GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L20606, doi:10.1029/2007GL031142, 2007

Demise of a submarine canyon? Evidence for highstand infilling on the Waipaoa River continental margin, New Zealand

J. P. Walsh,[1] C. R. Alexander,[2] T. Gerber,[3] A. R. Orpin,[4] and B. W. Sumners[1]

Received 29 June 2007; revised 6 September 2007; accepted 24 September 2007; published 31 October 2007.

[1] Submarine canyons are major geomorphologic features on the Earth's surface. Their formation has received considerable debate, but their demise has received less attention. Research of modern canyons with cores and moorings has documented active sediment transport and deposition, but extrapolation of these local observations over larger areas is precluded by complex canyon geomorphology. High-resolution multibeam and chirp data presented here provide convincing evidence of an infilling canyon head on the Waipaoa River margin of New Zealand. Tens of meters of Holocene sediment have accumulated on the outer shelf and in Lachlan canyon as a result of off-shelf sediment transport. Regardless of the ultimate fate of this system over geological time scales, this research demonstrates highstand sedimentation as a possible mechanism for canyon burial and cause of canyon demise, which has important implications for the evolution of canyons globally. **Citation:** Walsh, J. P., C. R. Alexander, T. Gerber, A. R. Orpin, and B. W. Sumners (2007), Demise of a submarine canyon? Evidence for highstand infilling on the Waipaoa River continental margin, New Zealand, *Geophys. Res. Lett.*, *34*, L20606, doi:10.1029/2007GL031142.

1. Introduction

[2] Submarine canyons are often thought of as erosional features, primarily carved out by turbidity currents and mass failures during sea-level lowstands. However, numerous studies have documented active sediment transport and deposition at discrete sites in canyons today, suggesting their continuing evolution [e.g., *Shepard et al.*, 1974; *Mulder et al.*, 2001; *Mullenbach and Nittrouer*, 2006], but the extent of fill in modern canyons has proven difficult to document due to technological limitations and complex geomorphology. Despite their steep relief that seemingly precludes infilling at any stage of sea level, seismic-reflection surveys on several margins have revealed buried paleo-canyons [*Pratson et al.*, 1994; *Mountain et al.*, 1996; *Bertoni and Cartwright*, 2005]. While much research has been focused on canyon creation, less attention has addressed when and how they fill and become defunct. Previous work has suggested the importance of highstand sedimentation. The current study documents appreciable, recent canyon head infilling, masking former relief. These observations clearly indicate active off-shelf sediment transport in a modern dispersal system and emphasize the importance of highstand sedimentation as a mechanism for submarine canyon burial and demise.

2. Background on Canyons and Off-Shelf Transport

[3] There are two basic types of canyons: slope-confined and shelf-indenting canyons, but the former can mature into the latter. Shelf-indenting canyons evolve from upslope- and downslope-directed erosive processes [*Farre et al.*, 1983; *Pratson et al.*, 1994]. Failures on the continental slope produce slope-confined canyons that can erode headward to become shelf-indenting canyons. Alternatively, fluvial systems can migrate across the shelf during low stands in sea level, and, igniting turbidity currents that erode and incise the shelf break, can create shelf-indenting canyons as originally hypothesized by *Daly* [1936] and tested in the lab by *Kuenen* [1937]. The form and location of canyons may be impacted by other factors such as pore-fluid flow, faulting, and capture of along-shelf transport [e.g., *Shepard et al.*, 1974; *Orange*, 1994; *Song et al.*, 2000].

[4] Sequence stratigraphic theory emphasizes sea level as a primary control on off-shelf transport and canyon incision [*Postmentier and Vail*, 1988]. Increased fluvial sediment fluxes to the slope are anticipated during sea-level regression and lowstand conditions, while decreased fluxes are typically associated with rising sea level and highstand conditions. Nevertheless, some margins with high sediment supply are presently exporting considerable amounts of sediment off the shelf [*Goodbred and Kuehl*, 1999; *Walsh and Nittrouer*, 2003], possibly indicating a completion of this classic sequence stratigraphic cycle (i.e., shelf accommodation space has been filled). Modern rates of accumulation on outer shelves and continental slopes may be relatively high (>2 mm y^{-1}) [e.g., *Alexander and Simoneau*, 1999; *Walsh and Nittrouer*, 2003; *Corbett et al.*, 2006; *Huh et al.*, 2006; *Orpin et al.*, 2006]. Sediment-trap, mooring, tripod and coring studies have shown that in many modern canyons sedimentation can be active locally [e.g., *Baker and Hickey*, 1986; *Puig and Palanques*, 1998; *Mulder et al.*, 2001; *Walsh and Nittrouer*, 2003; *Mullenbach and Nittrouer*, 2006; *Puig et al.*, 2004; *Goni et al.*, 2007]. However, a major challenge to understanding canyon sedimentation is extrapolating isolated observations over a large spatial scale. Geophysical data can be useful in this regard.

[5] Research on the stratigraphic record of paleo-canyons has shown lithologically diverse infill, but strata commonly fine upward into muddy deposits [*May et al.*, 1983; *Mountain et al.*, 1996]. These sequences have been hypothesized to

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[1] Department of Geological Sciences, East Carolina University, Greenville, North Carolina, USA.

[2] Skidaway Institute of Oceanography, Savannah, Georgia, USA.

[3] Nicholas School of the Environment, Duke University, Durham, North Carolina, USA.

[4] National Institute of Water and Atmospheric Research, Wellington, New Zealand.

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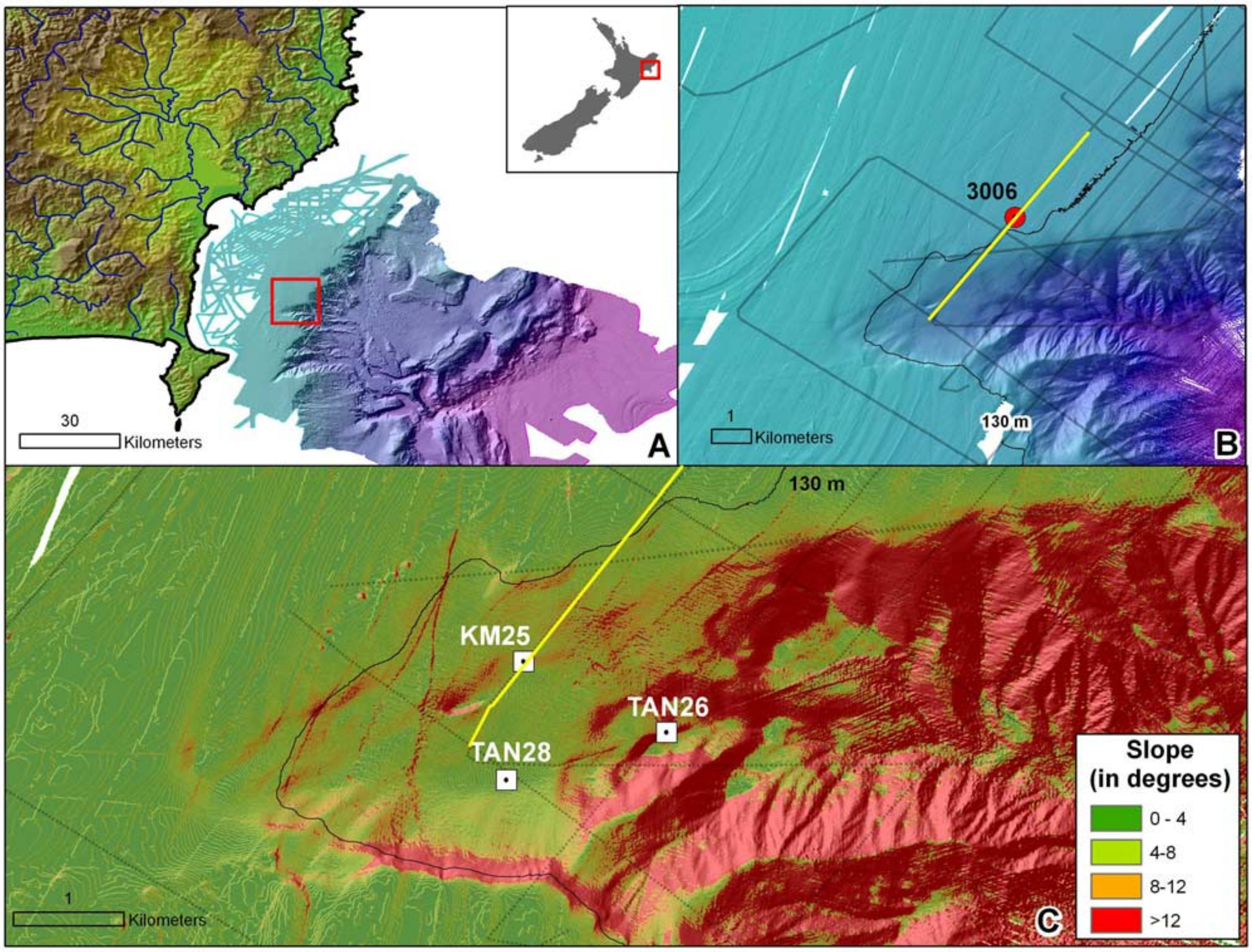

Figure 1. (a) A base map of the WRM on the East Coast of the North Island of New Zealand: a higher resolution view of (b) Lachlan canyon and (c) seafloor slopes of Lachlan canyon. In Figure 1a, the Waipaoa River drainage basin is subtly shaded yellow, and a New Zealand location map is displayed. The shaded bathymetry is shown, and the aerial coverage of Figure 1b is identified by the red box. In Figure 1b, the location of the chirp line in Figure 2 is highlighted in yellow, and core site MD152-3006 is shown. The fence diagram of Figure 3 is constructed with the faint black lines shown in Figures 1b and 1c, and the 130-m isobath is the bolder black line.

reflect a rising sea-level scenario in which sediment supply diminishes as progressively more distant rivers supplied sediment to the flooding shelf. Such a situation is presented herein. It should be noted that like incised-valleys, filling of canyons also may occur during the lowstand and subsequent transgression as subaerially exposed sediments are reworked by near-shore hydraulic processes [*Postmentier and Vail*, 1988; *Goodwin and Prior*, 1989; *Dunbar et al.*, 2000; *Sommerfield and Lee*, 2004]. Alternatively, highstand systems may undergo reduced sedimentation or erosion due to active intra-canyon tidal and storm-forced currents [e.g., *Shepard et al.*, 1974].

3. Investigation of the Waipaoa River Margin

[6] The Waipaoa River Margin (WRM) lies in a tectonically active oblique subduction zone, which has produced extensive deformation in the region [*Barnes et al.*, 2002]. Inboard (west) of the WRM lies the rhyolitic Taupo Volcanic Zone (TVZ). Multiple tephras erupted from the TVZ during the Quaternary, and these serve as useful chronostratigraphic markers [e.g., *Froggatt and Lowe*, 1990; *Carter et al.*, 1995, 2002]. Tectonics are a major control on postglacial sediment accumulation on the WRM [*Barnes*, 1995; *Foster and Carter*, 1997; *Orpin et al.*, 2006]. Sediment accumulation on the WRM is occurring in two mid-shelf basins and one outer-shelf lobe, which are separated by the Lachlan and Ariel anticlines [*Foster and Carter*, 1997; *Orpin et al.*, 2006; *Kuehl et al.*, 2006]. The seaward edge of the outermost shelf is incised by several small gullies and three large canyons (Figure 1) that comprise the Poverty Canyon system. The northernmost of these large canyons, named herein Lachlan canyon, has a complex, meandering morphology; it is incised roughly 5 km into the shelf edge, has a width of ~4 km and relief of ~400 m (Figure 1). The oceanography and sediment transport on the WRM outer shelf and upper slope are poorly constrained, variable and complicated by ephemeral eddies and complex bathymetry [*Foster and Carter*, 1997; *Chiswell and Roemmich*, 1998; *Chiswell*, 2000, 2005]. Storm-related waves and near-bed

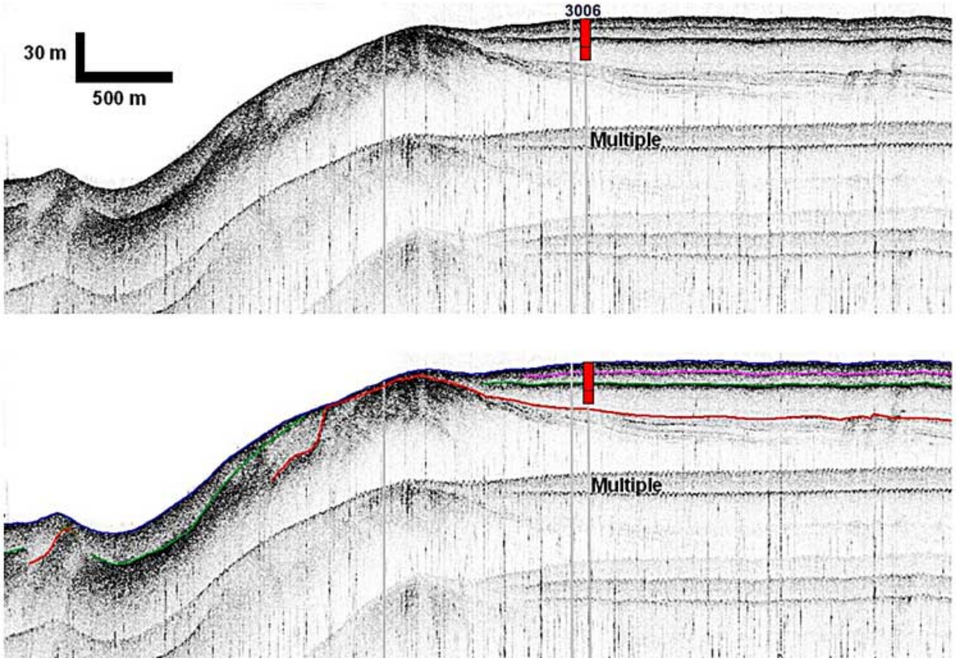

Figure 2. A raw and interpreted chirp seismic-reflection profile. Three reflectors are identified, and these can be mapped laterally across much of the shelf and into the canyon. The approximate location and depth of core site MD152-3006 is shown; the black line represents the depth of the radiocarbon sample.

currents are the likely drivers for sediment transport but have not been measured. Despite these uncertainties the observed pattern of sedimentation reflects the dominant transport pathway to the outer shelf and beyond. Rapid rates of modern sediment accumulation ($\sim$1 cm/y) are found on the WRM outer-shelf lobe [*Orpin et al.*, 2006], and seismic data indicate sedimentation has occurred in this area through the Holocene [*Foster and Carter*, 1997; *Orpin et al.*, 2006]. However, sediment accumulation and thicknesses (over centennial and longer timescales) are certainly variable. Landward of the outer-shelf lobe Neogene rocks of Lachlan anticline are exposed, and sediments thin dramatically northward. Consequently, the infilling discussed below for Lachlan canyon is not expected (and apparent) in other canyons of the area.

[7] As part of the Margins Source-to-Sink Initiative supported by the National Science Foundation, research cruises were undertaken in Jan.–Feb. 2005 and Feb. 2006 aboard the R/V *Kilo Moana* and the R/V *Marion Dufresne*, respectively [*Kuehl et al.*, 2006; *Proust et al.*, 2006]. During the 2005 fieldwork, chirp seismic (Edgetech 512i), multibeam (EM1002 and EM120), and box and 5-m long gravity corers were used across the WRM. In Feb. 2006, several Calypso (giant piston) cores were obtained around New Zealand, including Marion Dufresne site MD152-3006 on the outer shelf of the WRM [*Proust et al.*, 2006] (Figures 1 and 2).

[8] Chirp seismic data were imported into analysis software (Kingdom Suite), and prominent reflectors were digitized across the study region. Sediment thicknesses between reflectors are estimated using a sound velocity of 1500 m s^{-1}. Multibeam data were processed by the Hawaii Mapping Research Group at the University of Hawaii and were gridded at 5.1-m pixel resolution over the upper slope. Box and gravity cores were subsampled and analyzed for sedimentological, radiochemical (^{7}Be, ^{234}Th, ^{137}Cs, ^{210}Pb) and geochemical attributes. Selected samples were analyzed for ^{14}C ages and tephra identification.

4. Observations and Insights

[9] New chirp seismic lines and cores support the interpretation of *Orpin et al.* [2006] that a thick accumulation (>40 m) of post-glacial material fills the outer-shelf basin. However, new data also indicate substantial post-glacial sediment at the head of Lachlan canyon and on the upper slope (Figure 2). The T1 (green) and T2 (pink) reflectors are both discrete tephras based on lithological evidence from long cores [*Proust et al.*, 2006]. Although these reflectors and the stratigraphic packages they define appear truncated at the uppermost canyon head, the reflectors clearly extend over the shelf break along the northern wall of the canyon (Figure 3). The fence diagram provides the necessary three-dimensional perspective to visualize the variable thickness of the infilling strata. A calibrated ^{14}C date of 5,935 y BP below T1 indicates that both tephras are mid-to-late Holocene in age, but exact ages from the geochemisty of these tephras have not yet been determined. These reflectors and the underlying R1 (red) reflector have been mapped regionally [*Lewis*, 1973; *Foster and Carter*, 1997; *Barnes et al.*, 2002]; the latter is likely a transgressive erosion surface. Collectively they stratigraphically define three post-Last Glacial Maximum stratigraphic units whose variability in thickness is likely related to transport along/around the uppermost canyon wall (Figures 2 and 3) where energy from physical processes (e.g., internal waves) presumably limits accumulation. Despite some uncertainty regarding the absolute age of the reflectors in the deposit, significant

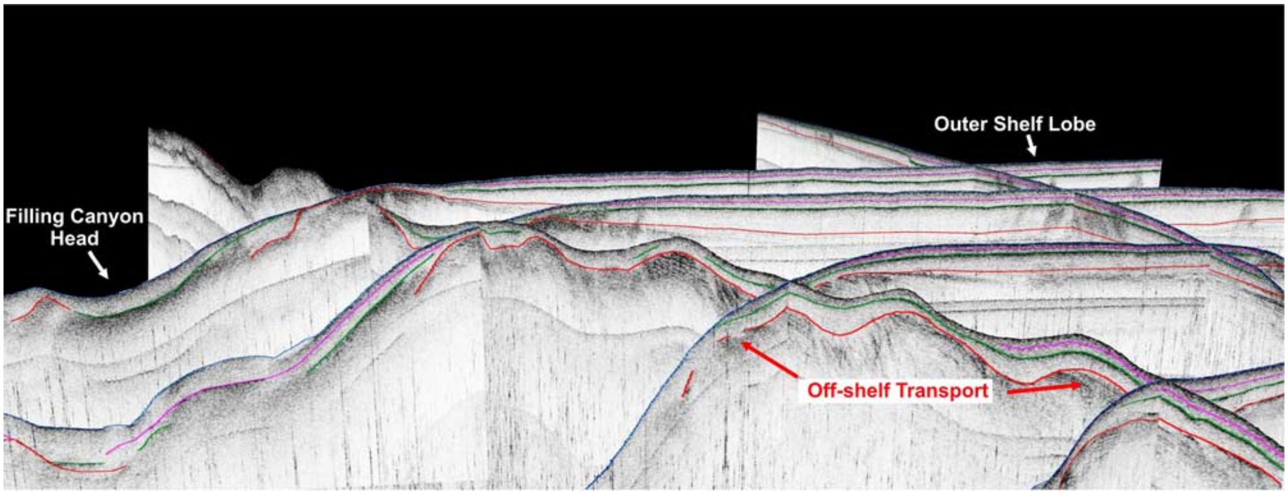

Figure 3. A fence diagram of chirp seismic lines across the Lachlan canyon and the adjacent shelf. Divergent reflectors on the shelf edge and strata within the canyon indicate appreciable Holocene sediment accumulation within and around the canyon.

Holocene sediment infilling is clearly evident (Figure 3), and divergent reflectors into the canyon provide compelling evidence for off-shelf transport (Figures 2 and 3). Note, off-shelf transport at the canyon head may be the result of across- and along-shelf flows, and the latter are likely to be critical here as in other canyon systems. Internal reflectors can provide important insight on the mechanisms and timing of infilling. Interestingly, here the absence of internal reflectors (other than the two tephras) between R1 and the surface is indicative of a continuous supply of similar sediment, presumably from similar processes.

[10] Cores collected within the canyon support the interpretation of modern off-shelf transport and canyon infilling. Rates of sediment accumulation determined by excess ^{210}Pb are high (>2 cm y^{-1}) in the canyon head, and are faster than those recorded on the outer shelf [*Alexander et al.*, 2006; *Orpin et al.*, 2006]. The absence of pronounced lithologic stratification in core X-radiographs indicates that the sediments accumulating are reasonably well-mixed by bioturbation, suggestive of relatively steady hemipelagic sediment supply [*Walsh and Nittrouer*, 2003; *Alexander et al.*, 2006]. Additional evidence for canyon filling is provided by the compelling multibeam bathymetry data which shows a loss (i.e., smothering) of relief at the canyon head (Figure 1 inset). The internal geometry of reflectors and rapid modern sedimentation rates suggest infilling has been on-going, but it likely accelerated as outer-shelf accommodation space has filled. Some filling during the transgression may have occurred but rapid sedimentation rates today highlight the importance of highstand sedimentation.

[11] On the New Jersey margin, Miocene canyon strata pinch out down canyon, indicative of sediments progressively filling seaward from the shelf, also known as "top-down" filling. Drilling of these strata has shown that the New Jersey canyon-head fill is composed largely of hemipelagic muds [*Mountain et al.*, 1996]. The observation on the WRM of off-shelf-dipping strata without notable slumping suggests a similar pattern and process. This top-down model of infilling differs considerably from the "bottom-up" mechanism proposed for the Rockall Trough where ponding and backfilling of sediment behind sidewall failures has been documented [*Cronin et al.*, 2005]. This range of behaviors is likely a product of differences in sediment supply. We speculate that in Lachlan canyon modest but sustained sedimentation has occurred, driven by circulation along and across the canyon head, possibly enhanced by the emergent bathymetry of the anticline.

[12] Research has shown that shelf width is a first-order control on the spectrum of systems experiencing modern off-shelf sediment transport [*Walsh and Nittrouer*, 2003]. The WRM lies in the middle of this range, with significant mud deposits on the shelf but also leaking a considerable amount of sediment to deeper water [*Orpin*, 2004; *Orpin et al.*, 2006; *Alexander et al.*, 2006]. For this reason we suggest that the infilling behavior observed here is not specific to the WRM, and upon detailed geophysical and geochronological investigation, would be expected at other canyon systems with narrow shelves adjacent to muddy sediment sources.

[13] Although the permanency of sediments actively accumulating in Lachlan canyon head can be questioned, the geophysical evidence for considerable highstand filling behavior is convincing and consistent with similar interpretations of highstand filling from the rock and deeper stratigraphic record [*May et al.*, 1983; *Mountain et al.*, 1996; *Bertoni and Cartwright*, 2005]. Indeed, the WRM is located within a tectonically active region, where several major co-seismic uplift events (M_w of 7.3-8.0) have occurred over the mid-late Holocene [e.g., *Berryman*, 1993]. However, no evidence for significant slumping or sliding is apparent in the multibeam or chirp data of this area. It is impossible to predict if complete burial of Lachlan canyon is imminent as this is dependent upon continued sediment accumulation with minimal flushing for a long time period over which tectonic processes are likely important. Regardless of the ultimate fate of Lachlan canyon, this research provides convincing evidence for highstand canyon-filling behavior, driven by shelf sediment escape, and has important implications for the past and future evolution of canyons globally.

[14] **Acknowledgments.** This research is part of the NSF Margins Source to Sink Initiative and was funded by OCE-0452166 and OCE-0405726. The data could not have been collected without the assistance from the Captain and crew of the R/V *Kilo Mona* and the R/V Marion Dufresne. Steve Kuehl and Lionel Carter are acknowledged for the considerable effort enabling the success of the New Zealand Source-to-Sink research. Lincoln Pratson loaned the use of his chirp system for this research and provided invaluable insight into canyon literature.

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C. R. Alexander, Skidaway Institute of Oceanography, Savannah, GA 31411, USA.

T. Gerber, Nicholas School of the Environment, Duke University, Durham, NC 27708, USA.

A. R. Orpin, National Institute of Water and Atmospheric Research, Private Bag 14901, Wellington, 301 Evans Bay Parade, Hataitai, Wellington 6021, NZ.

B. W. Sumners and J. P. Walsh, Department of Geological Sciences, East Carolina University, Greenville, NC 27858, USA. (walshj@ecu.edu)