Geomorphic response of submarine canyons to tectonic activity: Insights from the Cook Strait canyon system, New Zealand

Aaron Micallef1,2,*, Joshu J. Mountjoy3, Philip M. Barnes3, Miquel Canals2, and Galderic Lastras2
1Department of Physics, Faculty of Science, University of Malta, Msida, MSD 2080, Malta
2GRC Geociències Marines, Facultat de Geologia, Universitat de Barcelona, E-08028 Barcelona, Spain
3National Institute of Water and Atmospheric Research, Private Bag 14901, Wellington, New Zealand

ABSTRACT

Active margins host more than half of submarine canyons worldwide. Understanding the coupling between active tectonics and canyon processes is required to improve modeling of canyon evolution and derive tectonic information from canyon morphology. In this paper we analyze high-resolution geophysical data and imagery from the Cook Strait canyon system (CS), offshore New Zealand, to characterize the influence of active tectonics on the morphology, processes, and evolution of submarine canyons, and to deduce tectonic activity from canyon morphology. Canyon location and morphology bear the clearest evidence of tectonic activity, with major faults and structural ridges giving rise to sinuosity, steep and linear longitudinal profiles, cross-sectional asymmetry, and breaks in slope gradient, relief, and slope-area plots. Faults are also associated with stronger and more frequent sedimentary flows, steep canyon walls that promote gully erosion, and seismicity that is considered the most likely trigger of failure of canyon walls. Tectonic activity gives rise to two types of knickpoints in the CS. Gentle, rounded and diffusive knickpoints form due to short-wavelength folds or fault breakouts. The more widespread steep and angular knickpoints have migrated through canyon-floor slope failures and localized quarrying and/or plucking. Migration is driven by base-level lowering due to regional margin uplift and deepening of the lower Cook Strait Canyon, and is likely faster in larger canyons because of higher sedimentary flow throughput. The knickpoints, nonadherence to Playfair’s Law, linear longitudinal profiles, and lack of canyon-wide, inverse power law slope-area relationships indicate that the CS is in a transient state, adjusting to perturbations associated with tectonic displacements and changes in base level and sediment fluxes. We conclude by inferring unmapped faults and regions of more pronounced uplift, and proposing a generalized model for canyon geomorphic evolution in tectonically active margins.

INTRODUCTION

Submarine canyons have long been recognized as principal sediment-transfer conduits that play an integral role in many aspects of continental margin development (Shepard, 1981; Normark and Carlson, 2003; Allen and Durrieu de Madron, 2009; Canals et al., 2013). The majority of published studies on canyon inception and development have been based on passive margin systems (e.g., Twichell and Roberts, 1982; Farre et al., 1983; Pratson et al., 1994, 2009; Pratson and Coakley, 1996). However, active tectonic margins compose a significant proportion of global continental margins and host more than half of submarine canyons worldwide (Harris and Whiteway, 2011). The morphology and evolution of canyons incising active margins are governed by climatic, sedimentary, and oceanographic processes that are similar to those on passive margins, although tectonism tends to exert a predominant control at both local and regional scales. In particular, seafloor deformation, through folding, faulting, uplift, or subsidence, has been shown to directly affect the location, alignment, and geometry of many submarine canyons and channels worldwide; large-magnitude earthquakes tend to influence facies distribution (e.g., Normark and Curray, 1968; Nagel et al., 1986; Lewis and Barnes, 1999; Laursen and Normark, 2002; Chiang and Yu, 2006; Le Dantec et al., 2010). Furthermore, canyons incising active margins tend to be shorter, steeper, and more dendritic and closely spaced than their counterparts in passive margins (Harris and Whiteway, 2011). While excellent quality ultrahigh-resolution autonomous under-water vehicle bathymetric data demonstrate detailed morphology of some canyon systems (e.g., Paull et al., 2011), most studies concerning canyons in active margins have been based on coarse-resolution bathymetric data, which only provide useful information on macroscale morphology. Detailed examination of relationships between active tectonics, seafloor processes, and canyon development can only be made with continuous-coverage, high-resolution bathymetric and seismic reflection data. It is therefore likely that the distinctive influence of active tectonics on submarine canyon morphology and processes has not been fully explored.

Tectonic geomorphology is a thriving field of subaerial geomorphology that examines the dynamic coupling between tectonics, climate, and erosion (Crosby and Whipple, 2006; Bishop, 2007; Whipple, 2009; Brocklehurst, 2010). The focus of tectonic geomorphology has been the fluvial network, which, because it maintains a direct connection to tectonic forcings, provides useful information on tectonic activity across a landscape (Wobus et al., 2006). Terrestrial river systems are known to respond to tectonics in several ways. Experimental results and field examples show how slope steepening due to uplift results in an increase in river sinuosity and convexity, as well as localized aggravation and degradation (Ouchi, 1985). Fault rupture to the land surface across a river bed can induce significant channel steps that propagate upstream. For example, the 1999 Chi-Chi (Taiwan) earthquake produced surface offsets of 0.5–8 m that evolved upstream as a series of knickpoints as high as 18 m over a period of 9 yr (Yanites et al., 2010). Regionally high uplift rates affecting the entire channel reach can alter the equilibrium profile of a fluvial system and induce knickpoint propagation up a riverbed until the system reattains some equilibrium state (Snyder et al., 2000).

For permission to copy, contact editing@geosociety.org
© 2014 Geological Society of America

Received 12 February 2014 ♦ Revision received 2 June 2014 ♦ Accepted 25 June 2014 ♦ Published online 18 August 2014

*Email: aaron.micalleff@um.edu.mt
drive knickpoint development and migration in some river systems (e.g., Berryman et al., 2010). Another response is the dramatic and long-lasting increase in sediment load due to earthquake-induced slope instability (Dadson et al., 2004). Many studies have dealt with quantitative analyses of digital elevation models, particularly focusing on channel morphology, to obtain information on the character, pattern, and rates of tectonic deformation, and to develop long-term landscape evolution models (e.g., Howard, 1994; Burbank et al., 1996; Demoulin, 1998; Whipple and Tucker, 1999; Snyder et al., 2000, 2003; Kirby and Whipple, 2001; Whittaker et al., 2008; Sougnez and Vanacker, 2011). Our ability to derive similar information from submarine canyon topography is severely limited by several factors. These include the paucity of data available to develop and calibrate process-based laws, the difficulties in obtaining in situ measurements of sediment flows, and the inapplicability of surface exposure dating techniques underwater (Huyge et al., 2004; Mitchell, 2006). Knowledge of the effects of active tectonics on submarine canyon development is thus still insufficient to enable quantitative studies of canyon evolution. Considering that most data available from submarine canyons are morphological, a better understanding of the coupling between active tectonics and submarine canyon morphology and processes is required.

In subaerial geomorphology, the stream power erosion model has been developed to relate the fluvial erosive process to larger scale landscape form. In many settings, local channel slope ($S$) and contributing drainage area ($A$) have been shown to be related by an inverse power law scaling (Flint, 1974; Howard, 1994; Whipple and Tucker, 2002):

$$S = kA^{-\Theta},$$

where $k$ is the steepness index and $\Theta$ is the concavity index. Inverse power law scaling in bedrock-eroding rivers has been interpreted to arise where there is a steady state between tectonic uplift and erosion. Thus, segments of individual slope-area profiles characterized by different values of steepness and concavity indices are often used to extract tectonic information from the landscape (Wobus et al., 2006). Channel steepness, in particular, has been predicted to correlate with rock uplift rates (Howard, 1994). These relationships are based on several assumptions, and their applicability is limited by many complexities, such as non-linearities in incision processes, adjustments in the channel, bed morphology or sediment size, and changes in climate or tectonic state (Whipple and Tucker, 1999, 2003; Snyder et al., 2000, 2003). On the continental margins of the Atlantic United States and Taiwan, slope-area relationships similar to those reported for sub-aerial rivers have been shown to be common for submarine canyons (Mitchell, 2004, 2005; Ramsey et al., 2006; Brothers et al., 2013). The relationships for submarine canyons have been explained by a model where the frequency of flows in the canyon increases downstream and with increasing contributing area, representing the upstream area of canyon walls with potentially unstable sediment capable of sourcing erosive sedimentary flows. In this model, erosion in the continental slope progresses toward a form of spatial equilibrium so that channels have concave-upward long profiles, and the downstream effect of increasing flow frequency is balanced by decreasing gradient. It is very difficult to corroborate this model with field data. The origin of the slope-area relationships is still unclear because erosion by rivers and gravity flows differs in many aspects, particularly in terms of density contrast, thickness, and flow transformation. Submarine canyons are characterized by increasingly resistant lithology with depth, flank slope failures, spatial and temporal changes in erosion mechanisms, and varied sediment input. The downstream change in dynamic behavior of submarine gravity flows is quite different from that of rivers because of the increase or loss of flow power with suspension or deposition of particle load (Gerber et al., 2009). It has also been suggested that drainage basin area in submarine canyons is not related to flow discharge as in terrestrial systems, but results from the aggregation of random walks (Straub et al., 2007). The details of submarine flow processes and their interaction with seafloor morphology and tectonic processes are therefore still too vague to justify using morphological parameters to extract tectonic information.

The purpose of this study is to carry out morphological and morphometric analyses of high-resolution bathymetric and seismic reflection data from the Cook Strait canyon system (CS), which incises the Hikurangi margin off New Zealand’s North Island, in order to (1) understand how tectonic activity influences submarine canyon morphology, processes, and evolution in an active margin, (2) deduce current or past tectonic activity across the Hikurangi margin, and (3) formulate a generalized model of canyon development in response to tectonic forcing based on morphometric parameters. Addressing these research objectives is important for developing a framework for reconstructing and predicting canyon dynamics in active margins; this has direct implications for canyon oceanography and biology, as well as deriving tectonic information from canyon morphology, information that can improve offshore neotectonic analyses and hazard assessment. Cook Strait is an excellent site to investigate the signature of tectonism in submarine canyons: it is an active subduction to strike-slip tectonic margin that is traversed by a series of active thrust and strike-slip faults, incised by New Zealand’s largest submarine canyon system, covered by high-resolution seafloor data (Mountjoy et al., 2009; Lamarche et al., 2011), and there are excellent quality seismic reflection data available for subsurface imaging of stratigraphy and tectonic structure. The tectonic strain rates from global positioning system (GPS) data and the ground shaking potential from earthquake sources derived from paleoseismic and seismological studies are very well known in this area, providing an excellent framework to assess the response of canyons to tectonic forcing.

**REGIONAL SETTING**

**General Setting and Geomorphology**

Cook Strait is the seaway between the North and South Islands of New Zealand and links the Tasman Sea with the Pacific Ocean (Fig. 1). The strait narrows to 22 km width at the central neck, and widens toward the north and south. The majority of the seabed is at water depths of <150 m; the exceptions are the Narrows Basin, where depths exceed 300 m, and to southeast of the strait. The seaway is subjected to strong tides, sustaining flows of 1.5–2 m s$^{-1}$ over large areas, that are known to mobilize sediment as large as cobble size (Carter et al., 1991; Stevens et al., 2012; Mountjoy et al., 2013). Active faults underlie the continental shelf (Barnes and Audru, 1999a; Pondard and Barnes, 2010), although the morphology of the shelf is strongly affected by tidal current scour and deposition (Lamarche et al., 2012). Beyond the continental shelf, active tectonic deformation is a primary driver of large-scale seafloor geomorphology, and is known to have a significant influence on the canyon system (Mountjoy et al., 2009). This region of the Hikurangi margin is referred to as the Cook Strait sector (Fig. 1).

**Tectonic Setting, Active Deformation, and Earthquake Sources**

The CS is located on the southern Hikurangi margin subduction system (Mountjoy et al., 2009) (Fig. 1). Subduction of the Pacific plate underneath the Australian plate is occurring at a rate of ~38 mm yr$^{-1}$ at 050° oblique to the plate margin (Beavan et al., 2002). Slip partitioning results in an orthogonal convergence at a rate diminishing from ~20 mm yr$^{-1}$ north of Cook...
Strait to ~6 mm yr$^{-1}$ south of the strait (Wallace et al., 2004). The convergence results in numerous active upper plate thrust and strike-slip faults occurring throughout the region (Fig. 2A; Barnes and Audru, 1999a, 1999b; Pondard and Barnes, 2010; Plaza-Faverola et al., 2012; Wallace et al., 2012; Henrys et al., 2013). Thrust faulting beneath the continental slope is expressed as margin-parallel ridges that reflect anticline development. Palliser and Opouawe banks are examples of folding and bathymetric uplift in the hanging wall of northwest-dipping thrust faults (Figs. 1 and 2A; Barnes and Audru, 1999a, 1999b; Pondard et al., 2004). The convergence results in as much as 2 m vertical motion across the lower part of the CS and subsidence of as much as 2 m around the uppermost canyon (Fraser et al., 2014) (Fig. 3B).

Active faults have been incorporated into the New Zealand National Seismic Hazard Model as generalized earthquake sources derived from quantification of active fault parameters across New Zealand (Stirling et al., 2012; Litchfield et al., 2014). The CS is expected to experience ground shaking levels of 0.4–0.6 g over the 1000 yr return period (Fig. 3A; Stirling et al., 2012). Mean vertical slip rates for the faults crossing the lower CS vary from 1 to 4 mm yr$^{-1}$ based on structural restorations and slip deficits (Barnes and Mercier de Lepinay, 1997; Wallace et al., 2012). Strike-slip faults crossing the upper canyon have horizontal rates of 4–12 mm yr$^{-1}$, with very little overall vertical slip (Stirling et al., 2012). Single event displacements expected during coseismic rupture of each of the faults are shown in Figure 3A.

Two large earthquakes have occurred in the Cook Strait in historical, preinstrumental time: the 1848 M7.5 Marlborough event and the 1855 M8.2 Wairarapa earthquake (Grapes and Downes, 1997; Grapes et al., 1998). Most recently, 21 July and 16 August 2013, two earthquakes (M6.5 and M6.6, respectively) occurred on offshore faults beneath the continental shelf of the southwestern Cook Strait; the shaking from these events was widely felt, but no surface rupture or geomorphic response was observed in postevent offshore surveys (Mountjoy, 2013). The potential for mega-thrust earthquakes on the Hikurangi margin is poorly constrained, partly as no large historical events have occurred, and partly due to poor paleoseismologic evidence (e.g., Clark et al., 2011). Dislocation modeling for a hypothetical M9 subduction earthquake rupturing the entire length of the Hikurangi margin, and accounting for ~1000 yr of strain accumulation, results in as much as 2 m vertical motion across the lower part of the CS and subsidence of as much as 2 m around the uppermost canyon (Fraser et al., 2014) (Fig. 3B).

**Submarine Canyons**

The CS comprises five major canyons, the flanks of which are characterized by numerous gully systems and landslide scars (Fig. 1). The Cook Strait Canyon is recognized as the major through-going feature; it extends from the shelf to the Hikurangi Channel at the toe of the margin (Mountjoy et al., 2009). In this paper we distinguish between the upper and lower reaches of the Cook Strait Canyon because they have distinctly different morphology and morphometrics. The Nicholson, Wairarapa, and Palliser Canyons, and a relatively small canyon referred to informally here as Boo Boo, are tributaries that feed into the Cook Strait Canyon.
Figure 2. (A) Depth-migrated regional multichannel seismic reflection (MCS) profile PEG-19 illustrating the active plate interface between the subducting Pacific plate and the overlying Australian plate (modified from Plaza-Faverola et al., 2012). Active faults in the upper plate are deforming the continental slope and forming ridges (e.g., Opouawe Bank) that have controlling influence on slope morphology. Location is shown in Figure 1. BSR—bottom simulating reflector, O-UF—Opouawe-Uruti fault, PF—Pahaua fault, MES—Late Cretaceous sequence, LIP—lithospheric plate, VE—vertical exaggeration. (B) Enlargement of part of the MSC profile (location in A) illustrating the shallow details of active fault tips as they approach the seabed. Green arrows are indicative of old canyons and/or channels that were subsequently infilled. CDP—Common Depth Point.
Figure 3. (A) Active faulting and ground shaking. Background colors show the peak ground acceleration expected for a return period of 1000 yr. The red lines represent the seismic sources in the probabilistic seismic hazard model used to generate the ground shaking levels and the associated values show the range of single event displacements expected for each fault (after Stirling et al., 2012). (B) The Hikurangi subduction zone beneath Cook Strait. Blue contours show the depth of the subduction interface (after Ansell and Bannister, 1996). White contours and green to red colors show the predicted uplift of the seafloor for a full rupture of the Hikurangi subduction thrust (after Fraser et al., 2014).
The Campbell and Opouawe Canyons are single branch canyons that also connect to the Hikurangi Channel, but not to the Cook Strait Canyon (Fig. 1). Canyon rims are as shallow as 50 m on the continental shelf, and exit to the Hikurangi Channel at depths >2500 m.

The Nicholson, Wairarapa, and the middle to upper reaches of the Cook Strait Canyon are incised in late Cenozoic sedimentary sequences of indurated and gently dipping mudstone, siltstone, or sandstone (Mountjoy et al., 2009). The northern walls of the Nicholson and Wairarapa Canyons may expose Torlesse Greywacke Mesozoic basement, consisting of well-indurated and slightly metamorphosed mudstones and silty sandstones. The Palliser, Opouawe, Campbell, and Boo Boo Canyons, and the deeper part of the Cook Strait Canyon are incised in Neogene slope and uplifted basin-floor turbidite sequences (Uruski, 2010).

The canyons can be divided in two groups. The upper canyons (Nicholson, Wairarapa and upper Cook Strait Canyons) incise the continental shelf, whereas the lower canyons (Palliser, Opouawe, Campbell, and Boo Boo Canyons) incise the continental slope. The morphological characteristics of each canyon are presented in Table 1.

### DATA SETS

#### Multibeam Echosounder Data

This study is mainly based on 8400 km² of multibeam echosounder data collected between 2002 and 2005 using a hull-mounted Simrad EM300 multibeam system operating at a 30 kHz frequency, and a Position and Orientation System for Marine Vessels (POS/MV) system with differential GPS, on board the RV *Tangaroa*. The navigational accuracy and vertical accuracy of the multibeam echosounder data in 1000 m water depth are ±5 m and ±2 m, respectively. Bathymetry and backscatter data grids of 10 m × 10 m bin size were derived from the multibeam echosounder data. The bathymetry data were processed with C & C Technologies HydroMap software (www.cctechnol.com) by accounting for sound velocity variations and tides, and by implementing basic quality control. The backscatter data were processed with SonarScope software developed by IFREMER (Institut Français de Recherche pour l’Exploitation de la Mer; Augustin and Lurton, 2005). Processing included signal calibration and compensation, speckle noise filtering, texture analysis, and image segmentation (Lamarche et al., 2011).

#### Multichannel Seismic Reflection Profiles

Wide-angle, deep penetration multichannel seismic reflection (MCS) data were collected from the Cook Strait sector of the Hikurangi margin in 2009–2010 (Ministry of Economic Development, 2010). Two-dimensional seismic profiles (n = 26) were acquired during the Pegasus survey and processed to pre-stack time migration by Geotrace (Ministry of Economic Development, 2010). These include five dip lines across the margin of the CS (PEG-09 to PEG-19), with an average line spacing of ~15 km, and two strike lines (PEG-02 and PEG-04).

#### Deep Tow Imaging System

During research cruise TAN1103 carried out on board the RV *Tangaroa* in 2011, we acquired high-definition video and still imagery of the seafloor along four transects in the Nicholson, Wairarapa, and Cook Strait Canyons using the New Zealand National Institute of Water and Atmospheric Research Deep Tow Imaging System (NIWA DTIS). Real-time data processing and recording were carried out using the NIWA Ocean Floor Observation Protocol (OFOP) software.

### METHODOLOGY

Standard morphometric attributes (slope gradient, slope aspect, profile, and plan curvature) were extracted from the bathymetric data set using the geographic information system (GIS) ESRI ArcGIS (www.esri.com/software /arcgis). Submarine gullies and canyon thalwegs were automatically mapped using standard GIS hydrology tools for terrestrial drainage network extraction, which included the computation of flow direction and flow accumulation routines across the study area after sinks in the grid were filled (Tubau et al., 2013). The resulting maps were validated by thorough visual inspection. Canyon longitudinal profiles were extracted along the automatically mapped canyon thalwegs. Morphological steps along the canyon floor were identified from slope gradient longitudinal profiles using a moving average that estimated the general trend of the slope gradient and eliminated peaks due to fine-scale roughness. The boundaries of submarine landslide scars were delineated from a geomorphometric map and an automated topographic classification (using the standard deviation of slope gradient) generated from the bathymetry data set using techniques described in Micallef et al. (2007). The boundaries of submarine canyons were delineated semi-automatically using morphometric attribute maps (slope gradient, slope aspect, profile curvature), the flow accumulation map, and the geomorphometric map. These maps clearly identify the pronounced and subtle changes in morphology along the canyon borders. The resolution of the maps is equivalent to the resolution of the bathymetric data, rather than the scale at which the landscape is being interpreted by the user (Micallef et al., 2007). Canyon relief was calculated by interpolating the bathymetry grid across the boundaries of submarine canyons and subtracting from the original bathymetry.

Thalweg slope gradient and upslope canyon area were extracted at 20 m isobath intervals along the floor of each canyon to generate slope-area plots (Brothers et al., 2013). Power law trend lines were fitted to the plots, from which the exponent (concavity index) and coefficient (steepness index) were derived from the power law equation. The plots comprised different segments of data points, which can be distinguished in terms of the trend followed by the data and the values of concavity and steepness indices. The division of the plots into segments was guided by a moving average calculated for all the data points in each plot. The theoretical and

### TABLE 1. MORPHOMETRICS OF THE COOK STRAIT CANYON SYSTEM

<table>
<thead>
<tr>
<th>Canyon</th>
<th>Length (km)</th>
<th>Maximum width (km)</th>
<th>Depth from canyon head to mouth (m)</th>
<th>General orientation</th>
<th>Area (km²)</th>
<th>Mean thalweg slope gradient (°)</th>
<th>Landslide density (km⁻¹)</th>
<th>Gully density (km⁻¹)</th>
<th>Maximum relief (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nicholson</td>
<td>21.3</td>
<td>8.9</td>
<td>600</td>
<td>NW-SE</td>
<td>113</td>
<td>1.28</td>
<td>0.0976</td>
<td>0.67</td>
<td>330</td>
</tr>
<tr>
<td>Upper Cook Strait</td>
<td>50.9</td>
<td>12.7</td>
<td>1000</td>
<td>NW-SE</td>
<td>386</td>
<td>1.07</td>
<td>0.233</td>
<td>0.27</td>
<td>440</td>
</tr>
<tr>
<td>Lower Cook Strait</td>
<td>79.0</td>
<td>14.8</td>
<td>1400</td>
<td>N-S</td>
<td>436</td>
<td>1.25</td>
<td>0.082</td>
<td>0.81</td>
<td>1200</td>
</tr>
<tr>
<td>Wairarapa</td>
<td>36.0</td>
<td>10.7</td>
<td>1000</td>
<td>NE-SW</td>
<td>320</td>
<td>1.28</td>
<td>0.1327</td>
<td>0.51</td>
<td>450</td>
</tr>
<tr>
<td>Boo Boo</td>
<td>12.1</td>
<td>5.6</td>
<td>1200</td>
<td>W-E</td>
<td>35</td>
<td>5.74</td>
<td>0</td>
<td>2.37</td>
<td>640</td>
</tr>
<tr>
<td>Palliser</td>
<td>22.1</td>
<td>11.9</td>
<td>1600</td>
<td>NE-SW</td>
<td>166</td>
<td>3.09</td>
<td>0.1847</td>
<td>0.86</td>
<td>500</td>
</tr>
<tr>
<td>Opouawe</td>
<td>58.1</td>
<td>13.7</td>
<td>2200</td>
<td>NE-SW</td>
<td>465</td>
<td>2.08</td>
<td>0.066</td>
<td>1.12</td>
<td>640</td>
</tr>
<tr>
<td>Campbell</td>
<td>47.5</td>
<td>12.0</td>
<td>2200</td>
<td>NW-SE</td>
<td>182</td>
<td>3.18</td>
<td>0.054</td>
<td>0.95</td>
<td>560</td>
</tr>
</tbody>
</table>

Note: NW-SE—northwest-southeast; N-S—north-south; NE-SW—northeast-southwest.
there is a change in direction or offset of the canyon axis (e.g., Wairarapa, Cook Strait Canyons) (Fig. 1). The Palliser, Opouawe, and Boo Boo Canyons are also parallel to thrust faults, including the Opouawe-Uruti and Pahaua faults (Barnes et al., 2010). Where the canyon intersects a strike-slip fault (e.g., Needles, Wairarapa faults), the canyon is wider downslope (e.g., Nicholson, Cook Strait Canyons) (Fig. 1). The floors of the upper canyons, excluding the upper sections of the Cook Strait and Nicholson Canyons, are characterized by low backscatter (Fig. 5A). In comparison, the floors of the lower canyons are associated with higher backscatter.

In cross section, the canyons are generally V shaped, and the floor widths reach 2.5 km. The canyon walls comprise the steepest terrain across this part of the Hikurangi margin, locally reaching slope gradients of 30°. Some of the canyon walls, such as those of the Wairarapa, Palliser, Opouawe, and Boo Boo Canyons, are parallel to faults (Fig. 1). The canyon walls are also asymmetric, with opposing walls of individual canyons showing a difference of as much as 10° in slope gradient. The canyon walls have been eroded by either linear to dendritic gullies (Micallef and Mountjoy, 2011), or submarine landslides (Micallef et al., 2012) (Figs. 5C, 5D). The highest gully densities are observed in the lower canyons (Table 1). There are 141 landslip scars on the walls of the CS; these have been interpreted as resulting from deep-seated translational landslides occurring in late Cenozoic to Pleistocene sequences (Mountjoy et al., 2009; Micallef et al., 2012). The landslide scars are located across the entire depth range covered by the canyons, although 65% of the scars (by area) occur in the shallow canyons (Fig. 5C). The landslide scars are predominantly small, with a median area of 0.82 km² and a median volume of 0.013 km³.

Estimated relief along the canyon thalwegs ranges between 330 m and 1200 m (Fig. 5B); the highest values are recorded in the lower canyons (Table 1). All canyons show a general increase in relief with distance down canyon. Abrupt changes in relief across canyons coincide with faults (Fig. 5B).

**Longitudinal Profiles**

The longitudinal profiles of the CS vary from convex (upper Cook Strait Canyon), to linear (Boo Boo, lower Cook Strait, Opouawe, Palliser, and Wairarapa Canyons) to slightly concave (Nicholson and Campbell Canyons) (Fig. 6). Breaks and concave changes in the longitudinal profile predominantly coincide with known faults (Fig. 7). The steepest mean thalweg slope gradients are observed in the lower canyons (Table 1). We also note that the Palliser and Boo Boo Canyons appear to be hanging above the lower Cook Strait Canyon.

### Steps and Depressions

The longitudinal profiles of the canyons are interrupted by 28 steps and 8 depressions, 92% of which occur in the lower canyons (Figs. 7 and 8). The steps consist of individual convex to concave changes in slope that are generally associated with high backscatter. The depressions, all of which are located downstream of the mouth of the lower Cook Strait Canyon, are smaller, occur in groups, and have upslope asymmetrical wave-like shapes in profile.

The heights of the steps vary between 20 m and 233 m, and slope gradients vary between 2.3° and 34.8°. All the steps correspond to the upper limits of crescent-shaped scars on the canyon floor, only a few of which extend across the entire canyon width. The higher and steeper the steps, the more likely the scar extends across the entire canyon floor. Downslope of some of the steps, the canyon walls have abundant landslide scars (Fig. 7D; Micallef et al., 2012). At least 4 steps (1, 17, 18, 28) have rounded lips, and are associated with low backscatter and with either faults or with propagating folds related to blind faults. The remaining steps have more angular lips, and the canyon floor downslope of the steps is associated with high backscatter. Half of the steps have a ridge at their base. DTIS transect 31 imagery of the seafloor downslope of step 4, located in the lower Cook Strait Canyon, shows the occurrence of bedrock containing rock mass defects exposed at the seafloor, large tabular and subangular blocks of mudstone, and angular fragments of mudstone scattered across the canyon floor (Figs. 7H and 8).

We measured the distance along the seabed of steps from either the regional base level or the floor of the canyon in which a tributary canyon hosting the step drains. Figure 9 is a plot showing how some of these steps from the Cook Strait, Palliser, and Boo Boo Canyons can be classified into three groups (steps 7 and 12; steps 11 and 14; steps 3, 10, and 13) according to their distances from the floor of the lower Cook Strait Canyon. We also plotted the total canyon area against the distance of steps in the lower canyons from their local base levels; the resulting plot shows a good power law relationship between these two variables (Fig. 10).

### Slope-Area Analyses

The thalweg slope-area plots for each submarine canyon are shown in Figure 11. The majority of the boundaries of the plot segments...
The lowest $R^2$ values for the inverse power law regression models occur in the Nicholson and Wairarapa Canyons, and the upslope segment of the Boo Boo Canyon, all of which are located upslope of faults or steps. Segments with the highest values of mean slope gradient are mapped in Figure 12; these correspond to the upper and lower reaches of the Campbell, Palliser, and Boo Boo Canyons, and the lower reaches of the Opouawe Canyon. Where not coinciding with the canyon heads, segments with the highest mean slope gradients are associated with canyon areas located upslope of either faults or steps.

**DISCUSSION**

**Control of Tectonics on Canyon Morphology, Processes, and Evolution**

**Control of Active Tectonics on Canyon Morphology**

The clearest influence of active tectonic deformation on canyons is in terms of location and planform shape. Alignment and proximity of...
Control of active tectonics on submarine canyons

Figure 5 (on this and following page). Maps and features of the Cook Strait canyon system. Canyon name abbreviations (circled) are as in Figure 1 legend. (A) Acoustic backscatter. (B) Relief.
Figure 5 (continued). (C) Landslide scars. (D) Gullies.
the Wairarapa, Palliser, Opouawe, and Boo Boo Canyons with faults indicates that canyon erosion is likely to have taken place along traces of major faults or has been constrained by structurally generated tectonic ridges. This would have taken place by steepening of the seabed associated with tectonic growth, diversion and/or focusing of gravity flows by topographic steps or lips, or dense fracturing of the bedrock by faults. The dendritic and sinuous pattern of the CS is thus predominantly a result of the numerous thrust and strike-slip faults that intersect the canyon system at various angles (5°–90°) across the continental shelf and slope. The new MCS data confirm that the tectonic ridges that are responsible for the sinuosity of the lower Cook Strait Canyon are active anticlines (Fig. 4). The upper Cook Strait, Nicholson, and Opouawe Canyons also show that canyon widening has occurred downslope of strike-slip faults intersecting the canyon axes. This is a result of the lateral shifting of the focus of erosion due to the displacement of the canyon by fault movement.

The occurrence of tectonic ridges is also partly responsible for the asymmetry observed in walls of the lower canyons, because the forelimbs of the tectonic ridges in Cook Strait are as much as two times steeper than their backlimbs (upslope facing) (Mountjoy et al., 2009). The longitudinal profiles of the CS are steep (mean thalweg slope gradient as high as 5.74°; Table 1) and predominantly linear. Both of these morphological characteristics are a result of active tectonic deformation steepening the continental slope and being more effective than incision by sedimentary flows (Huyge et al., 2004; Covault et al., 2011).

The morphological patterns identified are similar to those documented in other submarine canyons in tectonically active margins, e.g., La Jolla Canyon (California; Le Dantec et al., 2010), Monterey Canyon (California; Greene et al., 2002), San Antonio Canyon (Chile; Laursen and Normark, 2002), Kushiyo Canyon (Japan; Noda et al., 2008), Kaoping Canyon (Taiwan; Chiang and Yu, 2006) and submarine channels in the Nankai Trough (Japan; Alves et al., 2014). These patterns, together with the breaks and/or changes observed in canyon longitudinal slope profiles and mean slope gradient, relief, and slope-area plots where the canyons intersect faults (Figs. 5B, 7, 11, and 12), indicate that tectonic activity leaves a clear topographic signature on the canyon morphology. These results are also similar to what has been reported for subaerial fluvial systems (e.g., Whipple, 2004; Wobus et al., 2006).

Control of Active Tectonics on Canyon Processes and Evolution

Sedimentary Flows

The high backscatter observed in the Opouawe Canyon is a response to the occurrence of gravel (Geoffroy Lamarche, 2014, personal commun.), and in the lower Cook Strait Canyon is due to dense sand (P. Barnes, 2014, personal observe.). Assuming that, for the entire CS, a high backscatter signal is indicative of coarser sediment or bedrock exposures (Mitchell, 1993a; Lamarche et al., 2011), we infer that the higher backscatter in the lower canyons, in comparison to the upper canyons, is indicative of a lack of fine-grained sediment of a certain thickness (Mitchell, 1993b). This implies that the sediment has been eroded by currents with velocities higher than the threshold of motion of fine-grained sediment. We suggest that this is a result of stronger, more frequent or more recent sedimentary flows (and the associated reduction in sediment deposition and increase in bedrock exposure) where thrust faults are located. The origin of these flows is likely earthquake-triggered mass wasting and knickpoint migration. The high backscatter and inferred high canyon flow in the upper Cook Strait and Nicholson Canyons, however, are associated with remobilization of sediment deposited by tidal currents and earthquake triggering of mass wasting events in the upper canyons (Mountjoy et al., 2013).

Submarine Gullies and Landslides

Submarine gully erosion in the Cook Strait sector occurs above a threshold slope gradient of 5.5° (Micallef and Mountjoy, 2011). Since the more intense gully erosion is observed on the walls of the lower CS, we suggest that active tectonics play a direct role in promoting submarine gully erosion by generating steep terrain. Submarine gullies, in turn, contribute to canyon evolution by establishing the template along which submarine canyons grow (as in Tubau et al., 2013; Vachtman et al., 2013). Submarine landslides, however, are mostly located in the upper canyons, where vertical tectonic deformation is the least pronounced because faults are predominantly strike slip. This confirms that landslide preconditioning is mostly related to canyon incision and wall undercutting. In addition, Cenozoic sedimentary basins within which the upper canyons formed are less tectonically deformed than units underlying the continental slope, resulting in stratigraphic geometries that are more prone to large bedding-parallel slope failure. Earthquake-generated ground motion is likely to be the primary slope-failure triggering mechanism for most landslides, however, and will act as a secondary preconditioning factor via slope deformation or generation of excess pore pressures in high-permeability horizons (Sultan et al., 2004; Mountjoy et al., 2009, 2013). Regardless of their causes, submarine landslides have an important influence in canyon evolution by eroding walls, extending canyons laterally, and introducing material into the canyon floor (Micallef et al., 2012).

Knickpoint Formation and Evolution

In the CS, the morphology and location of some steps, such as those in the Nicholson (step 1), upper Opouawe (steps 17 and 18), and lower Opouawe (step 28) Canyons, reflect deformation of the canyon floor, either as short-wavelength folds or fault breakouts (e.g., Wharekauhau fault; Mountjoy et al., 2009) (Fig. 8). This explains...
the generally low slope gradients measured at these steps (Table 2). We suggest, however, that the majority of the steps across the CS have predominantly formed by slope failures on the canyon floor and localized quarrying and plucking, both driven by sedimentary flows. Our inference is based on morphological evidence, i.e., the crescent-shaped depressions on the canyon floor, which are likely the scars of rotational slope failures (e.g., Paull et al., 2011), and the ridges at their base and the subangular blocks observed on the DTIS imagery that are evidence of slope failure and quarrying and/or plucking processes (Fig. 7). Steps associated with slope failures and erosion have higher slope gradients than fold- and/or fault-controlled steps, which is likely a result of landslides revealing more cohesive material, whereas only shallow buried sediments are currently being eroded at folds and/or faults.

In view of the above, we interpret the steps as knickpoints, which in fluvial systems are defined as steep-gradient sections along a course (Howard, 1994). Submarine knickpoints have been widely reported in active tectonic margins (e.g., Kukowski et al., 2001; Orpin, 2004; Adeogba et al., 2005). In submarine canyon-channel systems, knickpoints are proposed to initiate either where tectonic motion has deformed the seafloor (Soh and Tokuyama, 2002; Mitchell, 2006; Heinio and Davies, 2007), or where channel levees have been breached (Pirmez et al., 2000; Estrada et al., 2005).

In the CS we differentiate between knickpoints associated with faults and folds and knickpoints formed by canyon floor slope failures and erosion. We also infer differences in the way in which these two types of knickpoints evolved. Knickpoints associated with folds and faults

Figure 7 (on this and following three pages). Longitudinal profile maps of all canyons in the Cook Strait canyon system (CS) denoting locations of faults known from seismic reflection data (in red), new faults mapped from morphological data (in purple), steps (in blue), and depressions (in green). The black dashed lines locate canyon thalwegs. Bathymetric maps with isobaths (20 m interval) are shown. (A) Step 1 in the Nicholson Canyon floor coincides with channelized morphology located southwest of a 70-m-high escarpment associated with the Wharekauhau fault. (B) Step 2 is a double arcuate scar on the Wairarapa Canyon floor with ridge below.
Control of active tectonics on submarine canyons

diffuse (Fig. 13), developing into smoother, gentler breaks of slope through upstream erosion and downstream deposition by channelized sedimentary flows until an equilibrium profile is restored (e.g., step 1 in Nicholson Canyon). This is similar to the mechanisms of gradient adjustments reported in submarine channels (Kneller, 1995; Pirmez et al., 2000; Georgiopoulou and Cartwright, 2013), and it would explain the lower backscatter observed along the canyon floor where such knickpoints are located. It is compatible with knickpoint evolution in terrestrial alluvial fans (e.g., Paola, 2000), but differs from examples of fault-induced knickpoint migration in river systems undergoing detachment-limited erosion (e.g., Yanites et al., 2010).

Knickpoints formed by canyon floor slope failures and erosion, however, are located upslope of both additional slope instabilities along the adjacent canyon walls (Fig. 7D) as well as canyon floors with high backscatter (Fig. 5A), both of which we interpret as suggesting upslope knickpoint migration. We propose that knickpoint migration is driven by base-level lowering (Fig. 13). For the entire CS, the regional base level is the Hikurangi Trough, which is lowered due to regional uplift of the margin (Fig. 3B). Given that the maximum coseismic uplift of the lower canyon system associated with subduction earthquakes may be ~2 m (Fig. 3B), it is likely that a major period of knickpoint migration is initiated after several uplift events rather than one. The upper reaches of the CS may have competing vertical tectonic processes from upper plate fault rupture contrasting with interseismic and coseismic subduction thrust deformation, which leads to ephemeral canyon longitudinal profile changes. Figure 3B, for example, shows that the

![Figure 7](continued). (C) Step 3 in the upper Cook Strait canyon. (D) Steps 12–15 are four crescent-shaped scars on the Palliser Canyon floor with similarly shaped scars across the canyon walls.
Nicholson Canyon is expected to subside by as much as 2 m during hypothetical giant subduction earthquakes, whereas fault rupture during the M8 1855 Wairarapa earthquake produced substantial coseismic uplift at Cape Turakirae (McSaveney et al., 2006) and presumably uplift of the upper reaches of the CS. For the Palliser and Boo Boo Canyons, the base level is the lower Cook Strait Canyon floor, which is lowered by canyon floor erosion. The latter is likely to have been affected by regional base-level lowering, but also by changing sediment fluxes associated with varying climates and sea levels. During sea-level lowstands associated with glacial periods, coarse clastic sediments were fed directly into the heads of the upper CS canyons by terrestrial rivers and longshore drift. This is likely to have led to entrenchment of the upper CS canyons and transient aggradation of the Cook Strait Canyon (e.g., Mountain et al., 1996). Sea-level rise accompanying the transition into interglacial periods disconnected the upper CS canyon heads from a direct sediment supply. Such a reduction in postglacial sediment supply is thought to have resulted in the erosion of the older lowstand canyon system and initiated localized knickpoint migration (Mountjoy et al., 2009). We propose that the knickpoint created by base-level lowering migrates up canyon as an entrenchment knickpoint that retrogressively downcuts and erodes the lower CS. This erosion takes place through slope failure and/or quarrying and/or plucking processes driven by sedimentary flows (e.g., Pirmez et al., 2000; Mitchell, 2006; Toniolo and Cantelli, 2007; Amblas et al., 2011; Turmel et al., 2011). Our inference is reinforced by the fact that the knickpoint lips are angular, indicative of advective migration (Mitchell, 2006), as well as the spatial

Figure 7 (continued). (E) Steps 7–11 are a series of five crescent-shaped scars on the Boo Boo Canyon floor; step 11 is the highest (233 m) across the entire CS. (F) Steps 17, 18, 19, and 28 in Opouawe Canyon.
association between knickpoints in the Palliser, Boo Boo, and upper Cook Strait Canyons that are located at a similar distance from their base levels (Fig. 9). The locations of knickpoints at similar distances from base levels are similar to what has been observed in subaerial fluvial systems, where knickpoints recording transient conditions are at a nearly constant elevation from the base level (e.g., Niemann et al., 2001). The wall slope failures located downslope of the knickpoints were probably triggered by undermining and loss of support (Sultan et al., 2007; Micallef et al., 2012). Knickpoints formed by canyon floor slope failures and erosion are therefore evidence of a renewed phase of incision in the lower reaches of the CS.

We do not exclude that, in the CS, knickpoints associated with faults also migrate upslope, as documented by Mitchell (2006), or that knickpoints associated with slope failure also diffuse. In our study area we do not have information on how the morphology of a knickpoint changes as it translates upstream through the canyon system. However, it is possible that a knickpoint degrades and reforms as it encounters regions of higher or lower erodibility, as documented in submarine channels (Pirmez et al., 2000) and subaerial fluvial systems (Crosby and Whipple, 2006).

In subaerial fluvial geomorphology, the stream power erosion model provides the most popular quantitative tool to describe knickpoint retreat (Howard and Kerby, 1983; Bishop et al., 2005; Crosby and Whipple, 2006). According to this model, knickpoint migration rate is a function of drainage area and local slope. The stream erosion model seems to be relevant to explain knickpoint evolution in the CS as well. Figure 10 shows a good positive relationship.

Figure 7 (continued). (G) Steps 20–26 in Campbell Canyon. (H) Depressions 29–36 are upslope and asymmetric, downstream of the mouth of the lower Cook Strait Canyon. Deep Tow Imaging System (New Zealand National Institute of Water and Atmospheric Research) photos from transect 31 downslope of step 4 are shown. The locations of transect 31 and A, B, D, E, and H are shown in Figure 8.
Figure 8. Map of steps (green circles) and depressions (red circles) across the Cook Strait canyon system. Canyon name abbreviations (circled) are as in Figure 1 legend. DTIS-31—Deep Tow Imaging System (New Zealand National Institute of Water and Atmospheric Research) transect 31.

Figure 9. Bar chart of the distance of selected steps from the local base level (floor of lower Cook Strait Canyon). Step numbers are in bold. Steps that have similar distances are denoted by same bar color.
Figure 10. Plot of canyon area against the distance of steps from the local base level (measured from either the regional base level or the floor of the canyon in which the canyon hosting the step drains) for lower canyons.

Figure 11 (on this and following three pages). (A–G) Thalweg slope-area plots for all canyons in the Cook Strait canyon system. A dashed black line in each plot represents a moving average estimated for all points in the plot. The moving average was used to divide the plot into segments (different colored points). Regression analyses were carried out to determine the regression model for slope (S) and area (power law; dark gray solid line), the coefficient of determination (R²), and the mean of the slope values (X) for each segment. Where possible, the boundaries between segments are associated with fault or steps.
between the area of lower canyons and the distance of knickpoints from their local base level, the latter being indicative of the rate at which knickpoints migrate upslope. An incisional pulse triggered by a change in base level is thus likely to be best transmitted in the main Cook Strait Canyon and to be slower in its tributaries and the other canyons. The fact that knickpoints migrate fastest in the largest canyons is likely a result of a higher and more erosive volume of sediment flows. The inference that the erosive capacity of sedimentary flows increases with canyon area is also supported by numerical models (Pratson and Coakley, 1996; Pratson et al., 2000). Based on these considerations, the rate of knickpoint migration should also decrease with time because, as it moves upslope, the canyon drainage area is bound to decrease.

Knickpoint formation and evolution may be attributable to factors other than folds and faults, changes in base level, or changing sediment fluxes. A factor that cannot be completely ruled out is variation in lithological resistance (Miller, 1991; Mitchell, 2004; Phillips et al., 2010). We are unable to constrain the stratigraphy of the floor of the entire CS, and it is plausible that where stratigraphy is truncated by erosion, resistant beds along the floors may create canyon steps (e.g., stratigraphy truncated by erosion in Fig. 4B). However, it is unlikely that we would observe the morphologies and morphometric patterns described herein (see the discussion of Steps and Depressions) if lithological resistance were the primary control of knickpoint formation and evolution. We therefore propose that the role of changing lithological resistance in knickpoint formation and evolution is secondary and localized, although sediment and rock properties may help explain differences in knickpoint morphology.

Cyclic Steps

Spatially periodic depressions occur downslope of the mouth of the lower Cook Strait Canyon, where sedimentary flows evolve from confined to unconfined conditions. We interpret these depressions as cyclic steps, which are manifestations of a fundamental morphodynamic instability of Froude-supercritical flow over an erodible bed (Parker and Izumi, 2000). Cyclic

![Figure 11 (continued).](https://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/10/5/905/3335983/905.pdf)

### Geosphere, October 2014

922
steps are long-wave erosional and/or depositional bedforms that are bounded by a hydraulic jump and that migrate upstream as a coherent, quasi-permanent train of permanent form (Fildani et al., 2006; Kostic, 2011). The upslope asymmetrical shape of cyclic steps in the CS is indicative of a low-energy setting because of a decrease in vertical thickness and velocity, and a resulting drop in the Froude number, due to spreading of the flow at the canyon mouth (Cartigny et al., 2011; Fildani et al., 2013). We propose that this zone of seafloor is an incipient channel developing along a train of cyclic steps that, with ongoing plate convergence and uplift of the continental slope and southeastward migration of the deformation front, would link the mouth of the lower Cook Strait Canyon with the Hikurangi channel.

**Canyon System State**

A channel equilibrium profile is a depth profile created by the erosional and depositional action of gravity flows over a period of thousands of years such that the prevailing sediment discharge is carried through the channel with minimum aggradation or degradation (Pirmez et al., 2000; Ferry et al., 2005). Factors such as the power, frequency, and geometry of flows, and the availability of sediment, are the dominant shaping mechanisms that determine the ability of a channel to reach equilibrium (Kneller, 2003). The ocean system is not a steady-state system; therefore, the channel equilibrium is transient and also dependent on other factors such current regime, slope stability, and strength of near-seafloor sediments (Georgiopoulou and Cartwright, 2013). Topographic steady state, however, entails a sustained balance between rock uplift and the erosion of the channel (Willgoose et al., 1991; Howard, 1994).

There are many indications that the lower CS is neither in equilibrium nor in a steady state, including the following.

1. The formation and migration of knickpoints (Fig. 8), which have been suggested as the dominant mode of channel adjustment in response to a perturbation, indicate a lack of equilibrium between tectonic and sedimentary processes (Whipple and Tucker, 1999; Crosby and Whipple, 2006).

2. The Palliser and Boo Boo Canyons tributaries do not approach the lower Cook Strait...
Canyon at the same elevation, disobeying Playfair’s Law and indicating disequilibrium across the entire canyon system (Playfair, 1802; Nienmann et al., 2001).

3. The longitudinal profiles of the canyons are predominantly linear (Fig. 6), in contrast to the graded profile associated with canyon systems in equilibrium (Gerber et al., 2009; Covault et al., 2011).

4. There is a general lack of canyon-wide, inverse power law slope-area relationships associated with a spatially equilibrated erosion rate (Fig. 11; Whipple, 2004; Wobus et al., 2006).

We therefore consider the lower CS to be in a transient state. The system is undergoing continuous adjustment to perturbations associated with tectonic displacements, base-level changes, and varying sediment fluxes. These perturbations dominate over the capacity of sedimentary flows to establish an equilibrium profile and topographic steady state.

**Tectonic Information from Canyon Morphology**

We use canyon morphology to extract information on two aspects of tectonic activity across the Cook Strait.

**Faulting**

The MCS data show that few fault tips actually propagate to the seafloor. Single event displacements on these faults may be high (e.g., 10 m across the lower Cook Strait Canyon, as in Fig. 3A); however, the uppermost tip of the fault is buried by several hundred meters of folded but unbroken sedimentary sequences. The response of the canyon floor to faulting is thus a localized upward flexure of as much as several meters. By analyzing the canyon longitudinal profiles (Fig. 7), we are able to propose four new sites where unmapped faults, not identified in the MCS data, may have caused localized upward flexure. All of these sites are prolongations of known faults across the canyon floor, and include the Wairarapa fault across the Nicholson Canyon, the Opouawo-Uruti fault at step 17 and another in the lower reaches of the Opouawo Canyon, and a fault in the upper reaches of the lower Cook Strait Canyon.
Control of active tectonics on submarine canyons

Uplift and Incision Patterns

The steepest canyon thalweg slope gradients are recorded in the Boo Boo, Campbell, Palliser and Opouawe Canyons (Figs. 7 and 12; Table 2). The highest relief and the canyon segments with lowest R² and highest concavity index values in the slope-area regression models occur in the lower Cook Strait, Boo Boo, Campbell, Palliser, and Opouawe Canyons (Figs. 5B and 12; Table 2). This indicates that the slopes hosting the lower canyons have been undergoing more pronounced rates of uplift and shortening than those hosting the upper canyons, as confirmed by Figures 2 and 4 (Whipple and Tucker, 1999; Snyder et al., 2000; Kirby and Whipple, 2001; Wobus et al., 2006; Cowie et al., 2008).

Model for Canyon Development in Response to Tectonic Forcing

Figure 13 summarizes the reported results in a generalized model of canyon geomorphic evolution in tectonically active continental margins. The model is based on the following.

1. Thrust and strike-slip faults control canyon location and planform shape, in particular width, sinuosity, and dendritic network patterns.

2. Uplift due to folds and/or faults results in linear to convex thalweg longitudinal profiles; abrupt changes in, and high values of, slope gradient; canyon wall asymmetry; dense gully erosion; hanging valleys at canyon confluences; and slope-area plots with low R² values. Where not affected by faults or knickpoints, the slope-area plots have high R² values for inverse power relationships.

3. Seismicity is a main trigger of slope instability across canyon walls, which are preconditioned by undercutting from canyon incision and are responsible for canyon elongation and widening. Seismicity is also associated with higher and more frequent sedimentary flows along the canyon thalweg.

4. Two types of knickpoint develop: a gentle and rounded knickpoint formed by folds or fault breakouts that diffuses by upstream erosion and downstream deposition; and steep and angular knickpoints, which are driven by base-level lowering (due to regional uplift or deepening of downstream canyons) or changing sediment fluxes and migrate upslope by canyon floor slope failures and localized quarrying and/or plucking. The knickpoint migration rate is a function of the canyon area and the associated sedimentary flow throughput.

Future work will focus on refining the quantitative relationship between canyon morphometric parameters and tectonic processes to enable the direct extraction of quantitative tectonic information from morphology.

Figure 12. Map of slope-area segments for each canyon shaded according to the mean slope gradient. Canyon name abbreviations (circled) are as in Figure 1 legend.

Table 2. Step and Depression Morphometrics, Cook Strait Canyon System

<table>
<thead>
<tr>
<th>Label</th>
<th>Type</th>
<th>Bathymetric depth (m)</th>
<th>Canyon</th>
<th>Height (m)</th>
<th>Gradient (°)</th>
<th>Extension</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>step</td>
<td>717</td>
<td>Nicholson</td>
<td>20</td>
<td>8.8</td>
<td>narrow</td>
</tr>
<tr>
<td>2</td>
<td>step</td>
<td>1033</td>
<td>Wairarapa</td>
<td>71</td>
<td>24.3</td>
<td>canyon floor width</td>
</tr>
<tr>
<td>3</td>
<td>step</td>
<td>1147</td>
<td>upper Cook Strait</td>
<td>21</td>
<td>6.8</td>
<td>narrow</td>
</tr>
<tr>
<td>4</td>
<td>step</td>
<td>1253</td>
<td>lower Cook Strait</td>
<td>33</td>
<td>2.3</td>
<td>narrow</td>
</tr>
<tr>
<td>5</td>
<td>step</td>
<td>1354</td>
<td>lower Cook Strait</td>
<td>54</td>
<td>13.9</td>
<td>canyon floor width</td>
</tr>
<tr>
<td>6</td>
<td>step</td>
<td>1586</td>
<td>lower Cook Strait</td>
<td>47</td>
<td>7.3</td>
<td>narrow</td>
</tr>
<tr>
<td>7</td>
<td>step</td>
<td>1340</td>
<td>Boo Boo</td>
<td>50</td>
<td>18.6</td>
<td>narrow</td>
</tr>
<tr>
<td>8</td>
<td>step</td>
<td>1256</td>
<td>Boo Boo</td>
<td>68</td>
<td>30.0</td>
<td>narrow</td>
</tr>
<tr>
<td>9</td>
<td>step</td>
<td>1199</td>
<td>Boo Boo</td>
<td>79</td>
<td>29.8</td>
<td>narrow</td>
</tr>
<tr>
<td>10</td>
<td>step</td>
<td>1065</td>
<td>Boo Boo</td>
<td>98</td>
<td>29.0</td>
<td>canyon floor width</td>
</tr>
<tr>
<td>11</td>
<td>step</td>
<td>816</td>
<td>Boo Boo</td>
<td>233</td>
<td>31.2</td>
<td>canyon floor width</td>
</tr>
<tr>
<td>12</td>
<td>step</td>
<td>1542</td>
<td>Palliser</td>
<td>125</td>
<td>25.7</td>
<td>canyon floor width</td>
</tr>
<tr>
<td>13</td>
<td>step</td>
<td>1483</td>
<td>Palliser</td>
<td>31</td>
<td>10.6</td>
<td>canyon floor width</td>
</tr>
<tr>
<td>14</td>
<td>step</td>
<td>1391</td>
<td>Palliser</td>
<td>28</td>
<td>9.0</td>
<td>narrow</td>
</tr>
<tr>
<td>15</td>
<td>step</td>
<td>1286</td>
<td>Palliser</td>
<td>88</td>
<td>19.0</td>
<td>canyon floor width</td>
</tr>
<tr>
<td>16</td>
<td>step</td>
<td>589</td>
<td>Palliser</td>
<td>59</td>
<td>26.4</td>
<td>canyon floor width</td>
</tr>
<tr>
<td>17</td>
<td>step</td>
<td>1499</td>
<td>Opouawe</td>
<td>21</td>
<td>6.7</td>
<td>narrow</td>
</tr>
<tr>
<td>18</td>
<td>step</td>
<td>1850</td>
<td>Opouawe</td>
<td>49</td>
<td>8.5</td>
<td>narrow</td>
</tr>
<tr>
<td>19</td>
<td>step</td>
<td>1917</td>
<td>Opouawe</td>
<td>115</td>
<td>19.2</td>
<td>canyon floor width</td>
</tr>
<tr>
<td>20</td>
<td>step</td>
<td>508</td>
<td>Campbell</td>
<td>85</td>
<td>31.6</td>
<td>canyon floor width</td>
</tr>
<tr>
<td>21</td>
<td>step</td>
<td>719</td>
<td>Campbell</td>
<td>32</td>
<td>28.5</td>
<td>canyon floor width</td>
</tr>
<tr>
<td>22</td>
<td>step</td>
<td>972</td>
<td>Campbell</td>
<td>114</td>
<td>34.8</td>
<td>canyon floor width</td>
</tr>
<tr>
<td>23</td>
<td>step</td>
<td>1400</td>
<td>Campbell</td>
<td>38</td>
<td>21.0</td>
<td>narrow</td>
</tr>
<tr>
<td>24</td>
<td>step</td>
<td>1995</td>
<td>Campbell</td>
<td>74</td>
<td>14.4</td>
<td>narrow</td>
</tr>
<tr>
<td>25</td>
<td>step</td>
<td>2149</td>
<td>Campbell</td>
<td>78</td>
<td>13.4</td>
<td>narrow</td>
</tr>
<tr>
<td>26</td>
<td>step</td>
<td>2217</td>
<td>Campbell</td>
<td>165</td>
<td>22.0</td>
<td>canyon floor width</td>
</tr>
<tr>
<td>27</td>
<td>step</td>
<td>2383</td>
<td>lower Cook Strait</td>
<td>58</td>
<td>8.1</td>
<td>narrow</td>
</tr>
<tr>
<td>28</td>
<td>step</td>
<td>2495</td>
<td>Opouawe</td>
<td>49</td>
<td>9.4</td>
<td>narrow</td>
</tr>
<tr>
<td>29</td>
<td>depression</td>
<td>2507</td>
<td>lower Cook Strait</td>
<td>120</td>
<td>6.8</td>
<td>narrow</td>
</tr>
<tr>
<td>30</td>
<td>depression</td>
<td>2538</td>
<td>lower Cook Strait</td>
<td>50</td>
<td>4.1</td>
<td>narrow</td>
</tr>
<tr>
<td>31</td>
<td>depression</td>
<td>2609</td>
<td>lower Cook Strait</td>
<td>60</td>
<td>11.3</td>
<td>narrow</td>
</tr>
<tr>
<td>32</td>
<td>depression</td>
<td>2639</td>
<td>lower Cook Strait</td>
<td>50</td>
<td>9.5</td>
<td>narrow</td>
</tr>
<tr>
<td>33</td>
<td>depression</td>
<td>2686</td>
<td>lower Cook Strait</td>
<td>25</td>
<td>4.8</td>
<td>narrow</td>
</tr>
<tr>
<td>34</td>
<td>depression</td>
<td>2683</td>
<td>lower Cook Strait</td>
<td>55</td>
<td>5.7</td>
<td>narrow</td>
</tr>
<tr>
<td>35</td>
<td>depression</td>
<td>2694</td>
<td>lower Cook Strait</td>
<td>30</td>
<td>3.4</td>
<td>narrow</td>
</tr>
<tr>
<td>36</td>
<td>depression</td>
<td>2687</td>
<td>lower Cook Strait</td>
<td>20</td>
<td>3.8</td>
<td>narrow</td>
</tr>
</tbody>
</table>
CONCLUSIONS

Tectonic activity, in the form of major faults and structurally generated tectonic ridges, leaves a clear topographic signature on submarine canyon location and morphology in the CS in the Hikurangi margin off New Zealand’s North Island, in particular dendritic and sinuous planform shapes, steep and linear longitudinal profiles, and canyon wall asymmetry and width. We also report breaks and/or changes in canyon longitudinal slope profiles and mean slope gradient, relief, and slope-area regression models at the intersection with faults.

Across the CS we observe two types of knickpoints related to tectonic activity. The first type consists of low slope gradient knickpoints that are rounded and diffusive, and form as a result of short-wavelength folds or fault breakouts; they are restored to an equilibrium profile by upstream erosion and downstream deposition. The second, more widespread, type of knickpoint has high slope gradients and linear profiles. These knickpoints have undergone upslope advective migration through slope failures on the canyon floor and localized quarrying and plucking by sedimentary flows. The migration is driven by base-level lowering due to multiple episodes of regional uplift of the margin and deepening of the lower Cook Strait Canyon floor by sedimentary flows, or by changing sediment fluxes. Variation in lithological resistance probably plays a secondary and localized role in knickpoint formation and evolution. The stream erosion model is applicable to the CS, and knickpoint migration is faster in the larger canyons. The formation and migration of knickpoints, the nonadherence to Playfair’s Law, the linear longitudinal profiles, and the lack of canyon-wide, inverse power law slope-area relationships indicate that the CS is a system that is neither in topographic steady-state nor in equilibrium, and that it is undergoing continuous adjustments to perturbations associated with tectonic displacement and changes in base level and sediment fluxes.

Canyon morphology also allows us to infer tectonic activity across the CS. From the canyon longitudinal profiles we can propose four new sites in the Nicholson, Opouawe, and lower Cook Strait Canyons where unmapped prolongations of known faults have caused localized upward flexure. The occurrence in the lower canyons of steep thalweg slope gradients, high relief, and low values of $R^2$ in the slope-area regression models, and their spatial association with faults and steps, indicate that the lower slopes have undergone more pronounced rates of uplift and shortening than those hosting the upper canyons.

The reported canyon morphological parameters and their response to tectonic activity allow us to propose a generalized model for canyon geomorphic evolution in tectonically active continental margins.

ACKNOWLEDGMENTS

This research was undertaken with funding from Marie Curie Intra-European Fellowship PIEF-GA-2009-252702 and Marie Curie Career Integration Grant PCIG13-GA-2013-618149 within the 7th European Community Framework Programme, NIWA (National Institute of Water and Atmospheric Research, New Zealand) under Coasts and Oceans Research Programme 2013/14, and the Royal Society of New Zealand International Mobility Fund contract.

Figure 13. Summary model illustrating modes of canyon response to active tectonic processes.
Control of active tectonics on submarine canyons


