1 Rapid sedimentation of iron oxyhydroxides in an active hydrothermal shallow
2 semi-enclosed bay at Satsuma Iwo-Jima Island, Kagoshima, Japan

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8

9 **Abstract**

10

11 Hydrothermal activity is common in the fishing port of Nagahama Bay, a small
12 semi-enclosed bay located on the southwest coast of Satsuma Iwo-Jima Island (38
13 km south of Kyushu Island, Japan). The bay contains red-brown iron
14 oxyhydroxides and thick deposits of sediment. In this work, the high concentration
15 and sedimentation rate of oxyhydroxide in this bay was studied and the sedimentary
16 history was reconstructed. Since dredging work in 1998, a thickness of ~1.0–1.5 m
17 of iron oxyhydroxide-rich sediments has accumulated on the floor of the bay. To
18 estimate the volume of iron oxyhydroxide sediments and the amount discharged

19 from hydrothermal vents, sediment traps were operated for several years and 13
20 sedimentary core samples were collected to reconstruct the 10-year sedimentary
21 history of Nagahama Bay. To confirm the timing of sedimentary events, the core
22 data were compared with meteorological records obtained on the island, and the
23 ages of characteristic key beds were thus identified. The sedimentation rate of iron
24 oxyhydroxide mud was calculated, after correcting for sediment input from other
25 sources.

26 The sediments in the 13 cores from Nagahama Bay consist mainly of iron
27 oxyhydroxide mud, three thick tephra beds, and a topmost thick sandy mud bed.
28 Heavy rainfall events in 2000, 2001, 2002, and 2004–2005 coincide with tephra
29 beds, which were reworked from Iwo-Dake ash deposits to form tephra-rich
30 sediment. Strong typhoon events with gigantic waves transported outer-ocean-floor
31 sediments and supplied quartz, cristobalite, tridymite, and albite sands to Nagahama
32 Bay. These materials were redeposited together with bay sediments as the sandy
33 mud bed.

34 Based on the results from the sediment traps and cores, it is estimated that the
35 iron oxyhydroxide mud accumulated in the bay at the relatively rapid rate of 33.3
36 cm/year (from traps) and 2.8–4.9 cm/year (from cores). The pore water contents

37 within the sediment trap and core sediments are 73%–82% and 47%–67%,
38 respectively. The estimated production of iron oxyhydroxide for the whole fishing
39 port from trap cores is 142.7–253.3 ton/year/5000 m². From sediment cores,
40 however, the accumulation of iron oxyhydroxide sediments on the sea floor is
41 39–95 ton/year/5000 m². This finding indicates that the remaining 63%–73% of
42 iron was transported out to sea from Nagahama Bay. Even with a high rate of iron
43 oxyhydroxide production, the sedimentation rate of iron oxyhydroxides in the bay
44 is considerably higher than that observed in modern deep-ocean sediments. This
45 example of rapid and abundant oxyhydroxide sedimentation might provide a
46 modern analog for the formation of iron deposits in the geological record, such as
47 ironstones and banded iron formations.

48

49 **Keywords**

50

51 Satsuma Iwo-Jima Island; iron oxyhydroxides; hydrothermal system;
52 accumulation rate; meteorological event

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54

1. Introduction

In the modern ocean, iron hydroxide sedimentation is observed in deep water (Honeyman and Santschi, 1989; Wo et al., 2004; Hawkes et al., 2013). Most oceanic areas have very low iron levels in seawater, and no thick accumulations of iron sediments form on the sea floor. Even for iron-rich sediments near hydrothermal vent systems, the sediments are less than a few centimeters in thickness or are formed of iron-oxide bacterial mats (e.g., Pichler and Veizer, 1999). Although deep-sea soluble–colloidal Fe concentrations have been identified at some ocean depths (Wu et al., 2001), the amount deposited in the modern ocean is small and slow speed. Deep-ocean hydrothermal environments, however, preserve iron oxyhydroxide sediments, as do sites such as the Loihi seamount and Santorini Island (e.g., Holm, 1987; Emanson and Moyer, 2010). The iron deposits reported in these areas are mainly precipitated by iron bacteria. Deep-sea hydrothermal areas may have a low organic content relative to other oxygenated sea floor sediments. There are two reasons for iron precipitation near vent systems in the deep sea: high levels of iron productivity and low amounts of organic matter, which consumes oxygen when oxygenic matter decay. Conversely, thick iron deposits do not form in

73 shallow water in the modern ocean because the iron oxyhydroxide is in the form of
74 colloids (submicron-size particles: 0.5 nm to 0.5 μm), which float and diffuse in the
75 open ocean (e.g., Pichler and Veizer, 1999; Tarasov et al., 2005). At Nagahama Bay,
76 on the island of Satsuma Iwo-Jima, Japan, rapid precipitation of oxyhydroxide with
77 oxygenated seawater circulation results in the preservation of oxygenic iron
78 oxyhydroxide deposits. This site is suitable for studies of the deposition of iron
79 oxyhydroxide mud.

80 Understanding modern iron sedimentation is also important for studies of
81 ancient iron-rich sediments. Most ancient iron formations are considered to have
82 been deposited in relatively shallow seas, and the iron is thought to have been
83 derived from hydrothermal activity and fixed at the ocean floor by biogenic activity
84 (e.g., Emerson and Moyer, 2011). Banded iron formations (BIF), such as Archean
85 and early Proterozoic examples, can be classified as hydrothermal-related (Algoma
86 type) and those with a continental shelf origin (Superior type). BIF formed as a
87 result of the chemical precipitation of iron from hydrothermal fluids (e.g., Trendall,
88 2001), iron absorption of ultraviolet radiation under abiogenic conditions
89 (Cairns-Smith, 1978), and anoxygenic phototrophy (Konhouser et al., 2007). Iron
90 oxyhydroxide may form from the oxidation of Fe(II) to Fe(III): solid Fe(III) oxide

91 kinetics are controlled by pH, temperature, and salinity (Millero et al., 1987).
92 However, the details of iron sedimentation (precipitation) processes and
93 mechanisms, especially under natural oceanic conditions, are still unclear (Cornelis,
94 2005; Konhouser et al., 2007). Also, it is still unknown how iron deposits are
95 precipitated. To understand the mechanism of iron sedimentation, observations
96 under natural ocean conditions (rather than laboratory conditions) are required to
97 identify the origin of iron material.

98 In this study, modern thick ferruginous sediment in a shallow oceanic setting at
99 Nagahama Bay, Japan, was investigated. The bay is protected by a breakwater and
100 is thus semi-enclosed, and it is influenced by hydrothermal hot springs. The
101 following three topics are addressed in this study: 1) identification of iron-rich
102 sediments below the reddish-brown colored ocean; 2) reconstruction of the
103 sedimentation history using weather records, which are readily correlated with the
104 sedimentary record in core samples; and 3) estimation of the rate and amount of
105 oxyhydroxide sedimentation in the bay area.

106 The sea floor in the fishing port (an area of about 5000 m²) in Nagahama Bay
107 has a high temperature (50–60°C) with several active hot springs with discharge
108 pipes (small chimneys and mounds) and thick deposits of iron oxyhydroxide

109 sediment. The hot springs at the coast in this bay have a pH of 5.3–5.5 and a
110 temperature of 36–60°C (Shikaura and Tazaki, 2001; Kiyokawa et al., 2012). Thus,
111 iron oxyhydroxides readily precipitate from the waters of the hot springs and are
112 preserved on the floor of the bay. This type of thick iron oxyhydroxide deposit is
113 very rare under modern ocean conditions. Because of this situation, Nagahama Bay
114 is especially well suited for observations of active iron oxyhydroxide sedimentation
115 in iron-rich, very shallow oceanic conditions. However, half of Nagahama Bay is
116 open ocean and is affected by natural weather, volcanic activity, and human
117 activities.

118 There are several advantages to conducting research at Nagahama Bay. First,
119 these thick iron-rich sedimentary deposits that formed under oceanic conditions in
120 close proximity to hydrothermal hot springs are rare. Second, the location and water
121 depth enable research that is difficult to perform under deep and abyssal ocean
122 conditions. Third, because of the shallow-water setting, samples and observations
123 can be obtained by scuba diving. The low cost of research in Nagahama Bay
124 compared with that in the deep abyssal ocean is a further advantage of carrying out
125 research in this bay.

126 Information on rapidly deposited iron sedimentary layers was obtained using

127 evidence from cores and sediment traps, and several episodes of iron deposition
128 were identified. The sedimentary history is reconstructed using 10-year sediment
129 core records correlated with weather records.

130 To investigate the sedimentary mechanisms of iron oxyhydroxide material,
131 studies were conducted on: (1) the stratigraphy of bay sediments, which involved
132 the collection of 13 sediment cores from the fishing port and the construction of
133 sedimentary cross-sections and details of the stratigraphic sequence; (2)
134 observations and chemical analyses of the sediments by smear slide images under a
135 polarizing microscope (Nikon, ECLIPSE LV100POL), X-ray fluorescence (XRF),
136 X-ray diffractometry (XRD), scanning electron microscopy (SEM), and energy
137 dispersive X-ray spectrometry (EDS); (3) comparisons of sediment core records
138 with meteorological observations, using available analog meteorological records
139 from the island; and (4) sediment trap studies, which measured recent
140 sedimentation rates using simplified sediment traps deployed on the floor of the bay.
141 These investigations allowed the reconstruction of the sedimentation history of
142 Nagahama Bay.

143 Finally, the volume of iron oxyhydroxide produced from hydrothermal vents in
144 the fishing port, which has an area of 5000 m², and the relative amount of this

145 material preserved in bay sediments versus that lost to the open ocean is estimated.
146 Thus, an example of very rapid sedimentation of oxyhydroxide hydrothermal
147 deposits in the modern ocean is described.

148

149 **2. Geologic setting**

150

151 Nagahama Bay, Satsuma Iwo-Jima Island, 38 km from Kagoshima Prefecture
152 (Fig. 1a), shows well-preserved iron material sedimentary stratification at
153 hydrothermal hot springs along the coast. Satsuma Iwo-Jima Island is in the
154 northern part of the Kikai caldera, which formed ca. 7300 years ago, as
155 demonstrated by studies of a corresponding distal tephra (the Kikai-Akahoya
156 tephra; Machida and Arai, 1978; Okuno, 2002; Maeno and Taniguchi, 2007). The
157 Kikai caldera rim extends southwest–northeast to the edge of the island (Matumoto,
158 1943). Active volcanism on Satsuma Iwo-Jima Island includes rhyolitic activity at
159 Iwo-Dake volcano and basaltic activity at Imamura Dake volcano (Ono et al., 1982).
160 Iwo-Dake volcano has been active since the 1990s, and small amounts of ash
161 periodically fell in the Nagahama Bay area between September 1997 and October
162 2004 (Shinohara et al., 2002; Japan Meteorological Agency, 2011b, c). In particular,

163 during an event in July 1998, small amounts of ash reached as far as Take-Shima
164 Island, which is 10 km from Satsuma Iwo-Jima Island (Shinohara et al., 2002).
165 From 2006 to 2013, the activity of Iwo-Dake weakened, and only volcanic fumes,
166 vapor, and minor ash were produced, with accumulation restricted to the summit
167 area of the volcano. However, direct volcanic ash falls during the active period may
168 not have been preserved in ocean sediment cores obtained some distance from the
169 volcano.

170 Satsuma Iwo-Jima Island contains several hot springs along the coastline.
171 Nagahama Bay, on the southwest coast of the island, is one of the most active
172 regions of hot spring discharge, among confined embayments near a small village
173 (Fig. 1). The bay water is a deep reddish-brown color and precipitation of iron
174 oxyhydroxide occurs in the bay as a result of the changes in pH when acidic hot
175 spring water is mixed with seawater (Nogami et al., 1993). Development of the
176 fishing port and breakwaters at Nagahama Bay has produced an increasingly
177 semi-enclosed environment (Fig. 1b).

178 Artificial structures have been constructed to protect the fishing port in the bay
179 from the effects of outer-ocean currents (Maeno et al., 2012). The fishing port is
180 mostly situated on the landward side of the embayment and contains a thick

181 sedimentary record on the floor of the bay. Sikaura and Tazaki (2001) reported that
182 bio-terraces were growing around the shallow beach at the fishing port in 1999. The
183 fishing port is divided into two parts, the E-site and the W-site, by a T-shaped
184 breakwater (Fig. 1b). The W-site was dredged in the spring of 1998, and most of the
185 previously accumulated sediments were removed to the level of bedrock
186 (Kagoshima Prefecture, 2012). Since then, the sedimentary conditions in Nagahama
187 Bay have been changed by the construction of artificial structures.

188 Several recent studies in Nagahama Bay have focused on the behavior of iron
189 oxyhydroxide material under oceanic conditions in the bay (Ninomiya and
190 Kiyokawa, 2009; Kiyokawa et al., 2012; Ueshiba and Kiyokawa, 2012; Minowa et
191 al., 2013, 2014). Ninomiya and Kiyokawa (2009) and Kiyokawa et al. (2012)
192 reported observations of water conditions along a transect at the E-site over a
193 two-week period (low tide to high tide). These studies were based on long-term
194 (two weeks) observations of ductility, pH, and temperature through a transect in
195 Nagahama Bay and surface monitoring by camera. This work demonstrated how
196 oxyhydroxide-rich red water moved during the two weeks of monitoring. The
197 results of this work showed that tidal conditions are important in terms of
198 sedimentation, that heavy rain produces iron-rich material from iron-rich beach

199 sand pores, and that typhoons are important in terms of mixing the sea floor
200 sediment.

201 Ueshiba and Kiyokawa (2012) also studied the influence of wind direction on
202 the movement of surface water using surface-monitoring cameras. Southerly winds
203 were important for the movement of iron oxyhydroxide to the outer ocean along the
204 ocean surface. The results of bathymetric and sediment thickness mapping showed
205 that the sediments at the W-site in the bay are more than 1 m thick. Minowa et al.
206 (2013, 2014) obtained more detailed lateral observations (at 10-cm intervals) of
207 turbidity, pH, and temperature with wind data over two weeks at Nagahama Bay.
208 These studies show that wind direction is an important influence on the bottom
209 water and the output of red-colored water to the outer ocean.

210 Three breakwaters (Fig. 1) have been constructed in Nagahama Bay since 1998
211 (Kagoshima Prefecture, 2012). The breakwaters are important because they protect
212 against the removal of iron oxyhydroxide material to the outer ocean. The timing of
213 the construction is well preserved in the core record. Breakwater 1 (constructed
214 from 20 October 2004 to 17 March 2005) was built in 3-m-deep water on the beach
215 side of the W-site, thus protecting the W-site from direct river flow. Breakwater 2
216 (constructed from early August 2000 to 25 March 2001) was built in ~5-m-deep

217 water, and extends from the T-shaped port entrance of the W-site; this breakwater
218 protects the W-site from direct outer-ocean waves. Breakwater 3 (constructed from
219 2000 to 15 March 2007, with the main portion built during 13–23 December 2006)
220 is at the entrance of Nagahama Bay; it is a large-scale breakwater ~80 m wide and
221 20 m deep, formed from more than 3000 tons of material. Breakwater 3 has isolated
222 Nagahama Bay from the outer ocean since the end of 2006. Since then, strong wave
223 activity has not directly affected Nagahama Bay.

224

225 **3. Sediment stratigraphy**

226 **3.1 Method**

227 At the fishing port, a thin ferruginous mud (<30 cm thick) and a medium to
228 coarse sand were observed in the sequence at the E-site. At the W-site, ferruginous
229 sediments are more than 1 m thick. The W-site was examined to understand the
230 origins of the relatively thick sediment accumulation. Thirteen core samples were
231 obtained (using clear acrylic coring tubes of 10 cm in diameter and 1–1.2 m in
232 length) to map the distribution of the sediments at the W-site. Core sampling was
233 carried out by scuba divers (Fig. 2). After the collection of six cores in April 2009,
234 the W-site was dredged in June 2009 (Kagoshima Prefecture, 2012). However, a

235 10-m-wide area on the interior side of the port was not dredged, in accordance with
236 a scientific protection measure initiated by Mishima village. In 2010 and 2011,
237 sampling was conducted in this protected area.

238 The scuba diving observations and coring show that the bay floor is covered by
239 a highly hydroscopic and unconsolidated gel layer of 20–30 cm thick, which
240 resembles the matter in the sediment cores, as described below. The surface of this
241 layer contains wave ripples and forms a clear boundary between the ocean and the
242 sediments. This bed was not removed by normal wave activity or by engine waves
243 from small boats. In this study, however, the focus is on long-term records to
244 elucidate the history of the bay, and so attempts were made to obtain a more
245 consolidated portion of these sediments. The lowest hard-packed beach sand bed
246 was defined as a basement layer and tephra beds as key beds.

247 The following studies were carried out after collection of the cores. (a)
248 Computed tomography (CT) images were obtained for each core (PRATICO,
249 Hitachi Medical Corporation, Tokyo, Japan) at the Center for Advanced Marine
250 Core Research, Kochi University, Japan. Bright portions in the images represent
251 high-density regions, and dark portions represent low-density regions (Fig. 2). (b)
252 The sliced surfaces of longitudinally cut cores were described, including detailed

253 descriptions of lithology with cross-checks carried out using polarizing microscope
254 (Nikon, ECLIPSE LV100POL) analyses of smear slide images. When the samples
255 were collected at the fishing port, the core sediments were always a reddish-brown
256 color. The cores were stored for more than 1 to 2 months at 6°C in a refrigerator at
257 the Kochi Core Center. During this time, the color of several beds altered to black,
258 showing clear bedding boundaries. However, less than 5 hours after cutting the core,
259 the black-colored bed changed to reddish brown. The black color may have formed
260 under reducing conditions during core storage in the laboratory refrigerator.

261

262 **3.2 Core lithology**

263 The cores contained the following three sedimentary components: iron
264 oxyhydroxide mud, tephra, and sandy mud (Fig. 3). In this section, the lithology of
265 these sediments is described and the stratigraphy in the bay is described.

266 The iron oxyhydroxide mud at the W-site is soft, reddish-brown, unconsolidated,
267 and formed of very fine (1 μm to 100 nm colloid size) particles (Figs 4, 6). The
268 upper 20–30 cm of sediment is composed of a hygroscopic and unconsolidated gel.
269 The surface of the unconsolidated portion preserved ripple structures form by tidal
270 currents and waves. Based on this observation, these beds were not mixed by strong

271 waves generated by passing fishing boats. There are several thick iron
272 oxyhydroxide mud layers within the cores. Microscopic observations show these
273 layers to be reddish-brown in color, consisting of material with a grain size of <1
274 μm (Fig. 4a). Most of these mud layers contain 10- μm -sized volcanic glass
275 particles (Fig. 4a–c).

276 Tephra beds are consolidated and form hard beds; they are gray-white or pink in
277 color. Microscopic observations showed that these beds are mostly composed of
278 10- μm -sized volcanic glass particles. The pore water content in the tephra bed is
279 ~ 24 wt% (Table 1). Lithologically contrasting tephra beds are named T1, T2, and
280 T3, from bottom to top. Bed T1 are pink in color, and beds T2 and T3 were gray
281 (Fig. 2).

282 The sandy mud bed are permeable and reddish-brown in color, and contained
283 sand grains of various sizes, rock fragments over 100 μm in size, volcanic glass
284 over 10 μm in size, and reddish-brown iron oxyhydroxide particles less than 1 μm
285 in size. The sandy mud are variable in thickness laterally, ranging from 30–40 cm
286 thick in the outer portions of the bay (cores 0904-C6, 0904-C5, and 0904-C3) to
287 5–20 cm thick in the inner portions (cores 1003-C4, 1003-C3, and 1003-C1).

288 One thick sandy mud bed in the upper part of the sequence, called the sandy

289 mud (SM) bed (Fig. 2), show a black color in most of the core samples when cut in
290 half. The pore water content of this bed was ~23.5% (Table 1). The black-colored
291 beds are mostly permeable coarse-grained beds, such as tephra and sand-rich beds,
292 which are altered under the anoxic conditions of the storage environment. Biogenic
293 activity are influenced by the change from oxic to anoxic conditions within the pore
294 water.

295 The basement sand are composed of well-sorted and well-rounded iron-coated
296 sand grains, and are identified as a beach sand (in cores 0904-C5, 0904-C3,
297 1103-C1, and 1003-C2). This sand resembles the sand from the beach along
298 Nagahama Bay. The sand is of volcanic origin and grains have a very thin coating
299 of iron oxide (<0.01 mm thick) that not represent overgrowth such as an oolite
300 texture.

301

302 **3.3 Sediment stratigraphy in Nagahama Bay**

303 The details of the stratigraphy and lithology varied from core to core; however,
304 five key beds (Basement sand, T1, T2, T3, and SM) were identified in most core
305 samples. The thick lithologically contrasting tephra beds (T1, T2, and T3) were
306 preserved in the lower portions of most cores. These key beds were used to divide

307 the sedimentary sequence into three units: lower, middle, and upper (Fig. 2), as
308 described below.

309 (a) The lower unit extended from the basement sand to the base of bed T1. At
310 the entrance to the central area of the W-site (cores 0904-C6, 0904-C5, and
311 0904-C3), the iron oxyhydroxide mud in the lower unit was mingled with the fine
312 sand bed. However, on the inland portside area of the W-site (cores 1003-C2,
313 1103-C1, 1003-C1, and 1003-C4) the lower unit is interbedded with thin
314 well-bedded stratified sandy mud beds (<2 cm thick).

315 (b) The middle unit extends from the base of bed T1 to the base of the sandy
316 mud. This unit contains three of the main tephra beds (beds T1, T2, and T3). Above
317 each tephra bed is a thin (<2 cm) sandy mud bed containing preserved tephra
318 laminae that are laterally discontinuous. Beds T1, T2, and T3 thinned slightly to the
319 inland port side of the W-site. The iron oxyhydroxide mud layers were especially
320 well preserved between beds T2 and T3, being bright orange in color and composed
321 of a laminated (1–2 mm) iron oxyhydroxide mud bed (cores 1003-C5, 0904-C3,
322 and 1003-C1; Fig. 3).

323 (c) The upper unit extends from the base of the sandy mud to the sediment
324 surface. This unit consists mainly of an orange-colored sandy mud bed and a few

325 thin tephra beds. This sandy mud bed was well preserved at the entrance to the
326 middle portion of the W-site (cores 0904-C6, 0904-C5, 0904-C3, 0904-C2, and
327 0904-C1). In the inland port side of the area, the sandy mud bed was mixed and the
328 matrix was muddy. Some cores were recovered near the port wall area, which
329 experiences weak refracted waves. In some cores (1003-C1, 1003-C2, 1003-C3,
330 and 1003-C4), the uppermost part of the core could not be fully recovered because
331 of instability of the unconsolidated gel-type sediment at the time of sampling.

332 To identify the details of the stratigraphy in the port, core samples from the
333 center of the W-site area were examined. Detailed observations and analysis of core
334 0904-C5 were compared with those of core 0904-C3 and with meteorological data.
335 Core 0904-C4, located in the southeast corner of the E-site, and core 1003-C6,
336 located at the north entrance of the W-site, did not contain well-preserved or
337 well-stratified sequences because of their locations in a continuous mixing zone
338 resulting from refracted waves and turbulence caused by boat propellers.

339

340 **4. Analysis**

341 **4.1 Analytical method**

342 The equipment used and details of the methods followed are described in this

343 section. X-ray fluorescence (XRF) was used to analyze the major element contents
344 of sediments. XRF measurements of the composition of iron oxyhydroxide mud,
345 tephra, and sandy mud beds in Nagahama Bay were obtained. After air drying,
346 samples (n = 20) were crushed for 10–12 min to less than 6 μm in size using a
347 vibrating mill (HEIKO, TI-100). The samples were packed into polyvinyl chloride
348 pellets by pressing at 3–4 tons for 30 seconds and at 10–20 tons for 2 minutes. The
349 pellets were analyzed by XRF (Rigaku, ZSX Primus II) at the Research Institute of
350 Environment for Sustainability, Faculty of Engineering, Kyushu University, Japan.

351 X-ray diffractometry (XRD) was used to identify the clay minerals within mud.
352 Samples were analyzed by XRD to examine their crystal structures. Eight samples
353 from core 0904-C5 (Fig. 5) were analyzed using an XRD (Rigaku, UltimaIV) at the
354 Department of Earth and Planetary Material Science, Kyushu University. The
355 analyses were conducted using a 4° – 64° scanning field and a $10^{\circ}/\text{min}$ scanning
356 speed.

357 Field emission scanning electron microscopy (FE-SEM) was used to identify
358 the shape and morphology of iron oxyhydroxides and other mud minerals, with
359 energy dispersive X-ray spectrometry (EDS) used to identify minerals. The iron
360 oxyhydroxide mud was dried in a freeze dryer (IWAKI, FRD-82M) and the dried

361 sample was fixed on a microscope slide using conductive tape. The slide was
362 coated with a 30-nm platinum film, using an ion sputtering device (JEOL,
363 JFC-1600). This sample was analyzed by FE-SEM and chemical elements were
364 measured using EDS (JEOL, JSM-6500F) at the Center for Advanced Marine Core
365 Research, Kochi University. We analyzed more than 50 samples of this sediment
366 core and trap.

367

368 **4.2 Analytical results**

369 The XRF data for samples 0904-C1 to 0904-C6, obtained from the top to the
370 bottom of each core, are provided in Table 2. Because of the pellets used in the
371 XRF analysis, the oxyhydroxides contain uncounted O and H such that the totals
372 were <100 wt%. The original analytical raw data are given here. The iron
373 oxyhydroxide mud consisted of 55–79 wt% SiO₂, 9–26 wt% Fe₂O₃ (average 16.8
374 wt%), and 1–7 wt% Al₂O₃. The tephra, which consisted mostly of glass fragments,
375 contained >90 wt% SiO₂, <2 wt% Fe₂O₃, and <1.3 wt% Al₂O₃. The sandy mud
376 consisted of 74–83 wt% SiO₂, 3–7 wt% Fe₂O₃, and 3–6 wt% Al₂O₃. The XRD
377 patterns of selected samples from core 0904-C5 are shown in stratigraphic order in
378 Fig. 5. The samples were not desalinated, and thus most samples showed a small

379 halite crystal peak derived from seawater. Four crystalline minerals were identified
380 in the samples: quartz (SiO_2), cristobalite (SiO_2), tridymite (SiO_2), and albite
381 ($\text{NaAlSi}_3\text{O}_8$). In the upper unit, two samples (iron oxyhydroxide mud sample
382 0904-C5-12 and a sample of sandy mud) contain albite peaks. Tridymite peaks
383 gradually increased at lower stratigraphic levels, indicating early-stage diagenesis.
384 However, a Fe-bearing mineral pattern could not be identified from the results of
385 the XRD analysis, indicating amorphous crystallinity. A very broad and weak peak
386 at 36.65° (2θ) implies the presence of ferrihydrite; however, our data did not well
387 contain a weak peak indicative of hydrated iron minerals (Fig. 4).

388 The iron oxyhydroxide mud was analyzed by FE-SEM and EDS (Fig. 6). SEM
389 images and EDS spectra for one sample are shown in Fig. 6. This mud mostly
390 contained two types of iron oxide and a few glass fragments ($<30\text{ }\mu\text{m}$; Fig. 6a). The
391 first type of iron oxide consisted of needle-shaped fragments of $<1\text{ }\mu\text{m}$ in size (L2,
392 L3; Fig. 6b). The second type of iron oxide consisted of raspberry-shaped rounded
393 grains of $<1\text{ }\mu\text{m}$ in diameter (L4; Fig. 6c). Grains of both types of iron
394 oxyhydroxide formed aggregates of $20\text{--}50\text{ }\mu\text{m}$ in size. In the SEM images and EDS
395 results, low-magnification image L1 shows only silica material.
396 Larger-magnification images L2 and L4 show very-fine-grained material that yields

397 an Fe peak in EDS analysis. These fine-grained materials are iron oxyhydroxide.
398 Image L3 shows finer fibrous matter with a strong Si peak, possibly representing
399 amorphous silica.

400 Because the mud contains some glass fragments, the maximum total iron
401 oxyhydroxide content of dry mud was 23 wt%. The sandy mud bed contained
402 higher concentrations of Al_2O_3 (3–6.2 wt%), which shows the results of mixing of
403 sands from the surrounding ocean and from rhyolitic volcanic (Iwo-Dake) sources
404 (Table 2). In the XRF and XRD results, the chemical and mineralogical
405 characteristics of iron oxyhydroxide show no changes with depth.

406

407 **5. Accumulation rate of iron oxyhydroxide estimated from sediment traps**

408

409 From the scuba and long-term camera observations, several oxyhydroxide
410 particles were identified in relatively clear ocean conditions (Fig. 7a, b). These
411 particles sink and are deposited more rapidly than smaller material. The sea floor in
412 Nagahama Bay is formed of a very soft, gel-type oxyhydroxide mud, which
413 contains wave ripples at the sea floor surface (Fig. 7a, b). Usually, fine
414 oxyhydroxide occurs as micro-particles that are very slow to settle, according to

415 Stokes' Law. Rapid sedimentation in Nagahama Bay may occur as a result of the
416 coagulation or adsorption of desorbed colloidal iron materials. These mechanisms
417 of concentrating colloidal iron (to >5–10 mg/l) are important for the rapid
418 sedimentation of very fine-grained particles (Honeyman and Santschi, 1989). The
419 high concentration of iron in the seawater and the thick sediment in this bay are a
420 good example of rapid sedimentation of iron oxyhydroxides under oceanic
421 conditions.

422 The sediment trap data were used to estimate the sedimentation rate in
423 Nagahama Bay. Simplified sediment traps (trap cores) were placed in trap boxes
424 (Fig. 7c, d) at a depth of 3 m on the bottom of the bay at the W-site (Fig. 1). The
425 trap cores were made of acrylic pipe, 7–10 cm in diameter and 1 m long. The cores
426 accumulated unconsolidated reddish-brown mud, which were examined under the
427 microscope.

428 The trap cores were set from 12 July 2009 to 3 October 2009 (82 days), 29
429 March 2010 to 5 April 2011 (373 days), 4 October 2009 to 20 November 2010 (413
430 days), and 3 October 2009 to 5 April 2011 (550 days). At these times, there were no
431 strong weather hazards in Iwo-Jima. The accumulated thickness on the sea floor
432 surface was estimated using data from the trap cores.

Microscopic observations indicate that most trap cores were formed of reddish-brown mud that included very fine ($<1\ \mu\text{m}$) reddish-brown particles (Fig. 4d). These particles may have formed from the rapid coagulation or adsorption of oxyhydroxide. From the trap core record, the thicknesses of the soft water-saturated reddish-brown mud collected in the four trap cores were 7.5, 24.0, 42.5, and 58.2 cm, for collection times of 82, 373, 413, and 550 days, respectively, yielding accumulated thicknesses at the W-site of 33.3, 23.5, 37.7, and 38.6 cm/year, respectively (average 33.3 cm/year; Table 3). The water contents of the traps were 73%–82% (Table 1). Based on the sea floor temperature, it is estimated that an area of $\sim 5000\ \text{m}^2$ at the E- and W-sites produced the precipitated iron oxyhydroxide material. The amount of discharge in the area of the sea floor with a temperature of $>50^\circ\text{C}$ during the last 12 years is $\sim 5000\ \text{m}^3$ ($0.333\ \text{m/year} \times 12\ \text{years} \times 5000\ \text{m}^2$). Taking the specific gravity of iron oxyhydroxide as $>3.4\ \text{g/cm}$ and assuming a water content of $\sim 80\%$ in trap samples, the estimated production of iron oxyhydroxide-containing mud in the fishing port (W and E-sites: $5000\ \text{m}^2$ area) is 713–1266 ton/year, and the production rate for $1\ \text{m}^2$ is 143–230 kg/year. Based on ocean surface observations, after March 2010 the sea color at the W-site was lighter more than at the E-site. The lower amount of mud produced at Trap 16 may indicate

451 weaker productivity of the hot spring at the W-site.

452

453 **6. Meteorological records**

454

455 Sediment deposition on the shallow sea floor of Nagahama Bay is strongly
456 affected by exogenous factors, including heavy rainfall and strong waves from the
457 south (Ninomiya and Kiyokawa, 2009; Kiyokawa et al., 2012; Ueshiba and
458 Kiyokawa, 2012). Meteorological records were obtained to correct the data for
459 these meteorological factors. Detailed local meteorological data from Mishima
460 Village Center included daily precipitation, wind speed, and wind direction data for
461 the period from 1 April 2000 to 31 March 2011.

462 Data on typhoon tracks passing across or near Satsuma Iwo-Jima Island between
463 2000 and 2010 were obtained from Japan Meteorological Agency (2011a; Fig. 8).
464 Strong typhoon events were identified based on the following criteria: a maximum
465 wind speed on Satsuma Iwo-Jima Island of >20 m/s and the location of the typhoon
466 within a 1100-km radius of the island. A total of 23 typhoon events were thus
467 identified during the period from April 2000 to December 2012; five of these
468 typhoons showed strong wind effects on the island (Fig. 8), with maximum wind

469 speeds of 40.3, 54.3, and 44.6 m/s in 2004, 43.3 m/s in 2005, and 50.2 m/s in 2007.

470 No strong wind effects were observed after 2007.

471 Seven heavy rainfall events (precipitation > 100 mm/day) were recorded
472 between April 2000 and March 2011 (Fig. 9); five events occurred during the June
473 rainy season, on 4 June 2000 (189.0 mm/day), 20 June 2001 (124.5 mm/day), 17
474 June 2002 (107.5 mm/day), and 3 July 2002 (122.0 mm/day). A heavy rainfall event
475 occurred on Iwo-Jima Island during a typhoon on 29 August 2004 (100.0 mm/day).
476 After 2004, no heavy rainfall events were recorded.

477

478 **7. Comparison of meteorological and stratigraphic records**

479

480 The W-site in Nagahama Bay was dredged in 1998 (Kagoshima Prefecture,
481 2012); therefore, the basement sand can be regarded as a marker bed for the base of
482 the stratigraphic sections. Comparisons between the well-preserved stratigraphy in
483 the core samples and the detailed meteorological records for the island allow
484 examination of the relationships between lithology and meteorological factors.

485 The stratigraphy of core 0904-C3 was compared with parameters representing
486 monthly volcanic activity (volcanic ash deposition), construction of breakwaters,

487 rainfall, and typhoon events between 1998 and 2011 (Fig. 9). This comparison
488 showed that tephra beds T1, T2, and T3 are correlated with heavy rainfall events in
489 2000, 2001, and 2002, respectively, and that the sandy mud corresponds to the
490 strong typhoon wind events of 2004 and 2005. The 2007 typhoon event is less well
491 represented in the bay, probably because the outer-ocean breakwater (Breakwater 3)
492 had been largely constructed by that time (the main construction period was in
493 December 2006), and this breakwater may have blocked the passage of strong
494 waves.

495

496 **8. Mechanisms of sedimentation mechanisms**

497

498 Based on the evidence described above, the following sedimentation
499 mechanisms for the main lithologies in the cores from Nagahama Bay are identified.
500 The tephra beds and the sandy mud bed are suggested to have been the result of
501 episodic strong weather conditions (rainfall and typhoon events, respectively); the
502 intervening mud layers represent periods of iron sedimentation during quiescent
503 conditions between the episodic heavy-weather events (Fig. 10).

504

505 **8.1 Tephra beds**

506 The most important evidence for the origin of the tephra beds in Nagahama Bay
507 is related to the sequence of heavy rainfall events that occurred in 2001, 2002, and
508 2003 (Figs 9, 10). Rhyolitic volcanism on Iwo-Dake was active from the 1990s to
509 2004, and ash-fall sediment was deposited around the summit area of Iwo-Dake
510 during this time. The ash is composed of volcanic glass and Si-bearing materials
511 such as quartz, tridymite, and cristobalite (Shinohara et al., 2002). However,
512 especially during heavy rainfall (over 100 mm/day), ashy materials are transported
513 by flood water down the creek that drains Iwo-Dake. Thus, the transport of ashy
514 material from Iwo-Dake and resedimentation of the material on the bottom of the
515 bay at the W-site led to the deposition of the tephra layers.

516 Deposition of the tephra in the bay was influenced by two factors. First,
517 breakwater 1, constructed in December 2004 (Kagoshima Prefecture, 2012),
518 blocked the direct input of sediment from the creek to the W-site. Second, the ash
519 fall that was active on Satsuma Iwo-Jima Island from 1998 to October 2004
520 (Shinohara et al., 2002; Japan Meteorological Agency, 2011b, c). After the heavy
521 rainfall events in the early 2000s, and with the weakening of volcanic activity from
522 2005 onwards, it is likely that the supply of Si-bearing material was exhausted, and

523 therefore the heavy rainfall events after 2004 did not result in well-preserved layers
524 of tephra in the sedimentary succession in Nagahama Bay.

525

526 **8.2 Sandy mud beds**

527 A comparison of the stratigraphic sequence in Nagahama Bay with the history
528 of typhoon events for Satsuma Iwo-Jima Island shows that the sandy mud bed in
529 the bay was generated by a strong typhoon (Figs 9, 10). Large waves, such as those
530 generated by storms and typhoons, strongly mixed the seawater and increased the
531 turbidity in the bay (Ninomiya and Kiyokawa, 2009; Kiyokawa et al., 2012;
532 Ueshiba and Kiyokawa, 2012). Sandy materials around Nagahama Bay, composed
533 of minerals such as albite, quartz, tridymite, and cristobalite, were resuspended and
534 mixed, and finally redeposited as a sandy mud bed.

535 The Japan Meteorological Agency (2011a) recorded five large typhoons (wind
536 speeds of >40 m/s) that passed over Satsuma Iwo-Jima Island between 1998 and
537 2011 (Fig. 8). Each large typhoon passed the island from either south to north
538 (Typhoon numbers T07-04, T04-16) or southwest to northeast (Typhoon numbers
539 T05-14, T04-06, T04-18). Under these conditions, strong southerly winds and
540 waves affected the waters of Nagahama Bay. The sandy mud bed was thus formed

541 as a direct result of typhoon-related turbulence of bay waters.

542 After the construction of Breakwater 2 in early 2001, the W-site was a more
543 closed environment and allowed more sediment to be deposited and preserved at
544 this site. However, the area was still affected by strong waves and currents during
545 typhoons. After the construction of Breakwater 3 in December 2006, strong wave
546 effects suddenly diminished, because Breakwater 3 protected the area from very
547 strong waves and water currents from the outer ocean. Therefore, the Typhoon-3
548 event in 2007 is not recorded in the stratigraphic sequence. Thus, the influence of
549 typhoons was significantly altered by the construction of breakwaters in 2006.

550

551 **8.3 Sedimentation of iron oxyhydroxide**

552 The sedimentation rates between beds T1, T2, and T3 can be approximated by
553 the accumulation rates of iron oxyhydroxide mud. The thicknesses were measured
554 and the average sedimentation rates were calculated for iron oxyhydroxide mud in
555 the different layers (Table 2). These rates, from the basement sand to T1, from T1 to
556 T2, and from T2 to T3, are 5.3, 2.5, and 6.8 cm/year, respectively.

557 Based on data from the five sediment traps, the present-day accumulation rates
558 of iron oxyhydroxides provide sedimentation rates of 38.6, 23.5, 33.4, 37.6, and

559 33.6 cm/year (average 33.3 cm/year; Table 3). The accumulation rates based on the
560 13 core samples are 2.5–6.8 cm/year (average 4.9 cm/year). The pore water content
561 in the cores and traps does not change with depth in the sediment, but it does
562 change with the type of sedimentary material (Table 3). The iron oxyhydroxide mud
563 in cores contains 50%–65% water and the mud in traps contains 73–82 wt% water.
564 The estimated pore water content of sediment cores is about 70%–80% of that of
565 the sediment traps (Table 3).

566 Observations of the ocean surface in Nagahama Bay (Kiyokawa et al., 2012)
567 indicate that a large amount of iron oxyhydroxide material is discharged from the
568 W-site to the open ocean. Before the construction of Breakwater 3 in 2006,
569 discharge of iron oxyhydroxide material might have been larger than that after
570 breakwater construction.

571 Here, the total volume of precipitated iron oxyhydroxide material preserved on
572 the sea floor at the fishing port is estimated. The calculations use the dry weight of
573 samples, a water content of trap samples of 74–81 wt%, and a water content of
574 oxyhydroxide mud in core samples of 40–67 wt% (Table 1). To obtain the pore
575 water content during deposition, the thickness of oxyhydroxide sediment in the core
576 was assumed to be ~80% of the trap thickness. These thickness data from core

577 samples were taken from data obtained before 2006 (i.e., before the construction of
578 Breakwater 3). Sedimentation after breakwater construction may have been greater
579 than the calculated amount.

580 Using a value of ~80% discharge of iron oxyhydroxide material to the outer
581 ocean, the amount of iron oxyhydroxide material deposited on the bay floor at the
582 fishing port is $\sim 100 \text{ m}^3$ ($0.029\text{--}0.68 \text{ m/year} \times 12 \text{ years} \times 5000 \text{ m}^2$). Using values
583 from XRF data of 59% pore water content and ~20 wt% iron content, the estimated
584 rate of deposition of iron oxyhydroxides is therefore 86–100 tons/year (dry weight)
585 at the fishing port (area about 5000 m^2 and density of iron oxyhydroxides of <3.4
586 g/cm^3). Accordingly, the precipitation rate at the fishing port is estimated to be
587 $\sim 59\text{--}139 \text{ kg/m}^2/\text{year}$. In the 13-year period between 1998 and 2011, the total
588 amount of iron oxyhydroxide precipitated in the port was about 700–850 ton.
589 Including material transported to the ocean, approximately 3500–4250 ton of iron
590 oxyhydroxide was produced in the bay.

591 The rate of iron oxyhydroxide deposition on the bay floor was more rapid than
592 the estimated rate of colloidal matter deposition calculated from Stokes' Law. The
593 behavior of metal colloids has been well studied in the laboratory and in the natural
594 ocean (e.g., McCave, 1984; Honeyman and Santschi, 1989). Based on Stokes' Law

595 for quiet-water conditions, deposition of colloids requires a long sinking time. For
596 example, at 30°C and for a grain size of 0.001 mm, seawater density of 1.04 g/cm²,
597 grain density of 3.4 g/cm², and water viscosity 0.008 g/cm•s, the terminal velocity
598 calculated from Stokes' Law gives a sedimentation rate of ~13.9 cm/day, and the
599 estimated 5-m fall time of a single particle is 36 days.

600 The high sedimentation rates in Nagahama Bay are an example of rapid iron
601 deposition under oceanic conditions. Under conditions with high concentrations of
602 iron oxyhydroxide, coagulation of colloids readily occurs (e.g., Honeyman and
603 Santschi, 1989) and the coagulations are deposited rapidly under oxidizing
604 conditions. The rapid and large amount of oxyhydroxide sedimentation in the
605 Nagahama Bay example strongly suggests that thick oxyhydroxide deposits will
606 form in ocean environments with high oxyhydroxide concentrations. This rapid
607 sedimentation might be identified in oxidized ocean environments during
608 Archean–Proterozoic time, when global oxygen levels quickly increased.
609 Phanerozoic ironstone formation might be facilitated in shallow, enclosed oceanic
610 settings with hydrothermal input.

611

612

9. Conclusions

This work estimated the present-day rapid sedimentation of oxyhydroxide in Nagahama Bay on Satsuma Iwo-Jima Island. Sediment cores from the W-site of the bay provide a >10-year record of sedimentation. Sediment traps at the W-site show modern rapid sedimentation with high concentrations of oxyhydroxide. The sedimentation history of the bay was reconstructed by comparing the weather history and sediment cores. The estimated average sedimentation rate from the traps is 33.3 cm/year. This rate of sedimentation is higher than the settling rate of iron oxyhydroxide particles. Deposition of iron oxyhydroxide particles occurs because the high iron oxyhydroxide concentrations cause coarse particles to form by colloidal aggregation. The estimated amount of oxyhydroxide deposited at Nagahama Bay from trap data is 39–95 tons/year in a 5000 m² area, which is equivalent to 57–139 kg/m²/year. This high rate and large amount of oxyhydroxide deposition is important in supporting a model of rapid iron oxide sedimentation in the geological record.

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755

756 **Figure captions**

757

758

759 Fig. 1. (a) Regional (left) and local (right) locality maps of Satsuma Iwo-Jima

760 Island. (b) Overview of Nagahama Bay (view to the east). The E-site and W-site are

761 designated research areas. The W-site was dredged between 14 November 1997 and

762 25 March 1998, and during May 2009, removing a ~3 m thickness of sediment. The

763 star at the W-site indicates the location of the trap box that was set in June 2009.

764

765 Fig. 2. Longitudinally sectioned core samples (left), core sketches (middle), and
766 computed tomography (CT)-scanned images (right) of core recovered from
767 Nagahama Bay. In the CT-scanned images, bright portions are higher-density
768 regions. Sample collection dates were: 0904-C4, 13 April 2009; 0904-C5, -C6, 14
769 April 2009; 1003-C2 to 1003-C6, 27 March 2010; 1003-C1, 29 March 2010;
770 1103-C1, 2 April 2011.

771

772 Fig. 3. (a) Close-up images of tephra beds T1, T2, and T3 from the lower
773 portion of core 0904-C1. Bed T1 is a pink-colored tephra. Beds T2 and T3 are
774 gray-colored tephra beds, which were originally white in color prior to storage
775 under anoxic conditions. Several hours after exposure, the black color had changed
776 to white due to oxidation. (b) Detailed image of the pink-colored T1 tephra and the
777 upper and lower well-laminated iron oxyhydroxide mud beds (0904-C1 core). (c)
778 Detailed image of the sandy mud (SM) bed in the upper portion of core 0904-C1.
779 Gray-brown layers are sand-rich beds. (d) Detailed image of well-laminated iron
780 oxyhydroxide mud between beds T2 and T3. Approximately 9–12 orange-colored

781 thin beds were identified in the reddish-brown mud bed.

782

783 Fig. 4. Smear slide images of core and sediment trap samples: (a) iron
784 oxyhydroxide mud (core 0904-C3; depth, 54 cm); (b) sandy mud bed (core
785 0904-C5, depth, 34 cm); (c) tephra bed (core 0904-C3; depth, 64 cm); and (d)
786 reddish-brown mud from trap (Trap-13). All images were taken under
787 plane-polarized light. Oxy, reddish-brown iron oxyhydroxide grains; Gl, volcanic
788 glass; Lithic, rock fragments.

789

790 Fig. 5. X-ray diffraction pattern of brown mud in core 0904-C5. The title of
791 sandy mud, T1, T2, and T3 beds indicate the muddy layers within these beds.

792

793 Fig. 6. (Left) SEM images of iron oxyhydroxide mud (core 0904-C5). (Right)
794 Patterns in EDS data for small segments of the stratigraphic sections shown at left
795 (L1–L4).

796

797 Fig. 7. (a) Long-term camera (Moguriku) view of the bottom of the W-site of the
798 fishing port. The middle portion contains a leaf. The width of the field of view is 20

799 cm, and the location is near 1003-C-4 in Fig. 2. (b) Long-term camera (Moguriku)
800 view of the bottom of the W-site of the fishing port. Wave ripples are preserved on
801 the surface. The width of the field of view is 20 cm, and the location is near
802 0904-C1 in Fig. 2. (c) Trap box system with trap cores. Cores of 1 m long were set
803 up within each square in the box. (d) A 7.5-cm-thick accumulation of iron
804 oxyhydroxide mud in a 1-m-long trap core (Trap-11) deployed from 12 July 2009
805 to 3 October 2009. (e) Detailed image of (d), showing a close-up view of the
806 7.5-cm-thick accumulation of sediments in the trap core. The sedimentation rate in
807 this core is 33.4 cm/year (calculated from the wet thickness). (f) Surface of a
808 longitudinally cut section of a 17-cm-thick trap-core sequence (Trap-15). The
809 sedimentation rate in this core is 33.5 cm/year (calculated from the wet thickness).

810

811 Fig. 8. Tracks of large typhoons that passed Satsuma Iwo-Jima Island in 2004,
812 2005, and 2007 (after Japan Meteorological Agency, 2011a).

813

814 Fig. 9. Comparison of the stratigraphy of core 0904-C3 with ash fall,
815 construction, rainfall events, and typhoon records on Satsuma Iwo-Jima Island. Ash
816 fall data indicate monthly accumulation in Nagahama Bay (Japan Meteorological

817 Agency, 2011b, c), although the direct record of ash falls during this time is unclear.
818 Construction data are for breakwater building in and around Nagahama Bay, and
819 for dredging work at the W-site. Rainfall and typhoon maximum wind speed data
820 were collected in Mishima village.

821

822 Fig. 10. Sedimentation model of coarse sediments in Nagahama Bay. (a)
823 Volcanic glass and Si-bearing materials accumulated around Iwo-Dake. Heavy
824 rainfall flushed this material to the bottom of the bay at the W-site and formed the
825 tephra bed. (b) Strong typhoons mixed sea floor sediments from in and around
826 Nagahama Bay and redeposited those sediments at the W-site. Various types of
827 material accumulated in the bay at different times and during different events.

828

829 Table 1. Estimated pore water ratios of core and trap samples.

830

831 Table 2. XRF data for cores 0904-C1 to 0904-C5 and 1003-C6.

832

833 Table 3. Estimated accumulation weights of iron oxyhydroxide mud in five
834 sedimentary traps during different time periods. Approximately 10 g of wet sample

835 of Traps 16 and 17 was obtained for each measurement, and was dried at 70°C in a
836 drying oven for 30 hours. Estimates of weight for Traps 11, 13, and 15 assumed a
837 water content of 82 wt%.

838

839 Table 4. Estimated one-year accumulation rates of wet sediment thickness
840 (cm/year) and weight (kg/year/m²) of dry iron oxyhydroxide mud in core samples.
841 For weight calculations, a pore water content of 59 wt% in wet sediment was
842 assumed.

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853 Figure 1

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859 Figure 2

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877 Figure 4

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887 Figure 5

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903 Figure 7

912 Figure 8

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925 Figure 9

Table 1

Core sample	0904-C2 mud	0904-C2 mud	0904-C2 mud	0904-C2 tephra	0904-C2 mud	average of mud (wt%)
depth (cm)	0.00	30.00	42.00	62.00	76.00	
wet weight (g)	12.20	13.07	12.77	16.94	14.00	
dry weight (g)	4.01	5.42	4.85	12.88	7.04	
water content(%)	32.89	41.45	37.99	76.01	50.30	59.34

Core sample	1003-C3 mud	1003-C3 mud	1003-C3 mud	1003-C3 mud	1003-C3 mud	average of mud (wt%)
depth (cm)	0.00	45.00	65.00	77.00	83.00	
wet weight (g)	14.08	13.19	14.76	12.93	17.24	
dry weight (g)	7.45	5.55	8.89	5.68	13.19	
water content(%)	52.87	42.08	60.24	43.96	76.50	50.21

Trap sample	Trap TR5 mud	Trap TR5 mud	Trap TR5 mud	Trap TR16 mud	Trap TR17 mud	average of mud (wt%)
depth (cm)	0.00	5.00	10.00	10.00	10.00	
wet weight (g)	11.78	11.47	11.03	9.84	11.54	
dry weight (g)	3.11	2.81	2.16	1.76	2.23	
water content(%)	26.37	24.50	19.56	82.11	80.68	78.47

Table 2

Sample Number	Depth (cm)	lithology	SiO2 (wt%)	FeO (wt%)	Al2O3 (wt%)	TiO2 (wt%)	MnO (wt%)	MgO (wt%)	CaO (wt%)	Na2O (wt%)	K2O (wt%)	P2O5 (wt%)	S (ppm)	Cl (ppm)	Ba (ppm)	Zr (ppm)	Total (wt%)
0904-C1-02	2	Iron-oxyhydroxides mud (Unformed)	67.78	13.13	5.57	0.68	0.30	1.06	1.60	1.97	0.99	0.16	6255	4621	286	226	93.20
0904-C1-08	8	Iron-oxyhydroxides mud (Unformed)	56.41	21.56	5.77	0.60	0.69	1.21	1.60	2.10	0.88	0.20	8174	7267	223	300	91.00
0904-C1-25	25	Iron-oxyhydroxides mud (Unformed)	56.57	19.54	6.57	0.64	0.31	1.22	1.96	2.33	1.03	0.21	1018 1	7750	255	297	90.40
0904-C1-30	30	Iron-oxyhydroxides mud (oganic)	68.29	8.66	6.24	0.88	0.20	1.09	1.36	2.16	0.93	0.20	1527 8	5666	436	146	90.00
0904-C1-46	46	Iron-oxyhydroxides mud (oganic)	60.94	16.69	3.71	0.71	0.39	1.21	1.41	2.02	0.68	0.20	1518 5	8038	341	335	88.00
0904-C1-53	53	Iron-oxyhydroxides mud	68.40	15.89	2.80	0.76	0.11	0.97	0.94	1.60	0.58	0.16	5923	6395	368	220	92.20
0904-C1-62	62	Tefra	91.61	1.68	0.93	0.92	0.00	0.61	0.73	0.65	0.57	0.04	5286	1573	403		97.70
0904-C1-65	65	Iron-oxyhydroxides mud	70.61	16.73	1.43	0.70	0.16	0.90	0.87	1.42	0.46	0.15	5570	6415	270	164	93.40
0904-C1-68	68	Iron-oxyhydroxides mud + tefra	82.65	8.18	0.62	0.83	0.05	0.77	0.67	1.19	0.44	0.10	3526	4288	257	148	95.50
0904-C1-74	74	Tefra	92.45	1.59	0.06	0.97	0.00	0.64	0.51	0.67	0.40	0.04	3988	1925	295		97.30
0904-C1-81	81	Iron-oxyhydroxides mud Tefra +	76.19	10.26	2.33	0.72	0.33	0.87	0.97	1.32	0.59	0.10	3437	3714	251	93	93.70
0904-C1-84	84	Iron-oxyhydroxides mud	82.97	7.19	1.28	0.78	0.12	0.75	0.76	1.09	0.51	0.08	2743	3280	239	62	95.50
0904-C1-86	86	Tefra	89.70	3.06	0.89	0.87	0.05	0.70	0.64	0.88	0.54	0.05	2992	2406	274	83	97.40
0904-C1-88	88	Iron-oxyhydroxides mud	68.57	16.18	2.67	0.69	0.19	0.93	0.97	2.29	0.64	0.16	4351	8488	326	182	93.30
0904-C2-71	52	Tefra	90.91	1.96	1.00	0.93	0.00	0.59	0.72	0.62	0.59	0.04	4016	1203	420	236	97.40
0904-C2-83	64	Tefra	94.79	0.78	0.00	0.89	0.00	0.58	0.45	0.46	0.34	0.02	2096	1179	212	217	98.30
0904-C2-87	68	Iron-oxyhydroxides mud	82.42	7.82	1.77	0.74	0.09	0.73	0.74	1.04	0.57	0.08	2669	2521	268	196	96.00
0904-C2-90	71	Tefra	86.73	5.80	1.04	0.80	0.00	0.67	0.63	0.81	0.53	0.07	2157	1973	272	209	97.10
0904-C2-97	78	Iron-oxyhydroxides mud (medium)	63.06	16.60	6.39	0.62	0.05	0.93	1.30	1.89	1.07	0.20	6322	3936	277	175	92.10
0904-C3-16	6	Iron-oxyhydroxides mud (Unformed)	57.70	19.47	5.69	0.56	0.61	1.11	1.83	2.23	0.96	0.20	5656	6840	263	151	90.40
0904-C3-20	10	Iron-oxyhydroxides mud	61.82	18.53	5.43	0.60	0.11	1.06	1.57	2.66	1.00	0.29	5719 1031	8045	297	159	93.10
0904-C3-25	15	Sandy mud	77.61	3.68	5.95	0.86	0.06	0.87	1.18	1.99	1.00	0.11	4	3516	437	223	93.30
0904-C3-33	23	Sandy mud (medium)	83.15	5.04	2.94	0.71	0.24	0.82	1.16	1.43	0.75	0.08	3638	3125	306	181	96.30
0904-C3-38	28	Iron-oxyhydroxides mud	70.51	11.49	3.44	0.69	0.03	0.92	0.93	4.61	0.74	0.16	1652 9	4966	364	183	93.50
0904-C3-49	39	Iron-oxyhydroxides mud	67.37	14.68	4.15	0.68	0.04	0.90	0.98	3.09	0.79	0.17	1056 5	5920	328	183	92.80
0904-C3-56	46	Iron-oxyhydroxides mud	70.41	16.89	1.65	0.64	0.02	0.83	0.70	1.65	0.50	0.17	4481	6537	272	170	93.50
0904-C3-64	54	Tefra Tefra +	93.13	1.64	0.12	0.86	0.00	0.61	0.52	0.63	0.40	0.03	2341	1399	268	218	97.90
0904-C3-70	60	Iron-oxyhydroxides mud	87.71	5.00	1.17	0.83	0.00	0.68	0.61	0.89	0.55	0.07	2588	2127	306	219	97.50

0904-C3-74	64	Iron-oxyhydroxides mud (fine)	63.45	19.42	4.60	0.61	0.03	0.90	1.05	1.59	0.85	0.23	5671	4655	242	174	92.70
0904-C3-85	75	Iron-oxyhydroxides mud (fine)	57.35	21.93	6.21	0.53	0.06	1.05	1.50	2.10	1.07	0.30	7113	6452	261	153	92.10
0904-C3-88	78	Sandy mud (very course)	69.38	6.70	10.54	0.62	0.11	1.30	2.88	3.47	1.89	0.12	1871	1570	342	173	97.00
0904-C3-95	85	Sandy mud (medium-course)	68.15	6.10	10.71	0.62	0.10	1.25	2.99	4.59	1.81	0.12	3223	6377	333	166	96.40
0904-C4-12	1	Iron-oxyhydroxides mud (Unformed)	59.34	16.44	5.16	0.49	0.15	1.28	1.65	5.46	0.94	0.15	4700	1733 6	235	134	91.00
0904-C4-20	9	Iron-oxyhydroxides mud (fine)	48.33	19.37	4.86	0.43	0.27	1.30	1.66	11.23	0.86	0.16	4693	3686 9	202	118	88.50
0904-C4-31	20	Iron-oxyhydroxides mud (sand mix)	70.32	10.87	5.72	0.57	0.11	1.11	1.79	3.03	1.10	0.13	2986	7021	267	156	94.70
0904-C4-35	24	Iron-oxyhydroxides mud (Tefra)	62.09	13.67	5.74	0.56	0.12	1.28	1.66	4.44	0.97	0.28	7910	1452 7	259	153	90.80
0904-C4-40	29	Iron-oxyhydroxides mud	66.65	15.75	4.05	0.56	0.09	1.08	1.38	3.15	0.79	0.13	3954	1072 7	225	149	93.60
0904-C4-45	34	Iron-oxyhydroxides mud	59.33	18.42	3.25	0.55	0.12	1.12	1.18	6.23	0.67	0.14	4702	2287 1	226	148	91.00
0904-C4-55	44	Iron-oxyhydroxides mud	22.37	26.68	2.90	0.20	0.44	0.93	1.00	24.66	0.45	0.18	3667	8031 5	87	61	55.10
0904-C4-65	54	Iron-oxyhydroxides mud	53.05	22.36	5.52	0.46	0.16	1.21	1.80	4.24	0.99	0.18	5981	1309 8	224	131	90.00
0904-C4-75	64	Iron-oxyhydroxides mud	54.63	19.00	7.62	0.49	0.29	1.25	2.31	3.76	1.32	0.20	4526	9369	261	138	90.90
0904-C4-85	74	Iron-oxyhydroxides mud	52.17	21.17	7.32	0.46	0.38	1.25	2.30	3.53	1.32	0.21	4955	8779	260	132	90.10
0904-C4-95	84	Iron-oxyhydroxides mud	37.66	24.77	5.11	0.31	0.52	1.20	1.53	12.53	0.83	0.24	5390	3711 5	156	93	84.70
0904-C4-99	88	Iron-oxyhydroxides mud	54.11	21.11	2.79	0.51	0.19	1.12	1.06	7.85	0.56	0.16	5636	2938 4	202	140	89.40
0904-C5-12	2	Iron-oxyhydroxides mud (Unformed)	66.92	15.72	6.07	0.57	0.11	0.95	1.74	1.86	1.10	0.15	4015	2684	241	157	95.20
0904-C5-18	8	Iron-oxyhydroxides mud (Unformed)	55.04	23.21	6.40	0.54	0.31	1.06	1.65	1.92	0.99	0.24	7197	5673	245	155	91.40
0904-C5-22	12	Sandy mud	74.38	7.63	6.83	0.61	0.12	0.98	1.95	2.47	1.21	0.09	3125	3366	292	164	96.30
0904-C5-24	14	Iron-oxyhydroxides mud	74.19	9.12	6.17	0.59	0.05	0.93	1.84	2.34	1.13	0.11	2754	3346	310	157	96.50
0904-C5-27	17	Sandy mud (fine-medium)	76.34	7.45	6.29	0.64	0.09	0.90	1.79	2.01	1.13	0.11	3037	1669	313	167	96.70
0904-C5-31	21	Sandy mud (SM)	78.25	4.67	5.82	0.84	0.10	0.87	1.23	1.72	1.00	0.14	9396	2690	416	219	94.60
0904-C5-34	24	Sandy mud (SM)	83.41	3.51	4.78	0.65	0.07	0.86	1.55	1.80	1.00	0.08	2492	2131	354	170	97.70
0904-C5-37	27	Sandy mud (SM)	83.99	4.82	3.17	0.74	0.11	0.80	1.14	1.38	0.78	0.09	3606	2691	346	186	97.00
0904-C5-44	34	Sandy mud (SM)	82.28	5.84	2.77	0.82	0.17	0.78	1.03	1.22	0.71	0.09	5970	2666	370	205	95.70
0904-C5-48	38	Sandy mud (SM)	82.02	5.97	3.45	0.79	0.06	0.80	0.96	1.33	0.73	0.13	4638	2959	366	207	96.20
0904-C5-53	43	Sandy mud	88.08	2.53	3.05	0.65	0.03	0.76	1.15	1.33	0.75	0.06	2406	1987	289	165	98.40
0904-C5-58	48	Tefra (T3)	90.87	1.77	1.34	0.91	0.00	0.62	0.76	0.79	0.61	0.05	6157	1766	396	230	97.70
0904-C5-63	53	Iron-oxyhydroxides mud	73.52	15.37	1.02	0.65	0.01	0.79	0.67	1.07	0.45	0.22	3464	4306	221	166	93.80
0904-C5-67	57	Iron-oxyhydroxides mud	76.61	13.29	1.00	0.71	0.00	0.76	0.62	0.90	0.45	0.18	3205	3276	242	189	94.50
0904-C5-71	61	Tefra (T2)	93.37	1.62	0.00	0.88	0.00	0.62	0.53	0.60	0.42	0.03	1633	1734	329	236	98.00

0904-C5-75	65	Tefra (T2)	94.60	0.87	0.00	0.83	0.00	0.60	0.48	0.58	0.35	0.03	2482	1485	221	186	98.30
0904-C5-81	71	Tefra (T1)	90.54	2.07	1.37	0.82	0.00	0.67	0.65	0.95	0.55	0.06	2695	1918	256	221	97.70
0904-C5-85	75	Tefra (T1)	91.24	2.46	0.81	0.82	0.00	0.65	0.59	0.79	0.53	0.06	2068	1900	260	212	97.90
0904-C5-90	80	Iron-oxyhydroxides mud	73.32	9.95	5.12	0.69	0.04	0.90	1.30	1.81	1.00	0.16	4033	3144	327	192	94.30
0904-C5-97	87	Basement sand	69.14	9.20	8.19	0.60	0.06	1.00	2.17	2.65	1.40	0.14	4172	2937	314	166	94.60
0904-C5-99	89	Iron-oxyhydroxides mud + sand	66.27	11.66	7.20	0.65	0.05	0.99	1.66	2.35	1.17	0.17	5483	4033	275	174	92.20
0904-C6-42	2	Iron-oxyhydroxides mud (Unformed)	63.78	16.19	6.33	0.56	0.05	1.09	1.82	2.26	1.10	0.12	3836	4597	274	145	93.30
0904-C6-47	7	Sandy mud (medium)	73.60	6.91	6.86	0.63	0.06	1.02	1.88	2.79	1.20	0.13	3478	4923	358	162	95.10
0904-C6-53	13	Sandy mud (course)	82.15	3.36	5.38	0.67	0.03	0.94	1.65	2.12	1.02	0.08	2159	3166	340	164	97.40
0904-C6-57	17	Iron-oxyhydroxides mud	79.44	7.26	2.81	0.77	0.02	0.82	0.95	2.01	0.70	0.14	5971	5762	387	187	94.90
0904-C6-61	21	Sandy mud (medium)	79.65	5.75	3.89	0.76	0.04	0.89	1.13	1.99	0.81	0.15	4915	5150	366	189	95.00
0904-C6-66	26	Sandy mud (medium)	85.16	2.91	3.49	0.74	0.01	0.81	1.04	1.64	0.76	0.08	3357	3492	339	180	96.60
0904-C6-70	30	Tefra (fine)	90.29	1.46	1.46	0.87	0.00	0.66	0.74	1.08	0.59	0.05	5427	2725	370	210	97.20
0904-C6-73	33	Tefra + Iron-oxyhydroxides mud	86.28	4.23	1.29	0.76	0.00	0.71	0.71	1.18	0.53	0.07	3460	3674	312	191	95.80
0904-C6-79	39	Tefra (very fine)	92.26	1.31	0.62	0.82	0.00	0.65	0.60	0.92	0.46	0.04	2966	2477	348	210	97.70
0904-C6-85	45	Tefra (fine)	91.06	1.71	1.50	0.81	0.00	0.67	0.67	1.02	0.56	0.05	2874	2164	316	213	98.00
0904-C6-91	51	Tefra (fine)	89.33	4.01	0.92	0.81	0.00	0.68	0.62	0.92	0.53	0.09	2265	2453	275	211	97.90
0904-C6-94	54	Tefra + Iron-oxyhydroxides mud	79.15	7.08	4.58	0.74	0.02	0.86	1.25	1.63	0.96	0.13	3530	2692	369	200	96.40
1003-C6-84	2.5	Iron-oxyhydroxides mud (Unformed)	64.94	16.76	4.53	0.64	0.21	1.09	1.39	2.81	0.88	0.18	5325	1024 3	256	171	93.40
1003-C6-80	6.5	Sandy mud	70.52	9.38	5.83	0.84	0.13	0.99	1.22	2.65	0.94	0.16	9097	7968	444	222	92.70
1003-C6-76	10.5	Tefra + Iron-oxyhydroxides mud	79.47	6.51	3.81	0.88	0.04	0.78	0.89	1.55	0.82	0.11	7606	4381	439	232	94.90
1003-C6-71	15.5	Sandy mud (very fine)	58.95	12.74	12.77	0.54	0.09	1.09	2.28	2.61	1.28	0.51	4123	4455	197	151	92.90
1003-C6-65	21.5	Iron-oxyhydroxides mud	66.15	19.57	2.81	0.68	0.21	0.91	1.02	1.34	0.61	0.15	4856	4705	258	177	93.40
1003-C6-55	31.5	Iron-oxyhydroxides mud	73.41	14.50	2.23	0.76	0.25	0.84	0.92	1.23	0.61	0.14	4445	3721	303	203	94.90
1003-C6-45	41.5	Iron-oxyhydroxides mud	69.29	16.99	2.66	0.73	0.25	0.91	1.01	1.40	0.64	0.15	5216	4676	254	193	94.00
1003-C6-35	51.5	Iron-oxyhydroxides mud	73.75	13.72	2.44	0.76	0.20	0.85	0.96	1.31	0.64	0.14	4730	3922	283	203	94.80
1003-C6-30	56.5	Sandy mud	70.79	14.29	3.92	0.69	0.18	0.86	1.26	1.56	0.82	0.14	4362	3263	267	181	94.50
1003-C6-25	61.5	Iron-oxyhydroxides mud	56.72	22.84	6.31	0.47	0.06	0.97	1.73	2.05	1.07	0.20	4577	4450	211	128	92.40
1003-C6-15	71.5	Iron-oxyhydroxides mud	55.81	24.78	5.49	0.44	0.06	0.95	1.53	1.79	0.94	0.25	4684	4676	206	122	92.00
1003-C6-05	81.5	Iron-oxyhydroxides mud +sand	60.99	17.71	6.91	0.55	0.30	1.00	1.70	2.09	1.16	0.18	5129	3957	277	160	92.60
1003-C6-01	85.5	Tefra + Iron-oxyhydroxides mud	84.31	7.92	1.02	0.76	0.00	0.69	0.65	0.90	0.53	0.07	2391	2608	302	198	96.80

Table 3

Trap No.	Period	Total date	Total Thickness (cm)	Estimate one year Thickness (cm/year)	Wet sample weight (g)	dry sample 30 hours at 70°C (g)	material ration (wt %)	precipitation volume (m3/year) 5000m2 (port area)	mud produced weight (kg/year/m3)	Estimate sediment weight (ton/year/ 5000m2)	Estimate iron oxide weight (ton/year/5000m2)
Trap 16	2010/3/29~2010/9/10/3~	373	24	23.5	9.84	1.76	17.87	209.8	142.7	>713	142.7
Trap 17	2011/4/5~2009/6/12~	550	58.2	38.6	11.53	2.23	19.29	372.5	253.3	>1266	253.3
Trap 11	2009/10/3~2009/10/4~	82	7.5	33.4	-	-	(18.0)	300.5	204.3	>1022	204.3
Trap 13	2010/11/20~2009/10/4~	413	42.5	37.6	-	-	(18.0)	338	229.9	>1149	229.3
Trap 15	2010/11/20	414	17	33.5	-	-	(18.0)	301.9	205.2	>1026	205.3

(iron-oxyhydroxides density > 3.4 g/cm3)

Table 4

Stratigraphic location	Sedimentation period (year.month)		0904-C6	0904-C5	0904-C3	0904-C2	0904-C1	0904-C4	
SM bed - Top	5.0~7.0	(2004.9-2009.9 ~2011.9)	5.0	20.0	12.0	10.0	25.0	-	
T3 bed -SM bed	2.0	(2002.6-2004.6)	10.0	5.0	5.0	20.0	11.0	-	
T2 bed -T3 bed	1.0	(2001.6-2002.6)	2.7	9.3	9.3	8.9	7.5	-	
T1 bed -T2 bed	1.0	(2000.6-2001.6)	0.5	0.5	0.5	5.3	6.8	-	
basement sand-T1 bed	2.5	(1998.1-2000.6)	10.0	9.4	16.8	9.0	6.0	-	
Stratigraphic location	Sedimentation period (year.month)		1003-C4	1003-C3	1003-C1	1103-C1	1003-C5	1003-C2	1003-C6
SM bed - Top	5.0~7.0	(2004.9-2009.9 ~2011.9)	30.0	35.0	15.0	30.0	30.0	-	-
T3 bed -SM bed	2.0	(2002.6-2004.6)	22.0	10.0	12.0	12.0	10.0	-	-
T2 bed -T3 bed	1.0	(2001.6-2002.6)	5.8	5.8	6.2	5.0	7.0	7.0	-
T1 bed -T2 bed	1.0	(2000.6-2001.6)	5.1	-	1.2	2.5	3.5	2.5	-
basement sand-T1 bed	2.5	(1998.1-2000.6)	13.0	-	10.0	12.0	8.0	10.0	8.0
	Average thickness (cm/year)	Estimate mud producted weight (kg/year/m2)	Total average			Average thickness (cm/year)		Estimate mud producted weight (kg/year/m2)	
SM bed - Top	3.8-4.9	100	before 2004.9			~ 4.2 ~		86	
T3 bed -SM bed	2.9	59	after 2004.9			4.9 ~		100	
T2 bed -T3 bed	6.8	139							
T1 bed -T2 bed	2.8	57	Specific gravity of iron-oxyhydroxides: >3400 kg/m2						
basement sand-T1 bed	4.2	86	Water content use avelage 59% for core sample						

Specific gravity of iron-oxyhydroxides: >3400 kg/m2

Water content use avelage 59% for core sample