Chapter – 3

Evolution of the Ghaggar river system in NW India and its archaeological connection

3.1 Introduction

The Ghaggar River of north-west India is a mostly defunct small ephemeral river system, originating in the Siwalik Himalayas near the Indian city of Chandigarh (Fig. 3.1). At present it gets flooded occasionally during the high monsoonal rains and mainly carries suspended sediments, reworked from older deposits of the interfluve (Singh et al., 2016a). Soon after crossing the state of Rajasthan, the dry river-bed (known as Hakra at downstream) vanishes in the Cholistan desert of Pakistan. It is one of the numerous foothill-fed rivers which flow in the interfluves between the mighty glacier-fed rivers of the vast Indo-Gangetic-Brahmaputra plains (Sinha and Friend, 1994). In spite of being small and mostly dry, the river valley has attracted a lot of attention because of its unique geological past and archaeological connection. More than a century of scholarly works have confirmed the existence of a network of buried paleo-channels along the Ghaggar-Hakra valley (Valdiya, 2017 and the references therein) indicating a strong fluvial past unlike the present scenario. These ancient water courses remain the centre of debate as they are speculated to be the relicts of an ancient glacier fed river and often been correlated with the mythical lost river Saraswati, first described in the three millennia old scriptures of Rig-Veda (Ghose et al., 1979; Kochar, 2000; Oldham, 1893; Pal et al., 1980; Radhakrishan and Merh, 1999; Valdiya, 2013). It is considered by many that this dramatic transformation of the river has occurred very recently, during the mid-Holocene, due to regional reorganisations of major Himalayan Rivers induced by neo-tectonics (Valdiya, 2013 and the references therein).

With the discovery of the Bronze Age Harappan/Indus Valley tradition the problem became more intriguing. Years of archaeological excavations indicated that, apart from the Indus River valley, a great majority of the Harappan settlements were concentrated along the dry beds of Ghaggar-Hakra river system (Misra, 2001; Stein, 1942). Considering the fact that availability of water is one of the key requirements for the development of civilizations, it can be considered that the ephemeral Ghaggar-Hakra stream must have had a strong fluvial history during the Indus Valley tradition. One of the two main hypotheses suggests that the drying up of Ghaggar-Hakra River owing to drainage reorganisation, could be a triggering factor for the sudden and puzzling decline of the Harappans four millennia ago (Kenoyer, 2008; Misra, 1984; Mughal, 1997; Possehl, 2002; Wright et al., 2008). But controversies do not cease to surround this lost river and its pre-historic civilization. Non-availability of relevant geochemical and geochronological data makes it difficult to constrain the antiquity

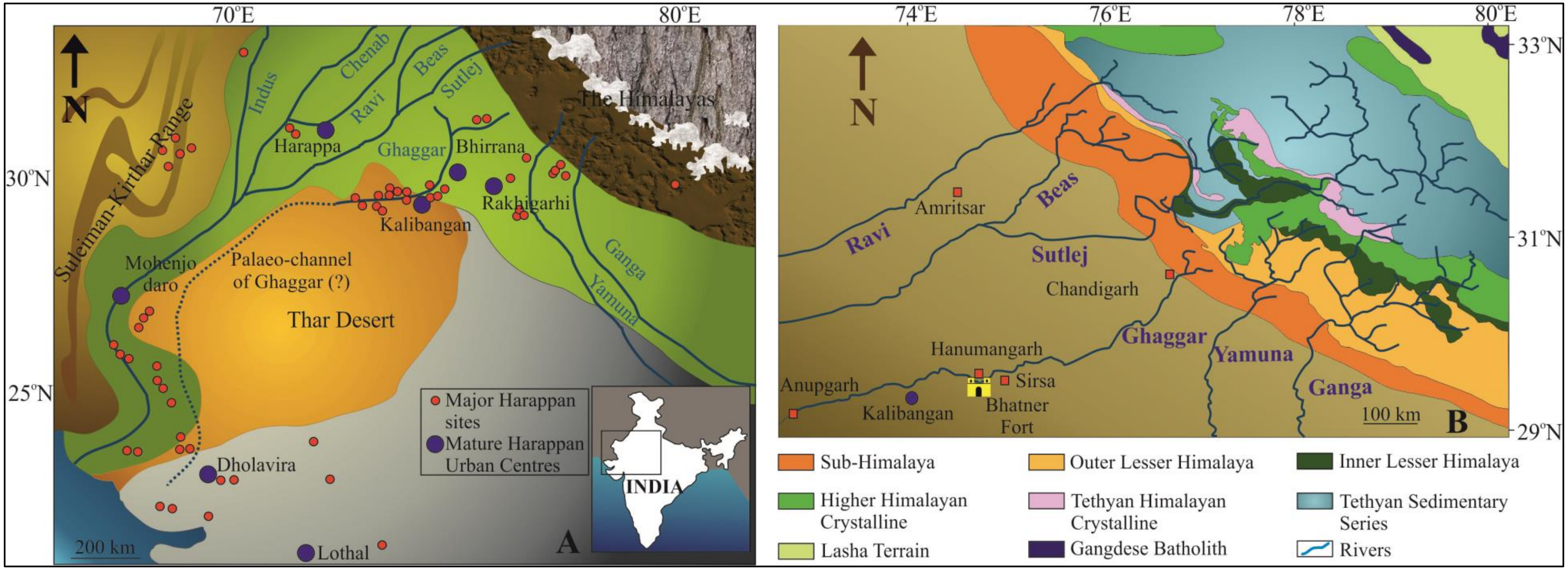

Figure 3.1: (A) Regional geomorphological map of north-western India showing the major landscapes. The putative course of paleo-Ghaggar is shown as dotted line and the pre-historic Harappan settlements are shown. Map is modified after Sarkar et al., 2016.
(B) Different litho-tectonic units of the Himalayas from where different western Indian rivers have originated. Also shown are the positions of Kalibangan and Bhatner Fort on the bank of the Ghaggar. Map is modified after Singh et al., (2016a).

of the fluvial past.

The other competing hypothesis argues that the geomorphic changes in the Ghaggar river valley had occurred much earlier during the Pleistocene (prior 10 ka) and the channels were abandoned at about 4-5ka (Clift et al., 2012). These studies also suggest that the river had already become foothill-fed monsoonal river and lost its glacial sources by the time Harappans settled on its banks (Clift et al., 2012; Giosan et al., 2012; Tripathi et al., 2004). Finally, the declining monsoon during mid-Holocene was detrimental for both the river and the civilization. This hypothesis however, cannot explain the younger fluvial activities (2.9-0.7 ka) which have been reported both from upper and lower Ghaggar-Hakra floodplains (Giosan et al., 2012; Saini and Mujtaba, 2012). Because a meandering river system frequently changes its course and creates numerous abandoned channels and therefore, depositional ages of sand from only a few sections may not reveal the true temporal extent of the river (Valdiya, 2013), and therefore, the issue of the paleo-fluvial condition of Ghaggar river and its archaeological connection remains far from settled.

For the present study, we sampled sub-surface sand bodies present beneath the modern Ghaggar-alluvium between Hanumangarh and Anupgarh along a stretch of ~120 km (Fig. 3.1). Using OSL and radiocarbon dating methods we constrained the ages of deposition of these sand bodies. We also studied trace element and Sr-Nd isotopic characteristics to constrain their provenance. Further, Ar-Ar ages of samples of detrital muscovite grains from these sand bodies were determined and used as source indicators, because white micas of different litho-tectonic units of Himalaya represent distinct chronological events. In addition to sediments, we also studied isotopic composition of archaeological artefacts to shed light on the living environments of the pre-historic people in the region. Ancient potters generally used materials available in their near geographical vicinity to create potteries (Krishnan, 2002). In case of the Indus valley tradition, source material for the potteries would have been the abundant flood-plain sediments deposited by the rivers on whose bank the Indus valley cities were built. Therefore, one would expect that the geochemical composition of potteries retrieved from the Ghaggar valley would provide insight into the sediment composition of the river during that period.

3.2 Background and earlier work

3.2.1 Palaeo-hydrological condition of the Ghaggar

The search for a lost river in the Indian desert goes back to at least two centuries, when British geographers were surveying their newly occupied colony. C. F. Oldham first traced the dry beds of the Ghaggar-Hakra and its tributaries. It was he who first proposed that the Sutlej used to flow through the Ghaggar channel during historic times (Oldham, 1893). It was hypothesised that the Ghaggar-Hakra used to be a parallel river system to the Indus, flowing separately all the way down to the Arabian Sea. The following centuries saw a plethora of scientific investigations in the Ghaggar valley that led to the discovery of chalcolithic Harappan civilization along the dry beds of this river. Based on geomorphological and archaeological evidence earlier workers had proposed a perennial glacieal-fed, through the Sutlej and Yamuna, Ghaggar river system (mythological Saraswati?) which ultimately got defunct due to river piracy. With the advance of satellite-radar imagery the search for the dry channels of the lost river became more intense during the last few decades. Ghose et al., (1979) and Gupta et al., (2011) based on such imageries proposed the existence of several buried palaeo-channels along the Ghaggar-Hakra flood-plains extending upto the Graet Rann of Kachchh. Several scholars have also attempted to reconstruct the buried paleo channels of the Upper Ghaggar alluvium based on geophysical and field surveys (Saini et al., 2009; Sinha et al., 2013) and they found evidence for existence of a multi-channelled mega-fluvial system during the Pleistocene and a smaller fluvial system during the mid-Holocene near Sirsa, Haryana. However, based on radar topographic studies and the existing knowledge on the dynamics of the Harappan settlements, Giosan et al., (2012) first proposed that the Ghaggar-Hakra river never had any glacier source during the Holocene and by the time early Harappans settled there, it was only a foothill fed monsoonal river. Studies based on U-Pb dating of detrital zircons in the middle reaches of the Hakra suggested that the Sutlej, Yamuna and Beas rivers were once tributaries of the Ghaggar-Hakra river making it a perennial one (Clift et al., 2012). However, these studies also suggested that the perennial glacier fed tributaries of the Ghaggar reorganised themselves to their present position abandoning the Ghaggar channel prior to 10 ka, and during the mid-Holocene (~4-5 ka) the Ghaggar River ceased to flow, eventually getting buried by progressive Thar Desert dunes by 1.5 ka. On the other hand, geochronological studies in the upper reaches of the Ghaggar suggested that the river was active until 2.9 ka (Saini et al., 2009; Saini and Mujtaba, 2010). In the absence of geochemical data these studies couldn't conclude on the provenance of these younger sediments. Other workers have also reported fluvial activities in the lower Ghaggar-Hakra floodplains (kown as Nara River) until about 700 years ago conforming to the earlier idea of C. F. Oldham (Giosan et al., 2012; Ngangom et al., 2012). However, these later studies described these younger fluvial activities to have been driven by increased Monsoon. Recent work of Singh et al., (2016a), proposed that the sediments of the Ghaggar-Hakra river were sourced from the glaciated higher and lesser Himalayas with the higher-Himalayan inputs in younger sediments. Thus, at present the fluvial history of the Ghaggar-Hakra remains inconclusive.

3.2.2 The Harappan settlements along the Ghaggar

The Indus Valley/Harappan cultural tradition developed along the North-Western Indian sub-continent during the mid-Holocene (Fig. 3.1). People of this culture settled over an area larger than the contemporaneous Mesopotamian and Egyptian civilizations. The duration of existence of this culture, based on radiometric dates from Harappa and nearby localities, have been divided into four phases/periods (Kenoyer, 1998; Wright et al., 2008; Dikshit, 2013). Around 5.7 ka agro-pastoral Ravi culture flourished, followed by the transitional Kot Diji Phase (~4.8 ka). The sophisticated urban civilization of the Mature Harappan phase started around 4.6 ka and disintegrated at ~3.9 ka, followed by a de-urbanisation era of Late Harappan phase that lasted until ~3.3 ka. Possehl, (2002) on the other hand, had proposed a much older age for the Harappan culture based on spatio-temporal distribution of archaeological remains that spread across the Indian sub-continent. Earlier, Mughal, (1997) had reported such older pre-Harappan settlements along the Hakra river of Cholistan desert and named it as the Hakra Phase. Later, numerous other sites of the Hakra phase were discovered along the dry beds of the Ghaggar (the upstream continuation of the Hakra) including Kalibangan (the present study site), Farmana, Bhirrana and Rakhigarhi. Based on available chronological information the antiquity of the Hakra Phase can be pushed back to ~ 9.5 ka (Sarkar et al. 2016 and the references therein). It is also believed that the Early mature Hrappan phase has started a few millennia earlier (~6.5 ka) in the Ghaggar-Hakra valley compared to that in the Indus valley (Possehl, 2002). Indeed in a study on spatio-temporal evolution of the Hrappan settlements Gangal et al., (2010) has demonstrated that 7 ka onwards settlements had started flourishing in three distinct geographical locations

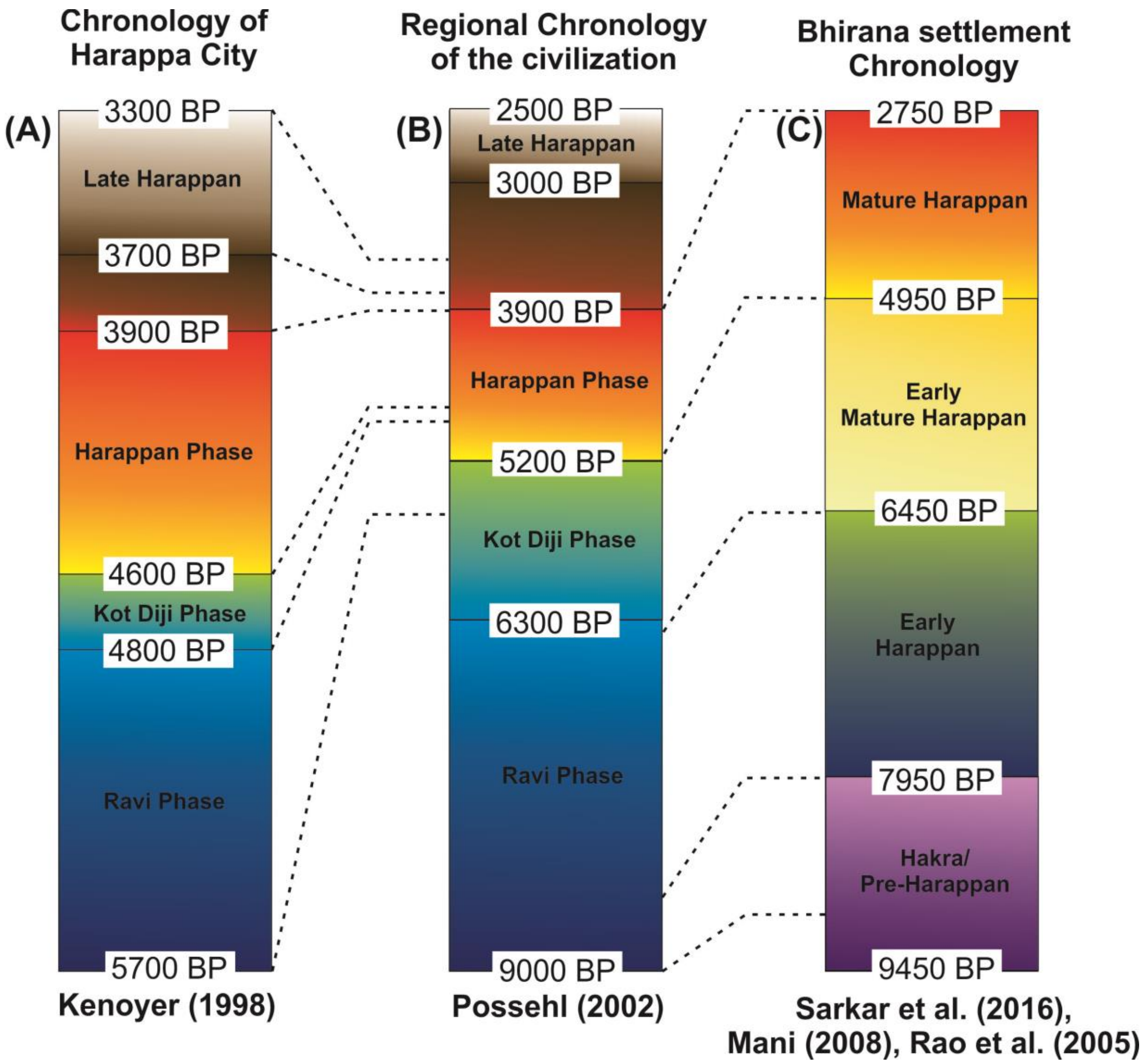

Figure 3.2: A comparison of chronologies of various phases in the Harappan cultural centres.
(A) Hrappan cultural chronology based on the cultural layers and dating from the acropolis of Harappa (Kenoyer, 1998).
(B) Hrappan cultural chronology inclusive of all regional settlements (Possehl, 2002).
(C) Hrappan cultural chronology based on the cultural layers and dating from the acropolis of Bhirana (Mani, 2008; Rao et al., 2005; Sarkar et al., 2016).

separated from each other in the Baluchistan region, the Ghaggar plain and the Gujarat region. Subsequent to this period saw a steady increase in the density of settlement, in these three localities. Surprisingly, the first settlements along the Indus river system started developing only during 5.2 ka, prompting the experts to suggest that the urban settlements of lower Indus-valley were the extensions of the Baluchisthan and Ghaggar settlements (Gangal et al., 2010). Finally, the civilization reached its zenith during 4.5 ka. From 3.9 ka onwards the de-urbanisation started and the density of settlement started decreasing in the main centres. It is observed that the Harappan settlements gradually shifted north-eastward to the upper Haryana plains during this period (Gangal et al., 2010; Giosan et al., 2012). A comparison of chronologies of various phases in the Harappan cultural centers is shown in figure 3.2.

During the course of the present study, we have visited Kalibangan which is one of the important Harappan cities situated on the southern bank of the river Ghaggar (Fig. 3.1B) and has a continuous history since the Hakra Phase, up to the Late Harappan (Thapar, 1975). The oldest dated sequence of Kalibangan is 7.6 ka (Sarkar et al., 2016). The settlement has two fortified sections, the Citadel (KLB-I) and the lower city (KLB-II) located to the east of the citadel (Fig. 3.3A). The Mature Harappan settlements are found over the ruins of the Hakra Phase in KLB-I mound, whereas, the mound of KLB-II is represented by only the former. Figure 3.3B shows the mound of KLB-II as photographed during our field work in 2014. The remains of brick walls and terracotta pipelines can be seen in Fig. 3.3C. To understand the source of the clay used in making the potteries and bricks by the Mature Harappans we restricted our sampling to the KLB-II mound. Photographs of some of these samples are shown in Fig. 3.3D.

The Ghaggar-Hakra valley was later re-occupied by the Painted Grey Ware sites during 3.0-2.6 ka. Also during the Medieval period fortifications were made along these floodplains (Mughal, 1997). The Bhatner Fort (12^{th} century AD) of Hanumangarh is one of them (Fig. 3.1B). For the present study we also sampled bricks from this fort.

Figure 3.3: (A) The settlement map of the Harappan acropolis of Kalibangan. Map is modified after Thapar (1975).
(B) The KLB-II mound of Kalibangan as photographed during field work in 2014.
(C) The remains of brick walls can be seen through the gaps in the mound. In the inset image terracotta drainage pipes can be seen.
(D) Samples of Mature Harappan potteries collected from the KLB-II mound.
Figures are modified from Chatterjee and Ray, (2017a).

3.3 Results and Discussion

3.3.1 Facies architecture of the Ghaggar alluvium

At present the course of the Ghaggar River is very difficult to trace downstream because of heavy irrigation and shallow channel chocked with heavy suspended load. The flood plain topography is monotonously flat land with aeolian dunes. The dry bed of the river can only be discretely recognised by ridges of discontinuous sand dunes bordering the floodplain. Interestingly, the subsurface sedimentary facies is quite different from what appears on the surface of the dry river bed. Figure 3.4 presents a comparison of the subsurface stratigraphy from different localities along the flood plain, constructed using field data from the present and earlier works. Samples for this study were collected mainly from shallow dug pits and wells along the 250km stretch of the Ghaggar alluvium (Fig.3.4).

Sampling locations are also shown in the figure. Following inferences can be drawn from the field observations in the Ghaggar alluvium.

- Layer of brown silty-clay occurs as the topmost alluvium cover. Its thickness varies from 10 – 20 m at different locations along the alluvium. The brown silty-clay directly overlies either a yellowish-brown fine fluvial sand deposit or a grey micaceous sand deposit.
- A detailed clay mineralogical study has been conducted by Alizai et al., (2012) which characterises the clay depositions of the Ghaggar alluvium, further downstream at Fort Abbas, Marot and Tilwala in Pakistan (Fig. 3.5). Considering that no tributaries join the Ghaggar downstream beyond Shatrana, it can be inferred that the clay mineralogical composition should have remained similar all along the floodplain. As suggested by Alizai et al., (2012) the most abundant clay mineral in the Ghaggar alluvium is smectite (51-59%), followed by illite (30-37%). The minor constituents are chlorite (5-7 %) and kaolinite (2-5%). It can be observed in figure 3.5 that the abundances of these four clay minerals had remained spatially and temporally invariant during the Holocene. The presence of illite as a major clay indicates that the sediments were sourced from the Himalaya where physical weathering dominates. On the other hand dominance of smectite, which is primarily a product of chemical weathering, is not in accordance with a Himalayan source where chemical weathering is very less. Such a scenario can be explained by two-cycle weathering (Singh et al., 2005), one at the source and the other within the floodplains with smectite being generated in the latter as a result of chemical weathering.
- During the course of present work, we encountered layers of sub-surface grey micaceous sand body all along the Ghaggar flood-plain. Raikes, (1968) first reported the occurrence of a thick body of coarse micaceous grey sand, resembling to the sediment carried by modern glacier-fed rivers like Ganga or Yamuna, buried below layers of silty-clay floodplain deposits of the Ghaggar near Kalibangan. Similar facies has also been reported from several other locations of the floodplain (Saini et al., 2009, Saini and Mujtaba, 2010, Singh et al., 2016a). The coarse and immature character of these sand layers probably represents their bed load and bears the testimony of being part of an extinct active fluvial system. The contact between the grey sand and overlying brown silty-mud is very sharp. In places root-casts can be observed along the contact. All observations suggest a depositional hiatus after the deposition of the grey sand. Quartz is the most dominant mineral in the grey sandy facies, followed by feldspar and muscovite. Accessory phases include biotite,

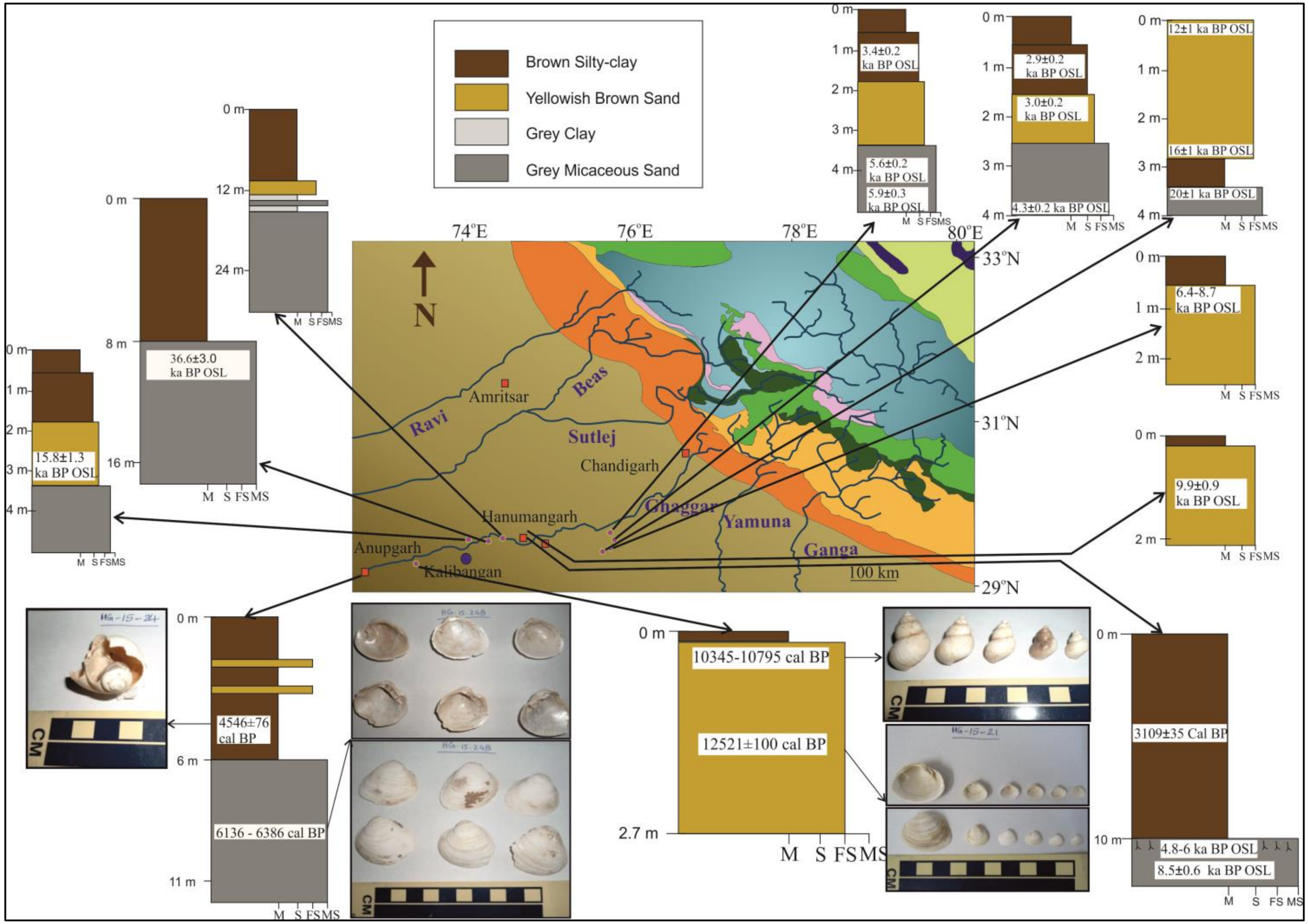

Figure 3.4: A comparison of the subsurface stratigraphy from different localities along the Ghaggar floodplain, constructed using field data from the present and earlier works. The sampling locations associated with each litho-section are marked with arrows in the map. The chronologies of different sedimentary horizons are mentioned alongside the stratigraphic columns. Also images of different bivalve and gastropod shells used for AMS C-14 dating are shown and the horizons from where the shells were collected are marked.

amphibole, kyanite, sillimanite, garnet and pyroxene (Saini et al., 2009). The clay content of the grey micaceous sand is almost negligible implying that these were high energy depositions.A typical facies association of grey micaceous sand and overlying floodplain deposits in trench sections across the Ghaggar alluvium is shown in figure 3.6A. Figure 3.6B represents the typical appearance of the Grey micaceous sand and the Brown clay observed in the Ghaggar alluvium.

- In three of the sections, the grey micaceous sand is found to be overlain /intercalated by a layer of grey clay. The thickness of this grey clay is much less than that of the brown silty-clay deposits.
- At other places these grey fluvial sand horizons are overlain by yellowish-brown fine fluvial sands. These fine fluvial sands appear to have been deposited by a weaker phase of fluvial activity and sediment reworking from local dunes and generally occur in fining upward sequences, overlain by silt and followed by clay horizons. Mineralogically, these sand deposits are predominantly composed of quartz and feldspar. Unlike the grey sandy facies, mica is less abundant and occurs as fine round-edged grains (recycled).

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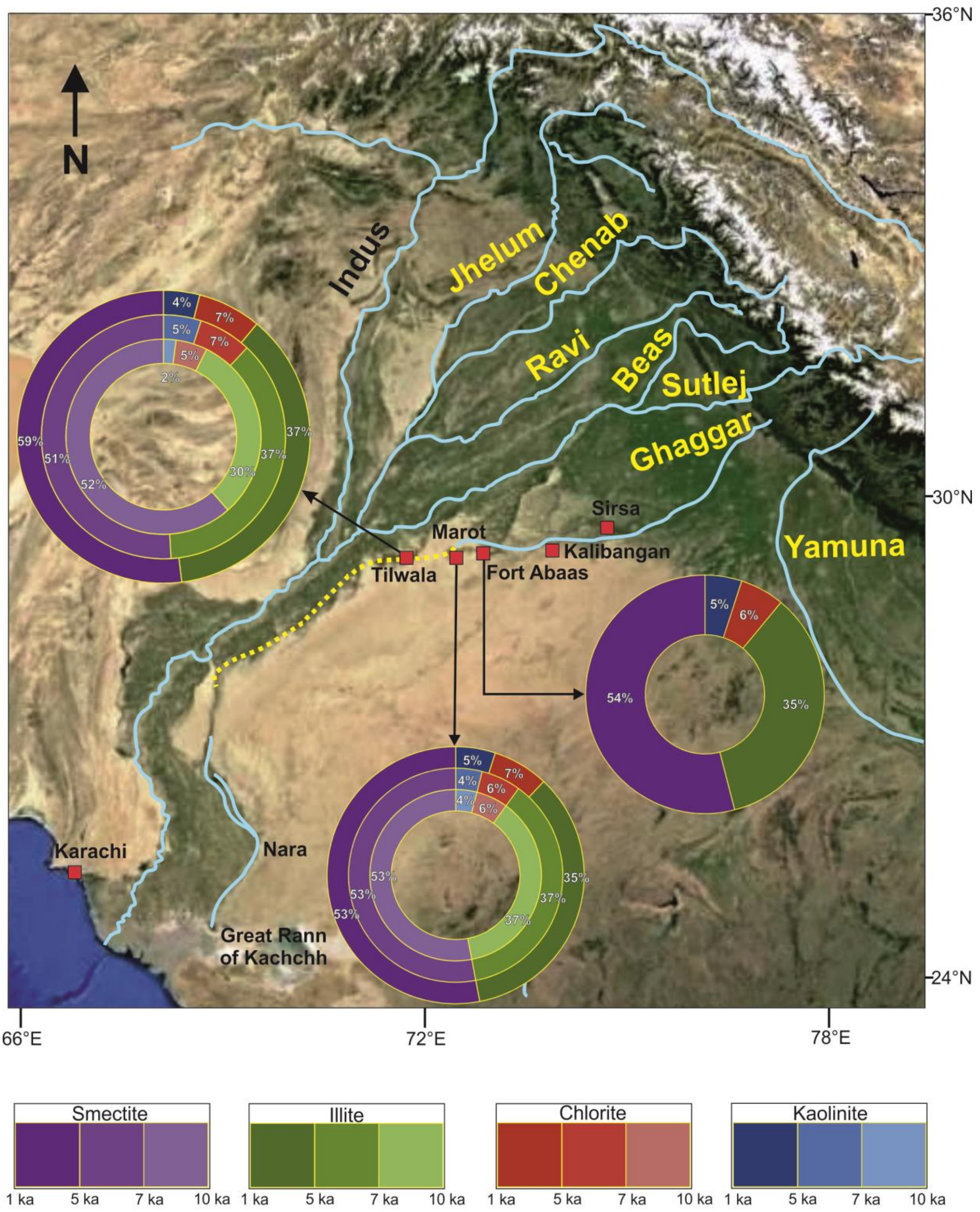

Figure 3.5: Pie chart showing the compositional variations of clay minerals across the Ghaggar alluvium during the Holocene. Figures is modified from Chatterjee and Ray, (2017a).

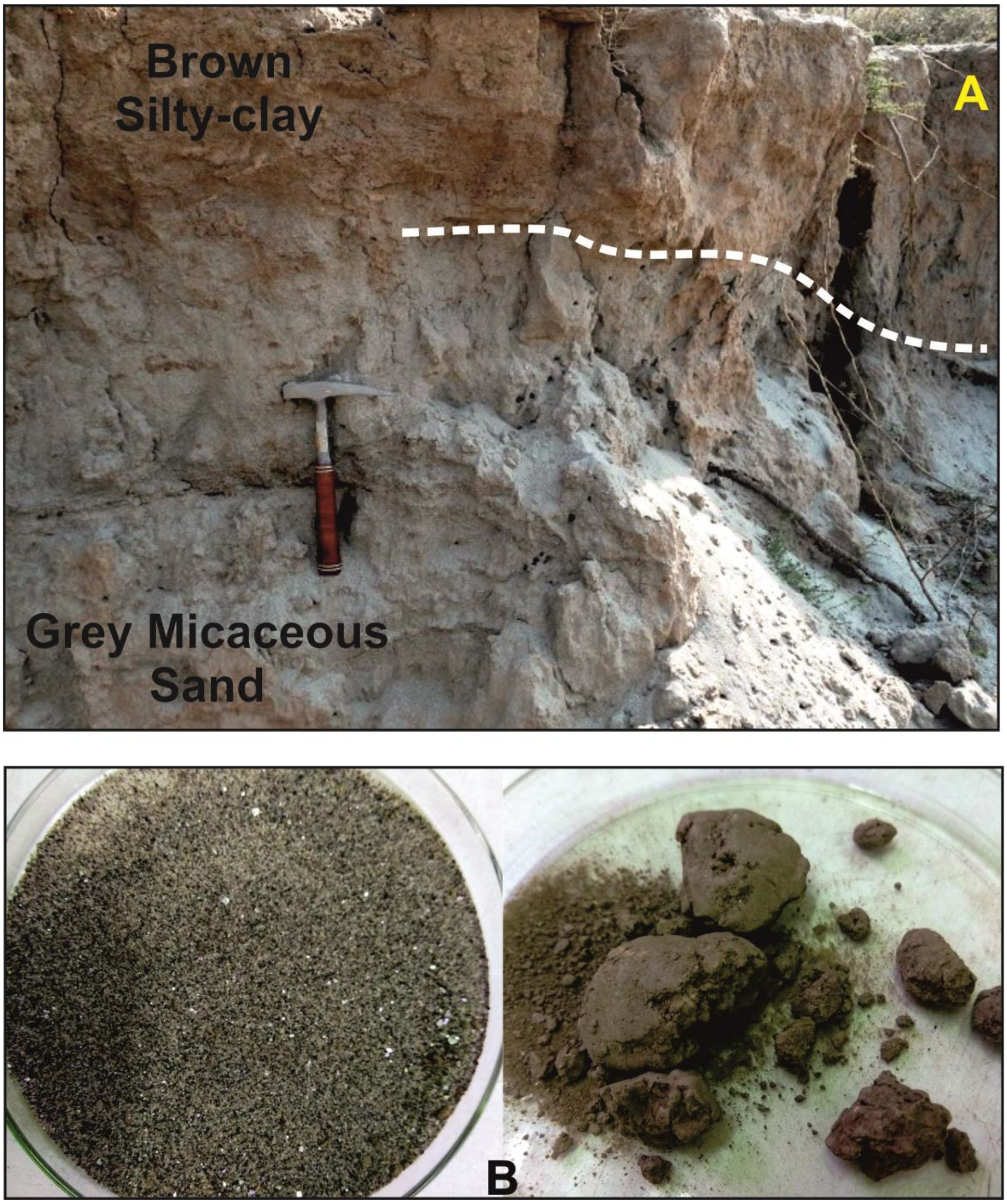

Figure 3.6: (A) A typical association of brown silty-clay and underlying grey micaceous sand in the Ghaggar alluvium. The sharp contact between the two facieses can be observed in this trench section.
(B) Appearance of grey micaceous sand (left hand side) and brown silty-clay (right hand side) in mesoscopic scale. The coarse muscovite grains can be observed within the grey sand.

3.3.2 Antiquity of the Ghaggar alluvium

Between Hanumangarh and Anupgarh a number of fluvial deposits have been dated during this work. Depositional ages of various samples analysed during the present work generally vary from the late Pleistocene to mid-Holocene. The details of OSL ages and C-14 ages are presented in Table 3.1. The age constrains and sedimentation history of the Ghaggar alluvium is discussed below.

3.3.2.1 Brown floodplain silt/mud :

- The AMS C-14 dating of the gastropod shells from the brown clay horizon near Hanumangarh yielded an age of 3109 ± 35 cal BP, which can be considered as the age of deposition of the layer (Fig. 3.4).
- Near Anupgarh gastropod shells from similar brown floodplain mud gave AMS C-14 age of 4564 ± 76 cal BP.
- Earlier Saini et al., (2009) had reported OSL depositional ages of 2.9 ± 0.2 ka BP and 3.4 ± 0.2 ka BP for the similar stratigraphic horizons from the Ghaggar floodplain, at Sirsa-Fatehbad region – upstream to our sampling sites.
- These results suggest that the sediment load of the river has been dominated by the suspended material at least since 4.5 ka. This in turn suggests that by 4.5 ka the river was already a foothill fed river similar to its present condition.

3.3.2.2 Grey micaceous fluvial sand:

- The depositional age of the underlying grey micaceous fluvial sand, on the other hand can be traced back to the Pleistocene.
- OSL dating of this sand horizon between Hanumangarh and Kalibangan gave an age of 36.6 ± 3.0 ka. Singh et al., (2016a) had reported depositional age of these grey micaceous sands from Kalibangan region to be from ~70 to ~20ka.
- In Pilibangan region, just north of Kalibangan, the yellowish brown fine sand overlying the grey sand horizon gave a depositional age of 15.8 ± 1.1 ka suggesting that the underlying grey sand might have been deposited during the last glacial maxima (LGM) period, i.e. during 22-16 ka (Clark et al., 2009).

- In contrast to the above, in several other places the grey micaceous sand yielded much younger depositional ages. For example, at Hanumangarh where it is in contact with the overlying floodplain mud, it gave OSL depositional ages of 6.0 ± 0.5 and 5.4 ± 0.6 ka. The deposition was probably continuous in this region for a few millennia, which is reflected in the depositional age of 8.5 ± 0.6 ka for the sand, a few centimetres below the contact.
- Evidence of the younger fluvial activity depositing similar grey sand also comes from downstream at Anupgarh region. At Anupgarh a colony of fresh-water bivalve shells was encountered embedded *in situ* within this micaceous grey sand layer (Fig. 3.4). The AMS C-14 dating of a few bivalve shells yielded ages of 6386 ± 62, 6307 ± 14, 6136 ± 98 cal yr BP respectively. The conventional C-14 date also gave similar age of 4652±198 cal yr BP. The fact that the shells were unaltered and embedded in their *in situ* position, the dates can be considered as the depositional age of the fluvial sand horizon.
- The youngest age for similar grey sand from upstream in the Sirsa-Fatehbad region is reported to be 4.3± 0.2 ka by Saini et al., (2009).

3.3.2.3 Yellowish brown fluvial sand:

- As discussed earlier, the yellowish brown fine sand lying on top of the grey sand yielded an OSL depositional age of 15.8 ± 1.1 ka at Pilibangan.
- Bivalve and gastropod shells recovered from similar sand horizon exposed in a freshly dug pit, downstream near Suratgarh gave AMS C-14 ages of 12521 ± 100, 10695 ± 100 and 10484 ± 139 cal yr BP.
- Although this particular type of sand was not encountered in the pit at Hanumangarh, it was found towards the north of Hanumangarh town. The OSL depositional age of this sand layer is 9.9 ± 0.9 ka.
- Another much younger phase of occurrences of this facies have been reported by Saini et al., (2009). In the upstream Sirsa region the depositional age is ~3ka.

The sedimentary facieses and their depositional ages suggest that there were multiple changes in fluvial activity in the Ghaggar floodplain. It appears that a much stronger fluvial system of past has gradually reduced into a dwindling meandering system during the Holocene. During the latter phase other plain-fed tributaries of the river started dominating the floodplain depositions (weaker system, thus finer sediments). For proper characterization of the sources of the sediments and to understand the depositional pathways, we studied the geochemical properties of these sediments along the Ghaggar floodplain.

3.3.3 Ar-Ar geochronology of detrital muscovite

The Ar-Ar ages of muscovite micas represent the time period when the rocks containing these grains get cooled below 350˚C (Hodges, 2003). Given the fact that different litho-tectonic units of the Himalaya had exhumed diachronously, they are likely to contain various age populations of muscovite representing each exhumation event. Therefore, the Ar-Ar ages of detrital muscovite, which represents their formation or Ar closure ages, can be used as powerful provenance indicators for the Himalaya derived sediments (Clift et al., 2010). The ranges of Ar-Ar ages of muscovite found in different Himalayan litho-tectonic units as documented by earlier workers are presented in the figure 3.7.

Muscovite grains are one of the abundant minerals in the sandy facies of the Ghaggar alluvium. The subsurface fluvial grey sands have a lot of coarse grained white mica flakes. Their coarse grained nature and angular character indicate low degree of reworking and/or chemical weathering of the host sediments. Therefore, it is safe to assume that these mica grains have been derived directly from the source rocks (not reworked from the older floodplain deposits) and can serve as a good provenance indicator.

In the present work, we have separated coarse (>150 μ) muscovite grains (concentrates) from three of the grey sand bodies from the Ghaggar floodplain and determined their Ar-Ar ages using the standard step heating protocol (Awasthi et al., 2015; Ray et al., 2015). The reason behind Ar-Ar analysis of multigrain mica concentrates as against single aliquot was to capture the predominant age group in order to zero in on the major sediment contributor to the ancient Ghaggar floodplain. Three, mica concentrates with depositional ages of ~37 ka, >16 ka and ~6.3 ka were chosen for the purpose. The oldest sample represented the strongest phase of the fluvial activity. It came from a layer that is present below a 15.8 ka yellowish-brown sandy layer possibly representing the dwindling phase of the river during the last glacial maxima. The youngest sample came from a layer that represented the youngest phase of fluvial activity, as discussed in Section 3.2. Figure 3.8

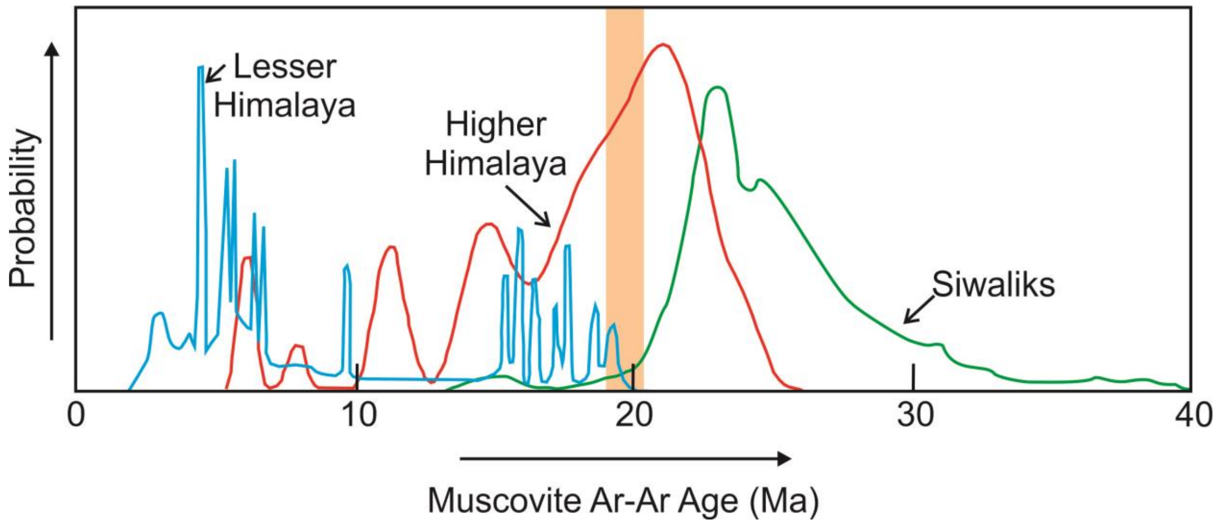

Figure 3.7: Probability density plots showing the range of Ar-Ar mica ages of possible source regions in different Himalayan litho-tectonic units as documented by earlier workers (Bollinger et al., 2004; Catlos et al., 2001; Inger, 1998; Metcalfe, 1993; Searle et al., 1992; Stephenson et al., 2001; Szulc et al., 2006; Vannay et al., 2004; Walker et al., 1999; White et al., 2002).The age range (18.6-20.1 Ma) of mica concentrates from the grey micaceous sand of the Ghaggar alluvium, measured during the present study is marked as an orange column in the figure.

shows the Ar-Ar plateau and isochron plots for the concentrates of white mica from these three samples. Based on the indistinguishable plateau and isochron ages and intercepts showing atmospheric $^{36}Ar/^{40}Ar$ compositions, we make the following observations.

- The plateau age of the micas can be considered as their formation or Ar-closure ages, suggesting that they belonged to magmatic or metamorphic rocks that had cooled down to ~350˚C during 20.1 and 18.6 Ma.
- With overlapping ages, it is clear that the sources of these micas had remained same or similar during the entire period of their deposition, i.e. ~37 ka to 6.3 ka.
- A comparison of these ages (20.1-18.6 Ma) with the distribution of available mica ages in literature from various litho-units (Fig. 3.7) reveals that the mica ages of our samples overlap with those observed in all the three units, i.e. the Higher Himalaya, Lesser Himalaya and Siwaliks.
- The Siwaliks could not have been the source of micas in Ghaggar because the Siwalik sediments themselves have been derived from the other two units and further recycling would only have produced clays as a result of weathering.

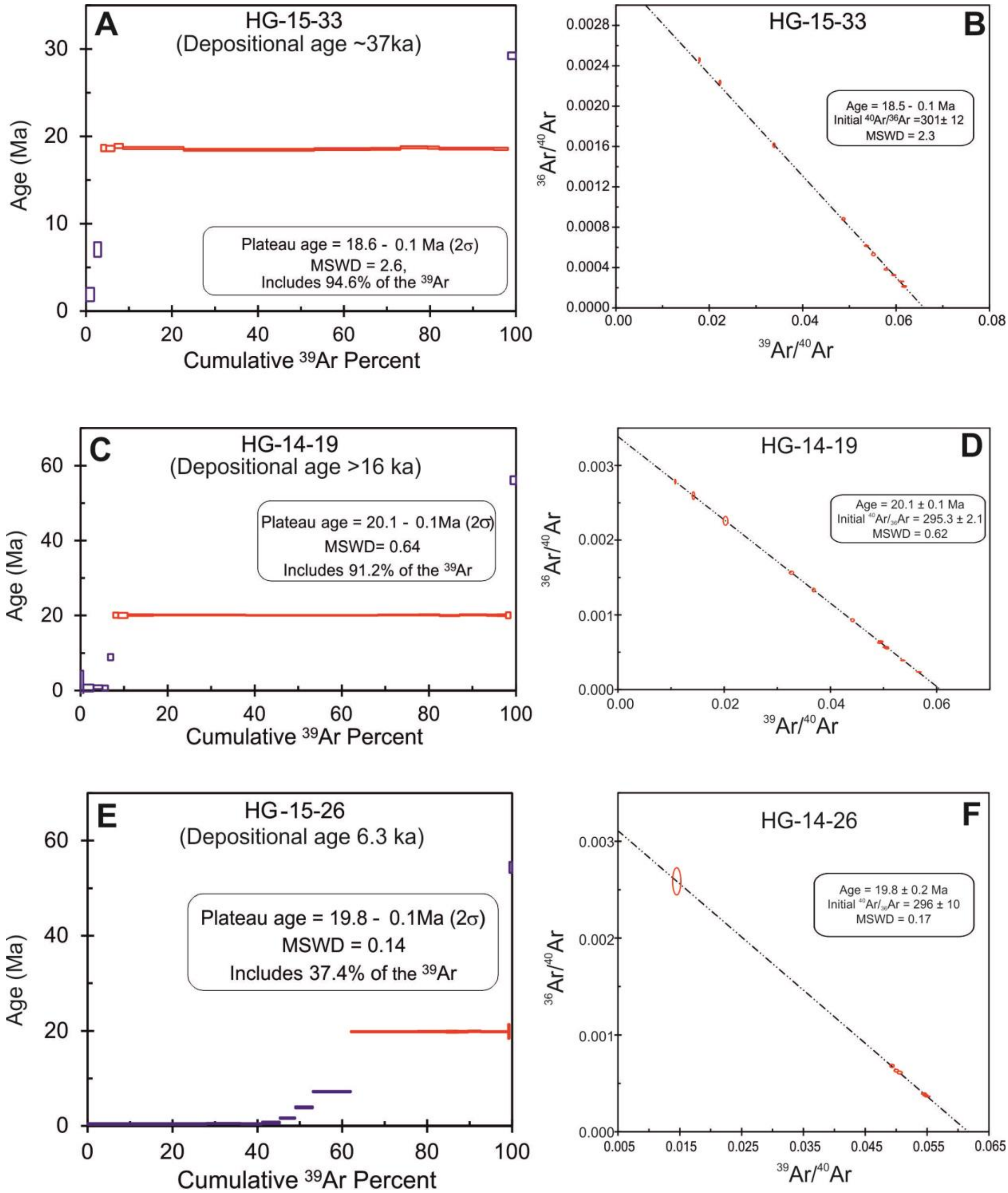

Figure 3.8: Ar-Ar plateau and isochron plots for the concentrates of white mica collected from three samples of grey micaceous sands. (A) & (B) are for the sample HG-15-33 (depositional age ~ 37 ka); (B) & (C) are for the sample HG-14-19 (depositional age > 16 ka); (D) & (E) are for the sample HG-15-26 (depositional age 6.3 ka).

- Sourcing from the Lesser Himalaya can also be ruled out because if that were the case then the mica concentrates should have shown an age of ~12 Ma, the average of the two modes in the age distribution of white micas.
- In view of the above two points, it is apparent that the white micas of the Ghaggar alluvium were derived from the Higher Himalaya. The dominant lithology which could have contributed the micas is the leucogranites, which were emplaced during 17-24 Ma and contain abundant muscovite (Sachan et al., 2010). These rocks were believed to have been exposed during the formation of the Himalayan Central Thrust (HCT) at ~21 Ma (Valdiya, 2010).
- It is therefore logical to conclude that like the micas their host grey sands have also been derived from the glaciated Higher Hiamalaya.

To further constrain the provenance of the Ghaggar alluvium we took help of geochemical proxies, which are discussed below.

3.3.4 Geochemistry of the Ghaggar alluvium

3.3.4.1 Trace element geochemistry

The trace element data of sediment samples are presented in Table 3.2 and plotted in Post Archean Australian Shale (PAAS) normalized diagram in figure 3.9. Following observations can be made from the figure.

- All different types of sediments show similar trace element patterns. Even the modern surface mud deposited during the latest flooding event shows a similar pattern.
- The only difference between different sediments is the elemental concentrations. The modern mud in the river has the highest trace element contents, whereas the oldest alluvium, the coarse grey sand, has the lowest content. This can be attributed to effect of dilution because of presence of abundant quartz in the latter.
- Notwithstanding the differences in the contents, comparable patterns of trace elements in different sediments, point to their derivation from analogous sources.
- The observed patterns are similar to that of sediments in rivers of Punjab. This suggests that the likely provenance of Ghaggar alluvium is the Himalayas.

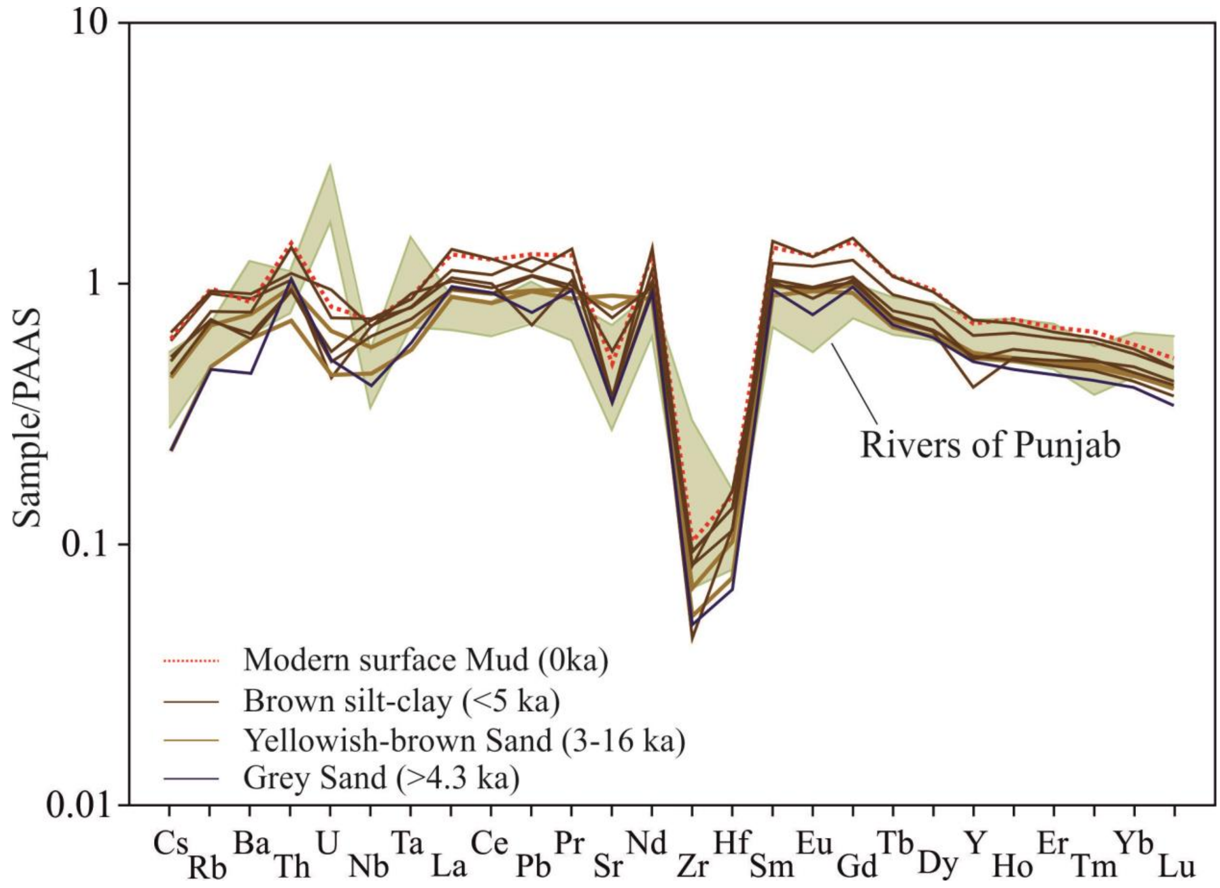

Figure 3.9: PAAS normalised trace element distribution of various sedimentary facies from the Ghaggar alluvium. The green coloured field in the background shows the range of composition observed in the rivers of Punjab. Data source: Alizai et al.(2011a).

The trace element characteristics of Ghaggar alluvium, however, do not make it clear whether the sediments were derived from the glaciated Higher and Lesser Himalayas or the Siwaliks.

3.3.4.2 Sr-Nd isotopic fingerprinting of the Ghaggar sediments

To resolve the above issue we took the help of Sr-Nd isotopic composition of bulk sediments. The isotopic data of the Ghaggar alluvium are presented in the Table 3.3. Different litho-tectonic units of the Himalayas are well characterised with respect to Sr-Nd isotopic compositions and can be used for tracing the provenance of the sediments in frontal alluvial plain. The Sr-Nd isotopic compositions of different Himalayan litho-tectonic units, based on the available data, are shown in figure 3.10.

The glaciated region of the Himalayas is made up of rocks of the Higher Himalayan Crystalline Series (HHCS) and Lesser Himalayan Series (LHS). Rivers originating from the glaciers carry sediments derived from these two sources and hence, they possess a mixed signal. In figure 3.11A we compare the Sr-Nd isotopic data for the Ghaggar alluvium with that of the sub-Himalayan lithologies and of sediments in the rivers originating from the Higher-Himalaya. From the figure the following observations can be made.

- All the grey micaceous sand bodies encountered in the Ghaggar alluvium during the present course of the study have high $^{87}Sr/^{86}Sr$ (>0.75) and low ε_{Nd} (<-17).
- The $^{87}Sr/^{86}Sr$ and ε_{Nd} values of the Holocene grey sand deposits (present study) overlap with the range of values shown by sediments in most glacier fed rivers thus suggesting a provenance in the glaciated Himalayas.

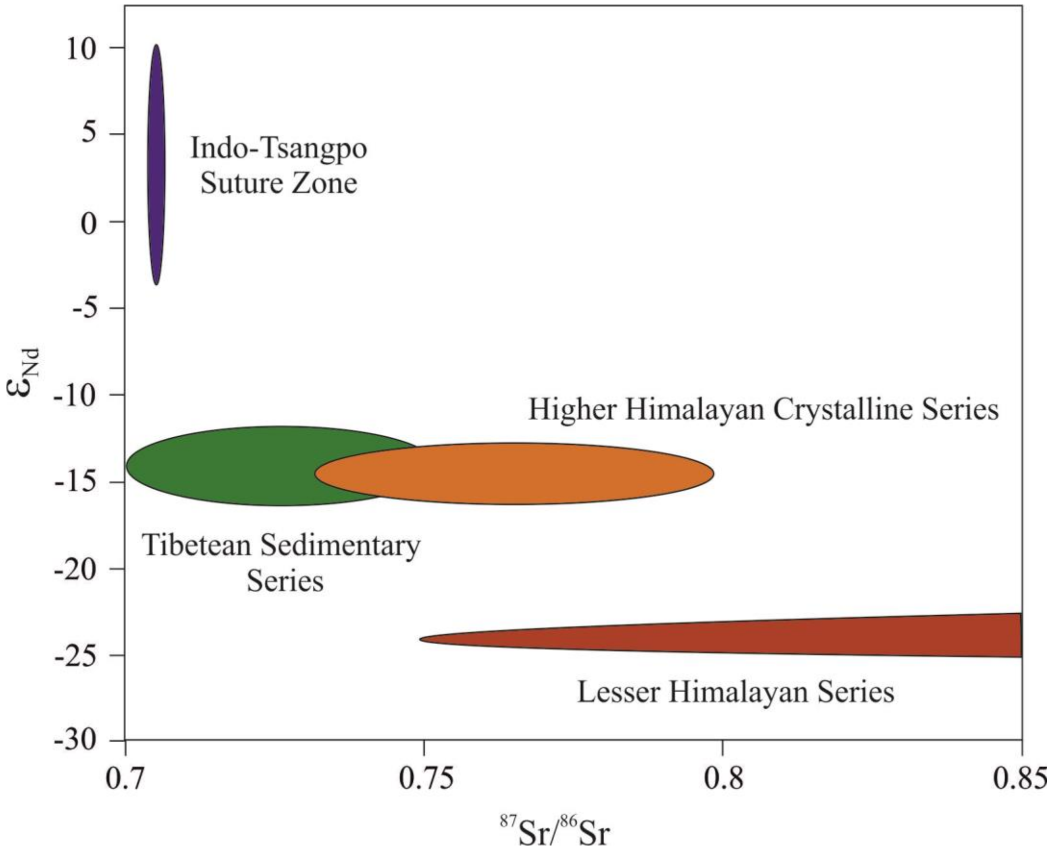

Figure 3.10: εNd vs. $^{87}Sr/^{86}Sr$ plot of major Himalayan litho-tectonic units showing their range of values. Data: Najman et al. (2000).

- The Sr-Nd isotopic ratios of older (>20 ka) grey micaceous sand bodies near Kalibangan also show similar (Singh et al., 2016a) compositions implying dominance of the higher Himalayan provenance.
- Binary mixing curves suggest that these grey sands were derived from a mixed HHCS and LHS sources (Fig. 3.11B).
- The thin layers of Grey clay encountered in a few of the sections (Section 3.1, Fig. 3.4) also show a higher Himalayan provenance. However, their Sr isotopic values are less radiogenic than that of the micaceous grey sands. This may be attributed to the dominance of physical weathering over chemical weathering in the Himalayas (Singh et al., 2008). Generally, higher chemical weathering leads to more radiogenic detritus which is largely controlled by higher $^{87}Sr/^{86}Sr$ bearing fine-grained (clay) fraction, primarily derived from high-Rb bearing micas in the source rocks (Garçon et al., 2014; Meyer et al., 2011). Therefore, in case of less chemical weathering the produced clay will be less radiogenic as the mica grains will be retained in the sand fractions.
- The brown coloured silty-clay possesses distinctly different isotopic ratios than that of the grey sand (Fig. 3.11 A and 3.11B); implying that the provenances of the formers are different from that of the Higher-Himalaya originated grey sands. These sediments are less radiogenic in Sr and more radiogenic in Nd isotopic composition with respect to the grey micaceous sand. They are also different in composition from the surrounding sand dunes, indicating very little, if any, input from the dunes via reworking.
- Figure 3.1B shows that the modern Ghaggar river has its catchment in the sub-Himalayas which includes the Siwalik Group, and formations of the Kasauli, Dagsahi and Subathu. Consequently, the river is expected to carry sediments derived from these lithologies. Sr-Nd isotopic compositions of these lithologies are shown in Fig. 3.11A. Tripathi et al., (2013) have argued for a significant contribution of the Subathu Formation in the Ghaggar Alluvium. However, our observations suggest that the Subathu Formation having very different isotopic compositions might have had very little influence on the Ghaggar sediments (Fig. 3.11A). It appears that the rocks of the Siwalik Group, Kasauli and Dagsahi Formations are the major sources for the brown mud and yellowish-brown sand of the Ghaggar flood-plain (Fig. 3.11A).
- The more radiogenic Nd of the marginal desert dunes can very well be the results of sediment mixing from the river Indus.

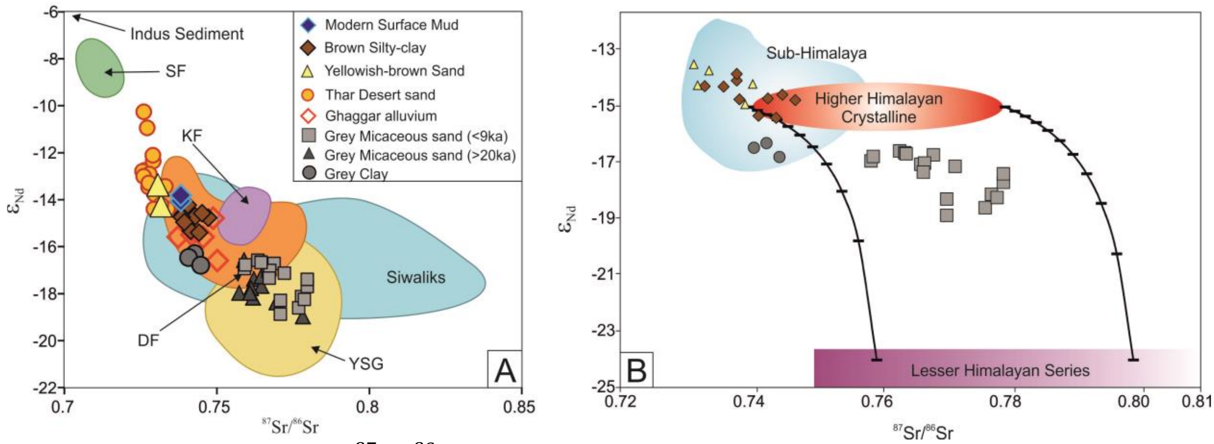

Figure 3.11: (A) ε_{Nd} vs. $^{87}Sr/^{86}Sr$ plot of various types of sediments from the Ghaggar alluvium compared with the sub-Himalayan provenances. Data for Ghaggar alluvium (red open diamonds) and grey micaceous sand (grey triangles) are from Tripathi et al. (2013) and Singh et al., (2016a) respectively. SF: Subathu Formation; KF: Kasauli Formation; DF: Dagsahi Formation; YSG: Yamuna-Sutlej-Ganga sediments.
(B) Binary mixing diagram involving the grey micaceous sands (<9 ka), grey clay and brown silty-clay. The two end-members are the glaciated Higher and the Lesser Himalayas.

Temporal variations of Sr-Nd isotopic compositions in the Ghaggar alluvium since the Pleistocene are presented in the figure 3.12. As can be seen the isotopic compositions changes with the lithology, in the composite stratigraphy which suggest change in sedimentary provenance over time. From the figure it can be observed that:

- The oldest micaceous grey sand has high $^{87}Sr/^{86}Sr$ (~0.76) and low ε_{Nd} (~ -16) values hinting at a mixed Higher and Lesser Himalayan origin for the source.
- A sharp change in provenance can be observed in the period following the last glacial maxima at ~20 ka.
- For a long period sediments showed a low $^{87}Sr/^{86}Sr$ and high ε_{Nd} values corresponding to sub-Himalayan sources.
- ~9 ka onwards a shift towards Higher and Lesser Himalayan provenance can be observed.

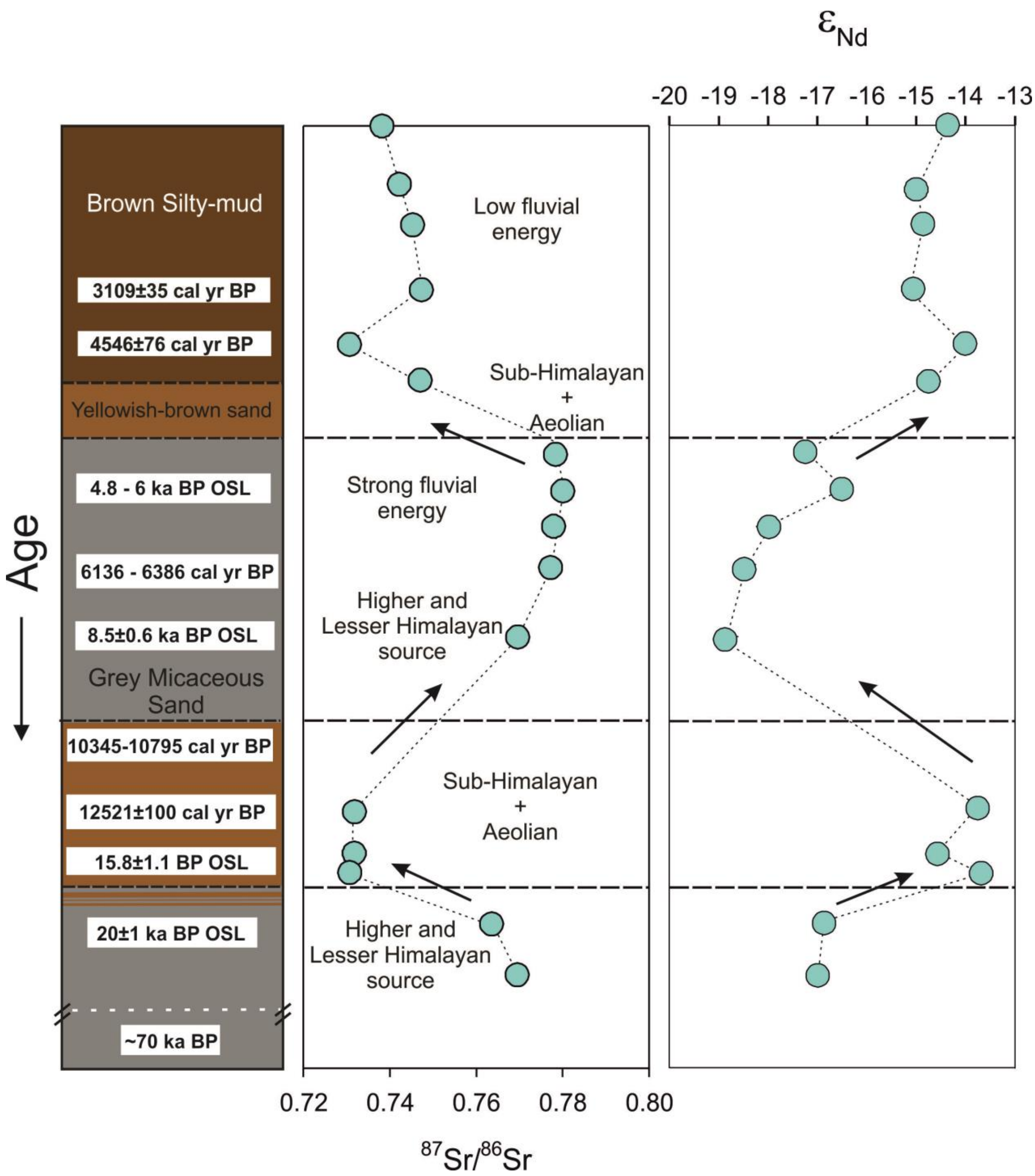

Figure 3.12: The temporal variation of $^{87}Sr/^{86}Sr$ and ε_{Nd} values in a composite stratigraphy of the Ghaggar alluvium.

- ~5 ka onwards the sediment provenance again shifted to the sub-Himalays, suggesting less importance of the Higher and Lesser Himalayan sediment sources in the Ghaggar river system.

The above observations appear to suggest that the Himalayan glacier-fed paleo-river(s) delivered sediments into the present day dry ephemeral river channel of Ghaggar during various periods in the past. However, Ghaggar river basin itself has no evidence of any direct connection with the glaciated Higher Himalayas. Therefore, the only possible pathways for the Higher Himalayan sediments to reach the Ghaggar alluvium could have been via the neighbouring rivers the Sutlej and the Yamuna. However, Clift et al. (2012) had suggested based on detrital zircon age data that the Yamuna had shifted from the Ghaggar channel probably at 45 ka. This leaves us with only one option for the choice of pathway for the glacial water and that is Sutlej. During the present work it was observed that the $^{87}Sr/^{86}Sr$ ratios of the *in-situ* mollusc shells from these sand bodies are 0.7187±0.0003 (Fig. 3.13) and resemble that of the water of the Sutlej rather than that of the Yamuna, which is generally more radiogenic ($^{87}Sr/^{86}Sr$: 0.7166 – 0.7218 , Karim and Veizer, 2000; Pande et al., 1994). This observation further confirms the inference that the Sutlej was the main pathway for the Higher Himalayan sediments into the Ghaggar valley (Danino, 2010).

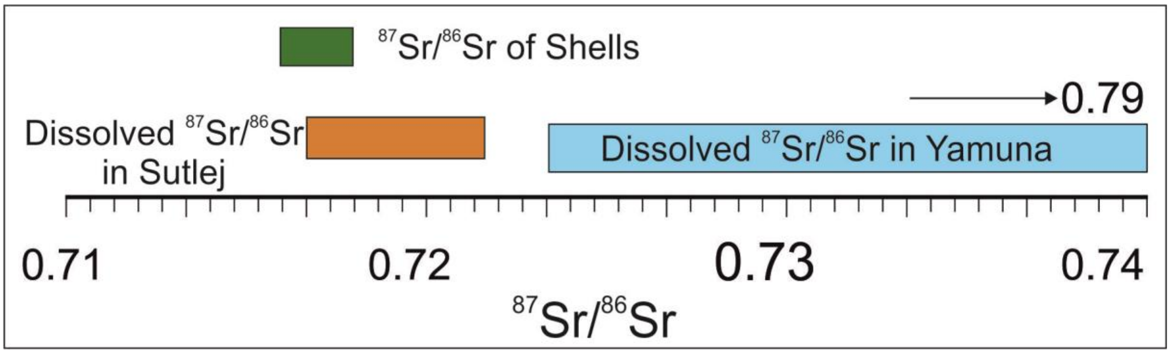

Figure 3.13: Range of $^{87}Sr/^{86}Sr$ values observed in the bivalve shells from the Ghaggar alluvium with respect to the dissolved $^{87}Sr/^{86}Sr$ values of the Sutlej and the Yamuna river.

In a recent work, (Mehdi et al., 2016) has found several paleo-channels connecting the present day Sutlej with the Ghaggar channel. This satellite based work further confirms our inference. However, Giosan et al. (2012) had proposed that no mega-fluvial system was active along the Ghaggar valley during the Holocene period. We therefore hypothesise that some distributaries of the Sutlej could have been flowing into the paleo-Ghaggar during the mid-Holocene (≥6 ka), which later migrated away making the Ghaggar an ephemeral river.

3.3.5 Isotopic Fingerprinting of Kalibangan Potteries

Potters of Bhirana, a Harappan acropolis on the bank of the Ghaggar, used to make earthenware using clay from nearby localities (Krishnan et al., 2012). Extending this finding to Kalibangan it could be argued that potters here too had utilized the silty-clay which was available aplenty in the nearby Ghaggar floodplain. The very fact that common clay (illite/smectite, kaolinite and micas) can be utilized for general ceramics (Valášková, 2015) it is highly likely that the Harappans at Kalibangan made use of locally available clays, the mineralogical details of which are shown in figure 3.5 and discussed in section 3.1. The usability of these silty-clay horizons is very much evident even today in the numerous active brick kilns all along the Ghaggar floodplain.

Another important understanding of ancient pottery making is that pure clay was never used for the purpose (Krishnan, 2002; Krishnan and Rao, 1994). For strengthening and creating different textures, various amounts of coarser material, generally sand, were mixed with pure clay to prepare the raw material. Therefore, one expects to find mixed geochemical signatures of sand and clay of the Ghaggar flood plain in the Kalibangan potteries. The Sr-Nd isotopic compositions of the potteries are presented in the table 3.4.

Figure 3.14 presents ε_{Nd} versus $^{87}Sr/^{86}Sr$ plot comparing the compositions of Harappan potteries with that of the different types of Ghaggar flood plain sediments. It can be observed that the isotopic compositions of pottery samples lie within the range of brown silty-clay/ surface mud and yellowish-brown sand. Possible contribution from surrounding aeolian sand cannot be ruled out. However, there appears to be a clear absence of any grey micaceous sand component within the pottery, which suggests non-availability of such sediment during pottery making. This, on the other hand, implies that by the time the Mature Harappans settled in Kalibangan, the glacial connection to the Ghaggar was significantly reduced and little sediment originating from glaciated terrains was depositing in the channels.

Validation of this hypothesis comes from isotopic compositions of the brick sampled from the Bhatner Fort. It is a well-known historical fact that the Fort was established on the banks of an ephemeral Ghaggar during 12th century AD. The bricks of the fort, made using Ghaggar sediments, show similar compositions as that of the pre-historic potteries. This clearly suggests use of identical raw materials even after two millennia which in turn supports the theory that the river was already ephemeral (not glacier fed) during the Mature Harappan Period.

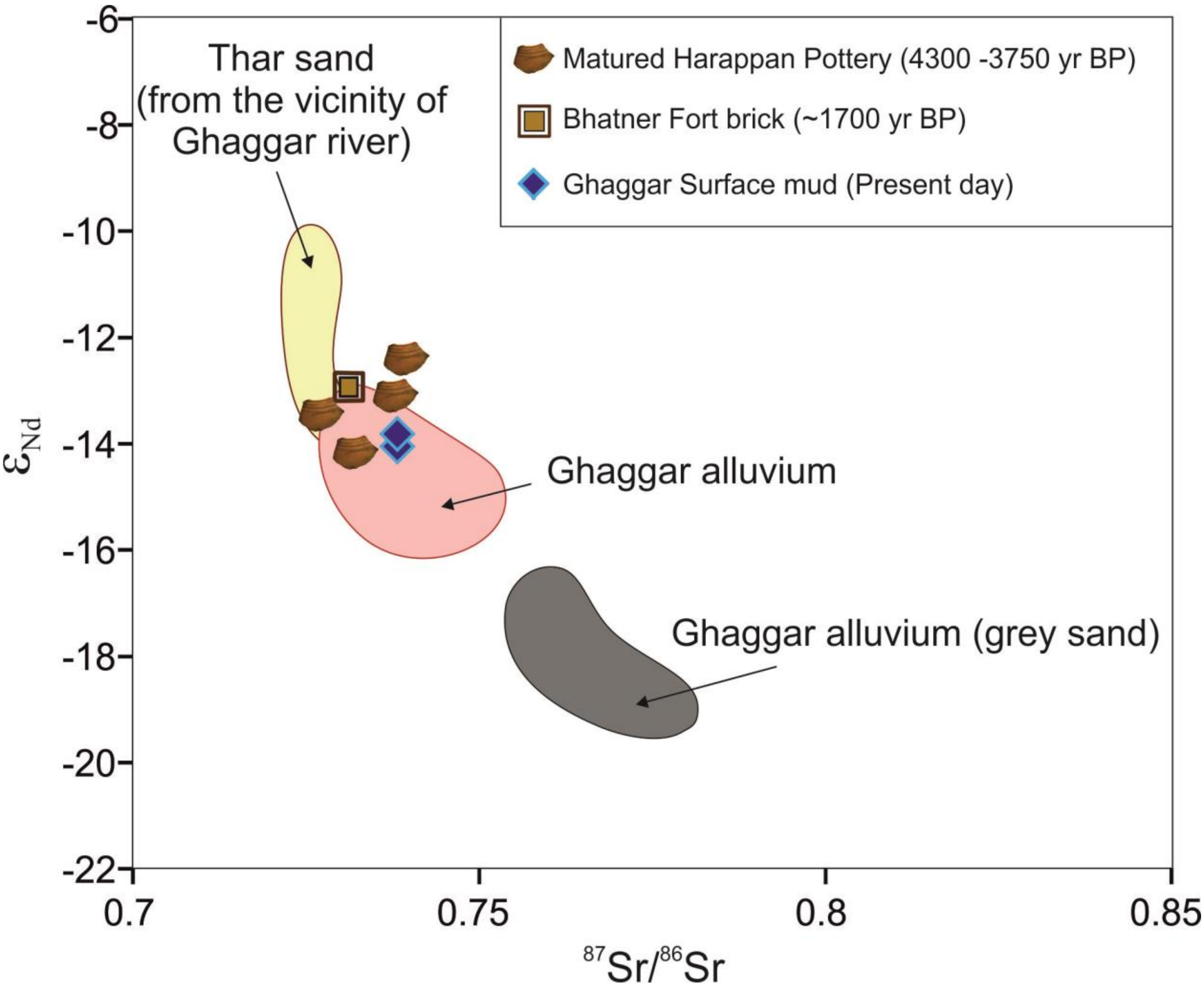

Figure 3.14: ε_{Nd} vs. $^{87}Sr/^{86}Sr$ plot of different archaeological artefacts compared with the probable raw material sources in the Ghaggar flood plain. Figure is modified from Chatterjee and Ray, (2017a).

3.3.6 The River – Culture – Climate connection

A graphical representation showing temporal dominance of different sedimentary facies within the Ghaggar flood plain during the last 70 kyrs and their relationship with the major climatic events and development of the Indus valley cultural tradition is shown in figure 3.15. The following observations and interpretations can be made from the figure.

- The earliest phases of grey micaceous sand deposition (~70-20 ka) occurred during the MIS-3 and MIS-4. During this period the sediments deposited in the Ghaggar valley had its origin mainly from the glaciated Higher Himalayan sources. The thick and continuous deposition of fluvial sand during this period (Singh et al., 2016a) is indicative of a strong fluvial system during this time.
- Towards the end of MIS-3 aridity started increasing (Petit et al., 1999). During the last glacial maxima (25 – 18 ka) and during the MIS-2 aridity and glaciation was at its peak. The discharge in the Himalayan rivers was at their lowest as evident from the incised river valleys, especially in the western India (Giosan et al., 2012). During this period the fluvial grey sand beds in the Ghaggar alluvium had become thinner with the appearance of alternate yellowish-brown sand layers. This observation suggests that during the glacial maxima, the river had started dwindling with limited discharge from the glacial sources. The yellowish brown sand deposited during this time appears to have been sourced from the provenance of the sub-Himalaya (Siwaliks) and reworking of local dunes.

During most of the period of the MIS-2 and the beginning of the MIS-1, Ghaggar valley witnessed deposition of yellowish-brown silty sand facies mainly. No record of grey sand facies was observed during this study or reported by earlier works. As discussed earlier, sediments were originating from the Sub-Himalayas and local reworking during this period which was probably a result of a weak monsoon. The fluvial activity was at its lowest.

- Indian Summer Monsoon is known to have been re-intensified in the MIS-1, subsequent to the LGM (Sarkar et al., 2016). This along with the melting of the glaciers should have increased discharge in the Himalayan rivers. During this period (~9 ka onwards), we observe appearance of grey micaceous sand again. Its deposition continued up to ~4.5 ka, albeit as limited channel fills.
- This second phase indicates renewed phase of fluvial activity originating from the Higher Himalayas. Bookhagen et al., (2005) had shown that during the intensified Holocene monsoon, sediment flux increased manifold from the higher parts of Sutlej valley in the NW Himalaya. This caused enhanced sediment evacuation in the Himalayan foreland basins. Probably during these phase of monsoon intensification and deglaciation, the Ghaggar received sediment and water originating from the Higher Himalayas via rejuvenated distributaries of the Sutlej.

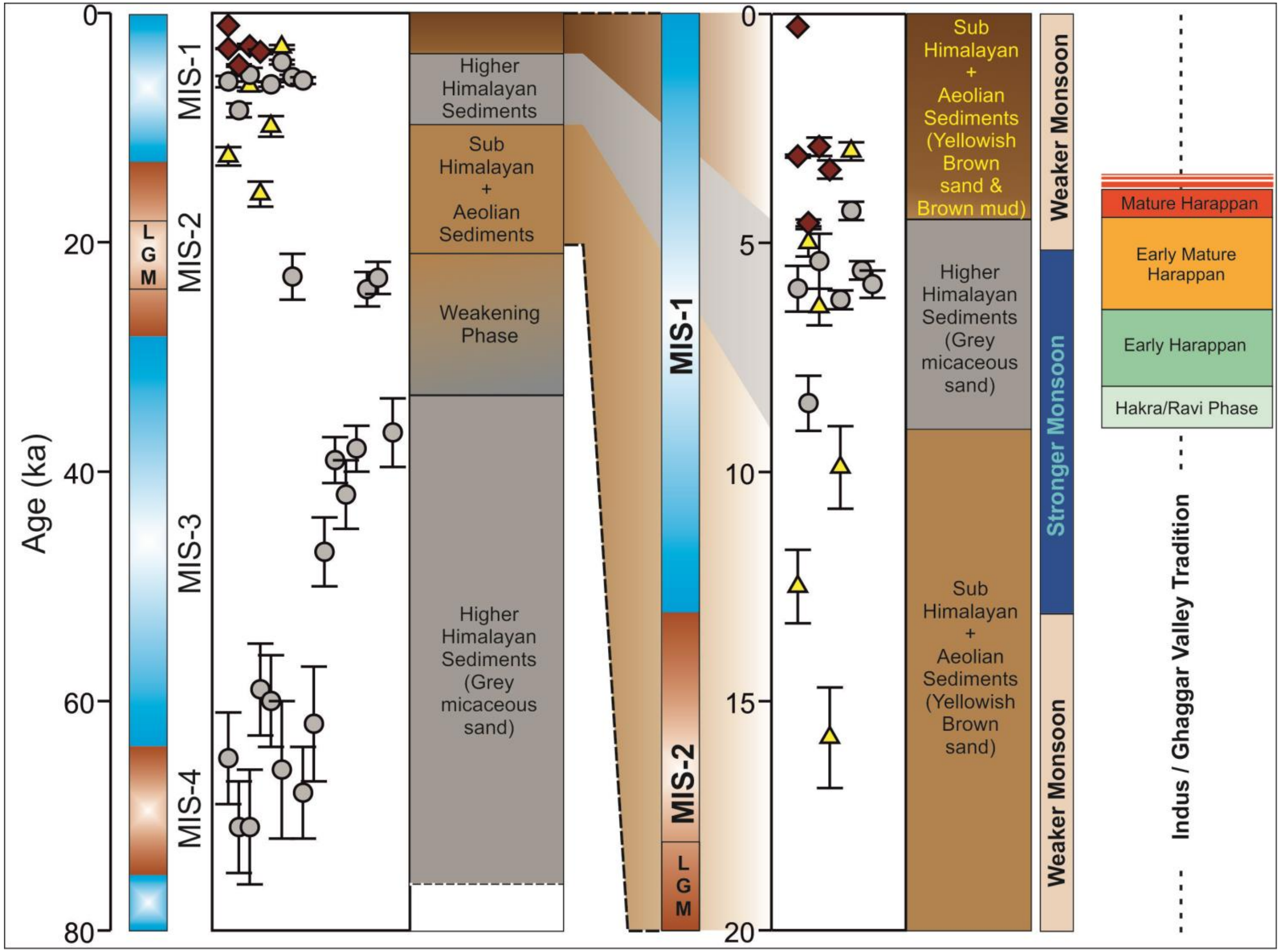

Figure 3.15: Graphical representation of the temporal dominance of different sedimentary facies within the Ghaggar flood plain during the last 70 kyrs and their relationship with the major climatic events and development of the Indus valley cultural tradition. The last 20 kyrs window has been zoomed in for better visualisation of the events happening during that period.

- One noticeable development during the renewed phase of the fluvial activity is the beginning of the earliest Indus valley (Harappan) tradition. The seed of the future Harappan civilization was being sown in the early Holocene. The earliest known settlement of Bhirrana in the Ghaggar valley dates back to ~9 ka (Sarkar et al., 2016). By 6 ka the Ghaggar valley was crowded with early Harappan (Hakra phase) settlements. This development during the renewed phase of the river indicates that the early settlers witnessed perenniality in the river system. Soon after they developed into the Early Mature Harappan tradition.
- The river had started to lose its glacial sources making it dependent on rainfall only when the Harappan civilization had entered into its mature phase, 4.6-3.9 ka. This is evident from the sedimentological and geochemical properties of alluvium and archaeological artefacts from the Ghaggar valley. By the time the Indus Valley/ Harappan Civilization had reached its peak (~4.6 ka), the Ghagagr river had lost its glacial sources completely. From ~5ka onwards sediments deposited in the Ghaggar valley had become silty clay dominated and were derived mainly from the sub-Himalayas.
- The zeneith of the civilization overlaps with the terminal phase of the river, which suggests that the rainfall was adequate for the Ghaggar valley dwellers to sustain their civilization.
- Gradually the climate became more arid and the river Ghaggar became an ephemeral rain-fed river much more like its present day condition. The Mature Harappans, who were dependent mainly on the monsoonal rain, also got affected by the rapid change in the climate and its negative effect on the flow of the Ghaggar. This caused a domino effect and within a few centuries the developed urban societies of the Harappans disintegrated of various reasons like crop cycling (Sarkar et al., 2016), diseases, abandonment of urban centres etc. Inadequate water supply was a major reason for the demise of the civilization. By 3.9 ka the people migrated from their localities towards the northern Himalayan foothills, where rainfall was much higher (Giosan et al., 2012).

3.4 Summary and Conclusions

Our study of chronology, geochemistry and isotopic compositions of various proxies from the present-day Ghaggar valley revealed the following information about the evolution of the river and its connection with the Harappan Civilization in the NW India.

- The Ghaggar alluvium is a repository of sediments originated from two distinct provenances: 1) the glaciated Higher and Lesser Himalayas, 2) the sub-Himalayas.
- The grey micaceous sand deposits had their source in the glaciated Higher and Lesser Himalayas. This sand appears twice in two distinct time period: 1) 70-20 ka, 2) 9-5 ka.
- The oldest phase of grey micaceous sand (~70-20 ka) got deposited during the MIS-3 and MIS-4 and suggests a strong fluvial past of the river.
- The geomorphology of the Ghaggar floodplain was very different at that time with the Yamuna and the Sutlej flowing into its channel making it a perennial river system (Fig 3.16A).
- Yamuna abandoned its course ~45 ka (Fig 3.16B).
- During the last glacial maxima (25-18 ka) the river started dwindling and the sediment influx from the glaciated higher Himalaya gradually decreased.
- During the drier periods of the MIS-2, sediments (yellowish-brown sand) originating mostly from the sub-Himalayas and reworked from the dune fields were deposited in the Ghaggar valley.
- At the beginning of the Holocene Indian Summer Monsoon intensified and the appearance of micaceous grey sand derived from glaciated Higher Himalayas reappeared in the Ghaggar stream (~9 ka onwards). This period roughly coincided with the MIS-1 period.
- During this period the Ghaggar received its share of Higher Himalaya originated glacier water probably via distributaries of the river Sutlej (Fig 3.16C).
- Also during this rejuvenated phase of the river the earliest people of the Indus valley tradition (pre-Harappans) settled down in the Ghaggar valley.
- By mid-Holocene the river had lost its glacial sources (Fig 3.16D). However, this did not affect the settlers along the river bank. Rather the civilization reached its peak during this period sustained by water from monsoonal rain. Therefore, the dramatic loss of the perennial glacier source from the Ghaggar river may not be a reason for the decline of the Harappan Civilization.
- Subsequently, the decrease in rainfall caused the river to be seasonal and unpredictable. This situation became detrimental for the survival of the settlements along the Ghaggar river valley.

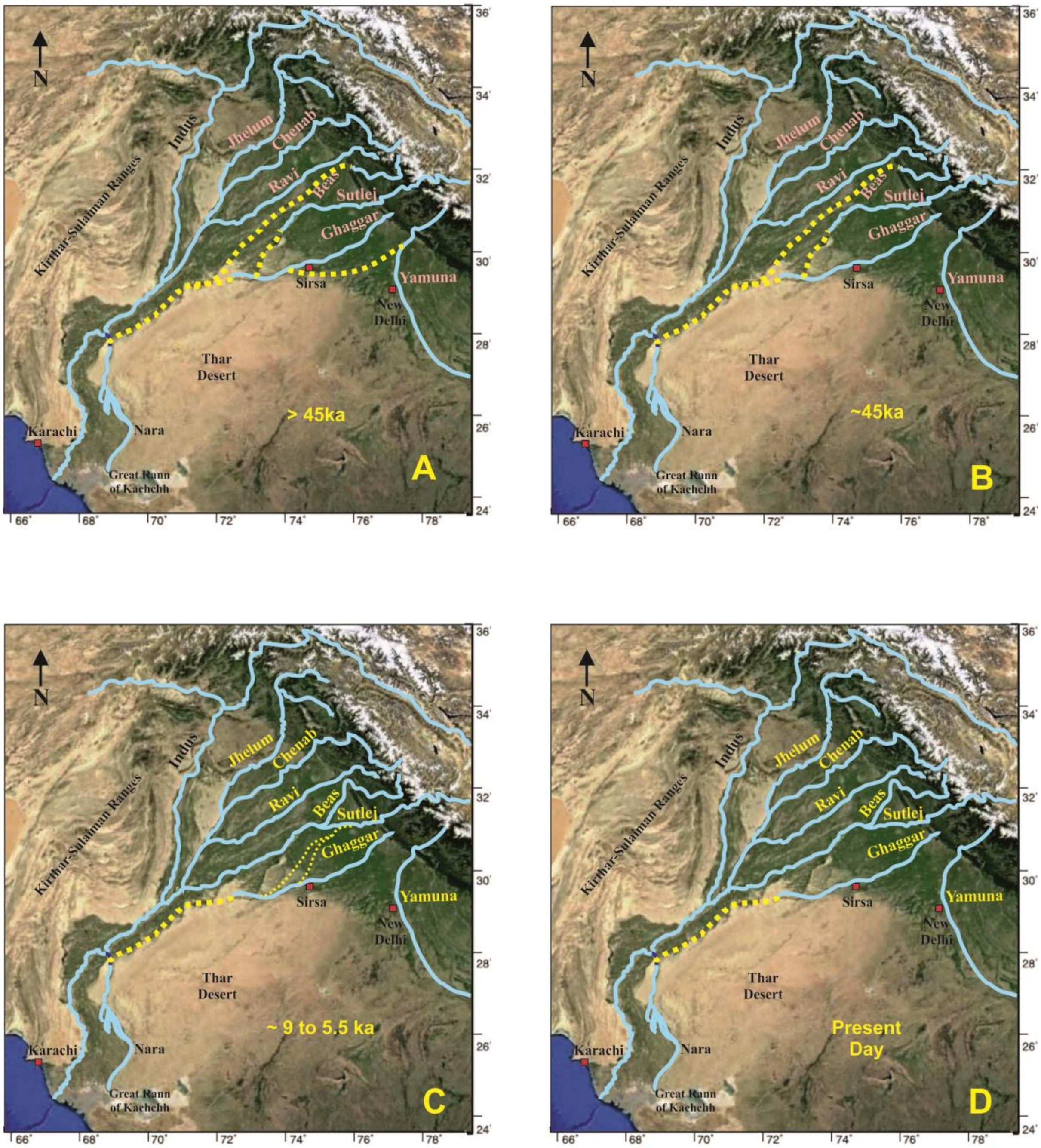

Figure 3.16: Reconstruction of the palaeo-drainage patterns in the western part of the Indian sub-continent. The blue lines represent the present-day drainage and the yellow dotted lines represent the proposed palaeo-drainages.
(A) Ravi, Sutlej and Yamuna used to flow into the Ghaggar river channel before 45 ka (figure modified from Clift et al., 2012).
(B) During 45 ka the Yamuna shifted away from the Ghaggar channel (figure modified from Clift et al., 2012).
(C) During 9-5.5 ka only some distributaries of the Sutlej river used to flow into the Ghaggar channel (reconstructed from the present study).
(D) The present day drainage pattern. It remained similar since the mid-Holocene.

- Although the decline of the Harappan Civilization along the Ghaggar valley postdates the dramatic changes in the fluvial activity, a stronger perennial fluvial system helped the early societies to sow the seeds of the earliest known civilization in India.

Table 3.1(A) Equivalent dose (De),Dose Rate and ages obtained on the Ghaggar sediments

Sample	OD	U(ppm)	Th(ppm)	K(wt%)	De	Dose rate (µGy/a)	Age (ka)
HG-OSL-7	27.5	4.43±0.07	20.0±0.4	1.43±0.02	20.6±0.7	3.46±0.23	**6.0±0.5**
HG-OSL-6	13.4	2.65±0.07	12.1±0.3	2.0±0.03	26.4±0.5	3.1±0.2	**8.5±0.6**
HG-OSL-4	23	3.25±0.09	14.4±0.4	1.73±0.03	49.5±1.3	3.1±0.2	**15.8±1.1**
HG-OSL-15-A(15/5)	29.7	2.20±0.07	10.2±0.4	1.47±0.03	24.3±1.5	2.5±0.2	**9.9±0.9**
HG-OSL-15-C(15/13)	34.6	3.83±0.09	17.5±0.5	1.39±0.03	106±14	3.2±0.2	**36.6±3.0**
HG-OSL-15-D/OSL-6	27	2.65±0.07	12.1±0.3	2.0±0.03	16.8±1.5	3.1±0.2	**5.4±0.6**

Table 3.1 (B) Details of the AMS C-14 dates of the mollusc shells

Sample	Sample type	age (y)	±(y)	$\delta^{13}C$ (‰)	Cal BC	±(y)	Cal BP
JSR-1	Gastropod	4,021	34	-1.3	2,546	76	**4,546**
JSR-2	Bivalve	5,506	36	-5.1	4,386	62	**6,386**
JSR-3	Bivalve	5,347	36	-5.7	4,307	14	**6,307**
JSR-4	Bivalve	5,285	35	-5.1	4,136	98	**6,136**
JSR-5	Bivalve	10,480	46	-8.2	10,521	100	**12,521**
JSR-6	Bivalve	9,410	44	-8.6	8,695	100	**10,695**
JSR-7	Gastropod	9,272	43	-5.6	8,484	139	**10,484**

Table 3.2 Trace element concentrations of the Ghaggar river sediments. Concentrations are in ppm.

Samples	HG-14-4 (Brown silty-mud)	HG-14-8 (Brown silty-mud)	HG-14-16 (Brown silty-mud)	HG-14-20 (Brown silty-mud)	HG-14-21 (Brown silty-mud)	HG-14-39 (Brown silty-mud)	HG-14-18 (Brown silty-mud)
Cs	7.49	8.98	6.67	9.67	6.48	7.78	9.14
Rb	124.1	145.2	113.7	148.7	109.7	115.6	151.9
Ba	501	565	414	589	493	396	546
Th	20.0	15.0	13.7	15.9	14.0	13.6	20.7
U	2.27	1.34	1.54	2.91	2.02	1.69	2.50
Nb	14	13	12	13	11	14	14
Ta	1.11	1.04	0.93	1.16	0.86	1.03	1.14
La	51	42	36	38	36	40	49
Ce	99	86	73	76	72	79	98
Pb	22.1	25.0	21.2	21.3	18.7	13.8	25.7
Pr	11.9	9.8	8.3	8.6	8.3	9.0	11.2
Sr	72	72	69	147	159	109	98
Nd	43	36	31	31	30	32	41
Zr	17	19	9	17	14	20	21
Hf	0.6	0.7	0.6	0.8	0.5	0.7	0.8
Sm	8.1	6.7	5.7	5.5	5.5	5.7	7.6
Eu	1.4	1.3	1.1	1.0	1.0	1.0	1.4
Gd	7.0	5.7	4.9	4.7	4.6	4.8	6.7
Tb	0.81	0.69	0.60	0.56	0.55	0.57	0.82
Dy	4.1	3.6	3.2	2.9	2.9	2.9	4.1
Y	19.4	16.9	13.7	10.7	14.5	14.1	18.8
Ho	0.70	0.64	0.55	0.51	0.51	0.50	0.72
Er	1.9	1.8	1.6	1.5	1.4	1.4	2.0
Tm	0.2	0.2	0.2	0.2	0.2	0.2	0.3
Yb	1.6	1.5	1.3	1.3	1.2	1.2	1.6
Lu	0.20	0.20	0.17	0.18	0.17	0.16	0.22
Samples	HG-14-17 (Grey sand)	HG-14-19 (Grey sand)	HG-14-29 (Grey sand)	HG-14-30 (Grey sand)	HG-14-31 (Grey sand)	HG-14-40 (Grey sand)	HG-14-22 (Yellow-brown sand)
Cs	3.40	6.01	3.68	3.80	4.70	3.88	3.38
Rb	74.2	112.9	86.5	86.7	102.5	84.2	76.0
Ba	292	407	332	325	370	332	396
Th	15.1	10.1	11.1	13.1	6.8	15.3	10.4
U	1.57	1.24	1.32	1.77	0.87	1.97	1.37
Nb	8	8	6	8	6	10	9
Ta	0.75	0.74	0.55	0.73	0.63	0.90	0.71
La	37	24	29	34	19	45	33

Ce	73	48	57	66	38	91	67
Pb	15.4	20.8	18.0	17.9	20.1	17.7	18.5
Pr	8.2	5.5	6.3	7.5	4.4	10.3	7.6
Sr	69	91	75	74	79	112	179
Nd	29	20	23	27	16	37	28
Zr	10	7	6	8	1	8	11
Hf	0.3	0.2	0.3	0.3	0.2	0.3	0.4
Sm	5.3	3.5	4.0	4.7	2.8	6.7	5.0
Eu	0.8	0.7	0.7	0.8	0.6	1.1	1.0
Gd	4.5	3.0	3.4	4.0	2.3	5.8	4.3
Tb	0.53	0.35	0.40	0.46	0.28	0.70	0.52
Dy	2.7	1.9	2.0	2.3	1.4	3.8	2.7
Y	13.4	9.5	9.8	11.6	7.1	17.0	13.9
Ho	0.46	0.34	0.34	0.40	0.25	0.68	0.50
Er	1.3	0.9	1.0	1.1	0.7	1.9	1.4
Tm	0.2	0.1	0.1	0.2	0.1	0.3	0.2
Yb	1.1	0.8	0.8	1.0	0.6	1.7	1.2
Lu	0.14	0.11	0.11	0.14	0.08	0.23	0.17

Table 3.3 Sr-Nd isotopic compositions of the Ghaggar river sediments.

Samples	**Brown Silty-clay (<4.5 ka)**							
	HG-14-4	HG-14-8	HG-14-16	HG-14-34	HG-14-35	HG-14-38	HG-14-39	HG-14-20
$^{87}Sr/^{86}Sr$	0.743022	0.745287	0.747306	0.744301	0.741571	0.738601	0.736119	0.733185
ε_{Nd}	-14.7	-14.6	-14.8	-15.4	-15.3	-14.7	-14.3	-14.3
Samples	**Modern surface mud**			**Yellowish brown sand**				
	HG-14-18	HG-14-18R		HG-14-21	HG-14-22	HG-14-36	HG-15-3	HG-15-19
$^{87}Sr/^{86}Sr$	0.738182	0.738182		0.731733		0.740603	0.739478	0.733869
ε_{Nd}	-14.1	-13.8		-14.3	-13.4	-14.2	-14.9	-13.7
Samples	**Grey Micaceous sand (>5 ka)**							
	HG-14-17	HG-14-19	HG-14-19R	HG-14-29	HG-14-30	HG-14-31	HG-14-31R	HG-14-33
$^{87}Sr/^{86}Sr$	0.768847	0.770905	0.770905	0.777894	0.776909	0.779743	0.779743	0.763566
ε_{Nd}	-16.7	-18.9	-18.3	-18.1	-18.6	-17.7	-17.4	-16.6
Samples	**Grey Micaceous sand (>5 ka)**							
	HG-14-41	HG-15-10	HG-15-10R	HG-15-12	HG-15-13	HG-15-24	HG-15-26	HG-15-28
$^{87}Sr/^{86}Sr$	0.772213	0.764594	0.764594	0.766860	0.767445	0.759107	0.759457	0.767271
ε_{Nd}	-17.1	-16.6	-16.7	-17.0	-17.0	-16.9	-16.8	-17.3
Samples	**Grey Micaceous sand (>5 ka)**				**Grey Clay**			
	HG-15-33				HG-15-34	HG-15-11	HG-15-17	
$^{87}Sr/^{86}Sr$	0.778758				0.742829417	0.740871862	0.744841974	
ε_{Nd}	-18.2				-16.3	-16.5	-16.8	

Table 3.4 Sr-Nd isotopic compositions of the potteries from Kalibangan and Hanumangarh Fort

Samples	Kalibangan Pottery and brick (4.6 – 3.9 ka)				Bhatner Fort Brick (~0.9 ka)
	KBP-1	KBP-2	KBP-3	KBP-4	HGP-1
$^{87}Sr/^{86}Sr$	0.739043	0.731819	0.737543	0.726857	0.730976
ε_{Nd}	-12.4	-14.2	-13.1	-13.5	-12.9

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