

1 A topographic signature of a hydrodynamic origin for submarine
2 gullies

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8 **ABSTRACT**

9 Submarine gullies - small scale, straight, shallow channels formed in relatively high
10 seafloor-slope settings - are ubiquitous features that play an important role in the general
11 evolution of continental margin morphology. The mechanisms associated with the origin and
12 evolution of submarine gullies are, however, still poorly defined. In this paper we present
13 evidence of a topographic signature of gully erosion in the Cook Strait sector of the Hikurangi
14 subduction margin, New Zealand. This signature indicates that submarine gully initiation is a
15 threshold process driven by unconfined, directionally-stable, fluid or sediment gravity flows
16 accelerating downslope. We propose cascading dense water, a type of current that is driven by
17 seawater density contrast, as the source of these flows. The sensitivity of such ephemeral
18 hydrodynamic events to climate change raises questions regarding implications for future
19 variation of the distribution and magnitude of a significant seafloor erosion process.

20 **INTRODUCTION**

21 Gullies are steep-sided, confined channels incised by surface or subsurface flow. Gullies
22 represent the first step in the fluvial dissection of landscapes (Bloom, 1991) and they have been

23 documented on both terrestrial and Martian landscapes (Malin and Edgett, 2000; Valentin et al.,
24 2005). As advanced surveying technology reveals meso-scale geomorphic details of the seafloor,
25 gullies are shown to be common features on continental slopes (Spinelli and Field, 2001),
26 submarine canyon walls (Lastras et al., 2007) and delta slopes (Maillet et al., 2006). Although no
27 specific definition exists, submarine gullies are distinguished from other seafloor erosional
28 features, such as furrows and grooves, because they are generally small scale (Surpless et al.,
29 2009), straight, shallow channels in the order of tens of meters deep (Field et al., 1999), formed
30 in relatively high seafloor-slope settings (Fedele and García, 2009). Submarine gullies play a
31 pivotal role in the general evolution of continental margins over relatively long periods of time
32 (Field et al., 1999). They are important agents of submarine erosion and downslope sediment
33 transfer from the upper slope to the continental rise (Dowdeswell et al., 2008), and they
34 contribute to the facies of slope deposits (Syvitski et al., 1996) and the architecture of petroleum
35 reservoirs (Hewlett and Jordan, 1993).

36 A lack of understanding of the primary processes and environmental controls on gully
37 system formation is problematic for modeling studies. The origin of submarine gullies has been
38 attributed to a variety of processes, among which are mass wasting, sea level oscillations, fluid
39 sapping, wind-induced rip currents, hyperpycnal flows and turbidity current scour (Chiocci and
40 Normark, 1992; Fedele and García, 2009; Flood, 1983; Izumi, 2004; Orange and Breen, 1992;
41 Spinelli and Field, 2001). Other significant processes identified in recent years as having the
42 potential to erode seafloor substrates include meso-scale oceanographic processes such as
43 internal waves and tides (Cacchione et al., 2002), and dense shelf-water cascading (Canals et al.,
44 2006). These latter processes can be strongly affected by climate change (Herrmann et al., 2008),
45 meaning that if these are shown to be globally significant for seafloor erosion, the dynamics of

46 underwater geomorphic development may undergo significant changes over human timescales.
47 Better definition of the mechanisms associated with the origins and evolution of submarine
48 gullies will assist future modeling studies to predict climate-change-induced variations in
49 seafloor erosion rates and processes.

50 In this paper we present quantitative morphological data demonstrating that submarine
51 gullies on the Cook Strait sector of the Hikurangi Margin, New Zealand, are initiated by
52 unconfined, directionally-stable, downslope-accelerating gravity flows. We infer that cascading
53 dense water is the source of these flows.

54 **STUDY REGION**

55 The Cook Strait sector of the Hikurangi subduction margin, to the south-east of central
56 New Zealand, is dominated by large-scale, tectonically-forced, margin-parallel ridges and
57 margin-scale bedrock-incised canyon systems (Fig. 1). In addition to the strong tectonic and
58 regional geological controls on geomorphic processes (Mountjoy et al., 2009), modification of
59 the seafloor in this area reflects climatic (sea-level cyclicity) and oceanographic processes
60 (Lewis et al., 1994). The oceanographic regime at the Cook Strait sector of the Hikurangi Margin
61 is characterized by regional north-south ocean currents, by localized and temporally-variable
62 coastal eddies, and by the strong, M2 tidal currents through the Cook Strait (Chiswell, 2000).
63 Very limited data are available on local scale ocean currents and, where these are available, they
64 cover too short a time scale to resolve seasonally-varying processes (Law et al., 2010).

65 A 100 km strike length of the Hikurangi Margin has been imaged with Simrad EM300
66 multibeam sonar bathymetry, from the Hikurangi Trough at ~3000 m water depth onto the
67 shallow continental shelf (Fig. 1b). Fourteen hundred gullies were automatically mapped from
68 the multibeam bathymetry data as lineaments, using standard Geographic Information System

69 (GIS) hydrology tools used for terrestrial drainage network extraction, and validated via a
70 thorough visual inspection. The gullies are restricted to the upper continental slope, structurally-
71 generated ridges and large-scale canyon walls, which constitute the steepest regions of the
72 seabed (Fig. 1b and c). Gully heads never extend into the continental shelf, but are always
73 located downslope of the shelf-slope break inflection. The gullies occur between a depth of 140
74 m and 2000 m below sea level. They are generally linear, sub-parallel, evenly-spaced and
75 oriented perpendicular to the local slope contours. The gully axial profiles are typically concave.
76 Gully length varies between 150 m and 1600 m, and a mean length of 570 m was estimated.
77 Gullies have a V-shaped cross-section and gentle to sharp interfluvial; the incision depth varies
78 between 10 m and 65 m. Depositional lobes and levées are generally absent. Two distinct gully
79 morphologies can be identified: (i) individual, short, shallow first-order gullies (group 1) and (ii)
80 dendritic networks of long and deep gullies (group 2). In this study we concentrate on the first-
81 order gullies in group 1 because they represent the initial stage of gully network evolution.

82 **RESULTS**

83 The frequency distribution of axial slope gradients shows that submarine gullies have a
84 mean axial gradient of $\sim 20.5^\circ$ and that they are incised only where the seabed gradient is higher
85 than 5.5° (Fig. 1d). Plotting slope-break-to-gully-head distance against the general gradient of
86 the slope defines an inversely proportional relationship, i.e. the steeper the gradient of the
87 seabed, the closer the gully head is to the break of slope (Fig. 2). This relationship indicates that
88 a slope-gradient-dependant erosion threshold sets the location of a gully head at a specific
89 distance down the slope, which we term the contributing length. This result is comparable to
90 field studies demonstrating that the upslope extent of terrestrial channels is defined by an inverse

91 relationship between contributing area and slope gradient (Montgomery and Dietrich, 1988,
92 1992; Patton and Schumm, 1975).

93 **DISCUSSION**

94 The topographic thresholds emerging from Figure 1d and 2 indicate that submarine gully
95 initiation is a threshold-dependent process. The threshold associated with gully erosion can be
96 interpreted as either a hydraulic threshold, whereby the flow of water and sediment above the
97 seabed is high enough to entrain sediment and transport it, or a slope stability threshold, where
98 seabed sediment is unstable above a particular slope gradient. We suggest that gullies form when
99 a hydraulic threshold is exceeded because: (i) the topographic threshold of 5.5° is presumably
100 below the angle of internal friction of the seabed material, (ii) the slope gradients of stable
101 interfluvial slopes between gullies and ungullied slopes can reach values of 30° , and (iii) the inversely
102 proportional relationship between contributing length and slope gradient (Fig. 2) can only be
103 explained in terms of hydrodynamic processes. Initiation of submarine gullies is therefore
104 inferred to be dependent on tractive forces exerted by a localized body of higher density, gravity-
105 driven fluid flow. The slope gradient threshold is determined by the value beyond which the
106 basal stress exerted by this flow is able to overcome the shear resistance of the seabed material.

107 We propose that these tractive forces are exerted by bottom currents, in the form of
108 unconfined, downslope, fluid or sediment gravity flows. Bottom currents are the most widely
109 recognized factor controlling the incision of furrows, which are morphologically similar
110 erosional features to gullies (Flood, 1983). The formation of linear, spaced gullies can be
111 explained in terms of flow concentration. This occurs in response to macro-scale roughness on
112 the slope, and/or a change in flow dynamics with increasing seafloor gradient beyond the local
113 break in slope. The change in flow dynamics can be triggered longitudinally by a change in the

114 flow regime from subcritical to supercritical (Izumi, 2004), or laterally by variation of bottom
115 shear stress as a centrifugal instability sets in at the current body interface (Fedele and Garcia,
116 2009). The hypothesis that submarine gullies are formed by unconfined, downslope flows is also
117 supported by experimental evidence (Fedele and García, 2009) and geologic interpretations of
118 sedimentary sequences of turbidites and dispersive hemipelagic sedimentation in gullied slopes
119 (Spinelli and Field, 2001). A relationship between a gullied topography and enhanced sediment
120 flux, on the other hand, has been demonstrated in modern delta-fed slopes (Porebski and Steel,
121 2003).

122 The downslope distance required for a flow to reach a velocity high enough to entrain
123 seabed sediment is termed the contributing length (Fig. 3). As the slope gradient of the seabed
124 increases, the flow will reach the threshold velocity required for sediment entrainment more
125 rapidly, and this explains why the contributing length decreases as the slope of the seabed
126 increases. The acceleration is driven by the tangential gravity component on the excess weight of
127 entrained sediment and density contrast, in the same way that turbidity currents self-accelerate
128 and erode the seabed (Akiyama and Stefan, 1985; Izumi, 2004). The positive feedback between
129 flow power and sediment entrainment is more pronounced in submarine than fluvial channel
130 systems because the density contrast of the flow with the ambient fluid is lower (Parker et al.,
131 1986). The gully head represents the upper-most location on a slope where the threshold velocity
132 for sediment entrainment is exceeded. Gullies end where the resistance of the seabed sediment to
133 erosion has increased, or because the eroding capacity of the current drops due to a reduction in
134 slope gradient or an increase in the volume of entrained sediment.

135 Numerous processes can give rise to unconfined, downslope fluid or sediment gravity
136 flows: (i) terrestrial river flooding, (ii) storms, (iii) cascading dense water, (iv) internal waves,

137 (v) tide-generated currents, (vi) ocean currents, and (vii) mass movements. Gully orientation
138 predominantly falls in a very narrow window between south and south-south-east (157.5° to
139 180°) (Fig. 4). As group 1 gullies have formed in varied large-scale geomorphic environments
140 (canyon walls, upper continental slope, structural ridges), this dominant orientation is inferred to
141 reflect a recurring, directionally stable and episodic flow that is sufficiently strong to erode the
142 seafloor. Submarine gullies occur at depths of down to 2000 m, indicating that they are beyond
143 the influence of terrestrial fluvial systems and storm processes, even during glacial lowstands.
144 Furthermore, fluvial sediment loading in Cook Strait is low (Hicks and Shankar, 2003). Mass
145 movements are episodic events that are unlikely to generate recurring and directionally stable
146 flow, and mass movement scars are more common on north-west facing slopes where gullies are
147 generally absent. Large-scale ocean currents are oriented north-east to south-west, parallel to the
148 coastline, and this is discordant with the predominant gully orientation (Fig. 1a). Tide-generated
149 currents may play a more important role in generating a recurring and directionally stable flow.
150 A strong tidal signal has in fact been identified at a depth of 1048 m just upslope of the gullied
151 seaward limb of Opouawe Bank (Fig. 1c), where near bottom currents can reach velocities of up
152 to 15 cm s^{-1} (Law et al., 2010).

153 We deduce that the hydrodynamic process eroding gullies in Cook Strait could be
154 generated by one or more of the following: tide-generated currents, cascading dense water or
155 internal waves. For the flow to accelerate down the continental slope due to gravity, as we
156 inferred from the gully morphological data, a density contrast with the ambient fluid is required.
157 We thus suggest that the most likely process incising gullies is some form of ephemeral
158 cascading dense water flow. This oceanographic process has not been documented in the Cook

159 Strait area, however, and significant oceanographic field work is thus required to prove its
160 existence.

161 **CONCLUSIONS AND IMPLICATIONS**

162 We have presented evidence of a topographic signature of gully erosion in the Cook
163 Strait sector of the Hikurangi Margin, New Zealand. This signature indicates that submarine
164 gully initiation is a threshold process driven by unconfined, directionally-stable, fluid or
165 sediment gravity flows accelerating down slopes with a gradient higher than 5.5°. We propose
166 cascading dense water as the source of these flows. A critical outcome of our study is the ability
167 of gravity currents to attain erosive capability without a long headward slope length. Recent
168 studies indicate that hydrodynamic processes, in particular cascading dense water flows, may
169 play an important role in the evolution of canyons (Canals et al., 2006). The topographic
170 signature defined in our study enables identification of areas of the seabed where gully erosion
171 can occur, which allows us to define where canyons can initiate on local slopes.

172 As submarine gullies are ubiquitous features of continental slopes, our results may imply
173 that temporally-variable, cascading dense water flows may be some of the most important, and
174 least documented, agents of seafloor erosion on the world's continental margins. If future climate
175 change alters the dynamics of ocean water-masses sufficiently, the impact on ephemeral, local-
176 scale hydrodynamic events could have significant implications for the distribution and
177 magnitude of principal seafloor erosion processes.

178

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273 **FIGURE CAPTIONS**

274 Figure 1. A: Location map of Cook Strait between the North Island (NI) and South Island (SI) of
275 New Zealand showing Pacific-Australian plate boundary and principal ocean currents (DC =
276 D’Urville Current; WCC = Wairarapa Coastal Current; SC = Southland Current; ECC = East
277 Cape Current). The black rectangle denotes the location of figure B. B: The 1400 extracted
278 gullies (groups 1 and 2) mapped on the Cook Strait bathymetry. Refer to Mountjoy et al. (2009)
279 for details of the bathymetric data. The white rectangle indicates the location of figure C. C: 3D
280 digital elevation model of gullies dissecting the Opouawe Canyon walls and the seaward limb of
281 the Opouawe Bank. D: Histogram plot of the frequency distribution of slope gradient of the
282 seabed in the study area (dark gray) and axial gradients of gullies in group 1 (light gray). The
283 frequency distribution and descriptive statistics of the slope gradient of the seabed in the study
284 area are significantly different from those of gullies, which indicates that the descriptive statistics
285 and the frequency distribution of axial gully gradients are not directly determined by the general
286 morphology of the seabed. The statistics for group 2 gullies, on the other hand, are not very
287 different from those of group 1, with the mean axial gully gradient measured at 20.12° , and a
288 maximum and minimum axial gully gradient measured at 35.31° and 5.84° , respectively.

289

290 Figure 2. Plot of contributing length of seabed upslope of gully head and slope gradient (tangent)
291 of gullied slope. The line below the lower limit of the scatter of the data represents the minimum
292 topographic threshold conditions for gullying. The scatter can be explained by spatial variations
293 in seabed sediment properties and strength/direction of the gravity flow (refer to DISCUSSION).

294

295 Figure 3. Schematic model of gully initiation by an unconfined, directionally-stable, gravity flow
296 accelerating downslope across the seaward limb of Opouawe Bank (Fig. 1c). The gully head is
297 located where the flow reaches the threshold velocity required for sediment entrainment, whereas
298 the gully mouth coincides with a drop in the eroding capacity of the flow due to a reduction in
299 slope gradient.

300

301 Figure 4. Rose diagram of the frequency distribution of: (A) downstream orientation of gullies in
302 group 1; and, (B) slope aspect of seabed having a slope gradient higher than 5.5° . The slope
303 aspect of the seabed has a broad range between east-north-east (67.5°) and west-south-west
304 (247.5°), being perpendicular to the general trend of the subduction margin. The frequency
305 distribution of the slope aspect of the seabed contrasts with the predominant orientation of
306 gullies, which have a narrow aspect window between south to south-south-east (157.5° to 180°).

307

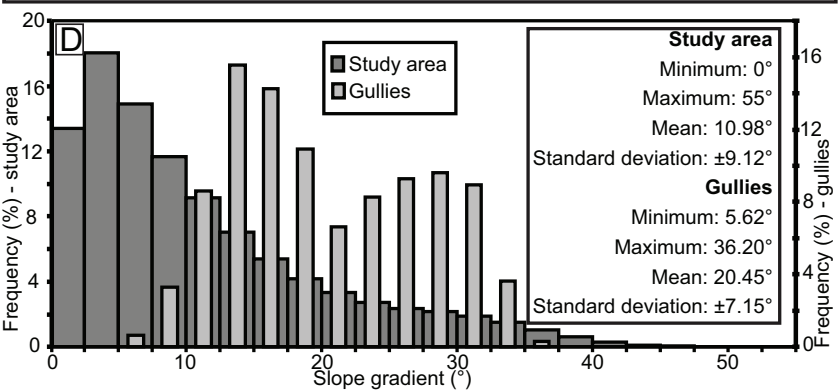
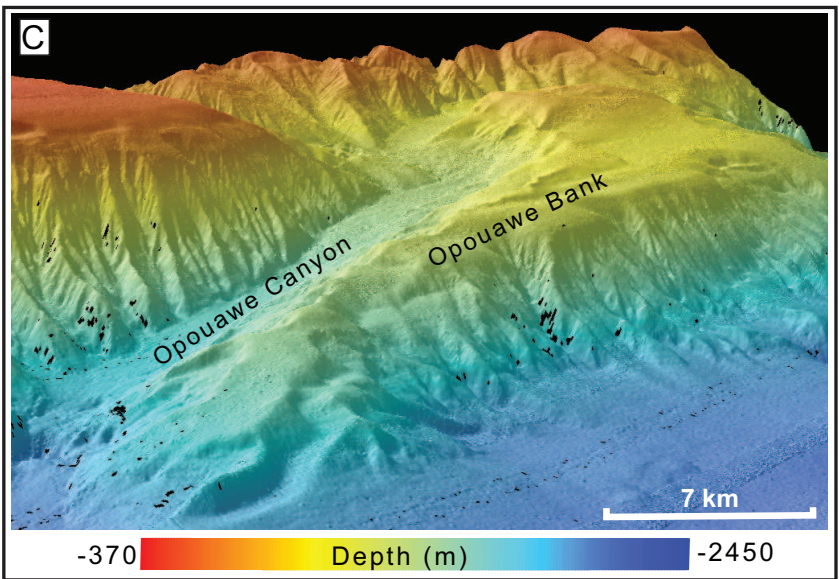
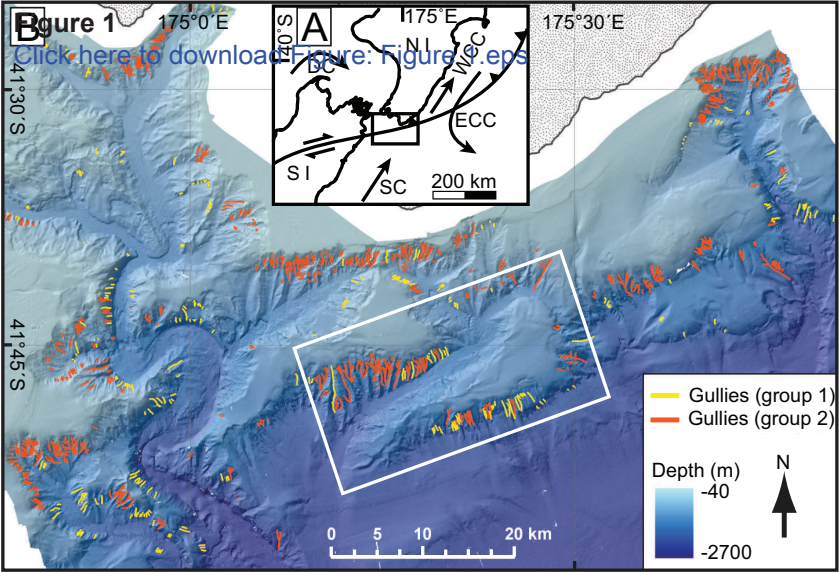


Figure 2

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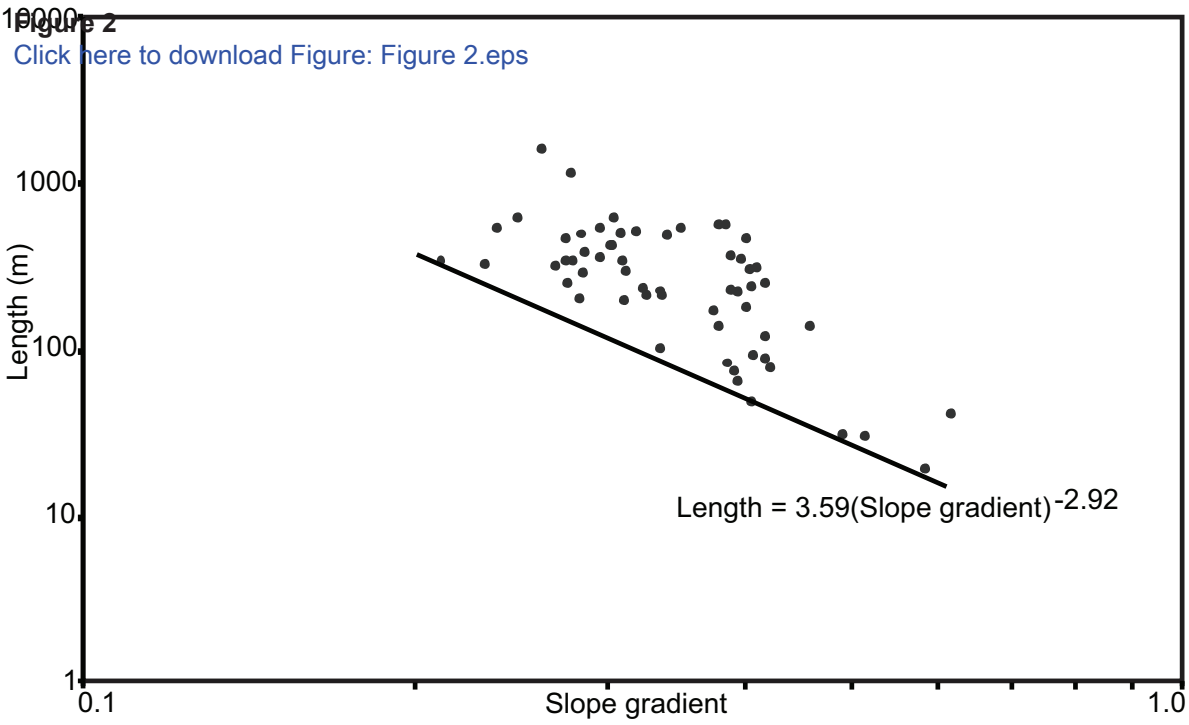


Figure 3
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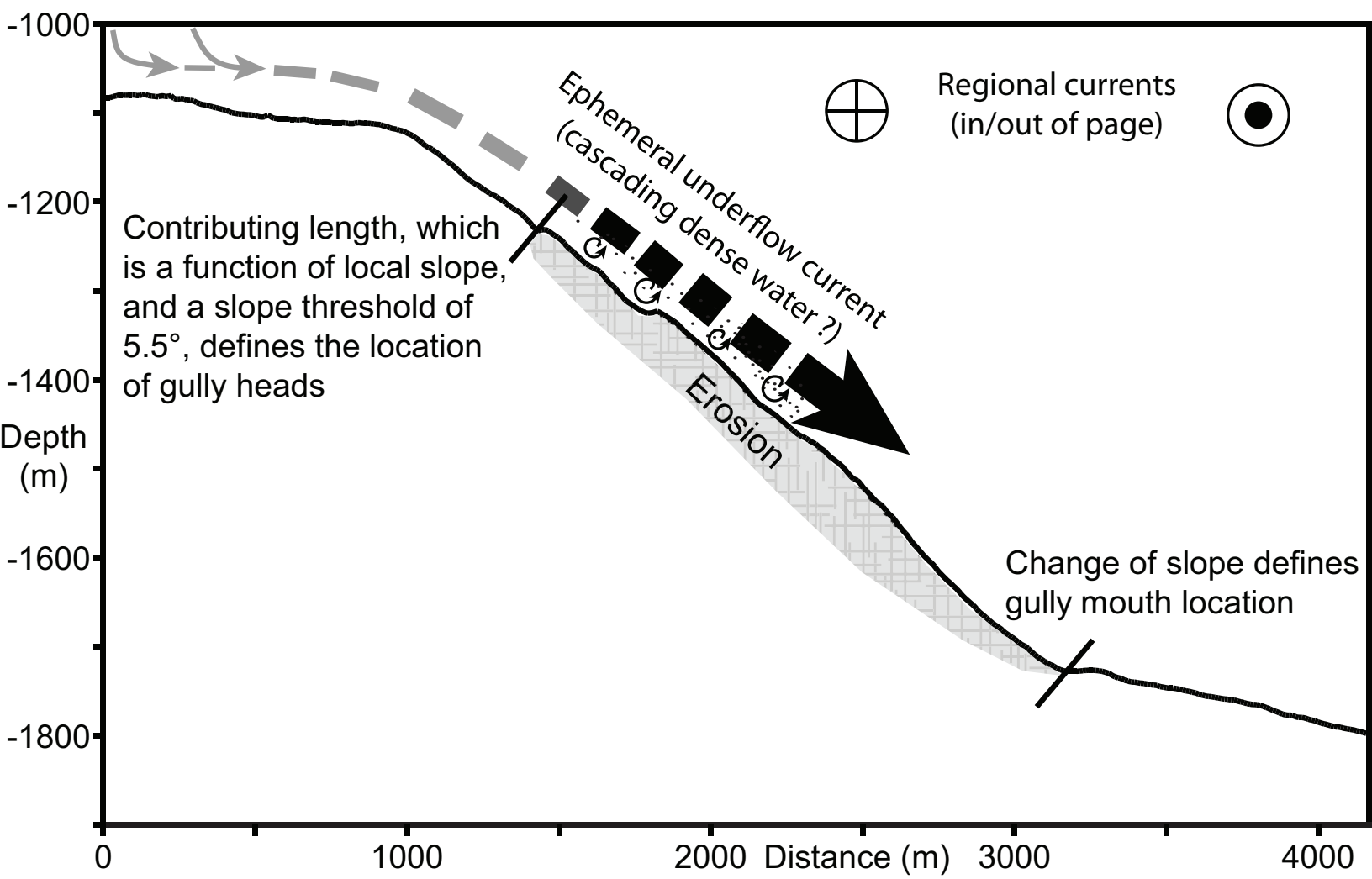


Figure 4
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