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A topographic signature of a hydrodynamic origin for submarine gullies

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ABSTRACT

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

INTRODUCTION

Gullies are steep-sided, confined channels incised by surface or subsurface flow. Gullies represent the first step in the fluvial dissection of landscapes (Bloom, 1991) and they have been documented on both terrestrial and Martian landscapes (Malin and Edgett, 2000; Valentin et al., 2005). As advanced surveying technology reveals meso-scale geomorphic details of the seafloor, gullies are shown to be common features on continental slopes (Spinelli and Field, 2001), submarine canyon walls (Lastras et al., 2007) and delta slopes (Maillet et al., 2006). Although no specific definition exists, submarine gullies are distinguished from other seafloor erosional features, such as furrows and grooves, because they are generally small scale (Surpless et al., 2009), straight, shallow channels in the order of tens of meters deep (Field et al., 1999), formed in relatively high seafloor-slope settings (Fedele and García, 2009). Submarine gullies play a pivotal role in the general evolution of continental margins over relatively long periods of time (Field et al., 1999). They are important agents of submarine erosion and downslope sediment transfer from the upper slope to the continental rise (Dowdeswell et al., 2008), and they contribute to the facies of slope deposits (Syvitski et al., 1996) and the architecture of petroleum reservoirs (Hewlett and Jordan, 1993).

A lack of understanding of the primary processes and environmental controls on gully system formation is problematic for modeling studies. The origin of submarine gullies has been attributed to a variety of processes, among which are mass wasting, sea level oscillations, fluid sapping, wind-induced rip currents, hyperpycnal flows and turbidity current scour (Chiocci and Normark, 1992; Fedele and García, 2009; Flood, 1983; Izumi, 2004; Orange and Breen, 1992; Spinelli and Field, 2001). Other significant processes identified in recent years as having the potential to erode seafloor substrates include meso-scale oceanographic processes such as internal waves and tides (Cacchione et al., 2002), and dense shelf-water cascading (Canals et al., 2006). These latter processes can be strongly affected by climate change (Herrmann et al., 2008), meaning that if these are shown to be globally significant for seafloor erosion, the dynamics of underwater geomorphic development may undergo significant changes over human timescales. Better definition of the mechanisms associated with the origins and evolution of submarine gullies will assist future modeling studies to predict climate-change-induced variations in seafloor erosion rates and processes.

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

STUDY REGION

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

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

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

RESULTS

The frequency distribution of axial slope gradients shows that submarine gullies have a mean axial gradient of ~20.5° and that they are incised only where the seabed gradient is higher than 5.5° (Fig. 1d). Plotting slope-break-to-gully-head distance against the general gradient of the slope defines an inversely proportional relationship, i.e. the steeper the gradient of the seabed, the closer the gully head is to the break of slope (Fig. 2). This relationship indicates that a slope-gradient-dependant erosion threshold sets the location of a gully head at a specific distance down the slope, which we term the contributing length. This result is comparable to field studies demonstrating that the upslope extent of terrestrial channels is defined by an inverse relationship between contributing area and slope gradient (Montgomery and Dietrich, 1988, 1992; Patton and Schumm, 1975).

DISCUSSION

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

We propose that these tractive forces are exerted by bottom currents, in the form of unconfined, downslope, fluid or sediment gravity flows. Bottom currents are the most widely recognized factor controlling the incision of furrows, which are morphologically similar erosional features to gullies (Flood, 1983). The formation of linear, spaced gullies can be explained in terms of flow concentration. This occurs in response to macro-scale roughness on the slope, and/or a change in flow dynamics with increasing seafloor gradient beyond the local break in slope. The change in flow dynamics can be triggered longitudinally by a change in the flow regime from subcritical to supercritical (Izumi, 2004), or laterally by variation of bottom shear stress as a centrifugal instability sets in at the current body interface (Fedele and Garcia, 2009). The hypothesis that submarine gullies are formed by unconfined, downslope flows is also supported by experimental evidence (Fedele and García, 2009) and geologic interpretations of sedimentary sequences of turbidites and dispersive hemipelagic sedimentation in gullied slopes (Spinelli and Field, 2001). A relationship between a gullied topography and enhanced sediment flux, on the other hand, has been demonstrated in modern delta-fed slopes (Porebski and Steel, 2003).

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

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

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

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

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

CONCLUSIONS AND IMPLICATIONS

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

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

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FIGURE CAPTIONS

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

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

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

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

Figure 1

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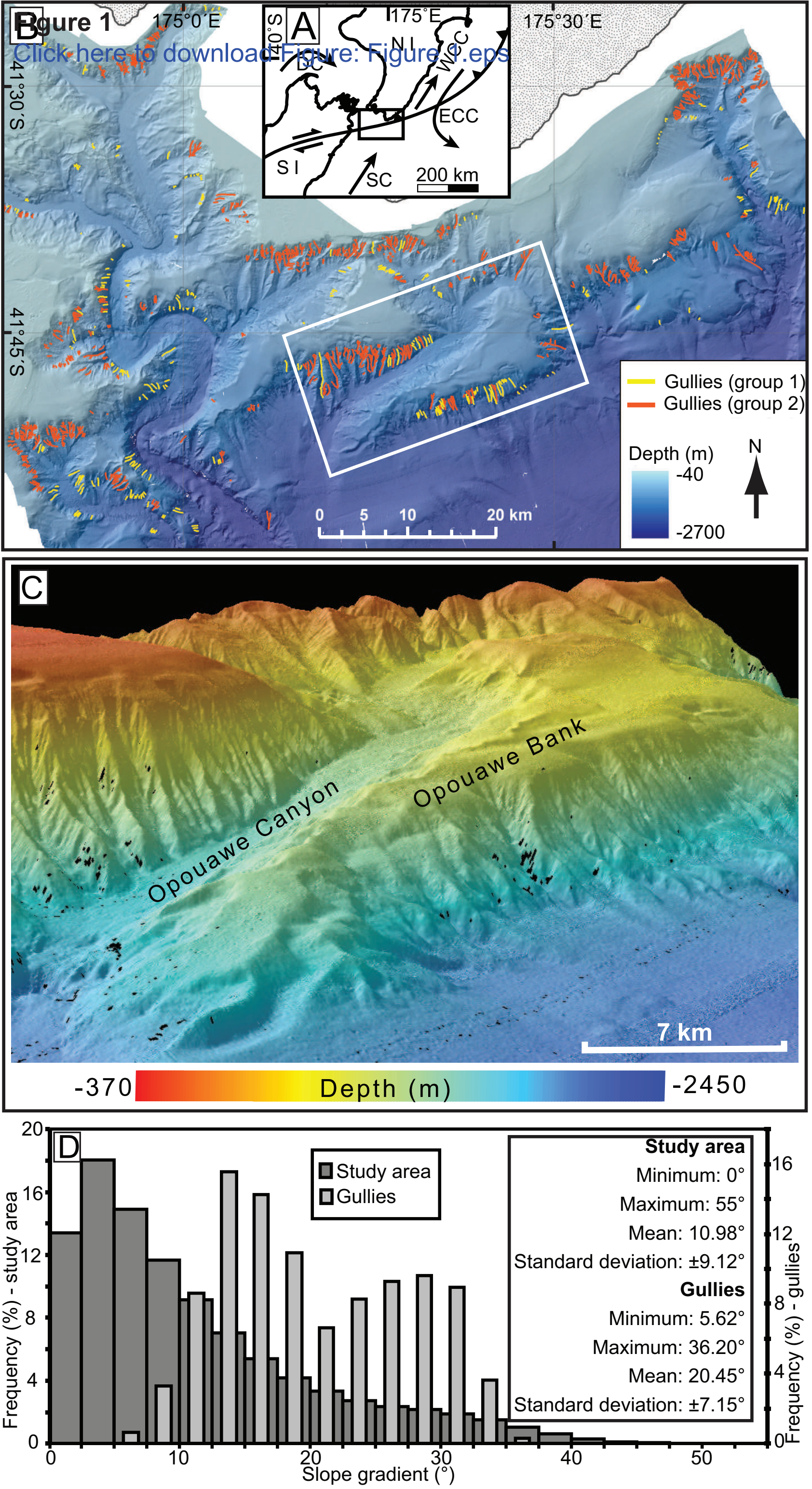

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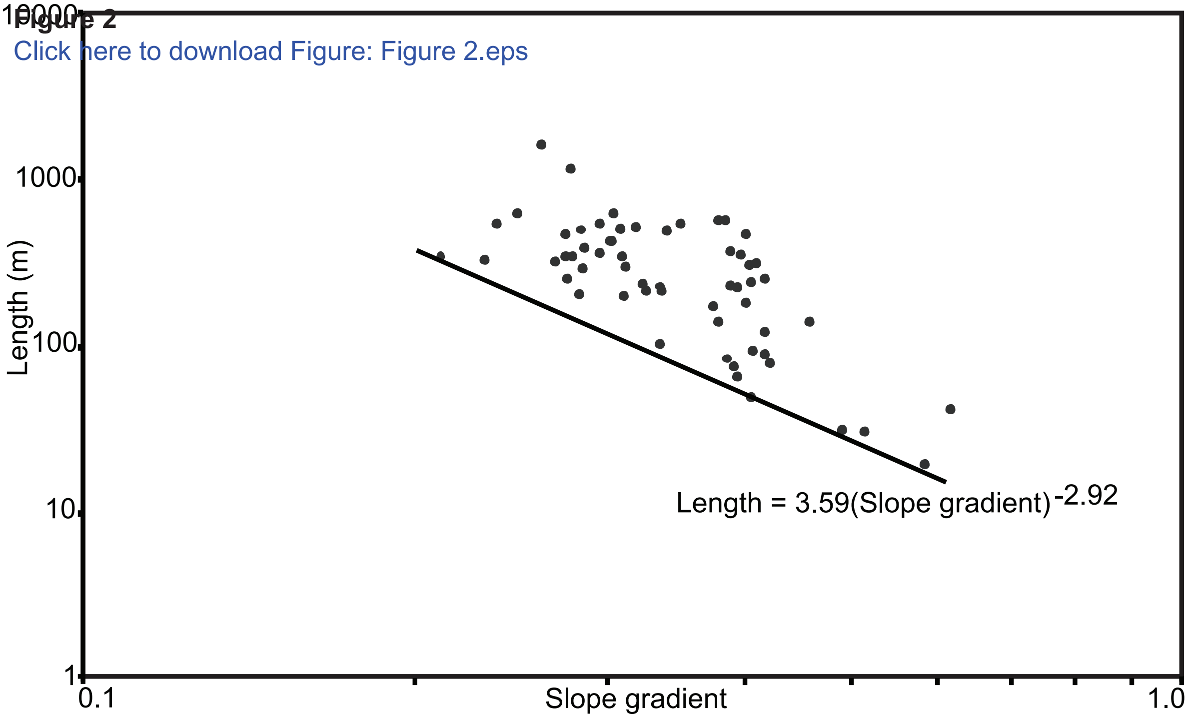

Figure 3

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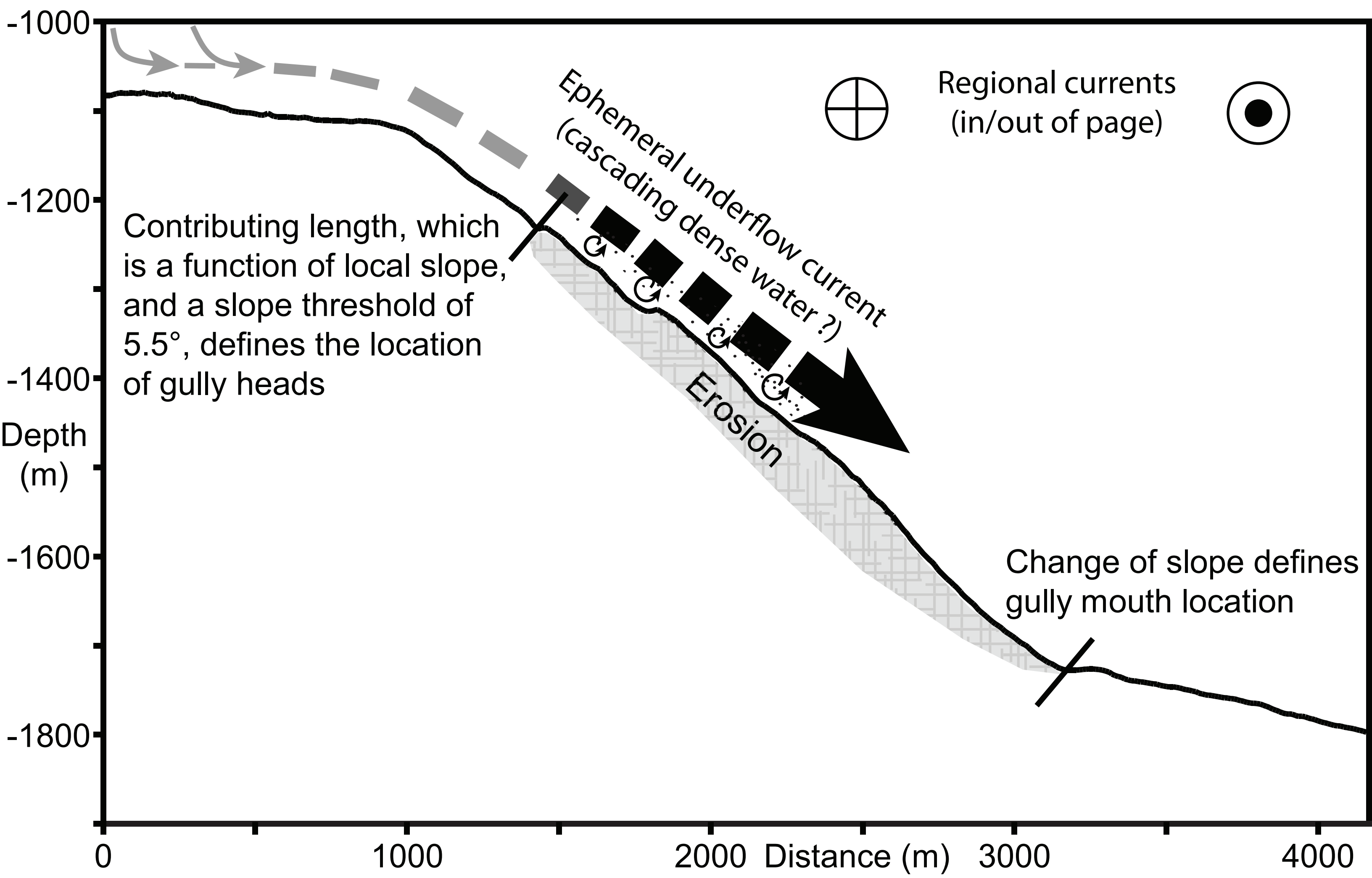

Figure 4

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