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

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ABSTRACT

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

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

KEYWORDS

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

INTRODUCTION

The Salt Range of Pakistan forms part of the Sub-Himalayan Mountains, which stretch for more than 180 km in an east-west orientation between the Jehlum and Indus rivers, along the southern margin of the Potwar Basin (Fig. 1). Within the Salt Range, a thick sedimentary cover, consisting of Precambrian to recent deposits, unconformably overlies low-grade metamorphic and igneous rocks (Gee, 1989). Within this cover succession the Lower Permian Nilawahan Group of the Gondwana Realm is subdivided into the Tobra, Dandot, Warchha and Sardhai formations. The Warchha Sandstone represents the deposits of a fluvial system that passed northwards into a coastal plain and estuarine system at the margin of the Tethys Sea (cf. Valdiya, 1997; Ghazi, 2009; Ghazi and Mountney, 2012a, 2012b). The Warchha Sandstone forms a clastic wedge of fluvial strata bounded both below and above by marine deposits of the Dandot and Sardhai formations, respectively (Ghazi and Mountney, 2009, 2012a) and, as such records a major episode of non-marine progradation. Overall, the Warchha Sandstone comprises a series of repeating fining-upward cycles with capping palaeosols (Figs. 1 & 2), which comprise part of a larger-scale depositional sequence. The Warchha Sandstone is one of many palaeosol-bearing alluvial successions characterized by a hierarchical record of depositional cycles that originated in response to the combined effect of autogenic and allogenic processes (e.g. Shanley and McCabe, 1994; McCarthy and Plint, 1998; Kraus and Aslan, 1999; Kraus, 2002; Atchley et al., 2004; McLaurin and Steel, 2007).

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

METHODOLOGY

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

REGIONAL SEQUENCE STRATIGRAPHIC FRAMEWORK

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

One of the first comprehensive and widely adopted sequence stratigraphic models for prediction of stacking patterns in continental fluvial successions was that of Shanley and McCabe (1994) who accounted for large-scale variations in architectural style based on and systematic variations in controlling processes. Their conceptual model is based on the notion of base-level fall and rise controlling fluvial behaviour by adjusting the graded equilibrium profile of the fluvial system to generate incised valleys during episodes of base-level fall and the subsequent filling of these valleys with stacked fluvial channel complexes during episodes of subsequent base-level rise. Ethridge et al. (1998) revised the model and discussed the complexity of multiple feedbacks that govern processes known to influence fluvial sequence development. Catuneanu (2002, 2006) emphasized the importance of stratigraphic base-level as a mechanism for maintenance of an equilibrium between erosion and deposition, whereby sediment accumulation occurs at sites where accommodation is generated in response to base-level rise. The interplay between base-level change and rate of sediment supply (sediment influx) controls whether a coastal fluvial system experiences transgression or regression (Bhattacharya, 2011).

Sequence stratigraphic framework of the Warchha Sandstone

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

At a large scale, the Warchha Sandstone forms a wedge of strata that thins to the north and which records an initially progradational and latterly retrogradational fluvial system. This wedge of strata forms part of a larger sequence architecture that records a major regressive and transgressive event at the shoreline of the northern margin of Gondwanaland, the nature of which is herein reconstructed via the analysis of lithofacies character and stacking patterns (Fig. 4). Variations in palaeo-shoreline position in the Salt Range region are documented by the vertical and lateral distribution of lithofacies belts; basinward-shift in lithofacies distributions record regression, whereas landward-shifts record transgression (cf., Mukhopadhyay et al., 2010).

Sequence boundaries

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

Lower sequence boundary SB I

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

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

The widespread occurrence of fluvial channel-fill elements characterized by coarse-grained lag deposits directly above the unconformity represents the base of the lowstand system tract (LST) of the succeeding Warchha Sandstone. The uppermost 60 to 80 mm of marine mudstone, claystone and micaceous siltstone, directly below the sequence boundary contains abundant broken bivalve remains, intense burrowing and root traces, indicative of a protracted episode of sub-aerial exposure prior to the onset of fluvial sedimentation. The relatively poor development of a palaeosol on this surface may reflect the removal of such a profile by erosion associated with fluvial channel scour. The appearance of a marine faunal assemblage, including the bivalve *Eurydesma*, in the strata directly below SB I marks an important change in climatic conditions from cold to less cold or relatively mild climatic conditions (cf. Singh, 1987; Veevers and Tewari, 1995; Fielding et al., 2006; Mukhopadhyay et al., 2010; Ghazi and Mountney, 2012a).

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

Upper sequence boundary SB II

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

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

Systems tracts

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

Highstand system tract (HST) of lower sequence

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

Lowstand systems tract (LST)

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

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

Transgressive system tract (TST)

The Warchha Sandstone passes upwards into overlying TST deposits of the overlying Sardhai Formation, of predominantly shallow-marine origin (Figs. 6 and 7), which is well exposed in parts of the western Salt Range. Continued relative sea-level rise resulted in marine transgression over the fluvial deposits (Mukhopadhyay et al., 2010), which led to the generation of a minor transgressive wave ravinement surface, prior to the onset of deposition of the overlying Sardhai Formation (cf. Catuneanu, 2006).

Maximum flooding surface (MFS)

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

PRESERVED CYCLICITY IN THE WARCHHA SANDSTONE

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

The large-scale regressive-transgressive cycle of the Sardhai and Warchha formations represents a full depositional sequence (Emery and Myers, 1996; Catuneanu, 2002; Folkestad and Satur, 2008; Ghazi, 2009). Biostratigraphic data from the Dandot Formation in the Salt Range demonstrates accumulation of this succession at a time of significant glacio-eustatic change during the Sakmarian (cf. Visser, 1997b; Singh, 1987) and this can be used to estimate the duration of the regressive-transgressive cycle (cf. Dickins, 1985; Visser, 1997b; Mack et al., 2003; Veevers, 2006). The Permian sea-level history as a whole represents a second-order cycle (Haq et al., 1988) with a total duration approximately 48 Myr (Wardlaw et al., 2004). The Lower Permian large-scale cycle discussed herein represents a third-order cycle, with a probable duration of 0.5 to 3 Myr, based on the fundamental units of sequence stratigraphy (Haq et al., 1988) and the nature of inferred trends in palaeo-shoreline shift (Catuneanu, 2006).

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

Large-scale cycles

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

Channel-fill fluvial facies directly overlie SB I in a manner that is consistent with a region-wide switch to a system characterised by non-marine fluvial sedimentation. The erosion surface at the base of the Warchha Sandstone incises 1 to 2 m into the underlying green to greenish-grey mudstone and siltstone marine deposits of the underlying Dandot Formation. The lowermost part of the Warchha Sandstone is composed of a 0.02 to 0.2 m-thick lag of pebble-size claystone and mudstone clasts derived from the reworking of underlying strata.

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

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

Small-scale cycles

A total of 54 small-scale cycles have been studied in detail in the Warchha Sandstone. These upward-fining cycles are each 2 to 40 m (though mostly 3 to 10 m) thick. Complete examples of such cycles (Figs. 2 and 3) are characterised by seven lithofacies (Table 1) that occur in a generally predictable order. Complete sedimentary cycles carry no indictors to suggest the duration or frequency of their development. Internally within each cycle, the thicknesses of component facies varies in all measured sections (cf. Duff et al., 1967; Casshyap, 1970, 1975). As is the case for the majority of cyclically arranged fluvial successions, most of the cycles in the Warchha Sandstone are incompletely developed and many are truncated in their upper part by the erosional bases of overlying cycles (Ghazi, 2009; Ghazi and Mountney, 2009). A complete cycle is generally divided into three parts (Figs. 3 & 9): a lower part consisting of facies Gt and St, a middle part consisting of facies Sp, Sr and Sh, and an upper part consisting of facies Fl and Fm (see Table 1 for facies descriptions). This tripartite succession of facies associations represents the successive occurrence of different depositional sub-environments within the fluvial system at a given point (Fig. 9; Ghazi and Mountney 2009, 2010, 2012b). The cross-stratified conglomerates and sandstones represent sediments deposited in channel as lags and a variety of types of mid-channel and point bars (Allen, 1964; Casshyap, 1970, 1975; Hota and Maejima, 2004). Ripple cross-laminated sandstones represent predominantly levee and crevasse-slpay elements (Casshyap 1970, 1975; Hota and Maejima 2004; Ghazi, 2009). Horizontally bedded and solitary sets of cross-stratified finer-grained sandstones were deposited by overbank sheet floods, and red claystone with siltstone and fine-grained sandstone lenses represent vertical aggradation of mud on the floodplain (Casshyap, 1970, 1975; Hota and Maejima, 2004; Ghazi and Mountney, 2009, 2011).

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

Type 1 cycles

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

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

Type 2 cycles

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

Interpretation: These cycles record significant channel incision and facies Gt, St, Sp, Sr, Sh, Fl and Fm each record the progressive fill of these deeper channels. The typical fining-upward succession and style of bedset development within these cycles is indicative of the preservation of thalweg deposits overlain by the lower part of multiple in-channel barforms (cf. McLaurin and Steel, 2007; Ghazi and Mountney, 2009). The presence of channel lag and very coarse-grained sandstone in the lower parts of the cycles indicates a high-energy regime, whereas the finer-grained sandstone in the middle part indicates a lower-energy bar later in the history of the channel fill. By contrast the top parts of these cycles were deposited in an overbank setting (cf. McLaurin and Steel, 2007). During their deposition, sediment-laden water likely overtopped the channel banks during flood events, enabling sediments to be deposited ouside the channel confine (cf. Stear, 1983).

Type 3 cycles

Description: These cycles, which are 10 to 15 m thick, constitute 26% of the Warchha Sandstone (Fig. 10). They preserve relatively thick fine-grained components and are well developed in the Saloi, Watli, Karuli, Matan, Nilawahan and Sarin areas (Figs. 10 and11). These cycles are divided into three parts: a lower part that is 4 to 6 m thick and composed of Gt, and St facies, commonly with thin intervals of channel-lag deposits in the form of sub-angular to sub-rounded intraformational claystone clasts; a middle part that is 1 to 3 m thick and composed mainly of facies Sp with minor contributions of Sr and Sh; an upper part that is 5 to 6 m thick and composed mainly of siltstone and claystone (facies Fl and Fm). Both lower and upper boundaries of these cycles are marked by erosional surfaces.

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

Type 4 cycles

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

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

Type 5 cycles

Description: These cycles are > 20 m thick (Fig.10), but constitute only 12 % of the Warchha Sandstone. The thickest observed cycle (from the Karuli area) is 42 m and similarly thick cycles exist in the Nilawahan, Amb and Sanwans areas. The uppermost 10 to 15 m of the uppermost cycles in the Sanwans area shows a significant marine signature, with hummocky cross-bedding, flaser and wavy bedding, cone-in-cone structures and trace fossils such as *Skolithos*. Marine signatures are also present in cycles at the top of the formation in the Nilawahan area, and these also include phosphatic nodules and the trace fossil *Helminthopsis*. these cycles are divided into three parts: a lower part that is 6 to 12 m thick and composed mainly of pebbly very coarse sandstone facies St with thinly developed facies Gt as channel lag deposits (missing in Nilawahan area); a middle part that is 10 to 15 m thick and composed of facies Sp, Sr and Sh (the latter missing in the Sarin area); an upper part that is 4 to 10 m thick and composed mainly of siltstone, claystone and thin mudstone facies Fl and Fm, with associated desiccation cracks, rain imprints, caliche nodules and rare bioturbation. Both upper and lower contacts of these cycles are erosional.

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

Causes of cyclicity in the Warchha Sandstone

Against a background of on-going basin subsidence, development of individual cycles was probably controlled principally by autogenic channel migration and avulsion (Casshyap, 1970; 1975; Ghazi et al., 2012a). Even after accounting for the removal of the uppermost part of the Warchha Sandstone by the major unconformity that separates the Permian from the Palaeocene succession in the eastern part of the Salt Range, the number of preserved cycles present in the Warchha Sandstone succession can be shown to systematically increase from east to west (Fig. 2). This direct relationship between cycle thickness and number of cycles is consistent with an origin driven by autogenic processes (cf. Hota and Pandya, 2002). If cycle development had occurred in response to allogenic processes, such as widespread diastrophic movements (Duff et al., 1967), climatic controls, or tectono-eustasy, then the number of preserved cycles would be expected to have remained constant throughout the basin (cf. Hota and Pandya, 2002). The absence of coal-bearing strata in the uppermost parts of the fining-upward cycles could be due to rapid avulsion (Allen, 1965) and high sedimentation rates, or alternatively (and more likely) may reflect a lack of a suitable anoxic coal-forming environments and the poor development of vegetation in a predominantly semi-arid climatic setting (cf. Nadon, 1994; Roberts, 2007). Both clay mineral analysis and sedimentary structures indicate a warm to hot, semi-arid climate with short-term seasonal rainfall, which would not have been conducive to coal accumulation (Ghazi and Mountney, 2011,2012b).

AUTOGENIC VERSUS ALLOGENIC CONTROLS ON SEDIMENTATION

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

Autocyclic controls

The various cycles of the Warchha Sandstone identified in the eight localities studied in detail cannot be correlated with each other directly. The nature of the small-scale cycles is consistent with autogenic depositional mechanisms proposed by Kraus and Aslan (1999), Atchley et al. (2004) and Cleveland et al. (2007): namely channel avulsion and floodplain aggradation. During the avulsion process, sedimentation rates were high and resulted in incomplete cycle development and generally only a thin development of capping palaeosol facies (cf. Kraus and Aslan, 1999). Pebbly to coarse-grained sandstone facies in channels are representative of downstream and lateral accretion macroforms of gravel and sandy bars or, in few cases, of progradational splay deposits (e.g. Type 1 cycles). The cause of channel avulsion arises via a combination of complex processes: controls on avulsion frequency include channel gradient, channel distribution, substrate composition and rate of background basin subsidence (Törnqvist and Bridge, 2002; Bridge, 2006). Controls on channel-element geometry (e.g. width and thickness of channel-belt deposits) include the size of the formative channel, its rate of lateral migration across the floodplain and the residence time of a channel on a given part of the floodplain – itself a function of avulsion frequency (Bristow and Best, 1993). The style of stacking of multiple cycles is a function of the freedom of the channel system to wander acorss a broad alluvial plain, which itself determines the frequency with which channels return to the same point on the plain, and the rate of subsidence, which determines the nature of channel stacking to form either single- or multi-storey channel complexes.

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

Allocyclic controls

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

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

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

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

DISCUSSION

Sequence stratigraphic models for fluvial strata proposed by Wright and Marriot (1993) and Shanley and McCabe (1994) are generally applicable to the lowstand system tract deposits of the Warchha Sandstone. However, for this succession, it multi-storey channel-fill complexes accumulated over a wide regional area during LST times, rather than being confined within a series of incised valleys, as originally envisaged in the early non-marine sequence stratigraphy models. This multi-storey stacking of fluvial channel elements in the lower part of the Warchha Sandstonelikely reflects the slow rate of base-level rise during the initial part of the LST. Within te succession, multi-storey channel bodies are progressively replaced by single-storey bodies that are representative of high-sinuosity meandering fluvial channel behaviour in the middle and upper parts of the formation (Ghazi and Mountney, 2009), reflecting increased rates of base-level rise and an accelerating rate accommodation generation. In particular, the presence of relatively thick floodplain elements within cycles in the middle and upper parts of the formation can be related to an increase in accommodation space and possibly to higher rates of sediment supply. The variation in lithofacies, the range of sedimentary structures, and the presence of marine-influenced lithofacies with diagnostic trace fossils in the uppermost part of the Warchha Sandstone indicates the onset of a transgressive system tract (Fig. 12; cf., Mukhopadhyay et al., 2010) at a time when the rate of accommodation generation was accelerating. Variations in rates of accommodation generation, sediment supply and discharge likely all played major roles in controlling channel sand-body stacking in this high-sinuosity meandering fluvial system.

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

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

CONCLUSIONS

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

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

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FIGURE AND TABLE CAPTIONS

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Facies	Code	Description	Interpretation
Stratified gravely 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

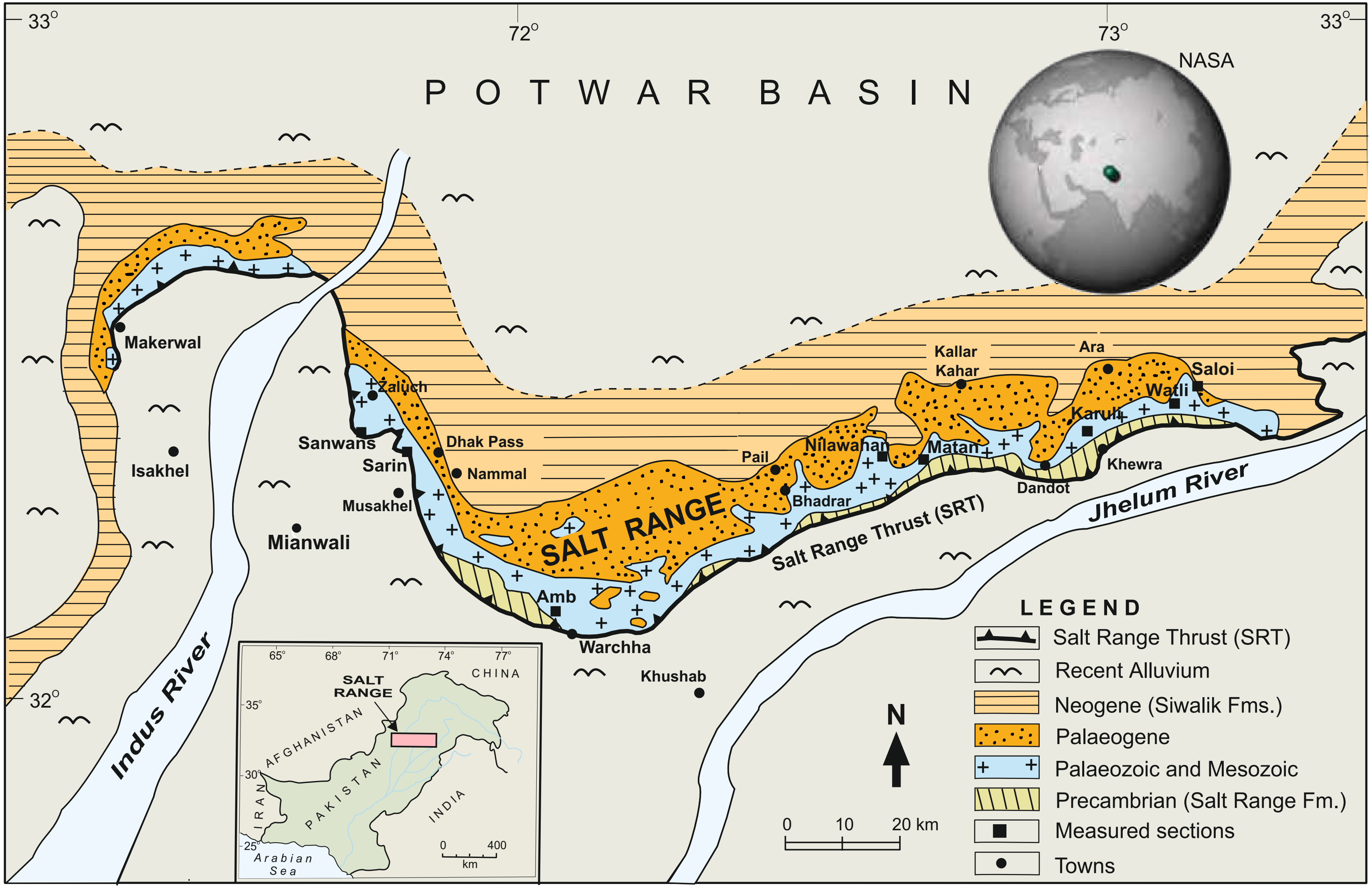
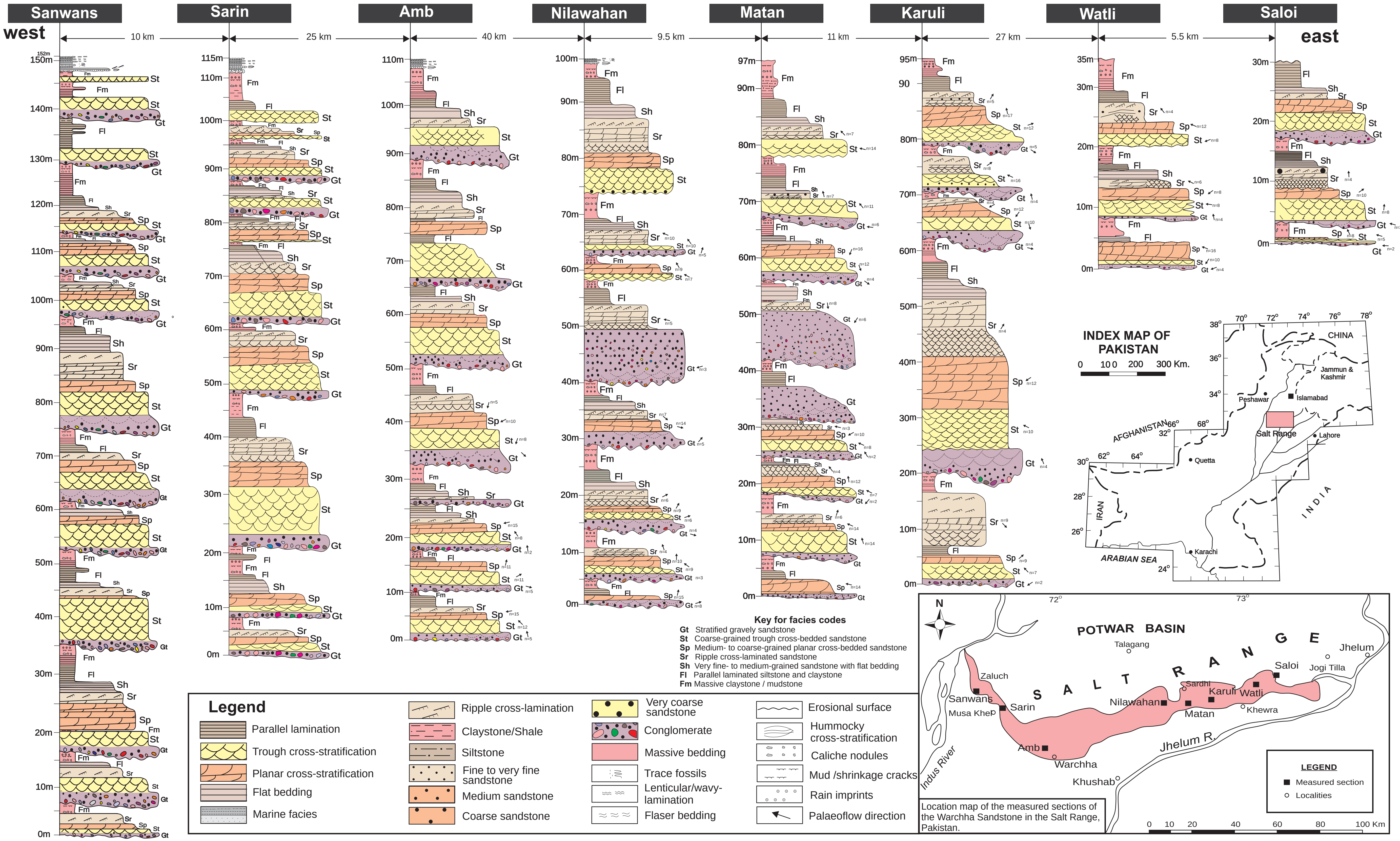

33°
72°
73°
33°
32°
POTWAR BASIN
NASA
Makerwal
Isakhel
Mianwali
Zaluch
Sanwans
Sarin
Musakhel
Dhak Pass
Nammal
SALT RANGE
Amb
Warchha
Khushab
Pail
Nilawahan
Bhadrar
Kallar
Kahar
Matan
Ara
Saloi
Watli
Karuli
Dandot
Khewra
Salt Range Thrust (SRT)
Jhelum River
Indus River
SALT
RANGE
CHINA
AFGHANISTAN
PAKISTAN
IRAN
INDIA
Arabian
Sea
65°
68°
71°
74°
77°
35°
30°
25°
0
400
km
N
0
10
20 km
LEGEND
Salt Range Thrust (SRT)
Recent Alluvium
Neogene (Siwalik Fms.)
Palaeogene
Palaeozoic and Mesozoic
Precambrian (Salt Range Fm.)
Measured sections
Towns

Figure 1



Sanwans
Sarin
Amb
Nilawahan
Matan
Karuli
Watli
Saloi
west
east
10 km
25 km
40 km
9.5 km
11 km
27 km
5.5 km
Key for facies codes
Gt Stratified gravely sandstone
St Coarse-grained trough cross-bedded sandstone
Sp Medium- to coarse-grained planar cross-bedded sandstone
Sr Ripple cross-laminated sandstone
Sh Very fine- to medium-grained sandstone with flat bedding
Fl Parallel laminated siltstone and claystone
Fm Massive claystone / mudstone
Legend
Parallel lamination
Trough cross-stratification
Planar cross-stratification
Flat bedding
Marine facies
Ripple cross-lamination
Claystone/Shale
Siltstone
Fine to very fine sandstone
Medium sandstone
Coarse sandstone
Very coarse sandstone
Conglomerate
Massive bedding
Trace fossils
Lenticular/wavy-lamination
Flaser bedding
Erosional surface
Hummocky cross-stratification
Caliche nodules
Mud /shrinkage cracks
Rain imprints
Palaeoflow direction
INDEX MAP OF PAKISTAN
0 100 200 300 Km.
CHINA
Jammu & Kashmir
Peshawar
Islamabad
Salt Range
Lahore
AFGHANISTAN
Quetta
IRAN
INDIA
Karachi
ARABIAN SEA
POTWAR BASIN
SALT RANGE
Talagang
Jhelum
Jogi Tilla
Saloi
Zaluch
Sanwans
Musa Khel
Sarin
Sardhi
Karuli
Watli
Nilawahan
Matan
Khewra
Amb
Warchha
Khushab
Jhelum R.
Indus River
LEGEND
Measured section
Localities
0 10 20 40 60 80 100 Km
Location map of the measured sections of the Warchha Sandstone in the Salt Range, Pakistan.

Figure 2

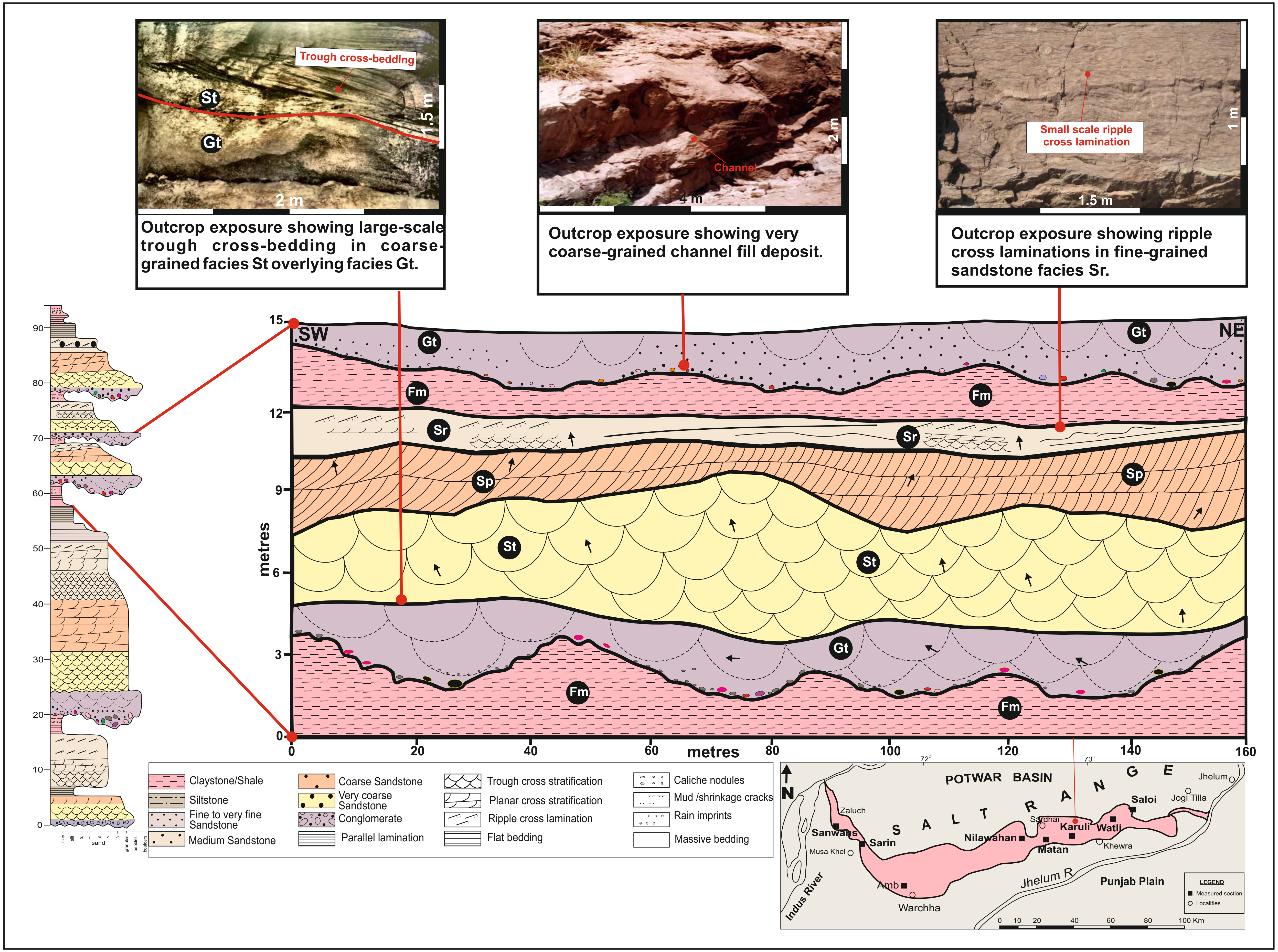

Trough cross-bedding
St
Gt
1.5 m
2 m
Outcrop exposure showing large-scale trough cross-bedding in coarse-grained facies St overlying facies Gt.
Channel
2 m
4 m
Outcrop exposure showing very coarse-grained channel fill deposit.
Small scale ripple cross lamination
1 m
1.5 m
Outcrop exposure showing ripple cross laminations in fine-grained sandstone facies Sr.
SW
NE
Gt
Fm
Sr
Sp
St
metres
metres
Claystone/Shale
Siltstone
Fine to very fine Sandstone
Medium Sandstone
Coarse Sandstone
Very coarse Sandstone
Conglomerate
Parallel lamination
Trough cross stratification
Planar cross stratification
Ripple cross lamination
Flat bedding
Caliche nodules
Mud /shrinkage cracks
Rain imprints
Massive bedding
POTWAR BASIN
SALT RANGE
N
Jhelum
Saloi
Jogi Tilla
Zaluch
Sanwans
Sarin
Musa Khel
Nilawahan
Karuli
Watli
Matan
Khewra
Amb
Warchha
Indus River
Jhelum R
Punjab Plain
LEGEND
Measured section
Localities
0 10 20 40 60 80 100 Km

Figure 3

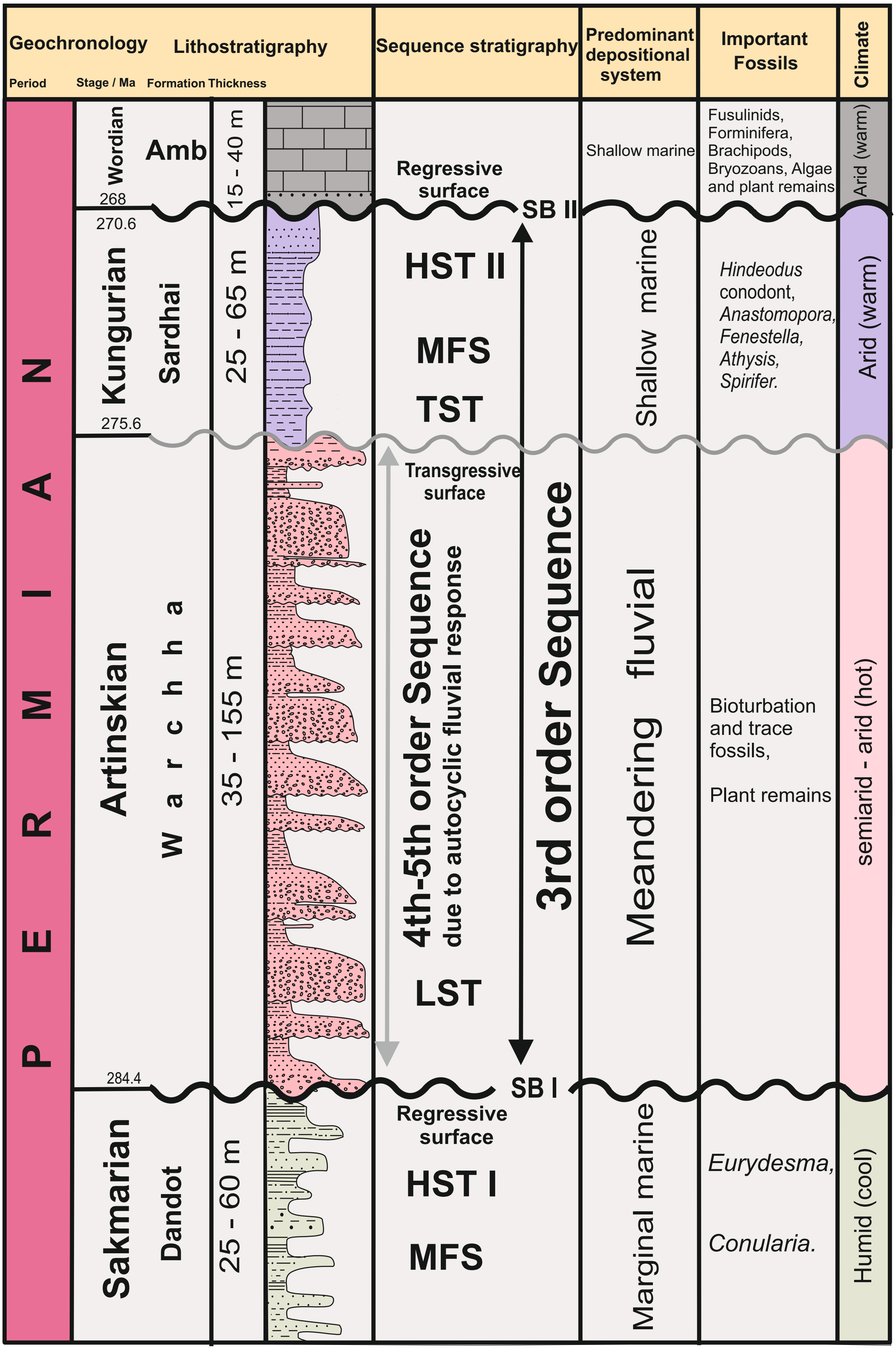

Geochronology
Lithostratigraphy
Period
Stage / Ma
Formation
Thickness
Sequence stratigraphy
Predominant depositional system
Important Fossils
Climate
P E R M I A N
Wordian
268
Amb
15 - 40 m
270.6
Kungurian
Sardhai
25 - 65 m
275.6
Artinskian
W a r c h h a
35 - 155 m
284.4
Sakmarian
Dandot
25 - 60 m
Regressive surface
SB II
HST II
MFS
TST
Transgressive surface
4th-5th order Sequence
due to autocyclic fluvial response
3rd order Sequence
LST
SB I
Regressive surface
HST I
MFS
Shallow marine
Shallow marine
Meandering fluvial
Marginal marine
Fusulinids, Forminifera, Brachipods, Bryozoans, Algae and plant remains
Hindeodus conodont, Anastomopora, Fenestella, Athysis, Spirifer.
Bioturbation and trace fossils,
Plant remains
Eurydesma,
Conularia.
Arid (warm)
Arid (warm)
semiarid - arid (hot)
Humid (cool)

Figure 4

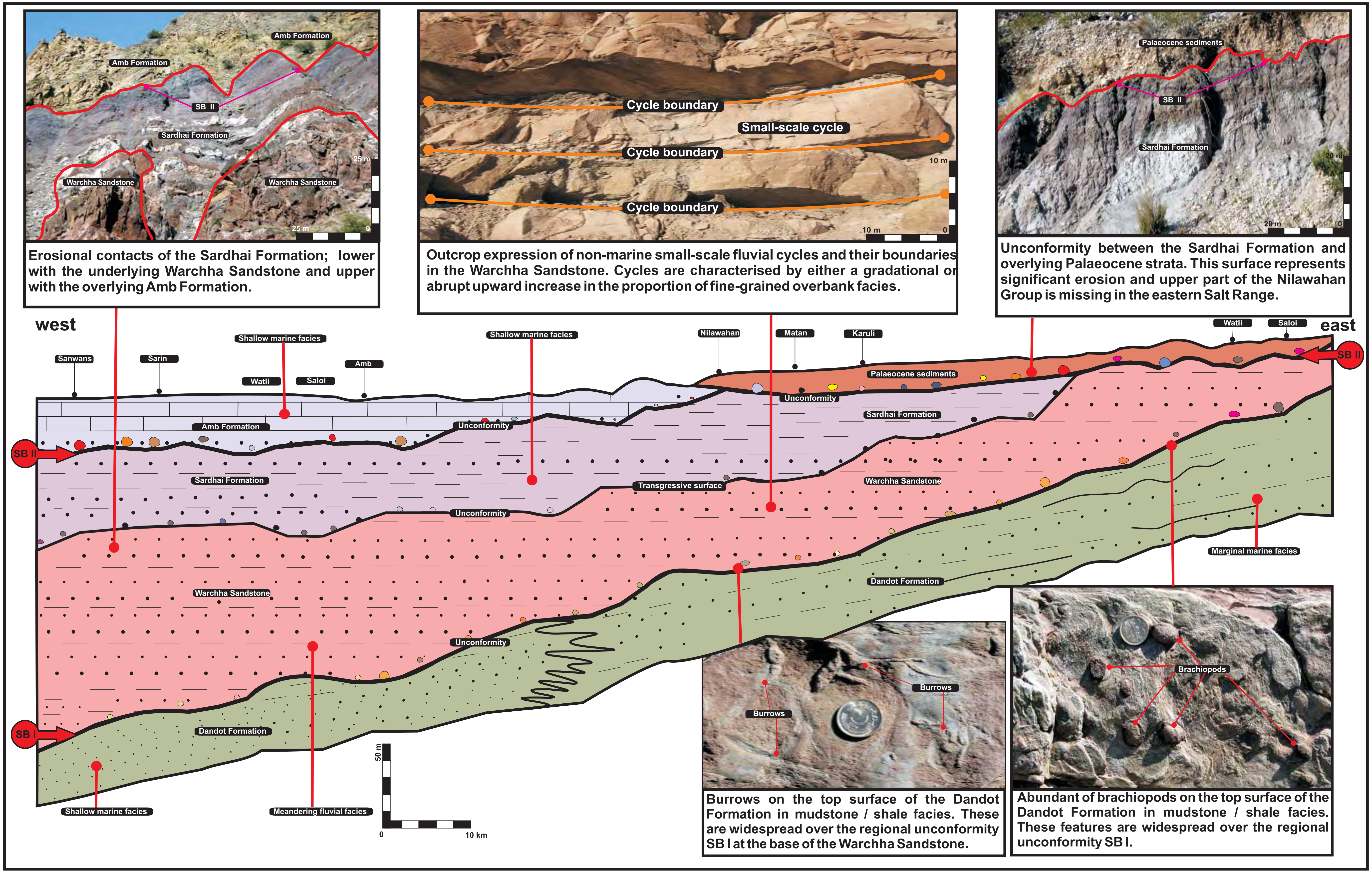

Amb Formation
Amb Formation
SB II
Sardhai Formation
Warchha Sandstone
Warchha Sandstone
25 m
25 m
0
Erosional contacts of the Sardhai Formation; lower with the underlying Warchha Sandstone and upper with the overlying Amb Formation.
Cycle boundary
Small-scale cycle
Cycle boundary
Cycle boundary
10 m
10 m
0
Outcrop expression of non-marine small-scale fluvial cycles and their boundaries in the Warchha Sandstone. Cycles are characterised by either a gradational or abrupt upward increase in the proportion of fine-grained overbank facies.
Palaeocene sediments
SB II
Sardhai Formation
20 m
20 m
0
Unconformity between the Sardhai Formation and overlying Palaeocene strata. This surface represents significant erosion and upper part of the Nilawahan Group is missing in the eastern Salt Range.
west
east
Sanwans
Sarin
Shallow marine facies
Watli
Saloi
Amb
Shallow marine facies
Nilawahan
Matan
Karuli
Watli
Saloi
SB II
SB II
Palaeocene sediments
Unconformity
Sardhai Formation
Amb Formation
Unconformity
Sardhai Formation
Transgressive surface
Warchha Sandstone
Unconformity
Marginal marine facies
Warchha Sandstone
Dandot Formation
Unconformity
SB I
Dandot Formation
Shallow marine facies
Meandering fluvial facies
50 m
0
10 km
Burrows
Burrows
Burrows on the top surface of the Dandot Formation in mudstone / shale facies. These are widespread over the regional unconformity SB I at the base of the Warchha Sandstone.
Brachiopods
Abundant of brachiopods on the top surface of the Dandot Formation in mudstone / shale facies. These features are widespread over the regional unconformity SB I.

Figure 5

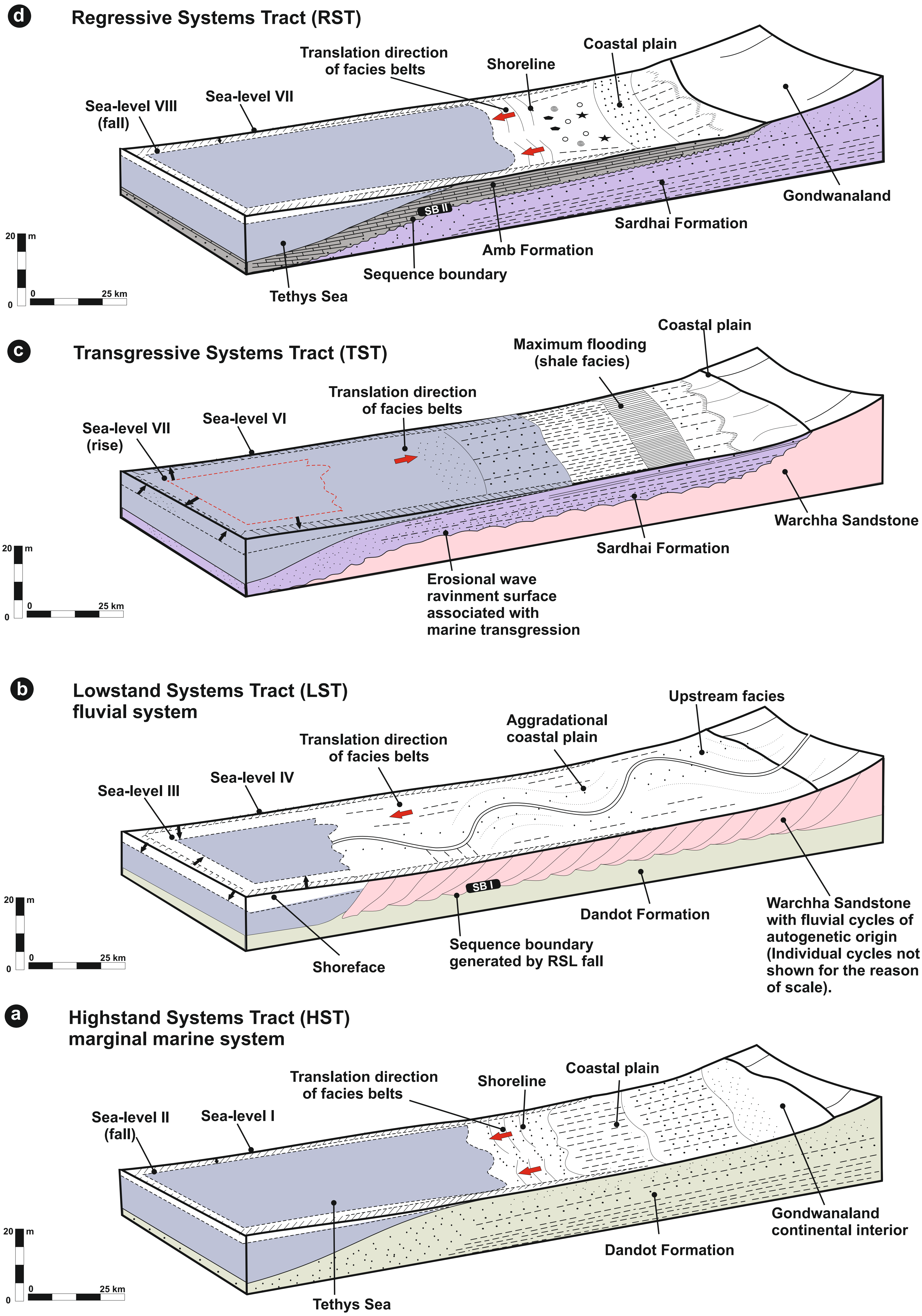

d
Regressive Systems Tract (RST)
Translation direction of facies belts
Shoreline
Coastal plain
Sea-level VIII (fall)
Sea-level VII
SB II
Gondwanaland
Sardhai Formation
Amb Formation
Sequence boundary
Tethys Sea
20 m
0
0
25 km
c
Transgressive Systems Tract (TST)
Coastal plain
Maximum flooding (shale facies)
Translation direction of facies belts
Sea-level VII (rise)
Sea-level VI
Warchha Sandstone
Sardhai Formation
Erosional wave ravinment surface associated with marine transgression
b
Lowstand Systems Tract (LST) fluvial system
Upstream facies
Aggradational coastal plain
Translation direction of facies belts
Sea-level IV
Sea-level III
SB I
Dandot Formation
Warchha Sandstone with fluvial cycles of autogenetic origin (Individual cycles not shown for the reason of scale).
Sequence boundary generated by RSL fall
Shoreface
a
Highstand Systems Tract (HST) marginal marine system
Translation direction of facies belts
Shoreline
Coastal plain
Sea-level II (fall)
Sea-level I
Gondwanaland continental interior
Dandot Formation
Tethys Sea

Figure 6

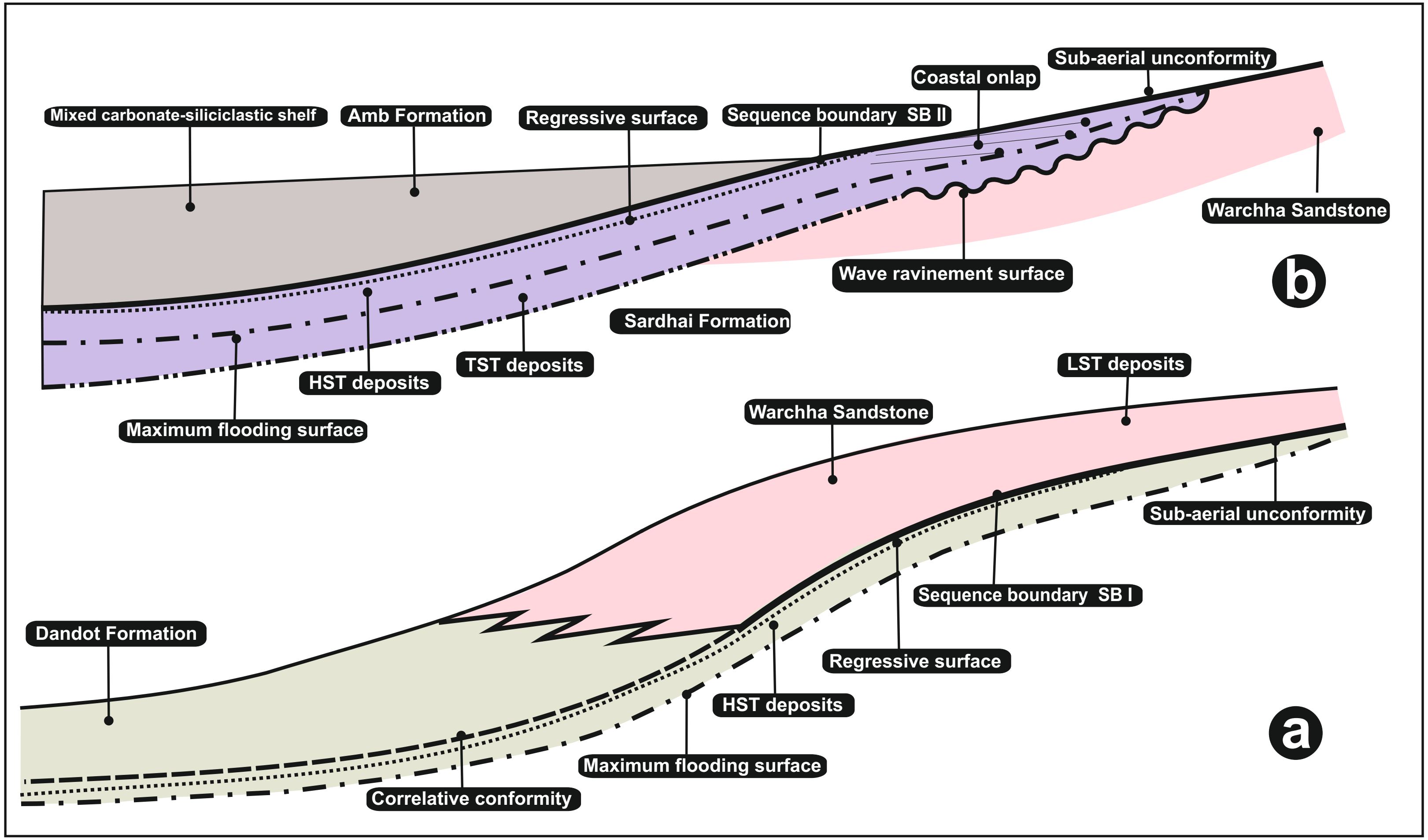

Sub-aerial unconformity
Coastal onlap
Mixed carbonate-siliciclastic shelf
Amb Formation
Regressive surface
Sequence boundary SB II
Warchha Sandstone
Wave ravinement surface
b
Sardhai Formation
TST deposits
HST deposits
Maximum flooding surface
LST deposits
Warchha Sandstone
Sub-aerial unconformity
Sequence boundary SB I
Dandot Formation
Regressive surface
HST deposits
a
Maximum flooding surface
Correlative conformity

Figure 7

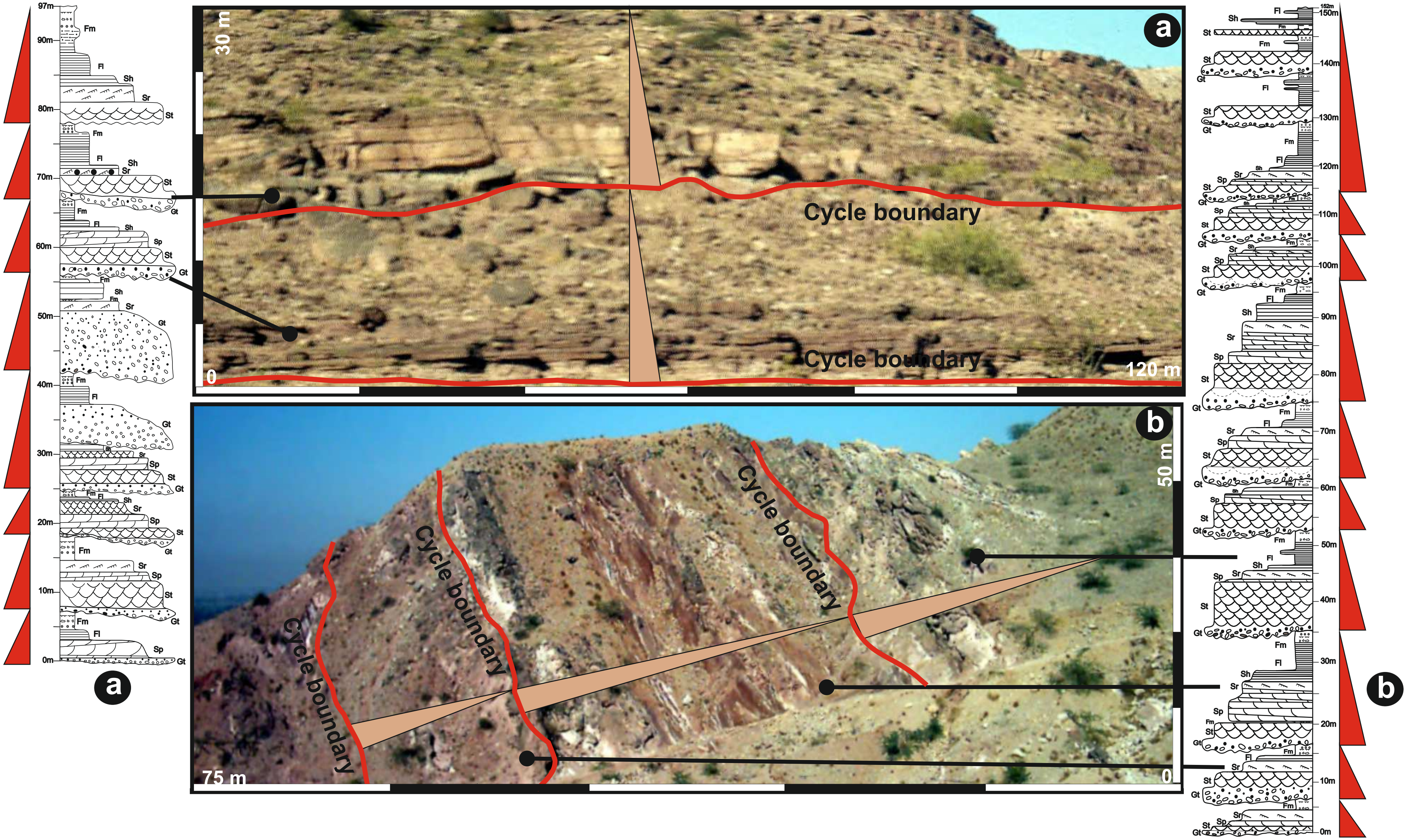
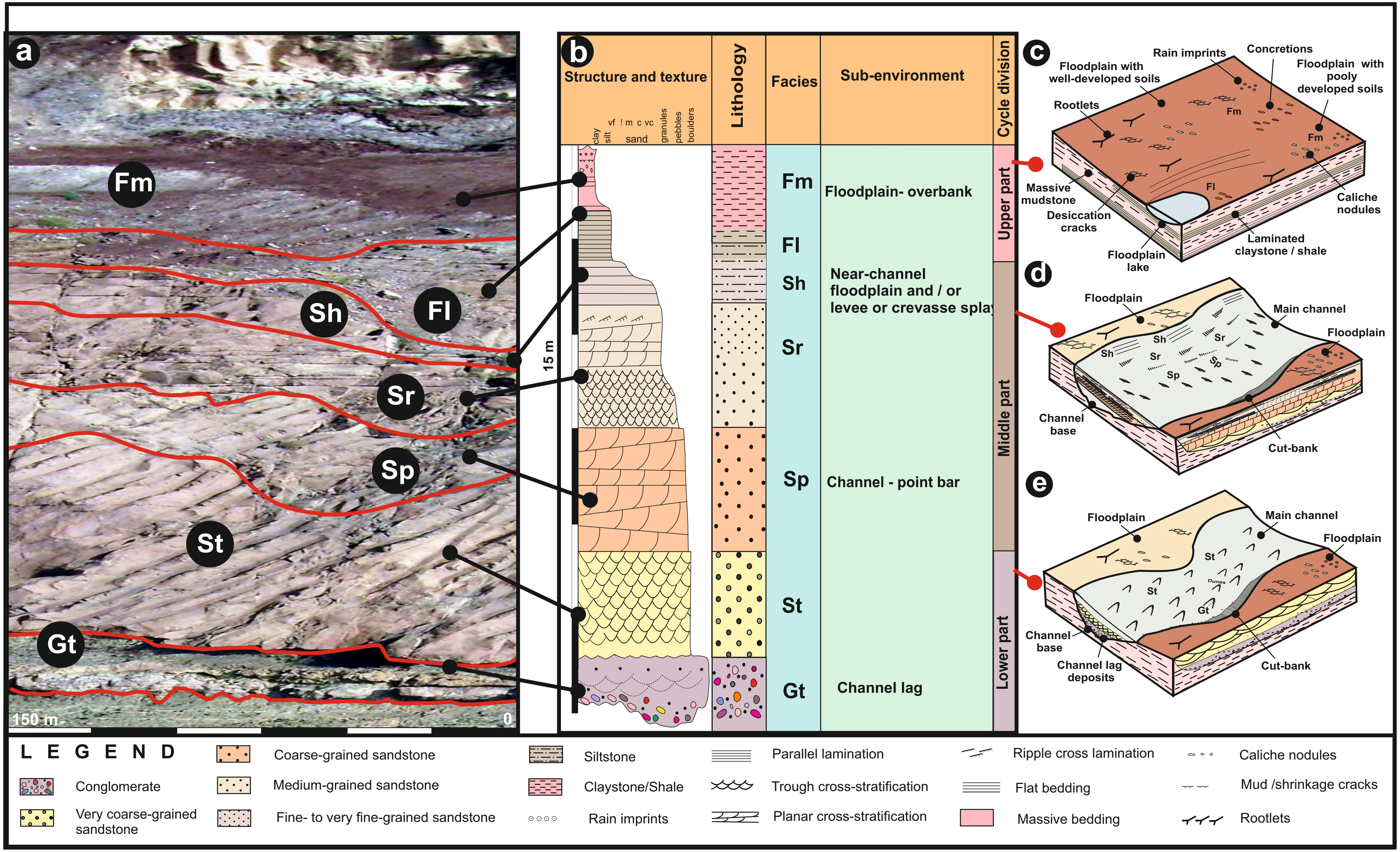
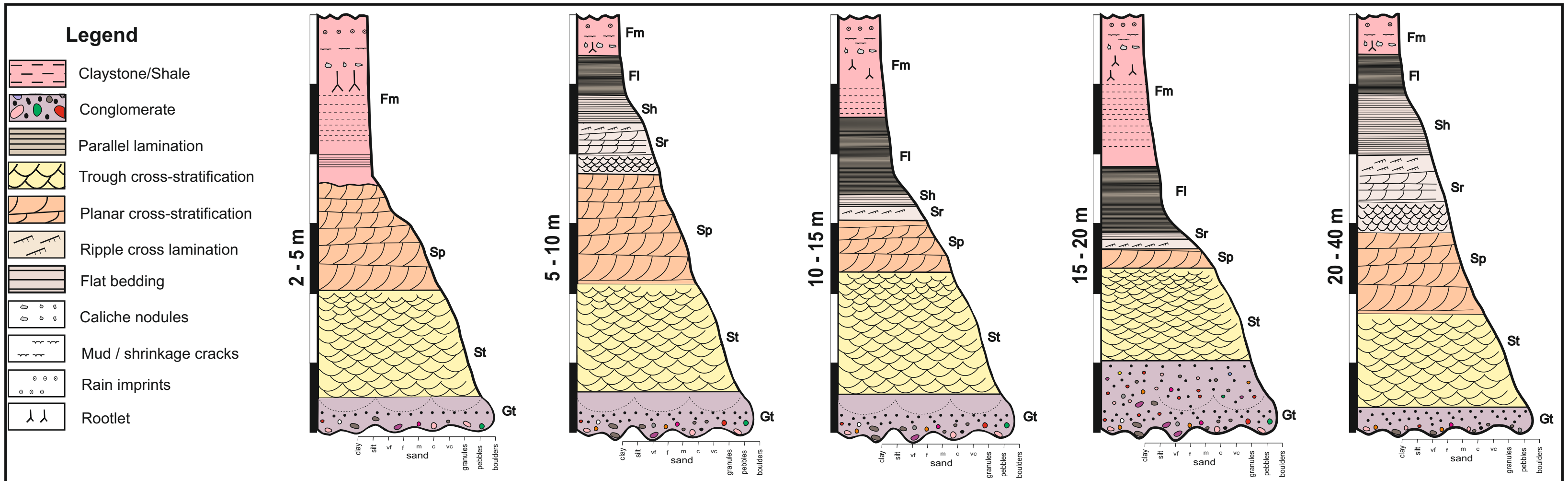

a
b
30 m
0
120 m
Cycle boundary
Cycle boundary
50 m
75 m
0
Cycle boundary
Cycle boundary
Cycle boundary

Figure 8



a
Fm
Fl
Sh
Sr
Sp
St
Gt
150 m
0
b
Structure and texture
clay silt vf f m c vc sand granules pebbles boulders
Lithology
Facies
Sub-environment
Cycle division
15 m
Fm
Floodplain- overbank
Fl
Sh
Near-channel floodplain and / or levee or crevasse splay
Sr
Sp
Channel - point bar
St
Gt
Channel lag
Upper part
Middle part
Lower part
c
Rain imprints
Concretions
Floodplain with well-developed soils
Floodplain with pooly developed soils
Rootlets
Massive mudstone
Desiccation cracks
Floodplain lake
Laminated claystone / shale
Caliche nodules
d
Floodplain
Main channel
Channel base
Cut-bank
e
Channel base
Channel lag deposits
LEGEND
Conglomerate
Very coarse-grained sandstone
Coarse-grained sandstone
Medium-grained sandstone
Fine- to very fine-grained sandstone
Siltstone
Claystone/Shale
Rain imprints
Parallel lamination
Trough cross-stratification
Planar cross-stratification
Ripple cross lamination
Flat bedding
Massive bedding
Caliche nodules
Mud /shrinkage cracks
Rootlets

Figure 4



Cycle type	Cycle type - 1	Cycle type - 2	Cycle type - 3	Cycle type - 4	Cycle type - 5
Thickness	2 - 5 m	5 - 10 m	10 - 15 m	15 - 20 m	> 20 m
% Volume of entire succession	2 %	40 %	26 %	20 %	12 %
Occurrence	Saloi, Nilawahan, Sarin, Sanwans	Watli, Karuli, Amb, Matan, Nilawahan, Sarin, Sanwans	Saloi, Watli, Karuli, Matan, Nilawahan, Sarin	Karuli, Matan, Amb, Nilawahan, Sarin, Sanwans	Karuli, Nilawahan, Amb, Sarin, Sanwnas
Major lithofacies	St, Sp, Fm	St, Sp, Sr	Gt, St, Sp, Fl, Fm	Gt, St , Fl, Fm	St, Sp, Sr, Fl, Fm
Minor lithofacies	Gt	Gt, Sh, Fl ,Fm	Sr, Sh	Sp, Sr, Sh	Gt, Sh
Architectural elements	CS, CH_b, FF	SB, DLA, CH_a	CH_a, CH_b, SB, DLA, FF, LS	CH_b, GB, SB, FF, LV	Ch_b , SB, DLA, FF, LS
Fluvial style	Sand-bed meandering	Sand-bed meandering	Sand-bed meandering	Conglomerate-sand-mud-beds	Sand-bed meandering

Figure 10

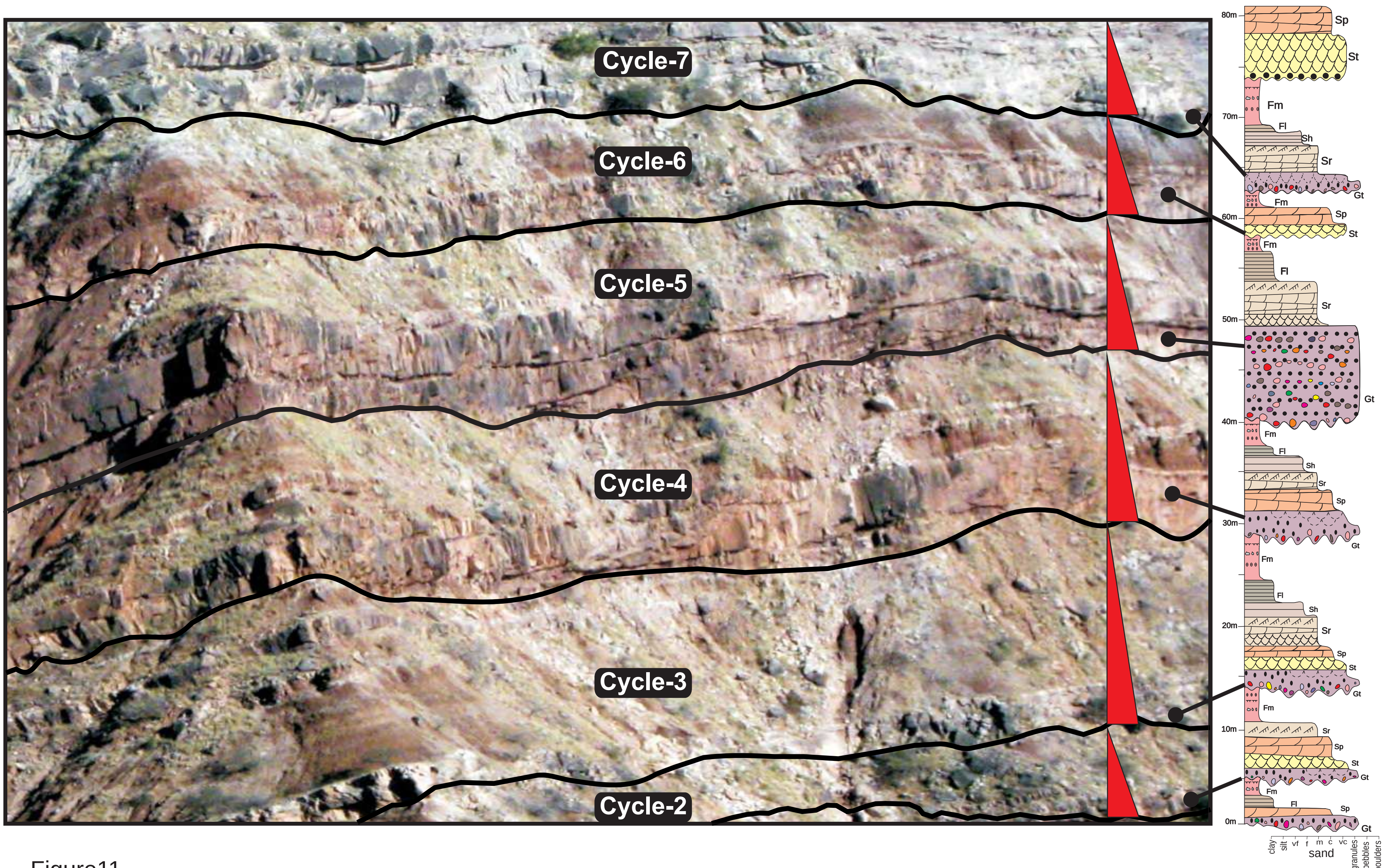
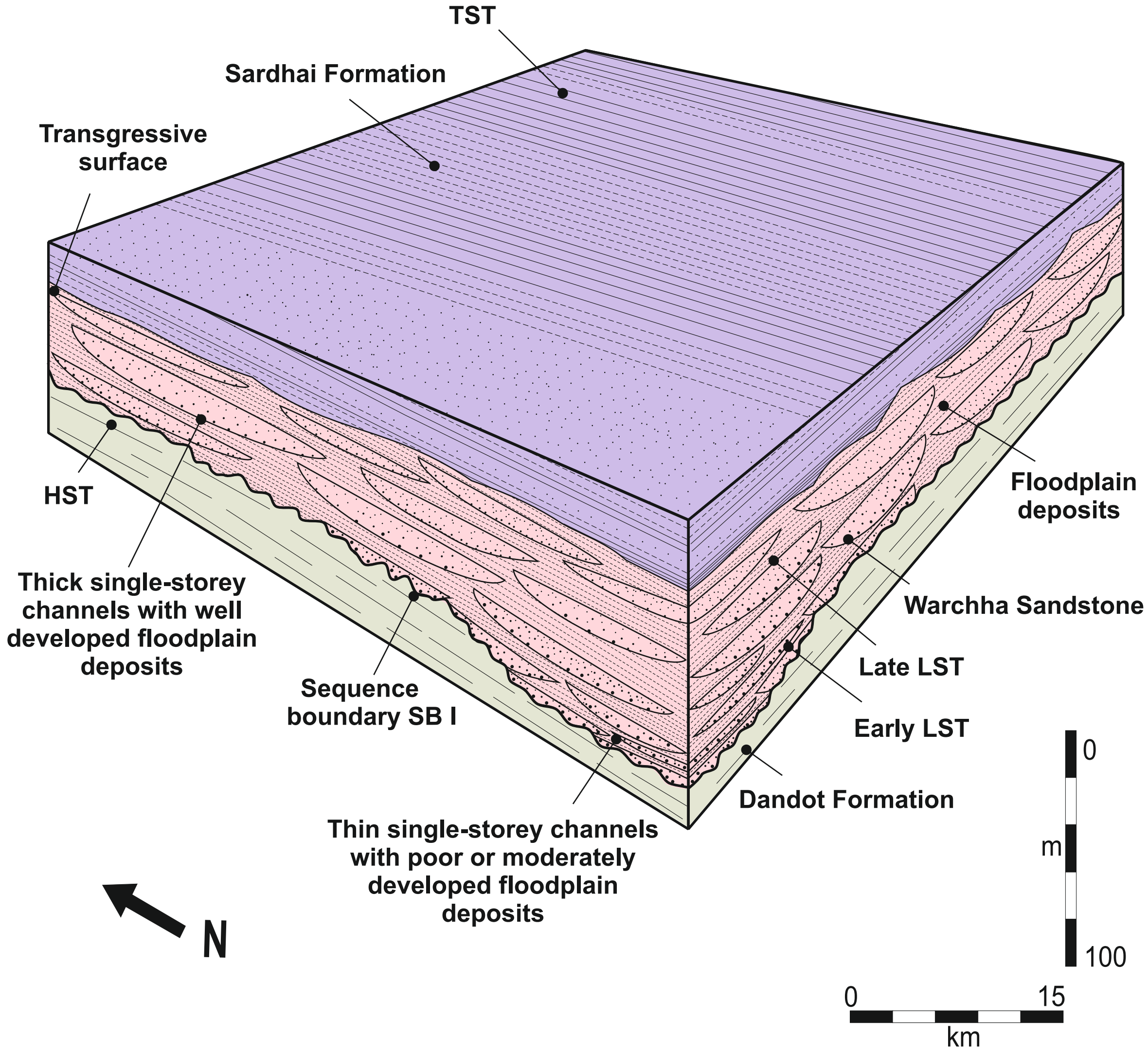

Cycle-7
Cycle-6
Cycle-5
Cycle-4
Cycle-3
Cycle-2
80m
70m
60m
50m
40m
30m
20m
10m
0m
Sp
St
Fm
Fl
Sh
Sr
Gt
clay
silt
vf
f
m
c
vc
sand
granules
pebbles
boulders

Figure11



TST
Sardhai Formation
Transgressive surface
HST
Thick single-storey channels with well developed floodplain deposits
Sequence boundary SB I
Thin single-storey channels with poor or moderately developed floodplain deposits
Floodplain deposits
Warchha Sandstone
Late LST
Early LST
Dandot Formation
N
0
m
100
0
15
km

Figure 12