped by a second
690 major sequence boundary (SB II), though this is only preserved in the central and
691 western Salt Range. This detailed study of sequence development demonstrates
692 how a major alluvial plain, estuarine, coastline and shallow marine system developed
693 at the northern margin of Gondwanaland responded to a major episode of glacio-
694 eustatic sea-level change.

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949 **FIGURE AND TABLE CAPTIONS**

950 Figure 1. Location map showing the location of measured sections of the Warchha
951 Sandstone in the Salt Range, Pakistan.

952 Figure 2. Fluvial fining-upward cycles in the Warchha Sandstone from eight localities
953 in the Salt Range. The number of preserved cycles increases with increasing
954 formation thickness from east to west. See Figure 1 for location of measured
955 sections.

956 Figure 3. Outcrop sketch illustrating the facies association in the Karuli area. Storey
957 bases are delineated with thicker lines and facies boundaries with finer lines. Arrows
958 indicate palaeoflow directions.

959 Figure 4. Stratigraphic overview of the Early Permian succession from the central
960 and western Salt Range. Data are compiled from Noetling (1901), Fatmi (1973),
961 Wardlaw and Pogue (1995), Mertmann (2003), Gradstein et al (2004) and from this
962 study. MFS = Maximum flooding surface, HST = Highstand system tract, LST =
963 Lowstand system tract, TST = Transgressive system tract, SB = Sequence boundary.

964 Figure 5. Schematic east-west section across the Salt Range showing the spatial
965 relationship of the main lithostratigraphic units and key stratigraphic surfaces. Note
966 the westward thickening of the Warchha Sandstone and its eastward truncation.

967 Figure 6. Schematic block diagrams to show morphological and sedimentary
968 response of Early Permian Warchha succession to relative sea-level change. a)
969 HST; b) LST; c) TST; d) RST.

970 Figure 7. Schematic model to depict the regional evolution of the depositional system
971 that prevailed at the northern margin of Gondwanaland during the Early Permian.
972 Systems tracts and key stratigraphic surfaces and their relation to the evolution of
973 the Warchha Sandstone are labelled. a) Deposition of highstand systems tract; the
974 Dandot Formation in its landward part is terminated by a major sequence boundary
975 (SB I) and is overlain by the development of the lowstand fluvial wedge of the
976 Warchha Sandstone. A correlative conformity is time equivalent to SB I in down-dip
977 regions. b) The Warchha Sandstone is capped by an erosional wave ravinement

978 surface. The overlying Sardhai Formation represents both the transgressive and
979 highstand systems tracts and is capped by a second sequence boundary (SB II).

980 Figure 8. Two styles of development of stacked fining-upward cycle in the Warchha
981 Sandstone. a) Near-horizontal bedding in the Matan area, central Salt Range. b)
982 Near-vertical bedding in the Sanwans area, western Salt Range.

983 Figure 9. Example of a complete fining-upward cycle in the Warchha Sandstone in
984 the Karuli area, Salt Range. a) Outcrop expression of complete cycle showing spatial
985 relationship of seven lithofacies in the Warchha Sandstone. b) Complete meandering
986 fluvial-fining-upward cycle showing the typical vertical stacking pattern of facies, and
987 associated interpretations. c) fluvial floodplain model for the upper part of a cycle. d)
988 point bar in the middle part of a cycle. e) channel-fill model in the lower part of a
989 complete cycle of the Warchha Sandstone.

990 Figure 10. Generalised profile of five types of small-scale cycle, showing grain sizes,
991 sedimentary structures, lithofacies and architectural elements in the meandering
992 fluvial system of the Warchha Sandstone.

993 Figure 11. Photograph showing typical fining-upward cycles in the Warchha
994 Sandstone in the Nilawahan Gorge, Salt Range. Photo taken looking north-east.
995 Each cycle commences with pebbly sandstone channel lag facies St and Gt and
996 terminates with overbank fine-grained facies Fm and Fl.

997 Figure 12. Block diagram illustrating the proposed sequence stratigraphic
998 development of the Warchha Sandstone in the Salt Range region. The Warchha
999 Sandstone was deposited as part of a lowstand systems tract (LST), probably as a
1000 meandering fluvial system. The underlying highstand systems tract (HST) is
1001 represented by shallow-marine deposits of the Dandot Formation which is separated
1002 from the Warchha Sandstone by type 1 sequence boundary (SB I). The overlying the
1003 transgressive systems tract (TST) is represented by shallow-marine deposits of the
1004 Sardhai Formation. Fluvial channel density and type in the Warchha Sandstone
1005 varies according to stratigraphic position.

1006 Table 1. Summary of the characteristic features of the lithofacies types encountered
1007 in the outcrop sections of the Warchha Sandstone in the Salt Range, Pakistan.

Facies	Code	Description	Interpretation
Stratified gravelly sandstone	Gt	This facies is always present as the lowermost deposits at the base of each complete cycle. It consists of trough cross-bedded, stratified gravels that commonly infill channel-like erosional basal surfaces. Clasts are mostly of granite, gneiss or quartzite, though rare claystone and sandstone intraclasts are also present. Geometrically, the facies consists of lens- or ribbon-shaped bodies, commonly interbedded with sandy deposits. The lower contact of this facies is always erosional and sharp, whereas the upper contact is usually gradational.	This facies is interpreted to have been deposited as channel lag under conditions of lower flow regime, with sediment transport occurring via traction currents .
Coarse-grained trough cross-bedded sandstone	St	This facies is most commonly overlies facies Gt. It consists of medium- to very coarse-grained sandstone arranged into trough cross-bedded sets and cosets. Geometrically, this facies occurs as lenticular or wedge-shaped bodies that are pebbly in places and which are commonly arranged into stacked trough cross-bedded cosets. The lower boundary is either gradational with facies Gt or is erosional with facies Fm, whereas the upper contact is sharp and flat with facies Sp.	This facies was deposited as dunes or bars under conditions of lower flow regime.
Medium- to coarse-grained planar cross-bedded sandstone	Sp	This facies consists of medium- to coarse-grained, poorly sorted, arkosic sandstone arranged into lenticular or tabular sets up to 2 m thick, which are characterised internally by planar cross-bedding. The lower contact of this facies is sharp and flat, whereas the upper contact is erosional either with facies Sr or Fl.	This facies was deposited as dunes or bars under conditions of lower flow regime.
Ripple cross-laminated sandstone	Sr	This facies succession, usually overlies facies Sp and consists of fine- to coarse-grained sandstone, which is generally well sorted and which is interlaminated with thin siltstone and claystone horizons. The sandstone is medium- to thick-bedded. It occurs as thin wedge-shaped bodies which pinch out laterally within few metres and which contain abundant ripple marks, flat bedding, and small-scale trough and planar cross-stratification and load casts. Alternations of flat-lying, parallel lamination with ripple-drift cross laminated sets and asymmetric current ripple marks are common .	This facies likely represents the temporary abandonment of bars during periods of elevated water level and/or the product of deposition in areas of slack or sluggish water between bars or in overbank areas
Very fine- to medium-grained sandstone with flat bedding	Sh	This facies consists of very fine- to medium-grained, horizontally laminated sandstone arranged into thin beds with a sheet or tabular geometry.	This facies accumulated as a plane bed under conditions of either upper or lower flow regime, either on bar top surfaces or as isolated sand sheets in overbank flood plain areas.
Parallel laminated siltstone and claystone	Fl	This facies consists of laminated siltstone and/or massive claystone units interbedded with millimetre-thick siltstone horizons. Its lower contact is gradational with facies Sh or Sr, whilst, in almost all cases, its upper contact is with facies Fm. Common structures include clay balls and iron concretions. Interlaminated siltstone horizons exhibit very small ripple marks and lenticular bedding. Geometrically, this facies is arranged into thin but laterally extensive sheet-like bodies.	This facies is interpreted to represent the deposits of waning stage flood deposition, chiefly in overbank areas, with the majority of deposition occurring from suspension settling and with only limited bedload transport via weak currents.
Massive claystone / mudstone	Fm	This is the most abundant facies type in nearly all the cycles and It consists of red, dark-brown, green and yellow claystone and shale with occasional grey to greenish-grey siltstone interbeds. The facies is generally massive, though at a few horizons it contains abundant bioturbation, clay balls, iron concretions, desiccation cracks, rain-drop imprints and caliche nodules up to 10 cm in diameter. The lower contact of this facies is typically gradational, whereas the upper contact is usually sharply truncated by the erosive base of the overlying cycle.	This facies is interpreted to represent deposition from suspension in overbank settings where the fine-grained sediments drape underlying deposits.

Table 1

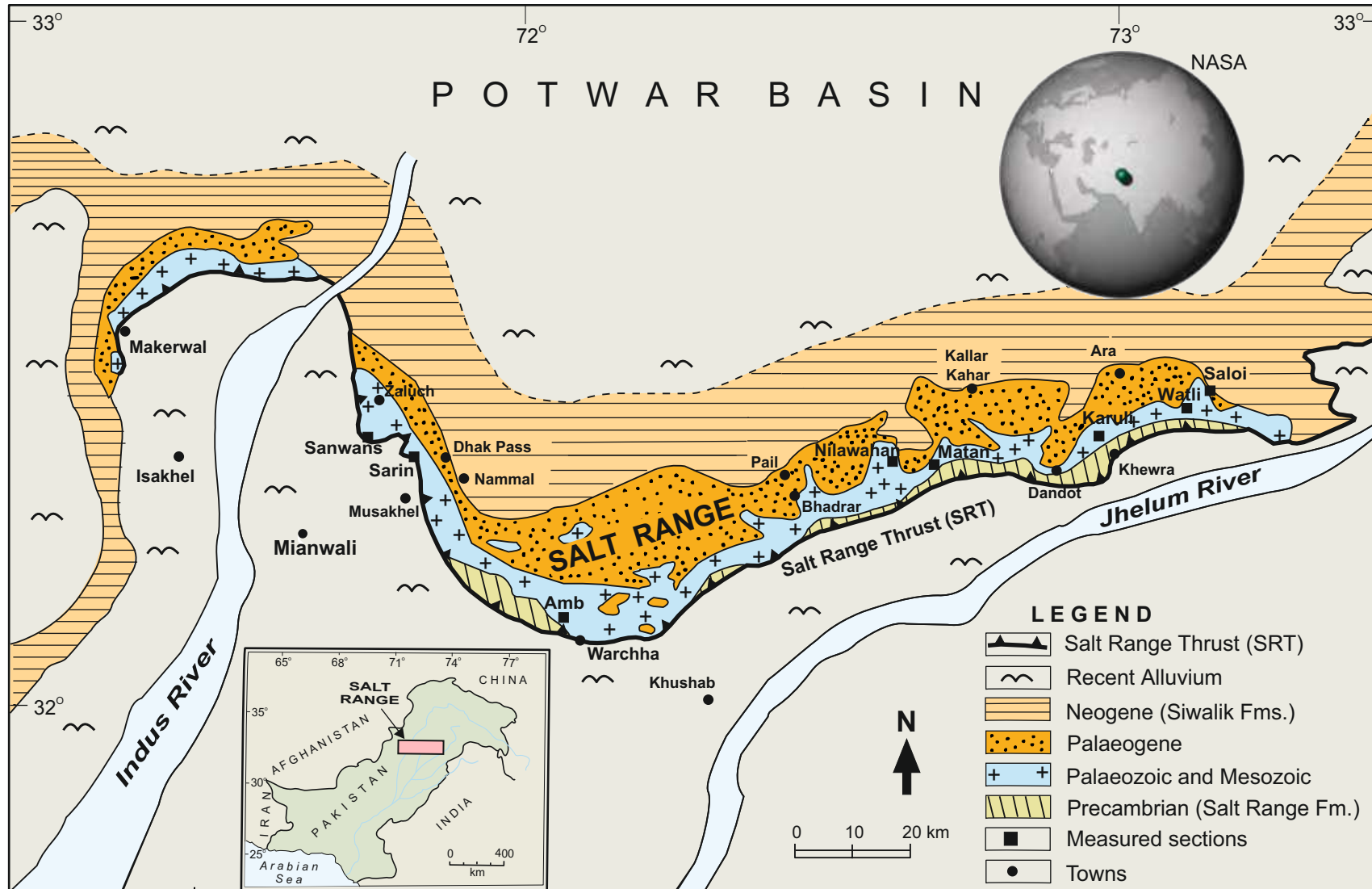


Figure 1

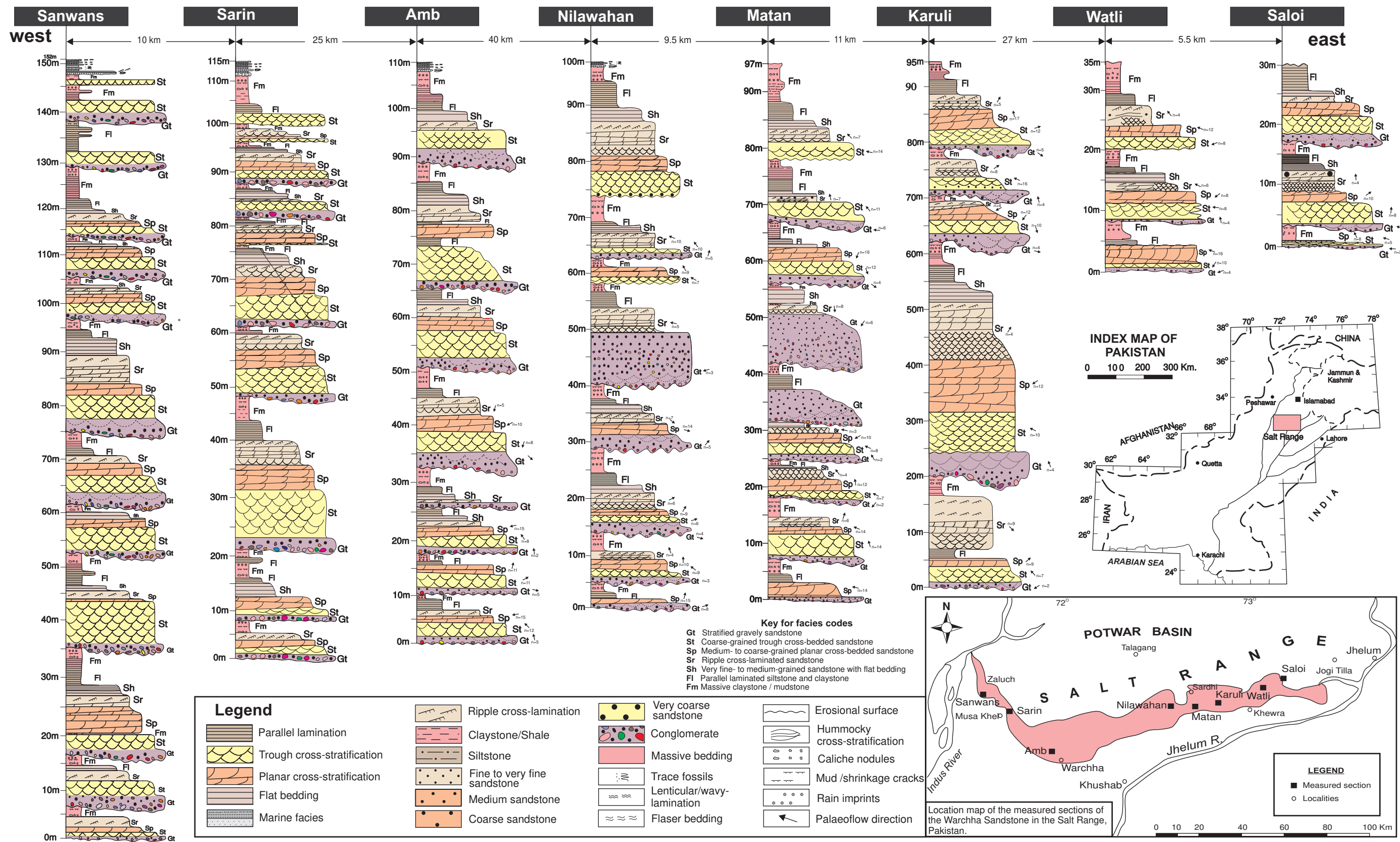


Figure 2

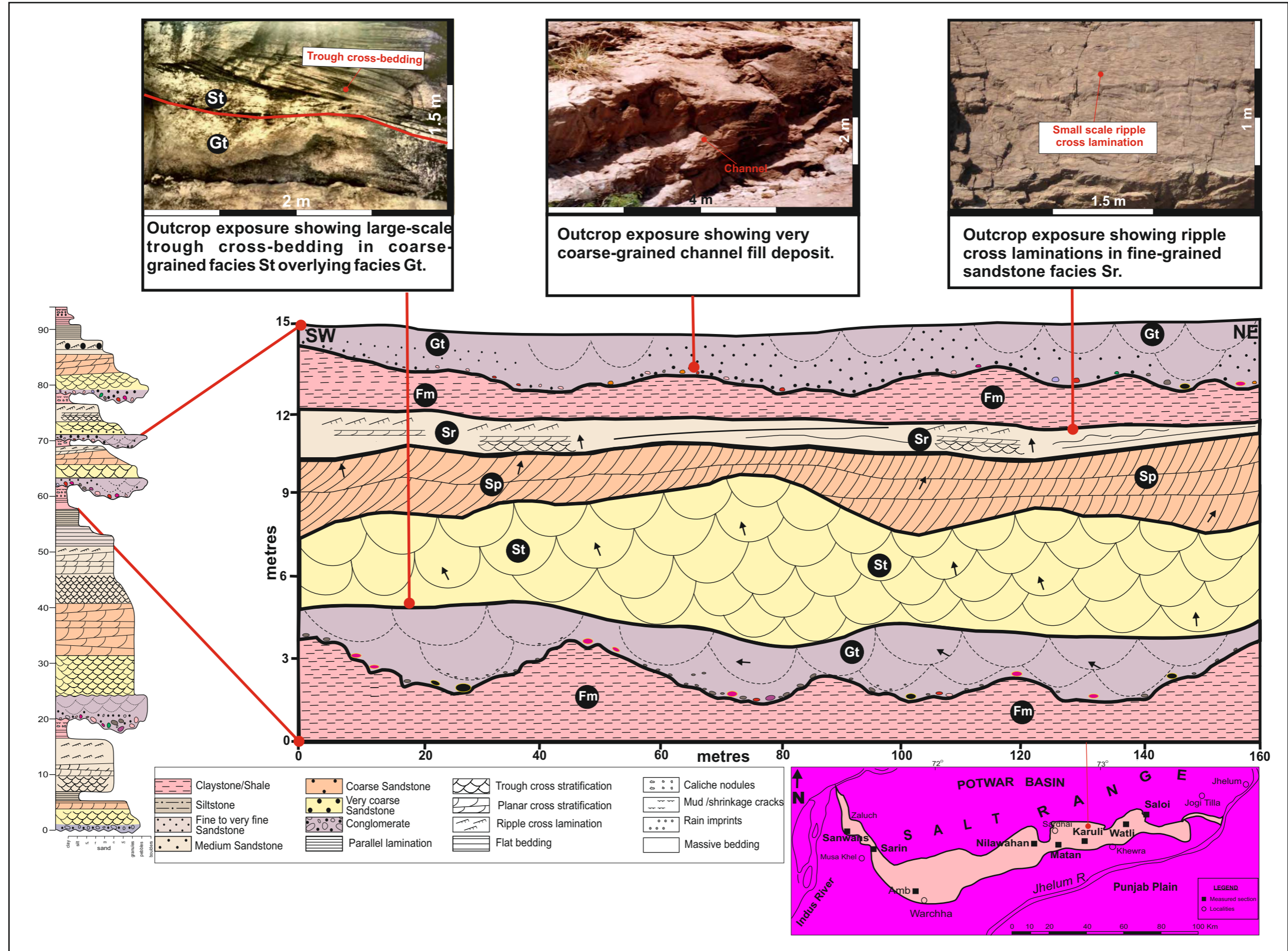


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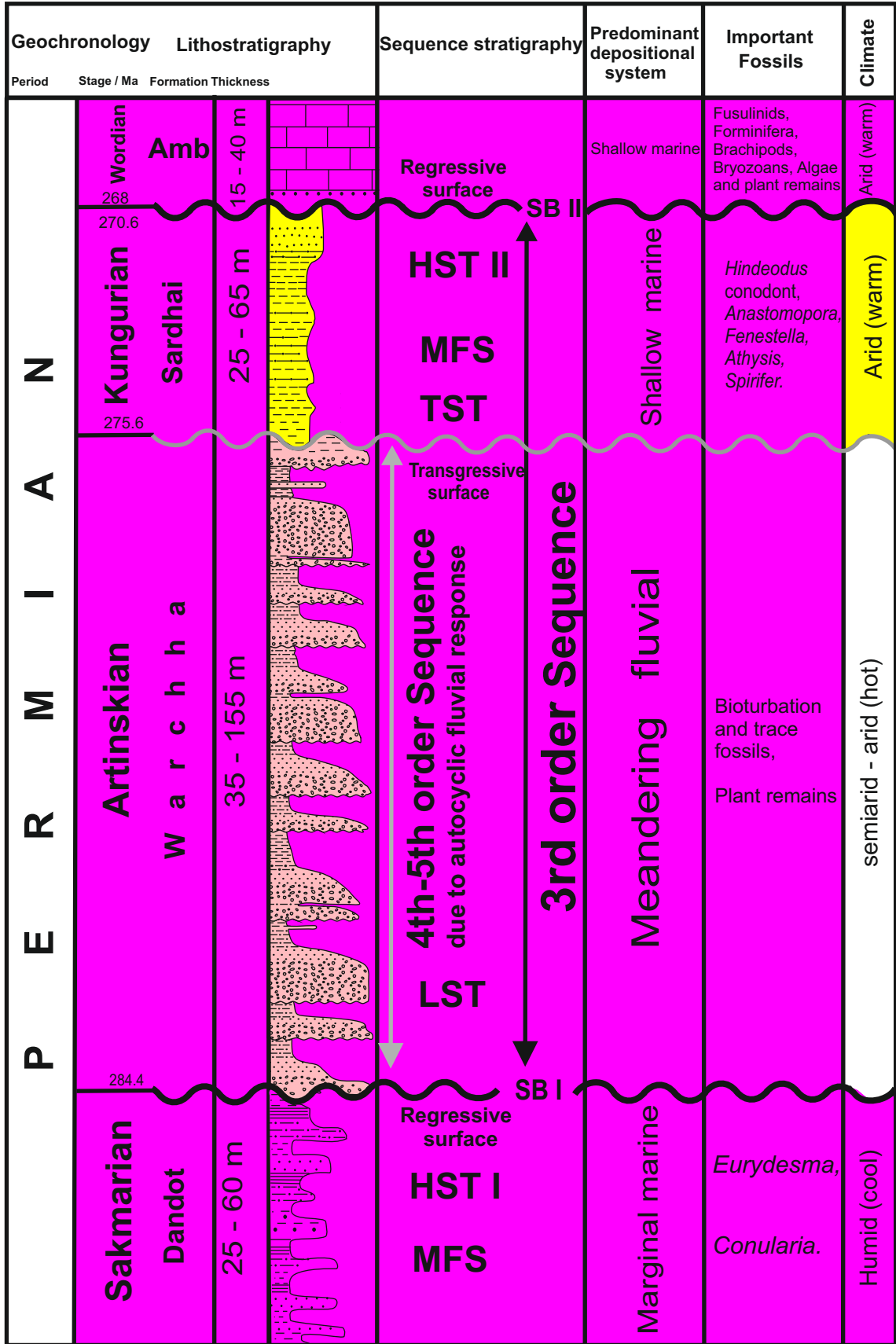
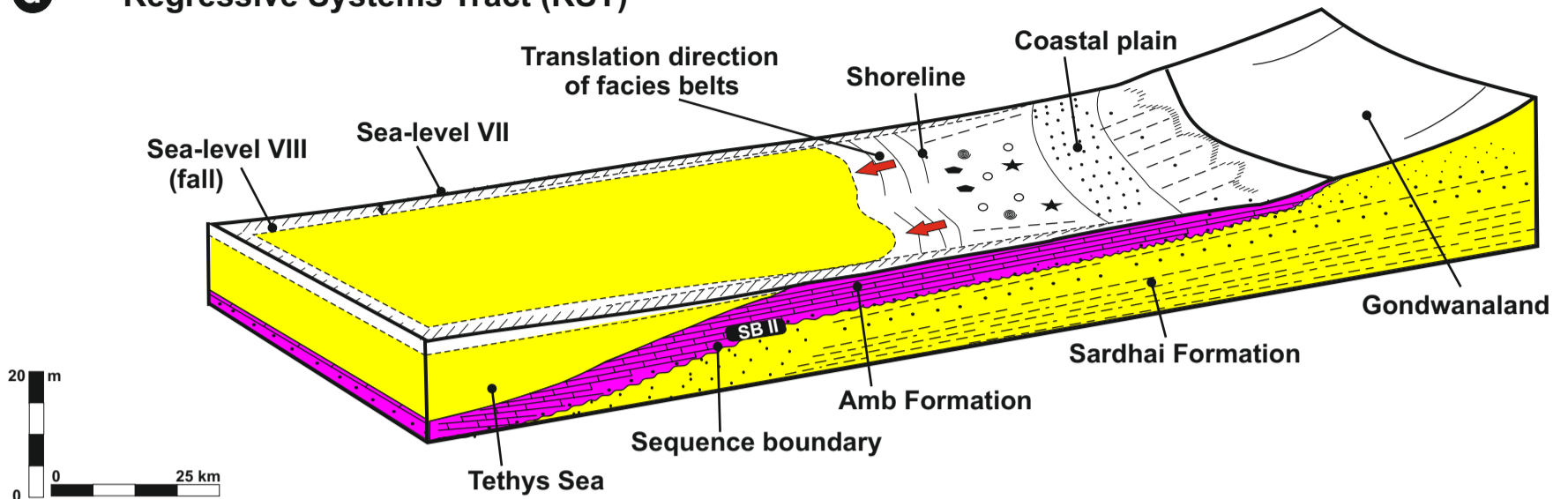
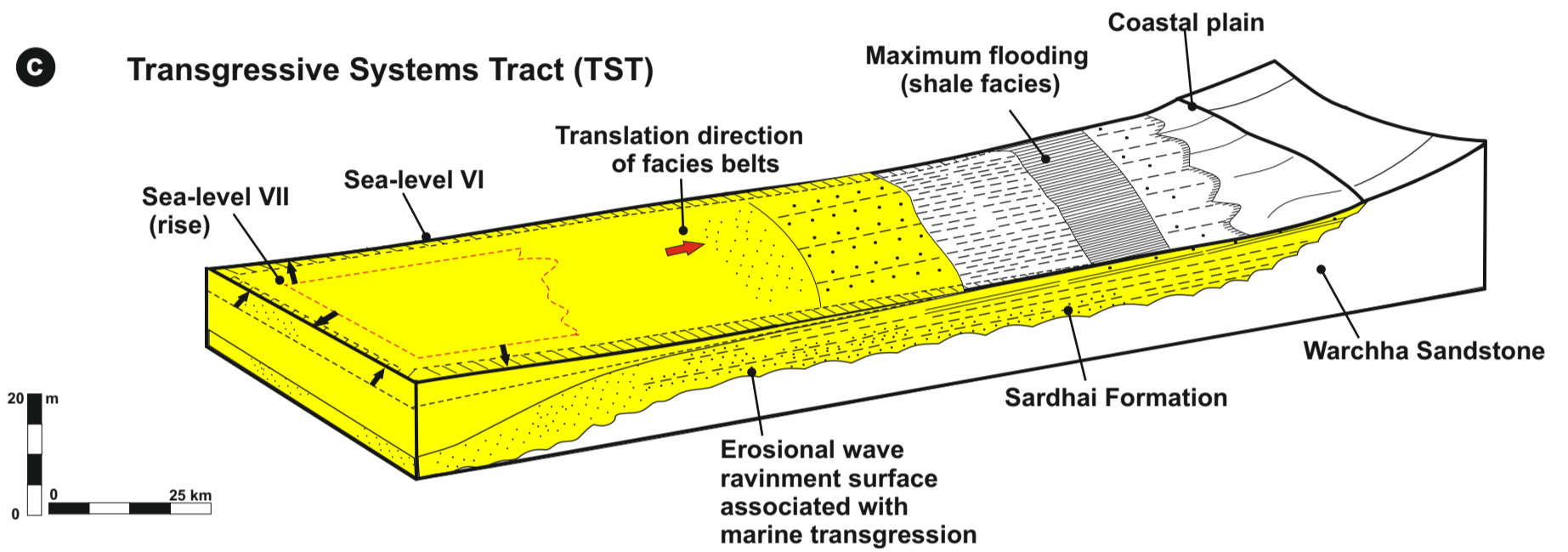


Figure 4

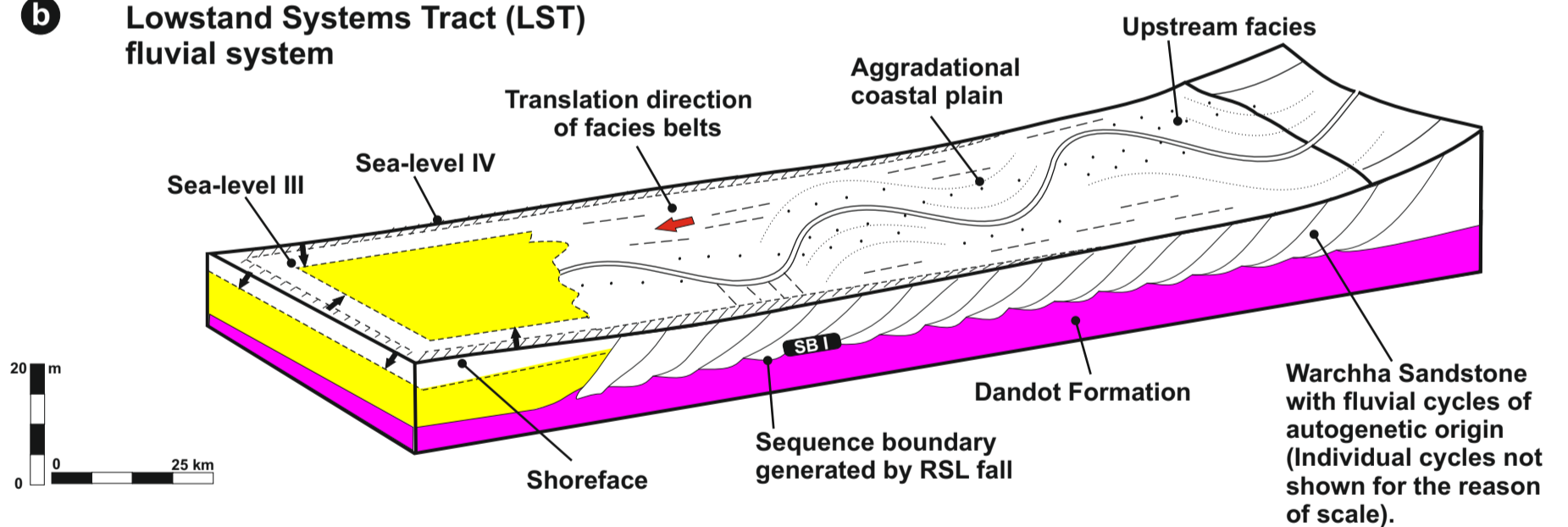
d Regressive Systems Tract (RST)



c Transgressive Systems Tract (TST)



b Lowstand Systems Tract (LST) fluvial system



a Highstand Systems Tract (HST) marginal marine system

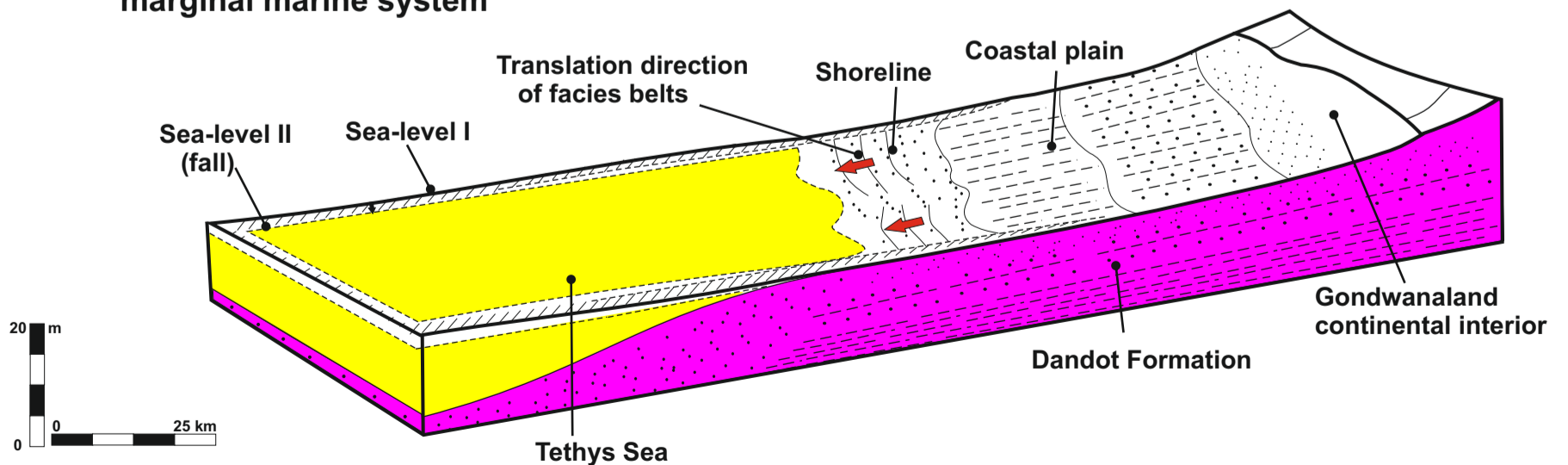


Figure 6

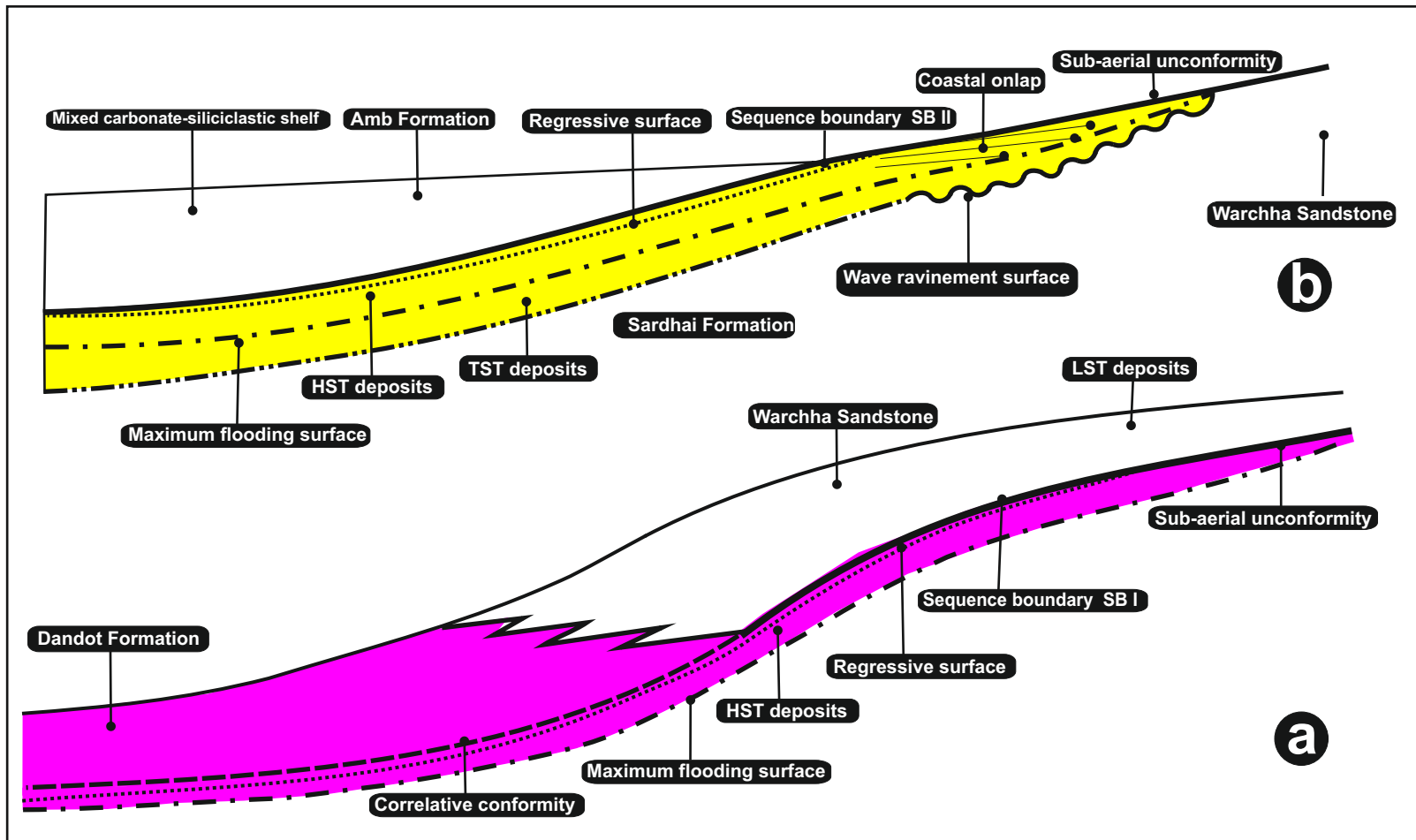


Figure 7

Ghazi and Mountney - Fluvial cyclicity and stratigraphic evolution

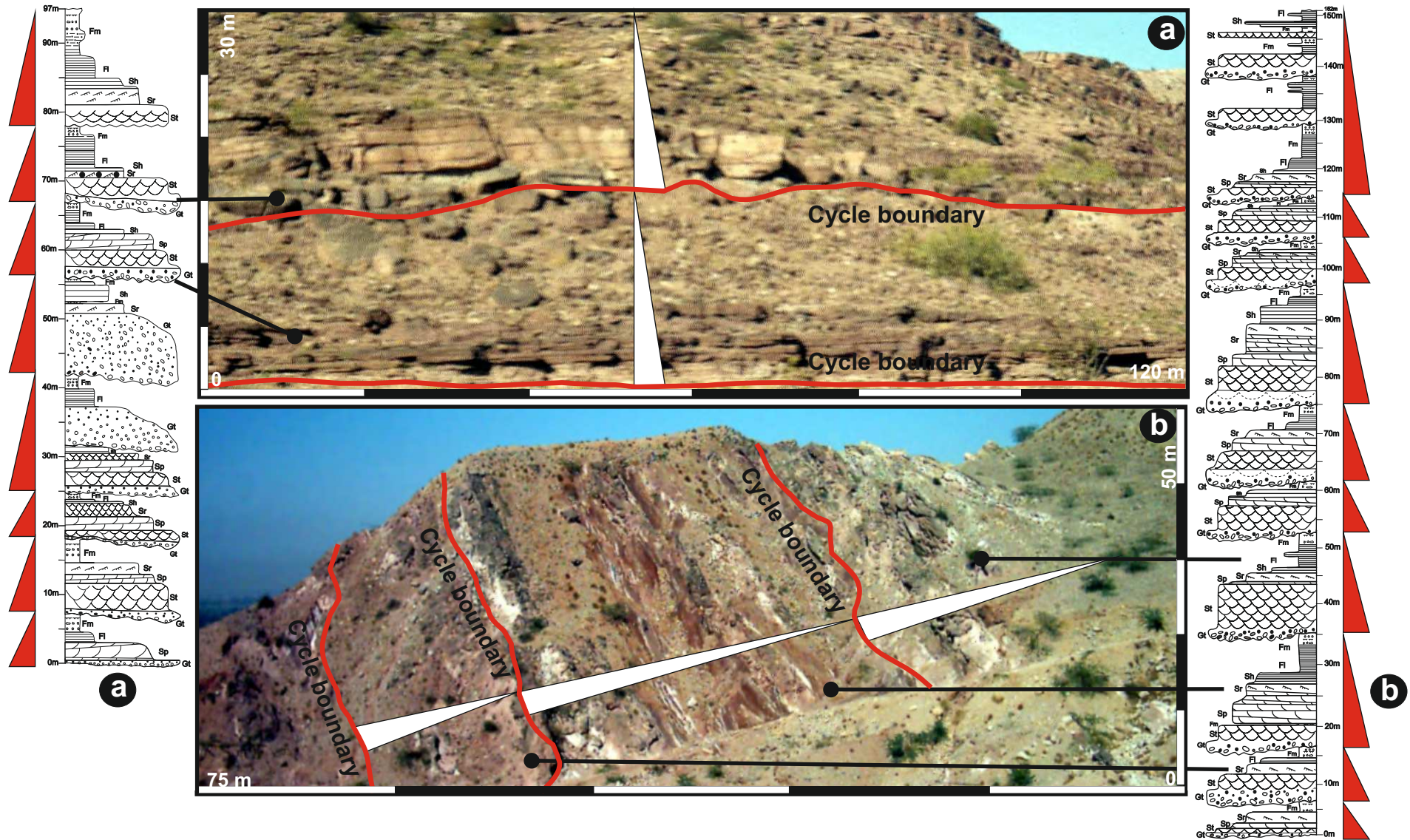


Figure 8

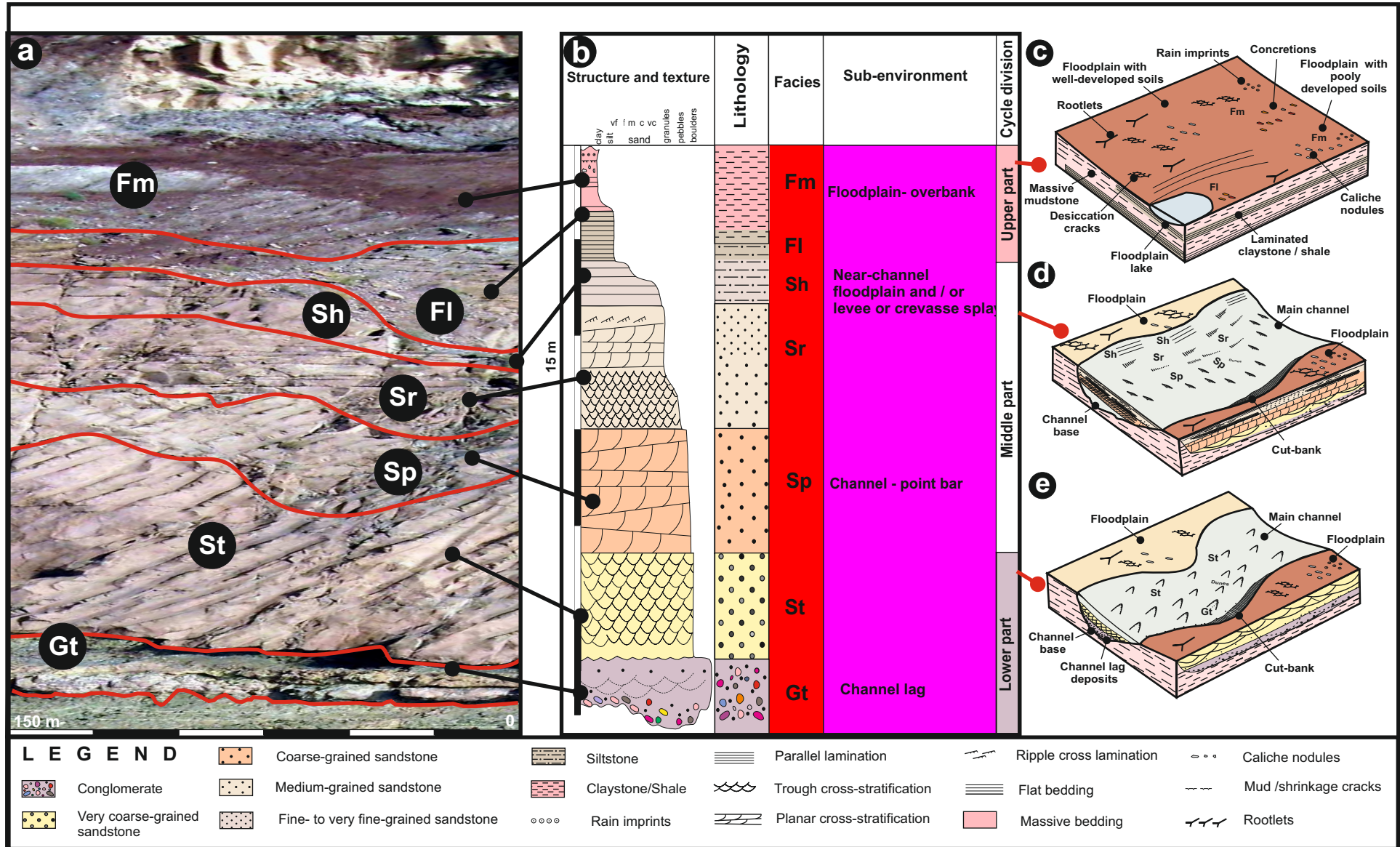


Figure 4

Ghazi and Mountney - Fluvial cyclicity and stratigraphic evolution

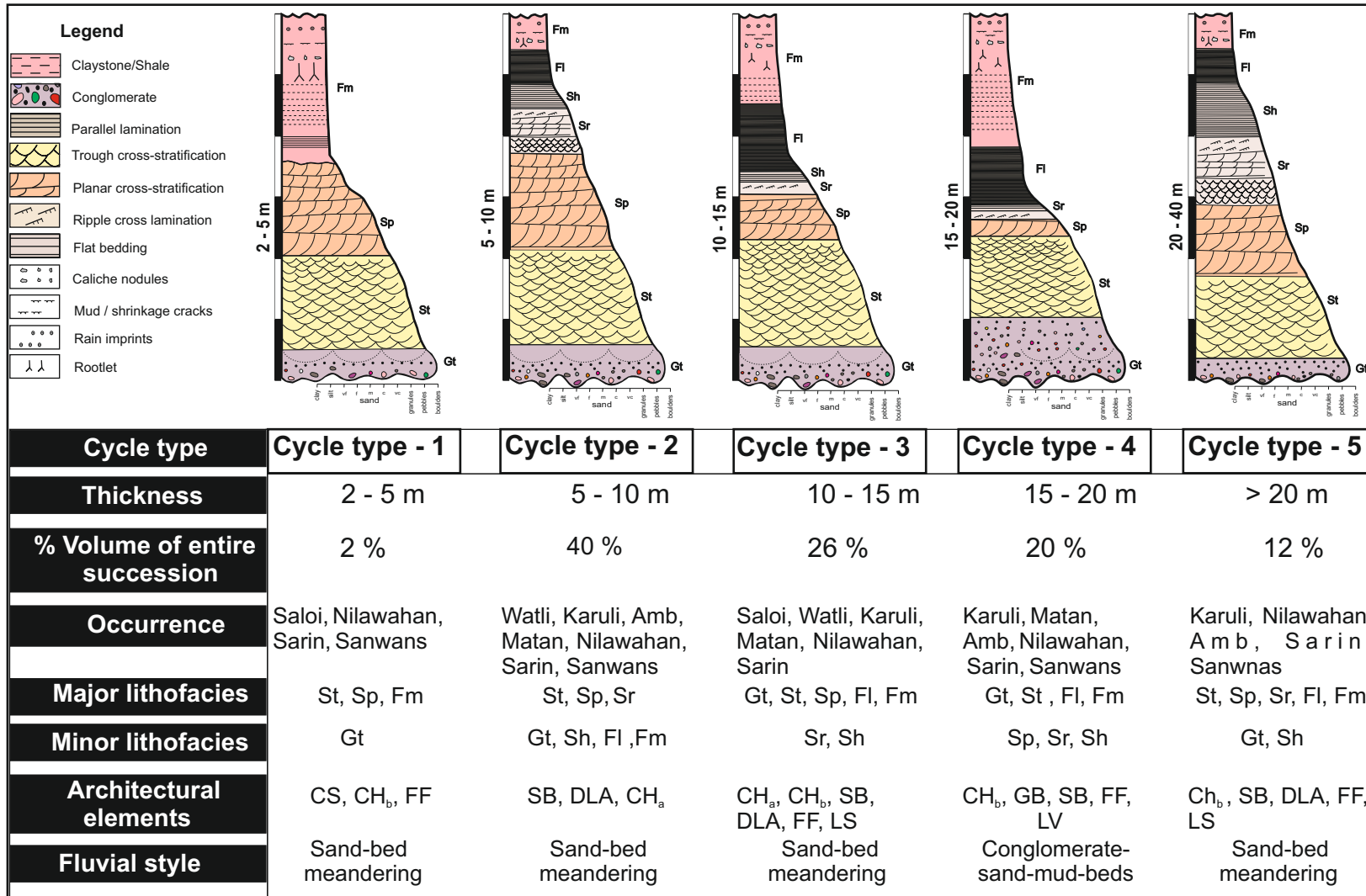


Figure 10

Ghazi and Mountney - Fluvial cyclicity and stratigraphic evolution

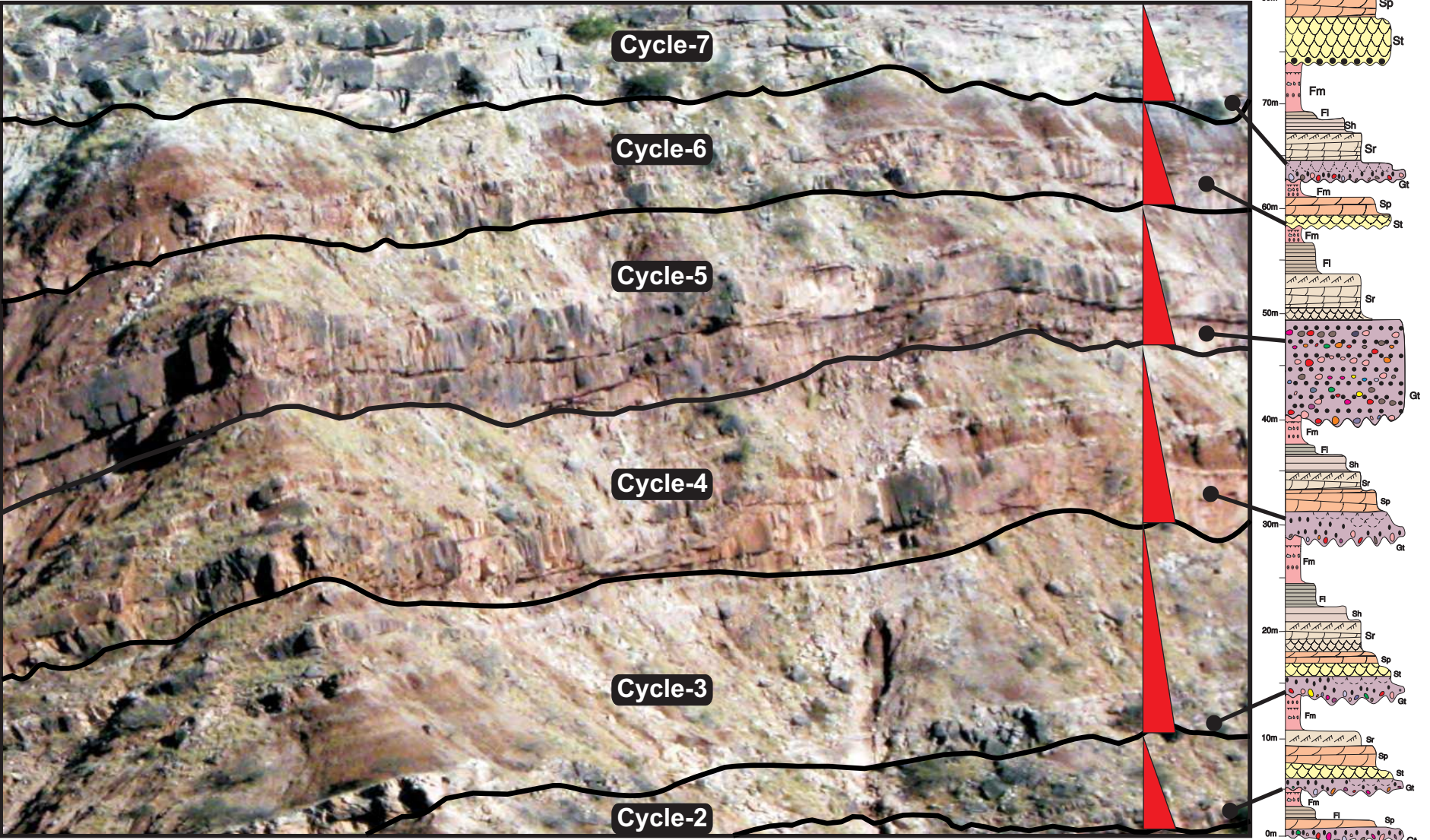


Figure11

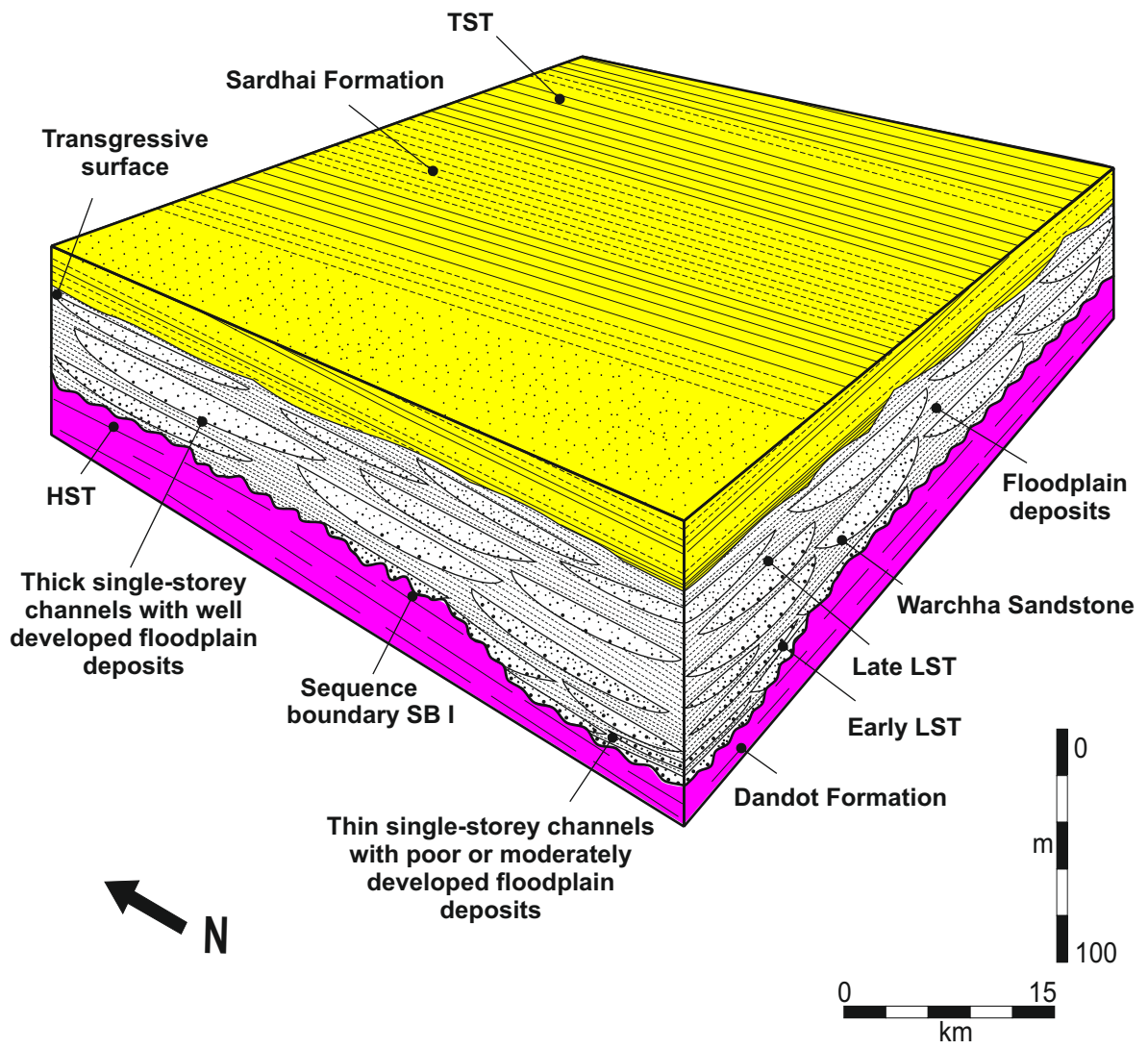


Figure 12