

STRATIGRAPHIC EVOLUTION OF THE GANGES-BRAHMAPUTRA LOWER DELTA
PLAIN AND ITS RELATION TO GROUNDWATER ARSENIC DISTRIBUTIONS

By

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CHAPTER I

Introduction

The Ganges Brahmaputra Meghna Delta (GBMD) was constructed by the fluvial transport of large sediment loads (currently about 1 billion tons/year) from the Himalayas to the Bengal Margin (Goodbred and Kuehl, 2000; Milliman and Syvitski, 1992). Throughout the Holocene, this large sediment load coupled with river avulsions, tectonic activity and eustasy to develop the complex stratigraphy of the delta (Goodbred and Kuehl, 2000a; Weinman et al., 2008). Given the nature of formation, evaluating the stratigraphy of the GBMD can be useful in predicting how the delta will respond to changes in the environmental setting such as a climatic shifts and rising sea level (Brammer, 2014; Goodbred et al., 2014). The response of the delta to a changing environment has major consequences for the 156 million people in Bangladesh, which sits on much of the GBMD. Because Bangladesh is a lower-middle income country in which almost half of the population is employed in agriculture, the cost of environmental disasters can have profound effects on the economy and the livelihood of many people throughout the country.

Additionally, Bangladesh is plagued by high concentrations of naturally occurring arsenic (As) in the groundwater, which has led to a widespread poisoning of the people living in this country (Smith et al., 2000). The distribution of arsenic within the aquifers is heterogeneous and linked with the complex stratigraphy of the GBMD through controls on hydrology and aquifer biogeochemistry (McArthur et al., 2010 and Yu et al., 2003). The lower delta plain of Bangladesh is also afflicted with saline groundwater, sourced from both seawater intrusion and paleo-seawater aquifers. The paleo-seawater aquifers developed during the construction of the delta when saline tidal water was trapped among deposited sediments (Goodbred and Kuehl, 2000a; Hoque et al., 2003; Worland et al., 2015). A better understanding of the heterogeneous nature of the stratigraphy can be useful in helping to decode both the distribution of As and the distribution of salinity within the groundwater aquifers of the lower delta plain.

Here we present the results from a sediment core transect (Transect G) spanning the entire lower delta plain of Bangladesh (Figure 1). This transect traverses the areas of greatest As contamination, as well as areas of known groundwater salinity. Transect G was also positioned to capture sedimentological features including the lowstand valleys of the main river systems, the lowstand interfluvial shown by McArthur et al. (2011) and Hoque et al. (2012; 2014) to have

relatively shallow As-free Pleistocene groundwater, and the advancing thrust front of the fold belt where groundwater As concentrations are also lower (Hoque et al., 2014).

Analysis of the Transect G boreholes provides information on the sediment source, the depositional history of the rivers and the stratigraphic architecture, and the tectonic history of the region, which allow us to reconstruct the formation and evolution of the delta. Combining this information with groundwater As measurements collected for this project as well as for the Bangladesh Arsenic Mitigation and Water Supply Program (BAMWSP), we evaluate whether sedimentary and stratigraphic attributes of Transect G are strongly correlated with groundwater As distribution in the lower delta plain.

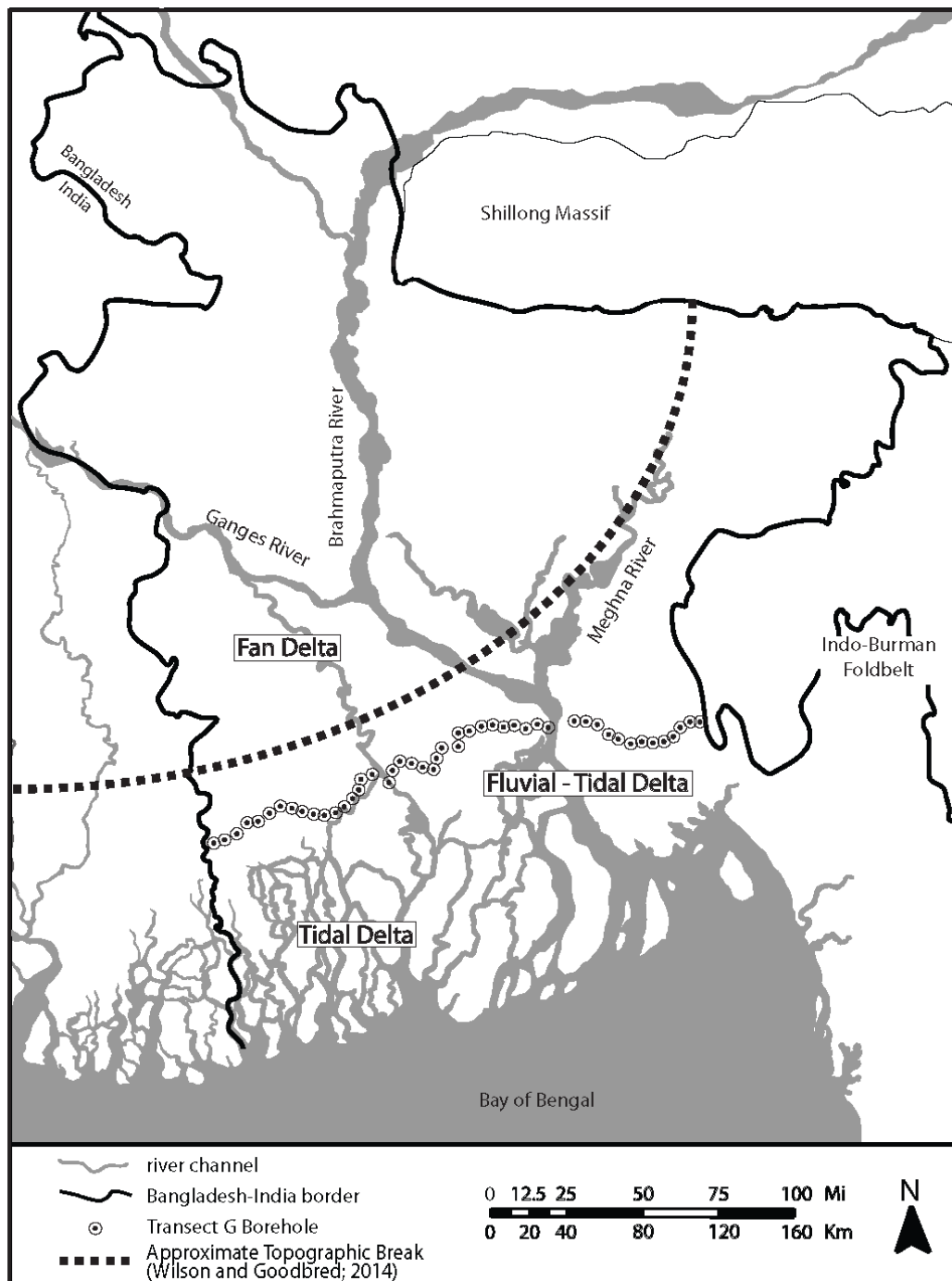


Figure 1. Map of Bangladesh showing the location of Transect G boreholes and the approximate topographic break of Wilson and Goodbred (2014). Map adapted from Pickering et al. (2014).

CHAPTER II

Background

Regional Setting

Stratigraphy

The GBMD was constructed by the transport of sediments from the Himalayas to the Bengal margin by the Ganges and Brahmaputra Rivers. River discharge and sediment transport are highly seasonal and peak during the summer monsoon which occurs between June and October. The transport of such a high sediment yield during a finite period of time leads to rapid channel aggradation and lateral migration of the rivers (Wilson and Goodbred, 2014). These avulsions coupled with river incision during sea level low-stands and the deposition of sand, silt and clay during sea level high-stands results in the heterogeneous stratigraphy seen throughout the delta (Acharyya et al., 2000; Goodbred and Kuehl, 2000).

In addition to heterogeneous stratigraphy, fluvial transport of sediments in northern Bangladesh and fluvial-tidal transport of sediments in southern Bangladesh has led to the development of a fan delta transitioning into a fluvial tidal delta (Figure 1). The fan-delta has a slope of about 10^{-4} while the fluvial-tidal delta has a slope of about 10^{-5} (Wilson and Goodbred, 2014). The upper region of the fluvial-tidal delta lies above the tidal limit, is generally sediment starved, and supports local peat basins, while the more seaward portion is tidally influenced and is supplied with sediment during regular inundations (Allison and Kepple, 2001; Wilson and Goodbred, 2014).

Tectonics

One principal control on stratigraphy is tectonics. Bangladesh sits within the convergence zone of the Himalayan and Burman Arcs with the Indian Plate. In the south eastern regions of Bangladesh, the collision between the Burman Arc and the oceanic crust of the Indian plate manifests as a shallowly dipping subduction zone. This subduction zone has created a fold belt region reaching into Myanmar that extends westward into Bangladesh, although the folds in the western region are buried beneath the deltaic sediments (Steckler et al., 2008). The Lalmai anticline is the westernmost exposed fold. Stratigraphic reconstructions in this region have shown that the Brahmaputra River was likely directed westward by this anticline during the late

Pleistocene (Williams, 2014). River redirection by tectonic activity would influence resultant stratigraphic composition and architecture, thereby potentially altering groundwater sources and flowpaths, and hence arsenic concentrations within tectonically active regions.

Arsenic Investigations

Given the vast number of people in Bangladesh consuming As contaminated groundwater, there is an urgent need to better understand the contaminant distribution and behavior. There have been a number of studies investigating the geochemical and hydrologic dynamics of As contamination in Bangladesh (e.g. Acharyya et al., 2000; Yu et al., 2003; Harvey et al., 2005; 2006; van Geen et al., 2008; Neuman et al., 2010). Two studies in particular, Neuman et al. (2010) and van Geen et al. (2008), highlight two viewpoints on the critical controls of As distribution. At their study site in the Munshiganj district of Bangladesh, Neumann et al. (2010) demonstrate that biogeochemical controls are the main influence on As distributions within Bangladesh aquifers. These authors show that local inputs of pond water recharge provide a source of labile organic matter to the shallow aquifer, which drive microbial respiration and reductive dissolution of iron oxyhydroxides, a process that releases As into the aquifer (Neumann et al., 2010). In contrast, van Geen et al. (2008) explored hydrogeologic controls on As distribution within different physiographic regions of the delta that vary in local slope, groundwater recharge rates, and aquifer grain size. Results showed that variance in As concentrations across these sites were due to grain-size related differences in local hydraulic conductivity. Rather than As distribution occurring solely as the result of iron-redox chemistry, they suggest that concentrations within shallow aquifers reflect the ability of an aquifer to ‘flush’ out mobilized contaminants. The conclusions of these two studies are not mutually exclusive, the authors simply disagree on which is the dominant control on As distribution.

Both biogeochemical and hydrologic controls on As are highly dependent on the stratigraphy and architecture of the aquifer, and in particular stratigraphic heterogeneity of the GBMD complicates the distribution of As. Correlations between As and stratigraphy have been investigated at both local and regional scales of Bangladesh to better understand the nature of the As distribution and determine adequate sources of un-contaminated groundwater. Weinman et al. (2008) investigated the stratigraphic heterogeneity within a shallow aquifer and found that high-energy channel environments and associated higher elevations (such as bars and levees) typically

have lower concentrations of groundwater As while low-energy channel environments that deposit fine grained material are associated with higher concentrations of groundwater As. Similar relationships between As, depositional environment and resulting stratigraphy were examined at a regional scale in this study. McArthur et al. (2011) and Hoque et al. (2012; 2014) studied the existence of stratigraphically distinct high and low As aquifers using soil borings from West Bengal, India and western Bangladesh. They recognized different types of shallow aquifers associated with paleo-interfluvial and paleo-channel sequences, the first defined by shallow Pleistocene deposits of oxidized brown sands usually capped by a thick paleosol, and the second defined by reduced grey sands capped by a thin silt or clay layer. Transect G traverses the southern front of one such paleo-interfluvial separating the Ganges and Brahmaputra valleys. The paleo-interfluvial sediments are characterized by low arsenic groundwater while the paleo-channel sediments contain arsenic contaminated groundwater. The paleo-interfluvial aquifers remain low in As due to the prevention of vertical migration of As contaminated water by the paleosol layer as well as the ability of the oxidized sediments to adsorb As within contaminated water transported laterally (McArthur et al., 2008; van Geen et al., 2013). By performing statistical analyses on groundwater As measurements throughout the country, Yu et al. (2003) conclude that large scale patterns of As distribution are controlled by differences in geologic and geomorphic regions. The present study takes a deeper look into relationships between stratigraphy and As concentrations by comparing detailed stratigraphy to measured As concentrations.

CHAPTER III

Methods

This study consisted of drill core samples to reconstruct stratigraphy, and bulk geochemical analysis as indicators of provenance. Water testing was conducted in the proximity of each borehole and quantitatively compared to groundwater As data collected as a part of BAMWSP. Finally, relationships between sedimentology and groundwater As data were explored.

Site Selection

Transect G begins at the western boundary of Bangladesh, just west of Khulna and transverses the country to the eastern border, just south of Comilla (Figure 1). The transect is located in the northern reaches of the fluvial-tidal delta within a region of generally higher As concentrations (Yu et al., 2003). The transition from fan delta to fluvial-tidal delta occurs further south in the western region; Transect G was placed entirely south of the slope change to allow for more direct comparisons between the Ganges and Brahmaputra deposited stratigraphy (Figure 1). Without the additional variable of this geomorphic change, we can better exclude that any lower concentrations are not due to increased flushing as a consequence of sandier stratigraphy and steeper head gradient.

To correlate stratigraphy with measured As concentrations within the groundwater, Transect G was also positioned with regard to available BAMWSP data (Figure 2). The BAMWSP project was conducted by the World Bank in an effort to reduce As poisoning, increase clean water supplies and increase treatment of As poisoning. As a part of the World Bank project, extensive groundwater field testing was conducted throughout Bangladesh (van Geen et al., 2006). Correlations of the sedimentological data with the observed As concentrations in tube wells across the same transect provide insight into geological influences on the distribution of As.

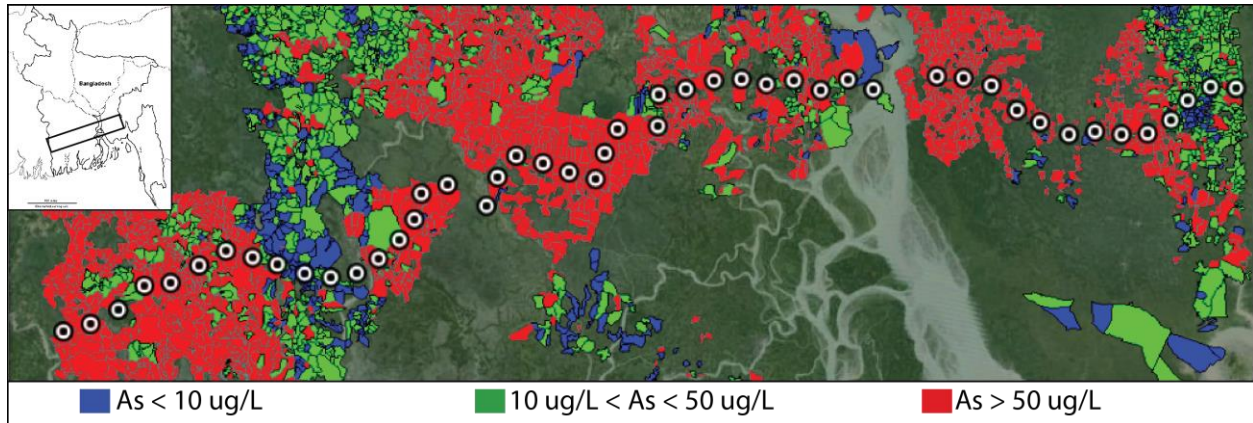


Figure 2. Transect G and BAMWSP data used in this study. Data is color coded by average As concentration in each mouza. Blue indicates average concentrations do not exceed World Health Organization (10 µg/L) or Bangladesh (50 µg/L) drinking water standards. Green indicates average concentrations exceed World Health Organizations standards but do not exceed Bangladesh drinking water standards. Red indicates average concentrations exceed both the World Health Organization and Bangladesh's drinking water standards.

Field Methods

Forty-eight boreholes spaced an average of 5.5 km apart were collected along the transect spanning the lower delta plain (Figure 1, Figure 3). Cores were drilled to a maximum of 91 meters below ground using a reverse-circulation, fulcrum-and-lever method. Samples were collected at 1.5m intervals with additional sample collection occurring where a substantial lithology change occurs. Descriptions of grain size, color and the presence of gravel or organic material were recorded during drilling (Pickering et al., 2014). A minimum of ten tube wells in a one-kilometer radius around each borehole were tested for As using Hach Arsenic Field Kits. Hach's As test kit manual mentions the detection limit of the test strips is 10 µg/L, the World Health Organization drinking water standard for As. van Geen et al. (2005) compared measurements of the Hach test strips to HR ICP-MS laboratory measurements of groundwater As in Bangladesh and found that 88% of wells accurately determined the contamination of wells relative to Bangladesh's drinking water standard (50 µg/L). Each sample in our study was measured one time. At the time of testing, the well depth and installation date were recorded. Electrical conductivity of the groundwater was measured using an HI98311 DiST 5 EC/TDC/Temperature Tester.

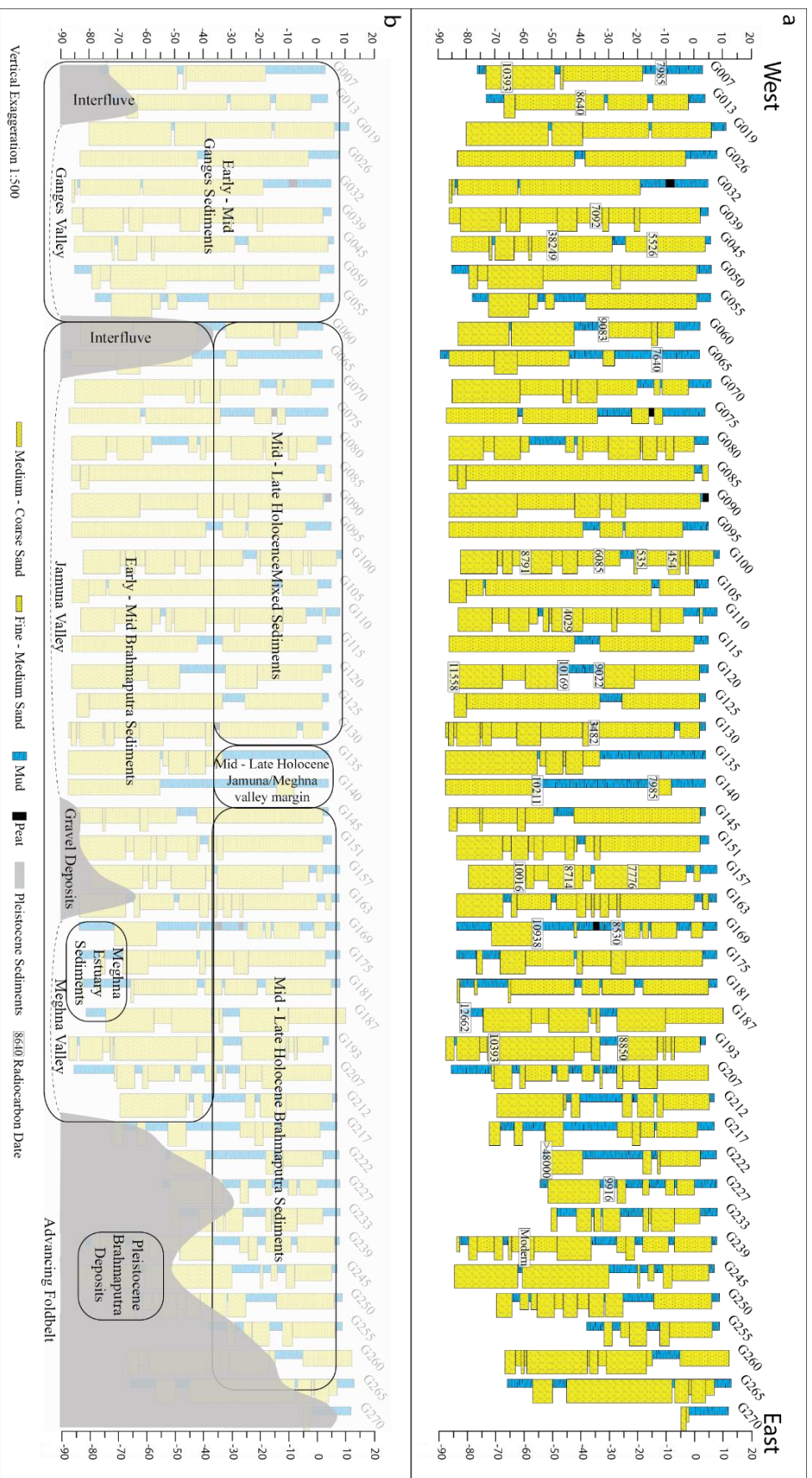


Figure 3. a) Stratigraphic cross section of Transect G. b) Annotated stratigraphic cross section.

Lab Methods

Cores were analyzed for lithology, provenance, and age. Provenance of the sediments is determined based on analytical measurements of Magnetic Susceptibility (MS) as well as measurements of bulk Sr concentrations. All samples were analyzed for bulk magnetic susceptibility (MS) using a Barrington Magnetic Susceptibility Meter. Generally, high MS values are indicative of Brahmaputra deposited sediments, low MS values are indicative of Ganges deposited sediments and median MS values are assumed to represent mixed sources (Pickering et al., 2014).

X-ray fluorescence (XRF) geochemical analysis was measured on every third sample until a lithology change was encountered. If a lithology change was encountered, that sample was analyzed regardless of position and every third sample from that point was analyzed until another lithology change occurred. The first and last samples were always analyzed. The bulk strontium (Sr) measured by the XRF is useful because, similar to MS, Sr is indicative of the provenance of fluvial sediments in the Bengal Basin (Pickering et al., 2014; Goodbred et al., 2014). As previously established, Sr concentrations greater than 140 ppm generally indicate sediments were deposited by the Brahmaputra River, Sr concentrations between 50 and 110 ppm generally indicate sediments were deposited by the Ganges River, and sediments between these two end members are assumed to represent mixed sources (Goodbred et al., 2014).

Once analytical measurements are determined, we look for vertically and laterally contiguous signals on the scale of the channel system in order to determine the migration and occupation history of the rivers. The distribution of Sr and MS in Transect G sediments (Figure 4) shows the general locations of the Ganges River in the west, the Brahmaputra River in the middle and the advancing fold belt in the east.

The age of sediments is established in two ways; first, Pleistocene sediments are visually identified and then the age of Holocene deposits is determined by radiocarbon dating. The Pleistocene boundary is distinguished by the presence of the paleosol oxidation surface, which represents a period of sea level lowstand within the late Pleistocene. The paleosol is generally underlain by oxidized brown/orange sediments (McArthur et al., 2011; Hoque et al., 2012; 2014; Pickering et al., 2014). Within Holocene deposited sediments, we determine the organic matter to be dated based on the quality of preservation as well as the overall distribution. We attempt to obtain a broad spread of radiocarbon ages that allow us to determine the depositional history of

the rivers (Figure 3a). Dates for 30 samples were obtained by the National Ocean Sciences Accelerator Mass Spectrometry Facility (NOSAMS) at the Woods Hole Oceanographic Institution. Raw radiocarbon ages were then calibrated using CALIB 7.1 software (Table 1).

Using the BAMWSP water data as well as groundwater As concentrations measured for this study, analysis of the distribution of arsenic was conducted. To make these comparisons, shallow (>91 m) groundwater As concentrations measured for this study (PIRE) were compared to various subsets of the BAMWSP dataset: 1) Only samples taken within the same mouzas as the samples collected for this study, 2) The data in group 1) as well as BAMWSP samples collected in nearest-neighbor mouzas, and finally 3) All BAMWSP data within a 50 km swath of the Transect G boreholes. (Figure 5)

Groundwater As concentrations were compared to stratigraphy by associating As measurements with the nearest Transect G borehole. Measurements collected during this study and BAMWSP measurements were then averaged in various groupings around each respective borehole (Figure 5; Figure 6). Measurements collected during this study and BAMWSP measurements collected within the same mouza were also grouped based on province and age (Figure 7).

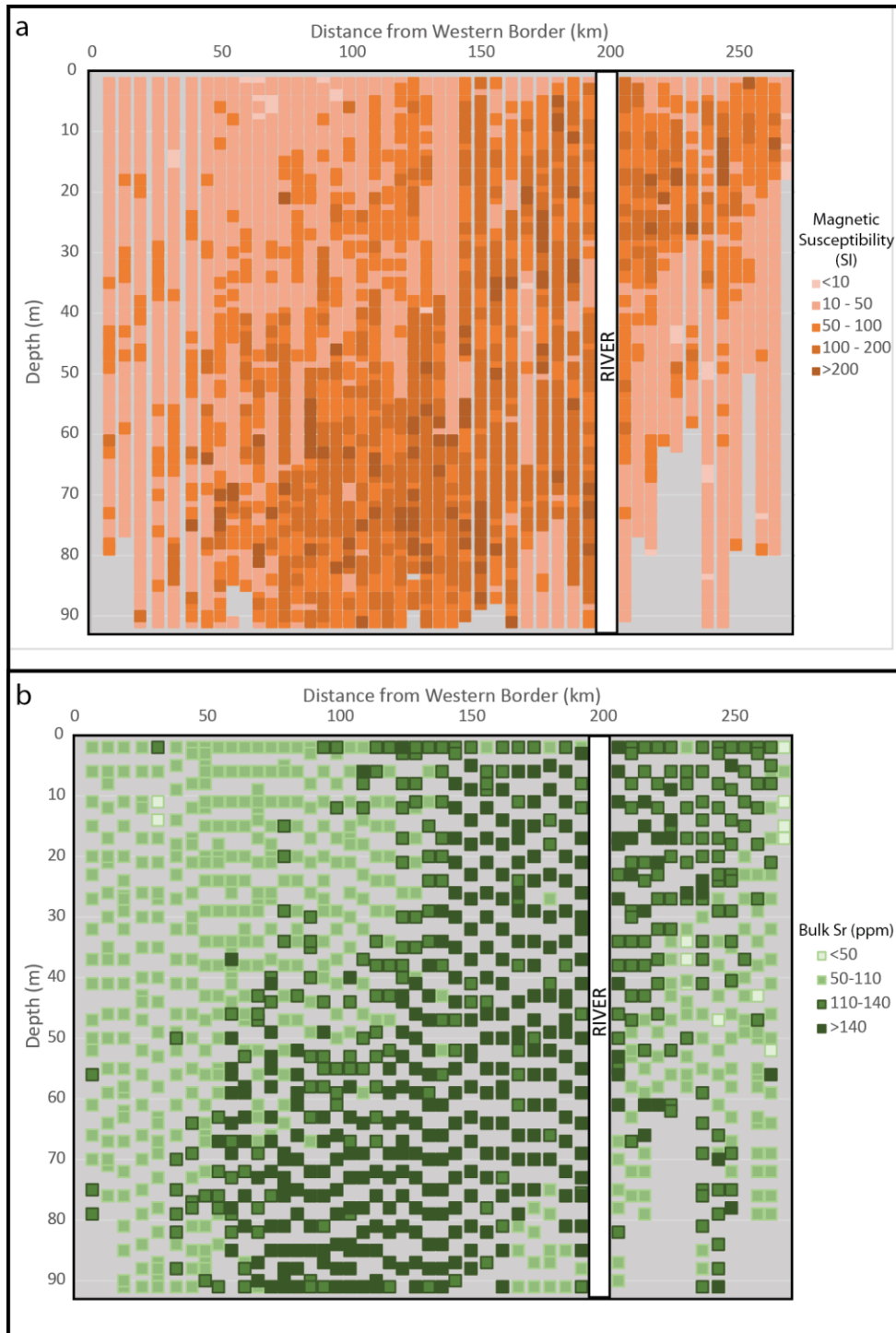


Figure 4. a) Magnetic Susceptibility (SI Units) measurements of Transect G sediments. b) Bulk Sr concentrations (ppm) of Transect G sediments.

Lab ID	Sample ID	Site	Depth (m)	Elevation	Material	$\delta^{13}\text{C}$	^{14}C age BP	Error	cal yr BP	2 σ upper	2 σ lower
OS-121287	BNG00715	007	15	-12	Plant/Wood	-28.86	7170	25	7985	7950	8019
OS-121209	BNG-G00769	007	69	-66	Plant/Wood	-28.98	9230	35	10393	10269	10505
OS-121337	BNG-G01344	013	44	-40	Plant/Wood	-26.37	7870	25	8640	8592	8752
OS-121338	BNG-G03940	039	40	-35	Plant/Wood	-27.84	6210	20	7092	7011	7235
OS-121339	BNG-G04521	045	21	-15	Plant/Wood	-12.4	4760	20	5526	5469	5584
OS-121340	BNG-G04556	045	56	-50	Plant/Wood	-25.19	33800	270	38249	37285	38867
OS-121341	BNG-G06035	060	35	-33	Plant/Wood	-29	8160	25	9083	9014	9243
OS-121342	BNG-G06515	065	15	-13	Plant/Wood	-27.35	6800	25	7640	7594	7676
OS-121343	BNG-G10014	100	14	-8	Plant/Wood	-27.79	370	15	454	330	498
OS-121344	BNG-G10024	100	24	-18	Plant/Wood	-26.17	525	20	535	514	619
OS-121345	BNG-G10040	100	40	-34	Plant/Wood	-28.32	5310	25	6085	5999	6181
OS-121346	BNG-G10064	100	64	-58	Plant/Wood	-27.96	7940	35	8791	8641	8979
OS-121347	BNG-G11050	110	50	-44	Plant/Wood	-15.33	3680	25	4029	3926	4090
OS-123351	BNGG12038	120	38	-34	Plant/Wood	-26.45	8090	40	9022	8785	9132
OS-123352	BNGG12050	120	50	-46	Plant/Wood	-28.89	8970	35	10169	9930	10228
OS-123353	BNGG12088	120	88	-84	Plant/Wood	-29.09	10050	35	11558	11361	11760
OS-123354	BNGG13040	130	40	-36	Plant/Wood	-27.86	3260	20	3482	3446	3561
OS-123355	BNGG14020	140	20	-16	Plant/Wood	-27.9	7170	30	7985	7943	8024
OS-123356	BNGG14059	140	59	-55	Plant/Wood	-30.43	9030	40	10211	10163	10248
OS-123357	BNGG15729	157	29	-23	Plant/Wood	-27.98	6950	30	7776	7690	7848
OS-123358	BNGG15750	157	50	-44	Plant/Wood	-27.98	7910	30	8714	8602	8973
OS-123359	BNGG15769	157	69	-63	Plant/Wood	-30.46	8860	30	10016	9786	10158
OS-123360	BNGG16934	169	34	-27	Plant/Wood	-28.93	7750	30	8530	8451	8592
OS-123309	BNGG16963	169	63	-56	Plant/Wood	-28.77	9610	40	10938	10774	11160
OS-123310	BNGG18791	187	91	-83	Plant/Wood	-26.38	10700	50	12662	12572	12721
OS-123361	BNGG19332	193	32	-25	Plant/Wood	-28.02	8010	30	8850	8774	9006
OS-123362	BNGG19376	193	76	-69	Plant/Wood	-28.86	9230	35	10393	10269	10505
OS-123363	BNGG22261	222	61	-53	Plant/Wood	-29.97	> 48000		> 48000		
OS-123402	BNGG22738	227	38	-30	Plant/Wood	-28.52	8840	95	9916	9610	10192
OS-123364	BNGG23970	239	70	-60	Plant/Wood	-28.85	>Modern		>Modern		

Table 1. Transect G radiocarbon data.

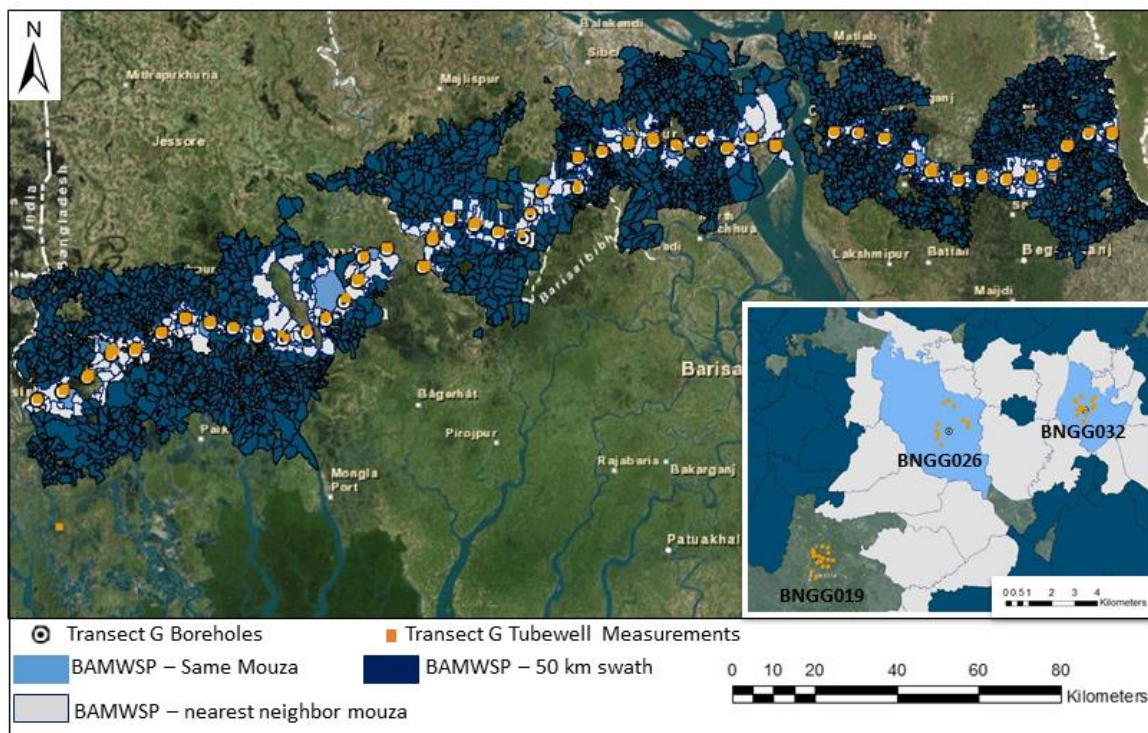


Figure 5. Map of Arsenic data subsets. Orange squares represent locations of tubewells sampled during this project. Mouza colors represent the different BAMWSP data subsets used to calculate average As concentrations.

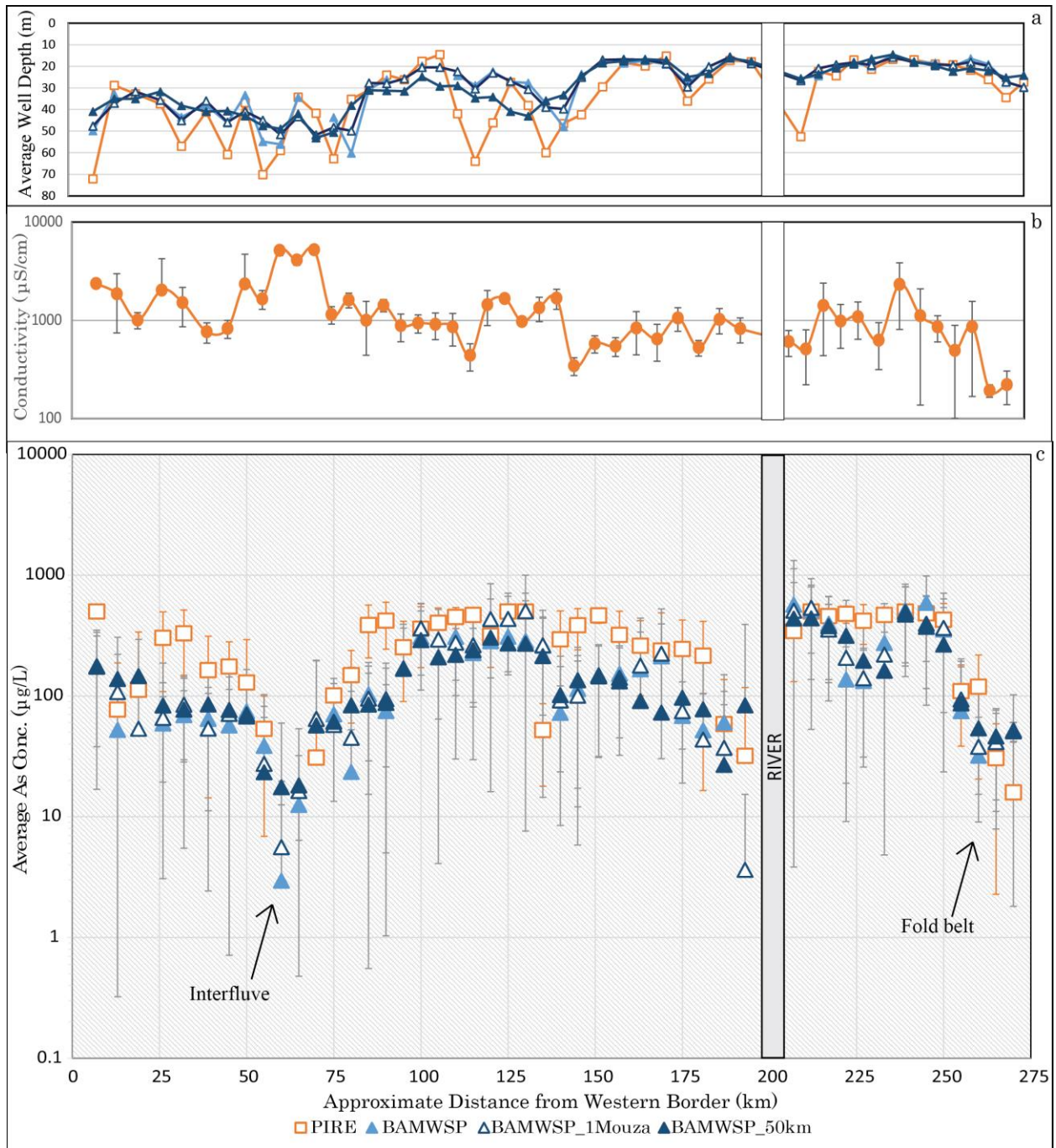


Figure 6. PIRE represents the data sampled for this study. BAMWSP represents a sub-set of the BAMWSP data that is within the same mouza as the PIRE data. BAMWSP_1Mouza represents a sub-set of BAMWSP data that is in the nearest neighbor mouzas of the PIRE data. BAMWSP_50km encompasses the entire 50 km swath of BAMWSP data around the Transect G boreholes. a) Average well depth of tubewells sampled for this study and for BAMWSP. b) Average PIRE conductivity measurements. c) Average As concentrations sampled for this study and for BAMWSP. Error bars represent one standard deviation of each of the data sub-sets.

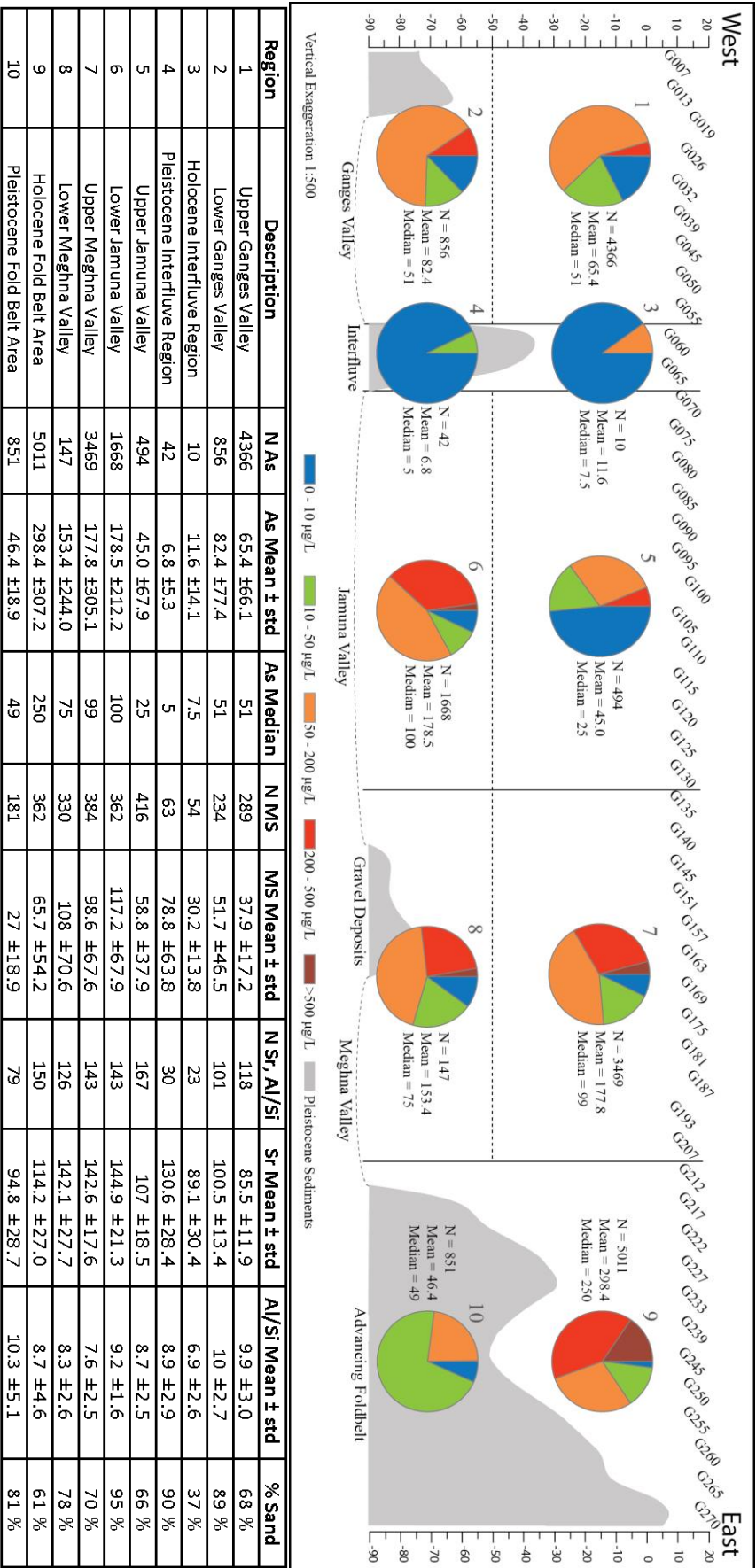


Figure 7. Measured As concentrations in the PIRE and BAMWSP same mouza data sets, organized into province regions. Region numbers correspond to descriptions in the table. The table also provides numerical information for each of the regions including the mean and median As concentration, mean MS, Mean Sr, Mean Al/Si and percent sand.

CHAPTER IV

Results

Stratigraphy

Discrete stratigraphic units within the GBMD can be distinguished by their lithology, provenance, and age. In general, the lithology of the GBMD consists of silty muds and coarse to fine sands. Typically, muds and sands are discrete lithofacies (Pickering et al., 2014; Goodbred et al., 2014). Transect G spans 270 km across the lower delta plain of Bangladesh and shows early Holocene sediments up to 91 mbgs (Figure 3a). Sediments are about 70% sand with most muds locally distributed. There tend to be coarser sediments at the base, which fine upwards through the section. We also observe generally coarser sands and more mud preservation in the eastern region of the transect.

From these cores and sediment characteristics, we identify four major provinces across the transect: the Ganges Valley, the Brahmaputra (Jamuna) Valley, the Meghna Valley and the west-advancing Tripura Fold Belt (Figure 3).

Ganges Valley

The western margin of the Ganges valley is seen in cores BNGG007 and BNGG013, where drilling terminated at 79 and 76 mbgs respectively, due to impenetrable deposits (gravel at BNGG007, stiff clay at BNGG013). We interpret the clay within these sections and the impermeable deposits to be the edge of a previously identified interfluvial divide that extends into West Bengal, India (Hoque et al., 2012; 2014). The eastern margin of the Ganges valley is found in cores BNGG060 and BNGG065 where we see coarse-grained sediments capped by a paleosol oxidation surface. This feature represents the southern extension of the low-stand interfluvial divide dividing the Ganges and Brahmaputra valleys.

Within the margins of the Ganges valley, drilling is completed prior to hitting a basal surface. The lithology in this region is generally coarser at depth and fines through the section. The thickness of the mud cap ranges from a few meters to upwards of 25 meters. The oldest radiocarbon age within this section is 10,393 cal BP. In core BNGG045 we obtained a radiocarbon age of 38,249 cal BP, but given the inconsistent nature of this age with respect to the other ages in this unit, we believe the material from which this date was obtained was likely reworked from older deposits.

In the upper half of sediments deposited in this region, the Sr and MS measurements reveal a pure Ganges signature. Sediments in the lower half of the section exhibit more of a mixed signature with Brahmaputra influences. We interpret this mixed signal at depth to be the result of tidal mixing that introduced Brahmaputra River sediments into the estuaries of this region during deposition.

Brahmaputra (Jamuna) Valley

The Jamuna Valley begins on the eastern side of the low-stand interfluvial and continues to the gravel deposits in the base of cores BNGG145, BNGG151 and BNGG157. These deposits represent the edge of the gravel valley base previously identified in upstream deposits of the Brahmaputra River (Goodbred and Kuehl, 2000; Montgomery et al., 2004; Pickering et al., 2014). Higher in the section, there are thick mud units within cores BNGG135 and BNGG140. We interpret this deposit to represent the Jamuna-Meghna valley margin during the mid-late Holocene. Cores within the Jamuna Valley were drilled to completion and no basal surface was encountered. Sediments in this valley are also generally coarser at depth and fine upwards through the section. Radiocarbon ages in this unit begin at 11,558 cal BP.

Sediments deposited at the base of this unit exhibit Sr and MS signatures indicative of deposition by the Brahmaputra River. Sediments within the upper half of this unit, however, exhibit Sr and MS signatures of a mixed Ganges/Brahmaputra source. This mixing represents the eastward shift of the Ganges River during the mid-late Holocene (Goodbred et al., 2014).

Meghna Valley

The Meghna valley begins on the eastern side of the gravel surface and continues to core BNGG217 where we encounter stiff clay underlain by coarse sand, which we interpret to be a Pleistocene surface. The base of this valley is composed of a mud unit 10 meters thick. Sr and MS measurements of these sediments reveals they were sourced from the Meghna River and radiocarbon dating gives a basal age of 12,662 cal BP. Within core BNGG187 the mud unit reduces to about 5 meters thick and within core BNGG193 it essentially disappears. Sr and MS measurements show the thinning mud layer is overlain by Brahmaputra sands indicating incision into this unit by the Brahmaputra River. Within core BNGG193 there is a full Brahmaputra sequence (coarse sands fining upwards to fine sands and eventually mud) beginning at about 70 mbgs and continuing up to about 25 mbgs. Radiocarbon dating at the base of this sequence

indicates it began around 10,400 cal BP and dating at the top of the section reveals completion around 8,850 cal BP.

Fold Belt

In the very eastern region of Transect G, distinct Sr and MS values reveal a clear fold belt signature (Figure 4). These sediments are oxidized and capped by muds, suggesting that they are Pleistocene in age. Radiocarbon dating just above the oxidation surface in core BNGG227 provides an age of 9,916 cal BP. The age and depth of this sample plot just above sea level (Figure 8) suggesting that this is a flooding surface that has experienced tectonic deformation. Additionally, peaks in the oxidation surfaces are spaced roughly 20 km apart, which is consistent with the Lalmai and Wari Betashar surface expressions of fold belt anticlines. Therefore, we conclude that these are buried anticlines associated with the advancing thrust front created by the subduction of Indian plate beneath the Burman Arc.

Within some cores (BNGG239, BNGG245, BNGG250), there is a clear Brahmaputra signal in the basal sediments. These sediments are not oxidized but we identify them as Pleistocene in age because, while the Sr signal remains strong, the MS signal has weathered out. This pattern has been previously identified in the Pleistocene deposits beneath Comilla terrace (Williams, 2014).

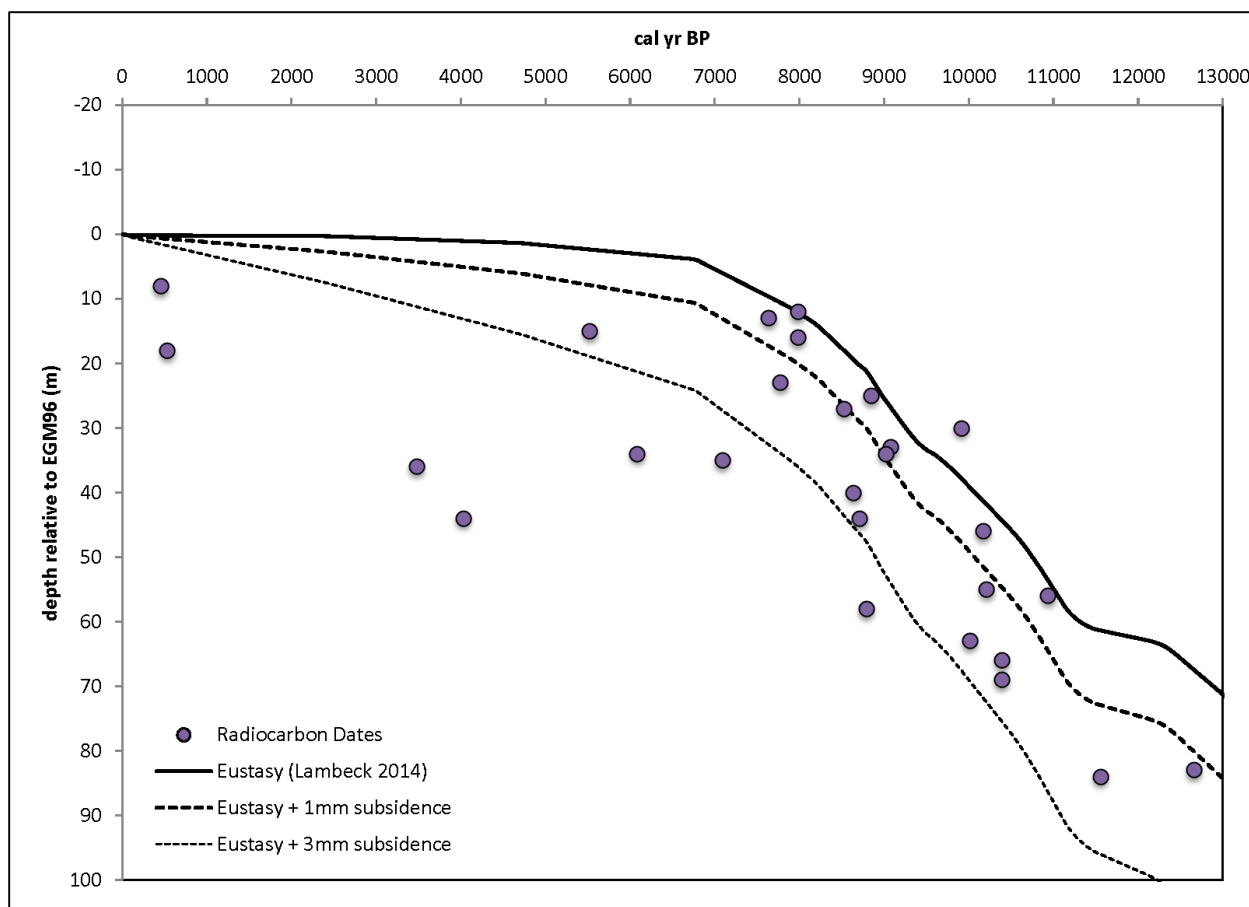


Figure 8. Transect G radiocarbon dates plotted with a Holocene sea level curve (Lambeck et al., 2014).

Shallow Groundwater Arsenic and Salinity

Collapsing the groundwater As and salinity measurements into average concentrations within the region of each borehole allows us to directly compare geochemical and stratigraphic changes across the delta. Despite the comparatively low sample size of the PIRE dataset (N=431) to the 50 km swath of BAMWSP data used (N=448,085), discrete populations emerge when we plot average As concentrations versus distance along Transect G (Figure 6c).

Within the Ganges valley, average concentrations for all three BAMWSP subsets generally hover around 100 $\mu\text{g/L}$. PIRE measurements collected within the Ganges valley, however, average $\sim 200 \mu\text{g/L}$ and range between 53 $\mu\text{g/L}$ and 500 $\mu\text{g/L}$. Groundwater As concentrations in the interfluvium between the Ganges and Brahmaputra valleys drops significantly to un-contaminated or near un-contaminated levels in all of our four data sub-divisions. Unfortunately, within this region of very low As concentrations we see a spike in conductivity to near 5,000 $\mu\text{S/cm}$ (Figure 6a),

which is above the Bangladesh Government guideline for salinity (2000 $\mu\text{S}/\text{cm}$) and is not even recommended for irrigation use (Hoque et al., 2003).

Within the Brahmaputra valley, two distinct groupings of As concentration averages emerge. Just east of the interfluvium, concentrations average around 100 $\mu\text{g}/\text{L}$. There is good agreement between the BAMWSP averages and the PIRE averages except for 85 and 90 km from the western border where PIRE concentration averages jump to ~ 400 $\mu\text{g}/\text{L}$. Continuing eastward, there is a 40km region where groundwater As concentrations are elevated in all datasets, averaging a few hundred $\mu\text{g}/\text{L}$. Between 120 and 140 km away from the western border, there is also a jump in salinity measurements, which elevate to ~ 1500 $\mu\text{S}/\text{cm}$.

Coincident with the mid to late Holocene Jamuna – Meghna valley margin seen in cores BNGG135 and BNGG140, there is a drop in average As concentrations to around 100 $\mu\text{g}/\text{L}$. These concentrations persist until the modern river, just beyond core BNGG193. Within this region, the PIRE averages remain elevated and we see some disagreement between the datasets.

On the eastern side of the modern river, concentrations spike to ~ 400 $\mu\text{g}/\text{L}$ for 43 km. Despite consistent well depths between 220 and 230 km away from the western border, concentration averages of all three BAMWSP data sub-sets drop to ~ 200 $\mu\text{g}/\text{L}$. Within this same 43 km region, average salinity concentrations rise and become more variable. This region is known to have groundwater with elevated As and salinity (Hoque et al., 2003; Yu et al., 2003). Average well depths for this region are particularly shallow, roughly 20 mbgs, in all datasets.

Although well depths remain shallow until we reach the eastern border, concentrations decrease to ~ 50 $\mu\text{g}/\text{L}$, Bangladesh's drinking water standard for As. In the easternmost two cores we also see a significant drop in salinity to ~ 200 $\mu\text{S}/\text{cm}$, the lowest seen in our measurements. This decrease in As concentrations and salinity is coincident with very shallow Pleistocene deposits of the advancing fold belt seen in cores BNGG255 through BNGG270 (Figure 3).

To better understand the relationship between groundwater As concentrations and stratigraphy, Transect G groundwater As measurements and BAMWSP measurements collected in the same mouza were associated with the stratigraphic provinces (Figure 7). Within the Ganges, Jamuna, and Meghna valleys, measurements were further divided into the upper valley and lower valley at 50 mbgs. Within the interfluvium and fold belt regions, measurements were further divided by whether they were screened in Pleistocene or Holocene sediments. The mean and median were calculated for the combined dataset within each of the 10 regions identified.

Overall, Figure 7 shows that concentrations generally increase towards the east, and that Pleistocene aquifers exhibit lower groundwater As concentrations than Holocene aquifers. In the Ganges valley, concentrations are fairly consistent throughout the section. The mean and median of the lower Ganges valley are 82.4 $\mu\text{g/L}$ and 51 $\mu\text{g/L}$, respectively, while in the upper Ganges valley, the mean is 65.4 $\mu\text{g/L}$ and the median is also 51 $\mu\text{g/L}$. The interfluvial region shows groundwater As concentrations are low in both the Pleistocene (mean = 6.8) and Holocene aquifers (mean = 11.6). We would not expect Holocene sediments above the interfluvial to exhibit such a low average (McArthur et al., 2008), but this likely due our small sample size within this region.

Within the Jamuna valley, there is a divergence between groundwater As concentrations in the upper and lower valley sections. Concentrations in the upper Jamuna valley average 45.0 $\mu\text{g/L}$, below Bangladesh's standard for As in drinking water. In contrast, concentrations in the lower Jamuna valley are high, averaging 178.5 $\mu\text{g/L}$. Moving eastward into the Meghna valley, concentrations remain high in both the upper (mean = 177.8 $\mu\text{g/L}$) and lower regions (mean = 153.4 $\mu\text{g/L}$).

Finally, in the fold belt region we see a large divergence between groundwater As concentrations in the Holocene and Pleistocene aquifers. The average concentration within the Holocene aquifer is 298.4 $\mu\text{g/L}$, the highest of any region in our transect. Just below this region, in the Pleistocene aquifers, the average concentration drops to 46.4 $\mu\text{g/L}$, below Bangladesh's standard.

CHAPTER V

Discussion

Our transect across the lower delta plain of Bangladesh captures the confluence of the three valley systems. The very narrow features separating these valleys indicate that the transect is just upstream of where the three merge before presumably connecting with the nearshore Swatch of No Ground canyon system. At the transect location, the interfluvial separating the Ganges and Brahmaputra valleys is merely ~10 km wide (BNGG060, BNGG065), or just one width of the rivers themselves. The boundary between the Jamuna and Meghna valleys is even more subtle, reflected only by several cores terminating at an impenetrable gravel layer that is characteristic of the lowstand Jamuna valley (Montgomery et al., 2004; Pickering et al., 2014) and by the abrupt shift from sandy Brahmaputra sediments to muddy, Meghna-derived sediments east of the basal gravel layer.

The stratigraphy overall is very sandy, although we do find more mud preservation than seen in upstream transects (Pickering et al., 2014). Calculations of the percentage of sand within each of our four provinces reveals Ganges valley sediments are about 79% sand, Brahmaputra valley sediments are about 75% sand, Meghna valley sediment are about 72% sand and the fold belt sediments are about 59% sand. These calculations also illustrate our observation that there is more mud preservation in the eastern region of the transect. Given the location of Transect G within the fluvial-tidal delta identified by Wilson and Goodbred (2015), as well as the proximity to previously drilled cores (e.g. Goodbred and Kuehl, 2000a), we expected to find much muddier stratigraphy. The abundance of sand in the base of our cores indicates that this area was a paleo-fan delta that developed into a fluvial-tidal delta with rising sea level in the mid-late Holocene.

Delta Evolution

Pleistocene

Interfluvial surfaces remaining after lowstand channel incision during the Pleistocene define the margins of the Ganges, Jamuna, and Meghna valleys. The lowstand Ganges valley is about 35 km wide or about three and a half times the width of the modern Ganges River. The Ganges valley width and location in our transect is consistent with the upstream paleo-channel deposits in the western cores of a transect drilled by Hoque et al. (2014). The lowstand Brahmaputra valley is about 80 km wide or about four and a half times the width of the modern

Brahmaputra River. The proportionally wider valley of the Brahmaputra River can be attributed to lake burst floods during the late Pleistocene, for which we see evidence in the gravel deposits on the eastern margin of the valley (Montgomery et al., 2004).

The Meghna valley begins on the eastern side of the gravel deposits and continues to the front of the advancing fold belt, which progressively displaces the Brahmaputra River. Provenance signatures buried within the fold belt provide evidence that the Brahmaputra River has previously routed into this region and potentially would again if it were not being actively excluded. The fold belt does not play a major role in the evolution of the delta, but we reference its influence here because of its relation to the distribution of As.

Early Holocene

During the early Holocene, the Ganges and Brahmaputra Rivers began rapidly infilling the Pleistocene lowstand valleys. Basal ages within the Jamuna and Meghna valleys show that this depositional phase began between 11,000 and 12,000 cal BP, just after the Younger Dryas. Climatic records from this time indicate there was an abrupt strengthening of the monsoon and rapid sea level rise (Weber et al., 1997; Goodbred and Kuehl, 2000b). We do not have age constraints on the Ganges Valley, although dated organic material just above the western interfluvial suggests similar basal ages.

All basal dates plot below sea level (Figure 8) indicating either these sediments were deposited below sea level or there is subsidence occurring. The subsidence theory would be consistent with the amount of flexural loading occurring in the delta due to an increased sediment load. Additionally, we have no indication of marine sediments such as heterogeneous lithology or marine fossils, rather we have clean, coarse grained fluvial sands. Therefore, the sediments must have been fluvially deposited near to sea level and later subsided.

Within the Ganges valley, provenance signatures indicate the Ganges River deposited approximately 70 meters of sediment within a period of about 3,500 years. Meanwhile, the Brahmaputra River deposited between 50 and 70 meters of sediment across roughly 130 km of the delta. About 20 meters of Meghna estuary sediments were deposited at the base of the Meghna valley before the Brahmaputra migrated over and began depositing fluvial sands in this region around 10,000 cal BP. In order to explain the deposition of this large volume of sediment over

such a wide area, the Brahmaputra River, fueled by a strengthened monsoon, must have been rapidly avulsing.

Mid-Holocene

Around 8,000 years ago, sediment deposition across the delta begins to decline as the rate of sea level rise slows and the monsoon weakens. The delta is prograding at this time and thus not trapping as much sediment (Goodbred and Kuehl, 2000a). Shallow radiocarbon dates within the Ganges valley are mid-Holocene in age indicating the Ganges River abandoned its valley during this time. Concurrently, sediments in the Jamuna valley begin to exhibit mixed provenance signatures, which suggests a migration of the Ganges River into this valley. A thick mud unit above the interfluvium in core BNGG065 establishes the new western margin of the Jamuna valley.

Meanwhile, provenance signatures and radiocarbon dates point to a temporally coincident eastward shift of the Brahmaputra River into the Meghna valley. This is consistent with upstream deposits that show the Brahmaputra was routing through Sylhet basin and into the Meghna valley between 7,500 and 5,500 years ago (Goodbred and Kuehl, 2000a; Pickering et al., 2014). It is not clear why sediments within the upper Jamuna valley exhibit Sr and MS signatures indicating mixed Ganges and Brahmaputra sources during this time, but we suspect it is due to the mixing of previously deposited sediments rather than river occupation.

Late Holocene

During the late Holocene, the majority of sediments are bypassing the delta and depositing off-shore (Goodbred and Kuehl, 2000a). Within the few late-Holocene sediments we do have preserved, we see evidence for a joint occupation of the Jamuna valley by the Ganges and Brahmaputra Rivers. Radiocarbon ages of organic material within core BNGG100 indicate late-Pleistocene deposition and provenance signatures suggest a mixed signal. The rivers are avoiding the region of cores BNGG135 and BNGG140 as evidenced by the thick mud unit separating the Jamuna and Meghna valleys. We are not sure why the rivers have been actively avoiding this area for the past 10,000 years, but it may simply be that it is a longer path to the coast and the rivers thus have no reason to avulse into this area.

Arsenic and Salinity

We find tractable trends in groundwater As concentrations across the lower delta plain of Bangladesh. By comparing these concentrations to detailed stratigraphy across the same expanse,

we evaluate relationships between stratigraphy and groundwater As concentrations at a regional scale.

Two areas of particularly low As concentrations stand out: the Ganges-Brahmaputra lowstand interfluvium and the west-advancing Tripura Fold Belt (Figure 3; Figure 6; Figure 7). Both of these regions are low in As because many of the tube wells are screened in shallow Pleistocene aquifers. The oxidized sediments of these aquifers adsorb As within the groundwater rather than release it, as is done by the reduction of iron-oxyhydroxides in grey Holocene sediments (McArthur et al., 2011). The interfluvium is the southern front of the feature previously identified by Hoque et al. (2014). The depth to Pleistocene in the interfluvium is 38 m and 47 mbgs in cores BNGG060 and BNGG065, respectively (Figure 3). In measurements collected as a part of this study, only one tube well sampled in this region is shallower than the depth to Pleistocene and no As was detected in any of the tube wells. Although this region is As free, conductivity measurements range between 3,770 $\mu\text{S}/\text{cm}$ and 5,790 $\mu\text{S}/\text{cm}$, well above 2000 $\mu\text{S}/\text{cm}$, the Bangladesh government guideline for salinity (Hoque et al., 2003).

The second low As region is found in the very eastern side of Bangladesh, coincident with the advancing fold belt. Hoque et al. (2014) identified this as a region low in groundwater As concentrations based on their observation of low As and Fe concentrations in DPHE groundwater data as well as the presence of a thick clay layer between 26 and 34 mbgs within DPHE well logs. As discussed above with regard to delta evolution, our stratigraphic reconstructions show that these low As aquifers are the result of the advancing thrust front, which has forced oxidized Pleistocene sediments higher in the stratigraphic section (Figure 3, Figure 4). The depth to the Pleistocene deposits in cores BNGG265 and BNGG270 are 23 m and 6 mbgs, respectively (Figure 3). Measurements collected in this region for the present study were all collected from tube wells screened within the Pleistocene sediments. In tube wells near BNGG265, four wells contained As above Bangladesh's drinking water standard (50 $\mu\text{g}/\text{L}$), four more wells contained As above the World Health Organization's drinking water standard (10 $\mu\text{g}/\text{L}$) and water within four wells was below both standards. In tube wells near BNGG270, three wells contained As above Bangladesh's drinking water standard and 14 wells measured As concentrations below both standards.

In borehole BNGG260 the depth to Pleistocene is 29 mbgs (Figure 3). Six out of 15 tube wells sampled in the region of this borehole were screened below the Pleistocene surface and water in two of those six tube wells was below both the Bangladesh and the World Health Organization

As drinking water standard. In borehole BNGG255 the depth to Pleistocene is 49 mbgs. Only one out of 13 tube wells measured is screened within the Pleistocene aquifer and the concentration measured in this well is 11 $\mu\text{g/L}$, just above the World Health Organization's drinking water standard but below Bangladesh's drinking water standard.

The oxidized sediments associated with the As-free groundwater also extends further west, but at increasingly greater depths (29-73 m) due to the west-sloping fold belt surface (e.g., cores BNGG 217-233, 245; Figure 3). None of the 63 wells measured in the area around boreholes BNGG 217 – 233, 245 were drilled deep enough to tap into the oxidized Pleistocene aquifers of the advancing fold belt. Concentrations in these wells range between 125 $\mu\text{g/L}$ and 500 $\mu\text{g/L}$, with 50 of the wells measuring 500 $\mu\text{g/L}$.

Our data shows that groundwater As concentrations in Pleistocene deposits of the fold belt are heterogeneous, but overall are much lower than concentrations in groundwater sourced from the adjacent Holocene deposits (Figure 6; Figure 7). We presume Pleistocene aquifers could provide low As groundwater, but the wells in these areas are screened at an average depth of ~20 mbgs and thus extract water from the As-bearing shallow Holocene aquifer. It is possible that the thick mud units in the Holocene deposits in many of these cores prevent people from accessing the deeper aquifers.

The fold belt region is also extremely low in salinity, with values ranging from just 130 $\mu\text{S/cm}$ to 400 $\mu\text{S/cm}$. Wells screened in the adjacent Holocene aquifer (BNGG 217-260) are overall higher, ranging between 230 $\mu\text{S/cm}$ and 1920 $\mu\text{S/cm}$. Adverse health effects are not expected from the consumption of water with these salinity levels.

Within areas of higher groundwater As concentrations seen in the Ganges, Brahmaputra and Meghna valleys, there are discrete regions of more or less contaminated groundwater having mean values of ~100 $\mu\text{g/L}$ to upwards of 400 $\mu\text{g/L}$ average As concentrations. Groundwater As concentrations in the Ganges valley, just east of the interfluvium and for 50 km just west of the modern river tend to average around 100 $\mu\text{g/L}$ while concentrations in the middle of the Jamuna valley and for 40 km east of the modern river average closer to ~400 $\mu\text{g/L}$ (Figure 6). Based on previous investigations that have explored the relationship between groundwater As and shallow stratigraphy (ie., Hoque et al., 2012; 2014; Weinman et al., 2008; van Geen et al., 2008) we considered multiple stratigraphic explanations for observed variations in groundwater As concentrations, including: (1) thickness of mud cap; (2) aquifer grain size; (3) sediment

provenance; (4) aquifer age. The thickness of the mud cap in each core was compared to the average As concentration in that region. It has previously been demonstrated in a localized environment that a thick mud cap is associated with higher groundwater As concentrations (Weinman et al., 2008). Our data shows no relationship between variations in groundwater As concentrations and the thickness of the mud cap at a regional scale. The study conducted by Weinman et al. (2008) showed small scale variances in As concentrations over tens of meters. If there is a mud cap control on the concentration of As in groundwater, we are not capturing it with our regional study, which examines variations across many tens to hundreds of kilometers.

van Geen et al. (2008) found that in wells less than 30 m deep within three localized areas of Bangladesh, variances in groundwater As concentrations were due to differences in grain size and resultant hydraulic conductivity. To evaluate grain size as a controlling factor on As distribution, we compared percent sand within the boreholes (Figure 3) as well as Si/Al ratios obtained through our XRF analysis with measured groundwater As concentrations. Within the Holocene sediments of our boreholes, sands compose between 42% and 95% of the total sediment. Plotting the percent sand within each borehole versus average As concentrations in that borehole reveal no correlation. Si/Al ratios of Transect G sediments fluctuate between ~3 and ~33. Variations in Si/Al ratios across Transect G do not resemble variations in groundwater As concentrations seen in Figure 6. We find that, at our regional scale, grain size is not a controlling factor on groundwater As distributions. We did not evaluate the hydraulic conductivity in these aquifers and therefore do not rule this out as a controlling factor.

Initial As results appeared to show higher As concentrations in the Jamuna valley relative to the Ganges valley, suggesting a possible provenance influence on As. Average groundwater As concentrations associated with individual boreholes reveal no correlation between provenance and groundwater As across our transect (Figure 6). However, separating the data based on province and age reveals clear differences between Ganges and Brahmaputra deposited sediments. Regions 1, 2 and 5 exhibit bulk Sr and MS signatures indicative of deposition by the Ganges River. In these regions, average groundwater As concentrations of the PIRE measurements and BAMWSP measurements within the same mouza range between 45.0 and 82.4 $\mu\text{g/L}$ and median concentrations range between 25 and 51 $\mu\text{g/L}$. Regions 6, 7 and 8 exhibit bulk Sr and MS signatures indicative of deposition by the Brahmaputra River. In these regions, average groundwater As concentrations range between 153.4 and 178.5 $\mu\text{g/L}$ and median concentrations

range between 75 and 100 $\mu\text{g/L}$. A Mann-Whitney comparison of these two datasets reveals that groundwater As concentrations within Ganges deposited sediments are statistically different from groundwater As concentrations within Brahmaputra deposited sediments ($p < 0.001$).

Finally, bulk Sr and initial As results showed that the Brahmaputra River was the source of sediments in the Jamuna in Meghna valleys where we see 40-50 km units of varying groundwater As concentrations (Figure 3, Figure 4). We explored the idea that different depositional ages of these units resulted in varying As concentrations by dating organic material within Transect G sediments, but our radiocarbon data indicates that this is not the case. Instead, as discussed earlier, we find that during the early Holocene the Brahmaputra River was rapidly avulsing and infilling valleys across 130 km of the delta (Figure 3). Additionally, Figure 7 displays the spread of groundwater As concentrations in the upper and lower Ganges valley (where sediments are all deposited by the Ganges River) and in the upper and lower Meghna valley (where sediments are all deposited by the Brahmaputra River). Within the Ganges valley, the means of the upper and lower regions are 65.4 and 82.4 $\mu\text{g/L}$, respectively and both regions have a median of 51 $\mu\text{g/L}$. Within the Meghna valley, the means of the upper and lower regions are 177.8 and 153.4 $\mu\text{g/L}$, respectively. The median of the upper region is 99 $\mu\text{g/L}$ and the median of the lower region is 75 $\mu\text{g/L}$. These results indicate that groundwater As concentrations are not governed by the depositional age of Holocene sediments.

In addition to examining correlations between groundwater As and stratigraphy, correlations between groundwater As concentrations and non-stratigraphic elements were examined. Unlike our stratigraphic comparisons where only shallow wells ($< 91\text{m}$) were considered, all groundwater measurements collected for this study were used to test the non-stratigraphic correlations. As concentrations were plotted against conductivity and well depth (Figure 9). Relationships between groundwater As concentrations and conductivity were not necessarily expected since the two parameters have different sources and function independently within the system. Figure 9a shows no correlation between groundwater As and conductivity. Well depths were compared to groundwater As concentrations because various studies have noted a peak in As concentrations around 30 mbgs (McArthur et al., 2001; Harvey et al., 2005; Neumann et. al, 2010). Our data does not exhibit a peak around 30 mbgs (Figure 9b). Although it seems that most of the deeper wells that we measured exhibit lower As concentrations, we still see fairly deep wells (up to 210 mbgs) with concentrations of 500 $\mu\text{g/L}$.

Ultimately, we find that regional As concentration trends are strongly dependent on the oxidation state of the sediments, which is observed in the lower concentrations of the interfluvial and fold belt. A Mann-Whitney comparison indicates that average groundwater As concentrations are significantly higher in the reduced Holocene aquifers than in the oxidized Pleistocene aquifers ($p < 0.001$). Within the more As contaminated groundwater extracted from Holocene aquifers, regional As trends do not relate to stratigraphic characteristics such as thickness of mud cap, grain size, or aquifer age. Sediment provenance, however, does play an important role and groundwater As concentrations are significantly lower in Ganges deposited sediments than in Brahmaputra deposited sediments.

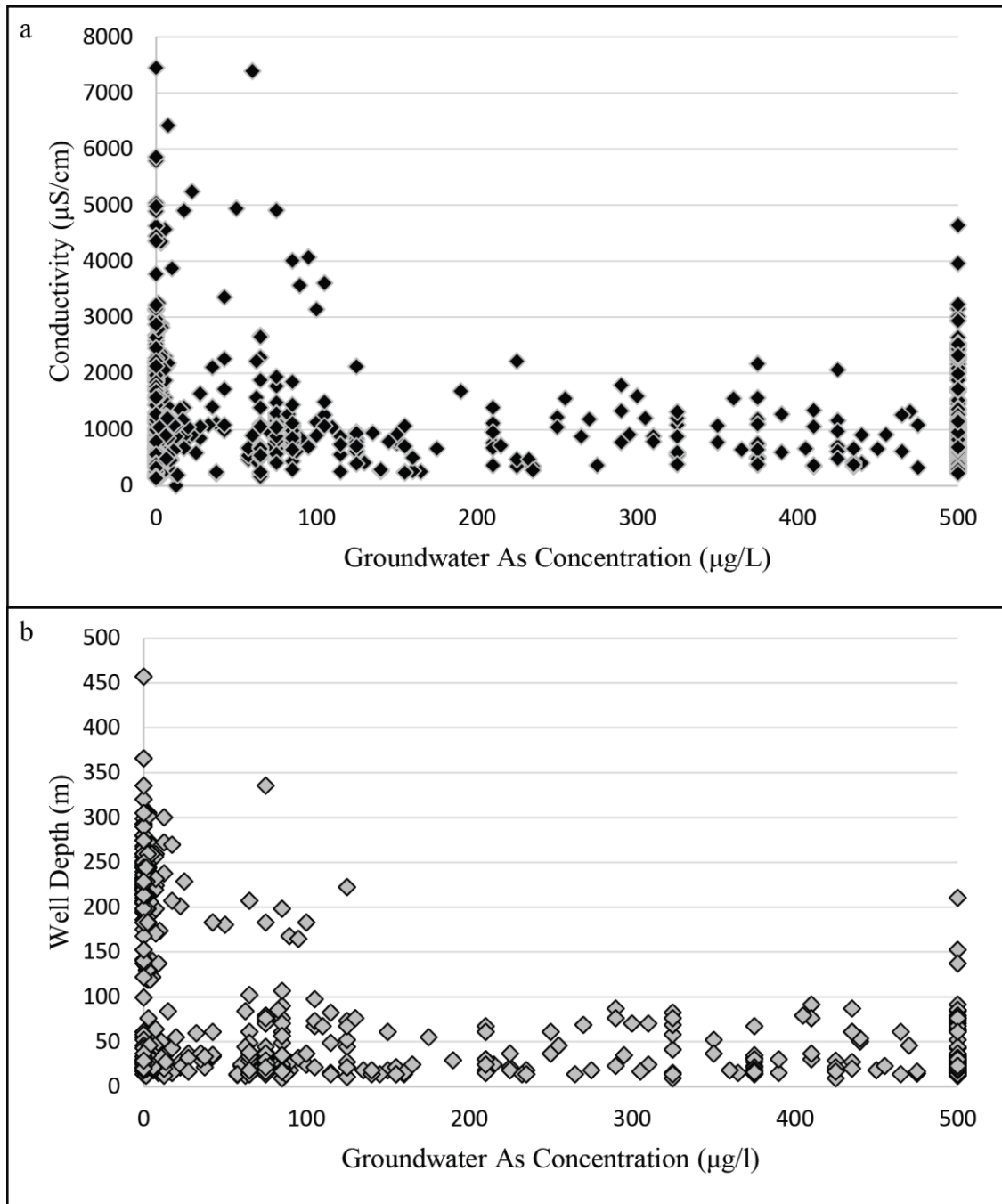


Figure 9 – a) Plot of conductivity measurements versus groundwater As concentrations. b) Plot of well depth versus groundwater As concentrations.

CHAPTER VI

Conclusions

Our transect traversing the lower delta plain of Bangladesh provides greater insight into the construction and evolution of the GBMD throughout the Holocene. The stratigraphy of our transect is comprised of 70% sand, much more than was previously thought to make up the stratigraphy in the lower delta plain. Provenance indicators show general locations of the Ganges River in the west, the Brahmaputra River in the middle and the advancing thrust front to the east. Radiocarbon dates help us to conclude that in the early Holocene the Ganges River was depositing sediments in a region three and a half times its modern size while the Brahmaputra Rivers was depositing sediments across 130 km of the delta. During the mid-Holocene, provenance signatures and radiocarbon dates show the eastward shift of the Ganges River. Finally, in the late-Holocene we see the convergence of the Ganges and Brahmaputra Rivers within the Jamuna valley (Figure 3).

By correlating our detailed stratigraphy and our understanding of delta evolution with groundwater As concentrations in nearby regions, we determine stratigraphic relationships to the widespread groundwater As contamination in Bangladesh. Our results show that generally oxidized Pleistocene deposited sediments have lower As concentrations than reduced Holocene deposited sediments. This is especially true in the interfluvial where our measurements do not detect any As contaminated groundwater in Pleistocene sediments. In the fold belt region, groundwater As concentrations are more variable, but still statistically lower than concentrations measured in the adjacent Holocene aquifers. All of the tube wells we measured in the area of cores BNGG 217-233, 245 are screened above the Pleistocene deposits and could potentially extract groundwater with lower As concentrations if they were drilled deeper. The largescale variations in groundwater As concentrations that we see in the contaminated regions across the delta can be attributed to provenance of the aquifer sediments. Aquifers composed of sediments deposited by the Ganges River are statistically lower in As than aquifers composed of sediments deposited by the Brahmaputra River.

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