Linking a late Miocene–Pliocene hiatus in the deep-sea Bounty Fan off South Island, New Zealand, to onshore tectonism and lacustrine sediment storage

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ABSTRACT

The cored record at Ocean Drilling Program Site 1122, located on the levee of the Bounty Fan off southeastern New Zealand, shows a major late Miocene to Pliocene (11.0–3.5 Ma) hiatus in sedimentation. This hiatus straddles a period of major uplift in the Southern Alps where the rivers that feed sediment to the Bounty Fan are ultimately sourced. There are no significant changes in sediment provenance across this interval. We link this hiatus to a combination of decreased sediment supply owing to tectonic disruption of fluvial drainage and a roughly simultaneous increase in bottom-current strength. Evidence for this scenario includes the distribution of current-generated structures in the core, the relative timing of an onshore transition from fluvial to lacustrine sedimentation, and a potential post-hiatus pulse of more weathered sediment into the Bounty Fan. This sediment pulse was possibly associated with the reestablishment of throughgoing drainage and the erosion and flushing of stored alluvial to lacustrine sediments through the system. Thus the Bounty Fan provides an excellent example of how the complex interplay between tectonic and paleo-oceanographic forces can affect the sedimentary record in deep-marine systems.

INTRODUCTION

In determining budgets for sediment flux to the deep sea, all parts of the system must be examined (Clift, 2006) rather than just proximal (e.g., Burbank et al., 1993) or distal (e.g., Rea, 1992) segments. This is the source-to-sink approach promoted by Driscoll and Nitttruer (2000) that has been successfully applied on margins across the globe including North Island, New Zealand (Carter et al., 2010). Large submarine fan systems associated with major orogens such as the Himalayas potentially record climatic, eustatic, and tectonic events that affect fluvial-deltaic systems within their source areas and can be used to reconstruct rates of continental erosion (e.g., Burbank et al., 1993; Clift, 2006; Clift and Blusztajn, 2005; Hoorn et al., 1995). This potential is often not realized. For example, concerns about autogenic switching of submarine fan lobes and stratigraphic completeness on the Indus Fan west of India forced Clift et al. (2002) to focus instead on the shelf-margin stratigraphic record to address sediment budgets. In contrast, on the Bengal Fan east of India, no pronounced breaks in sedimentation were observed (Cochran et al., 1989). Intraplate submarine fan systems on Atlantic-style passive margins, where eustatic and climatic processes are thought to dominate, are not immune to tectonic signals in that they can be created or influenced by distant plate-marginal tectonic events that reorganize drainage patterns (e.g., Hoorn et al., 1995) or affect sediment provenance (e.g., Potter, 1986).

The Bounty Fan system off South Island, New Zealand, combines aspects of both orogenic and passive systems. Like the Bengal system mentioned above, the Bounty system exhibits a major temporal disconnect from source to sink, with a period of tectonism in the source orogen (Southern Alps) correlating to a major submarine hiatus on the passive-margin Bounty Fan instead of a major sediment pulse as might be expected. To fully understand the implications of a major hiatus in Bounty Fan sedimentation documented at Ocean Drilling Program Site 1122, we evaluated the entire source-to-sink system, combining previously published petrological, sedimentological, and stratigraphic data sets from onshore and offshore segments with some new geochemical data.

William Normark also embraced such a holistic approach to deep-sea fan formation and evolution. As his work on deep-sea fans evolved (e.g., Normark, 1970, 1974; Normark et al., 1984; Piper and Normark, 2001), so did his realization that the answers to submarine fan evolution, the ultimate sediment sink, lay to some extent in the source region, above the slope (e.g., Normark et al., 2009). So it is very fitting that our Bounty Fan example be included in a volume dedicated to his memory and research.

BOUNTY TROUGH AND FAN SYSTEM

The Cenozoic Bounty Channel (Fig. 1) developed in a Late Cretaceous continental rift, the Bounty Trough (Carter et al., 1994). This abandoned rift is currently proximal to or within a zone of transpressional deformation originating at the Alpine fault plate margin near the rift apex in southern South Island. Source river(s) draining this transpressional tectonic highland feed sediment across a wave-dominated shoreline onto a wave-dominated continental margin where Neogene deposition has been strongly controlled by eustatic fluctuations of sea level (e.g., Carter et al., 1985). Seismic profiles across the shelf show it to be covered by thin sediment wedges that pinch out landward (Carter et al., 1986). Shelf sediments include modern, relict-palimpsest terrigenous sand and gravel, as well as bioclastic sediments (Carter et al., 1985, 1986). During highstands, bedload and coarse suspended load contribute to the inner shelf prism with fine suspended load moving along and across shelf to contribute to local shelf depocenters in the lee of major promontories and a proximal slope-fan complex (Otago fan, Fig. 2A) (Carter and Carter, 1993). During lowstands, sediment was dispersed mainly across the shelf to contribute directly to the proximal Otago slope-fan complex, a series of coalescing fans fed by nine major submarine canyons along the Otago continental slope (Carter and Carter, 1988), or to long distant transport via a series of three submarine feeder channels that merge into the 900-km-long Bounty Channel (Figs. 1and 2; Carter and Carter, 1988). Note that the Otago fan complex has not been drilled, but Carter and Carter (1993) infer it to potentially be of late Pliocene or younger age.

The Bounty Channel follows the Bounty Trough axis for 670 km and empties out onto
the Southwest Pacific Basin to form the abyssal Bounty Fan (Carter and Carter, 1996). Seismic facies and their ages, as determined by biostratigraphy and magnetostratigraphy at Site 1122, suggest that the channel has been active since at least 16 Ma (see Shapiro et al., 2007). Specifically, Carter et al. (1994) contend that the steady northward migration of axial sandy channel facies (see arrow in purple box in Fig. 2) indicates that the channel facies are linked to adjacent units and not a younger, superimposed feature. The character of the seismic units (A, B, C, Fig. 2C) associated with the fan have, however, changed through time. For example, Carter et al. (1990) relate the development of pronounced sediment waves in the Bounty levee in seismic Unit A (Fig. 2C) to a sea-level lowstand at ~3 Ma when there was direct fluvial input to the feeder channels at the shelf edge and a concomitant rapid input of large volumes of sediment to the levee system.

The continental Campbell Plateau and Chatham Rise, submerged since at least the Oligocene, flank the trough, therefore the main post-Oligocene terrigenous sediment source has been the narrow, plate-collision zone in southern South Island (Carter et al., 1994). This strike-slip dominant zone became more compressive at 6.4 Ma resulting in crustal shortening and increased uplift (Walcott, 1998). Tectonic uplift (topography), glacial development, eustatic change, and enhanced sediment supply were likely linked (Carter and Carter, 1996; Carter, R.M., et al., 2004). Maximum sedimentation rates on the margin and in the trough were attained in late Pliocene to Pleistocene glacial periods with intervening interglacial characterized by pelagic deposition in the trough as it was bypassed by establishment of high-stand, along-shelf sediment transport regimes (Carter et al., 1990). Furthermore, as outlined in Carter, L., et al. (2004), fan sedimentation was variably affected by the Pacific Deep Western Boundary Current (DWBC), part of the global thermohaline circulation, and the mainly wind-driven Antarctic Circumpolar Current (ACC), which initiated in the region during the early Oligocene (Fig. 1).

Here we focus on results of drilling of the Bounty Channel at Ocean Drilling Program Site 1122 (Carter et al., 1999) where a 617.8 m succession of lower Miocene to upper Pleistocene turbidites, pelagic to hemipelagic sediments and contour current-modified deposits were recovered from the channel levee (Figs. 2 and 3). Sandy laminae and beds represent overbank deposits from turbidity currents that traversed and overspilled the Bounty Channel in the process, building up the channel levees (see discussion of processes in Carter et al., 1999).

The Miocene section extends from 617.8 to 490 meters below sea floor (mbsf), ranges in age from ~16 to 11 Ma, and accumulated at an average rate of ~20 m/m.y. It is unconformably overlain at ~490 mbsf by lower Pliocene sediments ~3.5 Ma in age (Fig. 3). Sediment accumulation was apparently continuous from the late Pliocene into the Pleistocene with accumulation rates reaching ~400 m/m.y. Carter et al. (1999) attributed this sedimentation pattern to uplift of the Southern Alps, but they did not address the cause of the major hiatus and/or unconformity at 490 mbsf. Rather than an angular unconformity, the hiatus at Site 1122 is more accurately described as a paraconformity unrelated to plate boundary deformation (Carter et al., 1999). This is evidenced by lack of pre-hiatus deformation on seismic data (Carter et al., 1999; Fig. 2). In a later publication, Carter, L., et al. (2004) attributed the hiatus to a strengthened ACC and correspondingly intensified bottom flow. They favored the ACC over the DWBC because of the timing of the hiatus and the relatively weak energy of the DWBC as compared to the overriding ACC as supported by the modern oceanography (Carter and Wilkin, 1999). We examine the composition and provenance of these sediments for clues as to the origin of the ~11–3.5 Ma gap in sedimentation and discuss the possible mechanisms for this significant hiatus.
Figure 2. On top (A) is a topographic and bathymetric image of the Bounty source-to-sink system (image from CANZ, 1996). Gray scale is subaerial; red is shelf areas with colors progressing to abyssal depths in dark blue. Red star marks general location of Site 1122. Boxed area is detailed below in (B), which shows selected features of onshore drainage, structure, and geology for Bounty Fan sediment source region (simplified from New Zealand Geological Survey, 1972). Note that Miocene basins are indicated only where patchy erosional outcrops are present today, and their distribution (and associated lacustrine environments) may have been more extensive. Lower image on right (C) is part of seismic section NZOI 2023 showing Site 1122 in relation to the Bounty Channel where A, B, C, D1, and D2 are seismic units and R3, R5, R7, R9, R10, and R11 are seismic reflectors (modified from Carter et al., 1999). Boundary between seismic units A and B (R5) corresponds to ~470 m at Site 1122, which is the approximate level of the hiatus. See Shapiro et al. (2007) for discussion of probable channel facies in area outlined in purple box.
Figure 3. Stratigraphic column for Site 1122 modified from Carter et al. (1999); see this reference for further definition of subunits. Sample intervals are as indicated. mbsf—meters below sea floor.

Sampled Intervals
- ▶ Sample not counted
- ▷ Point-counted sand

Leg 181 Site 1122
The Miocene–Pliocene sections drilled at several other Leg 181 sites (Fig. 1) provide no consistent trends (Carter et al., 1999). The 500-m sedimentary section recovered at Site 1119 was <3 Ma in age, younger than the hiatus (Carter et al., 1999). Site 1120 on the Central Campbell Plateau showed a decrease in sediment accumulation rates at ~10 Ma, which the shipboard scientists (Carter et al., 1999) attributed to current and productivity changes rather than tectonic events given the largely pelagic nature of the sedimentary record at this site. Site 1121 to the south on the Campbell “Drift” shows a major hiatus from 65 to 3 Ma. Deep Sea Drilling Project Site 594, which is located at the head of the Bounty Trough, closer to the zone of Southern Alpine deformation, has a complete stratigraphic section of calcareous ooze to calcareous mud from the early Miocene (Kennett, et al., 1986). This range of marine records emphasizes that the response to tectonic events may differ across the region depending on the depositional setting.

METHODS

Representative unconsolidated sandy samples taken from cores recovered at Site 1122 (Fig. 3) were split into two equal portions for geochemical and petrographic analyses summarized here. For petrographic analyses, sample splits were sieved for the sand fraction and thin sections prepared from the sand were stained for feldspar recognition and point-counted using the Gazzi-Dickinson method as outlined in Shapiro et al. (2007). Geochemical samples were ground for 10–15 min in an agate ball mill before fusion according to the method of Norrish and Chappell (1977). Major-element analysis was carried out on fused glasses by X-ray fluorescence spectroscopy using a Phillips PW 2400. Presented here are only chemical index of alteration (CIA) ratios. Chemical index of alteration is defined as molar (Al2O3)/((Al2O3 + CaO* + Na2O + K2O) (Nesbitt and Young, 1984), where CaO* is the calcium associated with the silicate fraction in the sediment. Owing to their small volume, bulk samples were not analyzed for carbonate concentration prior to geochemical analysis. A linear (R2 = 0.9018) relationship between loss on ignition (wt%) and CaO (wt%) was used to estimate and correct for CaCO3 (wt%) allotting a proportion for phosphatic Ca. This technique could be used because of the low CaO concentrations of the Bounty minerals (e.g., albite feldspar). Removing this eustatic biogenic signal (Carter and Carter, 1993) was important in being able to decipher detrital mineral provenance.

SEDIMENT COMPOSITION AND PROVENANCE ACROSS HIATUS

Sediment composition is relatively uniform within the cored section at Site 1122 with no distinct changes in sediment provenance across the 11–3.5 Ma hiatus. This is evident in both the sand detrital modes (Fig. 4) and bulk-sediment geochemistry. The very fine to fine sand samples are micaceous and arkosic with grains of quartz, albite, muscovite, and chlorite, and a minor metamorphic lithic component. These are also the most abundant components in the Otago-Haast schist and derived fluvial sediments from the modern Clutha River (Fig. 2B; Shapiro et al., 2007). The main provenance signal in the sand fraction is that of the Clutha River (Otago schist), and this signal remained relatively constant across the hiatus (Shapiro et al., 2007). Note that volcanic lithic fragments are fairly rare in the Bounty sand fractions, but there are discrete tephra-rich horizons (Shapiro et al., 2007). Despite the active onshore mafic magmatism during the hiatus (see volcanic rock distribution in Fig. 2B), there is no significant increase in mafic volcanic lithic content in the post-hiatus section. This is not surprising because the weathering of basaltic volcanic rocks produces mainly clay minerals as opposed to sand-sized detritus (see discussion in Marsaglia, 1993). In addition, because the volcanism was concentrated in the north-east segment of the study area (Fig. 2B), any epiclastic signal may have been preferentially translated to the northeast along the shelf and slope north of the Dunedin volcanic complex.

Major- and trace-element compositions of Bounty Fan sediments are also consistent with a mainly Clutha River (schist) source (Kautz et al., 2007).
DISCUSSION

There are several possible causes for the development of a major hiatus in a Bounty submarine fan system including the following:

**Autogenic Switching of Bounty Channel**

Curry et al. (2002) show that channel avulsion in the Bengal Fan is limited to the upper and upper middle fan, whereas channel migration on the lower fan is slower and less important. However, the Bengal Fan is largely unconfined. In contrast, the course of the Bounty Channel is largely structurally (basement) controlled and confined to the relatively narrow Bounty Trough (Carter and Carter, 1996). There is some evidence for slight channel migration, but no evidence for pre-Pleistocene channel avulsion and reestablishment in the vicinity of Site 1122. Thus the pronounced left bank, channel levee at Site 1122 should provide a detailed pre-Pleistocene record of sediment delivered to the Bounty Fan.

**Sea-Level Change**

Modern highstand sediment is transported mainly along the shelf and therefore largely bypasses Bounty Trough (Carter and Carter, 1993). Any sediment pulse in the system would first be stored in the nearshore shelf sediment wedge or prism (Carter and Carter, 1986), which would only supply sediment to the deeper trough when it prograded to the platform edge. During lowstands, therefore, a major part of the terrigenous sediment supply (note that some sediment was contributed to Otago margin fan system) should have been distributed downslope and directly fed into the feeder channels of the base-of-slope fan complex (Carter and Carter, 1989). The sediment pattern in the Miocene–early Pliocene at Site 1122 is not what one would expect if eustasy were the main control; in fact, it is the exact opposite. At ~10.5 Ma, when there is a major global fall in sea level (Haq et al., 1988), deposition ceased on the Bounty Fan, whereas fan deposition was reestablished in the early Pliocene just after a period of relatively high sea level (Haq et al., 1988). Such out-of-phase development contradicts the paradigm of submarine fan buildup during sea-level lowstands (see Covault et al., 2007 for discussion and additional southern California examples). Therefore something other than sea-level change must have diminished input and/or removed sediment sometime between ~11 and 3.5 Ma.

**Submarine Erosion and Transport**

Sediment flux throughout the upper and lower regions of the Bounty marine system may have been strongly influenced by abyssal current activity. Shelf-edge–parallel transport of sediment along the base-of-slope fan complex has been influenced by a major intermediate water flow as described by Lu and Fulthorpe (2004). At Site 1122, sedimentary structures suggest likely reworked and redistributed sediments occur both above and below the hiatus, with current-generated bedforms being best developed in the core that contains the hiatus (Carter et al., 1999). Today, south of the Bounty Trough, erosion prevails under the influence of a strong and dominating ACC. The paleolatitude of the Bounty Fan would place it under the influence of the ACC prior to 10 Ma (Carter, L., et al., 2004). As New Zealand drifted north to its present position, the Bounty Fan moved to the periphery of the main path of the ACC, although it is likely to be affected during glacial periods (e.g., Crumwell et al., 2008) and is periodically influenced in modern times by ACC-generated eddies (e.g., Bryden and Heath, 1985). Against the background of an episodic impact of the ACC, the Fan is continually bathed by the DWBC. By 1.4 Ma, this northward shift, coupled with the influx of sediment from a rapidly uplifting Alps that were exposed to more intense glacial-interglacial cycles, resulted in fan deposition overwhelming the remaining erosional effects of the abyssal flow of the DWBC and episodic ACC, although the middle fan appears to be undergoing minor erosion under the present flow (Carter and Carter, 1996). Such a scenario is independent of the supply of sediment to the fan, which may not have been uniform throughout the span of the hiatus.

Shapiro et al. (2007) argue that the presence of channel facies (purple box in Fig. 2) suggests that there was turbidity current input throughout deposition of the recovered section at Site 1122. They describe the pre–3.5 Ma section as a Bounty Channel–fed contourite succession that evolved into the Bounty submarine fan system. It follows then that contour currents were a secondary rather than a primary depositional input mechanism during accumulation of Units II and III.

**Changes in Sediment Input**

Paleogene postrift thermal subsidence and marine transgression of the Otago region were interrupted by transpressional tectonics at the inception of the Alpine fault (Cooper et al., 1987) at ~23 Ma (Carter and Norris, 1976; Kamp, 1986). Subsequent late Miocene (Kairouan) deformation is linked to transpression along the Alpine transform plate boundary (Molnar et al., 1975) brought about by changes in the Australia-Pacific instantaneous pole positions first at 12 Ma and then later at 5 Ma (Sutherland, 1995; Cande et al., 1995). This deformation produced an estimated 20-km exhumation along the Alpine fault since 10 Ma (Cooper, 1980) and more rapid uplift and exhumation since 6.4 Ma (Walcott, 1998).

The lower age limit of the hiatus at Site 1122 roughly corresponds to the onset of early Miocene tectonics, reemergence of central Otago, development of the so-called “Dunstan” fluvial system, and deposition in onshore terrestrial basins (Youngson and Craw, 1996; Youngson et al., 1998). The Dunstan paleoriver, which evolved from a coarse, conglomeratic, braided to a finer-grained, sandy, meandering system, was eventually transgressed by lacustrine deposits of the Bannockburn Formation (Douglas, 1986; Youngson et al., 1998; Youngson and Craw, 2002). The formation of this large lake or series of lakes at ~11–13 Ma, signaled the tectonic disruption of the Dunstan paleoriver drainage, owing to reactivation and reverse movement along Cretaceous normal faults (e.g., Bishop and Laird, 1976). The lake geometry is roughly defined by the spatial distribution of lake-deposit remnants, which if connected, suggest that the lake(s) may have been extensive (see Fig. 2B). Associated uplifts produced clastic successions (Wedderburn Formation and Maniototo Conglomerate) that fed into and eventually filled the lake (Youngson et al., 1998). From 13 to 10 Ma these faults also served as conduits for mafic magma producing the Dunedin volcanic complex (shield volcano) and outlying mafic intrusions (Coombs et al., 1986). Correlatives of these fluvial and lacustrine deposits, known at the Kurow Formation or Group, are also present in the Waitaki River drainage basin to the north (Fig. 2B; Youngson et al., 1998) indicating that fluvial drainage in this region was also affected.
Thus the Bounty hiatus may have been produced when sediment input was shut off during onshore fault reactivation and magmatism that created a “tectonic obstacle course” for the drainage that needed to be overcome before sediment could be resupplied to the Bounty Channel. This trapping of sediment in onshore basins in the late Miocene to Pliocene may have been similar to the effects of sediment trapping in glacial lakes in the Waitaki River headwaters during the past 10,000 yr (Carter and Carter, 1990). Breaching may have been gradual or more sudden and catastrophic, similar to that of glacial Lake Missoula, which is known to have delivered large volumes of sand to abyssal fans in the northeast Pacific Ocean (Zuffa et al., 2000; Normark and Reid, 2003; Prytulak et al., 2006). In the Bounty example, it may have taken some time for the signal to propagate down the fan system to Site 1122, consistent with Curry et al.’s (2002) findings for the Bengal Fan, where they showed the time span of a significant hiatus decreased up the fan. The paleogeography of the pre- and post-hiatus river systems (Clutha, Waitaki, and smaller Taiieri rivers) are poorly constrained and may have been very different, but the relatively uniform composition of sand across the hiatus at Site 1122 (Shapiro et al., 2007) suggests that since the Miocene the major sand-contributing rivers to the Bounty Fan were largely developed on Otago schist terrains.

The reestablishment of flow-through drainage could have conceivably produced a pulse of more weathered material temporarily stored in the interior basin successions into the Bounty Trough. The sediment pulse would have to make its way down the Bounty system and once near Site 1122, largely exceeded the erosive capacity of the ACC and DWBC. Sand detrital modes show no evidence for recycling (increase in quartz) across the Miocene–Pliocene hiatus. However, there are indications in the bulk geochemical data of changing proportions of weathered material through time as demonstrated in the plot of CIA versus age in Figure 4. The CIA reflects the bulk parent- rock chemistry and relative leaching of soluble elements (Ca, K, and Na) during weathering; lacustrine sediments generally undergo higher rates of chemical weathering and consequently have high CIA (~70–90; e.g., Das and Haake, 2003; Selvaraj and Chen, 2006). Comparative data for unweathered versus weathered schist and modern Clutha River versus Miocene basin (fluvial-lacustrine) sediments are as shown, with higher indices corresponding to more weathered material. For comparison, modern Clutha River sediments exhibit CIA values ranging from 50 to 60 depending on grain size and distance downstream. It is interesting to note that the highest CIA index (~73) is recorded in the Pliocene interval overlying the hiatus, a value suggesting significant weathered input consistent with recycling of onshore Miocene sediments. This pronounced peak cannot be linked to any specific climatic event. However, gradual fluctuations in the overlying section could be climate related, e.g., the maximum at ~290 mbsf roughly correlates with the mid-Pleistocene transition in glacial and interglacial cycles, the origin of which is still debated (e.g., Lisiecki and Raymo, 2007). It has been linked to a major glacial event, Marine isotope stage 22 (see discussion in Mildenhal et al., 2004). Perhaps this second CIA maximum and high values in overlying sections represent further flushing of Miocene terrestrial sediments associated with enhanced glacial runoff.

CONCLUSIONS

We can eliminate autogenic channel switching and eustasy in creating the hiatus at Site 1122. We favor a model where the system was affected by tectonically driven changes in sediment flux superimposed on the erosive effects of the ACC and DWBC. The sediment accumulation pattern observed at Site 1122 could be produced if the sediment flux varied with a relatively sudden decrease at ~11 Ma, moderate input after 3.5 Ma and higher input from 2 Ma onwards. The change in sediment input at ~11 Ma is best related to tectonic disruption of onshore drainage in Central Otago schist terrains, the main sediment source as determined using sand detrital modes and geochemistry. The erosive effects of the ACC and DWBC may have postponed the signal of enhanced tectonism at 6.4 Ma to >3.5 Ma. The CIA values document input of more weathered material that could be linked to drainage development within the system periodically tapping into and flushing older terrestrial lacustrine and fluvial deposits into the submarine system. We note that it may be difficult to separate out tectonic from paleoceanographic signals (erosive currents) in deep-sea successions, especially where the current development and strength are partly linked to movement of tectonic plates.

Insights from the Bounty system, where tectonic-induced fluvial drainage reorganization can be directly linked to the deep-sea record, are applicable to ancient systems, particularly those potentially affected by fluvial drainage-disrupting tectonic events (e.g., Rio Grande fluvial-deltaic system, Connell et al., 2005). Furthermore, the Bounty Fan has also been influenced by submarine currents and so provides insights in other systems such as the Barra Fan (Armishaw et al., 2000).

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