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1 **Synthesis of the Distribution of Subsidence of the Lower Ganges-**  
2 **Brahmaputra Delta, Bangladesh**

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24 **Author contributions:**

25 MSS: Wrote text, drafted figures, interpreted results, installed GNSS and helped with other  
26 equipment

27 BO: Processed GNSS data, wrote and edited text, drafted figure.

28 CAW: Installed and analyzed RSETs, wrote and edited text

29 CG: Analyzed well data, wrote and edited text

30 SLN: Helped install GNSS and compaction meter, seasonal correction to GNSS data, edited text.

31 DRM: Tide gauge analysis, aided in GNSS processing, augering at Temple

32 SHA: Installation and maintenance of GNSS

33 SD: Installation of compaction meter and analysis of results

34 SLG: Analysis of tube well data, augering at Temple

35

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37 **Keywords:** land subsidence, deltas, Bangladesh, compaction, sediments, sustainability

38

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40

41 **Abstract**

42 Deltas, the low-lying land at river mouths, are sensitive to the delicate balance between sea  
43 level rise, land subsidence and sedimentation. Bangladesh and the Ganges-Brahmaputra Delta  
44 (GBD) have been highlighted as a region at risk from sea-level rise, but reliable estimates of land  
45 subsidence have been limited. While early studies suggested high rates of relative sea-level rise,  
46 recent papers estimate more modest rates. Our objective is to better quantify the magnitude,  
47 spatial variability, and depth variation of sediment compaction and land subsidence in the lower  
48 GBD to better evaluate the processes controlling them and the pattern of relative sea level rise in  
49 this vulnerable region. We combine subsidence and compaction estimates from hand-drilled tube  
50 wells and historic sites (1-5 mm/y), GNSS and river gauges (4-8 mm/y) and RSET-MH and  
51 borehole vertical strainmeters (9-10 mm/y) in SW Bangladesh. The differences between the  
52 different types of measurements reflect the different timescales, spatial distribution and depth  
53 sensitivity of the different observations. Rates are lower for times >300y providing data on the  
54 timescale of compaction. We also observe differences related to the degree to which different  
55 devices measure shallow and deep subsidence. Higher values reflect a greater component of  
56 subsidence from young shallow deposits from soil compaction and organic matter degradation.  
57 Thus, we observe different rates for different environments and physical settings. These  
58 differences indicate that in planning adaptation for rising sea level, hard construction with a solid  
59 foundation may experience different subsidence rates than open fields or reclaimed land with  
60 recent natural or anthropogenic sedimentation.

61

62 **Significance Statement**

63 Land subsidence increases the impact of sea level rise. We combine six different types of  
64 measurements that examine land subsidence in coastal Bangladesh. The results show that causes  
65 of subsidence, including compaction of the sediments varies both spatially and with depth, and  
66 that compaction and organic matter degradation from young shallow deposits is a significant  
67 contribution to subsidence. This suggests that hard construction with a solid foundation, such as  
68 buildings and embankments, may experience a lower subsidence rates than open fields or  
69 reclaimed land with recent natural or anthropogenic sedimentation.

70

71

## 72 1. INTRODUCTION

73 Deltas, the low-lying land at river mouths, are particularly sensitive to the delicate balance  
74 between sea level rise, land subsidence and sedimentation (Milliman et al., 1989). An estimated  
75 350 million people globally inhabit these vulnerable landscapes (Edmonds et al., 2020), thus  
76 processes that control growth versus loss of land is vital to the stability of coupled human-natural  
77 deltaic systems (Syvitski et al., 2009; Tessler et al., 2015). Low-lying river deltaplains grow by  
78 receiving sediments transported to the coast. On the other hand, the weight of the sediments  
79 causes compaction and isostatic loading that induces subsidence, which reduces the growth of  
80 the delta. Human modification, especially subsurface fluid withdrawal, can further exacerbate  
81 subsidence (e.g., Dixon et al., 2006; Akhter et al., 2009; Minderhoud et al., 2017; Erkens et al.,  
82 2016). Upstream damming and river diversions have substantially decreased the sediment supply  
83 to many deltas (e.g., Syvitski et al., 2005; Blum and Roberts, 2009; Giosan et al., 2014; Kondolf  
84 et al., 2014; Gebremichael et al., 2018). A detailed understanding of the balance between sea  
85 level rise, sedimentation and subsidence is critically important for assessing the sustainability of  
86 deltas. The elevation balance at deltas can be summarized by the following equation modified  
87 from Syvitski et al. (2009):

$$88 \quad \Delta_{REL} = -\Delta E - C_n - C_a - M + A \quad (1)$$

89 Where  $\Delta_{REL}$  is the rate of relative vertical change in delta surface elevation,  $\Delta E$  is Eustatic  
90 sea level rise rate,  $C_n$  is the rate of subsidence from Natural Compaction,  $C_a$  is the subsidence  
91 rate of Accelerated Compaction due to human activities,  $M$  is the rate of vertical crustal  
92 Movement (including both tectonics and isostatic motions), and  $A$  is the sediment Aggradation  
93 rate. Thus, multiple components of subsidence increase elevation loss while sedimentation  
94 counters elevation loss by the deposition of organic and inorganic material in areas of new  
95 accommodation.

96 As the boundary between land and sea, a number of studies have found that deltas are at risk  
97 from sea level rise and climate change, and are becoming increasingly vulnerable to flooding,  
98 erosion, and salinization (Ericson et al., 2006; Syvitski et al., 2009; Ostanciaux et al., 2012;  
99 Tessler et al., 2015, 2018). A recent study (Nienhuis et al., 2020) found globally deltas are still  
100 gaining land, but with accelerating sea level rise and anthropogenic changes this is likely not  
101 sustainable. However, most large and medium size deltas have insufficient sediment supply to  
102 maintain their current size (Giosan et al., 2014) and there is declining sediment supply to most  
103 major deltas due to climate change and human intervention (Dunn et al., 2019). While accurate  
104 estimations of  $\Delta_{REL}$  are critically needed for addressing the human sustainability in deltas, these  
105 estimates are plagued with difficulties, such as constraining all the parameters that play out both  
106 locally and regionally, and having sufficient long-term instrumental records that capture  
107 interannual variability. In order to fully understand  $\Delta_{REL}$ , a variety of measurements are  
108 required, as different instruments provide distinct information on compaction and subsidence.  
109 For example, different instrument anchoring depths yields different results (Keogh et al., 2019).  
110 This can lead to a large variability in measurements, such that the regional pattern is difficult to  
111 distinguish. This is the case for the Ganges-Brahmaputra Delta (GBD), the largest delta in the  
112 world (Brown and Nicholls, 2015; Paszkowski et al., 2021). We present here a coherent  
113 synthesis of vertical elevation change, compaction, and subsidence in this region, revisit  
114 previously published data, and update this dataset with newly acquired data. Finally, we analyze

115 these datasets together to extract significant information about the temporal and spatial  
116 variability of subsidence in the GBD, one of the most densely populated regions of the world.

## 117 2. REGIONAL SETTING

118 The GBD, the largest delta in the world, is formed by two of the world's major rivers (Fig.  
119 1). The GBD has been highlighted as a region at risk from rising river and ocean water levels  
120 (e.g., Milliman et al., 1989; Ericson et al., 2006; Syvitski et al., 2009; Tessler et al., 2018). It  
121 receives  $>3/4$  of the water and sediment drained from the Himalayas (Milliman and Farnsworth,  
122 2011) creating a fertile and densely-populated delta in which  $>130$  million people live. This low-  
123 lying land, with half of Bangladesh at elevations  $<10$  m, undergoes riverine flooding every  
124 monsoon season: in a normal year, 20-25% of the land is submerged, but can reach 60-70%  
125 during an extreme flood (Mirza, 2003). The GBD is still net gaining land, with growth at the  
126 river mouth outpacing land loss along the coast farther west (e.g., Allison, 1998, Brammer,  
127 2014). While parts of the delta near the Lower Meghna River mouth (Fig. 1) are receiving  
128 sufficient sediment and gaining land, other regions away from the major rivers are in decline  
129 (Wilson and Goodbred, 2015). In the tidal delta near the coast, sediment supply averages 11  
130 mm/y in the Sundarbans (Rogers et al., 2013) and 23 mm/y farther east (Rogers et al., 2017) with  
131 large variability. Anthropogenic channel infilling in the delta interior also contributes to net land  
132 gain (Wilson et al., 2017). However, large tracts of coastal Bangladesh have been embanked  
133 (poldered), halting sediment delivery within the polders. This region, where natural and  
134 anthropogenically-enhanced subsidence is no longer offset by sedimentation, is where the land is  
135 at greatest risk (Wilson and Goodbred, 2015; Auerbach et al., 2015). This has exacerbated  
136 waterlogging of the embanked islands and a shift from rice cultivation to shrimp farming  
137 (Alauddin and Hamid, 1999).

138 In the fluvial delta farther upstream, sedimentation is focused near the rivers while  
139 subsidence is distributed broadly. Elevation increases near rivers while areas farther away  
140 subside. This increasing elevation contrast through time drives river avulsions (Slingerland and  
141 Smith, 2004), thereby spreading the sediments delta-wide over sufficiently long (geologic)  
142 timescales (Reitz et al., 2015). Major tributaries to the upper delta, such as the Tista are also  
143 highly avulsive, in part associated with flexural loading across the hinge zone (Grimaud et al.,  
144 2020). The result is a dynamic landscape where sedimentation and subsidence patterns are  
145 continually in flux. Around the turn of the 19th century, there was the well-known westward  
146 avulsion of the Old Brahmaputra River to its present Jamuna channel (Fig. 1). This is one of  
147 several Holocene avulsions of the Brahmaputra, which averages avulsions every  $\sim 1800$ y (Reitz  
148 et al., 2015; Sincavage et al., 2017). The Ganges has also undergone avulsions. Prior to the mid  
149 1600s, the Hooghly River (Fig. 1) was the main channel of the Ganges River (Eaton, 1993;  
150 Parua, 2010). The Mathabhanga, Gorai, Arial Khan, among others, were major distributaries to  
151 the east of the Hooghly. The shift of the Ganges to the Padma led to a reduction of water and  
152 sediment to these channels. The resulting increased salinity incursion in the lower deltaplain led  
153 to the building of polders (embankments) in the 1960s and 70s to improve agricultural  
154 production. Now, the Farakka Barrage in India diverts water from the Ganges into the Hooghly  
155 and efforts have been made in Bangladesh to restore flow to the Gorai. Sometime in the late 19th  
156 century the Ganges shifted from flowing down the Arial Khan and Tetulia channels to join the  
157 Brahmaputra in the Lower Meghna channel (Fig. 1). As a result, the Lower Meghna is widening  
158 while the Arial Khan and Tetulia are narrowing (Allison, 1998; Brammer, 2014).

159 The interplay of sedimentation, subsidence and sea level at the GBD is further complicated  
160 by active tectonics at the eastern half of the delta (Fig. 2). The IndoBurma subduction zone  
161 (IBSZ) is the along strike continuation of the Sumatra subduction zone. While most subduction  
162 zones are submarine, in Bangladesh the incoming plate is capped by the GBD with its 16-20 km  
163 of sediment (Singh et al., 2016; Mitra et al., 2018; Ismaiel et al., 2019) and as a result, the  
164 accretionary prism is entirely subaerial (Fig. 1). It encompasses to a >300 km area hosting a  
165 series of bivergent anticlines (Betka et al., 2018). The less well-developed frontal anticlines are  
166 blind and buried by the delta, but are known from gas exploration. The position of the  
167 deformation front (Fig. 1) is based on mapping these anticlines (Betka et al., 2018). East of the  
168 deformation front, there is additional subsidence from flexural loading, and uplift from  
169 shortening and thickening in the accretionary prism. Furthermore, the earthquake cycle produces  
170 cycles of subsidence and uplift through elastic loading of the megathrust underlying the entire  
171 area (Fig. 2). Akhter (2010) suggested that the avulsion of the Old Brahmaputra to the current  
172 Jamuna channel (Fig. 1) may have been due to tectonics, perhaps triggered by a 1787 earthquake.  
173 Furthermore, earthquakes can produce pulses of sediment delivery downstream. Enhanced  
174 sediment flux from the 1950 Assam earthquake has been documented (Goswami, 1985; Sarma,  
175 2005; Sarker and Thorne, 2006) along with progressive changes in the Brahmaputra River width  
176 and braiding from the sediment pulse. Given these additional complexities, this paper's primary  
177 focus is on the components of elevation change, compaction, and subsidence in the non-tectonic  
178 part (i.e., west of deformation front, Fig. 1) of the GBD in southwest Bangladesh as defined by  
179 Grall et al. (2018).

180 The extensive natural and anthropogenic changes in the sediment distribution within the  
181 GBD illuminate the importance of addressing of how subsidence is distributed across the delta,  
182 particularly on the lower tidal delta plain. While sedimentation drives compaction and isostatic  
183 adjustment, the long timescales of these responses mean that they have significant lags and that  
184 subsidence continues after rivers have shifted their depocenters. This sets up a cycle of delta lobe  
185 progradation followed by degradation after abandonment, similar to the Mississippi Delta  
186 (Allison et al., 2003). However, reliable estimates of land subsidence and relative sea level rise  
187 (the combination of sea level rise and subsidence) at the GBD have been limited. Early global  
188 studies that included the GBD suggested high rates of relative sea level rise (Ericson et al., 2006;  
189 Syvitski et al., 2009; Tessler et al., 2018), while more recent local papers suggest modest rates  
190 (Pethick and Orford, 2013; Grall et al., 2018; Becker et al., 2020). Knowing the current rates of  
191 sediment compaction, tectonic land movement and isostatic loading (Fig. 2) is critical for  
192 understanding the sedimentation patterns in the GBD and the prospect for near future land loss  
193 and salinization. Recent studies (Karpytchev et al., 2018; Krien et al., 2019), suggest that  
194 isostatic loading by the sediments contribute significantly to the subsidence of the delta. The  
195 contribution of sediment compaction and organic matter degradation may be large at the GBD  
196 (Higgins et al., 2014) given the high sedimentation rates (Rogers et al., 2013, 2017) and  
197 thicknesses (Singh et al., 2016; Mitra et al., 2018; Ismaiel et al., 2019). While the GBD is  
198 predominantly considered a mineralogenic delta plain, some organogenic wetland areas exist, and  
199 Higgins et al. (2014) documented that these fine-grained organic regions have experienced  
200 substantial subsidence after reclamation. In addition, groundwater extraction is significant near  
201 Dhaka (Akhter et al., 2009), but widespread irrigation is broadly lowering the water table  
202 (Shamsudduha et al., 2009).

203 Quantitative estimates of these multiple factors throughout the GBD are poorly known.  
204 Chamberlain et al. (2020) provided an overview of methods for quantifying the sedimentation

205 and subsidence history of the GBD, and a summary of efforts to date. Here we compile previous  
206 and recently published subsidence measurements with new evaluations of GNSS, tide gauge, and  
207 historical building measurements, and discuss the nuances between shallow vs deep and short- vs  
208 long-term processes. Our objective is to better quantify the magnitude, spatial variability, and  
209 depth variation of compaction and subsidence in the GBD to better evaluate the processes  
210 controlling it and the pattern of relative sea level rise in this vulnerable region.

### 211 **3. COMPACTION PROCESSES**

212 As sediments are buried, they undergo a variety of sediment compaction and consolidation  
213 processes resulting in the loss of porosity and decrease in sediment layer thicknesses through  
214 time and with depth, inducing subsidence of the overlying strata (Fig. 2). With greater depth,  
215 sediment grains reorganize into more compact arrangements, particularly platy clay minerals that  
216 rotate to horizontal orientations. Smaller grains can fill pores between larger grains. With  
217 increasing pressure and temperature, grains can dissolve at inter-grain contacts and reprecipitate  
218 into pore spaces to further lower porosity. Additional dissolved minerals may be transported  
219 through the basin and contribute to cementation. Chemical reactions, such as dehydration of  
220 clays, further reduce the sediment water content. At still greater depth, metamorphic reactions  
221 reduce sediment volume. The progressive reduction of porosity with depth or lithostatic  
222 overburden has been modeled by a variety of empirical formulas, often with an exponential form  
223 (e.g., Athy, 1930; Terzaghi and Peck, 1967; Sclater and Christie, 1980; Gluyas and Cade, 1997;  
224 Kooi and DeVries, 1998; Bahr et al., 2001; Sheldon and Retallack, 2001; Kominz et al., 2011).  
225 The initial porosity of the sediments and its decay with depth depend strongly on the lithology of  
226 the sediments. Organic-rich clay and silt generally have higher initial porosities and undergo  
227 greater compaction than coarser sediments (Sheldon and Retallack, 2001; Meckel et al., 2007;  
228 van Asselen, 2011; Kominz et al., 2011). Another factor is that low permeability sediments, such  
229 as shale, may hinder the upward flow of fluids, slowing or halting compaction and creating  
230 overpressure in the sediments (e.g., Gluyas and Cade, 1997; Gordon and Flemings, 1998). In the  
231 GBD, extensive overpressure is present below depths of 3-5 km where sediments are mainly  
232 deeper-water shales (Zahid and Uddin, 2005).

233 Another important consideration impacting compaction is the incision of the delta during the  
234 last glacial maximum (LGM). While lowstand deltas are found offshore near the shelf edge  
235 (Palamenghi, 2012), within the GBD, a large valley 60-90m deep was incised into older  
236 Pleistocene-aged sediments during the LGM (Fig. 1, Pickering et al., 2014; Goodbred et al.,  
237 2014). Previously buried sediments do not significantly decompact with unloading (Chapman,  
238 1983). Further compaction only occurs when the valleys are subsequently filled and overburden  
239 pressure exceeds the previously level. Thus, during the Holocene, compaction in the GBD has  
240 primarily occurred in the Holocene-aged sediments and not in the underlying older strata (Fig.  
241 2).

242 At shallow depths, compaction of young sediments can be rapid, particularly for highly  
243 porous muddy sediments (Hedberg, 1936; Kominz et al., 2011; van Asselen, 2011). Peat and  
244 other organic rich soils undergo even more rapid compaction in the near surface than other soils  
245 (Sheldon and Retallack, 2001; van Asselen, 2011). Oxidation of peats due to groundwater  
246 lowering can cause significant subsidence (van Asselen et al., 2018). However, few true peats  
247 with very high percentages of organic matter are found in the GBD (Brammer, 1990; Goodbred  
248 et al. 2003, Best et al. 2007). Large water level fluctuations and biologic respiration lead to  
249 oxidation of most organic material before it is deeply buried. In addition, roots occupy soil

250 volume, which can reach 10-20% in the Sundarbans mangrove forest in the near surface  
251 (Auerbach et al., 2015) leading to thickness loss as the plants senesce, dewater, and are oxidized  
252 with burial. Bioturbation and animal burrows can further increase the porosity at very shallow  
253 levels. These effects can contribute to a large amount of effective sediment compaction in the  
254 upper few meters of the sediment column.

255

256

#### 257 **4. PREVIOUS ESTIMATES OF SUBSIDENCE IN THE GBD**

258 A limited number of studies have examined subsidence rates in the GBD. Alam (1996) and  
259 Hoque and Alam (1997) compiled radiocarbon dates on Holocene samples and obtained  
260 subsidence rates from 0.53 (Kolkata) to 5.48 mm/y (Khulna) (Fig. 1), but suggested that rates  
261 could reach 20-30 mm/y in places. Alam (1996) assigned the reported top of the Plio-Pleistocene  
262 Dupi Tila formation in the 1960 Hazipur-1 well as corresponding to the beginning of the  
263 Holocene. As a result, he estimated a subsidence rate of 22 mm/y that is likely too high (see  
264 supplement). This was used in a global analysis of delta subsidence (Ericson et al., 2006) to  
265 suggest a high subsidence rate in the GBD. Radiocarbon data on auger and vibracores up to 7m  
266 depth across the lower delta plain (Allison et al., 2003) indicated sediment accumulation rates of  
267 1-7 mm/y and subsidence rates of 1-4 mm/y. A summary of the papers discussed in this section  
268 is provided in Table S1.

269 In a study of global deltas, Syvitski et al. (2009) suggested a GBD subsidence rate of up to 18  
270 mm/y. Their estimate is based on a high rate of subsidence at the Khepupara tide gauge.  
271 However, our examination of the 1977-2010 record of this gauge using hourly Bangladesh  
272 Inland Water Transportation Authority (BIWTA) data shows several decadal-scale changes in  
273 rates (Fig. 3), with at least one change in 2000 corresponding to when the gauge was relocated  
274 based on local interviews. The publicly available data (1987-2000) from the Permanent Service  
275 for Mean Sea Level (PSMSL) corresponds closely to the period of high subsidence of the gauge,  
276 and thus should be regarded as an overestimate (Fig. 3). Ostanciaux et al. (2012) studied global  
277 trends of coastal vertical motion and estimated high rates at the GBD of 11-20 mm/y, again  
278 biased by the public Khepupara gauge data.

279 In contrast, Sarker et al. (2012) examined plinth elevations relative to the surrounding ground  
280 levels (Fig. 6) at four historic sites that are 200-600 years old and determined low subsidence  
281 rates of 0-2.5 mm/yr. However, as described below, a reanalysis of one site, the Shakher Temple  
282 in the Sundarbans, yields a higher rate of 3.4 mm/y (Chamberlain et al., 2020). At Katka Beach  
283 in the Sundarbans, Hanebuth et al. (2013) discovered 300-year old salt kilns uncovered by  
284 coastal erosion. The kilns would have been built just above spring high tide level indicating 4.1  
285 mm/y subsidence. The remains of additional salt kiln sites in the region have been discovered  
286 and are being dated (H. Kudrass, Pers. Comm., 2020).

287 Brown and Nichols (2015) compiled a comprehensive suite of >200 measurements of  
288 subsidence in the GBD. Methodologies included carbon dating, borings/wells/auger logs,  
289 archaeological sites, InSAR, GNSS, optically stimulated luminescence dating, geomorphology,  
290 estimates of compaction from groundwater depletion, and magnetostratigraphic dating. However,  
291 by mixing multiple types of measurements with insufficient constraints on their settings, they  
292 obtained subsidence rates that varied from 44 to -1 mm/y, including broad ranges of values at



293 individual sites. Their comprehensive mixture of samples with limited context also shows the  
294 “Sadler effect” (Sadler, 1981), with mean subsidence rates decreasing with increasing timescale  
295 of measurement. A critical problem is the need to distinguish between subsidence and sediment  
296 accumulation rates. For example, if incision by a river is followed by rapid deposition when the  
297 river migrates or avulses, the net effect is younger river channel sediments replaces older  
298 sediments. This “channel incision effect” yields incorrect high apparent subsidence rates (Fig. 4).  
299 Grall et al. (2018) used >400 tube wells with almost 200 <sup>14</sup>C dates (Fig. 5), as well as seismic  
300 data along the Brahmaputra River and offshore, to estimate average Holocene subsidence rates.  
301 The authors identified and removed samples affected by the channel incision effect, and  
302 distinguished components due to sediment accumulation, eustatic sea level rise and subsidence.  
303 Results revealed a systematic variation of subsidence rates across the delta. In the lower GBD,  
304 subsidence increases from near zero rates landward of the Hinge Zone to 4.5 mm/yr at the  
305 southern coast of Bhola Island (Fig. 5). The Hinge Zone is the track of the Eocene shelf edge,  
306 which also corresponds to the boundary between the thinly sediment-covered Indian craton and  
307 the thick sedimentary depocenter of the Bengal Basin (Fig. 1; Steckler et al., 2008).

308 Recently, Becker et al. (2020) analyzed groups of river and tide gauges to reconstruct  
309 subsidence rates in the delta (Fig. 5). The averaging of 19-24 stations for each zone, along with  
310 the corrections and analysis in the paper, minimized the effect of poor tide gauges, such as  
311 Khepupara. They estimate a maximum of up to 7 mm/y subsidence for the period of 1993-2012.  
312 This is noticeably higher than the Holocene rates of Grall et al. (2018) (Fig. 5), but the pattern is  
313 generally coherent for the different morphodynamic units (Grall et al., 2018). In the tectonic  
314 areas east of the IBSZ deformation front, elastic loading by the locked megathrust (Steckler et  
315 al., 2016) is expected to contribute 3-4 mm/y of subsidence (Oryan et al., 2020) that would be  
316 countered by earthquake related uplift in the average Holocene rates, which are significantly  
317 lower.

318 GNSS geodesy provides another means of assessing current subsidence rates. Our GNSS  
319 stations in Dhaka and Sylhet showed locally high subsidence rates of 12 mm/y (Fig 1, Steckler  
320 et al., 2010). Reitz et al. (2015) expanded the results to include 18 stations. Sites in NW  
321 Bangladesh at or landward of the Hinge Zone showed subsidence rates <1 mm/y, while sites in  
322 Sylhet, a tectonically active basin, showed high rates (7-12 mm/y). The high subsidence rate in  
323 Dhaka at 12 mm/y from groundwater withdrawal was confirmed in the longer time series. Rates  
324 in the foldbelt farther east were variable depending on the structural position of the GPS site.  
325 Their three sites in the coastal belt showed moderate but variable rates of 3–8 mm/yr.

326 Higgins et al. (2014) used InSAR measurements with the ALOS-1 satellite to create a map of  
327 subsidence rates across a >10,000 km<sup>2</sup> swath of central Bangladesh (location in Fig. 5). They  
328 obtained rates from 0 to >18 mm/yr, with the lowest rates primarily in Pleistocene Madhupur  
329 Clay and the highest rates in Holocene organic-rich muds. One high subsidence area follows an  
330 eastern branch of the Lower Meghna that previously flowed past Noakhali (approximately the  
331 position of the M in Lower Meghna in Figure 1), but was filled with sediments following the  
332 1950 Assam earthquake (Sarker et al., 2013). These young deposits are clearly undergoing rapid  
333 compaction. Dhaka has high rates of subsidence from groundwater withdrawal (Steckler et al.,  
334 2010), and the InSAR (Higgins et al., 2014) shows variable rates that correlate with the  
335 underlying geology. Further investigations using InSAR from the Sentinel-1 satellite are ongoing  
336 (Woods et al., 2019).

## 337 5. UPDATED SUBSIDENCE RATES

338 We present our efforts to expand and improve the data on subsidence of the GBD and  
339 attempt to construct a coherent pattern of subsidence taking into account the different timescales  
340 of the measurements, the spatial distribution of sites in the context of the geology of the delta,  
341 and the depth component of each type of measurement.

### 342 ***5.1 Revised Long-term Subsidence from Historic Sites***

343 As mentioned above, human historic sites can provide evidence of subsidence over hundreds  
344 of years. Sarker et al. (2012) examined four historic sites, two Hindu temples and two Muslim  
345 mosques. A key component in determining subsidence from historic sites is identifying the plinth  
346 level, the base or platform upon which the building is built (Fig. 6). Construction typically  
347 includes a base that is built up from the original Tidal Platform Level (TPL) to the Homestead  
348 Platform Level (HPL), which is close to SHWL (Spring High Water Level), and then a plinth  
349 level (Fig. 6) that is 0.5-0.8 m higher to protect against floods. The thickness of the homestead  
350 platform is equal to  $a/2$  (Fig. 6), or half the difference between the NHWL (Neap High Water  
351 Level) and SHWL, placing the TPL at mean high water.

352 For the two 15<sup>th</sup> century mosques at Bagherat, subsidence is estimated as  $1.9\pm 0.6$  mm/y  
353 (Sarker et al., 2012). Lower rates of 1.25 mm/y and  $0.14\pm 0.74$  mm/y were found for the two  
354 ancient Hindu temples, the Shakher Temple and Doyamayee Mondir. We re-evaluated the  
355 subsidence at one of these temples during a visit (Fig. 7). We believe that the plinth level of the  
356 400-year old the Shakher Temple in the Sundarbans was misidentified. In their analysis of the  
357 temple, Sarker et al. (2012) placed the plinth level at the entrance of the temple at the top of the  
358 stairs, even with the interior of the temple (Fig. 7). While Muslim mosques are communal prayer  
359 halls that often are open at ground level, Hindu temples are commonly raised, as they are the  
360 home to gods (in this case, the Goddess Kali). Thus, one ascends the temple to enter the home of  
361 the goddess (Sharma and Deshpande, 2017). We believe the previous evaluation (Sarker et al.,  
362 2012) missed this architectural feature. Instead, we located a ridge in the bricks near ground level  
363 (Fig. 7) that we associate with the plinth level (Chamberlain et al., 2020). In addition, augering  
364 discovered a buried brick layer 1.5m below the surface. We interpret the brick layer as the  
365 original TPL level minus any excavation for preparing and leveling the site for construction. The  
366 brick layer and revised plinth level are consistent and yield a new subsidence rate of  $3.4\pm 0.5$   
367 mm/y (details in the supplement). We have not visited the other Hindu Temple, but it may have  
368 the same issue, so we exclude it from our calculations.

### 369 ***5.2 New Recent Shallow Subsidence From RSET-MH***

370 Rod surface elevation tables and marker horizons (RSET-MH) is a method of determining  
371 surface elevation changes and sedimentation rates in deltas and wetlands (Cahoon et al., 1995,  
372 2002). Elevation measurements are made from a rod driven into the ground to the depth of  
373 refusal or a maximum 24.38 m (80 ft.) (D. Cahoon, pers. comm., 2009). Following the  
374 procedures in Cahoon et al. (2002), a horizontal arm is attached to the rod from which 9  
375 measurements of surface elevation surrounding the site are taken at 8 different positions for a  
376 total of 72 measurements. Tile marker horizons are used to measure sediment accumulation rates  
377 at each site visit. Shallow subsidence above the base of the rods is determined by the difference  
378 between the elevation change and the sedimentation rate. What distinguishes these measurements  
379 from those described earlier is that the RSET-MH measure subsidence up to the surface in places  
380 with active sediment deposition. Thus, these rates include very shallow and seasonal near surface  
381 sediment consolidation and organic matter decomposition. Wilson et al. (2021) has established a

382 network of 22 RSET-MH in the tidal delta plain of the GBD (Fig. 8) with measurements made  
383 twice a year, before and after the monsoon that is responsible for most of the sedimentation. At  
384 Polder 32, there are 8 RSET-MHs, including 4 inside the polder and 4 in the adjoining  
385 Sundarbans forest (Bomer et al. 2020). The remaining sites have a pair of RSET-MHs. This  
386 enables us to obtain measurements both inside and outside of the embankments around the  
387 deltaic islands (polders, N=14), and within the Sundarbans mangrove forest near stream banks  
388 and interiors (N=8). Most were installed in 2019 co-located with our GNSS stations to  
389 distinguish shallow and deep subsidence (Keogh and Törnqvist, 2019; Karegar et al., 2020).  
390 Reliable rates for the new sites are not yet available as approximately 5 years are needed to  
391 establish long-term rates for all the measurements (elevation change, sediment accretion, shallow  
392 subsidence) and to separate the long-term trends from seasonal variations. Furthermore, our  
393 measurements have been disrupted due to the COVID-19 pandemic. However, preliminary  
394 results show seasonal shallow subsidence appears to be exacerbated during the dry season,  
395 especially in embanked settings where farmers drain their rice paddies and allow fields to go  
396 fallow (Wilson et al., 2021; Bomer et al., 2020). With maturation of the paired RSETs inside and  
397 outside of embankments, we should be able to remove this seasonal anthropogenic signal over  
398 time. A set of 4 stations in the natural Sundarbans mangrove forest adjacent to Polder 32  
399 established in 2014 yielded seasonal shallow subsidence rates of 7-18 mm/y over a 5-year  
400 period, averaging  $9.7 \pm 1.6$  mm/y (Bomer et al., 2020), significantly higher than other  
401 measurements despite not including deep subsidence from below the base of the RSET.

### 402 ***5.3 New Recent Compaction from Vertical Strainmeters***

403 DeWolf et al. (2013, in prep.) installed two sets of optical fiber strainmeters in hand-drilled  
404 wells in Bangladesh. The site in southwest Bangladesh at Bhanderkote, Khulna (called the  
405 Khulna compaction meter or KHLC, Fig. 8) contains 6 wells drilled to depths of 20, 40, 60, 80,  
406 100 and 300 m. Each well contains two pairs of optical fibers grouted into the bottom of the well  
407 and attached to a concrete monument at the top. The length of each fiber was measured weekly  
408 from 2011 to 2016 by local collaborators. In March 2015, the river adjacent to the site was  
409 dredged to improve navigation. Readjustment of the river profile led to bank erosion that  
410 destroyed KHLC in 2016. Measurements show a seasonal extension of the fibers during the  
411 summer monsoon due to clay swelling or poroelasticity with a longer-term subsidence trend.  
412 Shortening rates of the fibers generally increase with depth (Figure 9A) and are consistent with  
413 an exponential curve for a total compaction rate of  $\sim 9$  mm/y for the upper 300 m, with most  
414 compaction occurring in Holocene strata above 60 m depth and no compaction below 100 m,  
415 within errors. Based on nearby tube well transects, the thickness of the Holocene strata here  
416 exceeds 90 m (Fig. 1, 8). Thus, KHLC is located in the broad incised valley excavated by the  
417 Brahmaputra River during the last glacial maximum (Fig. 1). The lack of compaction beneath the  
418 Holocene is not unexpected, as the sediments below experienced compaction prior to the  
419 lowstand incision.

420 Additional interpretation needs to take into account recent sedimentation on the site. The  
421 river at KHLC was previously  $>300$ m wide (Fig. 9B), but historical imagery shows it narrowed  
422 dramatically between 1989 and 1999 (Wilson et al., 2017) and OSL dating of samples from an  
423 auger hole at the site shows 4.44 m of deposition since  $1987 \pm 3$  CE due to the channel filling  
424 (Chamberlain et al., 2020). KHLC was installed on the bank of this narrow ( $<10$  m) river in  
425 2011. Boat traffic on the river could only move at high tide leading to the government decision to  
426 dredge it. The compaction meter on the river bank was the site of sediment deposition, averaging

427 10-15 mm/y of tidalites per year until the river was widened (Fig. 9C; Chamberlain et al., 2020).  
428 Deposition likely occurred only during high tides during the monsoon when the river level was  
429 sufficient to flood the site. Thus, the high subsidence rate measured in the shallower strainmeters  
430 is associated with active sediment deposition and consolidation of recently deposited sediments  
431 near the surface.

#### 432 **5.4 New Recent Subsidence from GNSS**

433 GNSS enables observations using fixed antennas over years to estimate rates of tectonic  
434 deformation as well as subsidence or uplift on the order of  $\pm 1$  mm/y or better. Generally, it takes  
435  $>2.5$  years to determine reliable horizontal rates and  $>4.5$  years for vertical rates (Blewitt and  
436 Lavallée, 2002). We find the vertical rates for the DHAK station, with seasonal corrections,  
437 stabilized after 6 years. In the GBD, GNSS show a large seasonal component of up to 5-6 mm/y  
438 (Steckler et al., 2010). This downward motion during the summer is due to loading by seasonal  
439 flooding and recharge of groundwater during the monsoon. It represents lithospheric-scale elastic  
440 deformation from an average of  $\sim 100 \times 10^9$  tonnes (maximum  $\sim 150 \times 10^9$ ) of water,  
441 approximately 7.5% of the annual flow of the Ganges, Brahmaputra and Meghna Rivers that is  
442 sequestered in Bangladesh. As a result, continuous GNSS sites are necessary for accurate vertical  
443 rates. In Bangladesh, most antennas have been mounted on either stainless steel threaded rods  
444 cemented or epoxied into reinforced concrete buildings, or on tripods constructed out of welded  
445 stainless-steel rods driven into the ground. These systems capture subsidence where they are  
446 coupled to the ground, either the foundation of the building or at the  $\sim 2$  m depth of the rods.  
447 Thus, GNSS, particularly building sites, may not measure the shallowest component of land  
448 surface subsidence (Keogh and Törnqvist, 2019).

449 We have processed all available GNSS data in the GBD using GAMIT/GLOBK (Herring et  
450 al., 2018) with 16 International GNSS Service (IGS) stations used for stabilization. The vertical  
451 rates are given in Table S1 and the vertical time series for each of the sites is shown in Figure S3.  
452 The first continuous GPS receivers in Bangladesh were installed in 2003 and the number of sites  
453 has grown over the years. We installed additional sites in southwest Bangladesh in 2012 and  
454 2019, and rehabilitated older sites in 2014 and 2019. In this study, we have also included sites  
455 that have been installed by the Earth Observatory of Singapore (Mallick et al., 2019) and the  
456 continuous station deployed by the French IRD (Institut de Recherche pour le Développement)  
457 through the Belmont Forum BanD-Aid project (Shum et al., 2014), which is maintained by  
458 CNRS-INSU (L'institut national des sciences de l'Univers). Continued measurements enhance  
459 the length of the record and thus the accuracy of subsidence rates. For all sites, the seasonal  
460 signal was removed by modeling the vertical deflection from water loading (Steckler et al.,  
461 2010). Water level was calculated using  $>300$  daily river gauge and  $>1200$  weekly ground water  
462 well measurements of the water table (Steckler et al., 2010; Nooner et al., in prep). The  
463 deflection from the regional water mass was calculated and removed using a best fit estimate of  
464 the Young's Modulus at each GNSS station with a best-fit trendline.

465 Figure 8 shows results for the coastal zone of Bangladesh and India. The font size used is  
466 proportional to the square root of the times series length to reflect the reliability of the rate  
467 estimates. The rates for the newest sites, established in 2019, are still too short to be reliable and  
468 are not further considered. The larger symbols correspond to sites that have recorded data,  
469 sometimes intermittently, for 5-17 years. In the coastal belt, GNSS subsidence rates near the  
470 sandy Brahmaputra (Lower Meghna) river mouth are 4-5 mm/y (Fig. 8), similar to the Holocene  
471 rates determined by Grall et al. (2018) and lower than the river gauge sites (Becker et al., 2020).

472 Farther west, we generally determined higher rates (5-8 mm/y for longer term stations) that  
473 exceed the Holocene average rates by several millimeters per year. We associate these higher  
474 rates with muddier settings farther from the river mouth that may partially reflect additional near-  
475 surface consolidation and organic matter oxidation.

## 476 6. DISCUSSION

### 477 *6.1 Temporal and methodological controls on subsidence rates*

478 The subsidence measurements presented here using different methodologies exhibit  
479 variations that show systematic patterns spatially—both in the horizontal and with depth—and  
480 temporally, (Fig. 10). In delta systems, it is recognized that thick sedimentary deposits loading  
481 the lithospheric plate enhance the subsidence rate. This isostatic adjustment to the sediment load  
482 likely contributes significantly to the long-term rate of subsidence (Karpytchev et al., 2018,  
483 Krien et al., 2019). Overall, subsidence rates are inversely time-dependent, with younger  
484 deposits consolidating at greater rates commensurate with their age (i.e., Sadler effect). We find  
485 this fundamental temporal control also holds true in the GBD. Holocene averaged subsidence  
486 rates (Grall et al., 2018) (Fig. 5) are lower than contemporary rates from tide gauges, GNSS,  
487 RSET and the vertical strainmeter. The rates from the 300-600 year old historic sites (Fig. 8;  
488 Sarker et al., 2012; Hanebuth et al., 2013; Chamberlain et al., 2020) are similar to the Holocene  
489 rates (Grall et al., 2018), providing a timescale for shallow sediment compaction similar to the  
490 Mississippi Delta (Jankowski et al., 2017; Keogh and Törnqvist, 2019). The Nile Delta also  
491 shows higher contemporary rates from GNSS and InSAR (6-10 mm/y; Gebremichael et al.,  
492 2017; Saleh and Becker, 2019) relative to Holocene rates (0-4.5 mm/y; Marriner et al., 2012).

493 GNSS subsidence rates from the past two decades (i.e., modern rates) generally show slightly  
494 higher values than the longer-term Holocene average rates (Figs. 5, 8). In the east, near the  
495 Lower Meghna River, rates are within a millimeter/year of the Holocene rates. However, farther  
496 west, GNSS subsidence rates are consistently a few mm/y higher than the longer-term rates. We  
497 tentatively ascribe this difference to greater sediment compaction in the muddier sediments as  
498 described in the next section. The modern rates from tide and river gauges (Fig. 5; Becker et al.,  
499 2020) show an overall similarity to the GNSS rates in being slightly higher than the Holocene  
500 average values. However, the rates to the west are lower while the rates farther east are higher,  
501 inconsistent with attributing the GNSS rate differences to lithology.

502 Farther east, the river gauges show substantial subsidence (5.2 mm/y) along and east of the  
503 Meghna River where the Holocene rates rapidly taper to zero (Fig. 5). We interpret this to reflect  
504 short-term subsidence associated with ongoing deformation above the locked subduction  
505 megathrust (Steckler et al., 2016; Mallick et al., 2019; Fig. 1), which may reach 3-4 mm/y  
506 (Oryan et al., 2020). Megathrust earthquakes would likely uplift this region. The 1762 M8.5  
507 earthquake farther south along the Arakan coast resulted in 2-7 m of coastal uplift (Aung et al.,  
508 2008; Wang et al., 2013; Mondal et al., 2018). Over the longer term, we expect that the net effect  
509 of the current interseismic subsidence, and infrequent coseismic and postseismic uplift would be  
510 a slight net uplift related to shortening on the blind detachment folds in the frontal foldbelt  
511 (Betka et al., 2018; Mondal et al., 2018, Mallick et al., 2021). Thus, we interpret the difference  
512 between the shorter-term and longer-term rates to reflect the seismic cycle in this region.

513 The highest rates of subsidence are located north of the coastal zone near Dhaka (Fig. 5, 8)  
514 due to groundwater extraction. At Dhaka, there is a significant cone of withdrawal from water  
515 pumping such that the water table is currently >70 m below sea level and had been dropping by

516 ~3 m/y since the 1980s (Akhter et al., 2009; Shamsudduha et al., 2009, 2011). GNSS sites at the  
517 center of the cone show subsidence rates of 9-13 mm/y (Fig. 8). The river gauges, covering a  
518 large area from the center of the cone out beyond the cone edge, yield 7.2 mm/y.

519 The devices measuring shallow subsidence, the RSET-MH and KHLC, show higher rates of  
520 9-10 mm/y (Fig. 8). These instruments, located in sites of active sedimentation, include shallow  
521 subsidence not recorded by either the river gauges or GNSS. The anchor depth of the river  
522 gauges in Bangladesh is unknown; they average 20 m in the Mississippi Delta (Keogh and  
523 Törnqvist, 2019). The GNSS sites in Bangladesh are mainly installed on reinforced concrete  
524 buildings. The depth of pilings for the foundations are unknown, however, the ground is  
525 compacted before construction and there is no young sedimentation. Thus, shallow subsidence  
526 above some significant depth is not measured by either river gauges or GNSS. RSET-MH in the  
527 Mississippi Delta (Jankowski et al., 2017) show that shallow subsidence is primarily focused in  
528 the upper 5-10 m of sediment, averaging  $6.4 \pm 5.4$  mm/year (Jankowski et al., 2017). GNSS-IR  
529 (interferometric reflectometry; Karegar et al., 2020) measures subsidence of the ground surface  
530 relative to anchored GNSS and found rates of 3-6 mm/y. Our results suggest similar amounts of  
531 shallow subsidence recorded by the RSET-MH and KHLC that are missed by the river gauges  
532 and GNSS sites because this subsidence occurs shallower than the depth at which the instruments  
533 are rooted. The GNSS do include deep subsidence that occurs below the base of the RSET or  
534 strainmeters. Thus, the total subsidence at a site with active sedimentation may be equal to the  
535 sum of the GNSS on buildings plus 3-6 mm/y of shallow subsidence, or equal to the RSET and  
536 KHLC with the addition of 2-3 mm/y or more of deep subsidence. The total subsidence may  
537 therefore reach values of 12-14 mm/y.

## 538 ***6.2 The role of lithology with subsidence***

539 Differences in subsidence rates indicate that there is a considerable amount of ongoing  
540 shallow subsidence in the GBD due to sediment compaction, consolidation and organic matter  
541 degradation. GNSS subsidence rates are consistently a few mm/y higher than the longer-term  
542 rates in southwestern Bangladesh farther from the sandy main mouths of the Ganges River: the  
543 Hooghly River in India prior to the mid 1600s, the Arial Khan/Tetulia Channel from then until  
544 the mid 1900s and the Lower Meghna River since then (Fig. 1). Thus, the recent sediments are  
545 expected to be muddier in this region between the major rivers. Thicker total Holocene  
546 sediments upstream of the Swatch of No Ground canyon in SW Bangladesh (Fig. 1) may also  
547 play a role in contributing to subsidence from compaction here.

548 More local lithologic differences may also contribute to variations in compaction. For  
549 example, while the GNSS on Polder 32 measures 5.6 mm/y subsidence, the RSET-MHs 6-9 km  
550 away in the Sundarbans record 9.7 mm/y of shallow subsidence (Fig. 8, 10). RSET-MH  
551 subsidence values only include compaction above the base of the rods (in this case, 24.4 m).  
552 Meanwhile, KHLC to the NE shows the shallow subsidence is distributed over a greater depth  
553 range (Fig. 9). While the total compaction of 9 mm/y is similar between KHLC and the RSET-  
554 MH, KHLC only records 3.1 and 5.6 mm/y at the shallowest 20 and 40 m depth wells. This  
555 indicates significant variability in the shallow subsidence between sites, with the natural  
556 Sundarbans mangrove forest having more compaction occurring at very shallow depths (Bomer  
557 et al., 2020). This may be due to the muddier nature of the deposits in the Sundarbans and the  
558 greater root density in the mangroves (Bomer et al., 2020) since muddy sediments undergo more  
559 shallow compaction than sands (Kominz et al., 2011). At the compaction meter site, in contrast,  
560 the deposits beneath the recent channel fill were mainly very fine sand (Wilson et al., 2015;

561 Chamberlain et al., 2020). Furthermore, shallow subsidence in natural areas such as the  
562 Sundarbans mangrove forest is driven by seasonal dewatering of the shallow subsurface (<2m)  
563 with lowering of the groundwater table during the dry season (Bomer et al., 2020).

## 564 **SYNTHESIS AND IMPLICATIONS**

565 The combination of multiple methods of estimating subsidence and compaction in the GBD  
566 leads to a pattern of subsidence varying with timescale, spatial location and depth (Fig. 10).  
567 Subsidence is lower at longer timescales. We attribute this to the rate at which fresh young  
568 sediments are undergoing initial compaction and organic matter degradation. As the rates for  
569 multi-century historic sites and Holocene sites are similar, we conclude this occurs at the century  
570 time scale and the longer time scales reflect compaction and isostasy from a more stable  
571 sediment porosity profile. Grall et al. (2018) found that the longer-term rates increase from near  
572 zero at the Hinge Zone to 4.5 mm/y near the coast. This likely reflects the increase in both the  
573 Holocene and total sediment thickness, as well as the increasing proportion of mud from the  
574 Hinge Zone toward the coast. River gauges and GNSS systems yield rates that are a few  
575 millimeters a year higher than the long-term rates (Fig. 10). These systems are rooted in the  
576 ground or on buildings and therefore do not measure very near surface compaction (<5 m).  
577 However, ongoing compaction of their underlying sediments contributes to greater current rates  
578 of subsidence than the long-term rates.

579 Systems that measure shallow subsurface compaction and subsidence (<100 m), such as  
580 RSET-MH and optical fiber strain meters, yield considerably higher rates of 9-10 mm/y (Fig.  
581 10). Neither of these systems measure deeper subsidence, so the total subsidence rate must be at  
582 least a few millimeters a year higher. These results also indicate that there is considerable  
583 subsidence arising from near-surface processes related to compaction, sediment consolidation  
584 and organic matter degradation. The upper few meters of sediments tend to be finer grained  
585 (Wilson and Goodbred, 2015; Bomer et al., 2020). These sediments are reworked by shifting  
586 channels so that the preserved sediments are generally coarse, although channels are less mobile  
587 in the tidal realm. However, these loose ephemeral sediments may contribute to high compaction  
588 rates in the near surface that could reach 5 mm/y or more. We note the depth distribution of the  
589 overall compaction contribution remains uncertain. The KHLC compaction meter suggests most  
590 compaction in the southwest region is occurring in the Holocene sediment deposited within the  
591 incised valleys. However, the RSET-MH suggests that most of the compaction may be even  
592 shallower, and that groundwater hydrology may play a large role. This significant shallow  
593 contribution needs further investigation to better quantify it.

594 Deep compaction of sediments below the Holocene appears to be limited, and we find that  
595 the bulk of the subsidence from compaction is from within Holocene-aged sediments.  
596 Viscoelastic modeling (Karpytchev et al., 2018; Krien et al., 2019) suggest 1-3 mm/y of isostatic  
597 adjustment from the sediment load. As noted earlier, the pre-Holocene sediments below the  
598 Brahmaputra incised valley may be overcompacted and contribute little to current rates. At  
599 depths greater than 3-5 km, the sediments in the GBD are highly overpressured (Zahid and  
600 Uddin, 2005), which also means that dewatering and compaction of these sediments are limited  
601 (Gordon and Flemings, 1998).

602 Given spatial and temporal variability of subsidence rates revealed here, we must ask which  
603 rates are significant for people living on a delta? When planning adaptations to rising sea level in  
604 the GBD, the physical environment and nature of any construction must be seriously considered.

605 Specifically, it should be acknowledged that subsidence rates can differ, even locally, and this  
606 has implications for nature-based solutions and/or hard constructed solutions. For example,  
607 designs for embankment construction must take rates of sea level rise and ground subsidence into  
608 account. Reinforced concrete buildings, such as those hosting the GNSS, are subsiding at 4-8  
609 mm/y. Are the embankments constructed of compacted sand and pilings faced with concrete  
610 blocks settling at a rate similar to the GNSS? In contrast, in regions of active sedimentation, we  
611 find significantly higher rates of subsidence. Is this high rate due to very near surface  
612 consolidation only present where there is active sedimentation? If sedimentation stops, how long  
613 will higher subsidence rates continue? From the historic sites, we estimate it is likely shorter than  
614 300-600 years. Still, the findings suggest that natural subsidence processes can continue for  
615 decades to centuries.

616 At Polder 32, we have all the different types of measurements available in a limited area. We  
617 found 2.4-3.2 mm/y of long-term subsidence, increasing to 5.5-5.6 mm/y of short-term  
618 subsidence (Figure 10, bottom). Shallow compaction measured nearby reaches 9-10 mm/y.  
619 Within Polder 32, Auerbach et al. (2015) found that there was a loss of 1.0-1.5 m of elevation  
620 relative to the Sundarbans over 50 years since the embankment was built. Using their values of  
621 11 mm/y of sediment accretion in the Sundarbans and an extra 20 cm of elevation loss from root  
622 extraction, these findings suggest 5-15 mm/y of subsidence in the polder interior since the  
623 embankment precluded natural sedimentation. This suite of values is consistent with the 3-6  
624 mm/y of very shallow compaction seen in the Mississippi Delta (Jankowski et al., 2017; Karegar  
625 et al., 2020). This means that for restoring polder elevation through nature-based solutions, such  
626 as Tidal River Management (Shampa and Pramanik, 2012; Islam et al., 2021), sediment volumes  
627 that are required need to account for expected compaction which will occur in the shallow  
628 subsurface and the resultant relatively high subsidence rate.

629 These results illustrate the complexity of subsidence and compaction as a function of depth,  
630 space and time, and begins to unravel the values in a densely-populated, vulnerable delta. One  
631 cannot characterize subsidence with a single value without reference to its context. While further  
632 work is still required to better understand the variability of subsidence rates and their relationship  
633 to the underlying geology and the physical processes that contribute to subsidence, our results  
634 begin to provide values for the Ganges-Brahmaputra Delta. Similar relative rates likely apply to  
635 other deltas as well. Which values are appropriate for mitigation of sea level rise and  
636 maintenance of the GBD and other deltas depend on both the local and regional settings. For  
637 instance, locally, subsidence appears to be lower for embankments and buildings, but higher for  
638 sites of active sedimentation. All of these rates can be exacerbated by anthropogenic  
639 modification, such as fluid withdrawal.

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#### 649 **References**



650 Akhter, H., M.S. Ahmed and K.B.S. Rasheed (2009). Spatial and temporal analysis of  
651 groundwater level fluctuations in Dhaka City, Bangladesh, *Asian J. Earth Sciences*, 2,49-57.

652 Akhter, S.H. (2010), Earthquakes of Dhaka, in *Environment of Capital Dhaka—Plants Wildlife*  
653 *Gardens Parks Air Water and Earthquake*, edited by M. A. Islam, pp. 401–426, Asiatic  
654 society of Bangladesh, Bangladesh.

655 Alam, M. (1996). Subsidence of the Ganges–Brahmaputra delta of Bangladesh and associated  
656 drainage, sedimentation and salinity problems. In: Milliman, J.D., Haq, B.U. (Eds.), *Sea-*  
657 *level Rise and Coastal Subsidence*. Kluwer Academic Publishers, Dordrecht, pp. 169–192.

658 Alauddin, M. and Hamid, M. A. (1999). Shrimp culture in Bangladesh with emphasis on social  
659 and economic aspects. *Towards sustainable shrimp culture in Thailand and the region*. Edited  
660 by P.T. Smith. Canberra: Australian Centre for International Agricultural Research. 53-62

661 Allison, M.A. (1998). Historical changes in the Ganges-Brahmaputra Delta front. *Journal of*  
662 *Coastal Research*, 14(4), 1269–1275.

663 Allison, M. A., Khan, S. R., Goodbred, S. L., & Kuehl, S. A. (2003). Stratigraphic evolution of  
664 the late Holocene Ganges-Brahmaputra lower delta plain. *Sedimentary Geology*, 155(3),  
665 317–342. [https://doi.org/10.1016/S0037-0738\(02\)00185-9](https://doi.org/10.1016/S0037-0738(02)00185-9).

666 Athy, L.F., 1930. Density, porosity, and compaction of sedimentary rocks. *Bull. Am. Ass. Petrol.*  
667 *Geol.*, 14: 1-24.

668 Auerbach, L., Goodbred, S., Mondal, D., Wilson, C., Ahmed, K.R., Roy, K., Steckler, M.,  
669 Gilligan, J., Ackerly, B. (2015). In the Balance: Natural v. Embanked Landscapes in the  
670 Ganges-Brahmaputra Tidal Delta Plain, *Nature Climate Change*. 5, 153-157, doi:  
671 10.1038/nclimate2472.

672 Aung T.T., K. Satake, Y. Okamura, M. Shishikura, W. Swe, H. Saw, T.L. Swe, S.T. Tun, T.  
673 Aung (2008). Geologic evidence for three great earthquakes in the past 3400 years off  
674 Myanmar, *Journal of Earthquake and Tsunami*, 2, 259–265.

675 Becker, M., F. Papa, M. Karpytchev, C. Delebecque, Y. Krien, J.U. Khan, V. Ballu, F. Durand,  
676 G. Le Cozannet, A.K.M.S. Islam, S. Calmant, C.K. Shum (2020) Water level changes,  
677 subsidence, and sea level rise in the Ganges–Brahmaputra–Meghna delta, *Proceedings of the*  
678 *National Academy of Sciences*, 117 (4) 1867-1876; doi:10.1073/pnas.1912921117.

679 Betka, P.M., L. Seeber, S. Thomson, M.S. Steckler, R. Sincavage, C. Zoramthara (2018). Slip  
680 partitioning above a shallow, weak décollement beneath the Indo-Burman accretionary  
681 prism, *Earth and Planetary Science Letters* 503, 17–28, 10.1016/j.epsl.2018.09.003.

682 Blewitt, G. and D. Lavallée (2002) Effect of annual signals on geodetic velocity. *Journal of*  
683 *Geophysical Research*, 107, 2145-2156, doi: 10.1029/2001JB000570.

684 Blum M.D., Roberts, H.H. (2009) Drowning of the Mississippi Delta due to insufficient  
685 sediment supply and global sea-level rise. *Nat. Geosci.* 2: 488–491. doi:10.1038/NGEO553

686 Bomer, E.J., Wilson, C.A., Hale, R.P., Hossain, A.N.M., and Rahman, F.M.A. (2020). Surface  
687 elevation and sedimentation dynamics in the Ganges-Brahmaputra tidal delta plain,  
688 Bangladesh: implications for the sustainability of natural and human-impacted coastal  
689 systems. *Catena*.187:104312.

690 Brammer, H. (1990). Floods in Bangladesh: Geographical background to the 1987 and 1988  
691 floods. *Geographical Journal*, 156, 12–22. <https://doi.org/10.2307/635431>

692 Brammer, H. (2014). Bangladesh’s dynamic coastal regions and sea-level rise. *Climate Risk*  
693 *Management*, 1, 51-62.

694 Brown, S., R. J. Nicholls, Subsidence and human influences in mega deltas: The case of the  
695 Ganges-Brahmaputra-Meghna. *Sci. Total Environ.* 527–528, 362–374 (2015).

696 Cahoon, D.R., D.J. Reed, and J.W. Day. 1995. Estimating shallow subsidence in microtidal salt  
697 marshes of the southeastern United States: Kaye and Barghoorn revisited. *Mar. Geol.* 128:1–  
698 9. doi:10.1016/0025-3227(95)00087-F

699 Cahoon, D.R., J.C. Lynch, B.C. Perez, B. Segura, R.D. Holland, C. Stelly, et al. 2002. High  
700 precision measurements of wetland sediment elevation: II. The rod surface elevation table. *J.*  
701 *Sediment. Res.* 72:734–739. doi:10.1306/020702720734

702 Chamberlain, E.L., S.L. Goodbred, R. Hale, M.S. Steckler, J. Wallinga, C. Wilson (2020).  
703 Integrating geochronologic and instrumental approaches across the Bengal Basin, *Earth*  
704 *Surface Processes and Landforms*, 45, 56-74., <https://doi.org/10.1002/esp.4687>.

705 Chamberlain, EL, Wallinga, J, Reimann, T, Goodbred, SL, Steckler, M, Shen, Z and Sincavage,  
706 R (2017). Luminescence dating of delta sediments: novel approaches explored for the  
707 Ganges-Brahmaputra- Meghna delta. *Quaternary Geochronology* 41: 97–111. DOI:  
708 <https://doi.org/10.1016/j.quageo.2017.06.006>

709 Chapman, R.E. (1983). Chapter 3: Compaction of sediment and sedimentary rocks, and its  
710 consequences, in R.E. Chapman, *Petroleum Geology, Developments in Petroleum Science*  
711 16, Elsevier, Amsterdam, 41-65.

712 DeWolf; S., S.L. Noonan; M.S. Steckler; M.A. Zumberge; S.H. Akhter, Optical Fiber Borehole  
713 Strainmeter Arrays for Measuring Sediment Compaction in Bangladesh, Abstract EP31A-  
714 0831 presented at 2013 Fall Meeting, AGU, San Francisco, Calif., 9-13 Dec. 2013.

715 Dixon, T. H., Amelung, F., Ferretti, A., Novali, F., Rocca, F., Dokka, R., et al. (2006). Space  
716 geodesy: Subsidence and flooding in New Orleans. *Nature*, 441(7093), 587–588.  
717 <https://doi.org/10.1038/441587a>.

718 Dunn F.E., S.E. Darby, R.J. Nicholls, S. Cohen, C. Zarfl and B.M. Fekete (2019). Projections of  
719 declining fluvial sediment delivery to major deltas worldwide in response to climate change  
720 and anthropogenic stress, *Environ. Res. Lett.* 14, 084034, doi: 10.1088/1748-9326/ab304e.

721 Eaton, Richard M. *The Rise of Islam and the Bengal Frontier, 1204-1760*. Berkeley: University  
722 of California Press, 192pp.

723 Edmonds, D.A., R.L. Caldwell, E.S. Brondizio & S.M.O. Siani (2020). Coastal flooding will  
724 disproportionately impact people on river deltas, *Nature Communications*, 11, 474, doi:  
725 10.1038/s41467-020-18531-4.

726 Ericson, J.P., Vörösmarty, C.J., Dingman, S.L., Ward, L.G., Meybeck, M., 2006. Effective sea-  
727 level rise and deltas: causes of change and human dimension implications. *Glob. Planet.*  
728 *Chang.* 50, 63–82. <http://dx.doi.org/10.1016/j.gloplacha.2005.07.004>.

729 Erkens, G., M.J. van der Meulen, H. Middelkoop (2016). Double trouble: subsidence and CO2  
730 respiration due to 1,000 years of Dutch coastal peatlands cultivation, *Hydrogeol. J.* 24, 551–  
731 568, doi: 10.1007/s10040-016-1380-4.

732 Gebremichael, E., Sultan, M., Becker, R., El Bastawesy, M., Cherif, O., & Emil, M. (2018).  
733 Assessing land deformation and sea encroachment in the Nile Delta: A radar interferometric  
734 and inundation modeling approach. *Journal of Geophysical Research: Solid Earth*, 123,  
735 3208–3224. <https://doi.org/10.1002/2017JB015084>

736 Giosan, L, J. Syvitski, S. Constantinescu and J. Day (2014). Protect the world’s deltas. *Nature*  
737 516, 31–33.

738 Gluyas, J., C.A. Cade, (1997). Prediction of porosity in compacted sands, AAPG Memoir 69:  
739 Reservoir Quality Prediction in Sandstones and Carbonates, Edited by J.A. Kupecz, J.  
740 Gluyas, and S. Bloch, 19-27.

741 Goodbred SL, Kuehl SA, Steckler M, Sarker MH. 2003. Controls on facies distribution and  
742 stratigraphic preservation in the Ganges-Brahmaputra delta sequence. *Sediment. Geol.*  
743 155:301–16

744 Goodbred, S.L., P.M. Paolo, M.S. Ullah, R.D. Pate, S.R. Khan, S.A. Kuehl, S.K. Singh, W.  
745 Rahaman (2014). Piecing together the Ganges-Brahmaputra-Meghna River delta: Use of  
746 sediment provenance to reconstruct the history and interaction of multiple fluvial systems  
747 during Holocene delta evolution. *GSA Bulletin* 126, 1495–1510. doi: 10.1130/B30965.1.

748 Gordon, D.S., Flemings, P.B. (1998). Generation of overpressure and compaction-driven fluid  
749 flow in a Plio-Pleistocene growth-faulted basin, Eugene Island 330, offshore Louisiana.  
750 *Basin Res.* 10, 177–196.

751 Govin, G., Najman, Y., Copley, A., Millar, I., van der Beek, P., Huyghe, P., Grujic, D.,  
752 Davenport, J. (2018). Timing and mechanism of the rise of the Shillong Plateau in the  
753 Himalayan foreland. *Geology* 46, 279–282. <https://doi.org/10.1130/G39864.1>.

754 Grall, C., M.S. Steckler, J.L. Pickering, S. Goodbred, R. Sincavage, C. Paola, S.H. Akhter, V.  
755 Spiess (2018) A base-level stratigraphic approach to determining Holocene subsidence of the  
756 Ganges–Meghna–Brahmaputra Delta plain, *Earth and Planetary Science Letters* 499, 23–36,  
757 10.1016/j.epsl.2018.07.008.

758 Grimaud, J.-L., Grall, C., Goodbred, S., Steckler, M. S., Sincavage, R., Pickering, J. L., Paola,  
759 C., Seeber, L., Hossain, M. S. (2020). Flexural deformation controls on Late Quaternary  
760 sediment dispersal in the Garo- Rajmahal Gap, NW Bengal Basin. *Basin Research*, 32,  
761 1242–1260. <https://doi.org/10.1111/bre.12425>

762 Hanebuth, T.J.J., Kudrass, H.R., Linstaedter, J., Islam, B., Zander, A.M. (2013). Rapid coastal  
763 subsidence in the central Ganges–Brahmaputra Delta (Bangladesh) since the 17<sup>th</sup> century  
764 deduced from submerged salt-producing kilns. *Geology* 41 (9), 987–990.  
765 <http://dx.doi.org/10.1130/G34646.1>.

766 Hedberg, H.D. (1936). Gravitational compaction of clays and shales. *Am. J. Sci.*, 31, 241-287.

767 Herring, T.A., R.W. King, M.A. Floyd, S.C. McClusky, 2018. Introduction to GAMIT/GLOBK  
768 Release 10.7, 54p.

769 Higgins, S.A., Overeem, I., Steckler, M.S., Syvitski, J.P.M., Seeber, L., Akhter, S.H. (2014).  
770 InSAR measurements of compaction and subsidence in the Ganges–Brahmaputra Delta,  
771 Bangladesh. *J. Geophys. Res. Earth Surf.* 119 (8). [http://dx.doi.org/10.1002/](http://dx.doi.org/10.1002/2014JF003117)  
772 (2014JF003117).

773 Hoque, M., Alam, M. (1997). Subsidence in the lower deltaic areas of Bangladesh. *Mar. Geod.*  
774 20 (1), 105–120. <http://dx.doi.org/10.1080/01490419709388098>.

775 Islam, Md.F., H. Middelkoop, P.P. Schot, S.C. Dekker, J. Griffioen (2021). Spatial and seasonal  
776 variability of sediment accumulation potential through controlled flooding of the beels  
777 located in the polders of the Ganges-Brahmaputra-Meghna delta of Southwest Bangladesh.  
778 *Hydrological Processes*. 35, 14119, doi.org/10.1002/hyp.14119.

779 Jankowski, K. L., Törnqvist, T. E., and Fernandes, A. M. (2017). Vulnerability of Louisiana’s  
780 coastal wetlands to present-day rates of relative sea-level rise, *Nat. Commun.*, 8, 14792,  
781 <https://doi.org/10.1038/ncomms14792>.

782 Karegar, M. A., Larson, K. M., Kusche, J., & Dixon, T. H. (2020). Novel quantification of  
783 shallow sediment compaction by GPS interferometric reflectometry and implications for  
784 flood susceptibility. *Geophysical Research Letters*, 47, e2020GL087807.  
785 <https://doi.org/10.1029/2020GL087807>

786 Karpytchev, M., V. Ballu, Y. Krien, M. Becker, S. Goodbred, G. Spada, S. Calmant, C. Shum,  
787 and Z. Khan (2018). Contributions of a strengthened early Holocene monsoon and sediment  
788 loading to present-day subsidence of the Ganges-Brahmaputra Delta. *Geophysical Research*  
789 *Letters*, 45, 1433–1442. <https://doi.org/10.1002/2017GL076388>

790 Keogh, M.E., and T.E. Törnqvist (2019). Measuring rates of present-day relative sea-level rise in  
791 low-elevation coastal zones: a critical evaluation. *Ocean Sci.*, 15, 61–73,  
792 <https://doi.org/10.5194/os-15-61-2019>.

793 Kominz M.A., K. Patterson, and D. Odette (2011). Lithology dependence of porosity in slope  
794 and deep marine sediments, *Journal of Sedimentary Research*, 2011, 81, 730–742, doi:  
795 10.2110/jsr.2011.60.

796 Kondolf G.M., Z.K. Rubin and J.T. Minear (2014). Dams on the Mekong: cumulative sediment  
797 starvation *Water Resour. Res.* 50, 5158–69

798 Krien, Y., M. Karpytchev, V. Ballu, M. Becker, C. Grall, S. Goodbred, S. Calmant, C.K. Shum,  
799 and Z. Khan (2019) Present-day subsidence in the Ganges-Brahmaputra-Meghna delta:  
800 Eastern amplification of the Holocene sediment loading contribution. *Geophys. Res. Lett.* 49,  
801 10764–10772.

802 Mallick, R., R. Bürgmann, K. Johnson, & J. Hubbard (2021). A unified framework for  
803 earthquake sequences and the growth of geological structure in fold-thrust belts. *Journal of*  
804 *Geophysical Research: Solid Earth*, 126, e2021JB022045. doi: 10.1029/2021JB022045

805 Mallick, R., E.O. Lindsey, L. Feng, J. Hubbard, P. Banerjee, and E.M. Hill (2019). Active  
806 Convergence of the India- Burma- Sunda Plates Revealed by a New Continuous GPS  
807 Network, *Journal of Geophysical Research: Solid Earth*, 124. doi: 10.1029/2018JB016480

808 Marriner, N., Flaux, C., Morhange, C., and Kaniewski, D. (2012). Nile Delta’s sinking past:  
809 Quantifiable links with Holocene compaction and climate-driven changes in sediment  
810 supply? *Geology*, 40(12), 1083–1086. <https://doi.org/10.1130/G33209.1>

811 Milliman J.D., J.M. Broadus and F. Gable, (1989). Environmental and Economic Implications of  
812 Rising Sea Level and Subsiding Deltas: The Nile and Bengal Examples. *Ambio*, 18, 340-345.

813 Milliman, J.D., and K.L. Farnsworth (2011). *River Discharge to the Coastal Ocean: A Global*  
814 *Synthesis*. Cambridge University Press, 384 pp.

815 Minderhoud, P.S.J., G. Erkens, V.H. Pham, V.T. Bui, L. Erban, H. Kooi and E. Stouthamer  
816 (2017) Impacts of 25 years of groundwater extraction on subsidence in the Mekong delta,  
817 Vietnam, *Environ. Res. Lett.* 12, 064006, doi:10.1088/1748-9326/aa7146.

818 Mirza, M.M.Q. (2003). Three Recent Extreme Floods in Bangladesh: A Hydro-Meteorological  
819 Analysis, *Natural Hazards* 28, 35–64.

820 Mitra, S., Priestley, K. F., Borah, K., & Gaur, V. K. (2018). Crustal structure and evolution of  
821 the Eastern Himalayan plate boundary system, Northeast India. *Journal of Geophysical*  
822 *Research: Solid Earth*, 123, 621–640. doi: 10.1002/2017JB014714

823 Mondal, D., C.M. McHugh, R.M. Mortlock, M.S. Steckler, S. Mustaque (2018). Microatolls  
824 document the 1762 and prior earthquakes along the southeast coast of Bangladesh,  
825 *Tectonophysics*, 745, 196–213, doi: 10.1016/j.tecto.2018.07.020.

826 Nienhuis, J.H., A.D. Ashton, D.A. Edmonds, A.J.F. Hoitink, A.J. Kettner, J.C. Rowland & T.E.  
827 Törnqvist (2020). Global-scale human impact on delta morphology has led to net land area  
828 gain. *Nature*, 577, 514-518, doi: 10.1038/s41586-019-1905-9.

829 Oryan, B., M.S Steckler, D.R. Mondal, S.H. Akhter, S. Singha, C. Grall, and E.O. Lindsey  
830 (2020) The Indo-Burma Detachment Geometry Constrained by an Updated Vertical and

831 Horizontal GPS Velocity Field in Bangladesh, Abstract T048-0021, AGU Fall Meeting, Dec.  
832 1-17, 2020.

833 Ostanciaux, É., Husson, L., Choblet, G., Robin, C., Pedoja, K. (2012). Present-day trends of  
834 vertical ground motions along the coast lines. *Earth Sci. Rev.* 110, 74–92. [http://dx.](http://dx.doi.org/10.1016/j.earscirev.2011.10.004)  
835 [doi.org/10.1016/j.earscirev.2011.10.004](http://dx.doi.org/10.1016/j.earscirev.2011.10.004).

836 Palamenghi, L. (2012) Tectonic and Sea Level Control on the Transport and Depositional  
837 Processes in a Siliciclastic Sedimentary Basin. Insights from the Ganges-Brahmaputra Delta,  
838 Bengal Basin, Bangladesh. Ph.D. Thesis, University of Bremen, 166pp.

839 Parua, P.K. (2010). The Ganga: Water Use in the Indian Subcontinent. *Water Science and*  
840 *Technology Library* 64, Springer, 404 pp. doi: 10.1007/978-90-481-3103-7

841 Paszkowski, A., Goodbred, S., Borgomeo, E., Khan, M. S. A., and Hall, J. W. (2021).  
842 Geomorphic change in the Ganges–Brahmaputra–Meghna delta. *Nature Reviews Earth &*  
843 *Environment*, 2, 763–780. doi: 10.1038/s43017-021-00213-4.

844 Pawlowicz, R., B. Beardsley and S. Lentz (2002). Classical tidal harmonic analysis including  
845 error estimates in MATLAB using T\_TIDE, *Computers & Geosciences* 28, 929–937.

846 Pethick, J. and Orford, J.D. (2013). Rapid rise in effective sea-level in southwest Bangladesh: Its  
847 causes and contemporary rates. *Global Planetary Change* 111: 237–245. doi:  
848 10.1016/j.gloplacha.2013.09.019

849 Pickering, J.L., S.L. Goodbred Jr., M.D. Reitz, T.R. Hartzog, D.R. Mondal, and M.S. Hossain  
850 (2014), Late Quaternary sedimentary record and Holocene channel avulsions of the Jamuna  
851 and Old Brahmaputra River valleys in the upper Bengal delta plain, *Geomorphology* **227**:  
852 123-136, doi: 10.1016/j.geomorph.2013.09.021

853 Reitz, M.D., Pickering, J.L., Goodbred, S.L., Paola, C., Steckler, M.S., Seeber, L., Akhter, S.H.,  
854 2015. Effects of tectonic deformation and sea level on river path selection: theory and  
855 application to the Ganges–Brahmaputra–Meghna River Delta. *J. Geophys. Res. Earth Surf.*  
856 <http://dx.doi.org/10.1002/2014JF003202>.

857 Rogers, K.G., S.L. Goodbred, D.R. Mondal (2013). Monsoon sedimentation on the ‘abandoned’  
858 tide-influenced Ganges-Brahmaputra delta plain, *Estuarine, Coastal and Shelf Science* 131,  
859 297-309, <http://dx.doi.org/10.1016/j.ecss.2013.07.014>.

860 Rogers, K., & Overeem, I. (2017). Doomed to drown? Sediment dynamics in the human-  
861 controlled floodplains of the active Bengal Delta. *Elementa Science of the Anthropocene*, 5,  
862 66. Doi: 10.1525/elementa.250

863 Sadler, P.M. (1981). Sediment accumulation rates and the completeness of stratigraphic sections.  
864 *The Journal of Geology*, 89, 569–584.

865 Saleh, M., and M. Becker (2019). New estimation of Nile Delta subsidence rates from InSAR  
866 and GPS analysis, *Environmental Earth Sciences*, 78, doi: 10.1007/s12665-018-8001-6

867 Sarker, M.H., J. Akter and Md.M. Rahman (2013). Century-scale dynamics of the Bengal Delta  
868 and future development, 4th International Conference on Water & Flood Management  
869 (ICWFM-2013), 91-104.

870 Sarker, M.H., Choudhury, G.A., Akter, J., Hore, S.K. (2012). Bengal Delta Not Sinking at a  
871 Very High Rate. *Daily Star* (23rd December 2012).

872 Sarker, M. H. & Thorne, C. R., (2006). “Morphological response of the Brahmaputra-Padma-  
873 Lower Meghna river system to the Assam Earthquake of 1950, In: *Braided Rivers: Process,*  
874 *Deposits, Ecology and Management* (ed. by G. H. S. Smith, J. L. Best, C. S. Bristow, & G. E.  
875 Petts).” 289–310. Special Publication 36 of the IAS, Blackwell Publishing, UK.

876 Sclater, J. G., and Christie, P. A. (1980), Continental stretching; An explanation of the post Mid-  
877 Cretaceous subsidence of the central North Sea basin: *Journal of Geophysical Research*, 85,  
878 3711-3739.

879 Shampa, M. & Pramanik, I.M. (2012). Tidal River Management (TRM) for Selected Coastal  
880 Area of Bangladesh to Mitigate Drainage Congestion, *Int. J. Sci. Technol. Res.* 1, 1–6.

881 Shamsudduha, M., Chandler, R.E., Taylor, R.G., and Ahmed, K.M. (2009). Recent trends in  
882 groundwater levels in a highly seasonal hydrological system: the Ganges-Brahmaputra-  
883 Meghna Delta. *Hydrology and Earth System Sciences* 13, 2373–2385.

884 Sharma, S., and S. Deshpande (2017). Architectural strategies used in Hindu temples to  
885 emphasize sacredness, *Journal of Architectural and Planning Research*, 34, 4, 309-319

886 Sheldon, N.D. and G.J. Retallack (2001). Equation for compaction of paleosols due to burial.  
887 *Geology*, 29, 247–250.

888 Shum, C., A. Liibusk, R. Ahmed, B. Braun, V. Ballu, S. Calmant, J. Chen, J. Guo, F. Hossain,  
889 M. Hossain, C. Jenkins, Z. Khan, M. Kuhn, J. Kusche, F. Papa; M. Becker, A. Bernzen, C.  
890 Brachet, M. Calzas, C. Dai, O. Francis, Y. Jia, J. Kim, C. Kuo, D. Maillard, C. Mayet, R.  
891 Rietbroek, K. Shang, L. Testut, K. Tseng, B. Uebbing, P. Valtý, J. Wan, K. Zhu (2014).  
892 Quantifying and projecting relative sea-level rise at the regional scale: The Bangladesh Sea-  
893 Level Project (BanD-AID), Abstract G21B-0439, EOS Trans., Fall American Geophysical  
894 Union Meeting, San Francisco, December 15–19.

895 Sincavage R., Goodbred, S., and Pickering, J., (2017) Holocene Brahmaputra River path  
896 selection and variable sediment bypass as indicators of fluctuating hydrologic and climate  
897 conditions in Sylhet Basin, Bangladesh: *Basin Research*, 30, 302–320,  
898 doi:10.1111/bre.12254. 2017

899 Singh, A., K. Bhushan, C. Singh, M.S. Steckler, S.H. Akhter, L. Seeber, W.-Y. Kim, A.K.  
900 Tiwari, R. Biswas (2016). Crustal structure and tectonics of Bangladesh: New constraints  
901 from inversion of receiver functions, *Tectonophysics*, 680, 99–112, doi:  
902 10.1016/j.tecto.2016.04.046.

903 Slingerland, R. and Smith, N. D. (2004). River Avulsions and Their Deposits, *Ann. Rev. of Earth*  
904 *and Planetary Sci.*, 32, 255-283.

905 Steckler, M.S., Akhter, S.H., and L. Seeber (2008). Collision of the Ganges-Brahmaputra Delta  
906 with the Burma Arc: Implications for earthquake hazard. *Earth and Planetary Science Letters*,  
907 273, 367-378.

908 Steckler, M.S., Mondal, D., Akhter, S.H. Seeber, L., L. Feng, J. Gale, E.M. Hill, M. Howe  
909 (2016) Locked and loading megathrust linked to active subduction beneath the Indo-Burman  
910 Ranges, *Nature Geosciences*, *Nature Geosciences*, 9, 615–618, doi: 10.1038/ngeo2760.

911 Steckler, M.S., Nooner, S.L., Akhter, S.H., Chowdhury, S.K., Bettadpur, S., Seeber, L., Kogan,  
912 M.G. (2010). Modeling Earth deformation from monsoonal flooding in Bangladesh using  
913 hydrographic, GPS, and Gravity Recovery and Climate Experiment (GRACE) data. *J.*  
914 *Geophys. Res. Solid Earth* 115, B08407. <http://dx.doi.org/10.1029/2009JB007018>.

915 Syvitski, J.P.M., Kettner, A.J., Overeem, I., Hutton, E.W.H., Hannon, M.T., Brakenridge, G.R.,  
916 Day, J., Vörösmarty, C., Saito, Y., Giosan, L., Nicholls, R.J. (2009) Sinking deltas due to  
917 human activities. *Nat Geosci* 2:681–686. doi:10.1038/ngeo629

918 Syvitski J.P.M., Vörösmarty, C.J., Kettner, A.J., Green, P. (2005) Impact of humans on the flux  
919 of terrestrial sediment to the global coastal ocean. *Science* 308:376–380.  
920 doi:10.1126/science.1109454

921 Terzaghi, K., Peck, R.B. (1967). *Soil Mechanics in Engineering Practice*, 2nd ed. Wiley, New  
922 York, 729pp.

923 Tessler, Z., C. J. Vörösmarty, M. Grossberg, I. Gladkova, H. Aizenman, J.P.M. Syvitski, E.  
924 Foufoula-Georgiou (2015). Profiling risk and sustainability in coastal deltas of the world.  
925 *Science*, 349 (6248), 638-643.

926 Tessler, Z. D., C. J. Vörösmarty, I. Overeem and J. P. Syvitski (2018) A model of water and  
927 sediment balance as determinants of relative sea level rise in contemporary and future deltas.  
928 *Geomorphology*.

929 van Asselen, S. (2011). The contribution of peat compaction to total basin subsidence:  
930 Implications for the provision of accommodation space in organic- rich deltas. *Basin Res.*  
931 23, 239–255

932 van Asselen, S., G. Erkens, E. Stouthamer, H. Woolderink, R. Geeraert, and M.M. Hefting  
933 (2018) The relative contribution of peat compaction and oxidation to subsidence in built-up  
934 areas in the Rhine-Meuse delta, The Netherlands. *Science of the Total Environment* 636,  
935 177–191, doi: 0.1016/j.scitotenv.2018.04.141.

936 Wang, Y., Shyu, J.B.H., Sieh, K., Chiang, H.-W., Wang, C.-C., Aung, T., Lin, Y.N., Shen, C.-C.,  
937 Min, S., Than, O., Lin, K.K., Tun, S.T., 2013. Permanent upper plate deformation in western  
938 Myanmar during the great 1762 earthquake: Implications for neotectonic behavior of the  
939 northern Sunda megathrust. *J. Geophys. Res. Solid Earth* 118, 1277–1303, doi:  
940 10.1002/jgrb.50121.

941 Wilson C., J. Bomer, S. Akter, M. Rana, M. Steckler, B. Oryan (2021). Impacts of poldering:  
942 elevation change, sediment dynamics, and subsidence in the natural and human-altered  
943 Ganges Brahmaputra tidal delta plain. Abstract EGU21-13928 presented at EGU General  
944 Assembly 2021, April 19-30.

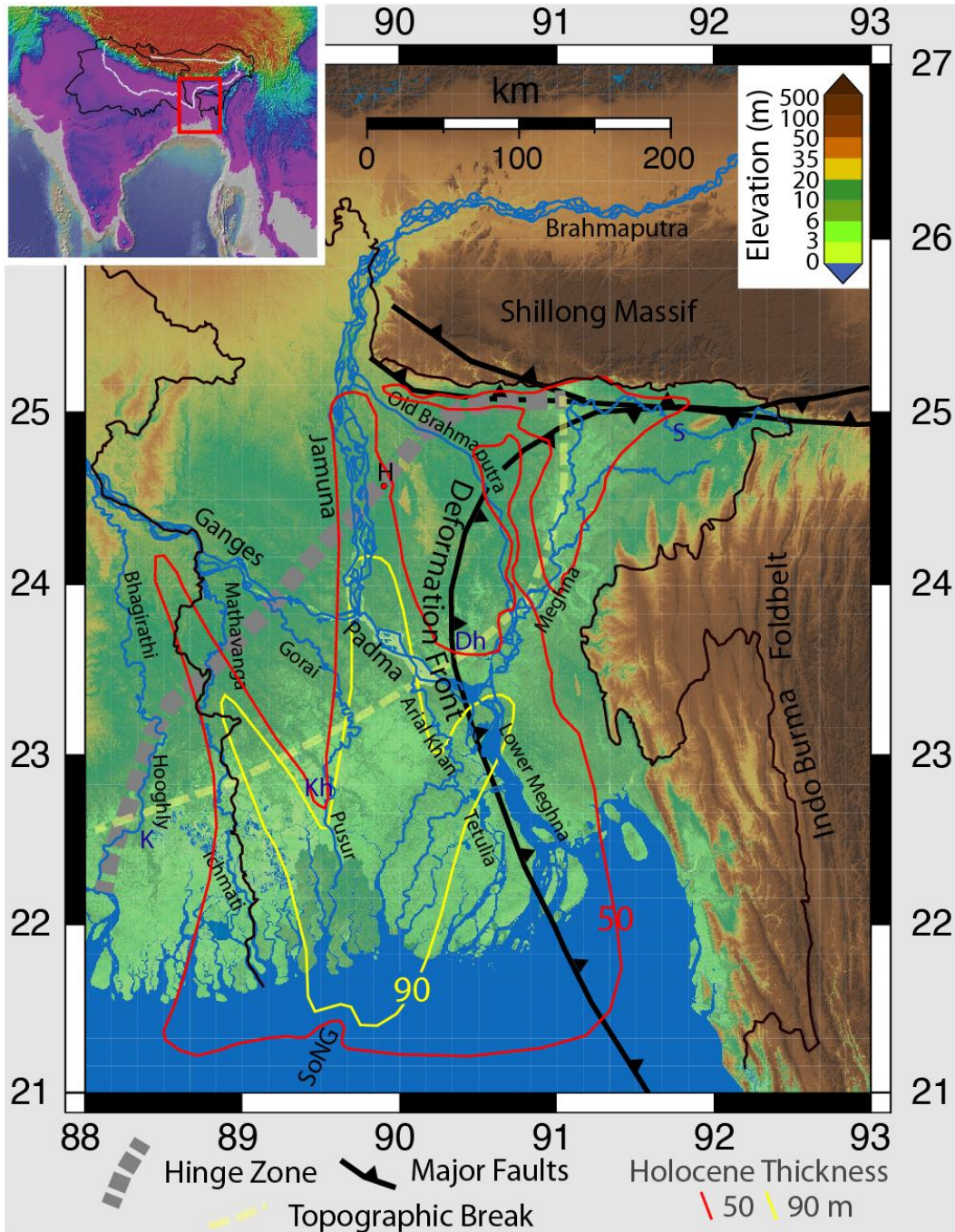
945 Wilson, C.A., and S.L. Goodbred (2015). Construction and Maintenance of the Ganges-  
946 Brahmaputra Meghna Delta: Linking Process, Morphology, and Stratigraphy. *Annual*  
947 *Review of Marine Science*, 7, 67-88.

948 Wilson, C., Goodbred, S., Small, C., Gilligan, J., Sams, S., Mallick, B., & Hale, R. (2017).  
949 Widespread infilling of tidal channels and navigable waterways in the human-modified tidal  
950 delta plain of Southwest Bangladesh. *Elementa-Science of the Anthropocene*, 5, 78. doi:  
951 10.1525/elementa.263.

952 Woods, C., I. Overeem, K. Tiampo, M. Steckler (2019) DInSAR Sentinel-1A time series  
953 analysis to map subsidence of the Ganges-Brahmaputra-Meghna Delta, Abstract G13B-0538  
954 presented at AGU Fall Meeting, San Francisco, Dec 9-13, 2019.

955 Zahid, K.M., Uddin, A. (2005). Influence of overpressure on formation velocity evaluation of  
956 Neogene strata from the eastern Bengal Basin, Bangladesh, *J. Asian Earth Sci.* 25, 419–429.  
957



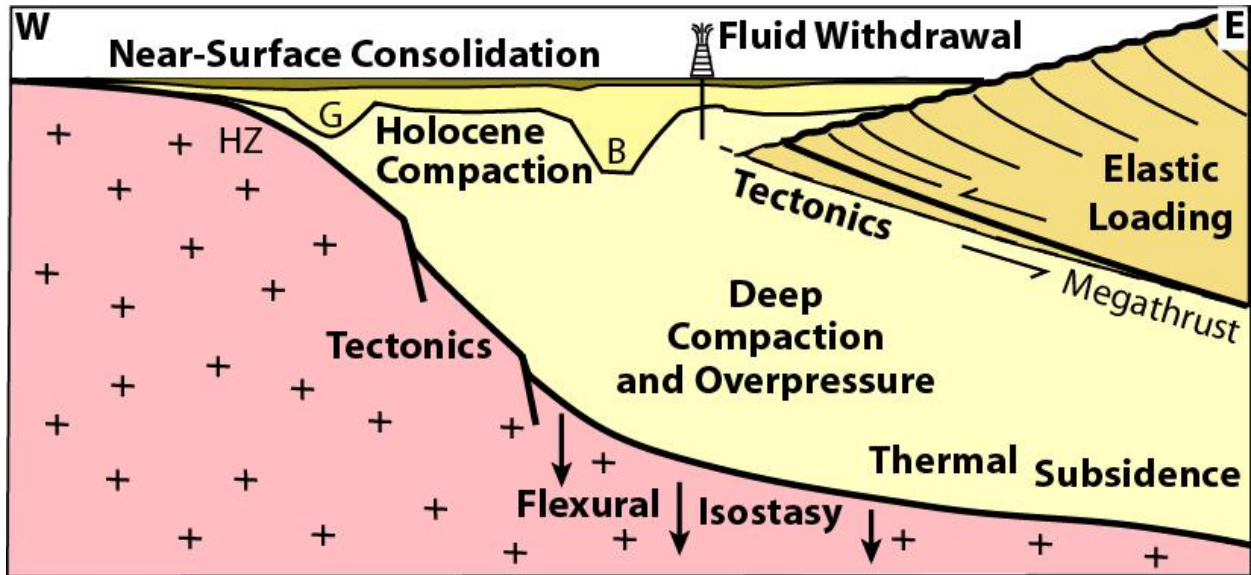


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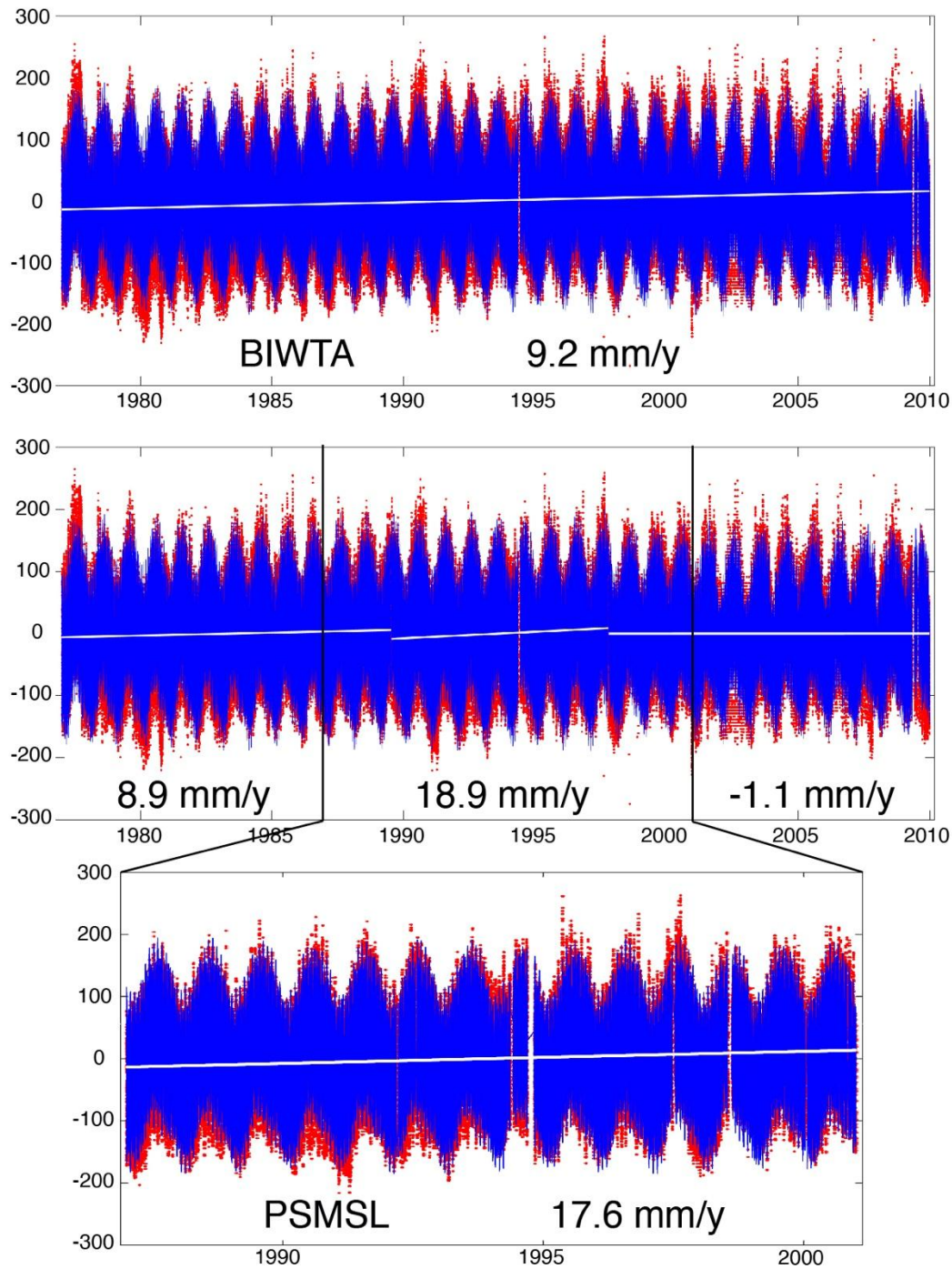
960 **Figure 1.** Location map of Bangladesh and the Ganges-Brahmaputra Delta showing major  
 961 tectonic and sedimentary boundaries, and significant rivers. The Hinge Zone is the transition  
 962 between the Indian craton and the Bengal Basin with up to 20 km of sediments. The Topographic  
 963 Break is the boundary between the Fluvial Fan Delta to the north and the flatter Fluvial-Tidal  
 964 Delta to the south (Wilson and Goodbred, 2015). K = Kolkata, Kh = Khulna, Dh = Dhaka, S =  
 965 Sylhet, H = Hazipur-1 well, SoNG = Swatch of No Ground Canyon. The inset shows the  
 966 regional topography with the outline of the drainage basin of the Granges, Brahmaputra and



967 Meghna River basins outlined in black and the rivers in white. The red box shows the location of  
968 the detailed figure.



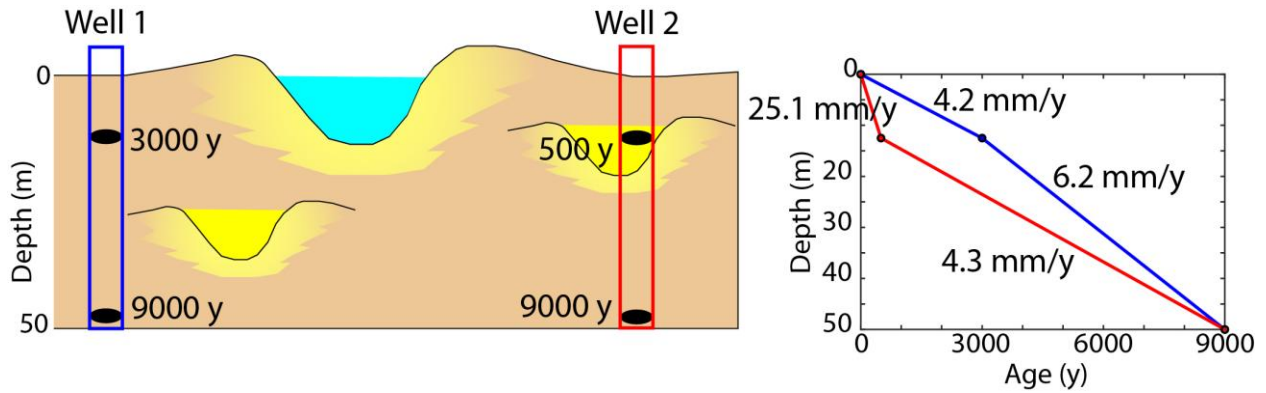
969  
970 **Figure 2.** Cartoon illustrating subsidence processes active in the Ganges-Brahmaputra Delta in a  
971 schematic, not to scale, cross section. In the eastern delta, the tectonics of the IndoBurma  
972 foldbelt and Shillong Plateau are significant. Elastic loading from the earthquake cycle adds  
973 interseismic subsidence that is reversed during earthquakes. Both the tectonics and sedimentation  
974 contribute to flexural isostatic loading of the lithosphere. The old passive margin of seaward of  
975 the Hinge Zone (HZ) is subject to thermal subsidence, but the rate is very low for this older  
976 margin. Within the sediments, deep compaction over kilometer-scale depth contributes, but is  
977 limited where overpressure slows fluid expulsion. More of the sediment compaction occurs in  
978 the Holocene sediments that have filled the incision from the last glacial period (G and B mark  
979 the Ganges and Brahmaputra incised valleys). In the very near surface, additional processes, such  
980 as organic matter degradation, come into play and contribute to large amount of compaction in  
981 the upper few meters of sediments.



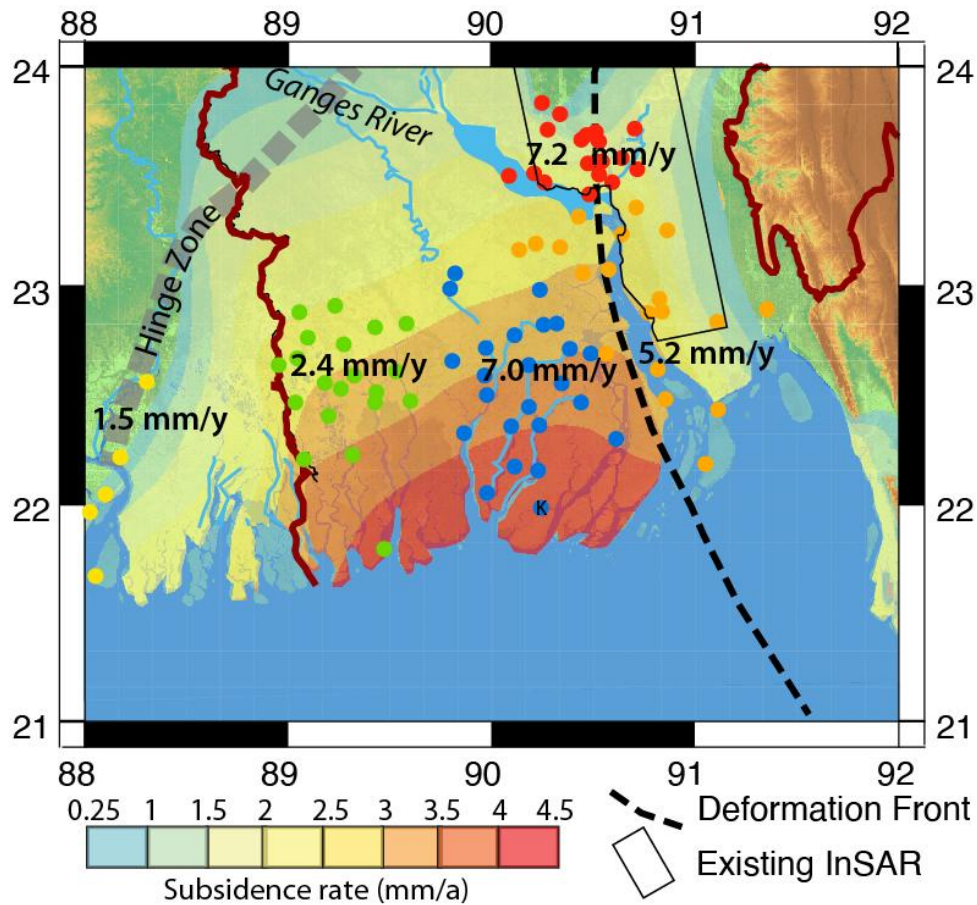
982

983 **Figure 3.** Water level data from the Khepupara tide gauge. The top shows hourly data from the  
 984 Bangladesh Inland Water Transportation Authority (BIWTA) in red and a tidal model from  
 985  $t\_tide$  (Pawlowicz, 2002) in blue showing a mean sea level rise rate of  $9.2 \text{ mm/y}$ , indicated by a  
 986 white line. However, examination of the data shows variable rates of sea level rise. The middle  
 987 shows fits to the three distinct regimes with the rates noted below each segment. The bottom  
 988 shows the more limited publicly-available time series from PSMSL. It corresponds

989 approximately to the central portion of the longer times series when the apparent sea level rise  
 990 rate was greatest.

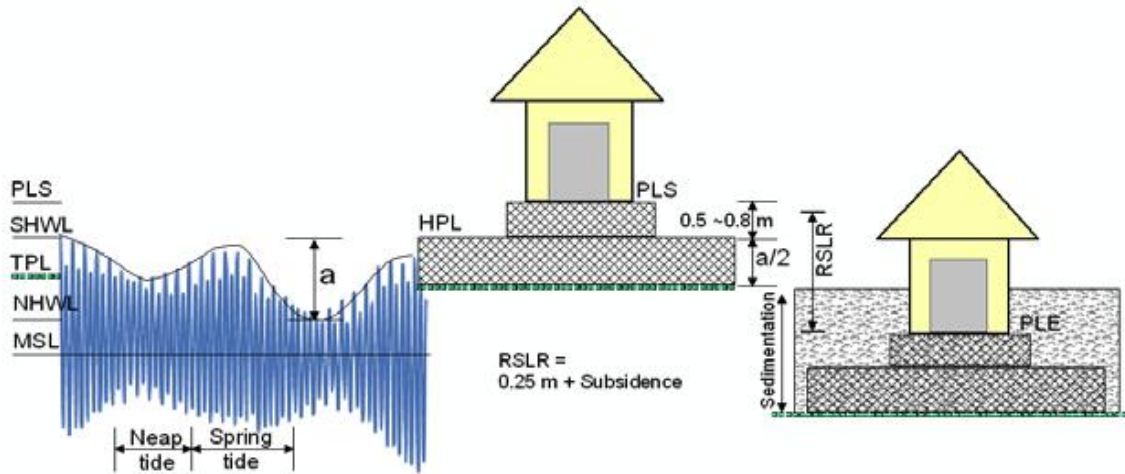


991  
 992 **Figure 4.** Cartoon and plot illustrating the channel incision effect. Well 1 records a continuous  
 993 section with close to linear subsidence rates based on two dated samples. In Well 2, a river  
 994 channel incised into the section, depositing sandy sediments before avulsing to a newer position.  
 995 The dates from this well record an anomalously high apparent subsidence rate due to the younger  
 996 river deposits and an underestimated subsidence rate for the lower section, illustrating the need  
 997 for the context of dated samples.



998  
 999 **Figure 5:** Map showing contours of Holocene average subsidence rates in the GBD (41).  
 1000 Subsidence increases seaward from the Hinge Zone. Superimposed are the locations of the river

1001 gauges (Becker et al., 2020) as colored dots with the corresponding average rates on subsidence  
1002 over a 20-year period for each set. The K indicates the position of the tide gauge at Khepupara.



1003  
1004 **Figure 6.** Diagram (Sarker et al., 2012) illustrating the computation of subsidence for historic  
1005 sites. RSLR = relative sea level rise with 0.25 m equal to eustatic sea level rise over the period  
1006 since the historic sites were built; MSL = mean sea level; HPL is the homestead platform level.  
1007 PLS and PLE are starting and ending plinth level, respectively. See text for other notations.  
1008

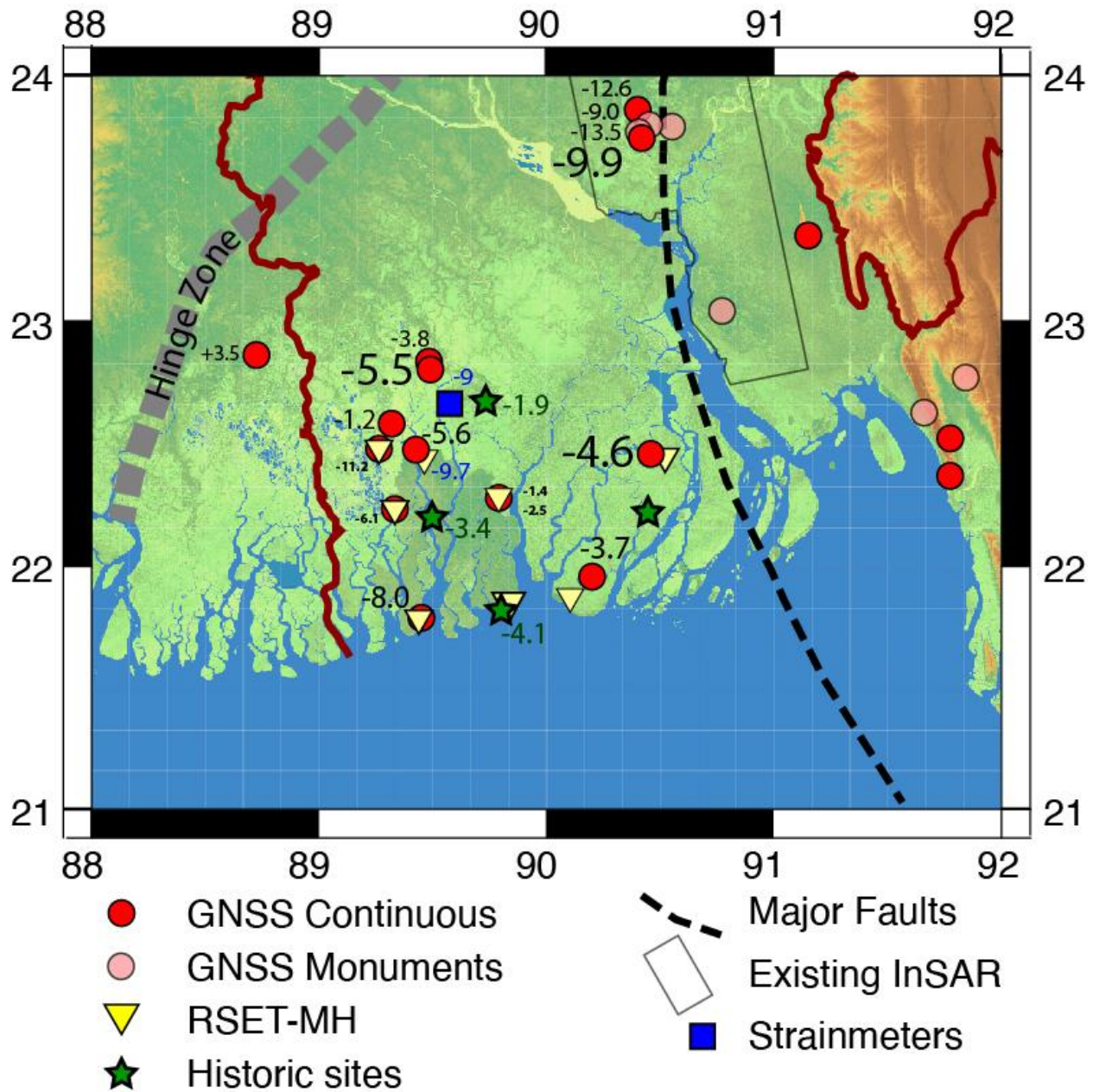


**Figure 7.** Photo of the ~400 year old Shakher Temple in the Sundarbans with a closeup of our interpreted plinth level in the lower left.

Sarker et al (2012) Plinth level

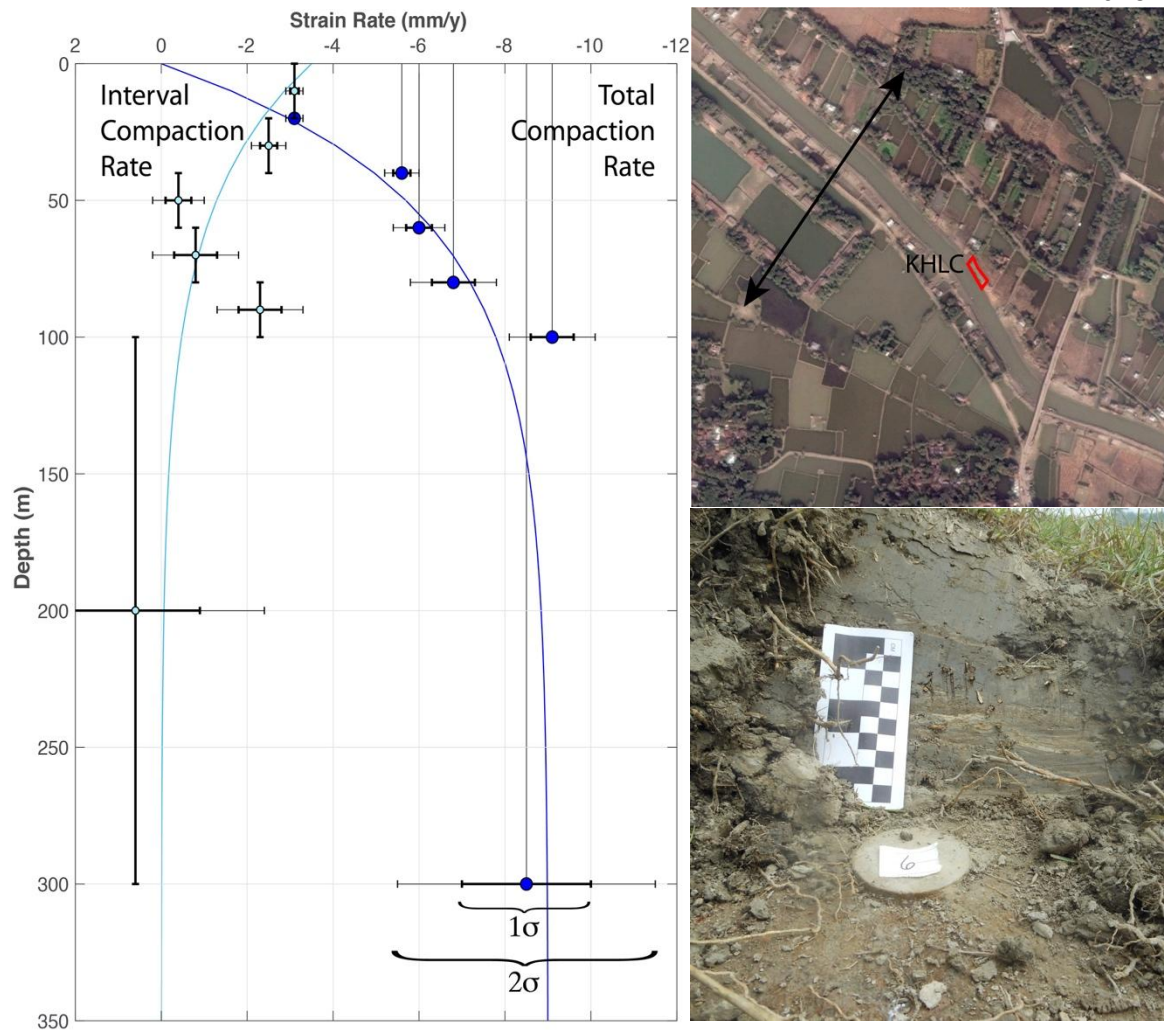
Revised plinth level



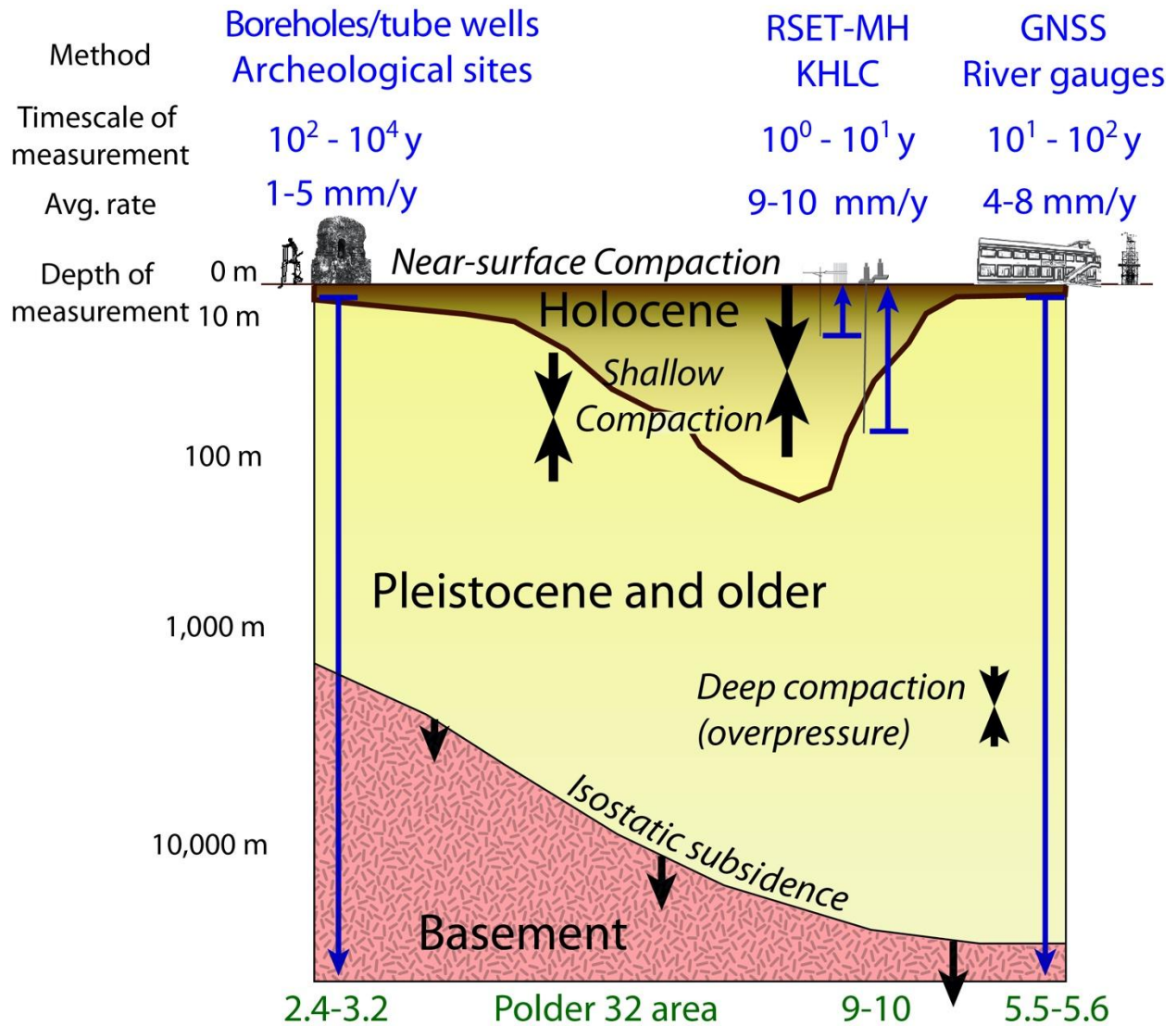


**Figure 8.** Subsidence rates in the lower GBD west of the deformation front. Except for historic sites, text size is proportional to the square root of the time series length to represent the reliability of the values. High rates around Dhaka reflect subsidence from ground water withdrawal. Historic sites yield values similar to Holocene average rates in Figure 4 (Grall et al., 2018). GNSS rates are similar to slightly higher, especially farther west. The vertical borehole strain meter (DeWolf et al., 2015, in prep.) and published RSET-MH value (Bomer et al., 2020) record compaction up to the surface and yield significantly higher rates.





1019 **Figure 9.** Results from the KHLC compaction meter. A) plot showing the decrease in  
 1020 compaction with depth. The blue dots show the shortening rate of the different length fibers and  
 1021 teal dots show the differential rate between pairs of fibers. Approximate exponential curves to  
 1022 the data for the total compaction and its derivative are shown. B) Google Earth image of the  
 1023 KHLC site. The wells were installed on the river bank in the red box. The double arrow shows  
 1024 the width of the river before 1989. Notice the large concrete bridge SE of KHLC over the now  
 1025 small river. C) photo of the marker at the base of one of the monuments taken in 2017 with a cm  
 1026 scale. The lower section shows ~6 cm of tidalites deposited over 4 monsoon seasons. Above are  
 1027 4-6 cm of muddy deposits in the 2 years since the March 2015 dredging.



1028  
 1029 **Figure 10.** Summary cartoon of subsidence and compaction measurements for a section centered  
 1030 the Brahmaputra incised valley (Fig. 2). Compacting sediments are in shades of brown to yellow  
 1031 with brown indicating faster compaction. The methods applied to distinguish rates and their  
 1032 timescales and values are shown in blue. The RSET and KHLC measure compaction from their  
 1033 base to the surface (upward arrows), while the other system measure subsidence below their base  
 1034 (downward arrows). At the bottom, values for long-term subsidence, shallow compaction, and  
 1035 short-term subsidence for the area around Polder 32, where we have all these systems, are given.