Evolution of Submarine Gullies over Geologic Time: Constraining Modern Analogs with Shallow 3D Seismic Data, Taranaki Basin, New Zealand

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Abstract

Submarine gullies are ubiquitous on the modern seafloor on both passive and active continental margins. However, the processes dictating gully formation and the role of gullies in deep-water sediment transport are topics of debate. High-resolution seafloor bathymetric data offer a detailed look at modern gully morphology, and incorporating near-surface acoustic data provides valuable constraints on bed-scale architecture. Modern submarine gullies have been documented in this fashion on a variety of continental slopes, including the Arctic and Antarctic, western Italy, western Africa, and northern California (Field et al., 1999; Spinelli and Field, 2001; Burger et al., 2003; Chiocci and Casalbore, 2011; Gales et al., 2013; Lonergan et al., 2013). However, while these types of data give a detailed glimpse of gullies at an instant in time, they do not provide a temporal record of gully evolution that can connect observations from the modern to their role in marine sedimentation over geologic timescales. Furthermore, modern gully morphologies may reflect an inactive, partially filled stage in gully evolution, as noted by Field et al. (1999) with respect to gullies in the Eel River Basin, California. Subsequent work by Burger et al. (2003) incorporating multi-channel seismic lines revealed distinct patterns in the longer-term evolution of those gullies, highlighting the importance of temporal context in understanding these features. In our study, through investigation of Pliocene-Pleistocene continental slope strata in the Taranaki Basin, New Zealand, we present results constraining the evolution of gullies in the recent geologic past (~3-1 Ma). We further compare these results with published gully metrics from modern and recent (<1 Ma) records. Together, these data provide a more complete assessment of the range of gully geometries and their role in seafloor sedimentation and slope evolution.

Study Area

The Taranaki Basin is a primarily offshore feature, covering over 100,000 km2 to the west of New Zealand's North Island. The 500 km2 Tui 3D seismic reflection survey is located ~40 km southwest of the Taranaki Peninsula. The upper portion of this seismic survey shows submarine gullies preserved in a ~1 km-thick package of Pliocene-Pleistocene aged prograding continental margin clinoforms, known informally as the Giant Foresets Formation (GFF). The 9-17 m vertical resolution of this shallow (<1.5 sec two-way travel time) seismic section allows for detailed gully mapping and measurement.

Data and Observations

Manual interpretation of eleven clinoform 'paleo-seafloor' surfaces within the GFF yields three distinct groups of clinoforms (Group I, II, and III), representing three stages in continental margin evolution. Semblance and RMS amplitude attributes on these clinoform surfaces reveal notable differences, with Group I clinoforms characterized by abundant sediment waves and mass-wasting scarps interspersed with or cross-cutting gullies, while Group II surfaces are smooth and dominated by the gully-forms (Figure 1). Group III clinoforms show tributary patterns and higher sinuosity channels that are attributed to shelfal sediment transport systems, and are therefore excluded from this study.

Gully geometries were obtained from detailed seismic interpretation on two surfaces, J and G, representing Group I and II clinoforms, respectively. On surface J, gullies are straight (1.02-1.14 sinuosity); roughly parallel; and roughly evenly spaced (~500-800 m spacing). We document gullies ranging from 20-500 m wide, 10-50 m deep, and at least 2-8 km long. Widths increase downslope, while depths remain constant or increase slightly. Gully longitudinal profiles are linear to concave-upward, with average gully slopes decreasing from 3.4-2.3˚ downslope. Interfluve gradients are nearly identical, decreasing from 2.9-1.7˚. On surface G, gullies are slightly sinuous in their upslope reaches and straight in downslope reaches (1.03-1.29 sinuosity); generally parallel, with some instances of downslope convergence; and roughly evenly spaced (~300-600 m spacing). These gullies are 10-400 m wide, 10-85 m deep, and 5 to >18 km long. Widths and depths increase slightly downslope, especially downstream of convergence points. Longitudinal profiles are linear to gently convex-upward, with average gully slopes increasing basinward from 1.1-2.3°. Interfluve profiles almost perfectly mimic gully axis profiles.

These gully metrics highlight the strong similarities among the gullies on surfaces J and G, but we also observe notable differences. Semblance imaging on surface J shows the remnants of a larger channel (~1 km wide), which in cross-section is identified as an older, passively filled feature. Some of the gullies mapped on surface J follow the edges of this former channel. Surface J is also characterized by a rough or chaotic texture, caused by slope-perpendicular sediment waves and small mass-wasting scarps. The mass-wasting scarps crosscut the gullies and form preferentially along gully axes. By contrast, no mass-wasting scarps, sediment waves, or larger channels were observed on surface G. In semblance imaging, surface G is mostly smooth, with chaotic texture only appearing at the distal-most end of the survey. Further differences are observed in cross-section. Surface J gullies are consistently observed as elements of larger gully “complexes” that range from V- to U-shaped, becoming more poorly-defined downslope before being obliterated by mass-wasting or sediment waves. Gullies on surface G instead grow from small, isolated incisions into wider, deeper gully complexes downslope, while maintaining a straight planform geometry and V-shaped, roughly symmetric cross-section. These observations are generally consistent within the respective clinoform groups, such that the gully complexes of Group I are larger and more variable in geometry than those of Group II.

Discussion

Modern gully metrics measured from high-resolution seafloor bathymetry and shallow subsurface data include width, depth, gradient, and/or between-gully spacing (e.g., Field et al., 1999; Spinelli and Field, 2001; Burger et al., 2003; Chiocci and Casalbore, 2011; Gales et al., 2013; Lonergan et al., 2013). Direct comparisons of these datasets against the metrics from this study show that the gullies of the GFF fall within previously measured ranges of width, depth, slope, and spacing. The downslope trends of width, depth, and spacing are paralleled in some datasets (Burger et al., 2003) and reversed in others (Lonergan et al., 2013).

Among the most notable features of submarine gullies, in this study and others, are their straight, parallel geometries and regular lateral spacing. The tendency for surface G gullies to lose sinuosity and increase in width at a consistent location along the slope suggests a change in some element of the slope or the gully-forming flows. As there is no measurable knick point in the gradient of surface G, the change is likely related to the flows themselves. The slightly concave-downward longitudinal profiles of the surface G gullies are similar to submarine canyon profiles of Gerber et al. (2009), which are interpreted as the result of changing sediment fallout with distance from the shelf edge. A similar process may explain the change in sinuosity and width of the surface G gullies. The regularity of gully spacing has been attributed to autogenic instabilities in sheet-like flows (Hall et al., 2008; Lonergan et al., 2013) or saturation of gullies on a slope such that new gullies are quickly captured by pre-existing ones (Gales et al., 2013). Although branching geometries are uncommon among the GFF gullies, the temporal record shows a strong tendency for pre-existing gullies and/or channels to dictate where younger gullies occur (forming gully complexes), perhaps supporting the saturation and capture hypothesis. Further detailed mapping of changes in gully spacing through time will test these hypotheses.

The remarkable similarity between the gullies of surfaces J and G, despite contextual differences between those surfaces, shows that these features can form in a variety of settings and under different conditions. A relationship between gullies and sediment waves has been proposed previously (Jobe et al., 2011; Lonergan et al., 2013), but our observations here show that similar types of gullies can form with or without sediment waves. Thus, sediment wave-forming flows may be capable of producing gullies, but are not a necessity. Similarly, the common presence of mass-wasting scarps on surface J suggests high sedimentation rates and/or muddy sedimentation, while their absence on surface G despite similar slope gradients implies a different style of sedimentation.

Gully complexes, found throughout the Group I and II clinoforms, are valuable records of gully activity through time, showing periods of inactivity (sediment draping and passive filling) interspersed with vertical aggradation and lateral migration of gullies in response to aggradation and progradation of the slope. Lateral migration is more common surface J gullies, resulting in asymmetric and irregularly-shaped gully complexes. This could be explained by high rates of aggradation relative to gully evolution, such that flows are less fully confined to pre-existing gullies and may create new gullies laterally. The more V-shaped gully complexes of surface G imply more effective trapping of flows. None of the gully complexes in the GFF show a strong tendency for lateral migration in one particular direction, suggesting a lack of dominant contour currents along the slope (cf. Zhu et al., 2010). This is consistent with the slope-perpendicular orientation of sediment waves, which implies formation by downslope currents. Although net aggradational, the gully complexes also contain clear evidence for erosion, invoking a complex history of downcutting and aggradation of individual gullies to generate a composite feature. The re-incision of filled or sediment-draped gullies suggests that even inactive gullies maintained topographic expression on the seafloor, preferentially channeling flows. The persistence of these gully complexes through slope progradation shows that gullies are long-lived features.

Conclusions

Submarine gullies are a common and integral element of continental slope sediment transport systems. 3D seismic datasets offer the opportunity to document gullies over geologic timespans, in context with the evolution of the surrounding environment. Gullies in the GFF were initiated by incision, but maintained through a combination of erosion, differential aggradation, and passive filling followed by re-incision or capture of subsequent flows. Although we document notable differences between the two studied clinoform surfaces, and although the gullies on each surface look qualitatively distinct, the gully metrics are nearly identical and fall within the range of previously documented geometries. Thus we show that gullies can form in a variety of settings: different styles or rates of progradation; in association with or in the absence of sediment waves (and sediment wave-forming flows); with or without mass wasting events; and with or without the influence of larger channels. We also show that the longer-term temporal history of gullies is key to constraining how and why they form in a particular environment, given the strong influence of pre-existing gullies on younger features. Combining these temporal studies with the greater detail and possible lithologic control of modern gully research will greatly contribute to our understanding of submarine gullies as an element of deep-water sediment transport.

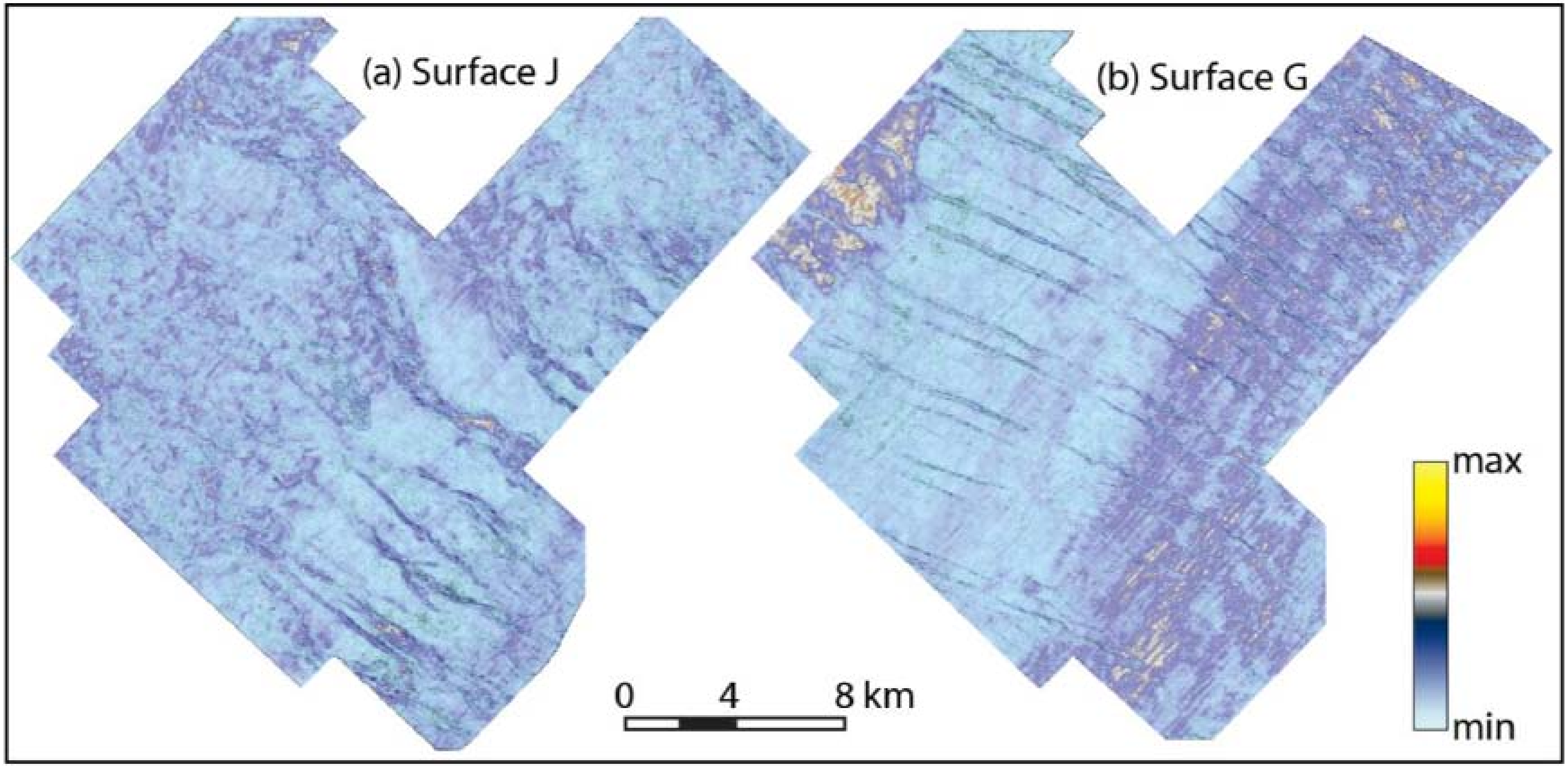

Figure 1. RMS amplitude and semblance attributes co-rendered on two paleo-seafloor surfaces. (a) Surface J has a rough texture and gullies are typically truncated by mass-wasting scarps. (b) Surface G has a smooth texture with straight, parallel gullies.

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