



Deposited via The University of Leeds.

White Rose Research Online URL for this paper:

<https://eprints.whiterose.ac.uk/id/eprint/167385/>

Version: Accepted Version

Article:

Baas, JH, Best, J and Peakall, J (2021) Rapid gravity flow transformation revealed in a single climbing ripple. *Geology*, 49 (5). pp. 493-497. ISSN: 0091-7613

<https://doi.org/10.1130/G48181.1>

Reuse

Items deposited in White Rose Research Online are protected by copyright, with all rights reserved unless indicated otherwise. They may be downloaded and/or printed for private study, or other acts as permitted by national copyright laws. The publisher or other rights holders may allow further reproduction and re-use of the full text version. This is indicated by the licence information on the White Rose Research Online record for the item.

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

Rapid gravity flow transformation revealed in a single climbing ripple

Jaco H. Baas¹, Jim Best² and Jeff Peakall³

¹School of Ocean Sciences, Bangor University, Menai Bridge LL59 5AB, UK, e-mail: j.baas@bangor.ac.uk

²Departments of Geology, Geography and GIS, Mechanical Science and Engineering, and Ven Te Chow Hydrosystems Laboratory, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA

³School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK

ABSTRACT

Sediment gravity flows possess a wide range of rheological behaviors and past work has shown how transformations between flow types generate spatiotemporal changes in the resultant sedimentary successions. Herein, the geometrical characteristics of a single climbing ripple are used to demonstrate how such flows can transform from a turbulent to a quasi-laminar plug flow, with the transitional clay flow sequence being manifested by abnormally large heterolithic sand–clay current ripples with small backflow ripples, and then abundant clay deposition associated with smaller ripples. Analysis of ripple size, angle of climb, grain size, internal erosional surfaces and soft-sediment deformation suggest that transformation in the rheological character of the sediment gravity flow was rapid, occurring over a period of tens of minutes, and thus probably over a spatial scale of hundreds of meters to several kilometers. The present study indicates how the character of flow transformation can be elucidated from the details of a small-scale sedimentary structure.

INTRODUCTION

Sediment gravity flows (SGFs) in oceans and lakes are a vital component of the global sediment cycle (Hessler and Fildani, 2019), and are equally important for the transport of organic carbon, nutrients and pollutants (e.g., plastics; Kane et al., 2020), pose a hazard to infrastructure (Clare et al., 2019), and their deposits may store hydrocarbons (Talling, 2014). The research and socio-economic relevance of SGFs is widely appreciated, but studying SGFs is challenging because of their unsteady

31 and non-uniform behavior. This is exacerbated by the fact that most SGFs carry clay particles that
32 aggregate to form floccules and gels, and thus enhance or suppress the shear-generated turbulence that
33 helps drive these flows and shape their deposits (Baas et al., 2009; Baker et al., 2017). Detailed
34 studies of SGF deposits have shown that these complex kinematics are expressed in the ability of
35 SGFs to transform between turbulent, transitional and laminar behavior (Haughton et al., 2009), on
36 which the concentration of suspended clay has a key influence (Baas et al., 2011). As clay
37 concentration increases, these flow types comprise: (a) turbulence-enhanced transitional flow (TETF),
38 in which turbulence is enhanced relative to clay-free turbulent flow; (b) lower transitional plug flow
39 (LTPF), in which near-bed enhanced turbulence exists below a moving plug with suppressed
40 turbulence; (c) upper transitional plug flow (UTPF), which has a thickened plug flow zone above a
41 thinned, near-bed, zone of attenuated turbulence; and (d) quasi-laminar plug flow (QLPF), in which
42 the plug extends down to the bed and turbulence is weak to absent (Baas et al., 2009). The
43 characteristic bedforms formed by transitional flow are large ripples in TETF and LTPF and low-
44 amplitude bed-waves in UTPF and QLPF (Baas et al., 2016). Large ripples have greater heights and
45 wavelengths than ripples formed in clearwater, and low-amplitude bed waves are significantly longer
46 and flatter than ripples generated in turbulent flows (Baker and Baas, 2020). Herein, we provide
47 evidence for progressive SGF transformation preserved in a single climbing ripple, which stores a
48 continuous record of bed aggradation and bedform migration. Since climbing ripples can form
49 rapidly, especially at steep angles of climb associated with rapid aggradation rates (Allen, 1963), our
50 analysis implies that flow transformation can occur in several tens of minutes. This timescale may be
51 typical of transforming SGFs in confined basins (e.g., Fongnesu et al., 2015), but it is considerably
52 shorter than for SGFs transforming in unconfined basins, which are usually 10s to 100s of km long
53 and last for several hours to days or even weeks (Azpiroz-Zabala et al., 2017).

54

55 MATERIAL AND METHODS

56 We investigated a climbing-ripple set in a polished slab from the Seathwaite Fell Sandstone
57 Formation (Ordovician, Elterwater Quarry, UK, 54.435°N, 3.046°W). This set forms a representative
58 part of a climbing ripple co-set with similar sedimentological properties (Fig. 1A; Supplementary
59 Material; Fig. S1), formed by deposition from a volcanoclastic mixed sand–clay gravity flow in a
60 caldera lake (Branney and Kokelaar, 1994). The Seathwaite Fell Sandstone Formation contains
61 various other types of primary current lamination, and soft-sediment deformation structures, denoting
62 high sediment accumulation rates and seismic instability (Barnes et al., 2006).

63 The climbing-ripple set was divided into three sectors, based on textural properties, and 21 ripple
64 positions were defined in these sectors by tracing ripple outlines (Fig. 1B). These positions were then
65 used to determine the evolution of ripple height (Fig. 1C; the vertical distance between ripple trough

66 and crest), and, where possible, ripple wavelength (the horizontal distance between adjacent ripple
67 troughs). Ripple brinkpoints were traced to determine changes in angle of climb, and the size of sand
68 grains was measured using a Dino-Lite digital microscope. Ripple types were then interpreted, based
69 on ripple size and their turbulent, transitional and laminar flow signatures (Baas et al., 2009, 2011,
70 2016). Finally, qualitative evidence for rapid bed aggradation was combined with quantitative
71 analysis using several methods (Fig. 1D) that have been proposed previously (Supplementary
72 Material; Ashley et al., 1982; Baas, 1993, 2004; Baas et al., 2000, 2009; Jobe et al., 2012) to
73 determine bed aggradation rates (Supplementary Material) and estimate the duration of deposition of
74 the climbing-ripple set.

75

76 **THE CLIMBING-RIPPLE SET EXPLAINED KINEMATICALLY**

77 *Description:* In Sector 1 (yellow lines, Fig. 1B), the ripple is sandy and climbs over a vertical
78 distance of 15.6 mm at a mean angle of 19.7°. Sector 2 is 27.7 mm thick, with a mean angle of climb
79 of 18.4° (orange lines, Fig. 1B), and possesses distinct foreset laminae of alternating sand and clay.
80 The mean sand size in Sectors 1 and 2 is 0.124 mm. Sector 3 (red lines, Fig. 1B) is clay-rich with
81 occasional thin, discontinuous, silty laminae; the ripple climbs over a vertical distance of 21.6 mm at a
82 mean angle of 44.2°. The ripple height in Sector 1 increases from 8.5 to 12.9 mm (Figs. 1C and 2),
83 and keeps growing in Sector 2, until it reaches a maximum height of 21.7 mm at the transition to
84 Sector 3 (Figs 1C and 2). In Sector 3, ripple height and wavelength decrease from 21.7 to 18.4 mm
85 (Figs 1C and 2) and from 174 to 183 mm (Fig. 1B), respectively.

86 *Interpretation:* The final ripple height of 12.9 mm in Sector 1 is less than 14.9 mm, the height at
87 which equilibrium ripples form in 0.124 mm sand under clearwater flow (Baas, 1993; Fig. 2). It is
88 therefore inferred that this ripple did not reach equilibrium and evolved between non-equilibrium
89 heights of 8.5 and 12.9 mm. The sandy nature of Sector 1 suggests that any suspended clay present
90 did not affect the flow kinematics or become incorporated into the bed. Hence, this ripple formed in a
91 ‘classic’ fully turbulent flow (Baas et al., 2011; Fig. 3B). The ripple grew in height throughout Sector
92 2 (Figs. 2 and 3C), with the final height of 21.7 mm matching the so-called ‘large ripples’ generated
93 in the laboratory (Baas et al., 2016) and described in outcrop (Baker and Baas, 2020; Fig. 2). Large
94 ripples form in TETF and LTPF (Baas et al., 2011; Fig. 3C), in which enhanced turbulence in ripple
95 troughs (Baas and Best, 2008) helps to increase ripple size. This turbulence enhancement requires a
96 local increase in suspended clay concentration, possibly combined with flow deceleration (Figs 3C
97 and S2). Further support for TETF and LTPF comes from: (a) alternating sandy and clayey laminae in
98 Sector 2, which mimics large ripples in the laboratory (Baas et al., 2011, 2016); (b) small backflow
99 ripples near the base of the ripple foreset (Fig. S3), pointing to strong vorticity and upstream flow
100 velocities in the ripple trough (Baas et al., 2011); and (c) a finer-grained core (sensu Baker and Baas,

101 2020), especially in the top half of Sector 2 (Fig. 1A), across which the sandy part of the ripple
102 migrated, signifying concurrent bedload transport of sand and fallout from suspension of clay. The
103 ripple in Sector 3 has a smaller height than in Sector 2 (Fig. 2), interpreted as the product of a further
104 increase in local suspended clay concentration combined with flow deceleration in an UTPF or QLPF
105 (Supplementary Material) that caused the ripple height to decrease (Fig. 3D). This is supported by the
106 high clay content in Sector 3, denoting significant fallout from suspension, and the fact that Baker and
107 Baas (2020) have shown that such flows form low-amplitude bed-waves, the height of which is much
108 smaller (mostly below 10 mm) and the wavelength of which is larger (200-800 mm) than for ripples
109 in turbulent and turbulence-enhanced flows. However, the bedform in Sector 3 did not reach these
110 heights and wavelengths (Fig. 2), probably because ripple development was temporarily constrained
111 and the high suspended clay concentration hindered evolution from large ripples to low-amplitude
112 bed-waves. These bedforms can therefore be classified as relict large ripples.

113 The ripple studied herein climbed at high mean angles of 18.4° to 44.2°, suggesting that the
114 vertical aggradation rate became larger relative to the migration rate (Supplementary Material).
115 Various quantitative methods (Fig. 1D; see Supplementary Material for details) show that a period of
116 the order of tens of minutes, with extremes in the Sectors 1 to 3 of 1.2-38.8 minutes, 5.9-125 minutes,
117 and 8.2-69 minutes, respectively, was sufficient to deposit the climbing-ripple set. Such rapid
118 development is also supported by qualitative data (Fig. 1A): (a) Strong erosion (>10 mm deep, Figs
119 1A and 3A) and soft-sediment deformation of clay-rich sediment at the base of the climbing-ripple co-
120 set indicate that the initial flow conditions were strong enough to deform and erode cohesive clay. The
121 occasional presence of mud clasts confirms that the substrate was firm. (b) Flow in the ripple trough
122 was fast enough to scour into the stoss side of the downstream ripple in Sectors 1 and 2 (Fig. 1A). (c)
123 soft-sediment deformation in Sector 3 (Fig. 1A) may indicate water-rich sediment linked to rapid
124 deposition (Barnes et al., 2006). This deformation was synsedimentary because local deformation is
125 healed by younger laminae.

126

127 **FLOW TRANSFORMATION IN CLIMBING RIPPLES: IMPLICATIONS**

128 The present study reveals that climbing ripples can preserve continuous records of transformation
129 from turbulent via transitional to laminar flow in a waning, mixed sand-clay, gravity current (Fig. 3),
130 and it confirms that kinematic process models for ripples in sand do not apply to ripples in mixed
131 sand-clay (Baas et al., 2016; Baker and Baas, 2020). This is not unique to the Seathwaite Fell
132 Sandstone Formation. Climbing-ripple co-sets with an upward increase in angle of climb, and
133 wavelength, are one of three climbing ripple patterns in the classification of Allen (1973), and have
134 been linked to ‘collapsing flows’ in SGFs (Jobe et al., 2012), implying that suspension fallout rates
135 increased during deposition relative to bedload transport rate. However, this does not explain the

136 simultaneous increase in ripple wavelength. We infer that the steep angle of climb near the top of co-
137 sets is caused not only by a strong increase in suspension fallout rate (e.g., Sorby, 1908; Allen, 1963;
138 Hunter, 1977) and a decrease in ripple migration rate at decreased flow velocity (cf., Jopling and
139 Walker, 1968), but also by a slowing of ripple migration through turbulence attenuation induced by
140 cohesive clay (Baas et al., 2011). The mud-rich, longer-wavelength bedforms similar to those in
141 Sector 3, found at the top of these sequences (Walker, 1963; Jopling and Walker, 1968; Bhattacharjee,
142 1970) also reflect flow transformation. For example, Bhattacharjee (1970) described muddy bedforms
143 in the Cloridorme Formation (Québec, Canada), 13.6 mm high and 353 mm long, which match the
144 size of low-amplitude bed-waves (Baas et al., 2016; Baker and Baas, 2020; Fig. 2). Bhattacharjee
145 (1970) also described ripples with a similar wavelength but a larger height (27 mm; his figure 8) in
146 clay-rich sandstones below climbing low-amplitude bed-waves, thus resembling large ripples (Baas et
147 al., 2016; Baker and Baas, 2020; cf., Stanley, 1974; Fig. 2). This change from large ripples to low-
148 amplitude bed-waves matches the climbing-ripple co-set studied herein, except that the bedforms in
149 the Cloridorme Formation were able to fully complete this change.

150 It thus appears that the climbing ripples described herein are a common sedimentary structure.
151 They resemble the Type-3 climbing ripple co-sets of Walker (1963; his table II), almost exclusively
152 found in turbidites. Therefore, in addition to providing evidence for flow transformation, the mixed
153 sand–clay climbing ripple co-sets described herein may also be a strong indicator for waning gravity
154 flows in deep-marine or lacustrine depositional environments. In most scenarios, waning mixed sand–
155 clay gravity flows must pass through flow types in which turbulence is first enhanced and then
156 attenuated (Fig. S1), and thus large ripples and low-amplitude bed-waves can be expected to be
157 common bedform types in mixed sand–clay climbing ripple co-sets. Together with sandy ripples,
158 these bedforms provide a novel tool to reconstruct temporal changes in SGF kinematics.

159 The present analysis illustrates that rates of flow transformation in SGFs, and thus rates at which
160 cohesivity may develop, can be as rapid as several tens of minutes. In the example described herein,
161 this duration converts into flow lengths of hundreds of meters to several kilometers for flow velocities
162 at which current ripples are stable. These temporal and spatial scales correspond to those inferred
163 from the deposits of SGFs that comprise a hybrid between turbulent and laminar behavior in confined
164 basins (e.g., Fonnesu et al., 2015). However, these scales are at least an order of magnitude shorter
165 than for unconfined basins, which usually contain rapid flows that are 10s to 100s of km long (e.g.,
166 Haughton et al., 2009; Talling, 2013; Talling et al., 2013) and may last for several hours to days or
167 even weeks (Azpiroz-Zabala et al., 2017). The present analysis shows that once such flows start to
168 decelerate, transformation can occur rapidly, and that SGF deposits can leave evidence of this flow
169 transformation at a scale of 10s of mm that can be recognized in cores and small outcrops.

170

171 **CONCLUSIONS**

172 The rate of flow transformation within a SGF is revealed by analysis of bedform size, grain size
173 and the microstructure of cross-stratification within a single climbing ripple set. The present study
174 demonstrates that an initially turbulent flow that is aggradational and generates climbing ripples,
175 begins to develop large ripples in TETF or LTPF, as the flow decelerates. These large ripples are
176 generated by increased turbulence in the ripple trough that causes additional scour that may also form
177 small backflow ripples. These large ripples are also characterized by heterolithic deposition on the
178 ripple leeward side, as fallout from suspension becomes more dominant than sand and silt avalanching
179 down the leeward slope. Further flow deceleration, and increases in clay concentration, cause more
180 rapid aggradation, and higher angles of climb, of the clay-rich current ripple, which also becomes
181 smaller due to the dampening of turbulence in UTPF or QLPF. Further analysis reveals that such flow
182 transformation, from turbulent to quasi-laminar plug flow, was rapid and occurred over a period of
183 tens of minutes, suggesting that the spatial distance over which such transformation took place was
184 hundreds of meters to several kilometers. Quantification of the microstructure of such climbing ripple
185 sequences may hold untapped potential for reconstructing the temporal fluid dynamics of clay-laden
186 SGFs in many sedimentary environments.

187

188 **ACKNOWLEDGMENTS**

189 We thank Fiona Cameron, Burlington Stone, UK, for arranging access to these materials, and Zane
190 Jobe, Matthieu Cartigny, and Bill Arnott for their insightful reviews.

191

192 **REFERENCES CITED**

193 Allen, J. R. L., 1963, Asymmetrical ripple marks and the origin of water-laid cosets of cross-
194 strata: *Liverpool Manchester Geological Journal*, v. 3, p. 187-236.

195 Allen, J. R. L., 1973, A classification of climbing-ripple cross-lamination: *Journal of the*
196 *Geological Society of London*, v. 129, p. 537-541.

197 Ashley, G. M., Southard, J. B., and Boothroyd, J. C., 1982, Deposition of climbing-ripple beds: a
198 flume simulation: *Sedimentology*, v. 29, p. 67-79.

199 Azpiroz-Zabala, M., Cartigny, M. J. B., Talling, P. J., Parsons, D. R., Sumner, E. J., Clare, M. A.,
200 Simmons, S. M., Cooper, C., and Pope, E. L., 2017, Newly recognized turbidity current structure can
201 explain prolonged flushing of submarine canyons: *Science Advances*, v. 3, e1700200.

202 Baas, J. H., 1993, Dimensional analysis of current ripples in recent and ancient depositional
203 environments: *Geologica Ultraiectina*, v. 106, p. 199.

204 Baas, J. H., 2004, Conditions for formation of massive turbiditic sandstones by primary
205 depositional processes: *Sedimentary Geology*, v. 166, p. 293-310.

206 Baas, J. H., and Best, J. L., 2008, The dynamics of turbulent, transitional and laminar clay-laden
207 flow over a fixed current ripple: *Sedimentology*, v. 55, p. 635-666.

208 Baas, J. H., Best, J. L., Peakall, J., and Wang, M., 2009, A phase diagram for turbulent,
209 transitional, and laminar clay suspension flows: *Journal of Sedimentary Research*, v. 79, p. 162-183.

210 Baas, J. H., Best, J. L., and Peakall, J., 2011, Depositional processes, bedform development and
211 hybrid flows in rapidly decelerated cohesive (mud-sand) sediment flows: *Sedimentology*, v. 58, p.
212 1953-1987.

213 Baas, J. H., Best, J. L., and Peakall, J., 2016, Predicting bedforms and primary current
214 stratification in cohesive mixtures of mud and sand: *Journal of the Geological Society*, v. 173, p. 12-
215 45.

216 Baas, J. H., van Dam, R. L., and Storms, J. E. A., 2000, Duration of deposition from decelerating
217 high-density turbidity currents: *Sedimentary Geology*, v. 136, p. 71-88.

218 Baker, M. L., and Baas, J.H., 2020, Mixed sand–mud bedforms produced by transient turbulent
219 flows in the fringe of submarine fans: Indicators of flow transformation: *Sedimentology*, v. 67, p.
220 2645-2671.

221 Baker, M. L., Baas, J. H., Malarkey, J., Silva Jacinto, R., Craig, M. J., Kane, I. A., and Barker,
222 S., 2017, The effect of clay type on the properties of cohesive sediment gravity flows and their
223 deposits: *Journal of Sedimentary Research*, v. 87, p. 1176-1195.

224 Barnes, R. P., Branney, M. J., Stone, P., and Woodcock, N.H., 2006, The Lakesman Terrane: the
225 Lower Palaeozoic record of the deep marine Lakesman Basin, a volcanic arc and foreland basin, *in*
226 Branchley, P.J., and Rawson, P.F., eds., *The Geology of England and Wales*, Geological Society,
227 London, *Geology Of Series*, p. 103-130.

228 Bhattacharjee, S. B., 1970, Ripple-drift cross-lamination in turbidites of the Ordovician
229 Cloridorme Formation, Gaspé, Québec [M.Sc. Thesis], McMaster University, Hamilton, Ontario,
230 Canada, 281 p.

231 Branney, M. J., and Kokelaar, P., 1994, Volcanotectonic faulting, soft-state deformation, and
232 rheomorphism of tuffs during development of a piecemeal caldera, English Lake District: *Geological*
233 *Society of America Bulletin*, v. 106, p. 507-530.

234 Clare, M., Chaytor, J., Dabson, O., Gamboa, D., Georgiopolou, A., Eady, H., Hunt, J., Jackson,
235 C., Katz, O., Krastel, S., León, R., Micallef, A., Moernaut, J., Moriconi, R., Moscardelli, L., Mueller,
236 C., Normandeau, A., Patacci, M., Steventon, M., Urlaub, M., Völker, D., Wood, L., and Jobe, Z.,
237 2019, A consistent global approach for the morphometric characterization of subaqueous landslides:
238 Geological Society, London, Special Publications, v. 477, p. 455-477.

239 Fonnesu, M., Haughton, P., Felletti, F., and McCaffrey, W., 2015, Short length-scale variability
240 of hybrid event beds and its applied significance: *Marine and Petroleum Geology*, v. 67, p. 583-603.

241 Haughton, P., Davis, C., McCaffrey, W., and Barker, S., 2009, Hybrid sediment gravity flow
242 deposits - Classification, origin and significance: *Marine and Petroleum Geology*, v. 26, p. 1900-1918.

243 Hessler, A.M., and Fildani, A., 2019, Deep-sea fans: Tapping into Earth's changing landscapes:
244 *Journal of Sedimentary Research*, v. 89, p. 1171-1179.

245 Hunter, R.E., 1977, Terminology of cross-stratified sedimentary layers and climbing-ripple
246 structures: *Journal of Sedimentary Petrology*, v. 47, p. 697-706.

247 Jobe, Z. R., Lowe, D. R., and Morris, W. R., 2012, Climbing-ripple successions in turbidite
248 systems: depositional environments, sedimentation rates and accumulation times: *Sedimentology*, v.
249 59, p. 867-898.

250 Jopling, A. V., and Walker, R. G., 1968, Morphology and origin of ripple-drift cross-lamination,
251 with examples from the Pleistocene of Massachusetts: *Journal of Sedimentary Petrology*, v. 38, p.
252 971-984.

253 Kane, I. A., Clare, M. A., Miramontes, E., Wogelius, R., Rothwell, J.J., Garreau, P., and Pohl, F.,
254 2020, Seafloor microplastic hotspots controlled by deep-sea circulation: *Science*, v. 368, p. 1140-
255 1145.

256 Sorby, H. C., 1908, On the application of quantitative methods to the study of the structure and
257 history of rocks: *Quarterly Journal of the Geological Society of London*, v. 64, p. 171-233.

258 Stanley, K. O., 1974, Morphology and hydraulic significance of climbing ripples with
259 superimposed micro-ripple-drift cross-lamination in lower Quaternary lake silts, Nebraska: *Journal of*
260 *Sedimentary Petrology*, v. 44, p. 472-483.

261 Talling, P. J., 2013, Hybrid submarine flows comprising turbidity current and cohesive debris
262 flow: Deposits, theoretical and experimental analyses, and generalized models: *Geosphere*, v. 9, p.
263 460-488.

264 Talling, P. J., 2014, On the triggers, resulting flow types and frequencies of subaqueous sediment
265 density flows in different settings: *Marine Geology*, v. 352, p. 155-182.

266 Talling, P. J., Paull, C. K., and Piper, D. J. W., 2013, How are subaqueous sediment density
267 flows triggered, what is their internal structure and how does it evolve? Direct observations from
268 monitoring of active flows: *Earth-Science Reviews*, v. 125, p. 244-287.

269 Walker, R. G., 1963, Distinctive types of ripple-drift cross-lamination: *Sedimentology*, v. 2, p.
270 173-188.

271

272 **FIGURE CAPTIONS**

273 **Figure 1.** (A) Climbing-ripple co-set in Seathwaite Fell Sandstone Formation, UK. Inset shows
274 location of (B). Flow direction is towards right. (B) High-contrast image of the climbing-ripple set,
275 highlighting 21 ripple outlines in Sectors 1 (yellow), 2 (orange), and 3 (red). Blue dashed line traces
276 the ripple brinkpoints. Inset shows location of Fig. S3. TF = turbulent flow; TETF = turbulence-
277 enhanced transitional plug flow; LTPF/UTPF = lower/upper transitional plug flow; QLPF = quasi-
278 laminar plug flow. (C) Horizontal position of the ripple brinkpoint vs ripple height and angle of climb
279 for the three sectors. Numbers refer to ripple outlines in (B). (D) Estimated durations of deposition of
280 Sectors 1 (yellow), 2 (orange), and 3 (red), using the methods described in the Supplementary
281 Material. Note that the range for bed sediment flux & ripple height in Sector 2 may be overestimated
282 (see Supplementary Material).

283 **Figure 2.** Compilation of wavelengths and heights for sandy ripples, large ripples and low-amplitude
284 bed-waves. Black box: predicted size range of non-equilibrium and equilibrium ripples in 0.124 mm
285 sand (Baas, 1993). Yellow dots: sandy ripples for a range of grain sizes. Note that all large ripples and
286 low-amplitude bed-waves are outside the size range of ripples in 0.124 mm sand.

287 **Figure 3.** Schematic model for the formation of the climbing-ripple set. (A) Erosion by turbulent flow
288 front. (B) Sandy ripples formed by turbulent body of flow. (C) Mixed sand–clay large ripples formed
289 by turbulence-enhanced flow. (D) Clay-rich ripples formed by turbulence-attenuated flow. (E)
290 Schematic temporal changes in flow velocity, near-bed clay concentration and turbulence, sand and
291 clay aggradation rate, and angle of climb. See Fig. 1 for explanation of flow types.

292

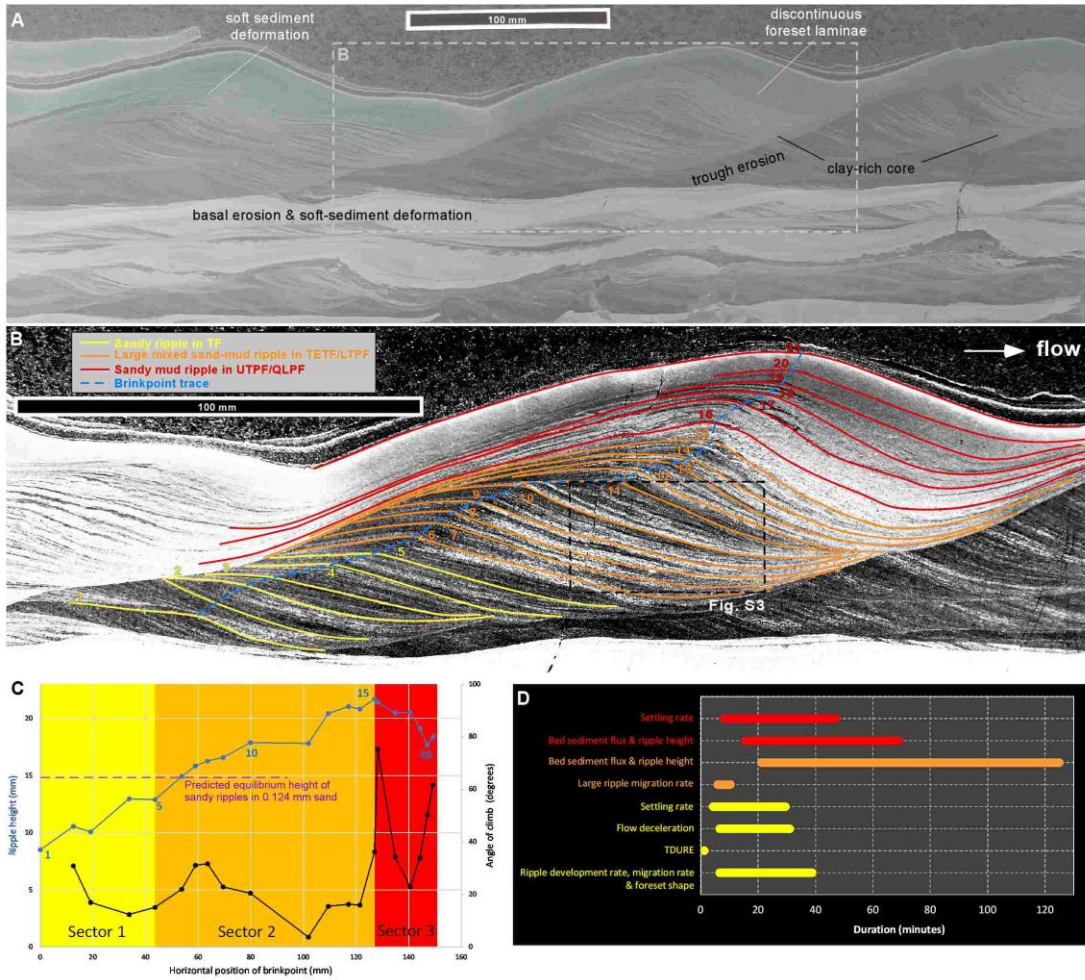
293

294

295

296

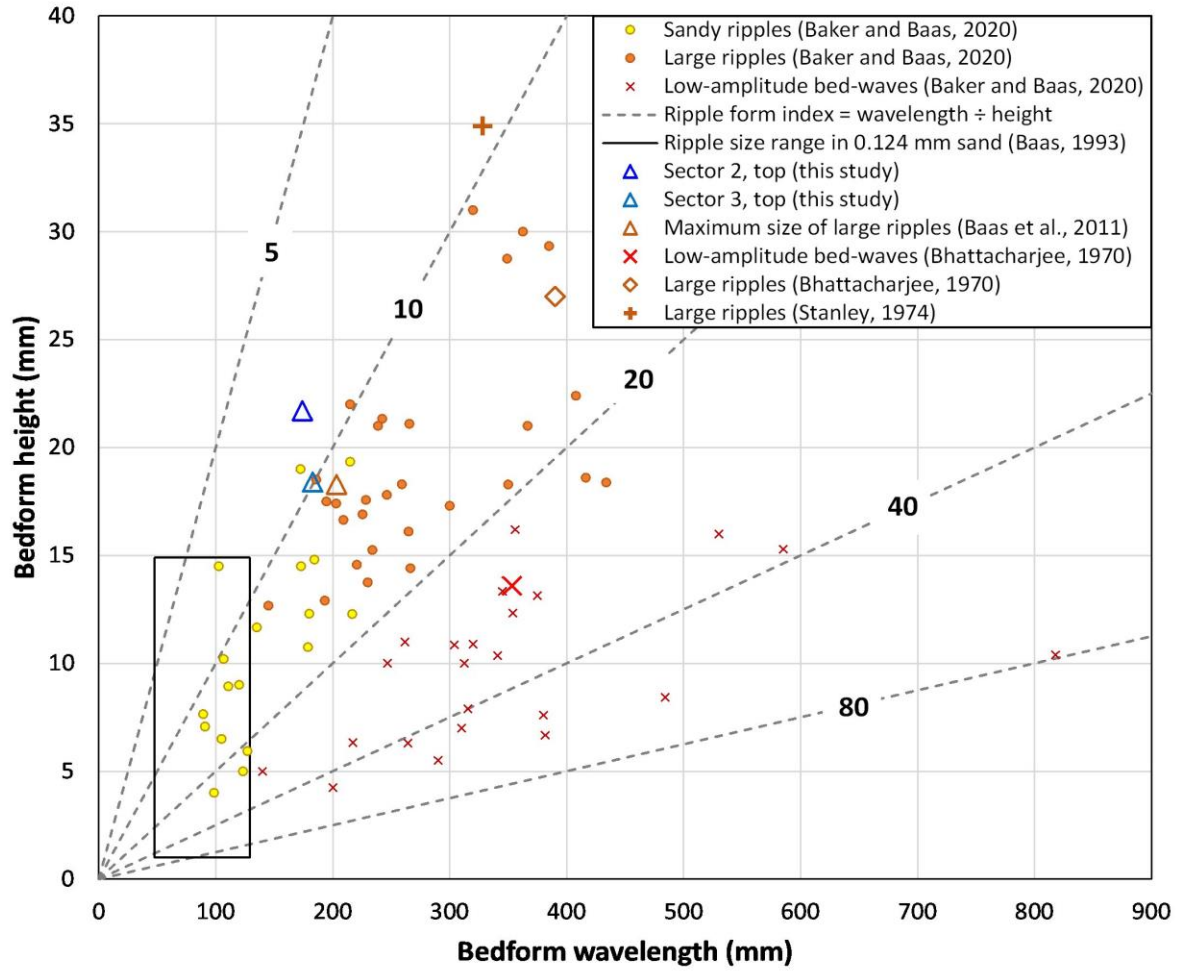
297



298

299 Figure 1

300

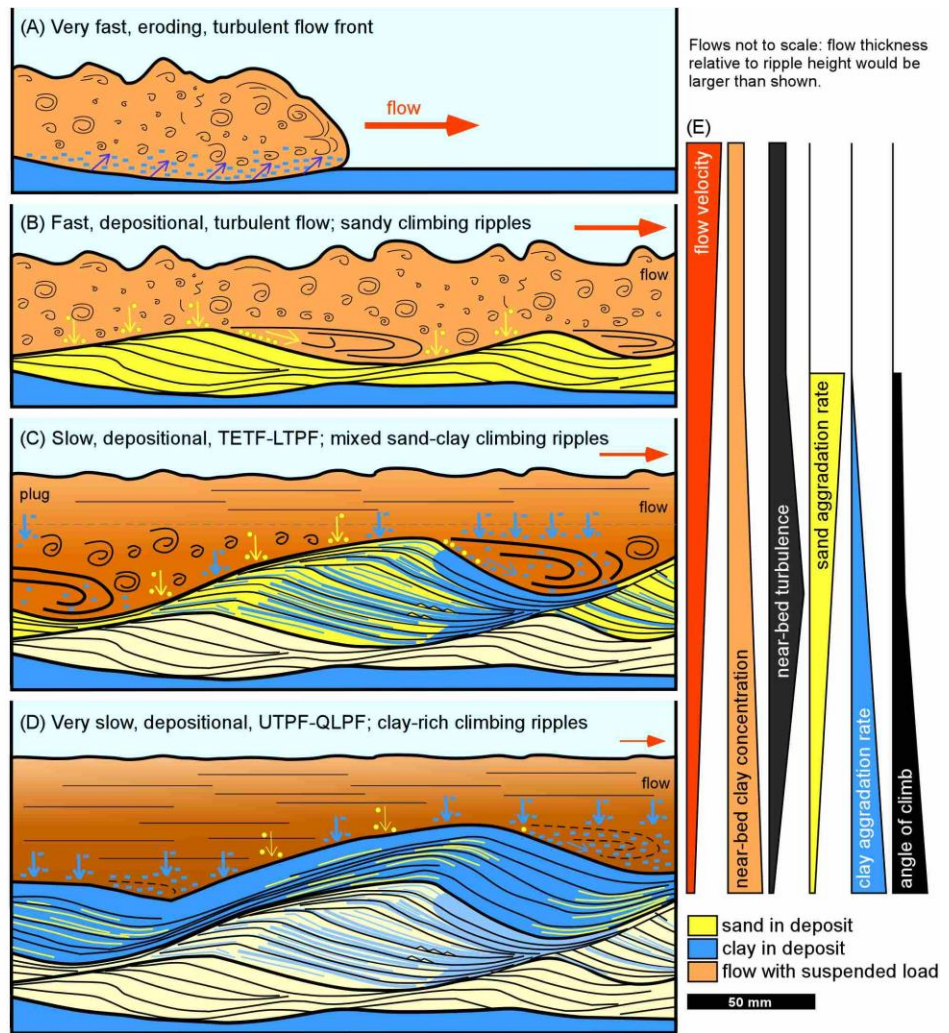


301

302 Figure 2

303

304



305

306 Figure 3

1 **COMPARISON OF CLIMBING-RIPPLE SETS**

2

3 The evolution of the height of the climbing ripple set described in the main text, as well as the climbing
4 ripple set immediately downstream (right-hand side of Fig. 1A), are compared in Fig. S1. For both
5 ripple sets, the height increases from *c.* 8 mm to 22-23 mm and then decreases to 15-17 mm. This
6 suggests that both ripple sets evolved from sandy ripples via large ripples to relict large ripples.
7 Moreover, low-amplitude bed-waves did not form, likely because of time constraints on ripple
8 development and high suspended clay concentrations hindered evolution from large ripples to low-
9 amplitude bed-waves, as described in the main text. Figure S1 also reveals that the downstream climbing
10 ripple set reached its maximum height over a shorter migration distance than the climbing ripple set
11 described in the main text, but the steepest decrease in height occurred at a similar migration distance.
12 This difference in the rate of development is inferred to result from the dynamic behavior of rippled
13 beds; individual ripples affect the local flow field, which may either promote or hinder the migration
14 rate and development rate of adjacent ripples (Baas, 1993). In this case, the climbing ripple set described
15 in the main text may have promoted the development of large ripples in the climbing ripple set
16 immediately downstream. Despite this difference in evolution, both climbing ripple sets are sufficiently
17 similar to support the main conclusion that evidence for rapid flow transformation can be preserved in
18 climbing ripple co-sets.

21 **QUANTITATIVE EVIDENCE FOR RAPID AGGRADATION IN THE** 22 **CLIMBING-RIPPLE SET**

23

24 The angle of climb of climbing-ripple co-sets is controlled by the ratio of the suspended sediment
25 fallout rate to the rate of downstream ripple migration. Although a steep angle of climb is more likely
26 caused by a high aggradation rate (Sorby, 1859; Reineck, 1961; Allen, 1963; Walker, 1963; Jopling &
27 Walker, 1968; Środoń, 1974; Banerjee, 1977; Jobe et al., 2012), Allen (1970) highlighted the main
28 limitation of deducing physical sedimentary processes from climbing-ripple co-sets: “On the cautionary
29 note, all that can be deduced from the geometrical properties of climbing-ripple cross-lamination is the
30 ratio of the sediment deposition rate to the bedload transport rate”. In other words, high angles of
31 climbing-ripple co-sets may be formed by any aggradation rate, provided that the ripple migration rate
32 is significantly lower than the aggradation rate. For example, simple trigonometry can be used to show
33 that a high climbing angle of 20° can be achieved at a low aggradation rate of 0.001 mm s⁻¹ by ripples

34 that migrate at a low rate of 0.003 mm s^{-1} , or at a high aggradation rate of 0.1 mm s^{-1} and with a high
35 ripple migrate rate of 0.3 mm s^{-1} . In very fine sand, these two ripple migration rates are associated with
36 either low flow velocities close to the threshold of sediment motion (c. 0.25 m s^{-1}) or high flow velocities
37 near the transition to washed-out ripples and upper-stage plane bed conditions (c. 0.60 m s^{-1}),
38 respectively (Baas et al., 2000). It is therefore essential to use other physical sedimentological
39 parameters, in addition to angle of climb, to estimate the aggradation rate from climbing-ripple co-sets,
40 and from this the duration of deposition represented by these co-sets. The main text of the present paper
41 provides qualitative support for high aggradation rates. Herein, a complimentary more quantitative
42 approach is outlined. It is assumed that the orientation of the climbing-ripple co-set is parallel to the
43 paleoflow direction, as supported by a maximum foreset slope angle of 27° , which is close to the angle
44 of repose for loose sand. This high slope angle also suggests that post-depositional compaction did not
45 significantly influence the ripple height.

46 As discussed in the main text, the climbing-ripple set is divided into three sectors, representing a
47 progressive change from turbulent flow (Sector 1), through turbulence-enhanced transitional flow and
48 lower transitional plug flow (Sector 2), to upper transitional plug flow and quasi-laminar plug flow
49 (Sector 3), with the transitional flow terms sensu Baas et al. (2009). Our quantitative assessment of
50 aggradation rates and duration of deposition for each of these three sectors in the climbing-ripple set is
51 given below, before estimating the total time needed to form the climbing-ripple set.

52

53 **Sector 1 – Sandy current ripples formed by turbulent flow**

54 *Ripple development*

55 Sector 1 of the climbing-ripple set has an average climbing angle of 19.7° , with a ripple migration
56 distance of 43.6 mm and an aggradation height of 15.6 mm. These sandy ripples grew in height from
57 8.5 mm to 12.9 mm between the base and top of Sector 1. The final height of 12.9 mm is below 14.9
58 mm, which, for the 0.124 mm sand observed herein, is the height at which the ripples are in equilibrium
59 with the flow conditions, based on the ripple size predictor of Baas (1993):

$$60 \quad H_e = 3.4 \log_{10}(D_{50}) + 18 \quad (\text{S1})$$

61 where H_e is the equilibrium height in millimeters and D_{50} is the median grain size in millimeters. It is
62 therefore inferred that in Sector 1 the ripples did not reach equilibrium and evolved between non-
63 equilibrium heights of 8.5 mm and 12.9 mm. Current ripples in 0.124 mm sand form at flow velocities
64 between c. 0.25 m s^{-1} and 0.80 m s^{-1} in flow depths of more than 0.25 m (Southard & Boguchwal, 1990;
65 their figure 3). Following the current ripple development model of Baas (1993) and interpolating
66 between 0.095 mm sand (Baas, 1994) and 0.238 mm sand (Baas, 1999), ripples at these velocities need
67 c. 2253 hours at 0.25 m s^{-1} and c. 6.6 minutes at 0.80 m s^{-1} to reach the observed final height of 12.9

68 mm. This large range in duration of deposition can be constrained in different ways, as detailed in the
69 following sub-sections.

70 *Migration rate*

71 The ripple migration rates for flow velocities between 0.25 m s^{-1} and 0.80 m s^{-1} , after conversion
72 from Shields parameter to flow velocity and interpolation between 0.095 mm and 0.238 mm sand (Baas
73 et al., 2000; their figure 1) range from 0.0037 mm s^{-1} to 2.18 mm s^{-1} , respectively. These migration
74 rates, at the migration distance of 43.6 mm in Sector 1, result in durations of deposition of between 0.3
75 minutes and 196 minutes. Hence, the time needed to deposit Sector 1 of the climbing-ripple set is
76 reduced to 6.6 - 196 minutes.

77 *Transition from angular to sigmoidal foresets*

78 Ashley et al. (1982) found experimentally that the foreset laminae of sandy climbing ripples change
79 from angular to sigmoidal, as the aggradation rate is increased from 0.0067 mm s^{-1} to 0.015 mm s^{-1} .
80 Since the cross-laminae in the climbing-ripple set are clearly sigmoidal (Fig. 1B), this approach can be
81 used to estimate the duration of deposition. At the aggradation height of 15.6 mm in the climbing-ripple
82 set under consideration herein, these aggradation rates translate into durations of deposition of 38.8
83 minutes and 17.3 minutes, respectively. This suggests that this set was formed within 38.8 minutes, thus
84 further constraining the duration of deposition to 6.6 - 38.8 minutes.

85 *Turbidite duration estimation (TDURE) model*

86 Baas et al. (2000) and Baas (2004) used the TDURE model to calculate the duration of deposition of
87 sediment from the thickness of Ta, Tb and Tc divisions, and the height and angle of climb of climbing
88 ripples in Bouma-type turbidites (Bouma, 1962). For the present case, TDURE yields a duration of
89 deposition for Sector 1 of 1.2 minutes. However, this duration is a crude estimate, because TDURE
90 assumes that: (i) the ripples start to form on an upper-stage plane bed; and (ii) the top of the climbing-
91 ripple co-set represents slow flow at the threshold of sediment motion. Both of these conditions need
92 not be representative of the sample studied herein. The base of the climbing ripple set may have formed
93 at any velocity in the current ripple stability regime; lower initial velocities would increase the predicted
94 duration of deposition of Sector 1. Moreover, the top of the set was probably formed at a velocity
95 significantly above the threshold of sediment motion (*c.* 0.25 m s^{-1} for 0.124 mm sand), given that the
96 ripples kept climbing steeply into Sector 2, which would decrease the predicted duration of deposition
97 of Sector 1. Yet, the short duration predicted by TDURE, together with the above constraint of the
98 duration of deposition to 6.6 - 38.8 minutes, renders it unlikely that the duration of deposition was
99 longer than several tens of minutes.

100 *Flow deceleration: the clay flow phase diagram*

101 Given the muddy character of the deposits below, above and within the climbing-ripple co-set, we
102 assume that the climbing ripples in Sector 1 were formed in a flow that carried cohesive clay. The
103 velocity range at which current ripples form in 0.124 mm sand is linked to clay concentration through
104 the clay flow phase diagram of Baas et al. (2009; Fig. S2). This diagram shows the stability regimes of
105 turbulent, transitional and laminar clay flow as a function of flow velocity and suspended clay
106 (kaolinite) concentration. Because the Sector 1 ripples formed in turbulent flow, the suspended clay
107 concentration should have been below 4% (*i.e.* where 0.80 m s^{-1} crosses the boundary between turbulent
108 flow [TF] and turbulence-enhanced transitional flow [TETF]), or at progressively lower maximum clay
109 concentrations if the Sector 1 ripples formed below 0.80 m s^{-1} , since the TF-TETF boundary shifts to
110 lower clay concentrations as the velocity decreases. The yellow, red and purple arrows in Fig. S2 show
111 three possible paths for the flow that formed the climbing-ripple set. The yellow arrow presumes that
112 the flow decelerates, but the suspended concentration is constant (or weakly decreasing or increasing)
113 during deceleration. This scenario is unlikely to explain the formation of the climbing-ripple set for two
114 principal reasons: (i) the flow would be incapable of reaching upper-transitional plug flow or quasi-
115 laminar plug flow behavior required to form Sector 3 of the climbing-ripple set before the velocity
116 becomes too low for ripple migration at 0.25 m s^{-1} ; and (ii) a constant (or weakly decreasing or
117 increasing) clay concentration is unlikely in waning flow and contrasts with the upward increase in clay
118 content in the deposit. The red arrow represents a scenario in which the climbing-ripple set starts to
119 form at a low velocity and then decelerates over a narrow range of velocities. This scenario requires a
120 strong increase in clay concentration of almost two orders of magnitude to pass the various clay flow
121 types needed to form all three sectors of the climbing-ripple set. This combination of weak flow waning
122 and strong bulking of the flow with clay would be difficult to achieve without invoking specific external
123 factors, such as tapping into an upstream clay source during development of the climbing-ripple co-set.
124 A combination of deceleration over a wider range of velocity and a narrower range of clay concentration
125 is a more plausible scenario (purple arrow in Fig. S2), because a large decrease in velocity is often
126 associated hydrodynamically with increased fallout of clay from suspension and thus an increase in clay
127 concentration above the ripple crest and in the ripple trough. This scenario thus also explains the vertical
128 increase in clay content in the climbing-ripple set. Moreover, the clay concentration does not need to
129 increase over two orders of magnitude, as the clay concentration of the flow that formed the first ripple
130 in Sector 1 of the climbing-ripple set may have carried up to 4% clay. Since a high initial velocity in
131 the ripple regime is required to achieve the strong flow waning in this scenario, this increases the
132 likelihood that the ripples in Sector 1 migrated rapidly and therefore the climbing ripple was exposed
133 to rapid aggradation to maintain the climbing angle. In turn, this suggests that the duration of deposition
134 of these sandy ripples was shorter than estimated with the above methods for determining flow velocity
135 and ripple migration rate, because migration rate increases exponentially with flow velocity (Baas et
136 al., 2000). For example, the above estimate of 6.6 - 196 minutes, based on maximum and minimum
137 ripple migration rate, is reduced to 6.6 - 31.0 minutes and 6.6 - 7.8 minutes, if the climbing-ripple set

138 was formed at Sector-1 averaged velocities of 0.35 m s⁻¹ and 0.45 m s⁻¹, respectively. These ranges are
139 comparable to those inferred from the foreset laminae shape (Ashley et al., 1982) and the TDURE
140 model (Baas, 2004) above.

141 *Settling rate*

142 Jobe et al. (2012) used the following relationship between aggradation rate and particle fall velocity
143 under hindered settling conditions for the analysis of climbing-ripple co-sets:

$$144 \quad w_{s,h} C_{susp} = U_{bed} C_{bed} \quad (S2)$$

145 where $w_{s,h}$ is the fall velocity corrected for hindered settling, C_{susp} is the concentration of sand or silt
146 particles in the flow, U_{bed} is the bed aggradation rate, and $C_{bed} = 0.65$ is the concentration of the sand or
147 silt particles in the bed, assuming a random packing density. Values for $w_{s,h}$ were calculated from the
148 hindered settling relationship of Richardson & Zaki (1954):

$$149 \quad w_{s,h} = w_s (1 - C_{susp})^{4.65} \quad (S3)$$

150 where w_s is the fall velocity of a single particle in clear water. The fall velocity for 0.124 mm sand
151 particles in clear water is 0.012 m s⁻¹ (Soulisby, 1997). Combining Equations S2 and S3 and using a
152 realistic range of C_{susp} -values for turbulent sediment gravity flows of 0.5% to 4% (*cf.* Fig. S2) yields
153 $0.088 < U_{bed} < 0.60$ mm s⁻¹. For Sector 1 of the climbing-ripple set, this converts into a duration of
154 deposition of between 0.4 minutes and 3.0 minutes. However, the fall velocity used herein may be
155 overestimated, because the very fine sand particles did not settle through quiescent water, and thus
156 turbulence in the flow will have reduced the fall velocity, and the presence of up to 4% clay will have
157 further reduced the fall velocity through enhanced hindered settling and increasing the water viscosity.
158 However, even if this reduction had been an order of magnitude, the duration of deposition of Sector 1
159 would have increased to only 4.3 - 29.5 minutes, well within the range of durations calculated with the
160 above methods.

161 *Summary for Sector 1*

162 Although no precise values for the duration of deposition for the sandy ripples in Sector 1 of the
163 climbing-ripple set can be calculated, the combination of methods used herein implies that Sector 1 was
164 formed rapidly, within time periods of minutes to several tens of minutes.

165

166 **Sector 2 – Mixed sand–clay large ripples formed by turbulence-enhanced transitional flow and** 167 **lower transitional plug flow**

168 Sector 2 of the climbing-ripple set has an average angle of climb of 18.4°, with a ripple migration
169 distance of 83.3 mm and an aggradation height of 27.7 mm. These heterolithic sand–clay ripples grew

170 in height from 12.9 mm to 21.7 mm between the base and top of Sector 2. Two different approaches
171 are taken herein to estimate the duration of deposition in the sub-sections below.

172 *Comparison with experiments of Baas et al. (2011)*

173 Large ripples in cohesive mixed sand–clay flows were described for the first time by Baas et al. (2011).
174 The kinematic behavior of large ripples is more poorly known than that of the type of sandy ripples
175 present in Sector 1, which have been studied for more than a century (*e.g.* Sorby 1859, 1908).
176 Consequently, the duration of deposition of the large ripples in Sector 2 is more difficult to estimate
177 than in Sector 1. Baas et al. (2011) described large ripples in heterolithic deposits of kaolinite clay and
178 poorly sorted silty sand (median diameter: 0.084 mm). These large ripples formed at a mean flow
179 velocity of 0.44 m s^{-1} , were up to 18 mm high and 203 mm long, and migrated at a rate that decreased
180 from 0.236 mm s^{-1} to 0.133 mm s^{-1} , as suspended clay concentration was increased from 1.1% to 8.0%.
181 These numerical values are of the same order of magnitude as those inferred to predict durations of
182 deposition, for the climbing ripple set examined herein, from the clay flow phase diagram of Baas et al.
183 (2009) (*e.g.* purple arrow in Fig. S2). Applying migration rates of 0.133 mm s^{-1} to 0.236 mm s^{-1} to the
184 climbing-ripple set in Sector 2 yields durations of deposition of 10.4 minutes and 5.9 minutes,
185 respectively. These durations should be considered approximate, because the mean velocity at which
186 the large ripples formed may not have been close to 0.44 m s^{-1} . A higher and lower mean velocity for
187 Sector 2 would decrease and increase the duration of deposition, respectively.

188 *Bed sediment flux and ripple height*

189 Interestingly, the bed sediment flux associated with ripple migration is nearly constant ($0.9 - 1.1 \text{ mm}^2$
190 s^{-1}) over almost the entire range of suspended clay concentrations (0.2 - 6.9%) at which ‘normal’ current
191 ripples and large ripples were the stable bedform phase in the experiments of Baas et al. (2011; their
192 figure 15c). Because the bed sediment flux is dependent on the product of ripple migration rate and
193 ripple height, and ripple migration rate decreased as clay concentration was increased in the experiments
194 of Baas et al. (2011), the bed sediment flux was governed primarily by the ripple height. Hence, an
195 increase in ripple height in steady flow should result in a proportional decrease in ripple migration rate.
196 If it is assumed that this relationship is applicable to other flow velocities and sediment sizes, and taking
197 the conservative estimate of the Sector 1 duration of deposition of 6.6 - 38.8 minutes, Sector 2 could
198 have been deposited in 21.2 - 125 minutes. This increase in duration reflects the increase in ripple height
199 from 12.9 mm in Sector 1 to 21.7 mm in Sector 2, and the larger aggradation distance of Sector 2.
200 However, these calculations do not include the possible contribution to the migration rate of the large
201 ripples by fallout from suspension of clay particles, which make up more than half of the foreset laminae
202 in Sector 2 (Fig. 1A,B), and that are also thicker than the clay-rich laminae shown in Baas et al. (2011).
203 Incorporating this extra downward flux is expected to reduce the duration of deposition of Sector 2, but
204 a precise reduction cannot be calculated at present.

205 *Summary for Sector 2*

206 We conclude that the two methods used herein suggest that several minutes to several tens of minutes
207 were required to form Sector 2 of the climbing-ripple set. The rapid aggradation rate in Sector 1 thus
208 continued into Sector 2.

209

210 **Sector 3 – Clay-rich ripples formed by upper transitional plug flow and quasi-laminar plug flow**

211 Sector 3 of the climbing-ripple set has an average angle of climb of 44.2°, with a ripple migration
212 distance of 22.2 mm and an aggradation height of 21.6 mm. The height of these clay-rich ripples
213 decreases from 21.7 mm to 18.4 mm between the base and top of Sector 3. The duration of deposition
214 of this section is estimated in two different ways detailed below.

215 *Bed sediment flux and ripple height*

216 As for the large ripples in Sector 2, a small amount of information is available from past work
217 concerning the kinematics of clay-rich bedforms, which are interpreted to have formed by upper
218 transitional plug flow and quasi-laminar plug flow in Sector 3 of the climbing-ripple set. Baas et al.
219 (2011; their figure 11) measured the aggradation rate in the same rapidly decelerated kaolinite clay
220 flows that formed the large ripples described above, but at higher suspended clay concentrations of
221 10.1% to 19.2%. In the first 15 minutes after flow deceleration, when the flow velocity was steady at
222 0.44 m s⁻¹, the mean aggradation rate ranged from 0.005 mm s⁻¹ to 0.023 mm s⁻¹. Using these aggradation
223 rates, the 21.6 mm thick Sector 3 is predicted to have been deposited in 15.5 - 69.0 minutes. However,
224 the aggradation rate at a fixed suspended clay concentration is expected to vary with flow velocity.

225 *Settling rate*

226 The settling velocity of clay particles is highly dependent on flocculation, but, owing to the low salinity
227 of the water in the caldera lake, the clay may have aggregated into microflocs (Eisma, 1986), rather
228 than staying as single clay particles that are rare in nature (Schieber et al., 2007), or forming larger
229 macroflocs that are common in more saline water. The diameter of microflocs was delimited by
230 Mikkelsen et al. (2006) to 0.036 - 0.133 mm, and the settling velocity of such microflocs is *c.* 0.126
231 mm s⁻¹ to 0.463 mm s⁻¹ (Fig. S4), which corresponds well with the mean settling velocity of 0.34 mm
232 s⁻¹ for fresh-water flocs derived from eight major rivers (Lamb et al., 2020). These settling velocities
233 were derived from the ‘model’ curve in Fig. S4, which denotes the relationship between the settling
234 velocity for a single floc, w_s , and floc diameter, D_f (Mehta, 2013):

$$235 \quad w_s = \frac{\alpha}{18\beta} \frac{(\rho_s - \rho_w)g}{\mu} D_p^{3-n_f} \frac{D_f^{n_f-1}}{1+0.15Re_f^{0.687}} \quad (S4)$$

236 where $\alpha = \beta = 1$ are particle shape factors, ρ_s is the density of the primary clay particle, ρ_w is the water
237 density, μ is the dynamic viscosity, D_p is the diameter of the primary clay particle, n_f is the fractal
238 dimension of the floc, taken herein as 2 (Fig. S4; Mehta, 2013), $Re_f = w_s D_f / \nu$ is the floc Reynolds
239 number, and ν is the kinematic viscosity. Typical suspended clay concentrations for upper transitional
240 plug flow and quasi-laminar plug flow within the expected range of flow velocities (Fig. S2) are
241 between 5% and 10%, and thus well within the hindered settling regime. Using Equations S2 and S3,
242 and following the same procedure as for the large ripples in Sector 2, estimated aggradation rates for
243 the climbing ripples in Sector 3 are between 0.0077 mm s^{-1} and 0.044 mm s^{-1} , which is equivalent to
244 durations of deposition of 8.2 - 47.0 minutes.

245 *Summary for Sector 3*

246 The two methods used herein to estimate the duration of deposition of the mud-rich climbing ripples in
247 Sector 3 both yield time periods of tens of minutes.

248

249 **Conclusion**

250 Our quantitative analysis of the climbing-ripple sets studied in this paper shows that the sandy ripples
251 in Sector 1 and the heterolithic mixed sand-clay large ripples in Sector 2 formed within minutes to tens
252 of minutes. The generation of the mud-rich ripples in Sector 3 may have needed somewhat longer, *i.e.*
253 of the order of ten of minutes. We conclude that the entire climbing-ripple set was thus deposited within
254 several tens of minutes. Such a duration supports the notion that the climbing-ripple set records rapid
255 transformation from turbulent via turbulent-enhanced to a turbulence-attenuated sediment gravity flow.

256

257 **References**

258 Allen, J. R. L., 1963, Asymmetrical ripple marks and the origin of water-laid cosets of cross-strata:
259 Liverpool Manchester Geological Journal, v. 3, p. 187-236.

260 Allen, J. R. L., 1970, A quantitative model of climbing ripples and their cross-laminated deposits:
261 Sedimentology, v. 14, p. 5-26.

262 Ashley, G. M., Southard, J. B., and Boothroyd, J. C., 1982, Deposition of climbing-ripple beds: a flume
263 simulation: Sedimentology, v. 29, p. 67-79.

264 Baas, J. H., 1993, Dimensional analysis of current ripples in recent and ancient depositional
265 environments: Geologica Ultraiectina, v. 106, p. 199.

- 266 Baas, J. H., 1994, A flume study on the development and equilibrium morphology of small-scale
267 bedforms in very fine sand: *Sedimentology*, v. 41, p. 185-209.
- 268 Baas, J. H., 1999, An empirical model for the development and equilibrium morphology of current
269 ripples in fine sand: *Sedimentology*, v. 46, p. 123-138.
- 270 Baas, J. H., 2004, Conditions for formation of massive turbiditic sandstones by primary depositional
271 processes: *Sedimentary geology*, v. 166, p. 293-310.
- 272 Baas, J. H., van Dam, R. L., and Storms, J. E. A., 2000, Duration of deposition from decelerating high-
273 density turbidity currents: *Sedimentary Geology*, v. 136, p. 71-88.
- 274 Baas, J. H., Best, J. L., Peakall, J., and Wang, M., 2009, A phase diagram for turbulent, transitional,
275 and laminar clay suspension flows: *Journal of Sedimentary Research*, v. 79, p. 162-183.
- 276 Baas, J. H., Best, J. L., and Peakall, J., 2011, Depositional processes, bedform development and hybrid
277 flows in rapidly decelerated cohesive (mud-sand) sediment flows: *Sedimentology*, v. 58, p. 1953-1987.
- 278 Baas, J. H., Best, J. L., and Peakall, J., 2016, Comparing the transitional behaviour of kaolinite and
279 bentonite suspension flows: *Earth Surface Processes and Landforms*, v. 41, p. 1911-1921.
- 280 Banerjee, I. 1977, Experimental study on the effect of deceleration on the vertical sequence of
281 sedimentary structures in silty sediments: *Journal of Sedimentary Research*, v. 47, p. 771-783.
- 282 Bouma, A. H., 1962, *Sedimentology of Some Flysch Deposits: A Graphic Approach to Facies*
283 *Interpretation*: Elsevier, Amsterdam/New York, 168 p.
- 284 Eisma, D., 1986, Flocculation and de-flocculation of suspended matter in estuaries: *Netherlands Journal*
285 *of Sea Research*, v. 20, p. 183-199.
- 286 Jobe, Z. R., Lowe, D. R., and Morris, W. R., 2012, Climbing-ripple successions in turbidite systems:
287 depositional environments, sedimentation rates and accumulation times: *Sedimentology*, v. 59, p. 867-
288 898.
- 289 Jopling, A. V., and Walker, R. G., 1968, Morphology and origin of ripple-drift cross-lamination, with
290 examples from the Pleistocene of Massachusetts: *Journal of Sedimentary Petrology*, v. 38, p. 971-984.
- 291 Lamb, M. P., de Leeuw, J., Fischer, W. W., Moodie, A. J., Venditti, J. G., Nittrouer, J. A., Haught, D.
292 and Parker, G., 2020, Mud in rivers transported as flocculated and suspended bed material: *Nature*
293 *Geoscience*, doi.org/10.1038/s41561-020-0602-5.
- 294 Mehta, A. J., 2013, *An Introduction To Hydraulics Of Fine Sediment Transport: Advanced Series On*
295 *Ocean Engineering*, World Scientific Publishing Company, v. 38, 1060 p.

296 Mikkelsen, O. A., Hill, P. S. and Milligan, T. G., 2006, Single-grain, microfloc and macrofloc volume
297 variations observed with a LISST-100 and a digital floc camera: *Journal of Sea Research*, v. 55, p. 87-
298 102.

299 Reineck, H. E., 1961, Sedimentbewegungen an Kleinrippeln im Watt: *Senckenbergiana Lethaea*, v. 42,
300 p. 51-67.

301 Richardson, J. F., and Zaki, W. N., 1954, Sedimentation and fluidisation: Part I: *Transactions of the*
302 *Institution of Chemical Engineers*, v. 32, p. 35-53.

303 Schieber, J., Southard, J. and Thaisen, K., 2007, Accretion of mudstone beds from migrating floccule
304 ripples: *Science*, v. 318, p. 1760-1763.

305 Sorby, H. C., 1859, On the structures produced by the currents present during the deposition of stratified
306 rocks: *The Geologist*, v. 2, p. 137-147.

307 Sorby, H. C., 1908, On the application of quantitative methods to the study of the structure and history
308 of rocks: *Quarterly Journal of the Geological Society of London*, v. 64, p. 171-233.

309 Soulsby, R., 1997, *Dynamics of Marine Sands: A Manual for Practical Applications*: Thomas Telford
310 Publications, London, 272 p.

311 Southard, J. B., and Boguchwal, L. A., 1990, Bed configurations in steady unidirectional water flows.
312 Part 2. Synthesis of flume data: *Journal of Sedimentary Petrology*, v. 60, p. 658-679.

313 Środoń, J. 1974, An interpretation of clipping-ripple cross-lamination, *Annales de la Société*
314 *Géologique de Pologne*: v. 44, p. 449-473.

315 Walker, R. G., 1963, Distinctive types of ripple-drift cross-lamination: *Sedimentology*, v. 2, p. 173-
316 188.

317

318 **Figure captions**

319 **Fig. S1.** Horizontal position of the ripple brinkpoint vs ripple height for two climbing ripple sets. Blue
320 dots denote the climbing ripple set shown in Fig. 1. The open circles denote the downstream climbing
321 ripple set (right-hand side of Fig. 1A).

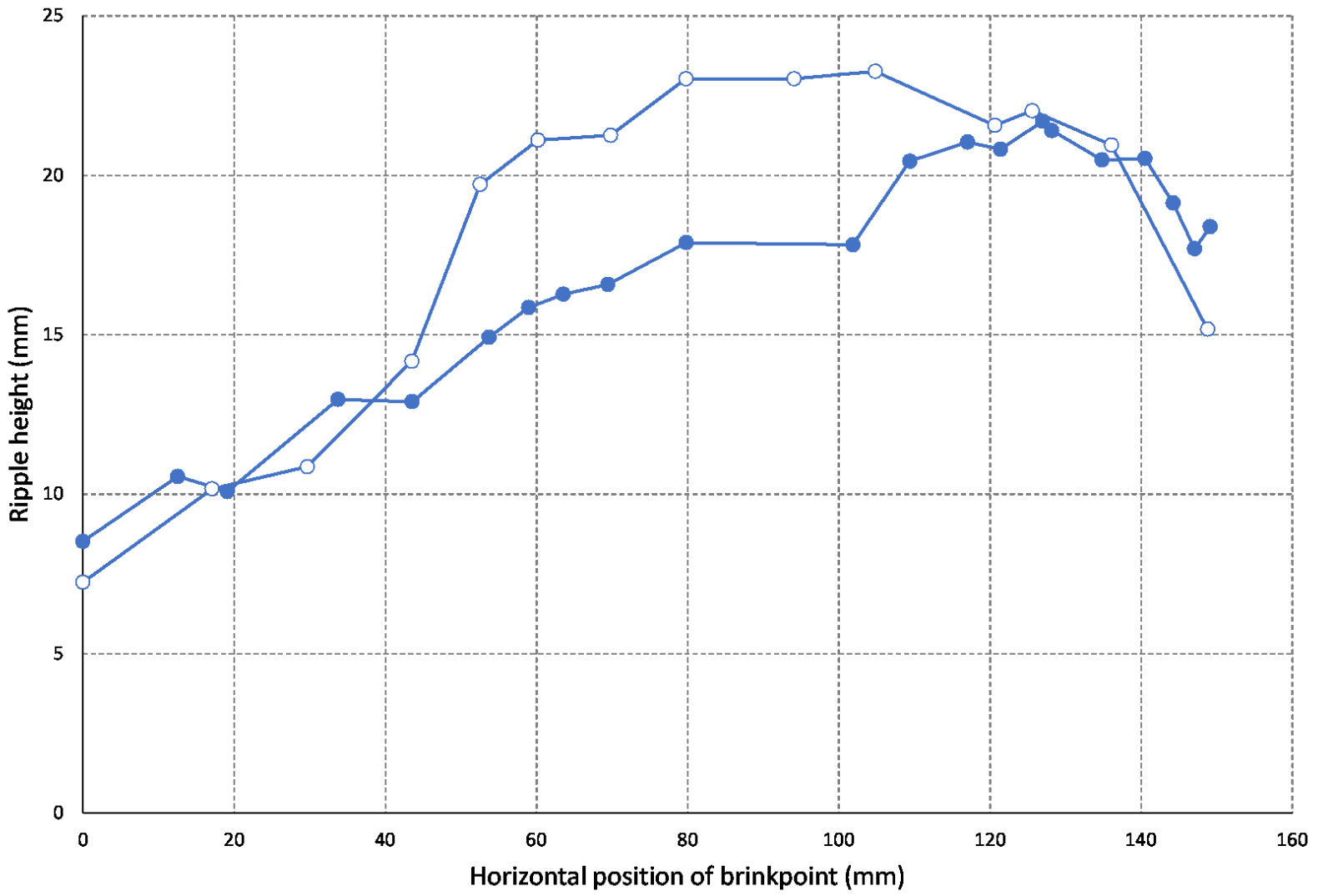
322 **Fig. S2.** Clay flow phase diagram, showing the relationship between suspended clay concentration, for
323 kaolinite clay, and depth-averaged flow velocity (modified after Baas et al., 2009). Turbulent,
324 transitional and laminar flow types are highlighted by orange shadings. The blue dashed lines indicate
325 boundary velocities between which current ripples form in very fine sand (Baas, 1993). The blue dot
326 denotes the maximum kaolinite clay concentration at which current ripples can be generated in turbulent

327 flow. Since kaolinite is a weakly cohesive clay mineral, this maximum concentration will be lower for
328 other clay minerals, such as illite and bentonite (Baas et al., 2016). The gray dashed lines signify flow
329 velocities of 0.35 m s^{-1} and 0.45 m s^{-1} used in the text. The yellow, red, and purple arrows indicate
330 different flow paths for the flow that generated the climbing-ripple set, discussed in the text.

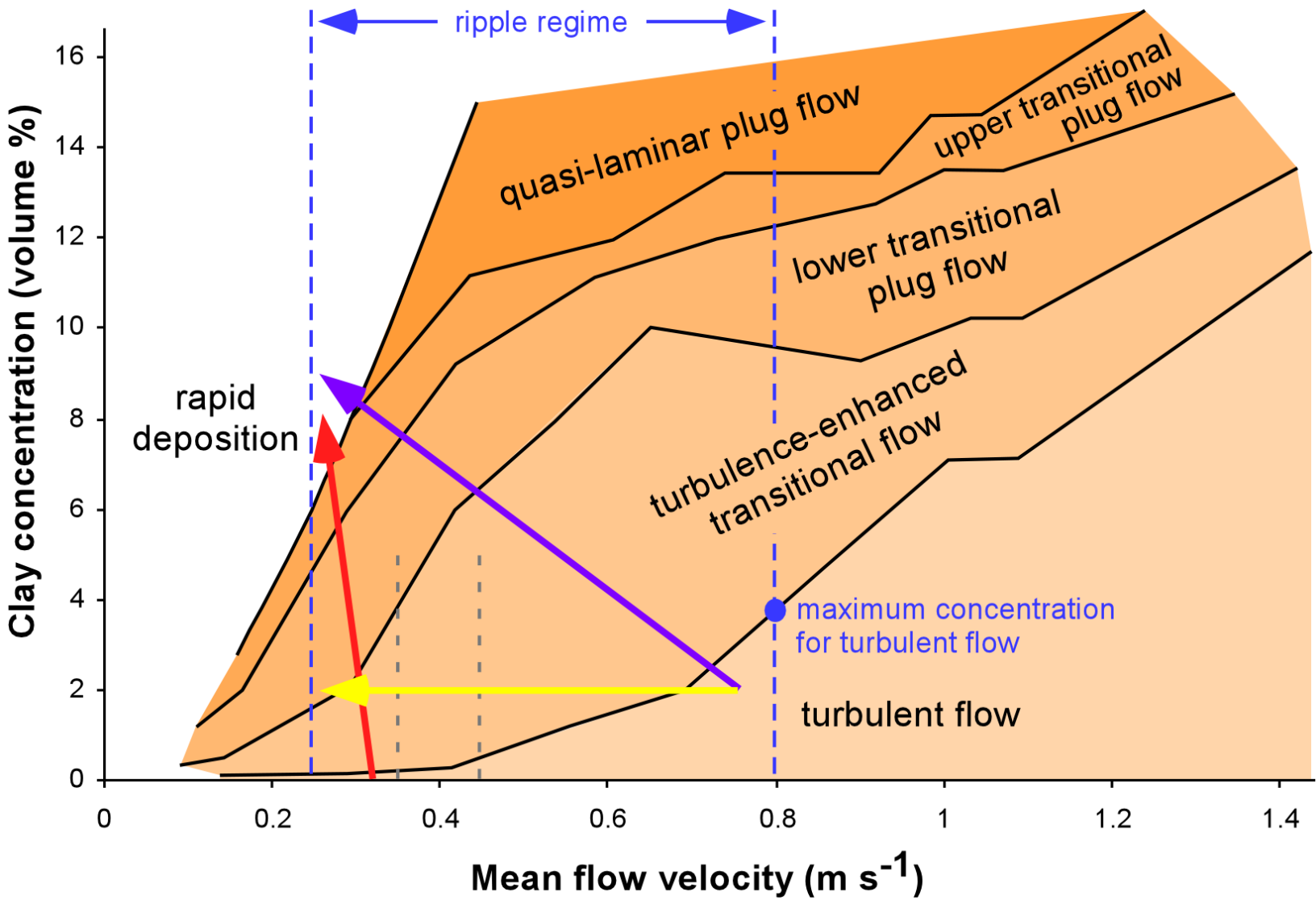
331 **Fig. S3.** Original (top) and interpreted (bottom) close-up photograph of backflow ripples on the lower
332 slipface of the climbing ripples. See Fig. 1B for location.

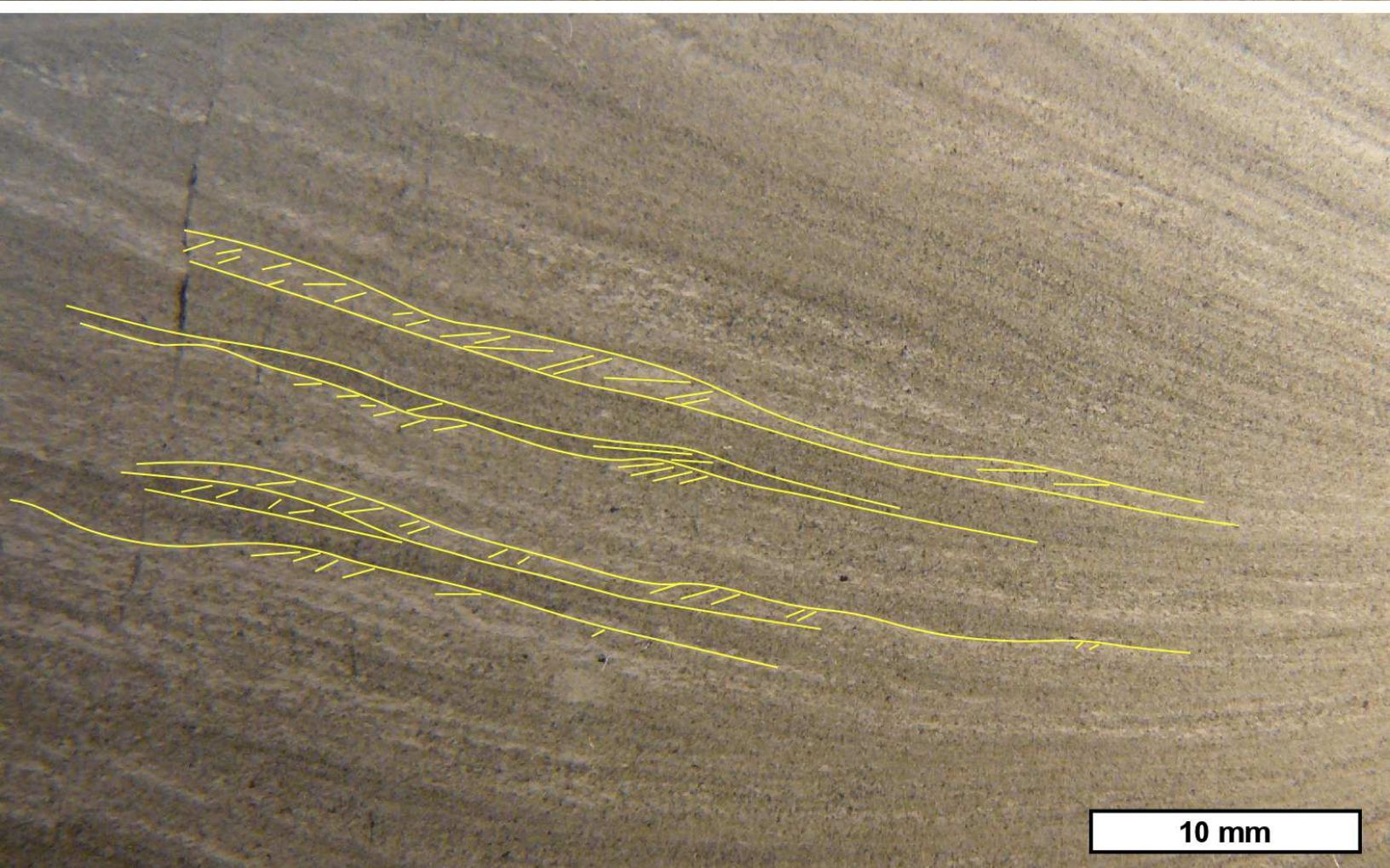
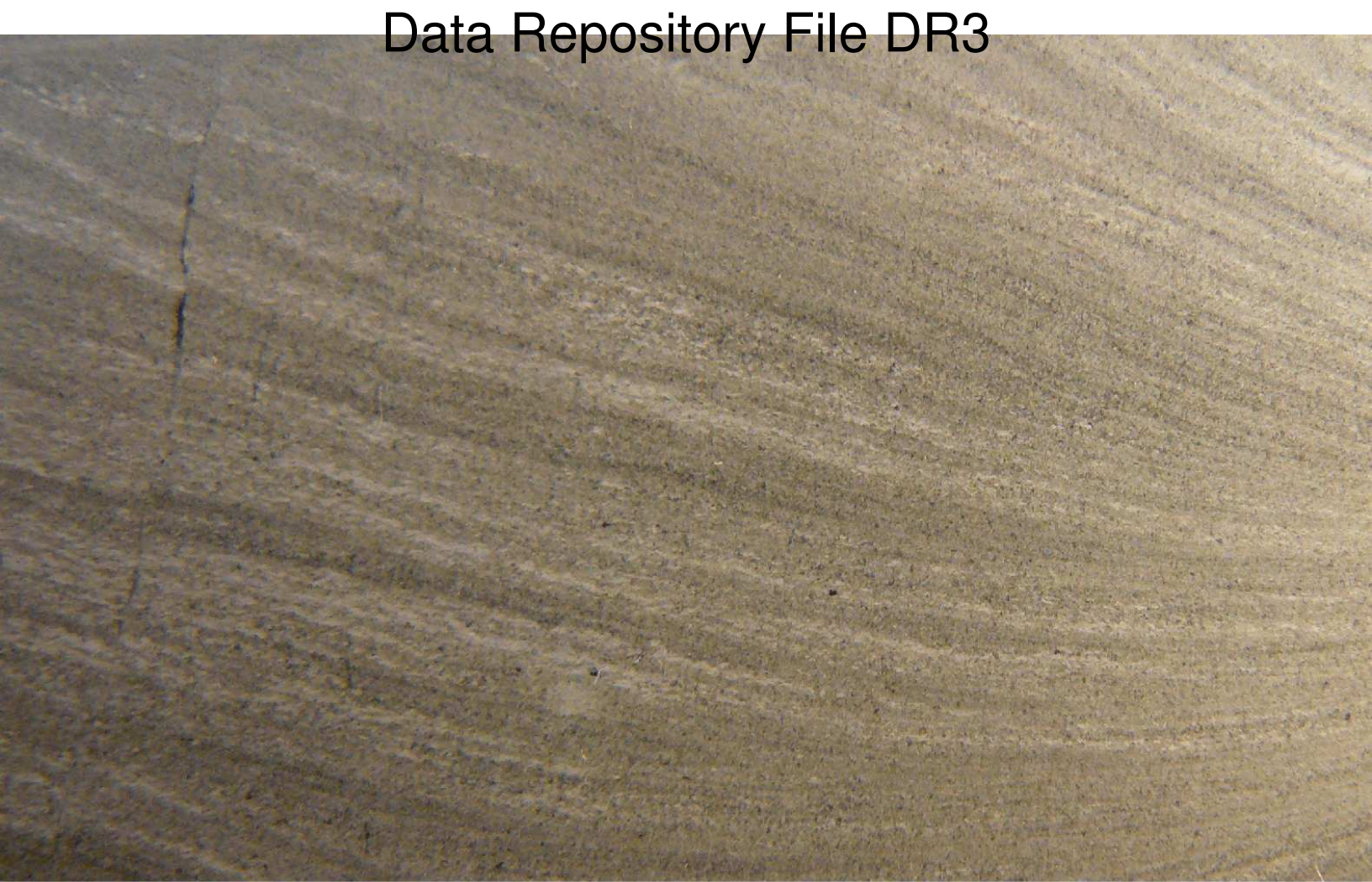
333 **Fig. S4.** Functional relationship between the settling velocity, w_s , and diameter of mud flocs, D_f
334 (modified after Mehta, 2013). The gray area delimits the field data used to define the black curves (see
335 Equation S4). The three curves use different fractal dimensions, n_f . The present study uses $n_f = 2.0$. The
336 blue dashed lines denote the limits of the size of microflocs in fresh water, according to Mikkelsen et
337 al. (2006).

338



Data Repository File DR3





10 mm

Data Repository File DR3

