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2 Deformation structures in the frontal prism near the Japan Trench: insight  
3 from Sandbox Models  
4

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43 **Abstract**

44 We have used sandbox experiments to explore the mechanics of the frontal  
45 prism structures documented by new borehole and seismic reflection data from IODP  
46 Expedition 343 (JFAST). This study investigated the effects of down-dip (across

47 trench axis) variations in frictional resistance along a decollement on the structural  
48 development of frontal wedges near subduction zones. To clarify our understanding  
49 on the wedge growth over horst-and-graben structures in the subducting plate near the  
50 Japan Trench, we performed sandbox experiments with alternate zone of relatively  
51 high and low friction on the basal decollement. Our experiments verify that high  
52 frictional resistance on the basal fault is needed to produce the observed internal  
53 deformation and fault-and-fold structures in the core samples collected during JFAST.  
54 Varying down-dip frictional resistance along the decollement causes a temporal  
55 change in the style of internal deformation within the wedge and often gives rise to  
56 two distinctive structural domains, separated by a break in the surface slope of the  
57 wedge: (i) complexly deformed inner wedge with steep surface slope and (ii) shallow  
58 taper outer wedge, characterized by a sequence of imbricate thrusts. Our experiments  
59 further demonstrate that the topographic slope-break in the wedge develops when the  
60 hinterland part of the wedge essentially stops deforming internally, leading to in-  
61 sequence thrusting with the formation of outer wedge with low taper angle. For a  
62 series of alternate high and low frictional conditions on the basal fault the slope of the  
63 wedge varies temporally between topographic slope-break and uniformly sloping  
64 wedge.

65 *Keywords:* sandbox experiments, inner and outer wedge, slope-break, horst-and-  
66 graben structure, fault friction

67

## 68 **1. Introduction**

69 It is now well known that the subduction of bathymetric features in the oceanic  
70 plate, e.g., seamounts, aseismic ridges, volcanic plateaus has a strong influence on the  
71 development of diverse morphological features and deformation structures in the

72 overriding plate (Domingues et al., 2000; Malavieille, 1984; von Huene and Culotta,  
73 1989; von Huene and Lallemand, 1990; Lallemand et al., 1992; Lallemand et al.,  
74 1994; von Huene et al., 2004; Park et al., 1999; Wang and Hu, 2006). However, their  
75 studies indicate that the styles of deformation in the overriding plate vary with the  
76 geometry of bathymetric features in the subducting plate. For example, the subduction  
77 of seamounts develops steeper surface slope in the inner wedge than that in the outer  
78 wedge (Park et al., 1999; Domingues et al., 2000). On the contrary, the subduction of  
79 aseismic ridges develops steep outer wedge slope associated with almost flat inner  
80 wedge (Lallemand et al., 1992). Despite dominance of horst-and-graben structure at  
81 most trenches, its influence on frontal wedge growth has still remained relatively  
82 unexplored. We therefore focus the present work to analyze the impacts of subducted  
83 horst-and-graben structures on the evolution of frontal wedge near the Japan Trench.

84           Geophysical investigations along several sections across the Japan Trench  
85 (Fig. 1b and c) recorded a series of horst-and-graben structures on the subducting  
86 plate beneath the frontal wedge (Tsuru et al., 2002; Kodaira et al., 2012; Nakamura et  
87 al., 2013). Moreover, earlier studies have shown that the sediment thickness in the  
88 incoming Pacific plate near the Japan Trench is thin and the thinning of sediment  
89 cover mostly occurs above the horst block (Groshong, 2006). The combination of the  
90 effects of the differences in sediment thickness and surface roughness over horst-and-  
91 graben structure in the subducting plate cause varying degrees of coupling at the plate  
92 interface, creating varying frictional properties on the decollement (Pacheco et al.,  
93 1993; Tanioka et al., 1997; von Huene et al., 1999; Bilek, 2007; Das and Watts,  
94 2009). In the present study we have used sandbox experiments to simulate the effects  
95 of down-dip variations in the frictional strength on the basal decollement to  
96 investigate the structural development of frontal wedge and finally, provide a

97 mechanical model for explaining the structural evolution of frontal wedge over horst  
98 and graben structure near the Japan Trench.

99 Integrated Ocean Drilling Program (IODP) Expedition 343 (JFAST) drilled to a  
100 depth of 836 meters below seafloor (mbsf) near the Japan Trench at site C0019  
101 through the plate boundary fault zone over the horst block, located about ~ 6 km  
102 westward from the trench axis (Fig. 1a). Core samples collected during the expedition  
103 have provided a great opportunity to compare our experimental results with the  
104 observed deformation structures within the frontal wedge (Chester et al., 2013,  
105 Kirkpatrick et al., 2014). Borehole data and associated seismic images provide new  
106 structural information that has been modeled in this study to show the effects of  
107 friction on the megathrust near the Japan Trench.

108 .

## 109 **2. Experimental methods and materials**

110 Sandbox experiments have proved to be useful in understanding the mechanics  
111 of thin-skinned accretionary wedges using the concept of critical taper theory  
112 (Chapple, 1978; Boyer and Elliot, 1982; Davis et al., 1983; Dahlen, 1990). The angle  
113 of critical taper is defined by the summation of basal inclination ( $\beta$ ) and surface slope  
114 ( $\alpha$ ). According to critical taper model, a wedge deforms internally and thereby,  
115 increases its taper and at a critically tapered angle the wedge develops internal  
116 stresses, leading the wedge on the verge of failure. At this stage, shear stress at the  
117 base reaches a value that assists frictional sliding at the decollement (Davis, 1983;  
118 Boyer and Elliot, 1982). Theoretically and experimentally it has been shown that the  
119 angle of critical taper is proportional to the frictional condition on the basal  
120 decollement according to the following equation (Dahlen, 1990):

121 
$$\alpha + \beta = (\beta + \mu_b) \left( \frac{1 - \sin \phi_c}{1 + \sin \phi_c} \right) \quad (1)$$

122

123 where,  $\mu_b$  is the coefficient of static friction on the decollement and  $\phi_c$  is the angle of  
124 internal friction of the frontal prism material.

125 In the present study, we have prepared our experimental models over varying  
126 down-dip frictional conditions on the decollement to simulate the effect of horst-and-  
127 graben structure along the basal decollement (Fig.2). We have considered relatively  
128 higher frictional coefficient on the decollement above the horst block because of its  
129 enhanced surface irregularities due to little or no sediment cover, leading to a strong  
130 coupling with the overriding plate than that over the graben sediments. Thus the horst  
131 and graben structure gives rise to alternate zones of relatively strong and a weak  
132 contact respectively with the overriding plate on the decollement. In the laboratory  
133 scaled experiments the higher basal friction ( $\mu_b = 0.46$ ), simulating the decollement  
134 immediately above the horst block, was achieved by pasting commercial sand paper  
135 (P30, average grit size 622.0 microns) on a glass plate and a relatively lower basal  
136 friction ( $\mu_b = 0.36$ ) was obtained by sieving a veneer of boric acid powder (0.001mm  
137 beads) over the glass plate in order to model the frictional strength above the graben  
138 sediments. However, in some experiments we pasted rigid block of 5mm thick acrylic  
139 sheet over the basal glass plate to model the horst block. However, in the second set  
140 of experiments, we had to stop the experiment once the buttress reached the edge of  
141 the acrylic block. Experimental results from these two different sets of experiments,  
142 however, show that frontal wedge propagation ceases once the decollement  
143 propagation reaches the high frictional patch / edge of the rigid acrylic sheet (see  
144 electronic supplementary Fig. S1). This finding suggests that the use of high frictional

145 patch on the basal glass plate is a suitable analog for simulating natural horst-block.  
146 The advantage of using sandpaper over rigid block is that the hinterland buttress can  
147 override the high frictional patch without limiting the amount of shortening during the  
148 experimental run.

149 In the model setup, Zone I represents a graben in the seismogenic plate interface  
150 and Zone II corresponds to a horst block in the subducting plate (Fig. 2). Although a  
151 majority of our experiments were carried out with one high frictional patch between  
152 zones of relatively lower friction on the basal fault, a few experiments were carried  
153 out with two zones of high frictional patches to understand the effects of a series of  
154 horst-and-graben structures. Experimental models were prepared by sieving sand  
155 layers from a constant height of 20 cm in a rectangular glass-walled sandbox  
156 apparatus over a rigid base of varying basal friction ( $\mu_b$ ) (Fig. 2). The length and  
157 width of the apparatus are 110 cm and 35 cm respectively. The model width was more  
158 than fifteen times its thickness to avoid the effects of friction at the interface of sand  
159 layers and the glass sidewalls (Souloumiac et al., 2012). The coefficients of basal  
160 friction ( $\mu_b$ ) were calculated separately from sliding experiments using dry non-  
161 cohesive sand. Note that the values of  $\mu_b$  used in our experiments are merely imposed  
162 qualitatively for simulating natural situation that do not claim the exact values for  
163 natural analogue. The glass walls of the sandbox were cleaned and dried carefully to  
164 remove surface moisture. This process is important in order to prevent sticking of  
165 sand to the glass walls. Experiments were carried out in controlled laboratory  
166 conditions to avoid the influence of atmospheric moisture contents.

167 We used dry, non-cohesive natural quartz-rich (>90%) sand, texturally matured  
168 with well rounded grains (average sphericity of 0.8), as analogue material for scaled  
169 model experiments simulating crustal scale brittle deformation (Davis et al., 1983;

170 Mulugeta, 1988; Koyi, 1995; Mandal et al., 1997; Schellart, 2000). The sand material  
171 had a bulk density of  $1600 \text{ kg/m}^3$ , and a coefficient of internal friction close to 0.57.  
172 Our model scales to nature with a ratio of  $2.7 \times 10^{-5}$ , where 1 cm in the model is  
173 equivalent to 360 m in nature (Table 1). The cohesion of model material (dry quartz  
174 sand) in our experiment is around 20 Pa, which scales to 2 MPa (Gutscher et al.,  
175 1998) for unconsolidated marine sediments (Hoshino et al., 1972). The models were  
176 deformed in a pure shear box at a uniform velocity of 5 mm / minute using a  
177 computer controlled step-up motor by setting a backstop at the rear of the sand layers.  
178 Previous studies revealed that buttress geometry is important in the development of  
179 wedge geometry in sand layers (Byrne et al., 1988; Persson and Sokoutis, 2002).  
180 However, we used planar vertical buttress in our experimental setup in order to model  
181 a mono-vergent accretionary wedge observed in the Japan Trench (Mulugeta, 1988;  
182 Storti and McClay, 1995; Gutscher et al., 1998; Bose et al., 2009). Although sand  
183 layer of 1cm thickness should have been used in our experiments according to the  
184 scaling law, we have exaggerated the thickness of sand layers to 2 cm in all  
185 experiments for obtaining better resolution of deformation structures as well as to  
186 understand the deformation mechanism clearly during the experimental run. However,  
187 we ran experiments with sand layers of 1 cm thickness to verify the influence of  
188 model thickness in experimental results. These experiments show broad resemblance  
189 in the first order geometry of the wedge (see electronic supplementary Fig. S2) and  
190 therefore validates the use of 2 cm thick sandlayers in the model experiments. During  
191 the experimental run, we photographed through the lateral glass wall continuously  
192 after an interval of 5 seconds, keeping the camera at a fixed distance from the model.  
193 Model deformations were analyzed from successive photographs taken during the  
194 experimental run.



195

### 196 **3. Experimental Results**

197       Our experiments suggest that the frontal wedge near the Japan Trench has  
198 evolved over varying down-dip frictional condition on the decollement during  
199 subduction of horst-and-graben. In our experiments, the wedge started to grow above  
200 Zone I by in-sequence thrusting at the *initial stage* and developed a gentle surface  
201 slope ( $\alpha$ ) at uniform shortening rate (Figs. 3b-3c, 4a). The vertical growth of the  
202 wedge at the backstop attained an almost stationary value when the model was  
203 shortened by 5 cm in all experiments (Fig. 4b). At this stage, the frontal propagation  
204 of the wedge dominated over the vertical growth through sequential thrusting until the  
205 deformation front reached Zone II. During this stage the wedge developed a critical  
206 taper,  $\alpha$  equals  $7.5^\circ$  (Figs. 3d, 4a), which is closer to the theoretical value of surface  
207 slope ( $\alpha$ ) of  $6^\circ$  obtained from “equation 1” for  $\beta=0$ ,  $\mu_b = 0.36$  and  $\phi_c = 0.57$ .  
208 However, the overestimation of  $\alpha$  in the experimental result is self-consistent.

209       The mode of internal deformation and its geometry changed completely when  
210 the decollement propagation reached the edge of high frictional patch (Zone II,  $\mu_b=$   
211 0.42), simulating a horst (Fig. 3e, see electronic supplementary Figs. S1 A [d] and B  
212 [d]). At this stage, decollement propagation ceased and the wedge formed over Zone I  
213 started deforming internally by increasing the wedge height consistently, developing a  
214 steep topographic slope (Fig. 4). This stage of wedge growth has been defined as  
215 *intermediate stage* (Figs. 3e-3f). The topographic slope of the wedge at this stage  
216 became much higher than the predicted value from “equation 1”, leading the wedge to  
217 grow to a super critical state. It is likely that the cessation of decollement propagation  
218 promotes the development of supercritical wedge in order to accommodate the  
219 amount of horizontal shortening, and eventually facilitates slope failure (Fig. 3f).

220 During this stage experimental models demonstrated mechanical rotation and  
221 reorientation of already deformed sand layers in the hanging wall, giving rise to a  
222 complex deformation structures within the deforming wedge.

223 With further horizontal shortening, the deformation front crossed the Zone II  
224 and propagated onto the region above zone I over low  $\mu_b$ , simulating another graben,  
225 by the process of in-sequence thrusting and eventually, developed a separate wedge  
226 with a low angle of taper as expected to occur over low basal friction. Such spatial  
227 and temporal variations in the style and intensity of deformation across the wedge  
228 finally gave rise to distinct topographic slope-break in the wedge geometry separating  
229 the steep inner wedge from the low tapered outer wedge (Figs. 3g-3h and 4a). During  
230 the growth of outer wedge, the internal deformation in the inner wedge completely  
231 stopped (Fig. 4b) and the horizontal shortening was entirely accommodated by in-  
232 sequence thrusting over weak frictional base. For simplicity in description, we describe  
233 this stage of wedge growth as *final stage*, which characterizes the development of  
234 topographic slope-break with the cessation of internal deformation within the inner  
235 wedge. Experiments with varying width of Zone II showed that increasing the width  
236 of the Zone II (e.g. 30 cm) required large amount of shortening for the development  
237 of the topographic slope-break (Figs. 5 and 4, see electronic supplementary Fig. S3).  
238 The development of slope-break in the wedge geometry thus can be treated as a  
239 potential indicator for interpreting long term frictional condition on the decollement.

240 Experiments with more than one high frictional patch (Zone II) on the basal  
241 fault showed that the surface slope of outer wedge (e.g., the wedge over low  $\mu_b$ ) was  
242 increasing progressively with ongoing shortening once the decollement propagation  
243 was again resisted by another high frictional patch in the front. As a consequence, the  
244 wedge geometry was completely modified along with the destruction of topographic

245 slope-break (Fig. 6h). With further shortening the outer wedge progressively merged  
246 with the inner wedge, giving rise to a single wedge with steep uniform surface slope  
247 (Fig. 6i). During this process of wedge modification, the inactive inner wedge again  
248 resumed to deform by mechanically rotating all preexisting structures and thereby,  
249 increasing the complexity of deformation structures towards the hinterland part of the  
250 wedge (Fig. 6i, 6k). With continuous shortening, the deformation within this steep  
251 wedge completely stopped once the deformation front propagated over another low  
252 frictional base in the front with the onset of the development of new outer wedge by  
253 in-sequence thrusting (Figs. 6j, 6k). Based on above results, it is evident that the  
254 geometry of the frontal wedge is essentially transient with varying down-dip frictional  
255 strength on the decollement in tectonically active convergent belts over long time  
256 scale.

257

## 258 **4. Discussion**

### 259 *4.1 Implication of varying down-dip basal friction*

260 On the basis of the above observations and interpretations on the experimental  
261 results we discuss below the role of basal friction in the structural development of  
262 frontal wedge near the Japan Trench. Our study reveals that varying down-dip  
263 frictional strength on the decollement causes a drastic change in the wedge taper,  
264 giving rise to a steep *inner wedge* and gentle *outer wedge*. This lateral change in the  
265 surface slope across the wedge separates the entire wedge into two distinctive  
266 structural domains: (i) complex internal deformation within *the inner wedge* and (ii)  
267 the *outer wedge* is deformed mostly by sequential thrusting. Experimental results  
268 show that the growth of the inner wedge begins by in-sequence thrusting over low  
269 frictional base following the model of critical angle of taper (Davis et al., 1983;

270 Mulugeta, 1988; Koyi, 1995; Gutscher et al., 1998; Yamada et al., 2006; Bose et al.,  
271 2009). However, with ongoing shortening the taper angle of the wedge progressively  
272 steepens with the termination of decollement propagation by the increased frictional  
273 resistance along the decollement. The steepening of the wedge slope couple with  
274 intense internal deformation within it continues until the deformation front crosses  
275 from the zone of high to low friction on the basal decollement. The progress of the  
276 deformation front over the lower frictional base immediately stops internal  
277 deformation within the deformed wedge (Figs. 3g- 3h) and thereby, initiates a  
278 renewed phase of in-sequence thrusting in response to continuing horizontal  
279 shortening, leading to the development of shallow taper outer wedge. This process of  
280 wedge propagation over varying basal friction gives rise to the development of  
281 topographic slope-break between the inner and the outer wedges. The characteristic  
282 geometry of the slope-break in the tectonic wedge becomes prominent when the  
283 wedge front continues to deform over a uniform low frictional base for large  
284 horizontal shortening (Fig. 5a-g).

#### 285 *4.2 Interpretation of wedge development near the Japan Trench*

286 The present study has an important implication in understanding the  
287 development of frontal wedge near the Japan Trench. Seismic sections across the  
288 Japan Trench show that the slope of the frontal prism over horst-and-graben structure  
289 changes from  $10^\circ$  in the landward part to  $4^\circ$  towards the trench (Fig. 1b). Comparing  
290 our experimental results with seismic data from frontal wedge near the Japan Trench  
291 suggest that the varying down-dip frictional strength along the basal decollement  
292 caused the present geometry of the wedge and deformation structures within it near  
293 the Japan Trench (Fig. 1b and 1c). Our experimental results suggest that the  
294 subduction of horst-and-graben structure near the Japan Trench are potential factors

295 for creating varying degree of coupling with the overriding plate that eventually  
296 developed the characteristic topographic slope-break. It further reveals that the inner  
297 wedge with steep slope over the horst block must have formed prior to the  
298 propagation of deformation front over the graben sediments. Our experimental study  
299 shows that initiation of growth of the outer wedge over low basal friction deactivates  
300 the internal deformation of the inner wedge. This has led to infer that the present day  
301 plate convergence near the Japan Trench is accommodating entirely by in-sequence  
302 thrusting over the low friction graben sediments. Previous experimental findings  
303 (Huiqi et al., 1992; Bose et al., 2009) along with the present study indicate that the  
304 occurrence of a series of imbricate thrusts over graben sediments, preserved in the  
305 outer wedge of the Japan Trench (Kodaira et al., 2012; Nakamura et al., 2013), have  
306 formed over relatively weak decollement (Figs. 7c).

307         The structural interpretations from the drill core samples collected during  
308 JFAST and seismic data reveal that the frontal prism lying over the subducted horst  
309 block (~ high frictional patch) is structurally chaotic, which is also consistent with the  
310 observed deformation structures in our experimental models. The dip of beds  
311 measured in the core samples varies from 20° to 80° and they are also traversed by  
312 numerous closely spaced core scale faults (Chester et al., 2013; Nakamura et al.,  
313 2013; Kirkpatrick, 2014) (Fig. 7). Our experimental results show that the complexity  
314 in the internal deformation within the inner wedge increases with the onset of  
315 steepening of inner wedge slope when the frontal propagation of the decollement is  
316 resisted by the high frictional patch during ongoing shortening (Figs. 3 and 4). This  
317 has led to infer that the variably steeply dipping beds in the core samples might have  
318 evolved through the process of mechanical rotation of earlier structures within the  
319 hanging wall when the decollement propagation was either temporarily stopped or

320 was very slow due to high-frictional resistance along the horst block. Based on above  
321 discussions, it appears that subduction of horst-and-graben structure played a crucial  
322 role in increasing the complexity of deformation structures observed at the drill site  
323 near the Japan Trench. With continued plate convergence over time the deformation  
324 front eventually crossed the high frictional patch resulting the break in the surface  
325 slope observed between the inner and outer wedges in the frontal prism. In the  
326 laboratory experiments, the break in the surface slope of the wedge becomes  
327 prominent once the backstop overrides the high frictional patch and consequently,  
328 develops outer wedge by in-sequence thrusting (Figs. 3g, 6f and 6j). Comparing our  
329 experimental results with seismic images reveal that the buttress (~ backstop in the  
330 experimental setup) in the natural situation near the Japan Trench currently lies on the  
331 west of the JFAST drilling site towards landward part of the wedge, as also predicted  
332 by earlier workers (Tsuru et al., 2002) (Fig. 7b and 7c). Our experimental results  
333 further reveal that the observed slope sediments between the inner and outer wedge in  
334 the Japan Trench might have accumulated during the growth of supercritical wedge as  
335 identified in the *intermediate stage* in experiments and the sediment accumulation  
336 continued until the deformation front crossed the horst block (Fig. 3f). This, however,  
337 does not rule out the possibility of rotational slumping of the slope sediments at the  
338 frontal wedge by later reactivation during the 2011 megaearthquake event (Strasser et  
339 al., 2013).

340         The present experimental study has also predicted why there is lack of natural  
341 examples of the occurrence of multiple slope-breaks in accretionary prisms.  
342 Experiments with two high frictional patches show that the cessation of the  
343 propagation of outer wedge by another zone of high frictional patch in the front  
344 modifies the wedge geometry thoroughly by mechanical rotation of all pre-existing

345 deformation structures including the zone of topographic slope-break, forming a  
346 wedge with a uniformly steep surface slope (Fig. 6). These observations have led to  
347 infer that the subduction of the horst block in the Pacific plate lying currently on the  
348 east of the Japan Trench will eventually modify the present wedge geometry having a  
349 topographic slope –break to a uniformly steep slope.

350

## 351 **5. Conclusion:**

352 Our main conclusions are as follows:

353

- 354 1) Down-dip frictional variations on the decollement cause temporal and spatial  
355 variations in the geometry of the frontal wedge.
- 356 2) Surface slope-break develops when the deformation front crosses from high to  
357 low basal friction. The break in the surface slope separates the entire wedge  
358 into two distinct structural domains: inner and outer wedges.
- 359 3) The inner wedge is characterized by steep wedge slope and complex internal  
360 structures, whereas the outer wedge is deformed by in-sequence thrusting,  
361 leading to shallow taper angle.
- 362 4) The experimental models thoroughly explain the structural evolution of the  
363 frontal wedge near the Japan Trench observed in seismic images and borehole  
364 data.
- 365 5) We interpret that the complexity of internal deformation observed in core  
366 samples and localization of steep surface slope towards the landward part of  
367 the wedge near the Japan Trench is caused by the cessation of decollement  
368 propagation by the horst block in the subducting plate lying beneath JFAST  
369 drill site.

370 6) The development of shallow taper outer wedge over the graben sediments by  
371 in-sequence thrusting marks the cessation of internal deformation in the rear  
372 part of the wedge (~ inner wedge), creating the topographic slope-break near  
373 the Japan Trench.

374  
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497

498 **Figure Captions:**

499

500 **Figure 1:** (a) Location map, showing the eastern coastline of Honshu, bathymetry

501 near Japan Trench and Tohoku earthquake epicenter (red star). The yellow arrow

502 indicates the direction of plate convergence. Inset map shows location of Expedition

503 343 site C0019 (red star) along seismic section Line HD 33B (Fig.1b). Line HD 26B

504 another seismic section line shown in figure 1c. (b) Image of seismic section Line HD

505 33B crossing the IODP drilling site C0019 with no vertical exaggeration. It shows

506 change in topographic slope (marked red lines) from inner wedge ( $\sim 10^\circ$ ) to outer

507 wedge ( $\sim 4^\circ$ ) (modified after Nakamura et al., 2013). (c) Image of seismic section

508 Line 26B with V.E.  $\sim 3$ , separated by 3.5 km from seismic line HD 33B.  $\alpha_i$  and  $\alpha_o$  are

509 relative slopes of inner and outer wedges respectively, showing changes in

510 topographic slope (modified after Nakamura et al., 2013). Pink line marks the

511 decollement surface and blue arrow indicates the zone of topographic slope-break in

512 both (b) and (c).

513 **Figure 2:** A sketch of the experimental setup showing 3D view of the model setup.

514 Zones I and II represent low and high frictional contact zone respectively. Arrows on

515 the right show the direction of shortening.

516 **Figure 3:** Progressive development of frontal wedge in sand models with 10 cm

517 width of the Zone II. (a) Initial model, (b-e) Initial stage, (f) intermediate stage and

518 (g-h) progressive development of wedge during the final stage (see text for details).

519 Note that the deformation propagation towards front stopped after shortening of 14.

520 40 cm, but hinterland elevation continued to increase (e). 18.10 cm shortening was

521 accommodated within the wedge, reorienting earlier structures during intermediate

522 stage (f). Further shortening moves the deformation front above the lower frictional  
523 base developing distinct slope-break (g-h).

524 **Figure 4:** Plots show different stages of wedge growth for varying width of zone II  
525 using high frictional patch (7 experiments) and rigid block (4 experiments). Wedge  
526 angle (a) and Wedge height at the backstop (b), are plotted as a function of actual  
527 displacement (horizontal shortening) in cm. In the initial stage of the wedge growth,  
528 wedge angle (a) and wedge height (b) reached a constant value with horizontal  
529 displacement. The intermediate stage marks the sharp increase in both wedge angle  
530 (solid line) (a) and wedge height (solid line) (b). In the final stage wedge height  
531 attained a constant value (dash line) (b) with decreasing wedge slope (dash line) (a).

532 **Figure 5:** Final stage of wedge development for varying widths of high frictional  
533 patch: 2 cm (a), 4 cm (b), 6 cm (c), 10 cm (d), 12 cm (e), 14 cm (f) and 30 cm (g). The  
534 width of the model is 35 cm for all experiments. White arrow marks the zone of  
535 topographic slope-break between inner and outer wedge.

536 **Figure 6:** Progressive development of frontal wedge growth over multiple high  
537 frictional patch, forming alternate uniform slope and topographic slope-break. (a-d)  
538 Initial stage, (e) intermediate stage with steep uniform slope, (f-g) final stage showing  
539 the development of slope-break, (h) the process of destruction of outer wedge  
540 observed in figure (g) due to another high frictional in the front, leading to steep  
541 uniform surface slope (i), (j) development of new slope-break in the wedge geometry  
542 low basal friction, (k) Plots show the variations of wedge angle (purple) and wedge  
543 elevation at the hinterland buttress (green) as a function of horizontal displacement.  
544 Note that the combination of low tapered wedge at constant wedge elevation implies  
545 growing of wedge over low frictional base (yellow shade).

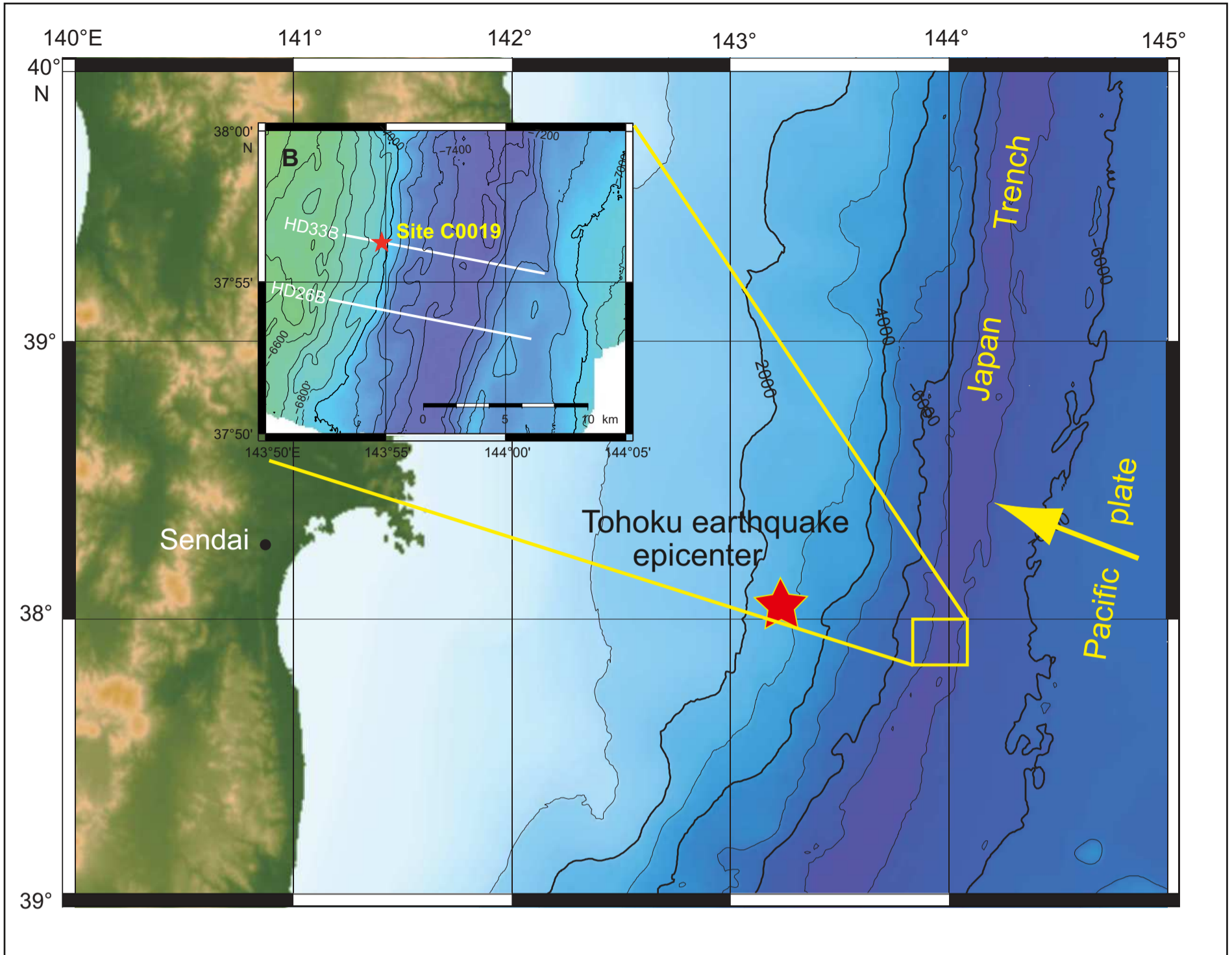
546 **Figure 7:** Compilation of core data with depth at IODP sites C0019 and comparison

547 with experimental model. (a) Deformation unit in the core data shows variations in  
548 bedding dip with depth and three structural domains are identified. (i) upper frontal  
549 prism (0-275 mbsf) shows gently inclined bedding, (ii) lower frontal prism (276-820  
550 mbsf) showing variable and steeply dipping beds characterized by folded and faulted  
551 sediments, (iii) base section (820 mbsf to base of the hole) with shallow to horizontal  
552 bedding represents in the footwall block in the subduction zone (modified after  
553 Chester et al., 2013). (b) Experimental model shows resemblance in the changes of  
554 bedding orientations with depth. Green arrows show the region in the experimental  
555 model comparable with core data set. White dash line in the model replicates the  
556 drilling site C0019 shown in Fig. 7c. (c) Details and interpretations of seismic image  
557 along section HD 33B. Vertical Exaggeration = 2:1 (Modified after Kodaira et al.,  
558 2012). Note that experimental model closely reproduces geometrical and structural  
559 features observed in seismic image. Both experimental and seismic section show that  
560 surface slope of the inner wedge is steeper than that of the outer wedge. Imbricate  
561 thrusts are prominent within the outer wedge. The blue arrow marks the zone of  
562 topographic slope-break between inner and outer wedges in Figs. 7b and 7c.

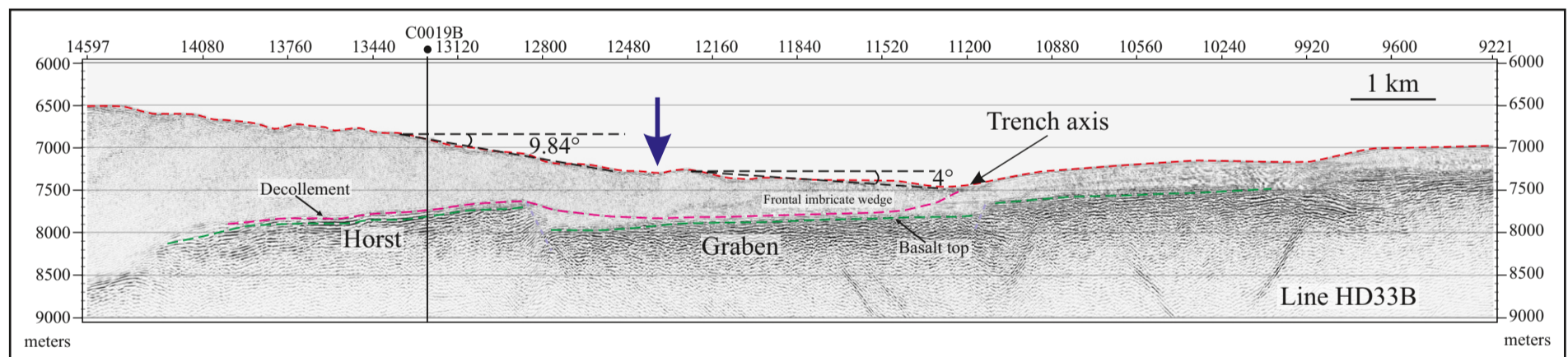
Table 1  
Modeling Parameters and material properties

<b>Parameter and model properties</b>	<b>Sand (analogue model)</b>	<b>Natural prototypes</b>	<b>Ratio: model/nature</b>
Length, L (m)	0.01	360	$\lambda = 2.7 \times 10^{-5}$
Density (kg m <sup>-3</sup> )	1600	2700	$\delta = 0.59$
Internal friction angle, $\phi$ (°)	~ 30	30 - 40	1 - 0.75
Cohesion (Pa)	20	$2 \times 10^6$	$1 \times 10^{-5}$
Gravity, g (m s <sup>-2</sup> )	9.8	9.8	$\gamma_g = 1$
Deviatoric Stress * ( $\sigma = \delta \cdot g \cdot L$ )	157 Pa	$9.5 \cdot 10^6$	$16.5 \times 10^{-6}$

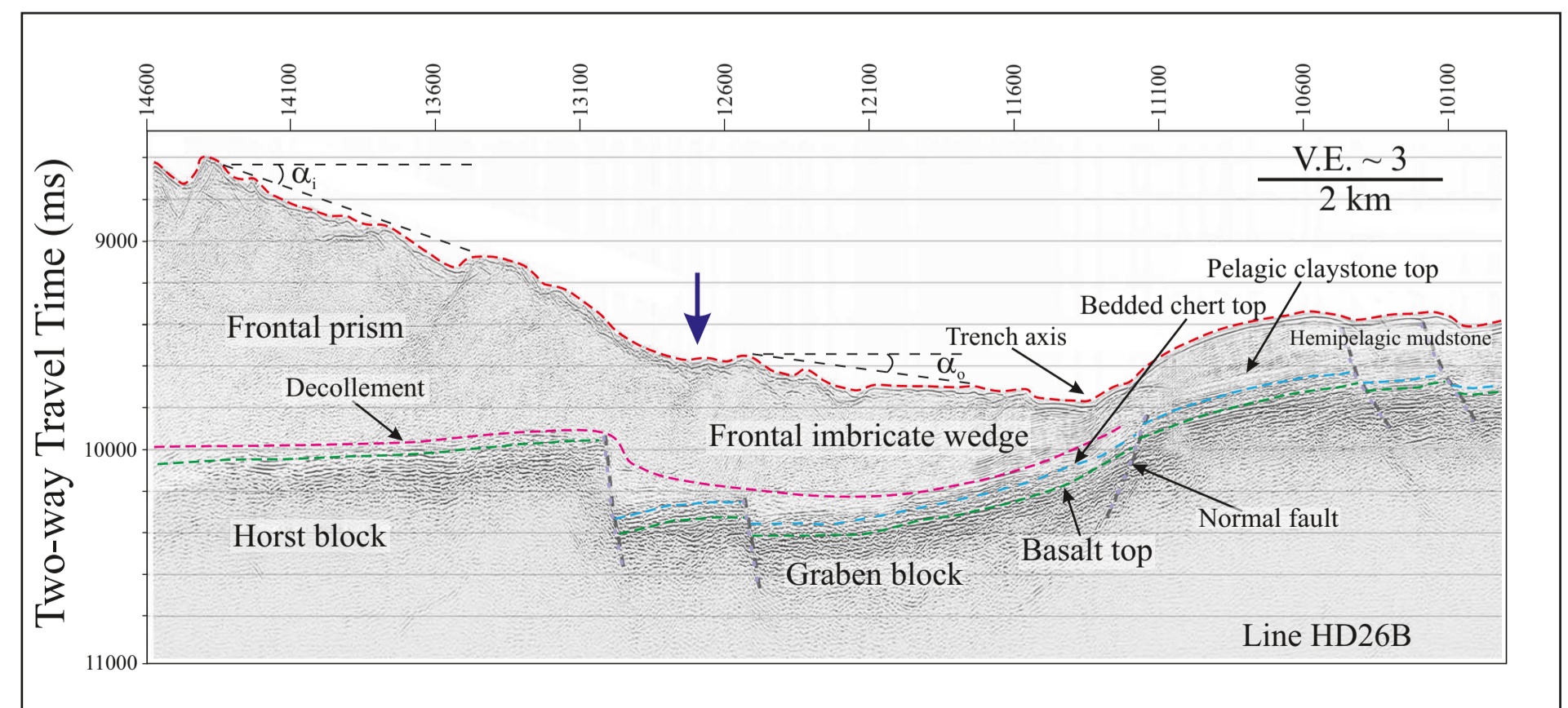
\* Based on Schellart, 2000



a

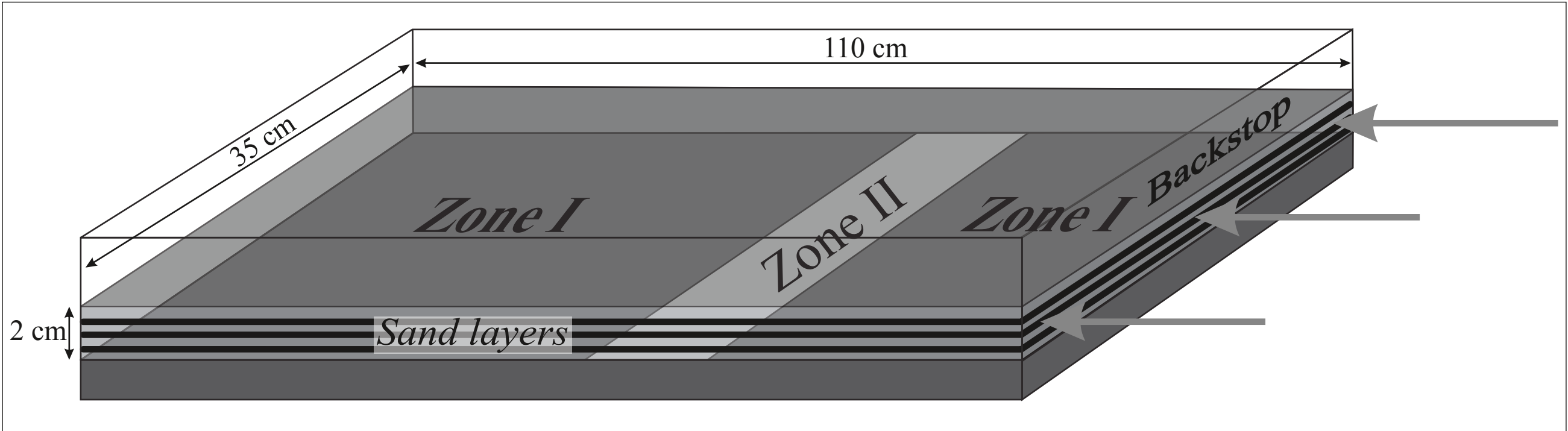


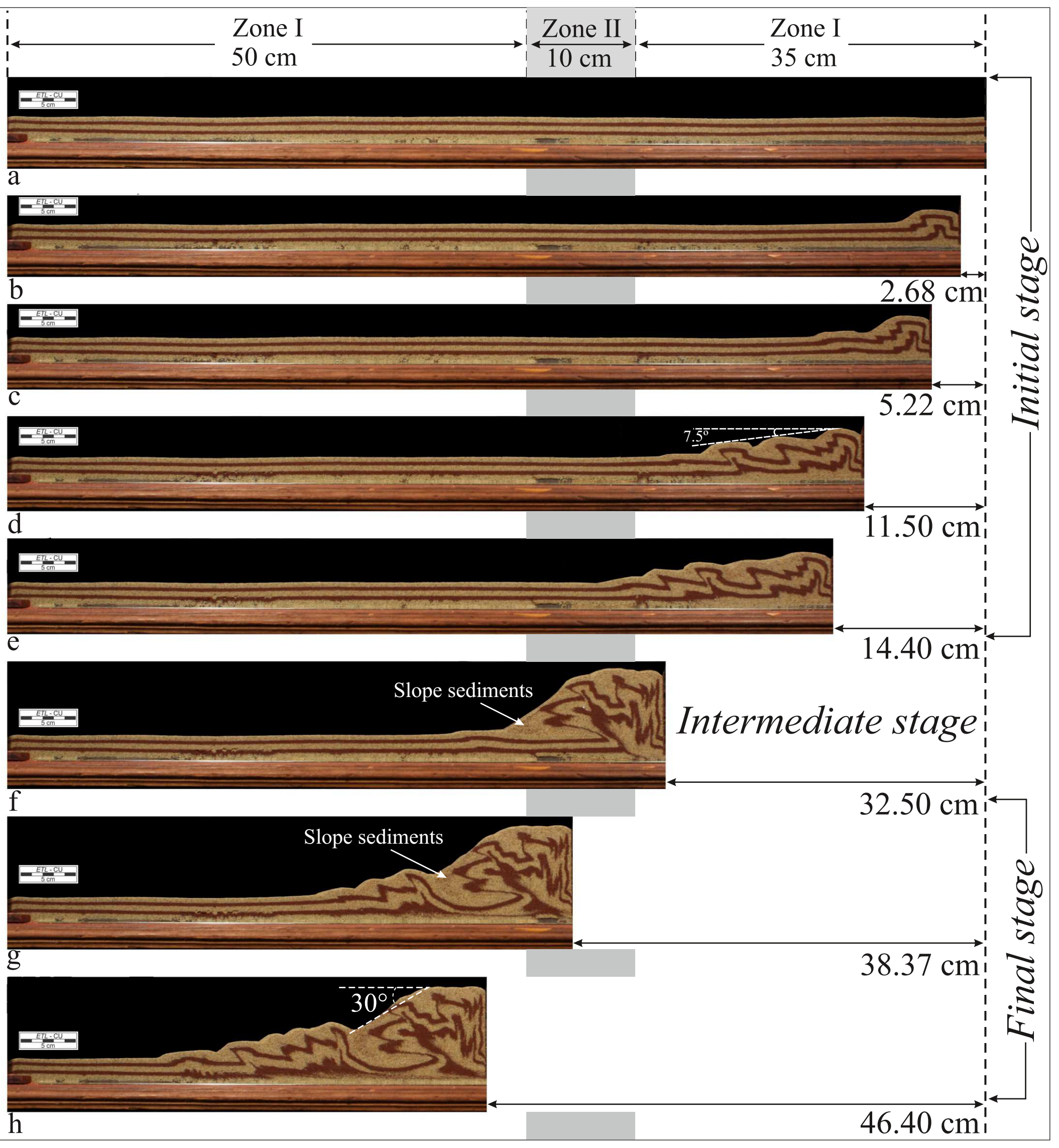
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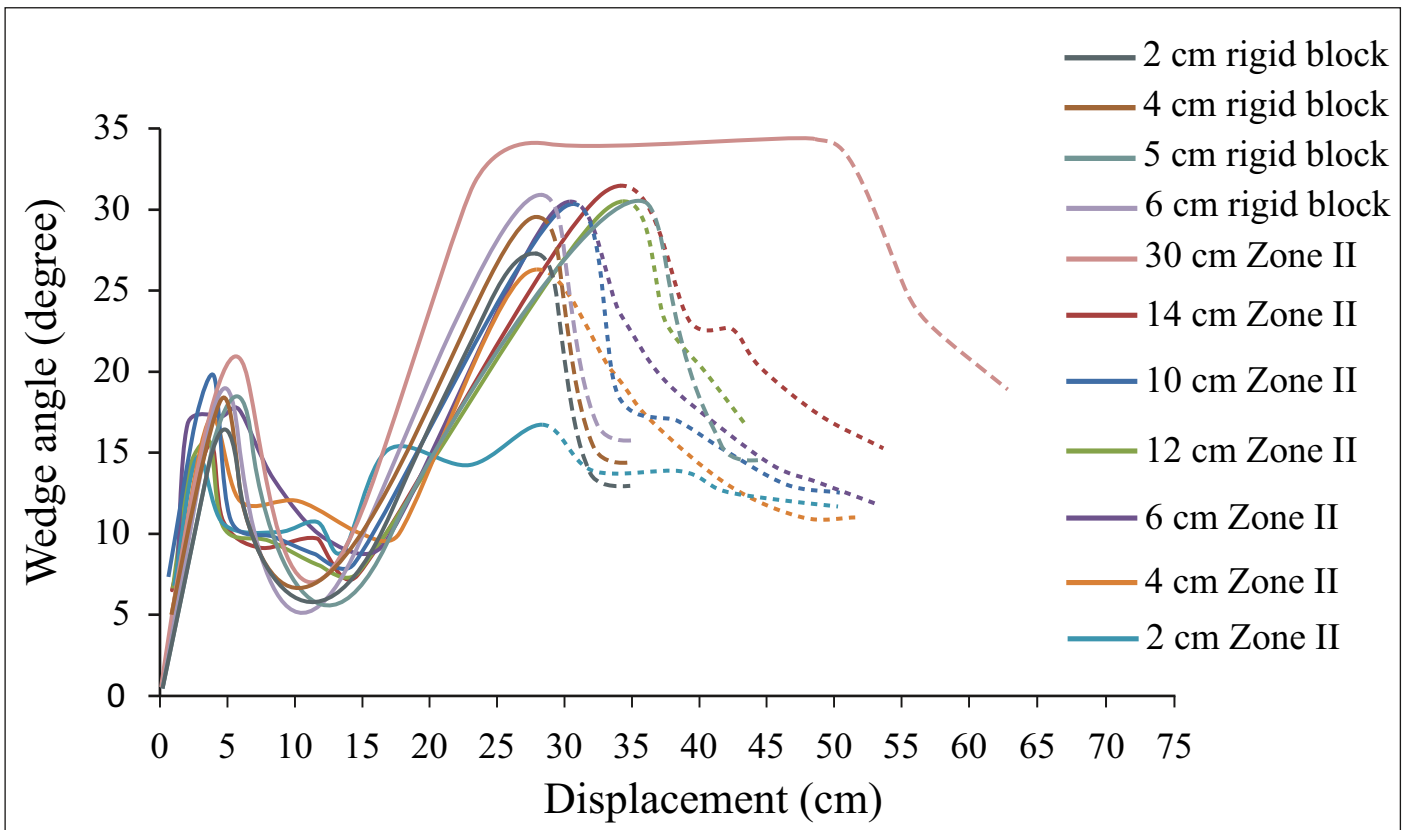


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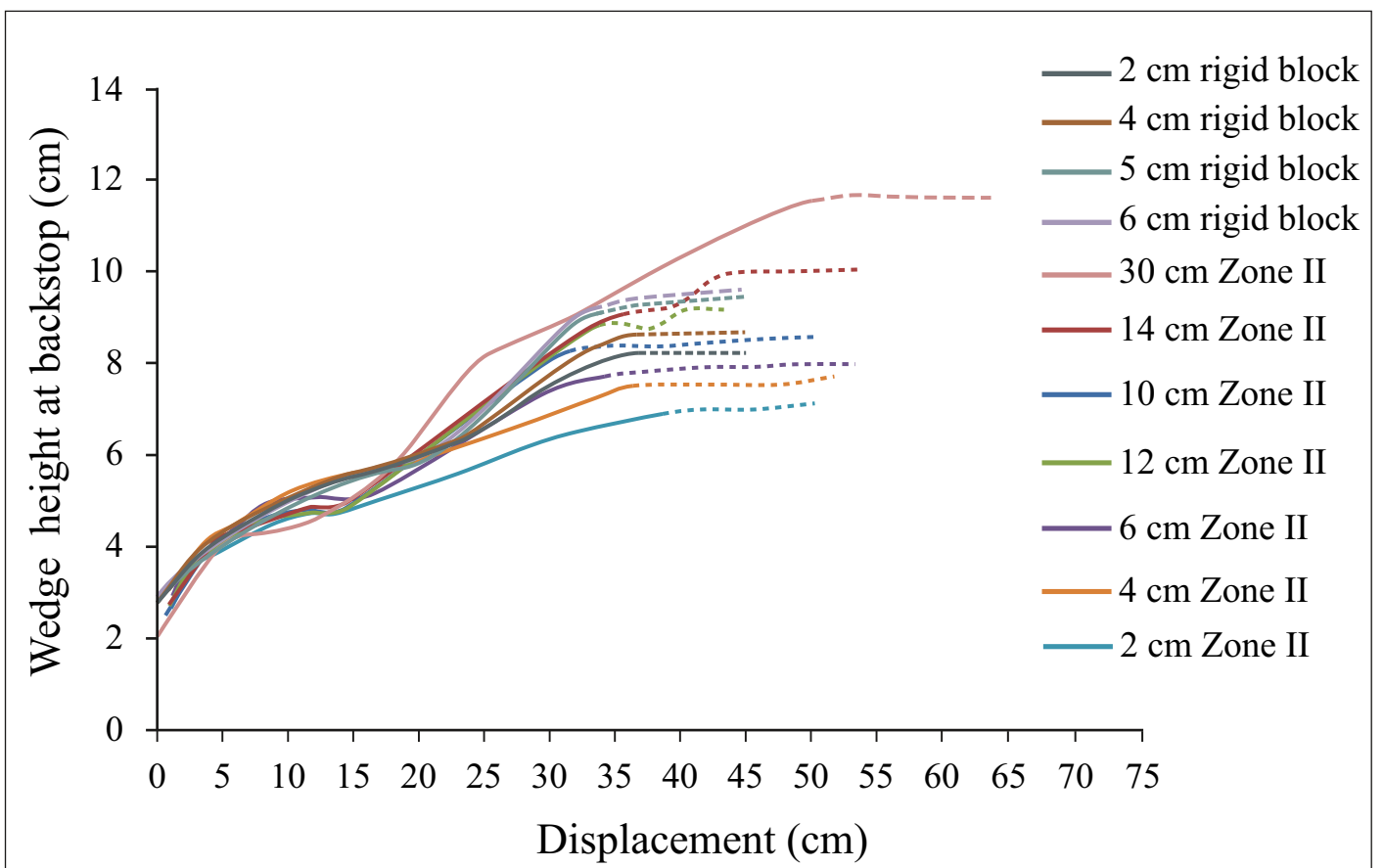




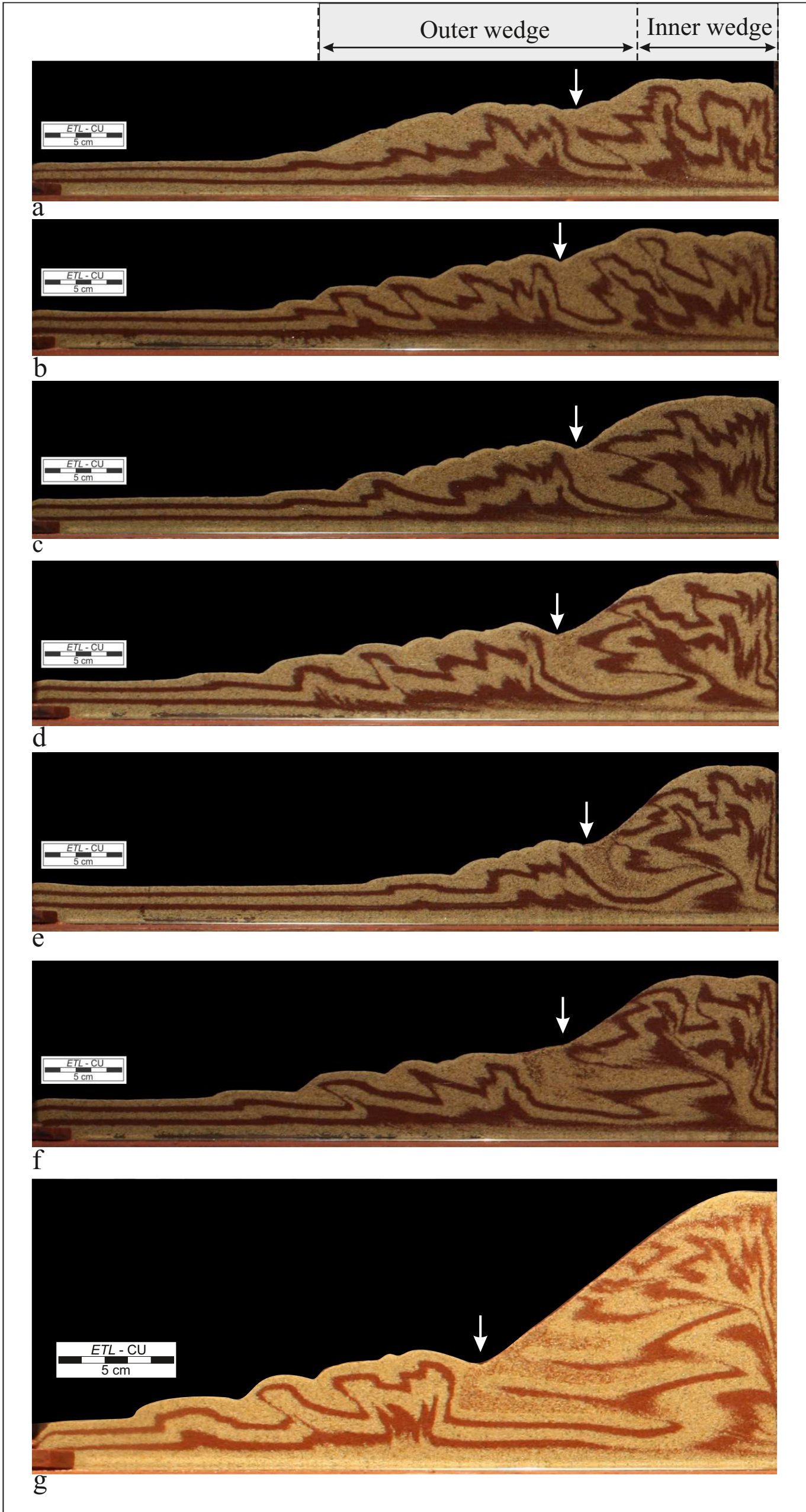


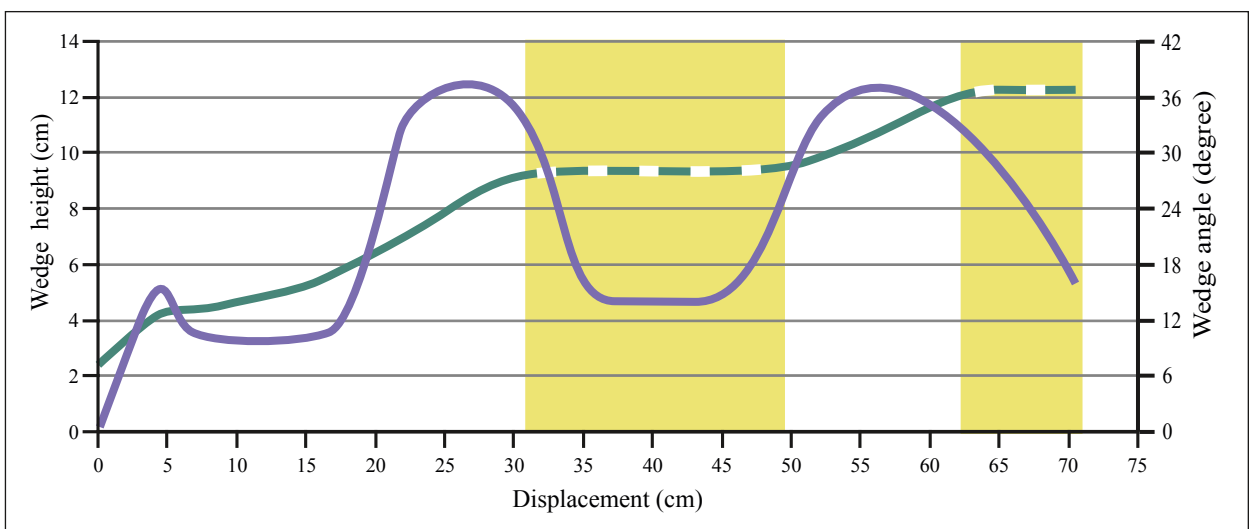
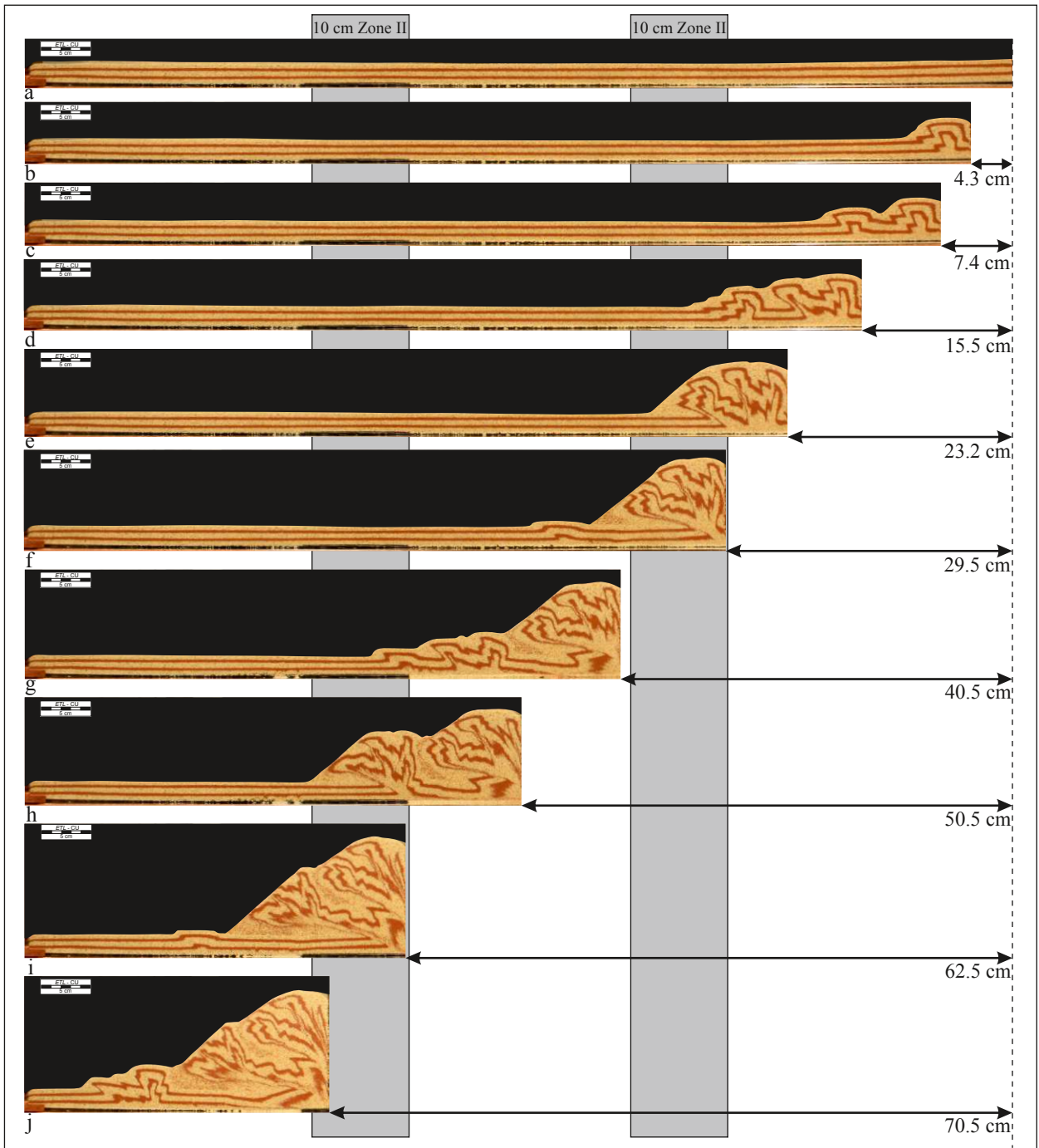


a



b





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