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4 Dominant updriftward sediment transport on the updrift-side of a
5 modern deflected delta, Ishikari coast, Hokkaido, Japan

6

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17

20 The Ishikari coast of Hokkaido, Japan is a wave-dominated semi-enclosed coast, the
21 sediments of which are primarily sourced from a single river (the Ishikari River),
22 forming a northeast deflected delta. Asymmetric and deflected deltas are generally
23 considered to be formed under net longshore sediment transport *downdriftward*;
24 however, through sedimentological and grain-size trend analysis (GSTA) of seafloor
25 sediments, along with some other observational data, we recognized dominant
26 *updriftward* sediment transport on the updrift-side of the deflected delta system. GSTA
27 showed that the most important trend in the coast is coarser, better-sorted, and more
28 positively skewed (CB+). CB+ trends around the river mouth converge from the lower
29 shoreface zone to the river mouth spit on the updrift side. The trends reflect the
30 combined effects of shore-normal wave action and river sediment discharge. Wave-
31 driven surface currents crossing over the delta lobe converge at the southwestern side of
32 the river mouth. In the deeper zone (lower shoreface), southwest (updriftward) oriented
33 CB+ trends prevail. These trends reflect successive re-deposition of delta front sands,
34 with progressive mud winnowing, driven by the strong south-westerly bottom currents
35 observed in the bay during winter storms. Although GSTA did not show any apparent
36 trend field in the nearshore zone, gradual fining of sand fractions to the southwest,
37 along with the chronological transition of the coastline after the construction of a large
38 port, suggest a dominant longshore sediment transport updriftward on the updrift-side of
39 the delta. Because the growth of deflected deltas depends on dominant sediment
40 accretion on the updrift-side, these results can be rationalised in the case of internally
41 sourced deflected deltas. Uncertainties remain regarding the net alongshore sediment
42 transport of the entire Ishikari coast; however, the deflected planform is controlled by
43 deflected mouth bars and river mouth jets due to the waves approaching the river mouth
44 at slightly oblique angle in winter, and is likely independent on the direction of
45 dominant sediment transport.

46 **Keywords** deflected delta, grain-size trend analysis, Ishikari Coast, sediment pathway,
47 wave-influenced delta

48 **1. Introduction**

49 Coastal regions are often the site of large cities and concentrated human activities,
50 especially delta plains have been highly developed for land use. However, recent global
51 environmental changes due to human impact are significantly affecting delta
52 morphology (Anthony, 2015; Nienhuis et al., 2020). Therefore, it is important to gain a
53 detailed understanding of sedimentary processes of delta systems to support predictive
54 environmental planning, sustainable development, and hazard mitigation (e.g., Kairytė
55 and Stevens, 2015; Nienhuis et al., 2020).

56 Recent advances in our understanding of wave-influenced delta systems have helped
57 improve their classification based on their planforms and facies architectures:
58 symmetric, asymmetric, or deflected (Bhattacharya and Giosan, 2003; Bhattacharya,
59 2006; 2010). Asymmetric and deflected deltas are thought to grow via sustained
60 downdriftward longshore currents generated by an oblique wave approach to the
61 coastline (Dominguez, 1996; Reading and Collinson, 1996; Bhattacharya and Giosan,
62 2003; Bhattacharya, 2006; 2010). In case of these deltas, predominant sediment
63 accretions on the updrift side are needed, and it is generally explained by a trapping of
64 externally sourced sediments in the updrift side by the groin effect of river mouth
65 (Reading and Collinson, 1996; Rodriguez et al., 2000; Bhattacharya and Giosan, 2003).
66 However, the asymmetric and deflected delta models are still conceptual, and the
67 hydrodynamic processes and resulting sediment distributions of real systems exhibit
68 much more complex variations (see Anthony, 2015 and references therein). For
69 example, the modern asymmetric Mitchell River Delta, Gulf of Carpentaria, Australia,
70 has a northward-deflected planform, whereas the mouth bar sediments show southward-
71 dipping cross-stratification opposite the expected direction (Ainsworth et al., 2016).
72 Difficulties in determining the sources, pathways, and final emplacement of sediments
73 in deflected deltas have hindered our understanding of the detailed growth mechanisms
74 of such systems (Anthony, 2015; Korus et al., 2015). In addition, it should be noted that

75 the definition of the updrift and downdrift sides of deflected deltas often depends only
76 on geomorphic features, not the actual direction of net sediment transport. In this study,
77 the adjective terms "updrift" and "downdrift" are also used in this way (i.e., geomorphic
78 direction).

79 The coast along the eastern margin of the Japan Sea is characterised by a low tidal
80 range and high wave energy and hosts several strand plains and delta systems. Among
81 these, the Ishikari coast of Hokkaido, northern Japan, consists of a highly deflected
82 delta at the mouth of the Ishikari River (Fig. 1). The delta has been developing under the
83 late Holocene high-stand condition after the Mid-Holocene sea-level maximum
84 (Ohshima et al., 1978; Matsushita, 1979). The coast is situated within a bay bordered by
85 rocky projecting land masses, and most of the sediment inputs originate solely from the
86 Ishikari River (e.g., Ohshima and Yokota, 1978). This single source condition enables to
87 interpret sediment pathways more certainly as no other inputs can scramble the
88 dominated transport signal.

89 The Ishikari Bay bottom sediments are mainly under the action of wind-driven currents
90 during winter storms; hence, its analysis should highlight the seasonal storm impact on
91 the granulometric sorting. In the present work, we conducted a grain size trend analysis
92 (GSTA) following the method of Poizot and Méar (2010), which has been shown to
93 successfully visualise sediment pathways (Maillet et al., 2011; Kairyte and Stevens,
94 2015). Though STA® (McLaren, 1981) and GSTA approaches have had successive
95 modifications on some of their aspects, only a small number of studies have scrutinised
96 the validity of McLaren's initial theory and trend cases definitions. Gao et al. (1994),
97 Asselman (1999), Carriquiry and Sanchez (1999), Carriquiry et al. (2001), Rios et al.
98 (2002), Poizot et al. (2013) found different trend cases than the initial McLaren's ones
99 under particular conditions. Poizot and Méar (2010) provided a software tool to perform
100 a GSTA approach in which no prior choice of trend case was made, thus enabling an
101 exploratory approach in choosing a single or combined trend case.

102 The backgrounds of studied area are introduced in Section 2. The Section 3 gives
103 details of the laboratory analysis, numerical treatments of the data set, and GSTA.
104 Finally, results (Section 4) and discussions (Section 5) explain our understanding of the
105 sediment transport processes in the Ishikari bay, before the conclusion in Section 6.

106

107 **2. Regional Setting**

108 The Ishikari delta, Hokkaido, northern Japan, is located in the inner area of Ishikari
109 Bay (Fig. 1). The 30 km-long sandy coastline, oriented northeast–southwest, curves
110 gently landward, and slightly protuberates seaward at the mouth of the Ishikari River as
111 a northeast deflected planform. Rocky projecting land masses border the coast on both
112 the southwestern and northeastern sides. The coast faces the microtidal and wave-
113 dominated shore of Japan Sea (Ohshima and Yokota 1978). The tidal range is less than
114 0.6 m (Hydrographic and Oceanographic Department, Japan Coast Guard, 2004), the
115 mean significant wave height is 0.92 m (based on 2013 data), and the maximum
116 significant wave height is 7.32 m (based on 2004–2007 data) (Kawaguchi et al., 2015).
117 Strong westerly–northwesterly winds prevail, especially in winter (i.e., winter
118 monsoon), which approach orthogonally to the coast (Fig. 1). Figure 2 shows the
119 maximum and significant wave heights and the wave orientations observed in the bay
120 during the survey years. High waves were dominant in winter corresponding to the
121 strong wind, and their up-current orientations concentrated to northwest perpendicular
122 to the coastline (Fig. 2).

123 Highly deflected wave-influenced deltas should be considered as strand plains
124 especially when the major sediment input is externally (Bhattacharya and Giosan, 2003;
125 Bhattacharya, 2006). However, large volumes of the sediments along the Ishikari coast
126 are sourced internally (i.e., from the Ishikari River), and the coastline slightly protrudes
127 toward the river mouth. The low planform aspect ratio of deltas is probably controlled
128 by wave-angle climates (Ashton and Giosan, 2011) and a fluvial dominance ratio

129 (Nienhuis et al., 2015), which is defined as river sediment input with respect to the
130 potential maximum alongshore sediment transport away from the river mouth.
131 According to these theoretical studies, the Ishikari coast has dominant high-angle waves
132 and low fluvial dominance ratio. We therefore treat the Ishikari coast as a deflected
133 delta, which is an end member of wave-influenced delta geomorphology (e.g., Nienhuis
134 et al., 2020).

135 The shore-normal wind-driven surface currents generate not only longshore currents,
136 but also shore-parallel southwest oriented bottom currents in the Ishikari Bay because of
137 Coriolis and Ekman effects. In addition, winds are stronger along the northeastern
138 region of the coast than the southwestern region, and the resultant pressure gradient
139 forces within the coastal water mass generate southwest oriented currents in the bay
140 (Mizutani and Nakajima, 1997; Yamashita et al., 1999). The bottom currents were
141 recorded in the zone of 15–30 m water depth by acoustic Doppler current profiler
142 (Yamashita et al., 1998; 1999) (Fig. 3). Southwest directed strong bottom currents
143 exceeding 0.4 m/s were widely observed in winter, while weak bottom currents directed
144 northeast were dominant in summer.

145 The seafloor topography of the Ishikari coast is simple (Figs. 1 and 5). The
146 bathymetric contours are parallel to the shoreline. The upper zone of the shoreface (≈ 4
147 m) dips at 1° , with slightly steeper gradients in local. The seafloor at water depths of 4–
148 16 m dips at $0.3\text{--}0.4^\circ$, and the deeper areas have gradients lower than 0.1° . Longshore
149 bars and troughs are formed at water depths of 2–6 m. A lobate mound is recognised at
150 the front of the Ishikari River mouth, which is considered a modern subaqueous delta
151 lobe (Ohshima et al., 1978). The plan-view morphology of the lobe slightly extends
152 northward (Fig. 1). The modern sediments cover seafloor at water depths shallower than
153 40 m, whereas relict sediments are distributed at a depth deeper than 40 m (Ohshima
154 and Yokota, 1978). According to Ohshima and Yokota (1978), the relict sediments
155 consist of medium to coarse-grained clean sand (medians are 1–2 ϕ , and mud contents

156 are less than 5 wt%), that are significantly coarser than the modern lower shoreface
157 sands (medians are > 3 phi).

158 The Ishikari River has a length of 268 km (364 km before artificial linearisation of the
159 river course) and a drainage area of about 14×10^3 km². The average water discharge
160 based on the past 50 years is 15 km³/year and the estimated sediment discharge is 2×10^6
161 t/year (Yamazaki and Yamashita, 2004). The Ishikari River is the only major river
162 entering Ishikari Bay. A large proportion of the coastal sediments is supplied from this
163 river (Ohshima and Yokota 1978; Suga and Hamada 2001), and about 80 % of the
164 annually discharged sediments are supplied in snowmelt season (Shimizu et al., 1998).
165 Suspended muddy sediments extend up to 50 km northward along the eastern margin of
166 the bay during the spring (Geological Survey of Hokkaido, 2003). Under fair weather
167 conditions in summer, a surface of the delta lobe is covered by muddy sediments at the
168 water depth deeper than 10 m (Suga and Hamada, 2001) (Fig. 1).

169 At the lower reaches, the Ishikari River has a single meandering channel that deflects
170 NE-ward parallel to the shoreline (Fig. 1). The channel is separated from the open ocean
171 by a river mouth spit with 10-m-high aeolian sand dunes (the Ishikari Sand Dune). The
172 location of the Ishikari River mouth had been migrating NE-ward with growth of the
173 spit and erosion of the downdrift (northeast) margin of the river mouth (Yamazaki and
174 Yamashita, 2004) (Fig. 4A). The growth rate of the spit during 1913–1976 was 17.8
175 m/year, as estimated by topographic maps and aerial photos (Arai, 1981). However, the
176 growth of the spit has been disrupted, and the river mouth stabilised since 1976 due to
177 revetment work at the downdrift margin of the river mouth (Yamazaki and Yamashita,
178 2004). Although the growth direction of the spit suggests net longshore sediment
179 transport NE-ward, several studies have suggested that foreshore sands are transported
180 both SW-ward (updriftward) and NE-ward (downdriftward) or predominantly SW-
181 ward. This is because drifted sands are predominantly trapped at the eastern side of the
182 artificial groin system (Ishikari Bay New Port: IBNP) (Fig. 4B, C) (Arai, 1981;

183 Yamashita et al., 2000; Suga and Hamada, 2001). The chronological change in the
184 coastline is further discussed in Section 4.3.

185

186 **3. Materials and Methods**

187 *3.1. Sampling and grain-size measurement*

188 Along the Ishikari coast, a total 249 samples of seafloor sediments were collected
189 mainly along 28 transects, oriented perpendicular to the coastline, spaced mainly 500 m
190 or 1000 m apart (Fig. 5). Sampling surveys were performed in summer, June 1996,
191 September 1997, September 2004, August 2014, and August 2016. Most of the samples
192 on the updrift side of the Ishikari coast were collected in 1996–1997 by K. Suga and S.
193 Hamada (Suga and Hamada, 2001). The samples were collected in 2004 by K. Nishina
194 to complement the data obtained around the river mouth. We performed new sampling
195 surveys in 2014 and 2016 to collect offshore sediments from the downdrift area, from
196 the foreshore to the uppermost shoreface sands throughout the entire coast.
197 Oceanographic conditions (maximum and significant wave heights and wave
198 orientations) in the Ishikari coast during the sampling survey years 2014 and 2016 were
199 shown in Figure 2. There was an extremely limited number of significant storm events
200 before these surveys in the summer season. Even if samples were collected at different
201 dates, they are all representative of a summer period. This mix of dates has the
202 advantage to “filter” any short-term event which could have impact sediment
203 characteristics. Only long-term sediment behaviour (over 10 years) will be highlighted,
204 which is the aim of the present work.

205 Surface sediment samples (up to 2 cm depth) of the seafloor at water depths of 2–23 m
206 were collected using a Smith McIntyre grab sampler (1/20 m², Rigo Co., Ltd, Japan).
207 Along the coastline, sand samples in the foreshore and shallow water depth zone (≈1 m)
208 were collected at 100–500 m interval. The former was collected directly using a scoop
209 at up to 2 cm depth, while the latter was collected using PVC pipes up to 5-10 cm depth.
210 The seafloor sands around the mouth of the Ishikari River were collected at closer

211 intervals. The collected samples were prepared by chemical dissolution of organic
212 matter and CaCO_3 using a 6% hydrogen peroxide solution and 20 vol.% acetic acid.
213 Grain-size analysis was performed with a laser microgranulometer (Coulter counter
214 LS230, Coulter Co., USA, 117 classes in size range 0.4 μm to 2 mm). Granules
215 exceeding the measurement range were removed via sieving through -0.5 phi (1.41 mm)
216 mesh before analysis. Few samples contained granules of $\approx 5\%$ weight. Statistical
217 parameters, mean, sorting (standard deviation (σ)), and skewness, were calculated by
218 the logarithmic method of moments using the GRADISTAT programme (Blott and Pye,
219 2001).

220 3.2. Grain-size trend analysis

221 The STA© (McLaren, 1981) was first introduced to interpret sediment transport
222 directions along survey lines (i.e., one-dimensional approach). It is based on the
223 comparison of three statistical parameters (mean, sorting and skewness) of grain-size
224 distributions of sediment samples and their relative changes. As summarized in Kairyte
225 and Stevens (2015), the main factors influencing grain-size composition of sediments
226 are the: (i) winnowing; (ii) selective deposition of a portion of the grain-size distribution
227 in transport; and (iii) total deposition. McLaren's model assumes that: (i) sediment in
228 transport must be finer, better sorted and more negatively skewed than its source
229 sediment (case: FB-); (ii) a lag must become coarser, better sorted and more positively
230 skewed (case: CB+); and (iii) successive deposits may become finer or coarser, but the
231 sorting must become better and skewness more negative or more positive with finer or
232 coarser deposits, respectively (McLaren and Bowles, 1985; Kairyte and Stevens, 2015).
233 Namely, the method assumes that the trends of FB- and CB+ have a higher frequency of
234 occurrence in the direction of transport between two points.

235 Gao and Collins (1991) modified McLaren's method and provided a procedure for
236 two-dimensional data treatment, in which each sample is compared with its nearest
237 neighbours in any direction. Through this refinement, a two dimensional grain-size
238 trend analysis (GSTA) is used as a qualifying method which defines trend vectors

239 (directions and patterns) based on the analysis of particular spatial relationships (trends)
240 between the mean size, sorting and skewness of sediment samples (Poizot and Méar,
241 2010). Poizot et al. (2008) reviewed the Gao and Collins' approach and proposed a
242 workflow to enhance the definition of trend pathways through the GSTA approach. One
243 of the main proposals was the introduction of geostatistical tools to perform some pre-
244 treatments allowing for a better choice of GSTA parameters. Most of the proposals were
245 integrated in a GIS based software GiSedTrend (Poizot and Méar, 2010).

246 Before the analysis by GiSedTrend, the variographic analysis of the data set allows the
247 characteristic distance (D_g) to be defined using GSTA computation and, the spatial
248 variation model of the statistical parameters (mean, sorting and skewness) to be defined.
249 The spatial models are then used to produce interpolation maps (Fig. 6) from which a
250 regular grid is extracted for each parameter. In the present study, a 200 m grid spacing
251 was defined. These grids were then at the inlet of the GSTA approach. The variographic
252 analysis and interpolation operations were performed under R Statistical language (R
253 Core Team, 2020) using the geostatistical package R Geostats (Renard et al., 2020). The
254 CircStats R package (Lund and Agostinelli, 2018) provided the circular statistics used to
255 compare trend case directions.

256 Following the above, three different GSTA analysis were performed using
257 GiSedTrend: a) the classical combined cases CB+ and FB-; b) FB- case alone; and c)
258 CB+ case alone. Results of the two latter trend cases were used to compare their relative
259 impacts to the combined trend case of CB+ and FB-. Some barriers (linear objects)
260 created to represent the coast and seawalls were considered during the GSTA
261 computation. The semi-variogram analysis (Matheron, 1973) of the interpolated dataset
262 showed that the distance where the model first flattened out (i.e., the range) ranged from
263 3200 m to 4000 m. These distances represent the spatial scale at which samples are
264 considered as neighbors (correlated). Therefore, characteristic distance (D_g) was defined
265 at 4000 m in the analysis, which is the highest distance between all the parameters.

267 4. Results

268 4.1. General grain-size characteristics

269 The modern seafloor sands in the Ishikari coast mainly consisted of medium- to very
270 fine-grained sands of poorly- to very poorly sorted and very fine-skewed grain-size
271 characteristics (Fig. 7). The maximum mud content of the samples was 70% (Figs. 5
272 and 7); these sands showed a simple fining trend as water depth increased (Fig. 7), a
273 typical sediments behaviour in wave-dominated coasts (Reading and Collinson, 1996).
274 Muddy sediments exhibited a focused distribution at relatively shallow depths in front
275 of the Ishikari River mouth during spring and summer, which were covering the delta
276 lobe (blue circles in Fig. 5). The samples of mode $\phi > 4$ were excluded from the
277 analysis, since sand movements are considered to be expressed under no cohesive
278 conditions, whereas muddier sediments are considered to move under cohesive
279 conditions.

280 Based on the grain-size parameters, four depth zones were defined: foreshore zone,
281 uppermost shoreface zone (water depth: ≈ 2 m), upper shoreface zone (water depth: 2–8
282 m), and lower shoreface zone (water depth: 8–23 m) (Fig. 7). The foreshore sands
283 showed coarser mode grain-sizes of 0.5–2.0 ϕ (mean ϕ : 0.5–2.3) and were classified
284 as poorly sorted sands ($1.0 < \sigma < 2.0$), although they were better sorted than the shoreface
285 sands (Fig. 7B, C, D). The uppermost shoreface sands were also coarse (mode ϕ : 0.5–
286 2.0) but showed a wider range of mean grain sizes (0.5–3.3 ϕ) than foreshore sands
287 and were classified as poorly sorted to very poorly sorted ($0.7 < \sigma < 3.4$). The mode grain
288 size of the upper and lower shoreface sands generally ranged 1.6–3.6 ϕ (mean ϕ :
289 0.6–5.6). The upper shoreface sands showed a clear fining trend to deeper waters, but
290 the sand in the lower shoreface had a small range grain size variation (Fig. 7B, C, D).

291 Skewness of the foreshore and the uppermost shoreface sands showed greater
292 variabilities, from symmetrical to very fine skewed (-0.4 – 8.0), whereas the sands of the
293 upper and lower shoreface were very fine skewed (1.0 – 4.0) (Fig. 7E). In terms of

294 kurtosis, most of the analysed sands were classified as leptokurtic to very leptokurtic
295 (Fig. 7F). On the scatter plot of mean vs. skewness, most of the samples negatively
296 correlated, however, 12 samples from foreshore and uppermost shoreface deviated from
297 this trend (Fig. 8 and supplement table). These sediment samples were excluded from
298 the GSTA analysis.

299 Interpolation maps of these grain-size parameters (mean, sorting and skewness)
300 suggest there are interrelationships among these parameters (Fig. 6).

301 *4.2. Spatial variation of grain-size parameters and grain-size trends*

302 The spatial variation of the grain-size parameters suggested several trends, both
303 perpendicular and parallel to the coastline (Figs. 6 and 9). The foreshore–upper
304 shoreface sands had the coarsest grain size neighbour at the Ishikari River mouth. With
305 increasing distance from the river mouth, the grain size of the nearshore sands became
306 finer both along-shore and cross-shore, exhibiting the highest gradients around the river
307 mouth (Figs. 6 and 9). Along the offshore dike of Ishikari Bay New Port (IBNP), the
308 shore-parallel gradient became unclear. In the western side of IBNP, westward fining
309 then coarsening trend appeared with a lesser intensity than the eastern side of IBNP
310 (Figs. 6 and 9).

311 The results of GSTA (Fig. 10) showed that systematic trend fields of CB+ existed
312 within a wide area with the high degree of confidence (i.e., long vectors). The vector
313 fields of the FB- trend case appeared very locally (Fig. 10). The combined CB+ & FB-
314 case exhibited the same main direction characteristics as the single CB+ trend case. The
315 directions shown in the wind roses, Figure 10 (right column), demonstrate that there
316 was little difference between the CB+ and CB+ & FB- trend cases. This indicates that
317 the CB+ trend provides the most significant information in the CB+ & FB- combined
318 trend case. Namely, the CB+ is the dominant trend case in the Ishikari coast. The vector
319 field CB+ was widely distributed, except in the nearshore zones (i.e., foreshore and
320 uppermost shoreface zones). The wind rose of the CB+ trend (Fig. 10, top right) shows

321 a globally southward vector direction (159.3° of mean direction). Two directions sustain
322 a higher number of vectors around the mean direction: SW-ward and SE-ward.

323 Despite the general trends highlighted in Figure 10 by analysis of the statistical
324 parameters, the CB+ trend vector field showed a more complex behaviour. According to
325 the vector field, three different sectors can be recognised each corresponding to one-
326 third of the studied area (Fig. 11). In the eastern sector centred on the river mouth
327 (*sector A* on Fig. 11), the trajectory of CB+ vectors draw a clockwise rotation in the
328 downdrift area, and an anti-clockwise rotation in the updrift area. These vectors
329 converge to the head of the spit at approximately 2000 m southwest (updrift side) of the
330 river mouth (Fig. 11). A small area in the sector, containing some FB- trend vectors (~30
331 vectors) oriented mainly SW-ward, is highlighted offshore (Fig. 10). The second sector
332 is centred on the IBNP (*sector B* on Fig. 11). CB+ trend vectors separate in two
333 directions at the tip of the outermost dike. Vectors located northeast of sector B turn
334 southward to concentrate 1 km north of IBNP. The other vectors turn gently from SW-
335 ward to southward near the dike. FB- trend vectors are present at two locations in this
336 sector, offshore with an eastward direction, and at the southern part of the sector with a
337 NE-ward direction (Fig. 10). The last sector starts, in the north, approximately 1 km
338 south of IBNP and ends at the southwestern side of the studied area (*sector C* on Fig.
339 11). In this sector, CB+ vectors show divergent paths start radially from the centre to the
340 E, ESE, S, SW, and W. North of this sector, CB+ trend vectors highlight a SE to East-
341 ward direction pointing to IBNP south inlet. In the south part of sector C, general vector
342 direction oriented southward in the offshore zone, which turned SW-ward as they
343 approached the coast. Some westward directed FB- trend vectors are present near the
344 coast at the Shinkawa river mouth (Fig. 10).

345 4.3. Interpretation of sediment pathway

346 The CB+ vector fields appeared globally in the lower shoreface zone. In sector A and
347 the northeastern part of sector B, the onshore directed CB+ trends predominant in the
348 shallower part of the lower shoreface reflect a spatial gradient in the degree of

349 winnowing of fine fractions controlled by water depth. The trend oriented perpendicular
350 to the bathymetric contour lines corresponds directly with the shoring storm waves
351 and/or the wind-driven surface currents. Bathymetric lines from -20 m to -3 m are
352 parallel to the coast and have a concave shape toward offshore. Because of refraction on
353 the seafloor, storm waves align progressively to the general bottom morphology. In
354 sector A, the onshore directed CB+ vectors converging to the head of the river mouth
355 spit (at the point approximately 2000 m southwest from the mouth) reflects combined
356 effects of the river sediment discharge and storm waves concentrated at the river mouth
357 due to bottom refraction on the delta lobe.

358 In the deeper zone of the lower shoreface, the CB+ trend wind rose graphic (Fig. 10,
359 top right) shows a globally SW-ward vector direction. The trend vectors correspond
360 with the decrease in mud content rather than the composition of sand fractions (Figs. 9
361 and 12). This SW-ward trend is parallel to the bathymetric contour lines and well
362 concordant with the orientation of strong bottom currents observed in the Ishikari Bay
363 (Mizutani and Nakajima, 1997; Yamashita et al., 1998; 1999). Thus, it is considered that
364 the lower shoreface sands have been re-deposited successively with progressive mud
365 winnowing by the bottom currents. Such behaviour is reinforced in sector B with the
366 presence of IBNP. At this location, the offshore dike divides the bottom currents
367 transport trend in two directions, SE-ward and SW-ward (Fig. 11, sector B). The
368 deflection of the bottom currents on the offshore side of the dike deviates sediment
369 transport to a westward direction. The meeting of the deflected currents on the dike with
370 the offshore currents causes a decrease in current particle transport. Very small size CB+
371 trend vectors at this location show that the trend has less confidence.

372 In sector C, an eastward CB+ trend appeared in the lower to upper shoreface zone at its
373 NE part. The trend is disharmonic with the global trend in the bay, and the origin of the
374 trend is uncertain. The trend reflects a decrease in mud content (Fig. 9). The finer
375 sediments are distributed at the front of the Shinkawa river (canal) mouth, and the trend

376 could have been affected by mud deposition discharged from the river during snowmelt
377 season.

378 Also, the FB- trend is shown in the wind rose (Fig. 10, bottom right). The trend shows
379 that two main opposite directions are present and are globally parallel to the coastline.
380 This behaviour is related to the alternative tide currents in the bay. The statistical
381 confidence for the vectors (the length) is not high, meaning the tide currents have a
382 small data set footprint that is, they do not provide enough energy to clearly impact the
383 sediment characteristics.

384 Due to the greater variability in skewness, GSTA revealed no apparent trend field in
385 the nearshore zone. This indicates that the grain-size composition of nearshore sands is
386 affected by numerous forces in the nearshore zone. However, the gradual fining of sand
387 fractions along the coastline, and the chronologic transition of the coastlines suggest
388 that longshore current is the dominant force. The symmetric fining trend of the
389 nearshore sands away from the Ishikari River mouth (sector A and northeastern part of
390 sector B), mostly reflect the sand-size fraction composition rather than the mud content
391 (Figs. 9 and 12). Such trends have also been recognised in the previous studies
392 conducted before the construction of IBNP (Taishi, 1977; Arai, 1981). This trend
393 indicates both a longer updriftward and downdriftward transport of finer-grained sand
394 fractions away from the river mouth by longshore currents, whereas coarser-grained
395 fractions remain along the head of spit, as lag deposits. Field experiment carried out in
396 1969 supports this interpretation. In the experiment, fluorescent colouring sands were
397 added to the water at depth of 0 m (beach), 3m, and 5m at the centre of the coast (7 km
398 southwest of the river mouth). These sands were transported south-westward (updrift)
399 during summer, but migrated both southwest- and northeast-ward in winter, resulting in
400 net nearshore sand transport directed south-westward (updrift) (Kougami et al., 1971).

401 The transition of the coastline between 1947-1971 (before IBNP construction, i.e.,
402 under natural conditions) suggests accreted sand was distributed almost evenly to both

403 the updrift and downdrift sides, with a slight preference toward the downdrift-side
404 (updrift:downdrift=44:56) (Fig. 4). Yamashita et al. (2000) evaluated the volume of
405 accreted coastal sands on the updrift-side from a depth of -12 m underwater to 4 m
406 above mean sea level during 1947–1976, and estimated that approximately $20 \times 10^4 \text{ m}^3$
407 sands was accreted annually. This volume was two-thirds of the annually discharged
408 sands (approximately $30 \times 10^4 \text{ m}^3/\text{y}$) from the Ishikari River. After the construction of
409 IBNP, the sand transported updriftward was trapped by the eastern side of IBNP (Fig.
410 4B, 4C). Fukuda et al. (2016) estimated the volume of sands trapped annually was $23 \times$
411 $10^4 \text{ m}^3/\text{y}$ from 2011–2015, and concluded that most of the sand fractions transported
412 updriftward were accreted there. In contrast, the coastline has regressed at average rate
413 of 0.44 m/y on the western side of IBNP (Fig. 4C). This suggests that sand starvation on
414 the western side of IBNP is due to the interception of sand transport along the shoreline.
415 These results also imply that sediment input from onshore-ward sediment transport by
416 waves is insufficient to sustain or grow the coastline in this area.

417 The remaining sand sourced from the river was deposited around the tip of the spit on
418 the downdrift side of the delta, and in the offshore area. However, the growth of the spit
419 has been restrained in recent decades due to a revetment that was constructed
420 simultaneously with IBNP. On the downdrift side of the delta, the groin protruding from
421 the revetment has disrupted the downdriftward sediment transport from the river mouth,
422 therefore, leading to a significant reduction in sand accretion on the downdrift side.

423

424 **5. Discussion**

425 In delta system, driving forces of sediment distribution, such as waves, tide, and river
426 inflows, are generally complex. In addition, conditions often drastically change with the
427 season (Davis, 1985; Reading and Collinson, 1996). Although the GSTA approach
428 highlights that the resultant grain-size trend is generated by the most influential trend
429 case or by combined effect of other factors. It underlines the strengths of studying trend

430 cases separately, as it enables better identification of environmental processes
431 responsible for spatial and quantitative sediment distribution. In this study, the dataset
432 used in the GSTA was composed of sediment samples obtained at different dates over
433 the years but always in the same season (summer). This acts as a time averaging filter,
434 avoiding “noise” which can be induced by non-recurrent or erratic events that may not
435 be recognized as "noise" from a single dataset. This allows for the general mean
436 processes acting on sediment sorting to be identified. In the same manner, working at
437 the scale of the Ishikari Bay, general spatial processes are apparent in the dataset.
438 Although it is possible that natural or human activity may change the sediment
439 dynamics (e.g. Anthony, 2015; Nienhuis et al., 2020) and resultant grain size parameters
440 of the seafloor sediments over many years, the variograms show that the granulometric
441 parameters of seafloor sediments collected in different years have a good spatial
442 autocorrelation and can be considered for trend analysis. In detail, the geostatistical
443 analysis performed prior to the GSTA provided variograms of the three statistical
444 parameters showing sills. This is an indication of the presence of autocorrelations over
445 the parameters (Journel and Huijbregts, 1976; Wackernagel, 1988), that is, the action of
446 one or multiple processes is highlighted. Consequently, the characteristic distance
447 defined during the variographic analysis is linked to the main processes and the GSTA
448 results show their spatial organisation.

449 As the CB+ trend is recognised as the dominant trend on the Ishikari coast, it can be
450 concluded that this trend is mainly related to energetic transport processes of winter
451 storm waves. In sector A, onshore CB+ vectors converging from the lower shoreface
452 zone to the head of river mouth spit reflects the combined effects of the river sediment
453 discharge and the winnowing of fine fractions controlled by water depth. Although a
454 similar trend was observed in the Rhône Delta, France using the GSTA approach
455 (Maillet et al., 2011), such behaviour was interpreted as a consequence of the swell
456 action which keeps most of fine fractions out of river mouth. Meanwhile, swells do not

457 develop in the Japan Sea (Sugimoto and Chikasawa, 2008), and therefore, the
458 winnowing of the nearshore sediments are mainly driven by storm waves in the case of
459 Ishikari coast.

460 In the offshore zone, the seafloor sediments have been successively re-deposited to the
461 southwest by the bottom currents, with progressive mud winnowing. In other words, the
462 subaqueous delta front deposits coarsen to the updrift side corresponding with the true
463 downcurrent direction. The southwest-ward bottom currents in the bay are generated by
464 strong north westerly winds during winter storms. The wind-driven, on-shore directed,
465 surface currents deviate southwest-ward above the seafloor of the lower shoreface by
466 Coriolis and Ekman spiral effects (Fig. 3). These processes have been confirmed by a
467 numerical study (Le et al., 2006). The footprint of the winter bottom currents persists
468 until summer, as the transport processes in the summer season, driven by calm waves,
469 cannot sufficiently modify the winter inherited sediment organization.

470 Although the net longshore sediment transport direction of the entire system remains
471 uncertain, nearshore sands are transported updriftward on the updrift-side of the delta,
472 especially during summer. It is generally considered that the growth of an asymmetric
473 and deflected delta requires dominant sediment accretion in the updrift side under a
474 downdriftward net longshore sediment transport condition. To explain this, external
475 sediment sources are often identified as the contributors to the enhanced updrift area
476 (Reading and Collinson, 1996; Bhattacharya and Giosan, 2003; Bhattacharya, 2006;
477 2010; Anthony, 2015). However, there are no major rivers nor sea-cliffs in the west of
478 Ishikari coast which can provide significant volume of sands. Therefore, it is considered
479 that the updriftward net longshore transport of the internally sourced sediments has been
480 sustaining the growth of the updrift side of the Ishikari delta (Fig. 13). Sediment
481 delivery patterns in the offshore zone are thought to have less influence on the planform
482 of deltas (Bhattacharya and Giosan, 2003; Ayranci and Dashtgard, 2016). Therefore, the
483 predominant updriftward sediment transport in the lower shoreface zone is not

484 surprising. However, sands covering the lower shoreface may enhance the progradation
485 of the delta-front on the updrift-side.

486 The cause of the northeast advance of the river mouth spit under the updriftward
487 sediment transport condition along the shoreline is still uncertain; however, it can most
488 likely be explained by the slightly oblique angle at which the waves approach the river
489 mouth. Such waves typically form swash bars and subaqueous levees on the updrift side
490 (Wright, 1977; Giosan, 2007), and can directly deflect river mouth jets (Nardin and
491 Fagherazzi, 2012; Nienhuis et al., 2016). Such processes occur in winter at the Ishikari
492 River mouth, since the river discharge is significantly smaller during winter. Once a
493 river course is deflected, the processes are enhanced and long-lasting, until spit
494 breaching occurs due to river currents that favour spit elongation/accretion on the
495 updrift side and erosion on the coast downdriftward from the river mouth. To further
496 understand the correlation between delta growth and sediment dynamics and validate
497 the conclusions of the present study, detailed modelling of the growth of the deflected
498 delta under with an internal sediment source will be required.

499

500 **6. Conclusion**

501 Sedimentological analysis and grain-size trend analysis (GSTA) of seafloor sediments
502 along with other observational data, revealed dominant updriftward sediment transport
503 on the updrift-side of a deflected delta system:

504 (1) Coarser, better-sorted, and more positively skewed (CB+) trends are dominant on
505 the Ishikari coast, this is mainly due to energetic sediment transport processes driven by
506 winter storm waves.

507 (2) The updriftward CB+ trends of the lower shoreface sands are caused by strong
508 bottom currents in the coast during winter storms, showing successive re-deposition of
509 seafloor sands with progressive mud winnowing.

510 (3) Gradual fining of foreshore sands, and the chronological transition of the coastline
511 after the construction of large a port suggest that longshore sediment transport also

512 directs updriftward on the updrift side of the Ishikari delta.

513 (4) The growth of deflected deltas depends on dominant sediment accretion on the
514 updrift-side. Thus, the dominant updriftward sediment transport condition on the updrift
515 side can be rationalised in the case of internally-sourced deflected deltas.

516 (5) The deflection of the Ishikari delta platform can most likely be explained by
517 deflected mouth bars and river mouth jets due to the slightly oblique angle at which
518 waves approach the river mouth. Consequently, the deflection of the Ishikari delta is
519 probably independent of the direction of dominant sediment transport.

520

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527

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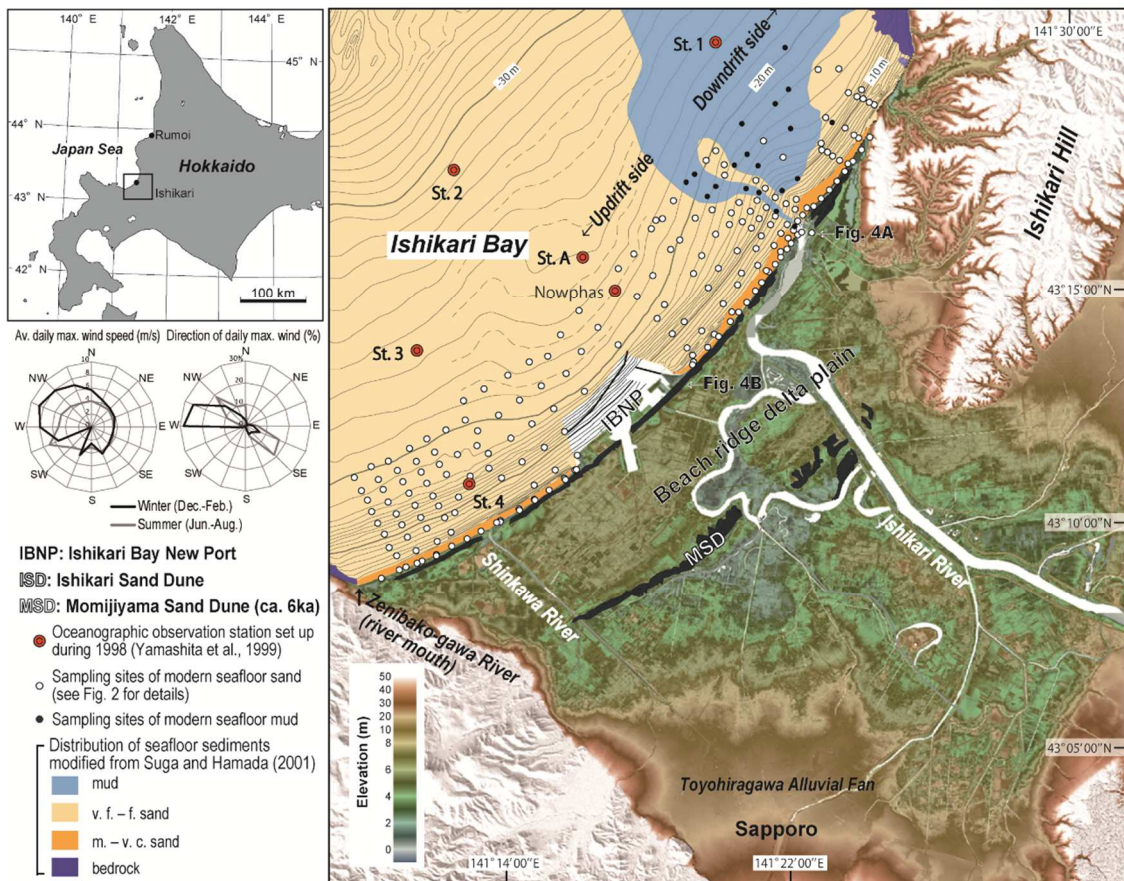
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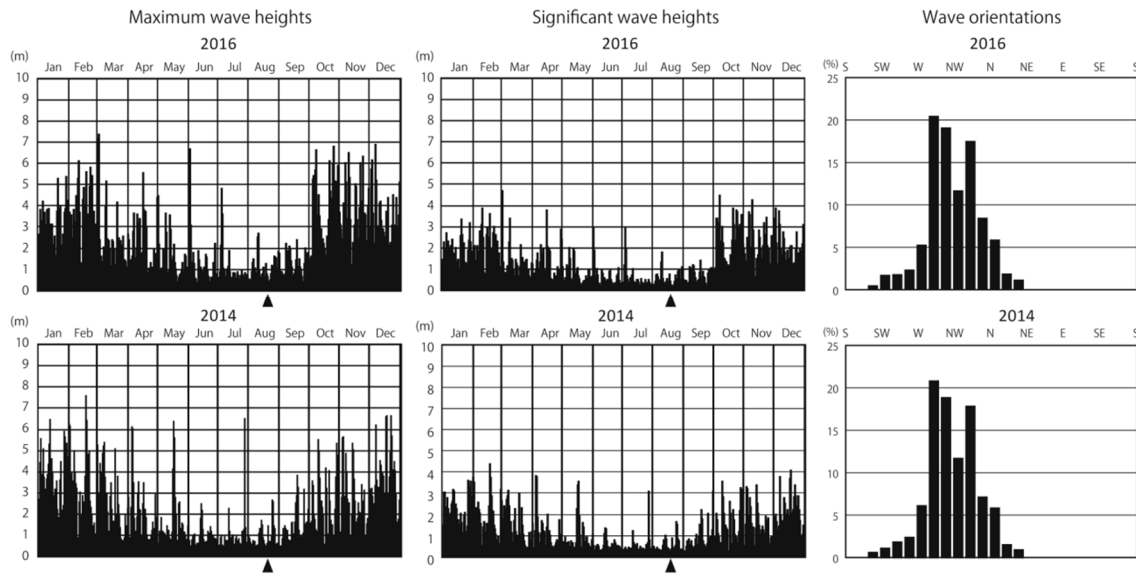
689



691

692 Fig. 1 Geographical map of the Ishikari Delta and the distribution of seafloor sediments in
 693 Ishikari Bay. Radar charts show wind speed and direction of daily maximum wind from 1990
 694 to 2017 in Ishikari Meteorological Observatory (Japan Meteorological Agency). The delta
 695 plain consists mainly of beach ridge sands. The present Ishikari River mouth is located
 696 near the northeastern margin of the coastline, showing a highly deflected planform. The
 697 left bank of the lower reaches of the Ishikari River is barriered by a river mouth spit. The
 698 digital elevation model is provided by the Geospatial Information Authority of Japan. The
 699 bathymetric contour lines are based on the “Digital Topography of Ocean Floor M7000
 700 Series” published by the Japan Hydraulic Association.

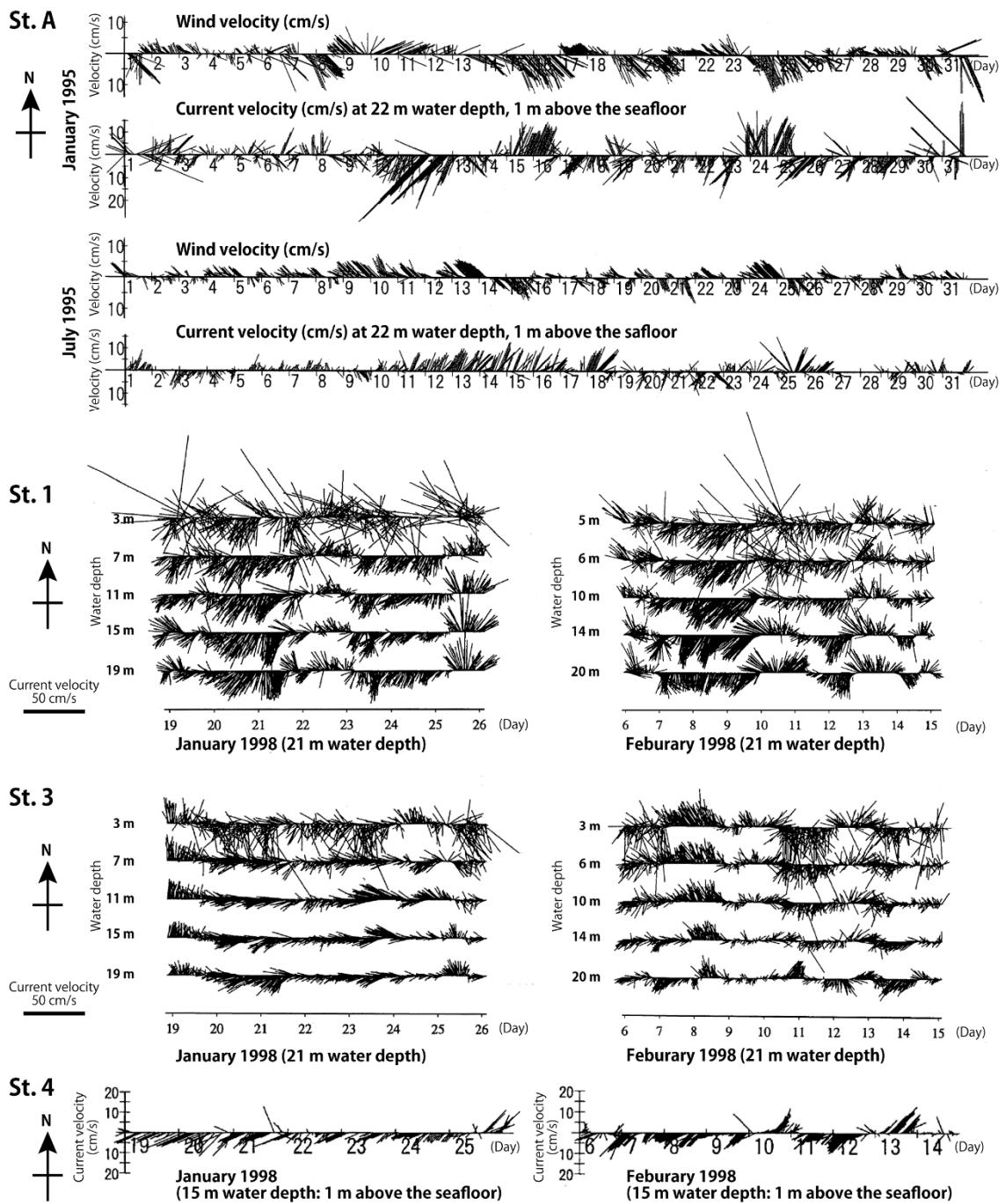
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703 Fig. 2 Maximum and significant wave heights and wave orientations (up-current) in the Ishikari
 704 coast during the survey years 2014 and 2016. The data are based on the 2 hours interval
 705 observation data of Nationwide Ocean Wave Information Network for Ports and Harbours
 706 (NOWPHAS) system provided by the Ministry of Land, Infrastructure, Transport and Tourism
 707 in Japan (data are available online at https://www.mlit.go.jp/kowan/nowphas/index_eng.html).

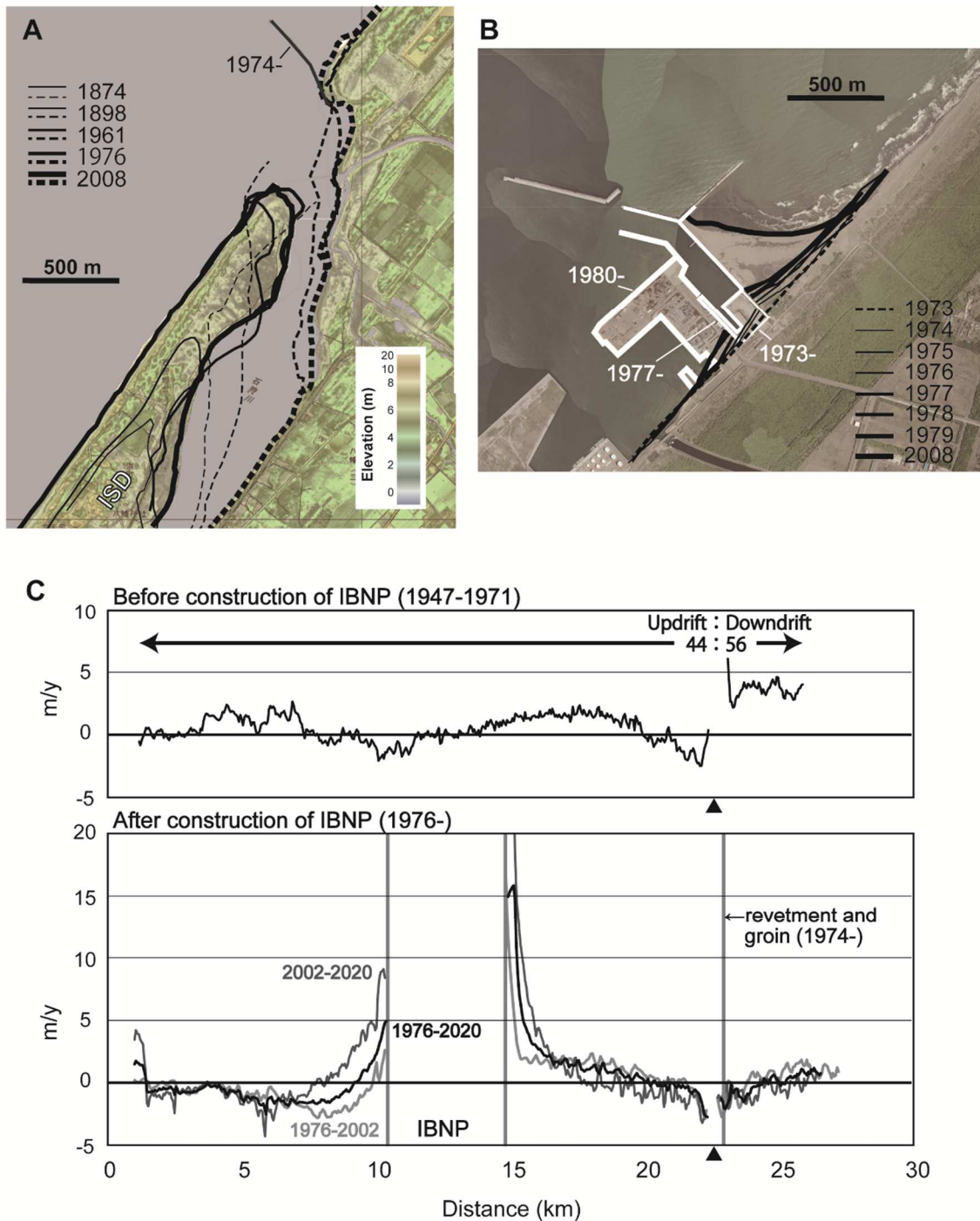
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709

710 Fig. 3 Directions and velocities of wind-driven currents in the Ishikari Bay measured using
 711 acoustic Doppler current profiler (after Yamashita et al., 1998; 1999). The wind condition
 712 at St.A is also shown. The current velocities at St. A were measured at 40 seconds interval,
 713 at St. 1 and St. 3 were at 10 minutes interval, and at the St. 4 were at 0.5 second interval
 714 for 20 minutes of every hour. These figures are reprinted with permission from the Japan
 715 Society of Civil Engineers. See Figure 1 for observation locations.

716



717

718 Fig. 4 (A) Growth history of the river mouth spit based on the aerial photos (modified from

719 Yamazaki and Yamashita, 2004). (B) Prograding coastline at the artificial groin (IBNP)

720 (modified from Arai, 1981). (C) Chronological transition of the entire Ishikari sandy

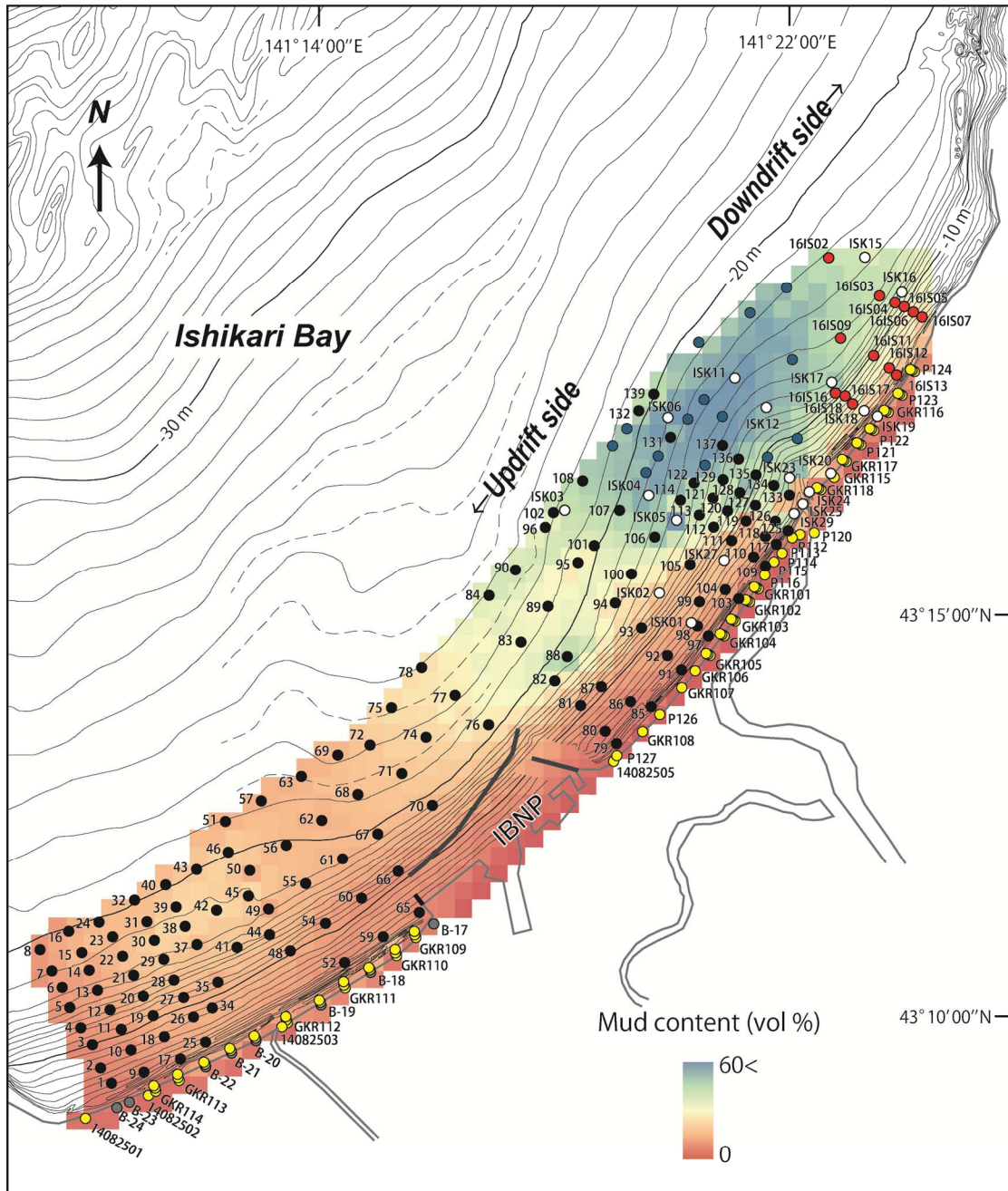
721 coastline before and after the construction of IBNP, showing the distributed ratio of

722 accreted sediments during 1947–1971. The black triangle shows the location of the Ishikari

723 river mouth. The aerial photo and the digital elevation model are provided by the

724 Geospatial Information Authority of Japan.

725



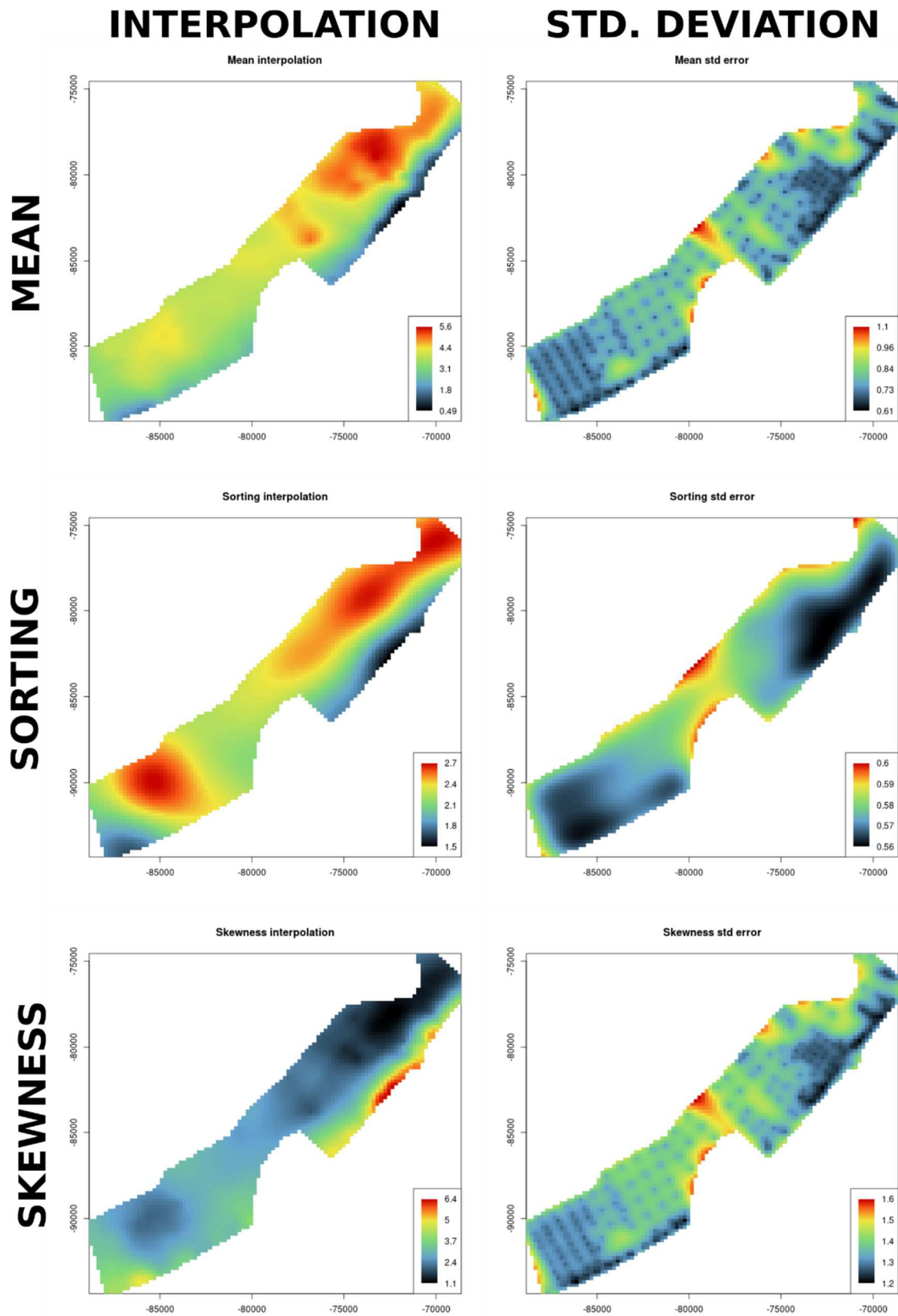
- Sampling sites of modern seafloor sand in 1996–1997 (Suga & Hamada, 2001)
- Sampling sites of modern foreshore sand in 1996–1997 (Suga & Hamada, 2001)
- Sampling sites of modern seafloor sand in 2004 (Geological Survey of Hokkaido, 2004)
- Sampling sites of modern foreshore and uppermost shoreface sand in 2014 & 2016
- Sampling sites of modern seafloor sand in 2016

- *Sampling sites of modern seafloor mud in 1996-1997 (Suga & Hamada, 2001), 2004 (Geological Survey of Hokkaido, 2004), & 2016 *excluded from GSTA

726

727 Fig. 5 Location and survey year of the collected samples in Ishikari coast. Suffix beside the
 728 circles shows sample code in the source. The colour gradients show the spatial variation of
 729 the mud content in the seafloor sandy sediments, as estimated by Kriging interpolation
 730 (400-m grid).

731

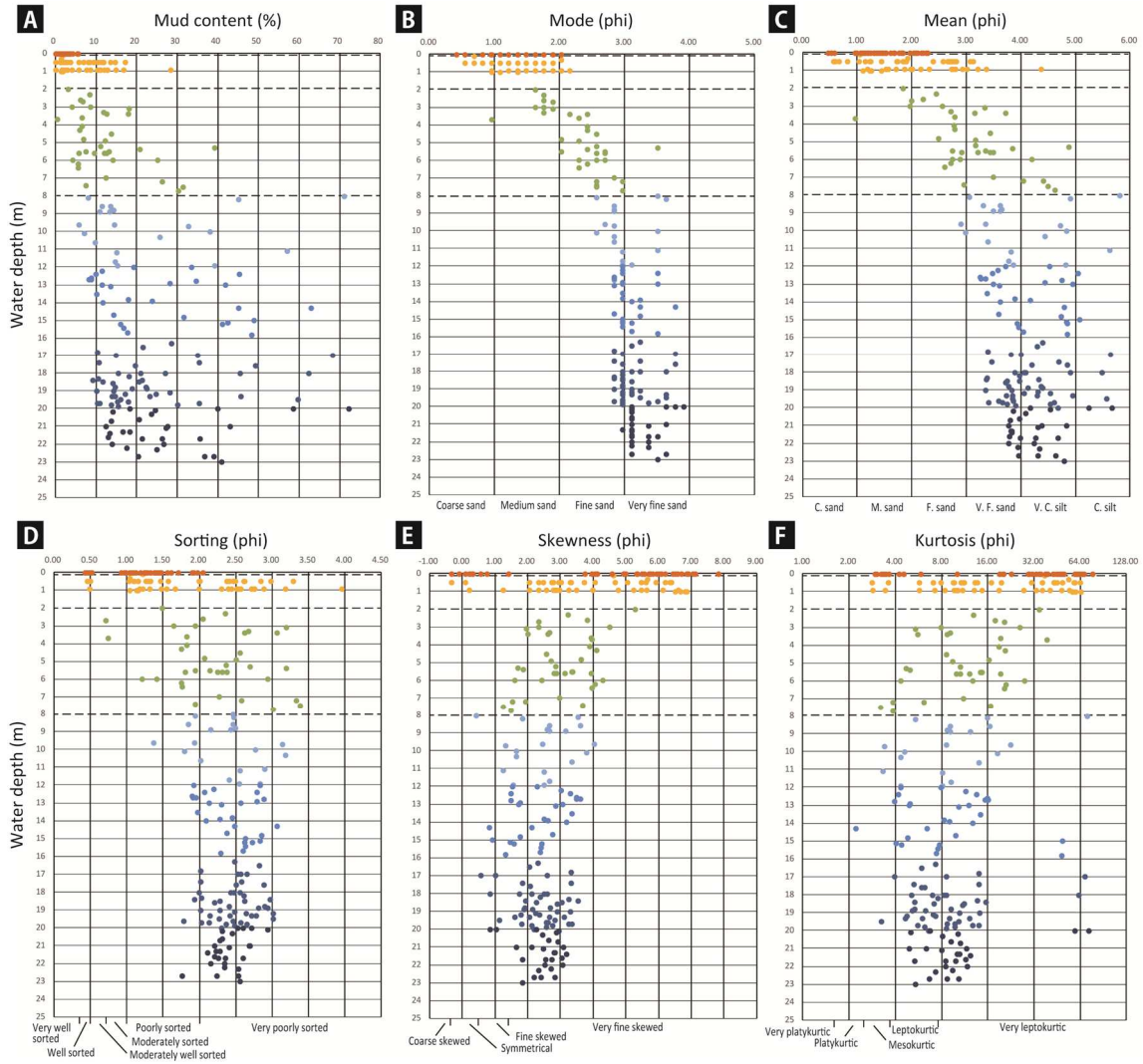


732

Fig. 6 Interpolations of the three statistical parameters (left column) and the variance of the interpolation error (right column), of respectively mean, sorting and skewness.

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736 Fig. 7 Grain-size composition of seafloor sediments analysed via logarithmic method of

737 moments: values of mud content (A), and statistical grain-size parameters (mode (B);

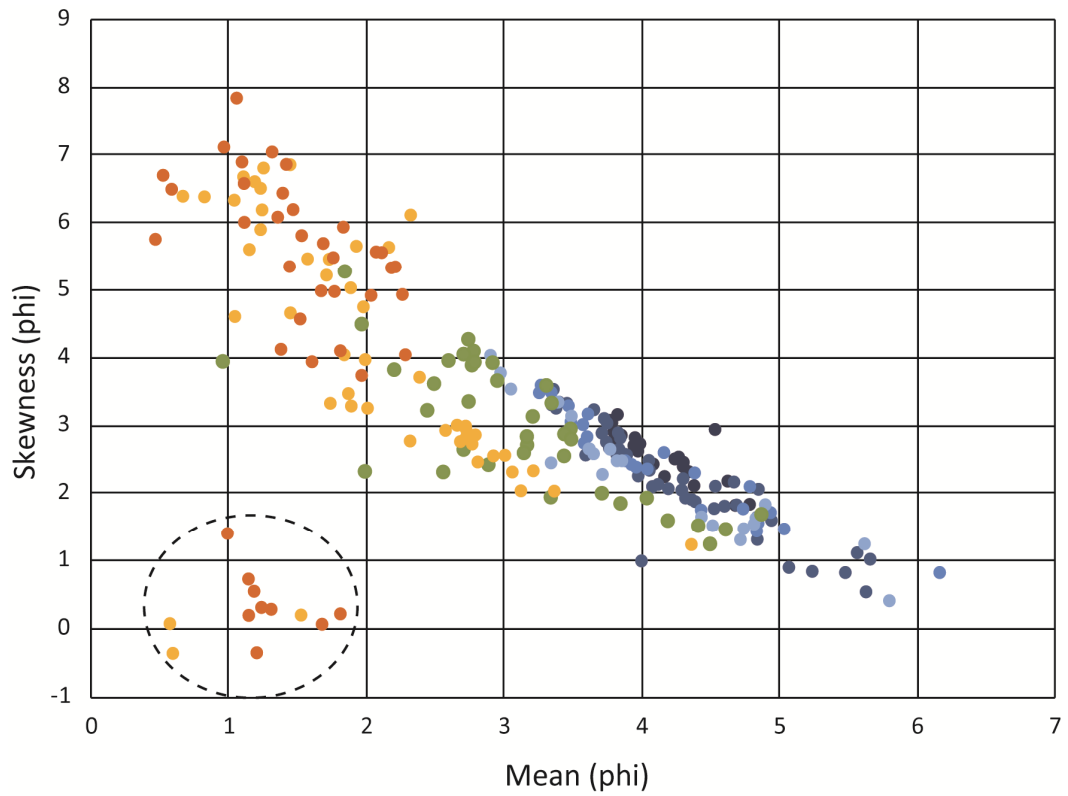
738 mean (C); sorting (D); skewness (E); and kurtosis (F)) versus water depth. The key to

739 colour is same as the Fig. 8.

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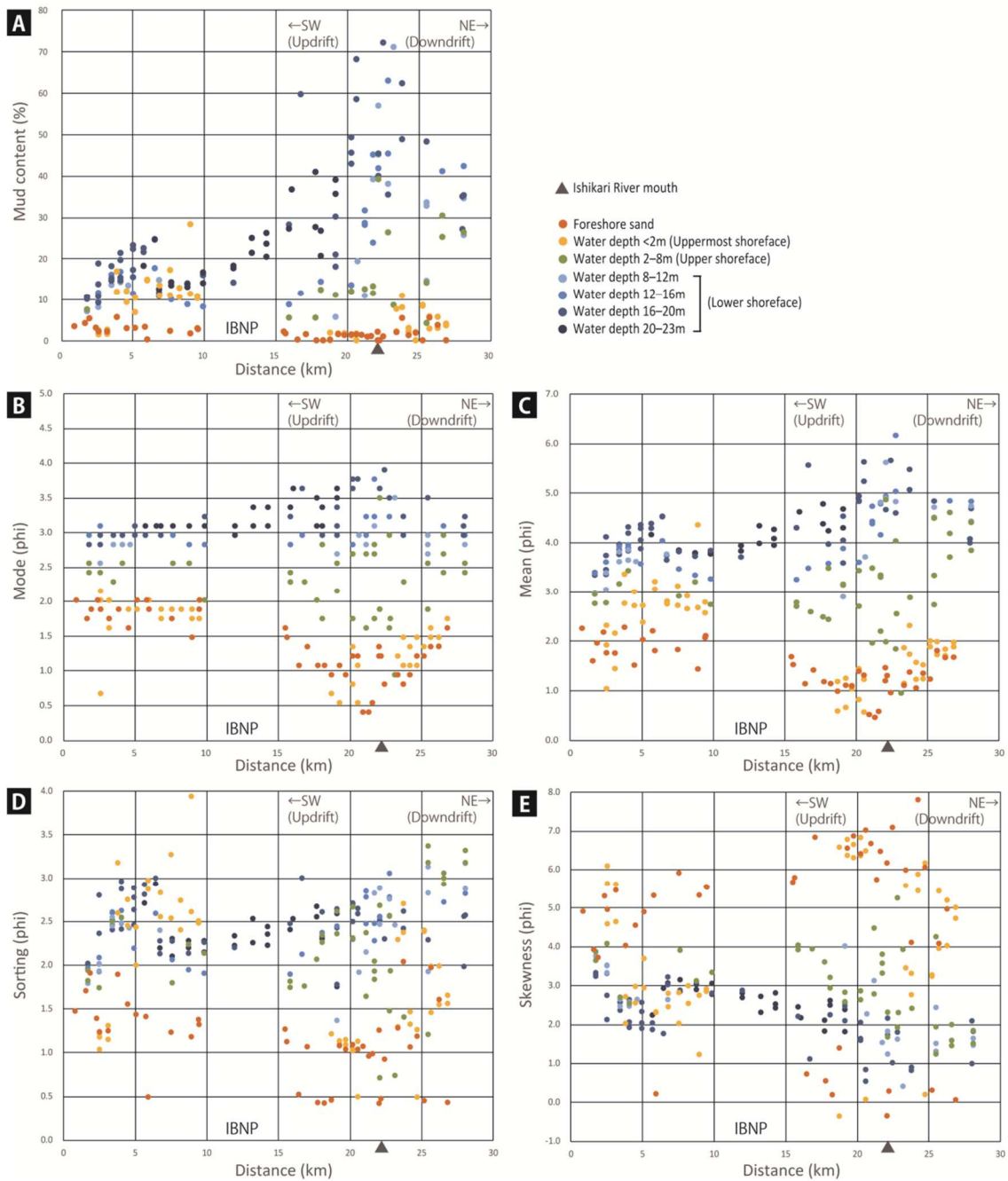
744 Fig. 8 Relationships between the value of mean and skewness of analysed sea floor sediments.

745 The key to colour is same as the Figure 8. The samples circled by dotted line were not

746 used for the interpolation and the GSTA analysis.

747

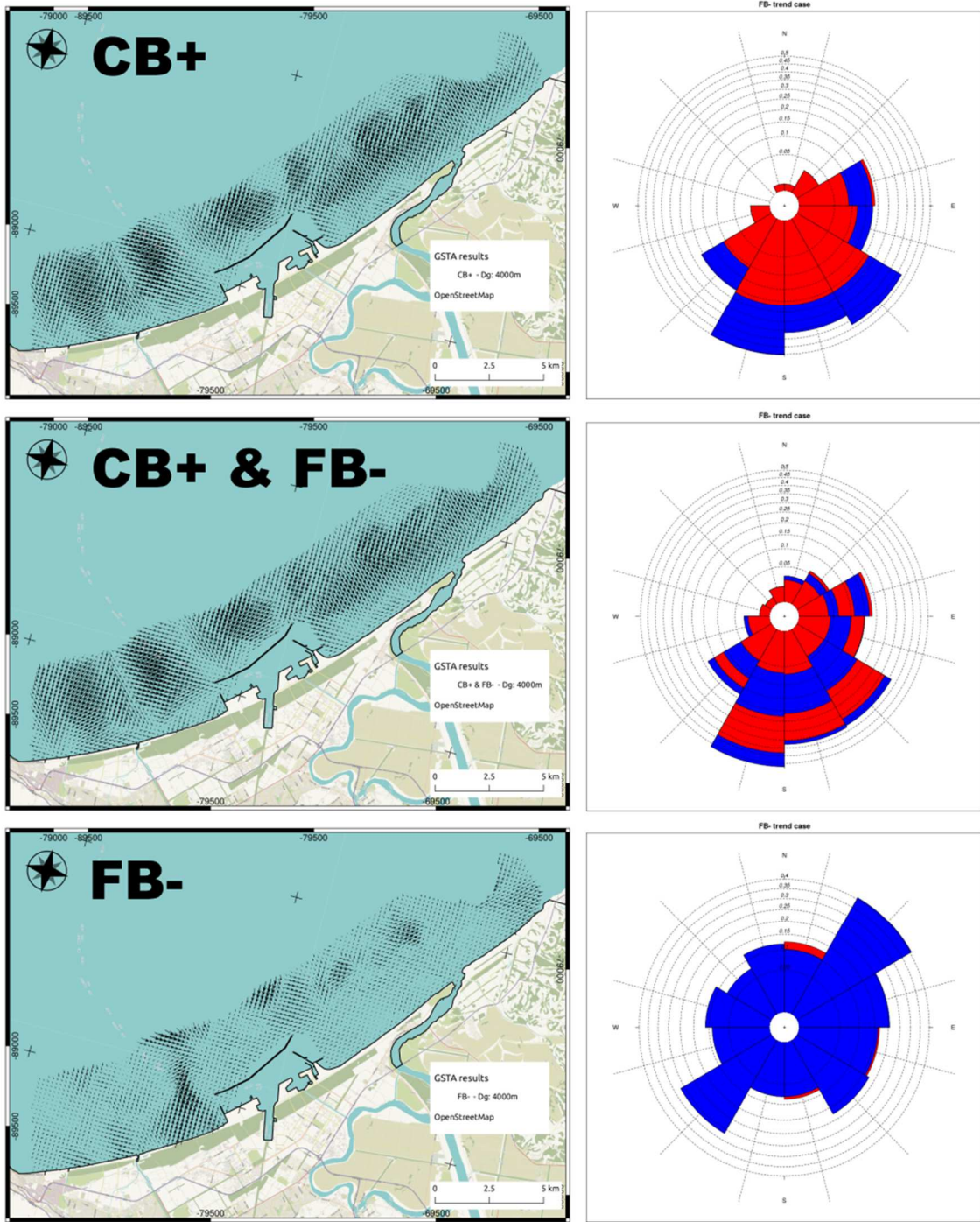
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749

750 Fig. 9 Alongshore spatial variation of mud content (A) and statistical grain-size parameters
 751 (mode (B); mean (C); sorting (D); and skewness (E)) of seafloor sediments. The distance
 752 is from the western end of the sandy coast (mouth of the Zenibako-gawa River, see Fig. 1
 753 for location).

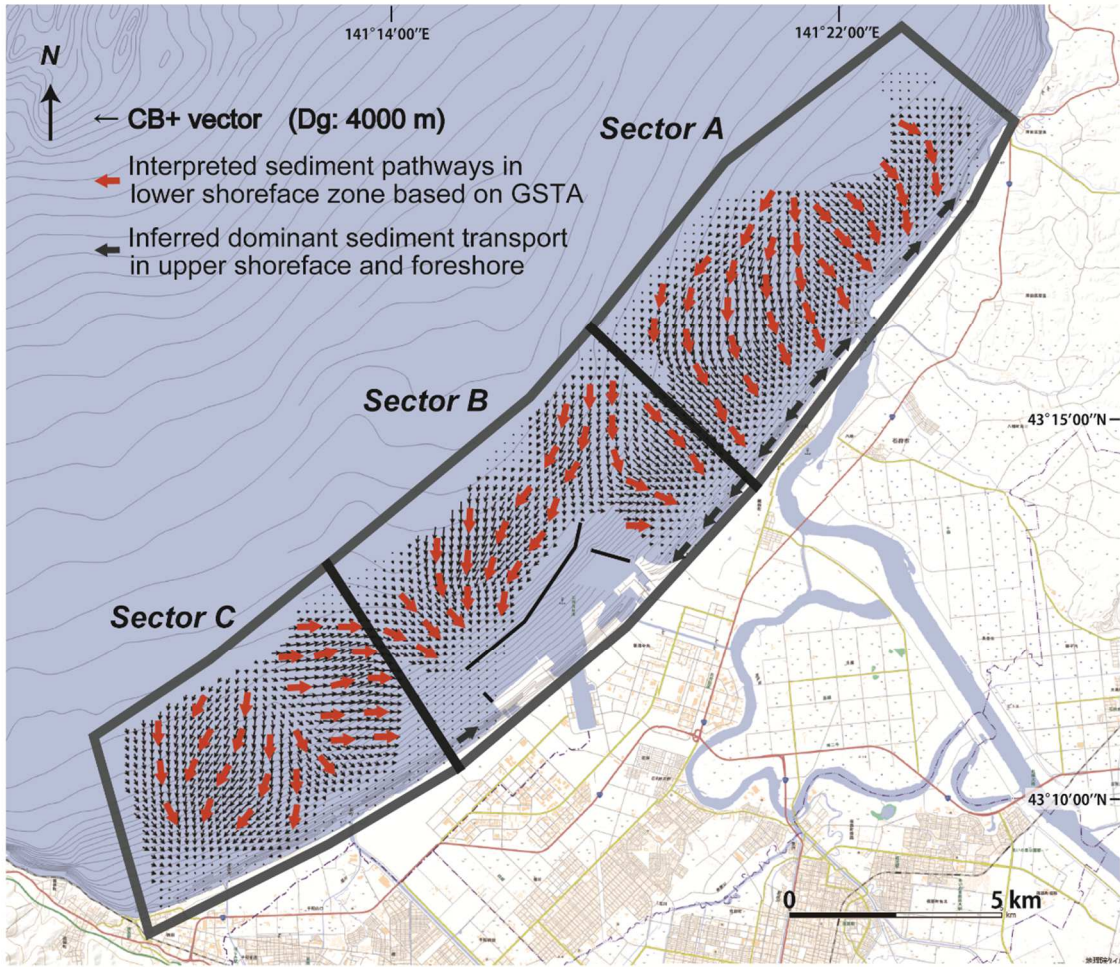
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755

756 Fig. 10 Results of GSTA using GiSedTrend. Vector fields (left column) and windrose diagrams
 757 (right column), for respectively CB+, CB+ & FB- and FB- trend cases.

758



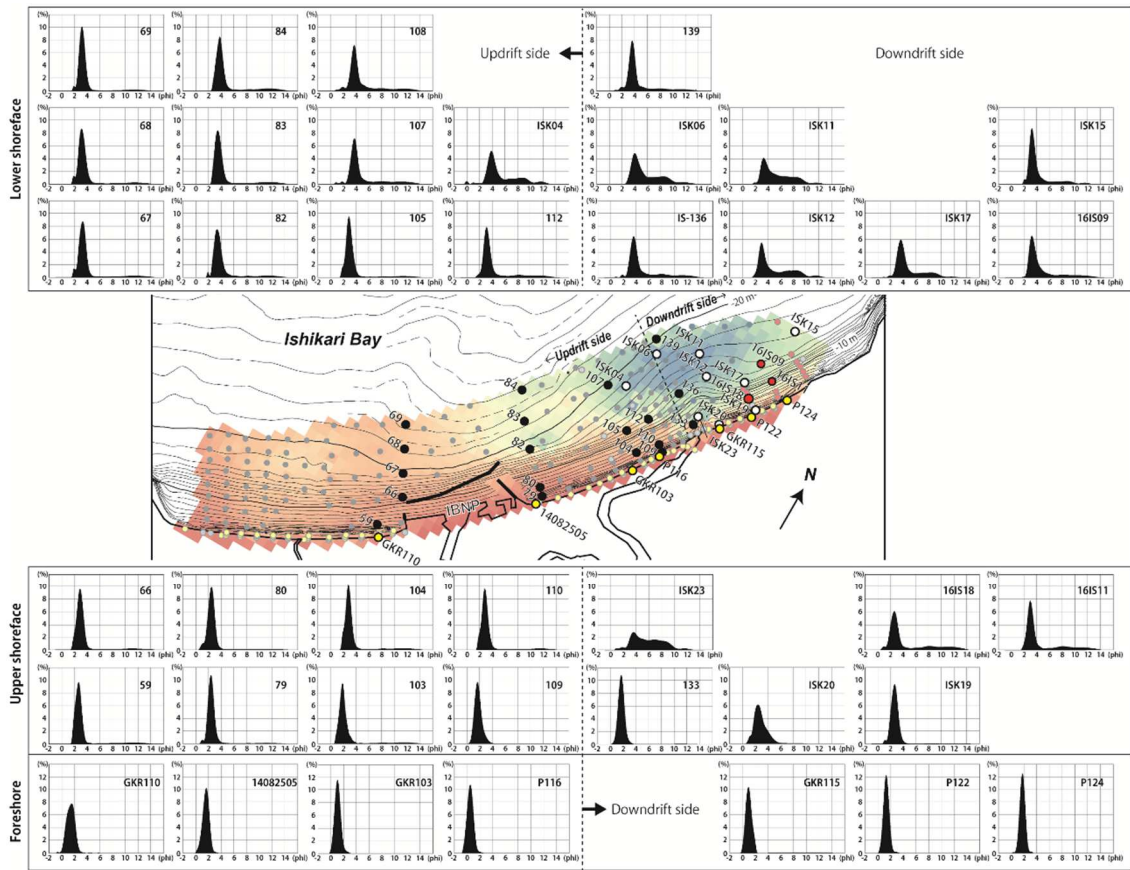
759

760 Fig. 11 Three different areas recognized on the CB+ trend case vector field, respectively A, B
 761 and C. Red arrows correspond to main transport directions.

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765

766 Fig. 12 Representative histograms of analysed sediment samples on a logarithmic scale (ϕ).

767 The enlarged circles on the inset map show the sampling sites. The dashed line at the

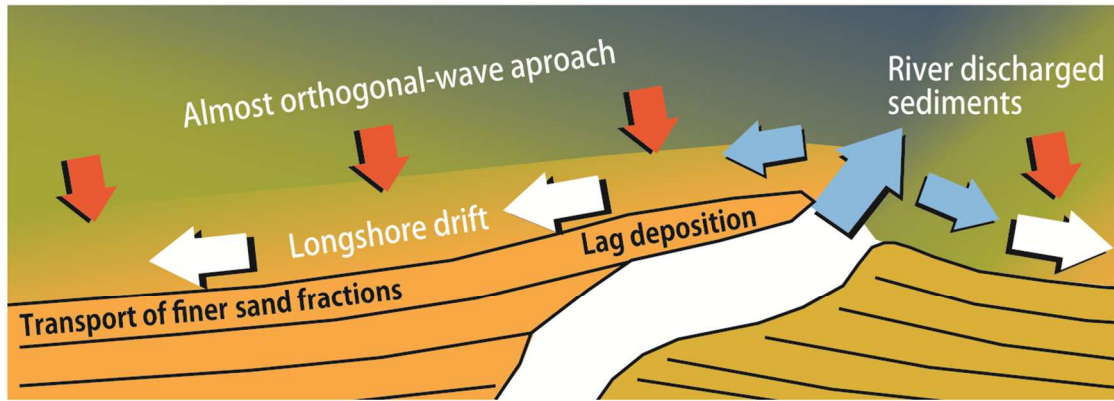
768 centre of the river mouth extending seaward represents approximate boundary line

769 between the updrift and downdrift sides. The colour gradient represents the spatial

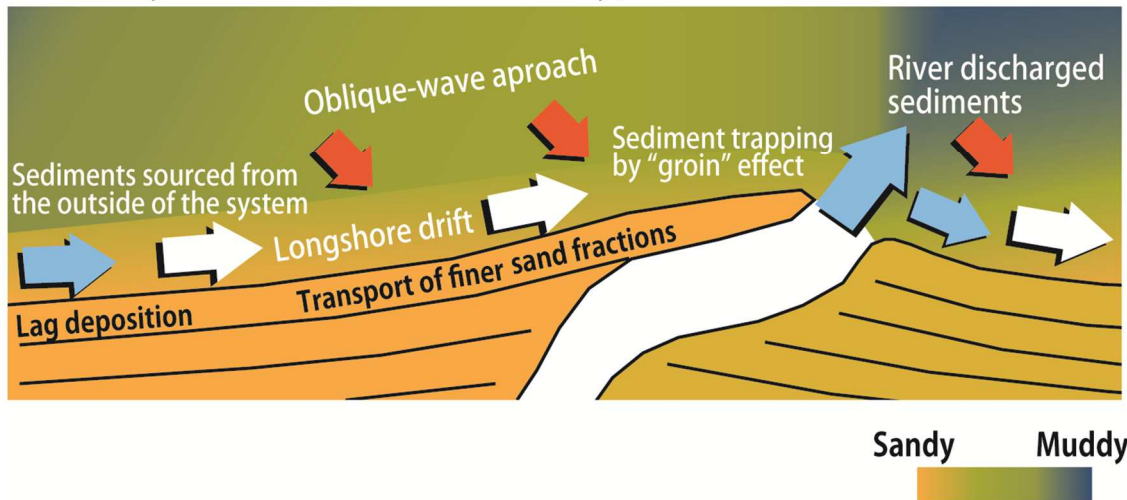
770 distribution of the mud content.

771

Internally sourced deflected deltas



Externally sourced deflected deltas (typical model)



772

773 Fig. 13 Comparison of sediment dynamics of internally sourced and externally sourced
774 deflected delta systems. Externally sourced deflected deltas (lower) grow under
775 net-downdriftward sediment transport, whereas the growth of internally sourced
776 deflected deltas (upper) depends on dominant updriftward sediment transport on
777 the updrift-side.

778

779