CONTROLS, DISTRIBUTION, AND SIGNIFICANCE OF GRAVEL IN THE HOLOCENE STRATIGRAPHY OF THE BRAHMAPUTRA RIVER

By

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To my wife, for your love and patience;

To my family, for always being there;

In memoriam: my father, Wendell L. Hartzog, Jr.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

The densely populated country of Bangladesh lies in the Bengal Basin, and about two-thirds of its land area is comprised of the Ganges-Brahmaputra-Meghna Delta (GBMD; Figure 1). The GBMD, one of the thickest accumulations of fluvio-deltaic sediments in the world, is heavily influenced by climate and tectonics. Monsoonal rainfall causes high rates of erosion within the GBMD catchment while two adjacent collisional plate tectonic boundaries cause differential subsidence within the delta. The result is a fluvio-deltaic system with one of the world's largest sediment loads in which the fluvial dynamics, sediment dispersal, and preservation of stratigraphy are continually evolving.

The Brahmaputra River is a large braided stream that undergoes a transformation annually in response to the India Summer Monsoon (ISM). Increased discharge and sediment transport in the Brahmaputra River during the ISM cause rapid lateral channel migration. This lateral channel migration is the main factor that directly influences the modern physiography of the GBMD (Goodbred et al., 2003). However, the degree to which tectonics influence the behavior of the Brahmaputra River is still not fully understood. An over-arching goal of the BanglaPIRE project, of which this study is a part, is to further explore the evolution of this tectonically active fluvio-deltaic system through a multi-disciplinary approach. This study focuses on the Holocene stratigraphy of the

Brahmaputra River in Bangladesh as a record of changes in sediment source, transport, and preservation.

Motivation and Objective

The modern Brahmaputra River is primarily a sand bedload system even though flow velocities are sufficient to transport significant amounts of larger sediments (i.e. gravel). However, gravels are quite common in the upper stratigraphy near the apex of the GBMD (i.e. the point where alluvial plain broadens to become upper-delta plain). This suggests that either the fluvial processes responsible for landform evolution have varied (e.g. lateral channel migration), or sediment contributions from adjacent tributaries have been greater than previously thought. The main objective of this study is to develop a model for the origin of gravel lithologies within the upper stratigraphy of the modern Brahmaputra River valleys.

This study addresses the main objective by categorizing gravel lithologies, correlating their stratigraphic position with geochemical data from interstitial sands, and determining the significance of the geographic distribution of the resulting populations. The model for the origin of gravel deposits is discussed through answering the following specific questions:

1. What do the grain-size distributions of gravel sized sediment suggest about their origin?

2. How closely linked is gravel lithology with associated sand bedload geochemical variation?
3. Does gravel deposition favor specific fluvial structures (i.e. bars, channels, etc.)?
4. What controls (i.e. fluvial behavior, sediment availability, etc.) have the largest effect on gravel sedimentation?

It is expected that this model will prove useful to future investigations of channel morphology, channel locations, and the frequency of channel reoccupation in the Holocene stratigraphy of the GBMD.

Background

Ganges-Brahmaputra-Meghna Delta

About 100,000 km^2 of Bangladesh's ~144,000 km^2 of land is comprised of the GBMD. The GBMD is located adjacent to the intersection of two active plate boundaries; the Indian-Eurasian continental collision and Indian-Burma collision that is transitioning from subduction to continental collision (Figure 2; Steckler et al., 2008). Rapid uplift of the Himalaya and Burma Ranges within the catchment of the Brahmaputra River due to these collisions allows for continual bedrock incision and sediment production by run-off of India Summer Monsoon rainfall (Singh, 2006). A sediment load of over 1.0 Gt y^{-1} and rapid subsidence in the

GBMD are the main factors that cause the filling of the Bengal Basin with thicknesses of sediment reaching >20 km in some areas (Alam et al., 2003). This unique stratigraphic record holds evidence for changes in sediment provenance, fluvial processes, tectonics, and eustatic sea-level (Goodbred et al, 2003).

<u>Tectonics</u>

The GBMD is located in one of the most tectonically active regions in the world. The tectonic collisions responsible for building the Himalaya and Burma Ranges have also produced deformation fronts that are encroaching on the GBMD. The encroachment of these deformation fronts causes frequent ruptures along extensive networks of faults within the GBMD (Figure 2). While some ruptures associated with fold-belt propagation are minor, there is evidence of large ruptures that have directly influenced the course of the Brahmaputra River, namely the Dauki Fault (Johnson and Alam, 1991; Steckler et al., 2008).

North of Bangladesh, the Dauki Fault is directly associated with the advancing deformation front of the Indian-Eurasian collision zone. Motion on the Dauki Fault is responsible for the uplift of the Shillong Plateau. This uplift in turn directed the course of the Brahmaputra River around the Shillong Plateau to the west (Figure 3; Johnson and Alam, 1991). Furthermore, flexural loading due to uplift of the Shillong Plateau has formed the Sylhet Basin to the south of the Dauki Fault. This study will consider uplift and subsidence along the course of

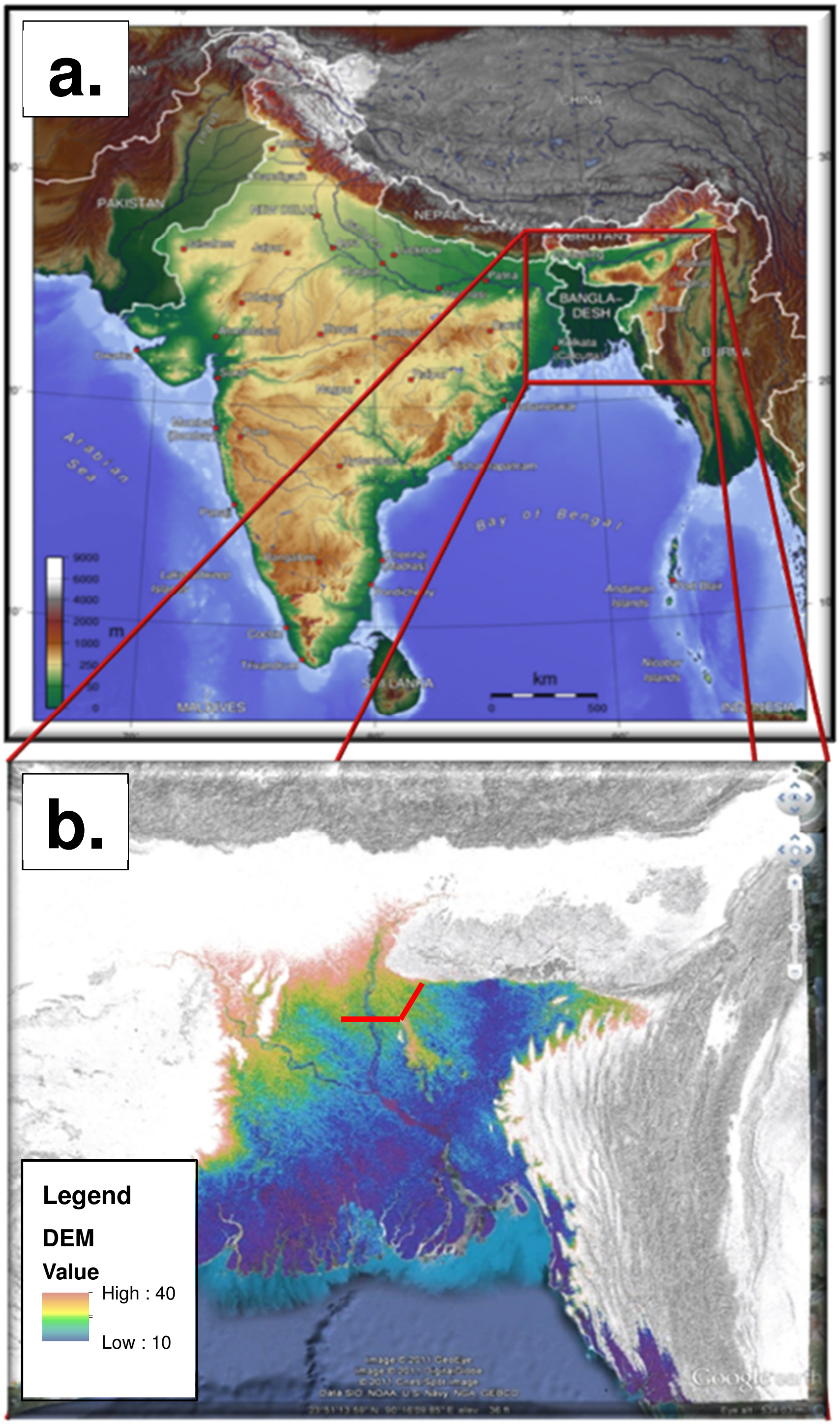

Figure 1. (a) Bangladesh is bordered by India to the West, North, and East, the Bay of Bengal to the South, and Burma in the Southeast. (b) A SRTM digital elevation model (DEM) is shown together with shaded relief. The DEM highlights the low-lying delta areas (<40 m elevation), and the red line indicates the approximate location of the drill line for this study.

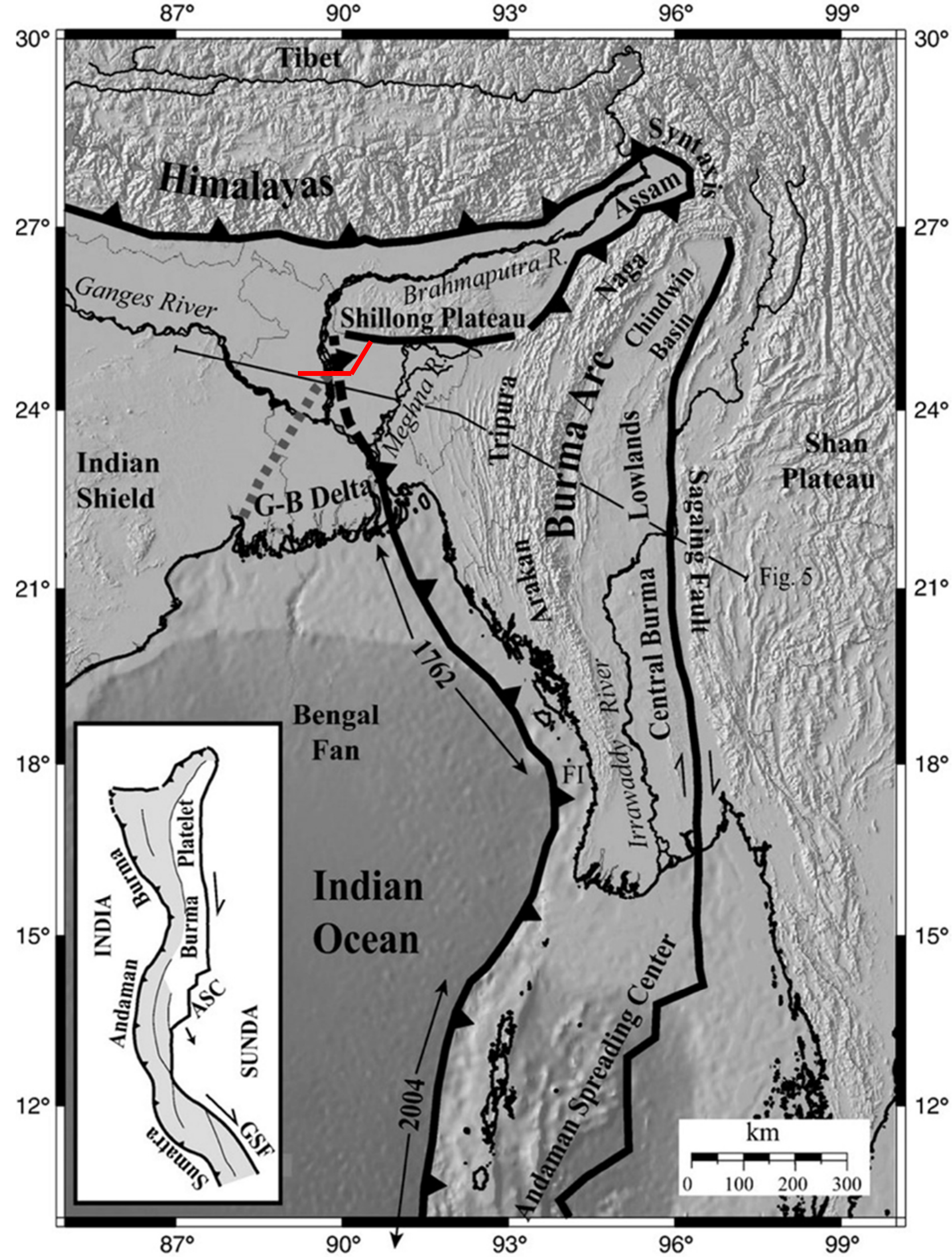

Figure 2. A map of the major plate tectonic features and shaded relief of the region surrounding the GBMD (from Steckler et al., 2008). The red line indicates the approximate location of the drill line for this study.

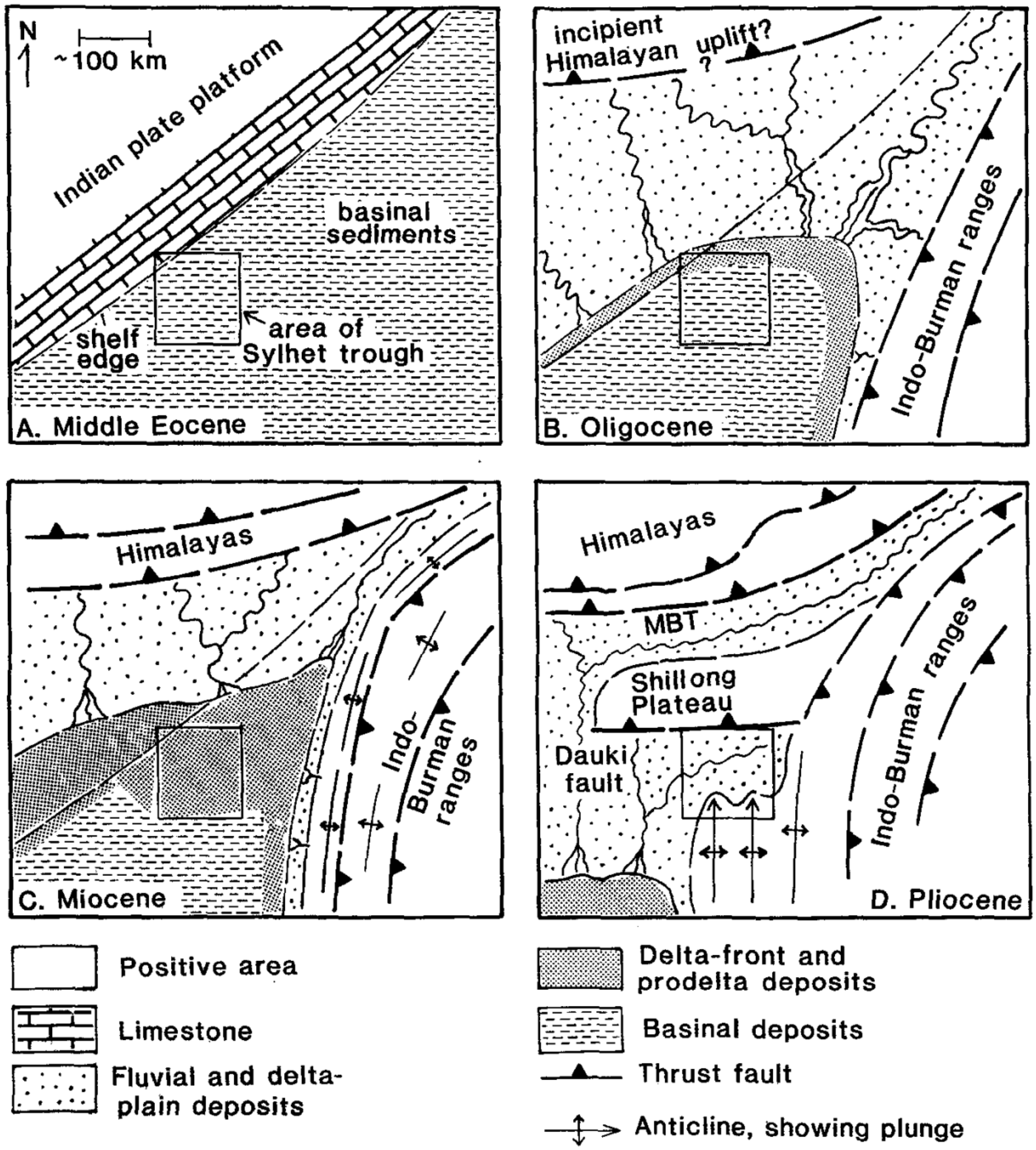

Figure 3. This series of schematics show the evolution of the GBMD and the deformation fronts that are encroaching on the GBMD (from Johnson and Alam, 1991). (d) Note the Pliocene development of the Dauki Fault, Shillong Plateau, and other fault and fold zones. The box in the middle of each schematic is the location of the present day Sylhet Basin.

the Brahmaputra River as controls on the presence of gravel in the Holocene stratigraphy.

Stratigraphy

Facies descriptions of Late Quaternary GBMD stratigraphy by Goodbred and Kuehl (2000) provide the context for this study's classification of gravel occurrences. The facies of interest are the Oxidized facies, Sand facies, and Thin Mud facies of the upper GBMD.

The Oxidized facies, described as stiff, orange to brown sediments, are interpreted to represent weathered paleosols of the Late Pleistocene lowstand (LPL). This facies is primarily composed of altered clays and iron-stained quartz sand lacking micas and heavy minerals. The Oxidized facies is preserved in paleo-uplands between lowstand alluvial valleys.

The Sand facies is described as clean, fine to coarse, gray sands with basal gravels and interbeds of the Thin Mud facies locally. This facies is interpreted as channel fill of alluvial valleys that would have initiated at the onset of transgression following the LPL. The basal gravels are interpreted to be indicative of the LPL sequence boundary.

The Thin Mud facies is interpreted as modern and recent overbank deposits. This facies is found overlying the Sand Facies near the ground surface throughout the GBMD. While interbeds of the Thin Mud facies are common near surface, they are mostly absent from the lower Sand facies stratigraphy.

Goodbred and Kuehl (2000) interpret this as evidence of erosion by lateral channel migration.

Determining the relationship between gravels in the Holocene stratigraphy of the GBMD and the facies of Goodbred and Kuehl (2000) is a major component of this study.

Avulsion History

The 1776 map of the provinces of Bengal and Bahar (Bihar) produced by the surveyor general of the East India Company, James Rennell, provide the first cartographic evidence of the avulsive nature of the Brahmaputra River (Figure 4). This map shows the large braided Burrampooter River (Brahmaputra) flowing east of the Madhupur Tract to its confluence with the Megna River (Meghna) northeast of the present day capital city of Dacca (Dhaka). Although the exact timing and length of the avulsion is debated, it is well noted that the course of the braided Brahmaputra mapped by Rennell is now occupied by an under-fit meandering river (i.e. a river too small to have carved the valley it occupies) named the Old Brahmaputra.

Rennell's map shows Seerpour (Sherpur) as a port on the eastern bank of the Old Brahmaputra. While Sherpur can be seen on modern DEM images to lie along the edge of the Old Brahmaputra braid-belt, the old port now lies ~7 km from the Old Brahmaputra River. The present day Brahmaputra River, now known as the Jamuna River in Bangladesh and referred to herein as the

Brahmaputra-Jamuna River when distinguishing between the two courses, flows ~30 km west of Sherpur, west of the Madhupur Tract to the Meghna confluence.

Cartographic evidence described by Best, et al. (2007; Figure 5) supports the avulsive behavior of the Brahmaputra River, but it does not answer the question of whether the mode of avulsion is catastrophic channel reoccupation, gradual lateral migration and stream capture, or any other possibility. By determining the processes responsible for the incorporation of gravel to the Brahmaputra River, this study hopes to provide evidence that will be applicable to answering this type of question.

Source Terranes and Strontium (ppm)

The Brahmaputra River and its tributaries drain a diverse group of terranes that are described in detail by Garzanti, et al. (2004). Due to their relevance to this study, the terranes of Shillong Massif and the Himalayan terranes drained by the Tista River that contribute to the Tista megafan are detailed in Table 1. Direct correlations can be drawn between the assemblage of lithologies within a catchment and the lithologies of that river's bedload sediments, which directly affect geochemistry (Garzanti, et al. 2004, 2010). This idea is central to the correlation of gravel lithology to sand bedload geochemistry for the determination of source terranes of gravel found in the upper stratigraphy of the GBMD.

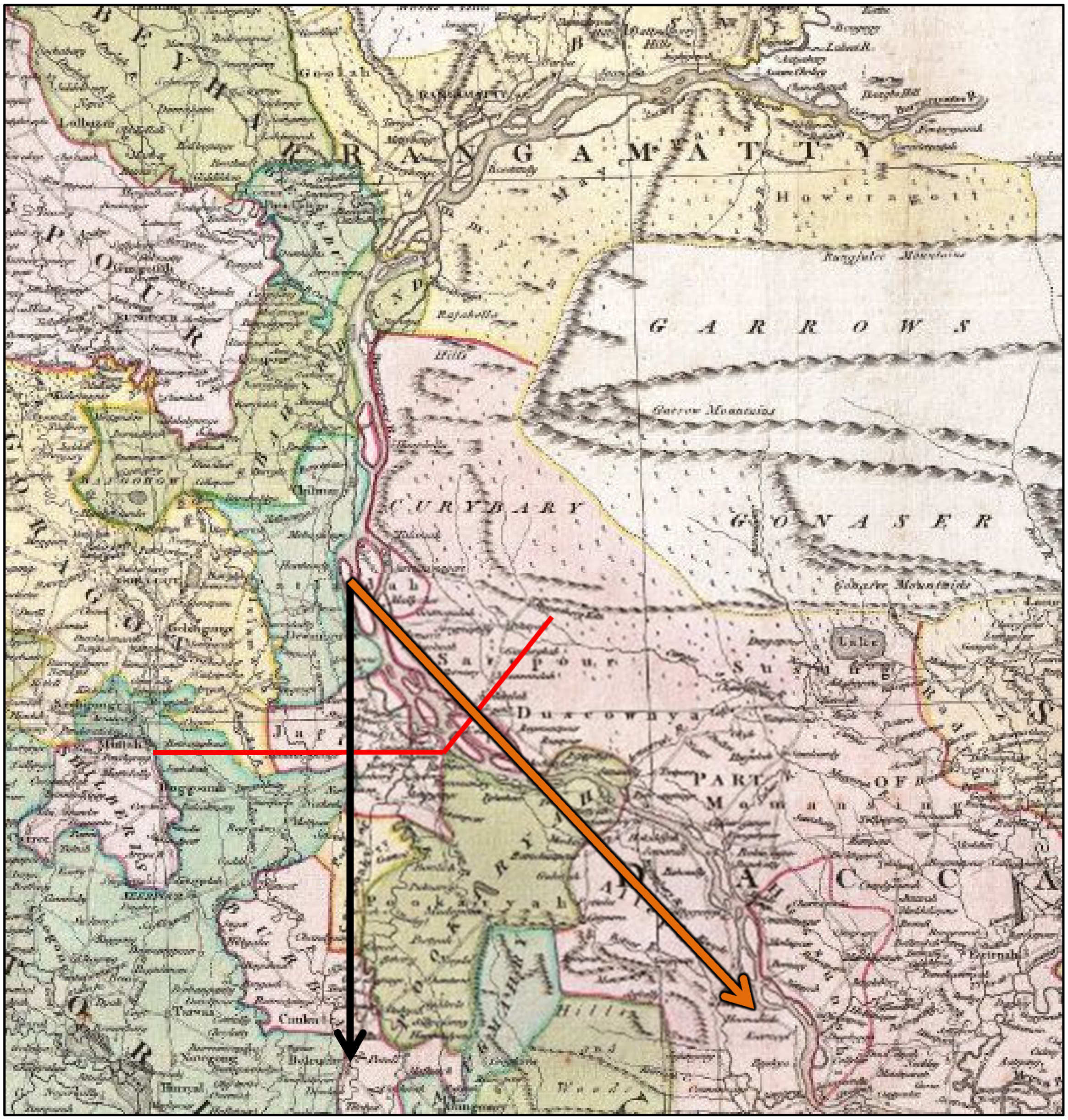

Figure 4. This excerpt from the 1776 map by James Rennell shows the course of the Brahmaputra River flowing to the east of its present day course to the Bay of Bengal. The orange and black arrows represent the courses of the Old Brahmaputra and Brahmaputra-Jamuna Rivers respectively. The red line approximates the drill line for this study. Figure 5 compares the two courses mentioned here.

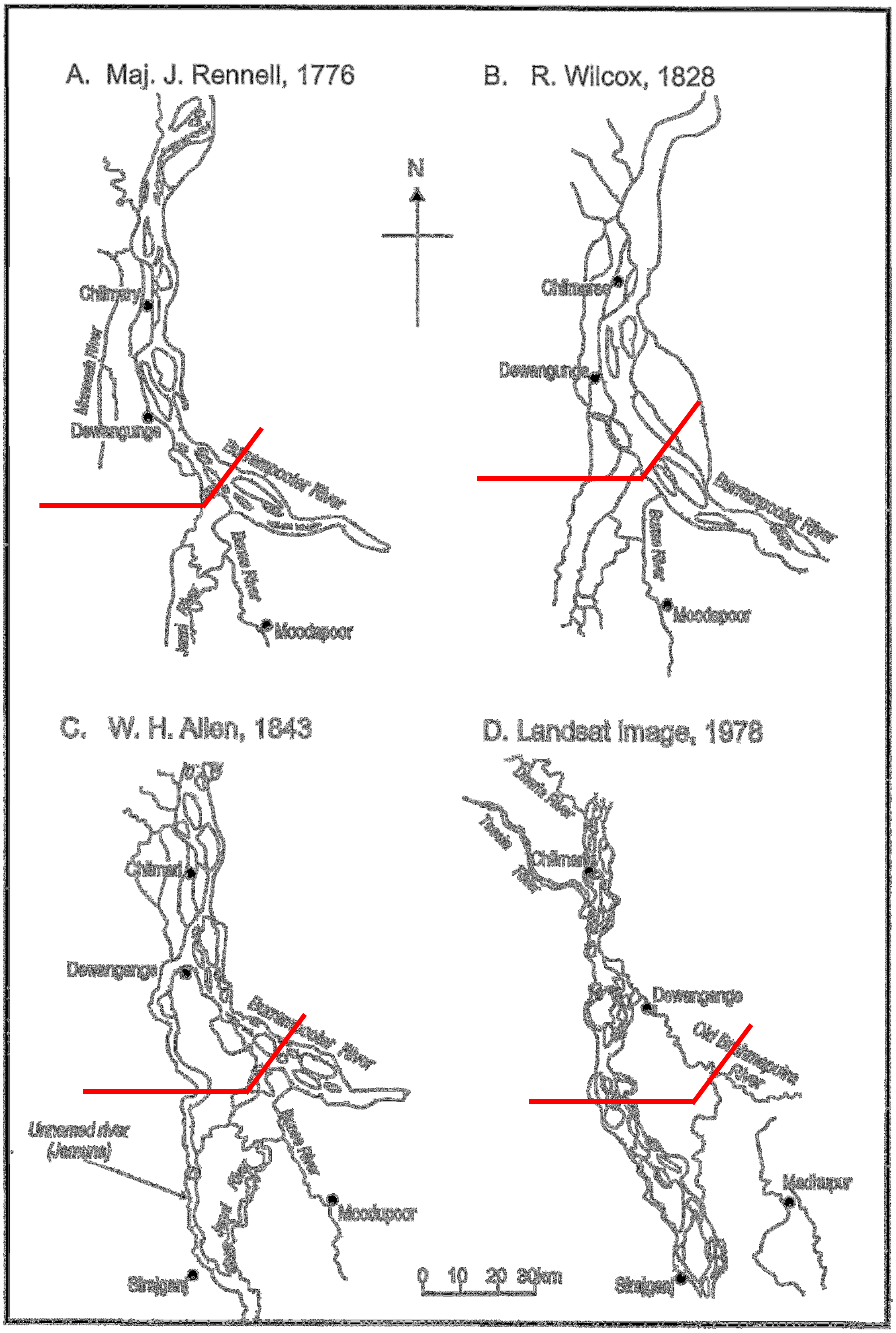

Figure 5. The cartographic evidence of the most recent Brahmaputra River avulsion event is detailed here in a series of figures outlining the Brahmaputra's course at different dates (from Best et al., 2007). The red lines approximate the location of the drill line from this study.

The Brahmaputra River stretches more than 2800 km along a path from the headwaters in a glacial mass at Kailash Mountain (~5200 m elevation) on the southern side of the High Himalayas to the Bay of Bengal (Islam et al., 1999). With such a great length and a catchment of ~640,000 km^2, the Brahmaputra has many sources of runoff and erodes many terranes with distinct geochemical signatures (Table 1; Islam et al, 1999; Singh, 2006, 2007; Singh and France-Lanord, 2002). The dominant strontium (Sr) concentration (ppm) source signatures in the catchment are: 400 ± 100 ppm in the Transhimalaya plutonic belt, and 70 ± 20 ppm in both the Higher Himalaya (HH) and Lesser Himalaya (LH).

The Sr (ppm) of Brahmaputra River sediments are considered to reflect mixing of the geochemical signatures of the source terranes in proportion to their contribution to the overall sediment load (Garznati, et al., 2004, 2010; Goodbred, et al., 2003; Singh and France-Lanord, 2002). When identified in fluvial deposits, variation in the geochemical signature of Brahmaputra bedload sediments provides insight into the controls on sedimentation throughout history. For example, earthquakes can alter the sediment flux from specific tributaries through landslides, channel cut-off, or avulsion (Kale, 2002). Because of complex lithologic assemblages present in the catchment, the variation in sand bedload Sr (ppm) is essential to determining the origin and controls on gravel deposits in the Brahmaputra River stratigraphy.

Table 1. Tista River and Shillong Plateau lithologies and geochemical signatures

Catchment/River	Terrane	Lithology	Sr (ppm)	Sr 87/86
Tista Basin	Transhimalaya Plutonic Belt	gabbro, diorite	400 ± 100	0.705 ± 0.004
	Higher Himalaya (HH)	schist, gneiss, marble, amphibolite, migmatite, leucogranite, calc-schist	70 ± 20	0.750 ± 0.02
	Lesser Himalaya (LH)	quartzite, schist, orthogneiss, dolerite, dolostone, shale, pebbly mudrocks, quartzose sandstone, coal, tillites, molasse	70 ± 20	0.850 ± 0.05
Tista River	bank sediments	quartz, feldspars, high-rank metamorphic rock fragments, micas, green-brown hornblende, garnet, and sillimanite	90 ± 3	0.817 ± 0.008
Shillong Plateau	Shillong Massif	amphibolite facies gneiss, basalt (Sylhet Traps), Tertiary shelf sediments	no data	no data
Basistha Dhara River	bank sediments	quartz, microcline, blue-green to green-brown hornblende, basalt to dolerite, laterite soil clasts	47.3	0.750154

Data and lithology descriptions from Singh and France-Lanord (2002) and Garzanti, et al. (2004); Only one data point for Sr (ppm) and Sr 87/86 of Shillong Plateau tributaries (Basistha Dhara).

Study Area

Selection of the study area for this investigation is motivated by the over-arching goal of the BanglaPIRE project to advance the understanding of fluvio-deltaic processes in a tectonically active basin. One main objective of the BanglaPIRE project is to assess the Holocene avulsion history of the Brahmaputra River using evidence from the Late Quaternary stratigraphy. Therefore, this study focuses on a transect that crosses both the Brahmaputra-Jamuna and Old Brahmaputra River alluvial valleys ~45 km south of the avulsion node.

The area of interest is located near the apex of the GBMD in Bangladesh. Figure 6 shows the line used to select drilling locations for this study, BNGA. BNGA is 123 km long, and it transects each of the minor geomorphic features of the area. BNGA stretches 70 km west to east from the city of Bogra across the Brahmaputra-Jamuna alluvial valley to the city of Jamalpur on the west bank of the Old Brahmaputra River. BNGA continues northeast crossing the Old Brahmaputra alluvial valley from Jamalpur through Sherpur to the border of Bangladesh and Meghalaya, India.

The stratigraphy of the GBMD along BNGA consists of Pleistocene terrace deposits (Oxidized facies), Holocene channel fill of the Brahmaputra River's low-stand valleys (Sand facies), and well preserved floodplain deposits (Thin Mud facies). The study area also sits in close proximity to 3 major geomorphic/tectonic features: the Himalaya orogeny, the Tista megafan, and the Shillong Massif.

Each of these features has a direct influence on the behavior of the Brahmaputra/Jamuna River (i.e. sediment load, basin deformation, concentration of monsoonal rainfall, etc.). Therefore, the study of Brahmaputra River stratigraphy in this area of the delta is crucial to determining where tectonics and climate have the greatest effect on the river's behavior in the GBMD.

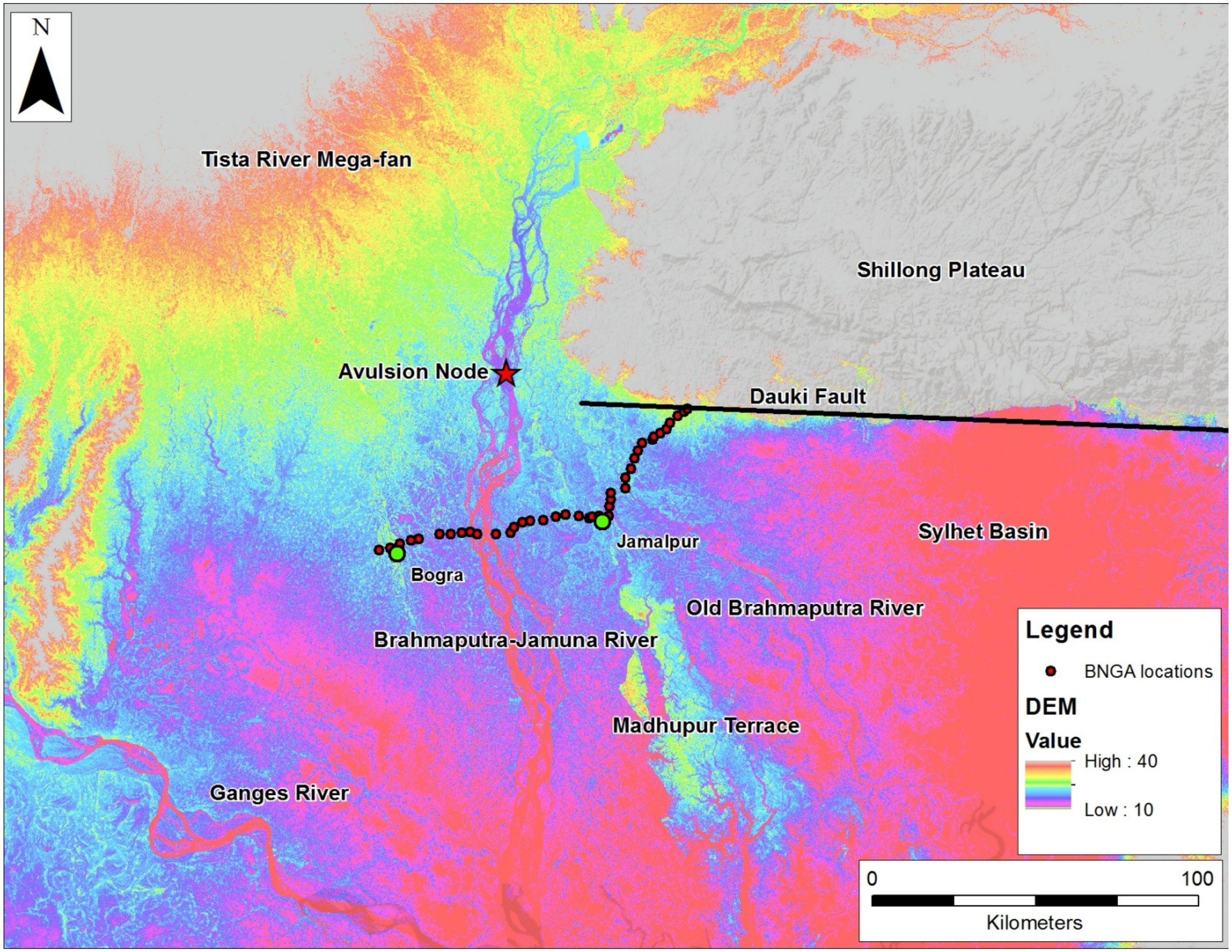

Figure 6. Map of project area with BNGA locations and Digital Elevation Model (DEM).

CHAPTER II

METHODS

Field Methods

In the spring of 2011, 41 locations along BNGA (Figure 6) were drilled using a local hand driven reverse circulation tube well installation technique. Locations were selected based on the latitude and longitude of each one kilometer interval recorded from the digitized line for BNGA in Google Earth, the use of handheld GPS to locate these locations, and proximity to a water source (i.e. pond or river) for the reverse circulation drilling. A three to four kilometer spacing of drilling locations was chosen to maximize coverage of the drilling campaign. This strategy allowed BNGA to transect both the Jamuna and Old Brahmaputra River valleys. Nine days of drilling and sample collection training were conducted along with graduate students from the Department of Geology at Dhaka University, Dhaka, Bangladesh. Thereafter, the team of Dhaka University graduate students overlooked the drilling campaign and returned samples via air freight to Vanderbilt University.

The local reverse circulation technique is a simple but highly effective technique for drilling through the unconsolidated sediments that cover most of Bangladesh. A rig of bamboo is lashed together with rope in a configuration consisting of two upright poles and one pole horizontal across the other two. An approximately half meter deep settling pit is dug in front of the rig and filled with water that will back fill the annular space of the borehole. Penetration by the drill string is achieved by manual operation of a lever that is lashed to the cross-bar of the bamboo rig and connected to the drill string by an adjustable chain (Figure 7).

Figure 7. This hand driven reverse circulation drilling technique is an economical and efficient method for sample collection from the unconsolidated fluvio-deltaic stratigraphy in Bangladesh.

In order to sample at five foot intervals, the primary drill pipes are five foot steel segments. Under the weight of the steel, the first fifteen feet are drilled. Then, the ten and fifteen foot intervals are replaced with a fifteen foot PVC pipe.

Therefore, the next depth before adding to the drill string is twenty feet. Drilling continues with the same rotation of two, five foot segments for a fifteen foot PVC segment to ensure accurate sampling at five foot intervals up to the goal of three hundred feet depth per day.

In order to drive the reverse circulation, a team member achieves suction on the top of the drill string using the palm of their hand as a check valve. As the remaining team members operate the lever, the water and cuttings within the drill string are expelled into the settling pit with every descending blow of the drill string. When the next five foot interval is reached, the lever operators pump quickly without penetration in order to drive an adequate amount of sediment sample from that interval to the surface for collection into a bucket by the check valve operator. The sample is drained of slime, logged by the geologists (i.e. depth converted to meters, grain size, and color), and sorted in duplicate for Vanderbilt University laboratory analysis and the foundation of a Bengal Basin sedimentology repository at Dhaka university.

Laboratory Methods

X-ray Fluorescence (XRF) Spectroscopy

X-ray fluorescence spectroscopy is used for bulk sample major and trace elemental analysis of igneous, metamorphic, and sedimentary rocks. The excitation of an electron in an inner shell of an atom by an incident X-ray leads to electrons from higher energy levels moving to lower shells to fill vacancies. The energy difference is emitted as X-rays, or fluorescent radiation. Fluorescent radiation energies are unique for every element on the periodic table. By measuring intensity of fluorescent radiation at specific energies, it is possible to determine not only the presence of an elemental component but also its abundance within a sample (i.e. parts per million, parts per billion, etc.) (Jenkins, 1999).

444 samples collected from the stratigraphy of the Brahmaputra River along BNGA were prepared for XRF analysis in the laboratories of Vanderbilt and Middle Tennessee State Universities. As discussed earlier, strontium (Sr) concentrations (ppm) of the silicate fraction of bulk sediment provide a reliable provenance indicator. In order to de- carbonate, samples were combusted at 600° Celsius for 48 hours. Further treatment of samples by leaching with a solution of deionized water and 10% by volume acetic acid assured no bias on Sr (ppm) results due to substitution for calcium (Ca) in carbonate minerals. The acetic acid leachate solution was drained from the samples, and the samples were dried in an oven at 50° C for 24 hours.

The sediment samples were crushed using a carbide steel grinding container and puck in a shatterbox shaking device. The resulting powders (< 4.0 micrometers) were pressed into pellets at approximately 11,000 psi without the use of bonding agents. The pellets were then analyzed for major oxide weight percent (wt%) on an Oxford Instruments MDX-1080+ multi-dispersive X-ray fluorescence spectrometer at Middle Tennessee State University. Analysis for Sr (ppm) was conducted on a Thermo Scientific Niton XL3t XRF Analyzer at Vanderbilt University.

Laser Diffraction Particle Size Analysis

Laser diffraction particle size analysis determines the size of the particles of a sample based on the angle and intensity of light scattered as they are passed through the path of a laser beam. Large and small particles scatter light at different angles and intensities, and the information collected from the pattern and intensity of the diffracted light is converted into particle size distributions (Ryzak and Bieganowski, 2011). The output from the instrument is a robust statistical dataset that includes mode, mean, standard deviation, and cumulative percentile values.

Laser diffraction particle size analysis was conducted using a Malvern Instruments Mastersizer2000 with Hydro MU adapter at Vanderbilt University. Ryzak and Bieganowski (2011) provide detailed descriptions of the instrument, adapter, components, operation, and limitations. The ultrasonic probe was utilized for 20 seconds for maximum disaggregation of the samples before analysis, and manufacturer suggested 10-20% obscuration limits were adhered to strictly. Clay-rich samples were treated with a solution of Calgon before analysis as described by Ryzak and Bieganowski (2011).

Gravel Sizing

During sample collection at the BNGA drilling locations, 179 samples of gravel sized sediment were collected. In most cases, these samples were bagged separately from the sand and mud fractions from their respective intervals. When this was not accomplished, separation of gravel sized sediment was conducted in the laboratory at Vanderbilt University. Further separation was performed to determine grain size within each sample using dry sieve techniques. Separated fractions are defined as: 4-12.5 millimeters (mm), 12.5-25.0 mm, and 25.0-50.8 mm. These fractions were named fine-pebble, medium-pebble, and coarse-pebble according to the descriptions of Friedman and Sanders (1978).

Observations of rounding and sphericity were made visually using the method description from Powers (1953). Lithologic observations were classified subjectively in hand sample as igneous/meta-igneous or sedimentary/meta-sedimentary. Total weight and the weight of each fraction of every sample were measured using an analytical balance. Also, a pebble count for every sample was conducted. Outstanding characteristics such as total number of fractured clasts, the occurrence of common and distinct lithologies, and signs of oxidation were also recorded.

CHAPTER III

RESULTS

During the Spring of 2011, 41 boreholes were drilled for a total of 2260 m (Figure 6). The sample-set for this study is a total of 1,132 sediment samples that represent all of the physiographic provinces and stratigraphic units intersected by the BNGA drilling campaign. This chapter reports the results from 443 geochemical analyses for Sr (ppm) and 179 analyses of gravel lithology, size, and location. In order to determine the stratigraphic significance of these results, they will be correlated with the descriptions and distributions of sedimentary facies determined by Pickering (2013) from lithology descriptions, 953 grain size analyses, and the Sr (ppm) results.

The samples used for geochemical analyses (sand and mud) will herein be referred to as “matrix sediment” since this study is interested in their association with gravel deposits. The matrix sediments are classified into 4 groups based on the XRF analysis results for Sr (ppm). The 179 gravel samples reveal three gravel types that are defined by their clast lithology, physical properties (i.e. size, rounding, and sphericity), and locations in the stratigraphy along BNGA.

Matrix Sediments

Strontium Concentration

Common influences on strontium (Sr) concentration (ppm) in bulk sediment analyses include but are not limited to: mineralogy, grain size, sorting, and weathering. This section presents the geochemical results in a manner to identify the most significant influences on Sr (ppm) in the matrix sediments.

The results from 443 XRF analyses on bulk matrix sediments reveal a range of Sr (ppm) from 9 to 195 ± 3 ppm, mean of 138 ppm, median of 150 ppm, and mode of 158 ppm. 81% of the samples analyzed show Sr (ppm) >120 ppm (Figure 8). Figure 9 displays Sr (ppm) in relation to location along BNGA. It is important to note that the location / borehole identification number along BNGA corresponds with distance (km) along transect from the west (e.g. BNGA070 = 70 km, Figure 6). Notice a lack of <120 ppm Sr results within the alluvial valleys of the Brahmaputra-Jamuna and Old Brahmaputra River alluvial valleys.

The alumina-silica ratio (Al_2O_3:SiO_2) of sediments is commonly used as a proxy for grain size. Clays become enriched in aluminum (Al) due to chemical weathering of micas and feldspars while sand grains, having undergone a lesser degree of weathering, retain their silica enrichment. Figure 10 shows that the >120 ppm Sr population is generally associated with an Al_2O_3:SiO_2 > 0.2, and the <120 ppm Sr population Al_2O_3:SiO_2 ranges from 0 to 0.45.

The d(.50) (i.e. median grain size) data from laser diffraction grain size analysis reveal that 93% of the >120 ppm Sr population correlate with the sand classifications of the Wentworth scale (> 62 µm) while 81% of the <120 ppm Sr population correlate with the mud classifications (< 62 µm; Figure 11). These results do show a bias in >120 ppm Sr toward samples with sand sized d(.50) values, and the inverse holds true for mud samples. However, the outliers of both populations reveal that grain size is not an absolute control on Sr (ppm). Therefore, data for other influences on Sr (ppm) in matrix sediments are presented below.

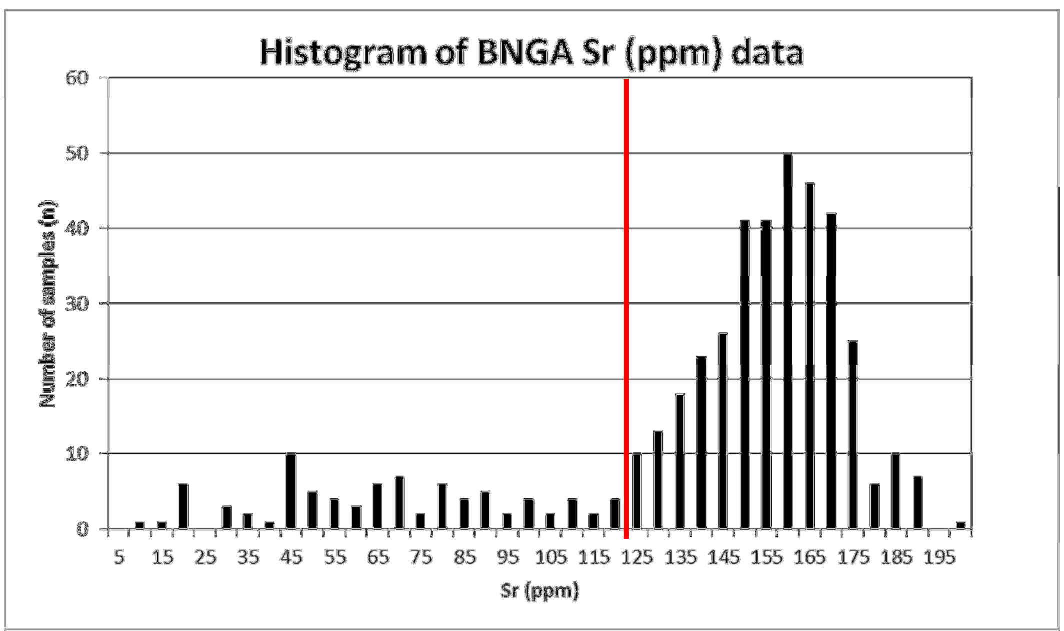

Figure 8. The histogram of BNGA Sr (ppm) data (n=443) reveals that 81% of the samples have Sr (ppm) >120 ppm.

Due to substitution of Sr for calcium (Ca) in the crystal lattice of Ca-bearing minerals (e.g. plagioclase, epidote, etc.), the mineral assemblage found in sediment has a direct effect on its bulk Sr (ppm). The geochemical data reveal that 100% of the >120 ppm population is associated with CaO > 1.5% by weight, and the <120 ppm population contains CaO (wt%) ranging from 1.0 to 1.7 (Figure 12). Note that the <120 ppm data with CaO (wt%) > 1.5 form a tight tail with the >120 ppm population. The direct correlation between CaO (wt%) and Sr (ppm) suggests that an increased presence of Ca-bearing minerals is a major control on Sr (ppm) in BNGA matrix sediments.

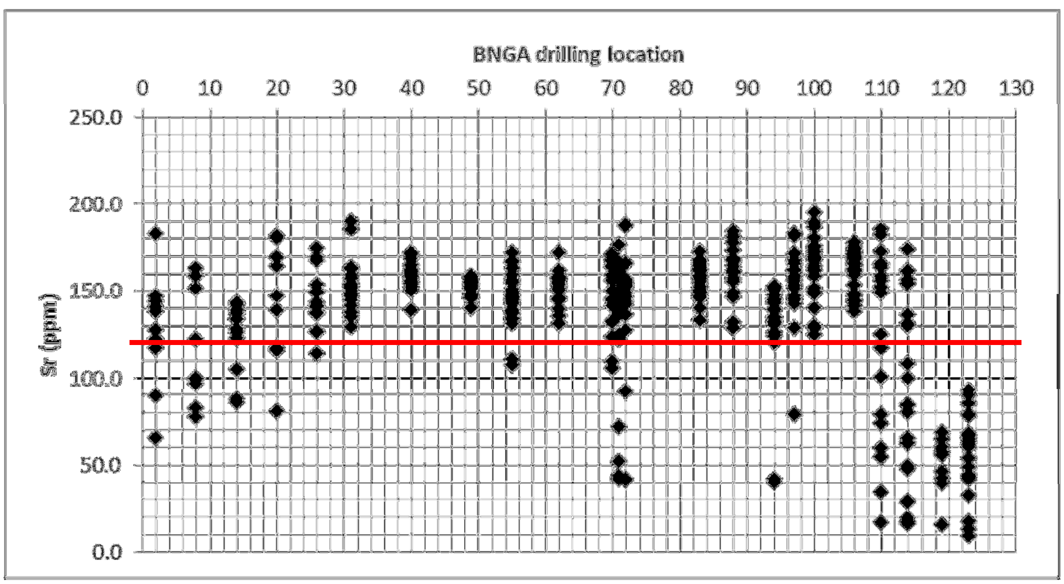

Figure 9. Sr (ppm) data plotted against sample location show an abundance of low Sr values at the eastern and western margins of the transect as well as in the middle (depth is not represented here). The red line marks 120 ppm. The x-axis represents the borehole ids which correspond with approximate distance along transect from the west (e.g. BNGA070 = 70 km).

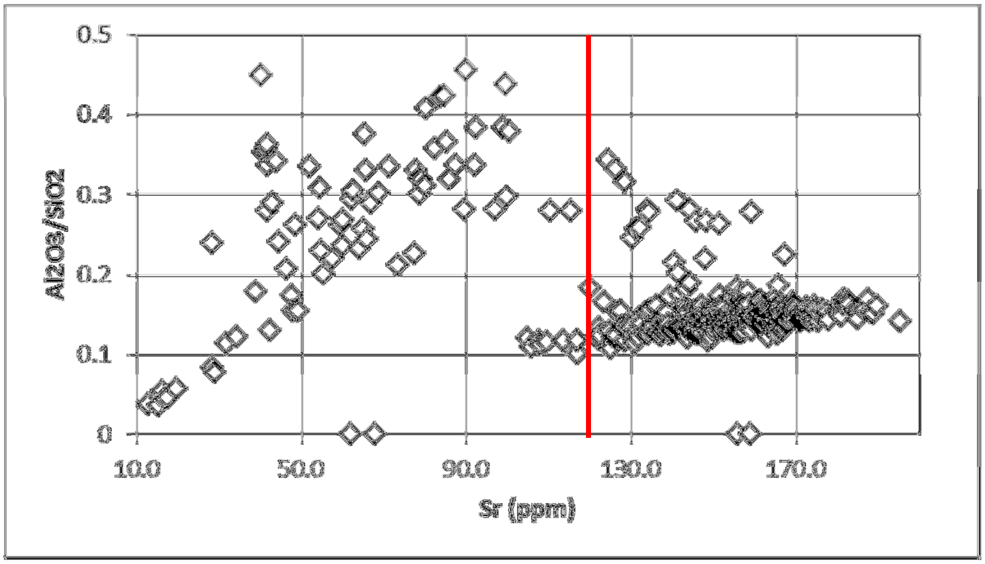

Figure 10. The data reveal that the >120 Sr (ppm) population is generally associated with a lower Al_2O_3:SiO_2 than the <120 Sr (ppm) population. However, used as a proxy for grainsize, these data show that both the fine and coarse matrix sediments contain a wide range of Sr (ppm). The red line marks 120 ppm. (n=443)

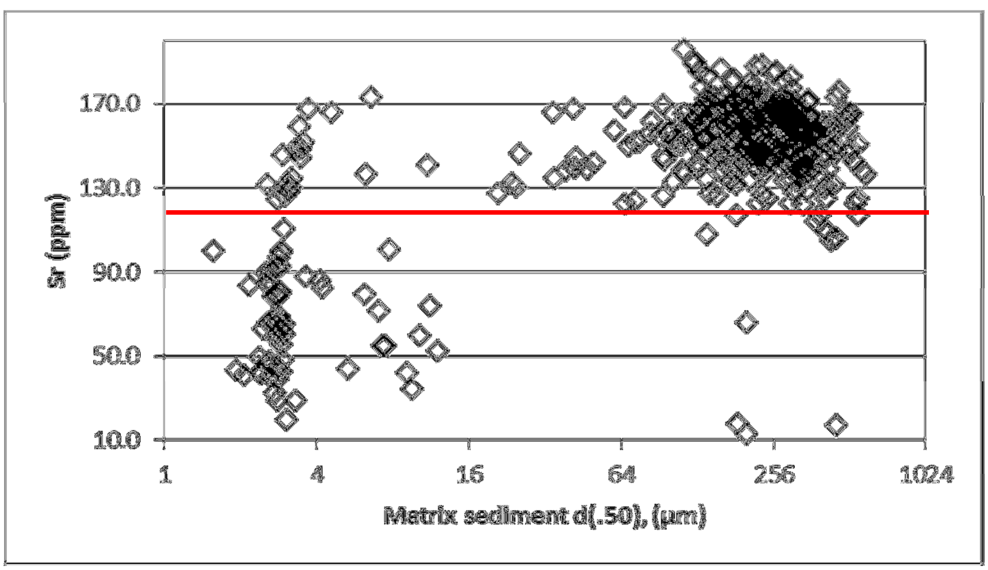

Figure 11. A comparison of grain size analysis d(.50) data versus Sr (ppm) of matrix sediments shows that the >120 Sr (ppm) population covers the full range of grain sizes present in this study. The <120 Sr (ppm) population is generally associated with clay grain sizes. However, there are sand samples present in this population with Sr (ppm) as low as 12 ppm. The red line marks 120 ppm. (n=418)

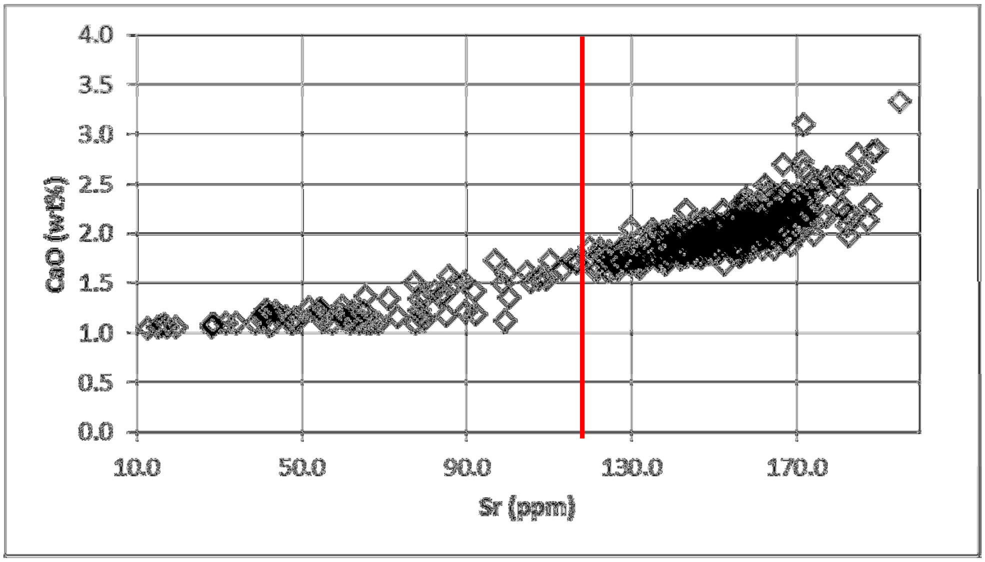

Figure 12. A positive correlation between CaO (wt%) and Sr (ppm) reveal that an increased presence of Ca-bearing minerals is a major control on Sr (ppm) in matrix sediments. Note that all of the >120 ppm population show CaO > 1.5 wt%. The red line marks 120 ppm. (n=443)

Lithology and Facies Distribution

The results from grain size analysis of 953 BNGA matrix sediment samples reveal that the stratigraphy in this study is dominated by sand with only minor clay and silt deposits. The mean and mode of all mean grain size data fall within the medium sand Wentworth classification (250-500 µm). Pickering (2013) reports that 51% of the mean grain size data are classified as medium sand and the remaining data are evenly distributed in the coarser and finer fractions (Figure 13).

Figure 14 from Pickering (2013) presents the spatial distribution of the mean Wentworth grain size data and the locations of gravel samples from this study. Note that the mud strata are generally located in the upper 20 m of the stratigraphy with the exception of the eastern end of BNGA. The general grain size trend at each location is a fining upward sequence from basal gravel beds to the muds of the active floodplain. Pickering (2013) uses the Sr (ppm) data of this study, mean grain size data, lithologic descriptions, and radiocarbon dates from 21 samples to define the facies intersected along BNGA. The facies along BNGA include Overbank Muds, Basinal Muds, Braidbelt Sands, Shillong Alluvium, and Pleistocene Gravel. Table 2 provides the detailed lithologic descriptions and facies interpretations from Pickering (2013).

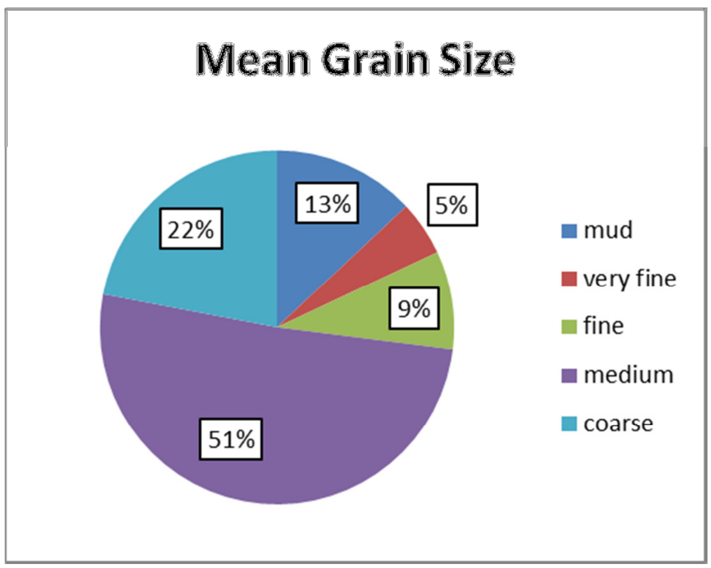

Figure 13. Wentworth classification distribution of mean grain size data from all BNGA samples that were analyzed (from Pickering, 2013).

Pickering (2013) describes the spatial relationships of the facies according to provinces divided by surface morphology features along BNGA (Figure 15). The five morphological provinces of BNGA are: the Bogra Terrace, the Brahmaputra-Jamuna Valley, the Jamalpur Terrace, the Old Brahmaputra Valleys, and the Dauki Foredeep. Figure 16 shows Pickering's (2013) interpretation of the stratigraphy in cross-section. The morphological provinces, described here from west to east along BNGA, will provide the framework for the discussion of results in this study.

The Bogra Terrace includes BNGA locations 002 to 008, and is composed of Pleistocene Overbank Muds, gravel rich Braidbelt Sands, and Holocene Overbank Muds. The shallow depth to gravel and abundant Pleistocene Muds suggest that this province was not incised by the Brahmaputra River during the Pleistocene.

The Brahmaputra-Jamuna Valley (BJV) includes BNGA locations 011 to 070 and is composed of Holocene Braidbelt Sands with preserved Holocene Overbank Muds at surface and Pleistocene Gravel at the base of the stratigraphy. This province is interpreted as Holocene alluvial valley-fill overlying the LPLS gravel and boulder surface.

The Jamalpur Terrace includes BNGA locations 071 and 072 and is composed of Pleistocene Overbank Muds overlying Pleistocene Braidbelt Sands. Akin to the Bogra Terrace, this province was not incised by the Brahmaputra River during the Pleistocene.

The Old Brahmaputra Valley (OBV) includes BNGA locations 081 to 109 and is composed of Holocene Braidbelt Sands overlying Pleistocene Braidbelt Sands. The valley is divided into two sub-valleys by a remnant of the Jamalpur Terrace. This province is interpreted as Holocene alluvial valley-fill overlying the LPLS surface which is not characterized by a thick gravel and boulder layer as it is in the BJV.

The Dauki Foredeep is the most lithologically distinct province. It includes BNGA locations 110 to 123 and is composed of Pleistocene Braidbelt Sands underlying Holocene and Pleistocene Basinal Muds that are thinly interbedded with Shillong Alluvium. It is interpreted that this province has not received Holocene Braidbelt Sands from the Brahmaputra River. Rather, the Holocene Basinal Muds have accumulated outside of the Old Brahmaputra braidbelt and are intermittently incised by small rivers draining the Shillong Plateau.

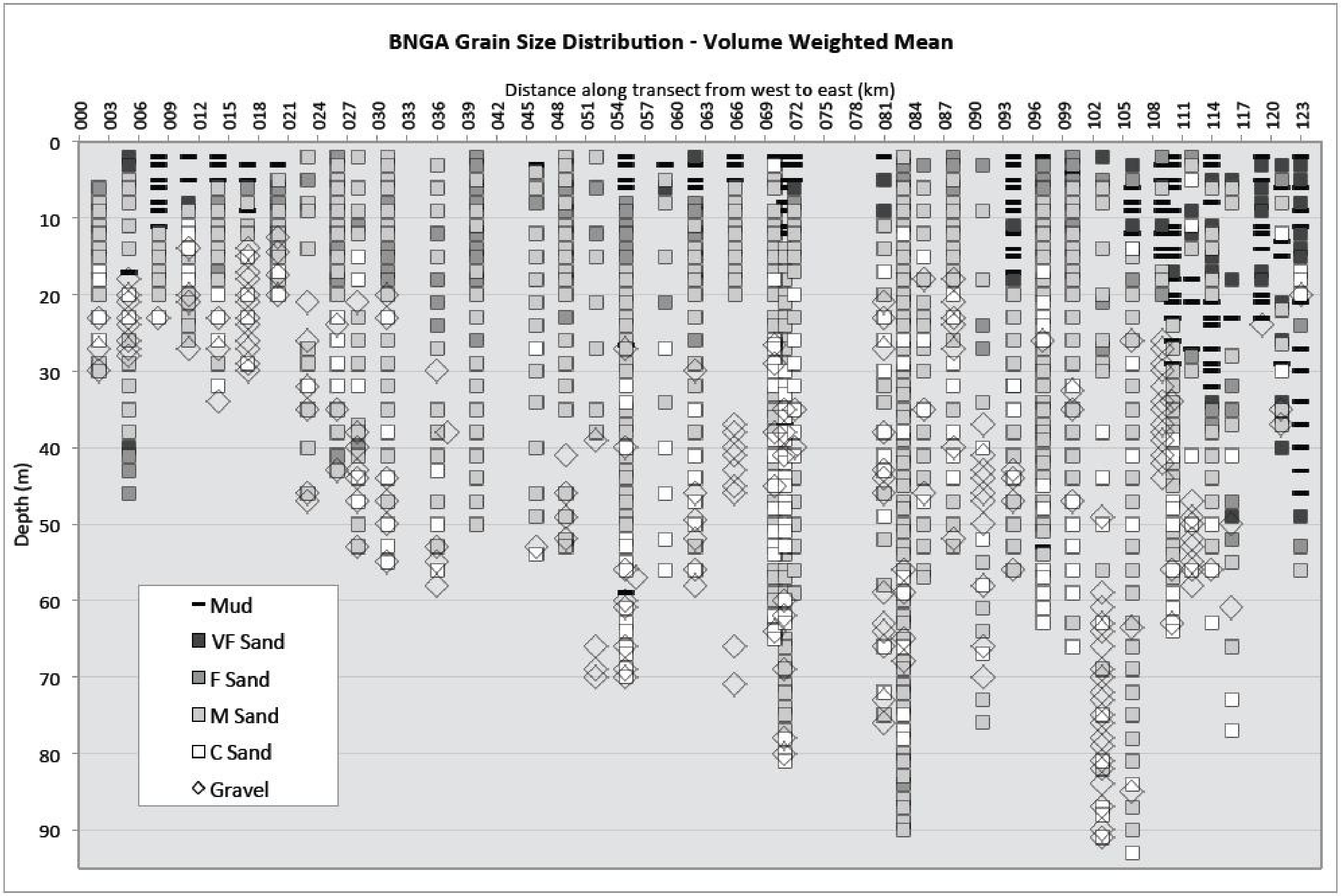

Figure 14. A cross-sectional representation of the mean grain size data and gravel locations (from Pickering, 2013).

Table 2. Facies description from BNGA drilling (from Pickering, 2013).

Facies	Lithology	Sr concentration	Spatial distribution	Thickness	Depth to top	Period of deposition	Interpretation
Holocene Fluvial Overbank Muds	Thin silt deposits	Typically >140 ppm but 120-140 ppm not uncommon; occasionally ~90 ppm in Bogra	Shallow subsurface at valley margins; occasional localized deposit at depth	Typically ~5 m; localized deposits are ~1 m at depth	Typically surface to <10 m at valley margins; few locally at depth	~10,000 BP to present	Modern and preserved overbank deposits
Pleistocene Fluvial Overbank Muds	Generally stiff silts often underlain by silts; typically gray matrix with orange mottling	Generally <120 ppm; up to 140 ppm in core 094	Prevalent in shallow subsurface of valley margins and upper ~20 m of core 094	1-20 m; typically ~5-10 m	Surface to ~55 m	Pre-Holocene (Late Pleistocene)	Overbank deposits with well-developed paleosols
Holocene Basinal Muds	Soft silts of varying color	Consistently <90 ppm	Locally in cores 109-123	Generally 15-20 m, with interspersed sands in some cores	0-20 m	Holocene	Dauki foredeep deposits
Pleistocene Basinal Muds	Generally stiff silts; stiffness decreases with depth below weathering horizon		Locally in cores 110-123	Up to 40 m with interspersed sands	10-60 m	Pleistocene	
Holocene Braidbelt Sands	Clean, quartz-rich very fine to coarse sands; typically gray or gray-brown in color; gravel often present	Generally >140 ppm; 120-140 ppm not uncommon; occasionally as low as 90 ppm	Widespread in paleovalleys	Up to 80 m thick in deepest parts of valleys	0-80 m	Holocene	Alluvial deposits of the Brahmaputra (valley fill)
Pleistocene Braidbelt Sands			Widespread below paleovalleys, mud-capped features, and Dauki foredeep	Up to 80 m thick in longest boreholes	15-95 m	Pre-Holocene (Late Pleistocene)	Alluvial deposits of paleo-Brahmaputra rivers
Shillong Alluvium	Angular and poorly sorted but generally coarse quartz sands and granules	<90 ppm	Locally in cores 109-123 (northwestern margin of Sylhet Basin)	<10 m	2-55 m	Pre-Holocene to recent	Shillong-sourced ephemeral stream deposits
Pleistocene Gravel	Rounded to sub-angular lithic material up to 50.8 mm diameter	Not analyzed	Occur below western half of transect at base of Jamuna paleovalley	Unknown	20-50 m	Pre-Holocene (Late Pleistocene)	Lag deposit from LGM valley incision

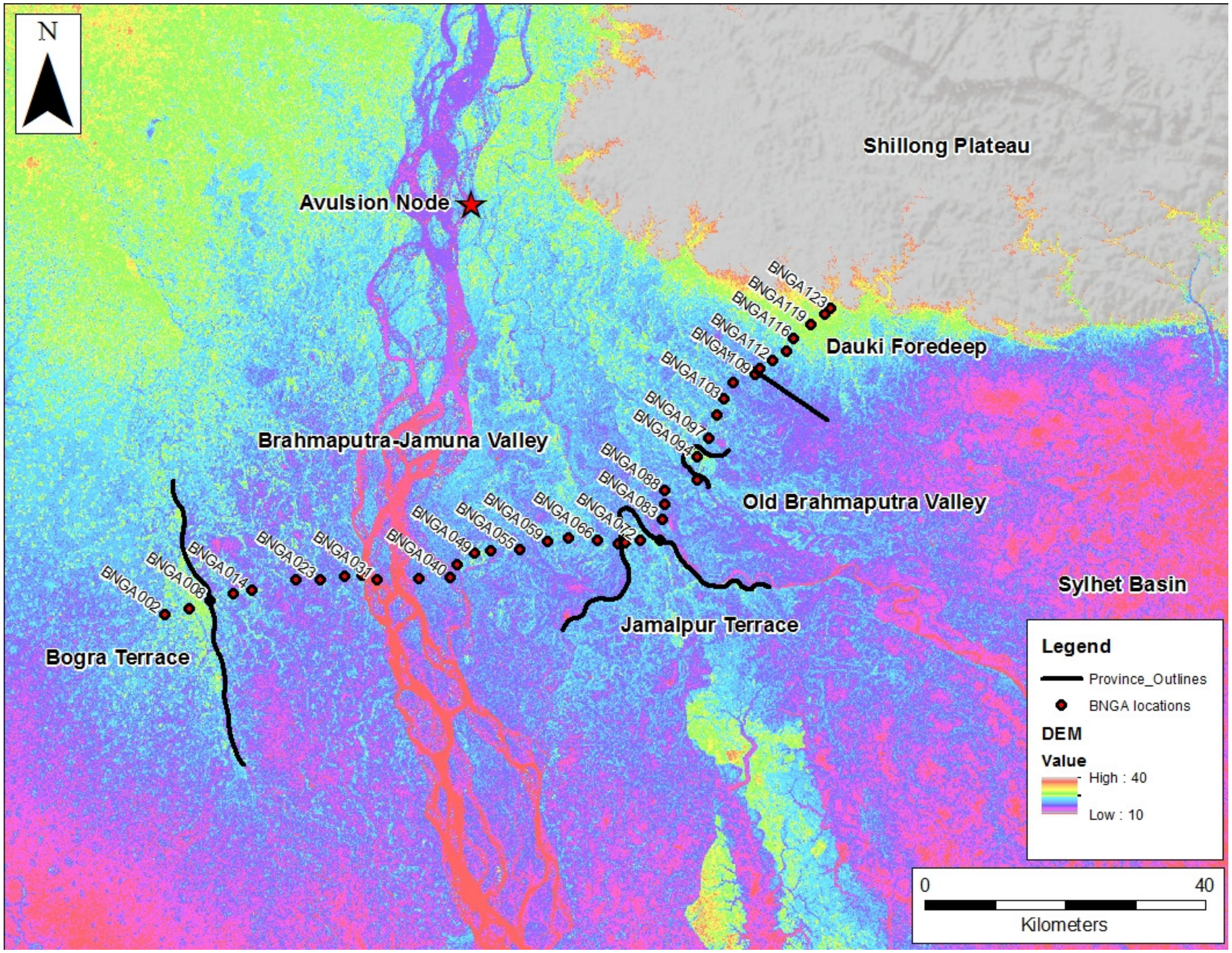

Figure 15. Plan view of BNGA with DEM highlighting the surface morphology features used to define the morphological provinces along BNGA.

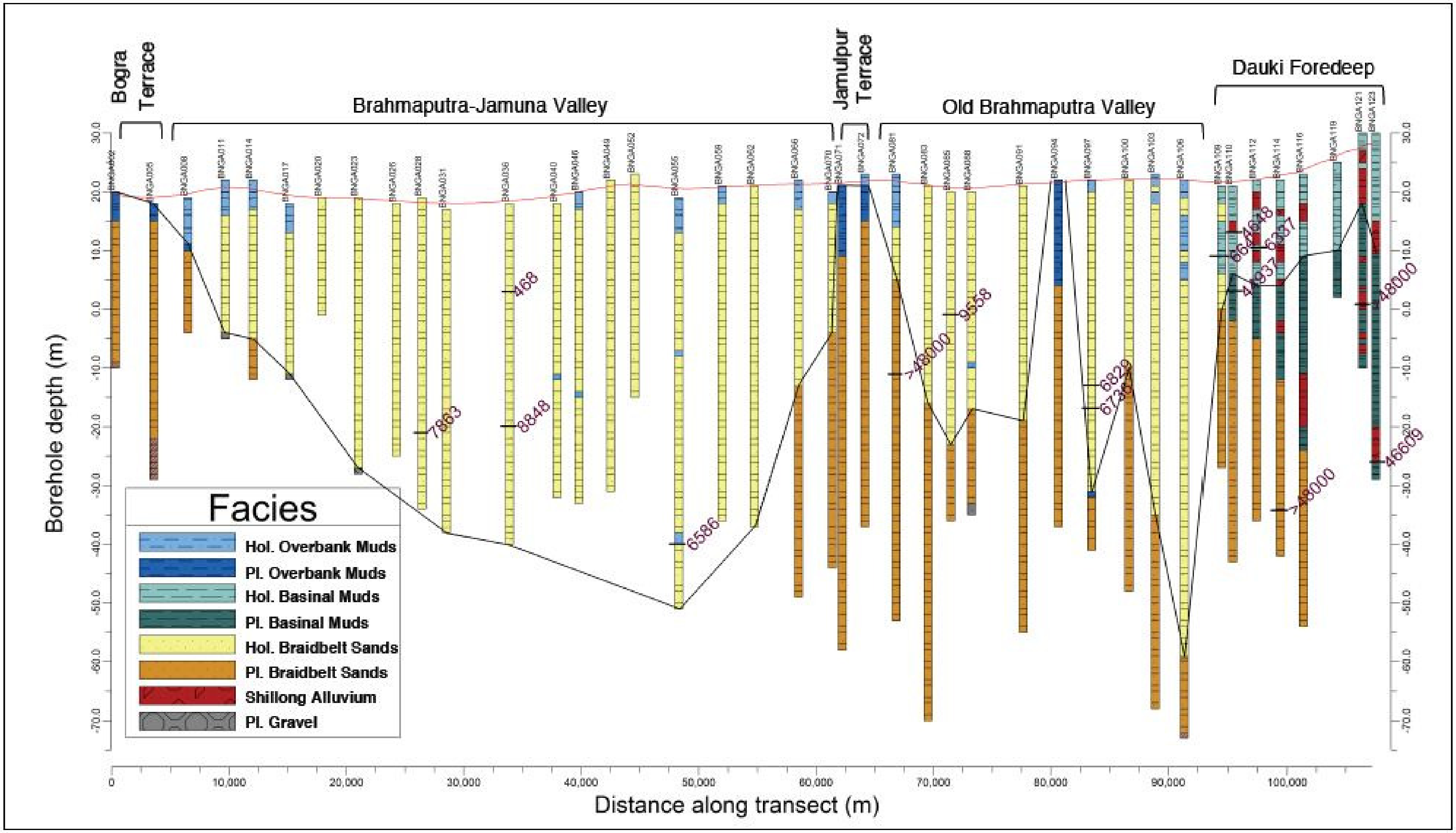

Figure 16. Cross-sectional interpretation of BNGA facies, morphological provinces, and Late Pleistocene Low Stand (LPLS) surface from Pickering (2013).

Gravel Deposits

Type-1 Gravel

Most gravel sized sediments recovered from BNGA drilling locations reveal a mixture of lithologies that include, but are not limited to: quartzite, quartzose sandstone, gneiss, schist, and mudstone (Figure 17). This heterolithic assemblage will herein be referred to as Type-1 gravels. Most recognizable and abundant throughout this assemblage are purple and maroon quartzite.

Figure 17. The assemblage of lithologies seen here is representative of all Type-1 gravels.

The sizes of Type-1 gravels, as determined by dry sieve method, cover a range from 4.0 to 50.8 mm (fine to coarse pebble). The upper limit of 50.8 mm corresponds to the sampling limitation of a two inch drill pipe (Figure 18). The size bins for Type-1 gravels follow the Wentworth grade classifications: fine pebble (F.P., 4-12.5 mm), medium pebble (M.P., 12.5-25 mm), and coarse pebble (C.P., 25-50.8 mm).

Figure 18. A gravel clast lodged in the 2 inch diameter drill string.

Figure 19 shows the size distribution of Type-1 gravels. The medium pebble (M.P.) fraction is the most abundant fraction accounting for ~53% of the total weight of all Type-1 gravels, but it is important to note that ~64% of all samples include clasts fractured during the drilling process (Figure 20). In fact, ~24% of all clasts catalogued show some evidence of fracture. This suggests that there is some bias toward smaller clasts size.

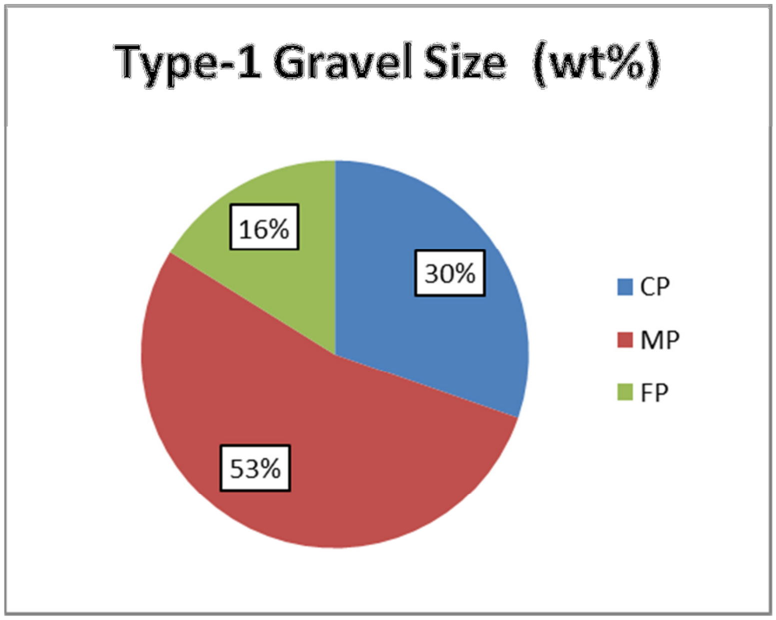

Figure 19. Type-1 gravel size distribution by weight percent: coarse pebble (CP), medium pebble (MP), and fine pebble (FP).

The abundance of fractured clasts is attributed to the sampling method. The method used in this study inherently creates error that skews the contribution of smaller fractions by fracturing clasts during drilling. However, the fraction size ranges are developed to reduce this error by using wider ranges with increasing size to increase the possibility of measuring a greater fraction of the population in the larger size ranges. Therefore, it is reasonable to accept that clasts larger than 50.8 mm diameter exist in the stratigraphy and that they contribute to the measured

25-50.8 mm fraction, but it does not seem that this effect is a major control on the dominant size classification of Type-1 gravels.

Although these properties are not quantified in this study, Type-1 gravels are judged to be sub-rounded to well-rounded, and they exhibit low to medium sphericity (Figure 17). The angularity and sphericity of Type-1 gravels are very consistent throughout the stratigraphy.

Figure 20. The abundance of fractured clasts is attributed the drilling method. This is important to consider when analysing the dry sieve results of gravel clast sizes and abundances.

Gravel deposits are not common in the upper 20 m of the stratigraphy along BNGA (Figure 14). Below 20 m depth, Type-1 gravel deposits generally have two modes of occurrence: thick deposits (5-15 m) associated with the LPLS surface, and thinner deposits (<5 m) isolated in the upper stratigraphy.

The gravels associated with the LPLS mantle the base of both the Brahmaputra Jamuna Valley (BJV) and Old Brahmaputra Valley (OBV), and they account for the majority of gravels in this study (Figure 14; Figure 16). The drilling results for the feasibility study on the Jamuna Bridge show that these deposits are continuous downstream and overlie a thick cobble and boulder unit (JICA, 1976). However, this study has not located any existing literature on the origins of the thinner gravel deposits that are not related to the LPLS.

Type-2 Gravel

The second classification of gravel sized sediments in this study, Type-2, is less abundant. Therefore, statistical analysis is not as robust as for Type-1. However, the physical and lithologic differences between these gravels and Type-1 gravels warrant distinction. Type-2 gravels are mainly composed of Fe-oxide coated quartz granules (2-4 mm), larger quartzose sandstone and quartzite clasts, and fragments of Fe-oxide material. They exhibit high angularity and medium to high sphericity (Figure 21). Type-2 gravels contain few lithic fragments. They only occur in strata of Shillong Alluvium in the Dauki Foredeep province.

Clay-clasts

The third distinct population of gravel sized sediment from the BNGA sample set is composed of well rounded, high sphericity, gray clay-clasts and fragmented clasts of oxidized clays. Only about 10% of all gravel samples contain clay-clasts.

Due to the poor induration of this population, many of the samples are fractured. Similar to fracturing in Type-1 and Type-2 gravels, this makes accurately quantifying the common sizes of these clasts difficult. However, several gray clay-clasts are undamaged and maintain a diameter greater than 25 mm (Figure 22).

Gray clay-clasts are found near the base and margin of the Jamuna Valley and OB Valley stratigraphy sections with only two outliers occurring in the upper stratigraphy. The reddish-brown fragments of oxidized clays occur mainly in Pleistocene age sediments of the Jamalpur Terrace and Dauki Foredeep provinces. They usually occur in correlation with Type-1 and Type-2 gravels that are also noted to include Fe-oxide coated sands (Pickering, 2013).

Figure 21. Type-2 gravels have distinctly different physical properties than Type-1 gravels. This sample of the 2-4 mm fraction of a Type-2 gravel shows the abundance of quartz grains and Fe-oxide fragments.

Figure 22. There were only a few clay clasts recovered during this study. The clast depicted here is the largest recovered (>25 mm). All clay clasts are well rounded, and those that are not fractured exhibit a high degree of sphericity.

Gravel and Strontium Populations

Type-1 gravels can be further classified based on their association with discrete ranges of matrix sediment Sr (ppm). Table 4 outlines these distinctions. Further context and interpretation on Type-1a, Type-1b, Type-1c gravels is provided in the discussion section.

Gravel Distribution

Type-1 gravels are found in all morphological provinces along BNGA whereas Type-2 gravels are associated exclusively with the Shillong Alluvium facies in the Dauki Foredeep province. Figure 23 shows the relative abundance of each size fraction of Type-1 gravels by weight percentage of all gravels.

The abundance of the fine pebble classification in the Jamalpur Terrace province agrees with the matrix sediment grain size data from Pickering (2013) that shows a relative abundance of coarse sands in this location (Figure 14). There is high uncertainty in the apparent abundance of coarse pebble sized gravels in the Dauki Foredeep province due to a limited sample set from this province. Otherwise, the gravels sampled along BNGA show a relative abundance of medium pebble sized gravels (12 to 25 µm) in the stratigraphy along BNGA.

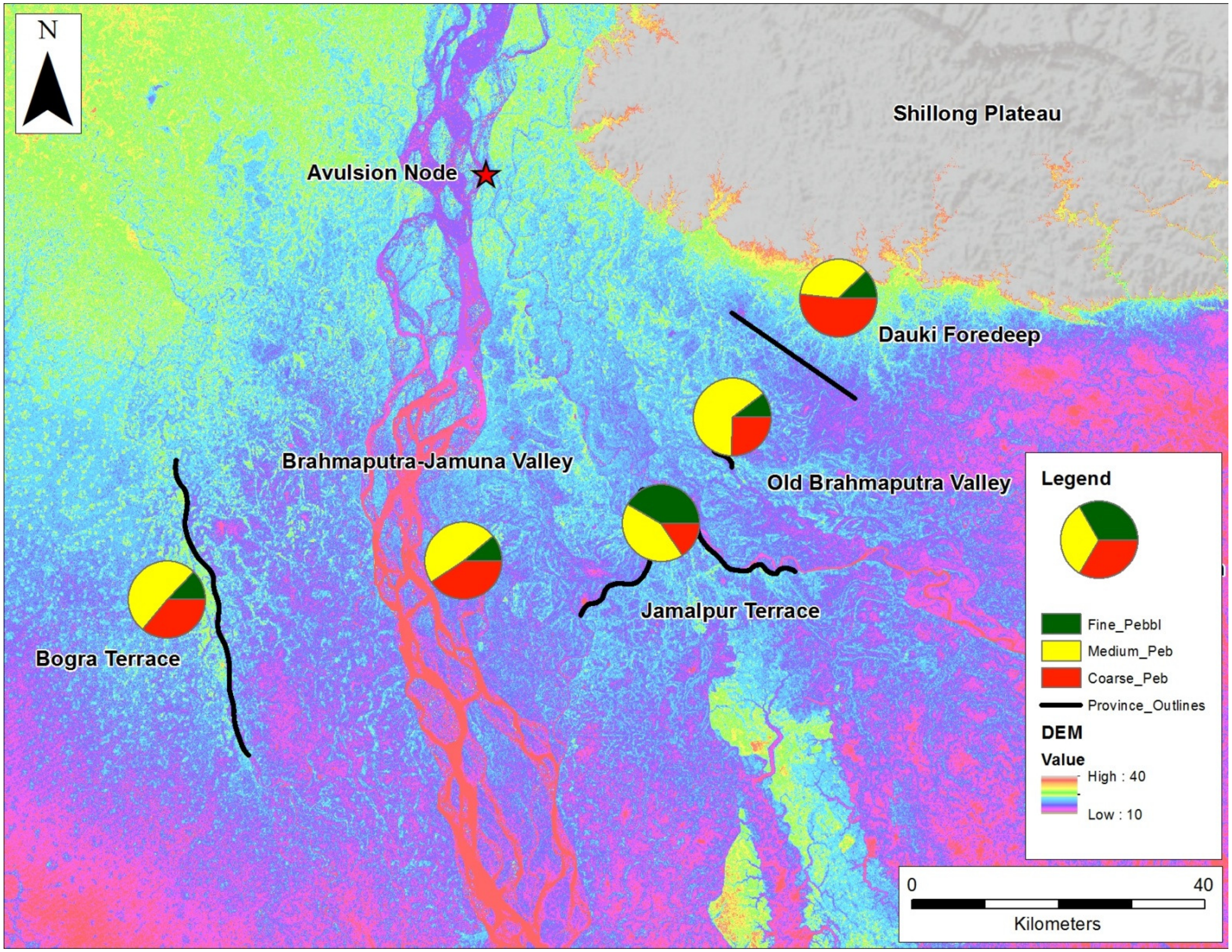

Figure 23. BNGA Type-1 gravel size distribution by province (weight % of total gravel sample weight) with DEM.

CHAPTER IV

DISCUSSION

Based on the analyses of sediment geochemistry, grain size, lithology, and depositional environment, this study has defined several distinct populations of genetically related sediments within the stratigraphy of the Brahmaputra River in the upper GBMD (i.e. Sr (ppm) populations, facies, and gravel types). This chapter presents a comprehensive comparison of these results with the goal of building a model for the origin of gravels in the Holocene valleys of the Brahmaputra River.

Goodbred et al. (2014) and Garzanti (2010) have demonstrated the use of Sr (ppm) as a reliable indicator of sediment provenance. A comparison of their research with the geochemical data from this study provides new insights into Sr (ppm) signatures found in the GBMD stratigraphy.

Pickering's (2013) characterization of morphological provinces provides the framework for quantifying the spatial distribution of gravels and the Sr (ppm) of their associated matrix sediment. This allows us to characterize the gravel bearing lithologies in each province and interpret their origins.

Strontium in GBMD Sediments

Strontium (Sr) concentration (ppm) is a reliable indicator of sediment source within the GBMD. Goodbred et al. (2014) and Garzanti et al. (2010) provide geochemical and petrographic studies that verify the use of Sr (ppm) as an indicator of stratigraphy built by the Brahmaputra River. Those studies conclude that mineralogy is the major control on Sr (ppm) in modern Brahmaputra River bedload sediments. Plagioclase feldspar and epidote are the main carriers of Sr (ppm) through substitution for calcium (Ca) (Garzanti, 2010). The data from this study reveal the same positive correlation between CaO (wt%) and Sr (ppm) (Figure 12).

Grain size and density sorting of heavy minerals are controls that can certainly affect the Sr (ppm) in Brahmaputra River bedload sediments (Garzanti, 2010). However, since the samples from BNGA are depth averaged composite samples, these effects are not quantifiable on bed scale. Furthermore, Goodbred et al. (2014) shows that the grain size effect on Sr (ppm) is minor when compared to mineralogy by comparing the aluminum to silica ratio (Al_2O_3:SiO_2) and Sr (ppm). The results from this study confirm that high and low Sr (ppm) are present in a full range of grain sizes (i.e. mud to coarse sand; Figure 11).

Goodbred et al. (2014) classifies the Sr (ppm) of Brahmaputra River sediments as the “Bengal high-Sr group”, which they define as >140 ppm. Using this classification, we see that ~66% of the BNGA matrix sediments analyzed for Sr (ppm) fall into this group. However, in this study, the comparison of CaO (wt%) and Al_2O_3:SiO_2 data to Sr (ppm) reveals a tail of Brahmaputra River data points that fall in the 120 to 140 ppm range. These data suggest that the Sr (ppm) of Brahmaputra River sediments includes the 120 to 140 ppm range. The 120 to 140 ppm tail is herein classified as the "depressed Brahmaputra-Sr group".

By adapting the Sr (ppm) classifications of Goodbred et al. (2014), the Sr (ppm) data from BNGA is herein classified as: Bengal high-Sr (>140 ppm), depressed Brahmaputra-Sr (120-140 ppm), Bengal intermediate-Sr (90-120 ppm), and Bengal low-Sr (<90 ppm).

Table 3. Sr (ppm) group classification distribution (%) by morphologic province.

Sr (ppm) Group	Bogra Terrace (n=32)	Brahmaputra-Jamuna Valley (n=144)	Jamalpur Terrace (n=47)	Old Brahmaputra Valley (n=144)	Dauki Foredeep (n=76)
Bengal low-Sr (90 ppm)	18.8	0.7	12.8	2.1	65.8
Bengal intermediate-Sr (90-120 ppm)	15.6	4.9	2.1	0	6.6
depressed Brahmaputra-Sr (120-140 ppm)	37.5	16	14.9	12.5	5.3
Bengal high-Sr group (>140 ppm)	28.1	78.5	70.2	85.4	22.4

Table 3 and Figure 24 show the distribution of the Sr (ppm) groups (% n) by morphological province. Figure 25 provides the same data in cross-section. It is important to note here several key observations from this comparison of the Sr (ppm) data with the provinces defined by Pickering (2013). Firstly, > 94% of the BJV and OBV provinces are composed of sediments with Sr (ppm) > 120 ppm. Secondly, the Bengal low-Sr group has a distinct distribution along BNGA that reveals relative absence in the BJV and OBV provinces and anomalously high abundance in the Dauki Foredeep province. Lastly, the depressed Brahmaputra-Sr and Bengal intermediate-Sr groups are relatively abundant in the Bogra Terrace province.

These observations show that the stratigraphy of the BJV and OBV provinces was solely built by the Brahmaputra River. The small population of sediments with Sr (ppm) <120 ppm in the OBV comes from BNGA094, which coincides with a Pleistocene terrace remnant within the OBV. While not all Pleistocene sediments from BNGA are low in Sr (ppm), these occurrences are interpreted as evidence of minor weathering and grain size controls on the Sr (ppm).

The anomalous abundance of Bengal low-Sr group sediments in the Dauki Foredeep province is evidence of the relative length of time since the last Brahmaputra River braid belt occupation of this area. Along the western margin of this province, Bengal high-Sr group sediments are intersected at depth underlying a thick cap of Overbank Muds. As this cap of Overbank Mud increases in thickness to the east, the only sand facies found is the Shillong

Alluvium. This suggests that during the Holocene the Dauki Foredeep has been occupied by small Shillong Plateau tributaries that have built low-slope alluvial fans that are characterized by a low sand to mud ratio. Furthermore, these data help constrain the northeastern limit of the Brahmaputra River braid belt since the LPLS.

As with the Bengal low-Sr group sediments of the Dauki Foredeep, the lower Sr (ppm) sediments found in the Bogra Terrace stratigraphy are directly influenced by a nearby sediment source. The abundance of samples classified as Bengal intermediate-Sr and depressed Brahmaputra-Sr groups in the Bogra Terrace province are interpreted as a product of increased sediment contributions from the Tista River system. As the Brahmaputra River migrated laterally to the west, it would have had to rework Tista River mega-fan deposits (Sr (ppm) < 90) in order to build the stratigraphy that we see today. These observations from the stratigraphy of the Bogra Terrace and Dauki Foredeep provinces are critical evidence to modelling the behavior of the Brahmaputra River since the LPLS in that they show us that variation in sediment contribution from local sources can play a major role in altering the geochemical signature of sediments.

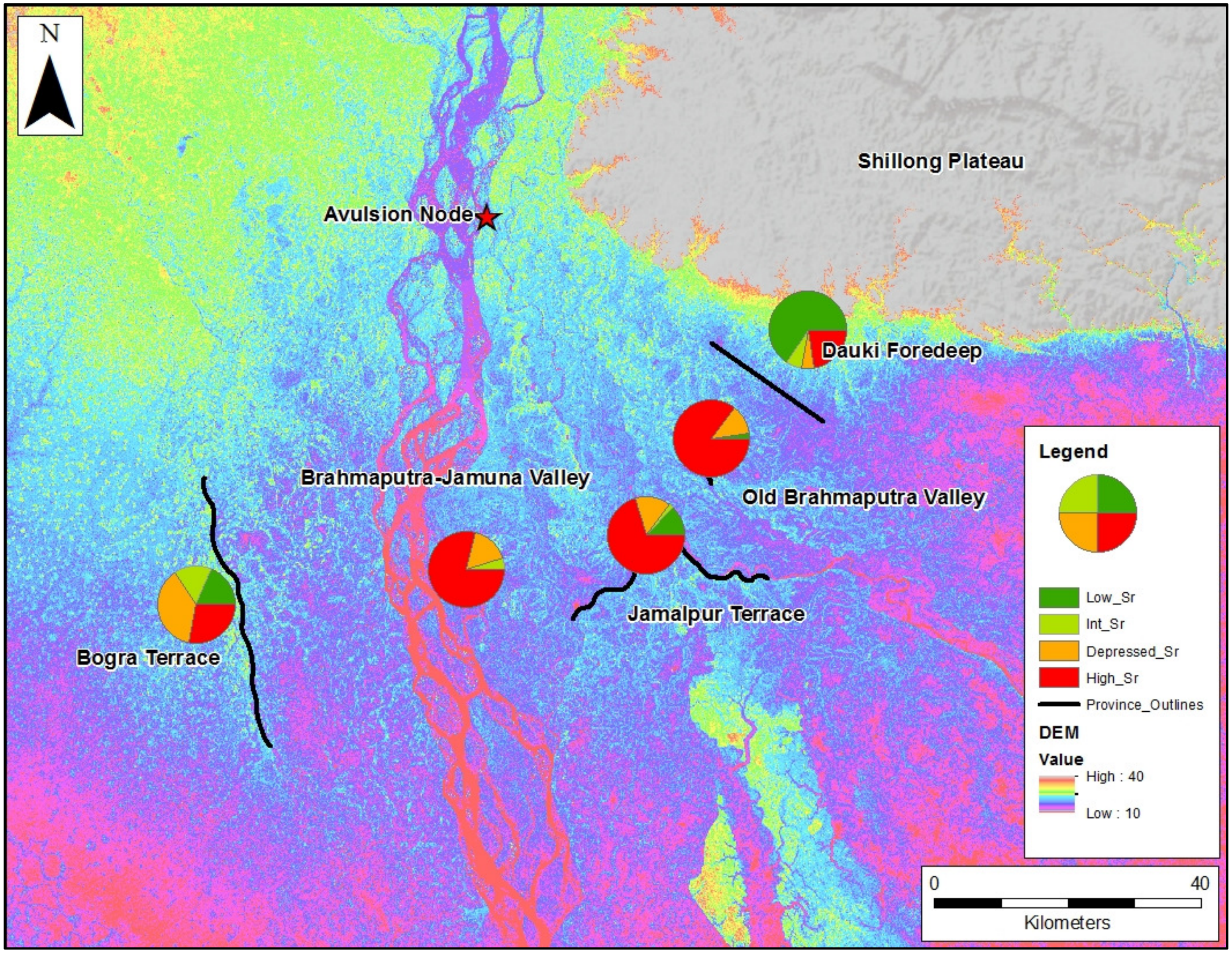

Figure 24. Sr (ppm) group classification distribution by province with DEM. See Table 3 for data.

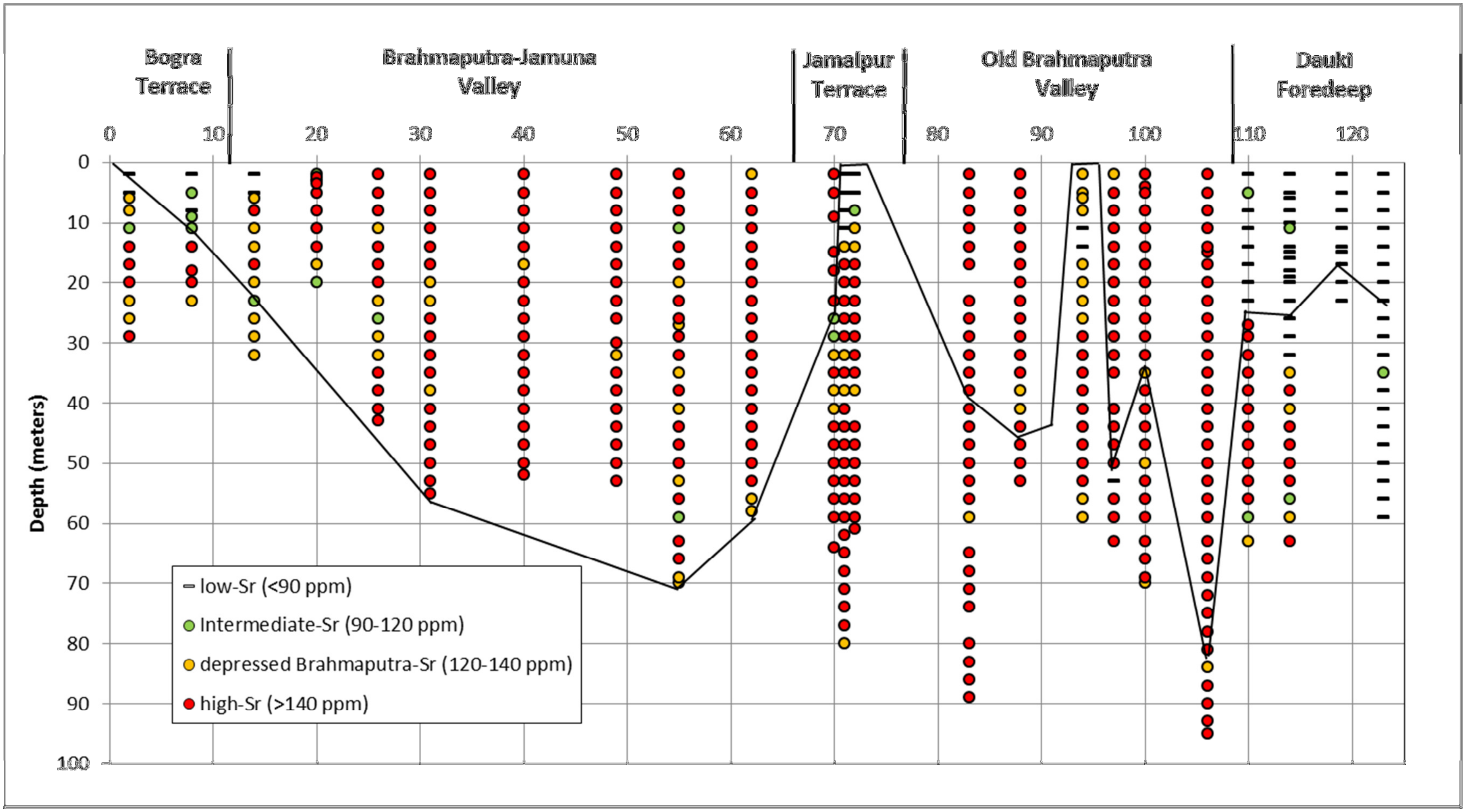

Figure 25. Cross-sectional representation of the Sr (ppm) groups with morphological province and Holocene-Pleistocene contact.

Proximal Sediment Sources

Garzanti et al. (2004), report mineralogical data and sediment contributions of groups of tributaries that confluence with the Brahmaputra River. The tributaries can be grouped into sub-basins based on differences in the mineralogy of their sediment load, which reflects the differing lithologies of the terranes that they drain. Of the two groups most proximal to BNGA, Shillong and Himalayan, the Himalayan group is estimated to contribute sediment at more than twice the amount of the Shillong tributaries. Furthermore, Himalayan tributaries drain a succession of Tethys Himalayan, Greater Himalayan, and Lesser Himalayan terranes. These terranes include the same assemblage of lithologies as Type-1 gravels. The proximity, higher sediment contribution, and similar lithologies suggest the possibility of a Himalayan origin of gravel sized sediment in the stratigraphy at BNGA.

The most proximal Himalayan tributary to BNGA is the Tista River. Although the Tista is not included in the estimate of Himalayan tributary sediment contribution, Garzanti et al. (2004), provide data that allow for some important observations about the Tista sediment contribution to the Brahmaputra River. The mineralogy and geochemistry of the Tista and Brahmaputra Rivers vary significantly, and the data suggest that there is also downstream variation within the Brahmaputra with respect to the Tista confluence.

The confluence of the Tista and Brahmaputra Rivers seems to mark changes in the Brahmaputra's mineralogy. Most significant to this study are variations in the minerals known to contribute to the Brahmaputra's high-Sr character: plagioclase feldspars and epidote. Like most Himalayan tributaries, Tista River sediments are low in Sr (ppm) (50-90 ppm), and data from Garzanti et al. (2010), reveal that this is very likely due to low plagioclase and epidote content. The input of sediment of this character appears to be significant enough to affect the overall bedload mineralogy of the Brahmaputra River by decreasing the plagioclase and epidote contributions to the bulk sediment composition (Garzanti et al., 2004). Therefore, an increase in sediment contribution from the Tista River system to the Brahmaputra River results in lower Sr (ppm) than upstream sediments. When identified in the stratigraphy, this variation is considered a signal of increased Tista River sand input through either westward lateral migration of the Brahmaputra River into Tista mega-fan deposits, or direct bedload contributions at the confluence.

Gravel - Matrix Sediment Associations

Type-1 Gravel

Together, the associations of Type-1 gravels with matrix sediments in the Bengal high-Sr / modern Brahmaputra River, depressed Brahmaputra-Sr, and Bengal intermediate-Sr groups suggest that within this classification there exist 3 distinct populations of gravelly sand deposits (Table 4). Type-1a is defined by the association of Type-1 gravel and the Bengal high-Sr group (>140 ppm). This suggests that many of the gravel size sediments are found within matrix sediments transported and deposited by the Brahmaputra River with no difference in Sr (ppm) signature than that of the modern river (Garzanti et al., 2010; Goodbred et al., 2014). Type-1a gravels represent ~61% of Type-1 deposits. Although there are examples of Type-1a in all of the BNGA provinces, the dominant populations are found in the BJV and OBV provinces, which mainly consist of Holocene valley fill (Figure 26).

The distinction of Type-1a gravels in association with modern Brahmaputra type matrix sediment suggests there is a deficit of Himalayan tributary matrix sediment contribution even though gravels of Himalayan lithologies are present. Since grain size and transport are eliminated from the geochemical model, variation in flow velocities and size/density sorting are not viable interpretations. Therefore, the possibility of non-Himalayan sources must be considered.

Type-1b, representing ~32% of the Type-1 population, is defined by their association with the depressed Brahmaputra-Sr group (120-140 ppm). This suggests that mixing of sediment contributions from Himalayan tributaries to the Brahmaputra River fluctuate significantly enough to alter the geochemistry of gravel bearing bedload sediments. Type-1b gravels are found in relative abundance throughout Pleistocene and Holocene aged stratigraphy of the Bogra Terrace, BJV, and OBV provinces (Figure 26).

Table 4. Gravel types

Gravel Type	BNGA Province	Sr (ppm) group	Sr (ppm)	% of Type-1
Type-1a	Brahmaputra-Jamuna Valley Old Brahmaputra Valley	high-Sr	>140	61%
Type-1b	Brahmaputra-Jamuna Valley Old Brahmaputra Valley Bogra Terrace	depressed-Sr	120-140	32%
Type-1c	Bogra Terrace Jamalpur Terrace Dauki Foredeep	intermediate-Sr	90-120	7%
Type-2	Dauki Foredeep	low-Sr	<90	--

The locations and ages of Type-1b gravels indicate that the controls on their transport and deposition are time transgressive. This finding and the association of Type-1b gravels with the depressed Brahmaputra-Sr group suggests that increased Himalayan tributary sediment contribution commonly correlates with gravel sized sediment despite the age of the deposits. Therefore, a second mode of Type-1 gravel transport, one with significant Himalayan tributary input, must be considered in the formulation of a model for the controls on their origin.

The remaining 7%, Type-1c, fall in the Bengal intermediate-Sr group (90-120ppm) below the defined range of the depressed Brahmaputra-Sr group. Type-

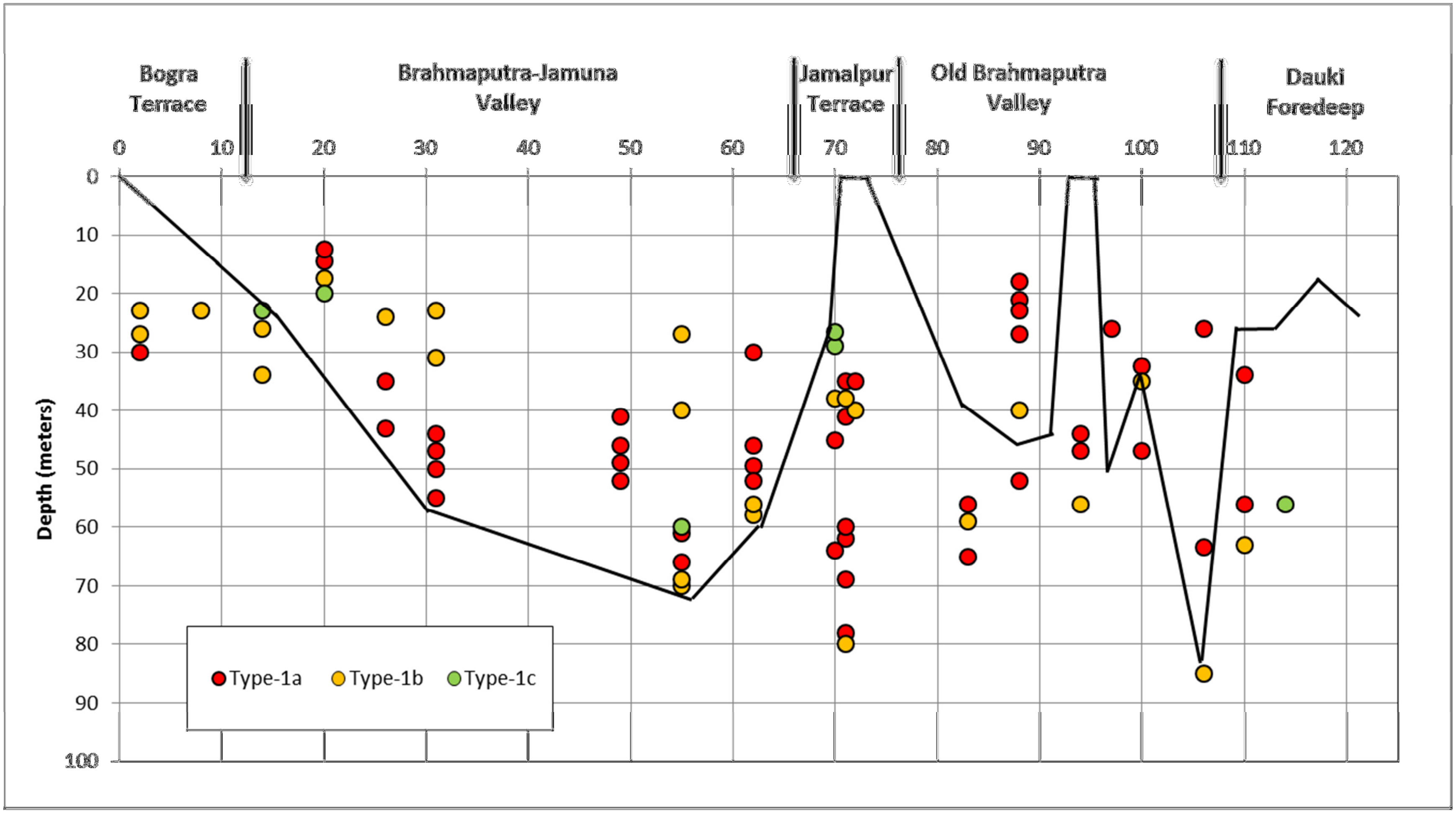

Figure 26. Cross-sectional representation of distribution of gravel types (i.e. 1a, 1b, and 1c) with morphological province and Holocene-Pleistocene contact.

1c gravels generally occur in the Pleistocene age deposits of the Bogra Terrace, Jamalpur Terrace, and Dauki Foredeep provinces (Figure 26). Neither published data nor the results of this study suggest a model for Brahmaputra River deposits with Sr in the 90-120 ppm range. Based on their ages, locations, and association with stratigraphic sections containing oxidized sediments, it stands to reason that in-situ weathering and variations in sediment contributions play a large role in the Sr (ppm) signature of Type-1c deposits. However, detailed sediment provenance analysis and further research on the effects of weathering on Sr (ppm) would be necessary to discuss their origin in any more detail.

Type-2 Gravel and Clay-clasts

Type-2 gravels, found in the Dauki Foredeep province, are found in association with Pleistocene age Bengal low-Sr group matrix sediments. The Bengal low-Sr group represents the possibilities of either pure Himalayan or Shillong tributary types. The proximity of Type-2 deposits to the Shillong Plateau suggest provenance from Shillong tributaries. Although this study is not focused on the origin of Pleistocene gravel deposits, the occurrence of Type-1a, Type-1b, and Type-2 deposits within the same province creates difficulty for formulating a model that explains the older history of the Dauki Foredeep province. Furthermore, the overall geochemical complexity of the Pleistocene stratigraphic sections make necessary further investigation of the weathering controls on Sr (ppm) in Pleistocene deposits and the tectonic history of the Dauki Foredeep province.

Unfortunately, the locations of the small population of gray clay-clasts and reddish-brown concretions do not correlate well with the locations of matrix sediments from which Sr (ppm) data were collected. However, the samples that do correlate show that they all lie well within the Bengal high-Sr and depressed Brahmaputra-Sr groups affirming Brahmaputra River origin for the deposits. This also reveals that the lateral bank migration most likely responsible for producing the clay-clasts must have been associated with the main Brahmaputra River channel.

Availability and Transport of Gravel Sized Sediments

Bogra Terrace and Jamalpur Terrace

Channel configuration of the Brahmaputra River changes rapidly during rising flood stages due to rapid thalweg migration (Coleman, 1969; Goswami, 1985). Previous studies also note considerable lateral bank migration as a definitive characteristic of the behavior of the Brahmaputra River (Best, et al., 2007; Coleman, 1969; Goodbred, et al., 2003; Goswami, 1985). In this system, bank failure and channel configuration are most directly influenced by perennial floods, high velocity hydraulic regimes, and erodibility of bank sediments. By substantially increasing sediment load, these controls directly contribute to the braided morphology of the Brahmaputra River (Coleman, 1969; Goswami, 1985; Kale, 2002). However, since the results from this study suggest that a majority of the gravel occurrences are not linked to direct input from proximal Himalayan tributaries, we suggest that the model for gravel origins is largely dependent on the positive feedback relationship between the erodibility of bank sediments and lateral channel migration behavior of the Brahmaputra River.

Based on observations that braided channel morphology is more prominent where bank material is less resistant to lateral bank migration, erodibility of bank sediments is an important control on this positive feedback relationship (Coleman, 1969). Differential tectonic subsidence and uplift throughout a basin leave deposits to be either preserved through rapid burial or exposed to reworking, respectively.

BNGA is situated in close proximity to several areas experiencing differential subsidence and uplift associated with active tectonic deformation. The Dauki Foredeep province represents preservation of thick floodplain packages due to subsidence, rapid burial, and little exposure to lateral bank migration (Pickering, 2013). On the other hand, the Bogra Terrace and Jamalpur Terrace provinces from Pickering (2013) represent gravel rich Pleistocene terrace surfaces (Morgan and McIntire, 1958) that lie exposed adjacent to the Brahmaputra River alluvial valleys. Since subsidence in these provinces is much less than that in the Dauki Foredeep province, the deposits have not been as extensively buried. Furthermore, the buried morphologies of the BJV and OBV have likely come to their present form through reworking of the Pleistocene terraces by means of continued lateral migration of the Brahmaputra River throughout the Holocene. Since they have been exposed to reworking and are gravel rich, the stratigraphy of the Bogra and Jamalpur Terrace provinces are possible sources for the origin of gravels in the adjacent BJV and OBV stratigraphy.

Tista River and Mega-fan

The Tista River exits the Himalayan range at the apex of the Tista mega-fan where it continues to its confluence with the Brahmaputra River in northwest Bangladesh. Chakraborty and Ghosh (2010) describe the Tista mega-fan as an alluvial fan that has built southward from the Himalayas to cover ~18,000 km^2 of the foreland basin. It has a maximum width and length of 145 and 166 km, respectively. Total relief from the apex to the Brahmaputra alluvial plain is ~150 m, and the Brahmaputra River flows along ~150 km of Tista megafan deposits (Chakraborty and Ghosh, 2010). With an average slope of 0.00094°, the Tista megafan falls in the braided fluvial fan category of Stanistreet and McCarthy (1993).

Sedimentation differs between fans with different sizes and slopes, but it is generally agreed that alluvial fans are a good indicator of basin-margin tectonism (Miall, 1996). Furthermore, tectonism is a source of seismic activity that commonly triggers landslides in areas of high relief such as the Tista River catchment (Kale, 2002). Landslides within the Tista River catchment produce significant amounts of coarse sediment of Himalayan lithologies available for transport. Chakraborty and Ghosh (2010) note the deposits in the stratigraphy of the Tista megafan as ranging from proximal boulders to distal fine sand and silt.

Although the bulk of the coarsest sediments are found proximal to the apex of the Tista megafan, seasonal discharge reaching ~2,000 m^3 per second means the Tista River has had plenty of capacity to transport coarse sediments to the distal fan areas (Chakraborty and Ghosh, 2010). Also, glaciers and landslides within the catchment are known to act as natural dams that occasionally fail releasing catastrophic discharge (Hewitt, 1982). These types of events are marked in the Tista mega-fan stratigraphy by the occurrence of distal coarse grained deposits.

Even though clast lithology, proximity to the deposits in question, and substantial length of its margin that is shared with the Brahmaputra River point to the Tista mega-fan as a likely source, the geochemical data from this study suggest that it would only be a secondary source for the origin of gravels in the Holocene stratigraphy along BNGA.

Gravel Transport

Miall (1996) describes gravel transport with an emphasis on flow conditions as major controls, but this study is interested in mechanisms that explain the origin of gravels into the Brahmaputra River stratigraphy that does not rely on hydrodynamic transport controls. Noting that sediment load is also a major controlling factor, Miall (1996) describes in some detail the common modes of gravel introduction to the bedload of a river and subsequent evolution of bedforms.

Bedform migration and cutbank erosion are the most common mechanisms for the release of gravel (Miall, 1996). Both of these mechanisms are well documented in the Brahmaputra River, and cutbank erosion is discussed earlier as lateral bank migration. However, the Brahmaputra River does not present the classical gravel bed river framework for the descriptions of bedform evolution from Miall (1996).

During the Holocene, aggradation of the Brahmaputra River has remained relatively unchanged in respect to sand dominated bedload and braided morphology (Goodbred, et al, 2003; Pickering, 2013). The sand dominated bedload of this braided system presents problems to applying existing models of gravel transport because most are developed under the assumption of clast support within a deposit. The uncertainties in this study about degree of clast support, or gravel to matrix sediment ratio, in a specific deposit require that existing models for various degrees of clast support are all considered.

Gravels released through bedform and lateral bank migration are introduced to the active channel in pulses known as “slugs”. The largest clasts are expected to be immediately deposited and buried by rapid migration of sand bedforms. This leaves a gravel deposit very proximal to its point of introduction to the river with the volume of available clasts determining the character of the resulting stratum. The slugs of small clasts would be transported downstream as channel lags only a few clasts thick (Miall, 1996). In an aggradational system such as the Brahmaputra River, the slugs of small clasts are deposited as thalweg lags that are elongated downstream. This mechanism also infers that these elongated gravel lags would decrease in grain size in the downstream direction.

Detailed work specifically investigating gravel deposit morphologies is required to determine the accuracy of this model. However, enough evidence is presented here to substantiate the hypothesis that the thin bedded gravel deposits in the upper stratigraphy of the Holocene Brahmaputra River valley fills represent thalweg lag deposits of gravels incorporated through cutbank erosion, or lateral bank migration.

CHAPTER V

CONCLUSIONS

The stratigraphy of the Holocene valley fills of the Brahmaputra River near the apex of the GBMD is dominated by fine to medium sand deposits with interspersed deposits of gravel. Previous studies do not describe gravel lithofacies in Holocene stratigraphy of the upper delta. However, the stratigraphy along BNGA is consistent with previous interpretations that describe a lack of fine grained sediments in the upper delta stratigraphy as indicative of regular lateral reworking of modern floodplain deposits through channel migration (Goodbred, et al., 2003; Pickering, 2013). This study adds to this interpretation a consideration of the origins and controls on the transport and deposition of gravel sized sediments.

Essential to the study of gravel origins, the geochemical data from this study provide further evidence that Sr (ppm) is a reliable indicator of sediment provenance that is mainly influenced by sediment mineralogy. This data also reveals the discovery of the depressed Brahmaputra-Sr group (120-140 ppm), which is interpreted to represent mixing of Bengal high-Sr group sediments (i.e. modern Brahmaputra River type; >140 ppm) with Bengal-low Sr group sediments (i.e. Tista River range; <90 ppm). The depressed Brahmaputra-Sr group is relatively abundant in the Bogra Terrace province. This is strong evidence of increased Tista River and mega-fan sediment flux to the Brahmaputra River during deposition of the stratigraphy west of the BJV. Future geochemical studies of Holocene and Pleistocene aged GBMD stratigraphy should consider Sr (ppm) values >120 ppm as evidence of stratigraphy built by the Brahmaputra River.

Comparison of the Sr (ppm) dataset with gravel location and distribution along BNGA reveals that gravels commonly occur in association with both the Bengal high-Sr and depressed Brahmaputra-Sr groups with no apparent bias other than the relative abundances of the two matrix sediment groups. This leads to the conclusion that although gravels do occur with depressed Brahmaputra-Sr group matrix sediments, the source of Type-1 gravels is not exclusively linked to sediment contributions from Himalayan tributaries (e.g. Tista River).

Even though the gravel clast lithologies sampled along BNGA seem to best fit the Himalayan source terrane lithologies described in the available literature, the geochemical data show us that determination of gravel origin based on clast lithology is not a viable method. This is mainly due to the complexity of the assemblage of lithologies present in the catchment and the subjectivity of clast lithology identification.

Type-1 gravels are abundant in the Holocene alluvial valley fill of both the BJV and OBV. This suggests that the origin of gravels is not directly influenced by the valley occupation history of the Brahmaputra River in Bangladesh.

In the GBMD, the likelihood of bank sediment erosion is directly proportional to exposure, or availability, and not strongly related to mechanical properties (e.g. cohesion). For example, due to rapid subsidence in the Dauki

Foredeep province, sediments are buried relatively quickly and are less likely to be eroded because of the lack of availability. Conversely, uplifted sedimentary blocks and terraces (e.g. Shillong Plateau, Bogra and Jamalpur terraces) are more likely to be eroded because they are available to be reworked through the process of channel migration. This makes the Pleistocene aged stratigraphy of the Bogra Terrace and Jamalpur Terrace provinces possible sources for some of the gravels found along the margins of the Holocene alluvial valley fills. **This study concludes that the availability of gravel bearing sediment to be eroded is the major control on the introduction of gravel to the Brahmaputra River.**

While local sources for gravels along the BJV and OBV margins can be identified from the BNGA drilling data, this model does not sufficiently explain the gravel deposits found “stranded” in the valley fill stratigraphy. Aside from these possible local sources, more fieldwork / drilling upstream of BNGA is required to identify gravel bearing stratigraphy that is periodically subjected to erosion through lateral bank migration of the Brahmaputra River. It is also recommended that further geochemical analyses of GBMD sediments be conducted to further define the Sr (ppm) range and spatial distribution of the depressed Brahmaputra-Sr group.

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