For submission to Geology

Tracking fluvial sand through the Waipaoa River Basin, New Zealand, using meteoric ^{10}Be

Lucas J. Reusser*
Paul R. Bierman
Geology Department and Rubenstein School of Environment and Natural Resources, University of Vermont, Burlington, VT 05405

**corresponding author: lreusser@uvm.edu*
(802) 656-3398 ph. (802) 656-0045 fax.

Keywords: Meteoric ^{10}Be, sediment mixing, sediment sources, gully erosion, Waipaoa River Basin, land management, cosmogenic.

ABSTRACT (250 words or less)

We use meteoric ^{10}Be measured in 24 sand samples collected along the mainstem and from prominent tributaries within the tectonically active Waipaoa River Basin, New Zealand, to identify the sediment sources and monitor the mixing of sediment as it travels from headwater basins to the sea. In the Waipaoa Basin, land clearance for agriculture at the turn of the century resulted in some of Earth's most sever erosion. Tributaries in the northern headwaters, where large amphitheater gullies that feed prodigious amounts of sediment to the mainstem are prevalent, yield exceptionally low concentrations of meteoric ^{10}Be (~1.5 x 10^6 at/g). In the more stable eastern and western tributaries, concentrations of meteoric ^{10}Be are nearly an order of magnitude greater (~14 x 10^6 at/g). Meteoric ^{10}Be concentrations in samples collected along the mainstem above and below tributary confluences steadily and predictably increase downstream (R^2 = 0.92) as gully-derived sediments are diluted with sediment from stable tributaries, providing strong evidence that meteoric ^{10}Be monitors sediment mixing in this fluvial network. Concentrations of meteoric ^{10}Be more than double between the headwaters and the outlet, suggesting that gullies provide nearly half of the total sediment carried by the Waipaoa, yet gullied terrain covers <7% of the landscape. These results suggest that meteoric ^{10}Be is an effective tool for rapid assessment of sediment dynamics and movement within fluvial networks. Since the application of meteoric ^{10}Be is not limited to basins containing quartz, its measurement in fluvial sediment allow much of Earth's surface to be interrogated cosmogenically.

INTRODUCTION

Through agricultural, forestry, construction, and mining practices, humans have become the dominant geomorphic force on our planet today, moving more sediment than any natural process (e.g. Hooke, 1994, 2000). Human activities affect how quickly landscapes erode and the pace at which rocks and sediments move across hillslopes and into river systems. For land managers attempting to restore watersheds to more natural conditions, determining the degree to which human actions have impacted landscapes and the specific locations and magnitudes of such impacts is critical (Wilkinson and McElroy, 2007).

Quantifying the volume and source of sediment moving into and through fluvial systems remains difficult; results are typically uncertain and may be biased (Meade, 1969; Trimble and Crosson, 2000) because contemporary sediment yield records are often short and thus may not incorporate incorporate high-magnitude, low-frequency events (e.g. Wolman and Miller, 1960). The concentration of ^{10}Be produced *in situ* by cosmic ray bombardment, has been used to determine sediment sources (e.g. Clapp et al., 2000; Cox et al., (in press)) but the method has several limitations. Because *in situ* ^{10}Be is isolated from quartz, only landscapes with quartz-bearing lithologies can be considered. Further, the *in situ* method presumes homogenous quartz distribution throughout the sampled basin; an assumption that is often violated (REFS).

Here, we present a new method for identifying sources of fluvial sediment and for tracking that sediment downstream – the measured concentrations of meteoric ^{10}Be in river sand. Our work, building on the pioneering approach of Brown *et al.* (1988), identifies major sediment sources within a moderately-sized (2,200 km^2) catchment, the Waipaoa River Basin. The Waipaoa Basin drains a rapid eroding landscape of predominately fine-grained calcareous mud and siltstones (Mazengarb and Speden, 2000), making *in situ* ^{10}Be analysis nearly impossible. The basin is tectonically active and has been severely impacted by land-clearance for agricultural and forestry purposes. The approach we detail enables researches to study sediment dynamics in landscapes previously beyond the reach of cosmogenic techniques, thus providing a valuable tool for land management.

METEORIC ^{10}Be

Unlike *in situ* ^{10}Be, produced at Earth's surface through cosmic ray bombardment, meteoric ^{10}Be is produced in the atmosphere through the spallation of ^{14}N (Lal and Peters, 1967). It rains onto the landscape, adheres to soil particles on hillslopes of all lithologies (Nyffeler et al., 1984), and is transported with them into and down river channels. Estimates of meteoric ^{10}Be delivery rates somewhat remain uncertain, and prior work suggests that delivery is both temporally and spatially variable over short time scales (Monaghan et al., 1986). Results from a number of studies suggest that, for mid-latitude humid regions, on average ~1.2 to 1.3 x 10^6 atoms ^{10}Be per cm^{-2} are delivered annually (Brown et al., 1988; Monaghan et al., 1986; Pavich et al., 1984; Pavich, 1985). Recent work (Jungers et al., 2006; Jungers et al., (in review)) suggest that meteoric ^{10}Be is held on sediment grains in amorphous Fe and Al coatings. Under acidic conditions, these coatings, and in turn the meteoric ^{10}Be within them can potentially become remobilized (REFS). However, because soils and sediments in the Waipaoa basin are derived from carbonate-bearing lithologies, the system is well buffered, ensuring that meteoric ^{10}Be is not remobilized and lost the either surface or ground water after initially adsorbing to soil particals.

WAIPAOA RIVER BASIN

The Waipaoa is one of several large catchments draining the northeast coast of New Zealand's North Island (Fig. 1). Rapid uplift rates along the subduction margin (~1 to 4 mm/yr) (Berryman et al., 2000; Brown, 1995; Mazengarb and Speden, 2000; Ota et al., 1992), heavily fractured and weakly cemented rocks (Black, 1980; Mazengarb and Speden, 2000), and periodic intense cyclonic activity (Hessell, 1980; Hicks et al., 2000) render the East Cape region of the North Island exceptionally susceptible to erosion. In the Waipaoa River Basin, these natural conditions, acting in concert with widespread land clearance for agriculture and forestry have resulted in some of the most dramatic erosional features in the world. The Waipaoa River's sediment yield (~6800 t km^{-2} yr^{-1}) is among the highest recorded in New Zealand, as well as around the globe for a basin of its size (Gomez et al., 2003; Hicks et al., 2000; Milliman and Robert, 1983).

The region was first settled by the Mauri ~700 ybp; however widespread land clearance did not begin until the early 1800's with the arrival of European Settlers. By 1880, the downstream portion of the Waipaoa Basin was largely cleared, and by the 1920's most of the headwaters were cleared as well, resulting in extensive hillslope erosion from gullying and deep-seated landslides accompanied by rapid and substantial aggradation in river channels (Hicks et al., 2000). The northern headwaters, underlain by exceptionally weak allochthonous lithologies (Mazengarb and Speden, 2000) were especially susceptible to the formation of large amphitheater gully complexes, which swamped the mainstem channel with gully-derived sediment (Figs. 2, 3a and b). Although reforestations efforts were implemented (Allsop, 1973; Marden et al., 2005) in an attempt to stabilize the landscape, in-channel aggradation, downstream sedimentation, and flooding continue to be problematic today. Although erosion in the Waipaoa has been studied extensively (e.g. Derose et al., 1998; Gomez et al., 2003; Hicks et al., 2000; Kettner et al., 2007; Marden et al., 2005; Reid and Page, 2002), it remains uncertain what proportion of sediment ultimately delivered to the sea is derived from the heavily gullied northern headwaters vs. the more stable eastern and western portions of the basin, less susceptible to extreme erosion (Fig. 3c). The uneven distribution of discrete, deep-seated sediment sources (gully complexes) in the Waipaoa Basin provides an ideal setting to test the utility of meteoric ^{10}Be as a monitor of sediment sourcing and mixing throughout a fluvial network.

METHODS

In May 2004 and March 2005, we collected samples of fluvial sediment down the mainstem of the Waipaoa River network, from all prominent tributaries contributing to the mainstem, as well as from numerous smaller tributary basins within the Waipaoa system, for meteoric ^{10}Be analysis. In theory, each sample represents the spatially averaged concentration of meteoric ^{10}Be of the landscape contributing sediment to the sample collection point. At each sampling station, we collected several kg of well-mixed channel sediment field sieved to a grain size of 250-850 microns. Here, we present and discuss ^{10}Be concentration from 24 unique isotopic analyses, made on 21 discrete samples collected at 18 different locations, including 3 full process replicates and 3 temporal replicates. These samples include 10 locations along the mainstem Waipaoa River, as well as 8 prominent tributary basins.

At the University of Vermont, we thoroughly dried each sample then milled a well mixed ~20g aliquot in a SPEX Centriprep 8500 Shatterbox to a fine powder. We prepared samples in three separate cosmogenic isotope laboratories located at The University of Vermont in Burlington, VT, the University of Washington in Seattle, WA, and the Hebrew University in Jerusalem, Israel. Meteoric ^{10}Be was isolated from a ~0.75 g aliquot through the rapid fusion method presented in Stone (1998), precipitated as a hydroxide, burned to produce BeO, packed into cathodes mixed with Nb power, and measured at Center for Accelerator Mass Spectrometry (CAMS), Lawrence Livermore

National Laboratory. We normalized measured ratios of $^{10}Be/^{9}Be$ to the 07KNSTD3110 standard (Nishiizumi et al., 2007) to arrive at our final ^{10}Be concentrations.

RESULTS

Concentrations of meteoric ^{10}Be vary by more than an order of magnitude across the Waipaoa Basin (1.44 ± 0.06 to 17.43 ± 0.56 x 10^6 at/g; Table 1). Tight agreement between all of our process replicates (2.2, 4.3, and 1.3 percent; Table 1) indicates that our laboratory procedures and ^{10}Be concentrations are reproducible, an important finding because we prepared the samples at three separate laboratories, and because analyses were made on three separate run dates at CAMS,

The lowest concentrations of ^{10}Be were from both mainstem and tributary samples located in the heavily disturbed headwaters of the basin (~1.5 x 10^6 at/g; Table 1, Fig. 4a). The highest concentrations of ^{10}Be (~14.4 x 10^6 at/g; Table 1) were measured in samples from the prominent western (Waikohu Stream) and eastern (Waihora Stream) tributaries that enter the Waipaoa River approximately half way down the mainstem channel (Figs. 1 and 4a). Samples along the mainstem, strategically collected both upstream and downstream of incoming tributary confluences, show a steady and predictable increase in ^{10}Be concentration (R^2 = 0.92) as tributaries contribute sediment containing higher concentrations of ^{10}Be to the mainstem (Fig. 4a).

TEMPORAL REPRODUCIBILITY

In landscapes where episodic delivery of sediment by mass wasting is common, such as the Waipaoa, the temporal homogeneity of isotopic concentrations of fluvial sediment may not be constant. In prior fluvial network studies, this critical assumption has remained largely untested. To test for temporal homogeneity of meteoric ^{10}Be concentrations, we re-collected sediment in March 2005 at three locations sampled ~9 months previously in May 2004 (Table 1). Of these replicates, two are from the mainstem; one where it exits the headwater region and the other in the mid-basin below the eastern and western tributary confluence, while the third is from the eastern (Waihora Stream) prominent tributary (Fig. 1).

The two temporal replicates along the mainstem reproduce well, with percent differences of 2.7% (WA1met and WA21met; 1560 km^2) and 2.1% (WA8met and WA19met; 237 km^2), well within both average analytic error ($\pm$3.6%) and average process replication differences (2.6%; Table 1). These results indicate that over our replication interval, the isotopic concentration of sediment carried by the mainstem Waipaoa is constant, and, by inference, that sediment is well mixed within the mainstem channel. In contrast to the mainstem samples, the one temporal replicate from the tributary basin (130 km^2; WA2met and WA23met) yields a substantially greater difference in meteoric ^{10}Be concentration between the two points in time (~19%). Although higher than for the mainstem, similar temporal differences in concentrations of *in situ* ^{10}Be at similar basin-scales (100s of km^2) have been noted in far more stable landscapes than the Waipaoa (Matmon et al., 2003a; Matmon et al., 2003b). The degree of variability probably represents the natural nuclide variance within river sediment exported from smaller catchments over time (Matmon et al., 2003b).

METEORIC ^{10}Be AS A USEFUL TRACER OF FLUVAIL SEDIMENT SOURCES

Meteoric ^{10}Be analyses of fluvial sediment demonstrate the progressive mixing and dilution downstream of low-concentration, gully-derived sediment by higher concentration sediment derived from less-disturbed tributary basins. The heavily gullied northern headwater region of the Waipaoa yielded the lowest concentrations of ^{10}Be (~1.5 x 10^6 at/g; Figs. 2 and 4a). Unlike the more stable eastern and western tributaries, where in channel sediment is more evenly sourced across the landscape, in the headwaters, the vast majority of sediment that reaches the channel originates from gullies etched deep into hillsides (Fig. 3a and b). In fact, in the most severely impacted tributary basins, >75% of the landscape is gullied (Fig. 2; Table 1; terrain ref-Basil). Because this sediment is rapidly excavated from deep below the land surface, it has had little chance to accumulate meteoric ^{10}Be. Samples collected from gullied terrains do not reflect the isotopic inventory contained in the landscape, but rather they predominately reflect the isotopic concentration of material source from the deep gullies.

The strong increasing downstream trend (R^2 = 0.92; Fig. 4a) in meteoric ^{10}Be along the mainstem channel reflects the dilution of gully sediments by sediment sourced from portions of the landscape where erosion is presumably less rapid and spread more evenly across the land surface. As concentrations of ^{10}Be steadily increase downstream, there is a correspondingly strong inverse relationship between the proportion of the landscape that is actively gullied and basin area (R^2 = 0.98; Fig. 4b). Similarly, a strong inverse relationship between the percent of the landscape that is gullied and the meteoric ^{10}Be concentration (R^2 = 0.88; Fig. 4c) demonstrates just how well ^{10}Be tracks the mixing of gully and non-gully derived sediment in the mainstem Waipaoa.

The Te Warroad Basin (WA52met; Figs. 1 and 4a) harbors the largest gully complex in the Waipaoa Basin, the Tarndale Slip. The low ^{10}Be concentration in sediment from this sample point ($1.62 \pm 0.05 \times 10^6$ at/g) sets the initial concentration of the downstream trend. Farther downstream, the incoming eastern and western tributaries mix sediment with ^{10}Be concentrations nearly an order of magnitude greater than the primarily gully-derived mainstem sediment. While the landscape supplying sediment to the eastern and western tributaries is periodically subjected to shallow landsliding, exacerbated by landclearance, and triggered either hydrologically (cyclones; (Hicks et al., 2000)) or by earthquakes, such shallow sliding does not appear to lower significantly the ^{10}Be concentration of sediment delivered by these tributaries, a concentration characteristic of the basin as a whole.

Concentrations of ^{10}Be increase more than two-fold from the headwaters (~1.5×10^6 at/g) to the outlet ($3.53 \pm 0.13 \times 10^6$ at/g). This finding implies that nearly half of the sediment leaving the Waipaoa system originates from gullies active across a disproportionately small amount of the overall basin. Using the mapped extent of actively gullied landscape in the Waipaoa (133 km^2 within our study region; ec terrain ref), ~50% of the sediment issuing from the Waipaoa today is derived from a maximum of ~7% of the landscape. Repeat channel surveys from the heavily gullied Te Weraroa Stream (29 km^2) from 1950 to 1988 suggest that, at the time of highest gully activity, the Te Weraroa Stream alone accounted for more the 5% of the total Waipaoa sediment yield, yet it occupies only ~1% of the total basin area (Gomez et al., 2003). While this ratio of percent total sediment yield to percent total area is high (5:1), meteoric ^{10}Be measurements suggest that gullies influence the total sediment yield to an even greater degree (~7:1).

IMPLICATIONS AND FUTURE RESEARCH

Measuring the concentrations of meteoric ^{10}Be in fluvial sand provides a spatially and temporally integrated glimpse at the sourcing, movement, and mixing of sediment in the disturbed and rapidly eroding Waipaoa River system. Our results are analytically reproducible, and particularly for the mainstem, temporally reproducible. We show that the method demonstrated here has the potential to address questions such as "where does sediment come from" and "proportionally how much sediment is generated in different parts of a basin;" findings that will allow land managers to more accurately target remediation strategies. While careful analysis of sediment yield data and repeat channel surveys offer critical information, these efforts are spatially limited and often take decades to complete (Derose et al., 1998; Gomez et al., 2003; Hicks et al., 2000; Reid and Page, 2002). This study suggests that fluvial network analysis with meteoric ^{10}Be can be used as a rapid assessment tool for understanding sediment dynamics within watersheds.

ACKNOWLEDGMENTS

We thank B. Gomez and M. Marden for introducing us to the Waipaoa field area, M. Jungers for field assistance, M. Marden for use of the Landcare Research facility in Gisborne, NZ, and R. Finkel and D. Ward for assistance with the AMS measurement. We thank J. Stone and A. Matmon for generously providing the use of their laboratory facilities. Project funded under NSF BCS-0317530 awarded to Gomez and Bierman.

REFERENCES CITED

Allsop, F., 1973, The Story of Mangatu: the forest which healed the land: Wellington, New Zealand, New Zealand Forest Service.

Berryman, K.R., Marden, M., Eden, D., Mazengarb, C., Ota, Y., and Moriya, I., 2000, Tectonic and paleoclimatic significance of Quaternary river terraces of the Waipaoa River, East Coast, North Island, New Zealand, *in* Anonymous, ed., Proceedings of the 9th Australia New Zealand Geomorphology Group (ANZGG) conference; programme and abstracts, Publisher Australia New Zealand Geomorphology Group, New Zealand, p. 5.

Black, R.D., 1980, Upper Cretaceous and Tertiary geology of Mangatu State Forest, Raukumara Peninsula, New Zealand: New Zealand Journal of Geology and Geophysics, v. 23, p. 293-312.

Brown, L.J., 1995, Holocene shoreline depositional processes at Poverty Bay, a tectonically active area, northeastern North Island, New Zealand: Quaternary International, v. 26, p. 21-23.

Brown, L.J., Pavich, M., Hickman, R.E., Klein, J., and Middleton, R., 1988, Erosion in the eastern United States observed with ^{10}Be: Earth Surface Processes and Landforms, v. 13, p. 441-457.

Clapp, E.M., Bierman, P.R., Schick, A.P., Lekack, J., Enzel, Y., and Caffee, M., 2000, Sediment yield exceeds sediment production in arid region drainage basins: Geology, v. 28, p. 995-998.

Cox, R., Bierman, P., and Jungers, M., (in press), Erosion rates and sediment sources in Madagascar inferred from 10Be analysis of lavaka, slope, and river sediment: Journal of geology.

Derose, R.C., Gomez, B., Marden, M., and Trustrum, N.A., 1998, Gully erosion in Mangatu Forest, New Zealand, estimated from digital elevation models: Earth Surface Processes and Landforms, v. 23, p. 1045-1053.

Gomez, B., Banbury, K., Marden, M., Trustrum, N.A., Peacock, D., and Hoskin, P., 2003, Gully erosion and sediment production: Te Weraroa Stream, New Zealand: Water Resources Research, v. 39, p. ESG 3-1 to ESG 3-7.

Hessell, J.W., 1980, The climate and weather of the Gisborne region: New Zealand Meteorological Service, Misc. Publ, v. 115, p. 29p.

Hicks, D.M., Gomez, B., and Trustrum, N.A., 2000, Erosion thresholds and suspended sediment yields, Waipaoa River Basin, New Zealand: Water Resources Research, v. 36, p. 1129-1142.

Hooke, R.L., 1994, On the efficacy of humans as geomorphic agents: GSA Today, v. 4, p. 224-225.

—, 2000, On the history of humans as geomorphic agents: Geology, v. 28, p. 843-846.

Jungers, M., Bierman, P., Matmon, A., Cox, R., Pavich, M., Larsen, J., and Finkel, R., 2006, Tracking Soil Transport Downslope using in-situ Produced 10-Be: Geological Society of America - Abstracts with Programs, v. 38, p. 283.

Jungers, M., Bierman, P., Matmon, A.S., Nichols, K.K., Larsen, J., and Finkel, R., (in review), Tracing hillslope sediment production and transport with *in situ* and meteoric 10Be: Journal of Geophysical Research - Earth Surface.

Kettner, A.J., Gomez, B., and Syvitski, J.P.M., 2007, Modeling suspended sediment discharge from the Waipaoa River system, New Zealand: The last 3000 years: Water Resources Research, v. 43, p. doi: 10.1029/2006WR005570.

Lal, D., and Peters, B., 1967, Cosmic ray produced radioactivity on the Earth, *in* Sitte, K., ed., Handbuch der Physik: New York, Springer-Verlag, p. 551-612.

Marden, M., Arnold, G., Gomez, B., and Rowan, D., 2005, Pre- and post-reforestation gully development in Mangatu Forest, East Coast, North Island, New Zealand: River Research and Applications, v. 21, p. 757-771.

Matmon, A., Bierman, P., Larsen, J., Southworth, S., Pavich, M., and Caffee, M., 2003a, Temporally and Spatially Uniform Rates of Erosion in the Southern Appalachian Great Smokey Mountains: Geology, v. 31, p. 155-158.

Matmon, A., Bierman, P.R., Larsen, J., Southworth, S., Pavich, M., Finkel, R., and Caffee, M., 2003b, Erosion of an ancient mountain range, the Great Smoky Mountains, North Carolina and Tennessee: American Journal of Science, v. 303, p. 972-973.

Mazengarb, C., and Speden, I., 2000, Geology of the Raukumara Area, Map 6, *in* Heron, D.W., and Isaac, M.J., eds.: Lower Hutt, New Zealand, Institute of Geological & Nuclear Sciences, p. 1 sheet 1:250,000, 60 pp.

Meade, R.H., 1969, Errors in using modern stream-load data to estimate natural rates of denudation: Geological Society of America Bulletin, v. 80, p. 1265-1274.

Milliman, J., and Robert, M., 1983, World-wide delivery of river sediment to the oceans: The Journal of Geology, v. 91, p. 1-21.

Monaghan, M.C., Krishnaswami, S., and Turekian, K.K., 1986, The global-average production rate of ^{10}Be: Earth and Planetary Science Letters, v. 76 (1985/86), p. 279-287.

Nishiizumi, K., Imamura, M., Caffee, M., Southon, J., Finkel, R., and McAninch, J., 2007, Absolute calibration of 10Be AMS standards: Nuclear Instruments and Methods in Physics Research B, v. 258, p. 403-413.

Nyffeler, U.P., Li, Y.-H., and Santschi, P.H., 1984, A kinetic approach to describe trace-element distribution between particles and solution in natrual aquatic systems: Geochemica et Cosmochemica Acta, v. 48, p. 1513-1522.

Ota, Y., Hull, A., Iso, N., Ikeda, T., Moriya, I., and Yoshikawa, T., 1992, Holocene marine terraces on the northeast coast of North Island, New Zealand and their tectonic significance: New Zealand Journal of Geology and Geophysics, v. 35, p. 273-288.

Pavich, M., Brown, E.T., Klein, J., and Middleton, R., 1984, Beryllium-10 accumulations in a soil chronosequence: Earth and Planetary Science Letters, v. 69, p. 198-204.

Pavich, M.J., Brown, L., Valette-Silver, J.N., Klein, J. & Middleton, R., 1985, 10Be analysis of a Quaternary weathering profile in the Virginia piedmont: Geology, v. 13, p. 39-41.

Reid, L.M., and Page, M.J., 2002, Magnitude and frequency of landsliding in a large New Zealand catchment: Geomorphology, v. 49, p. 71-88.

Stone, J., 1998, A rapid fusion method for separation of beryllium-10 from soils and silicates: Geochemica et Cosmochemica Acta, v. 62, p. 555-561.

Trimble, S.W., and Crosson, P., 2000, U.S. soil erosion rates - Myth and reality: Science, v. 289, p. 248-250.

Wilkinson, B.H., and McElroy, B.J., 2007, The impact of humans on continental erosion and sedimentation: GSA Bulletin, v. 119, p. 140-156.

Wolman, M.G., and Miller, J.P., 1960, Magnitude and frequency of forces in geomorphic processes: Journal of Geology, v. 68, p. 54-74.

FIGURE CAPTIONS

Figure 1. Location map of the Waipaoa River Basin, located in the East Cape region on New Zealand's North Island. Map shows all data points included in our study; black circles represent samples collected down the mainstem channel of the Waipaoa River, while black triangles denote samples from prominent tributaries that mix into the mainstem. Arrows labeled "Rep" indicate the locations of the three temporal replicates discussed in the text. Inset panel shows amphitheater gullies active in the northern headwater region of the basin.

Figure 2. Map of the distribution of dominant lithologies across the Waipaoa River Basin. Opaque red regions show portions of the landscape that are heavily gullied today.

Figure 3. Field photos from the Waipaoa River Basin. A. photo oriented app. NW looking up the feeder channel of the Tarndale Slip, the largest gully complex active in the Waipaoa today. B. gully-derived sediments in the mainstem app. 2 km downstream from the confluence of the Te Weraroa Stream, which harbors the Tarndale Slip. C. photo shows an example of hillslopes along the Waihuka Stream in the western tributary region. Although deforested, and susceptible to occasional episodes of shallow landsliding, this region of the basin is more stable than the northern headwaters due to more competent underlying lithologies.

Figure 4. Synthesis of data presented in our study. A. basin area vs. meteoric ^{10}Be concentrations for all samples. Flags represent the contributing area of each tributary as they mix into the mainstem. B. basin area vs. the percent of land area that is heavily gullied for all mainstem samples. Gully percent decreases exponentially by more than 6 fold from the headwaters to the outlet. C. meteoric ^{10}Be vs. percent land area gullied for all mainstem samples. The strong relationship between the percent gully and ^{10}Be concentrations demonstrates the influence gully sediments exert on the concentration of ^{10}Be within mainstem sediments.

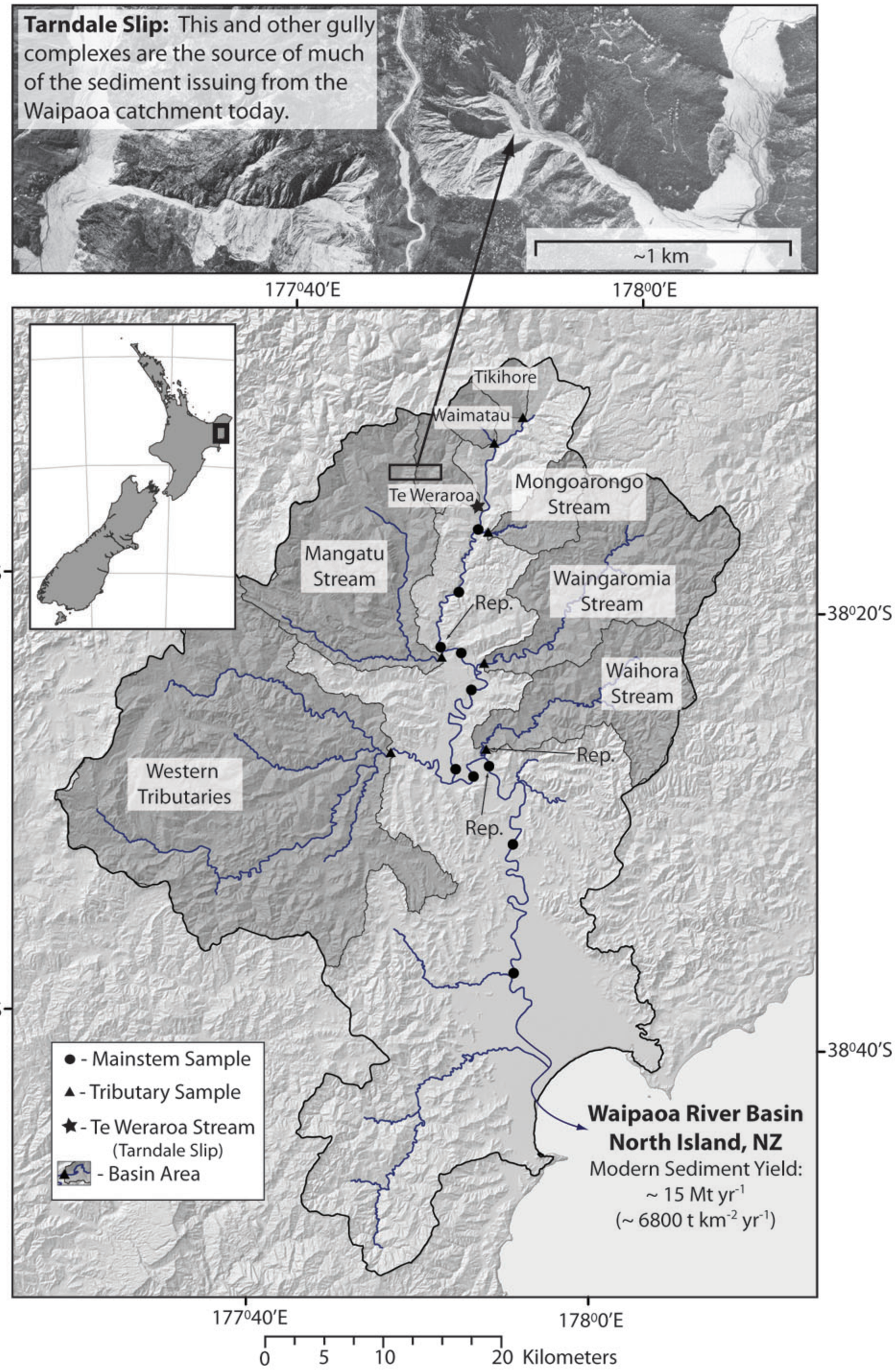

Figure 1 - Location Map

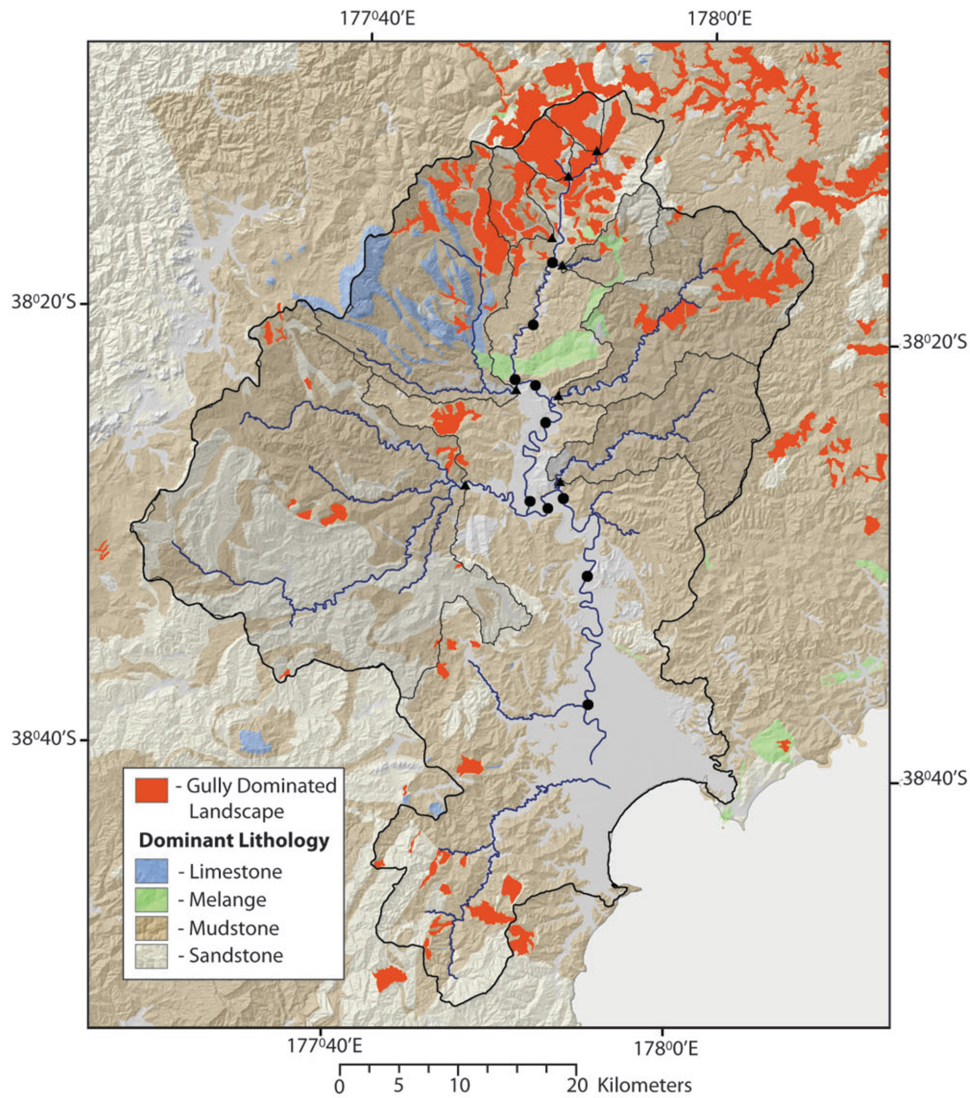

Figure 2 - Geology

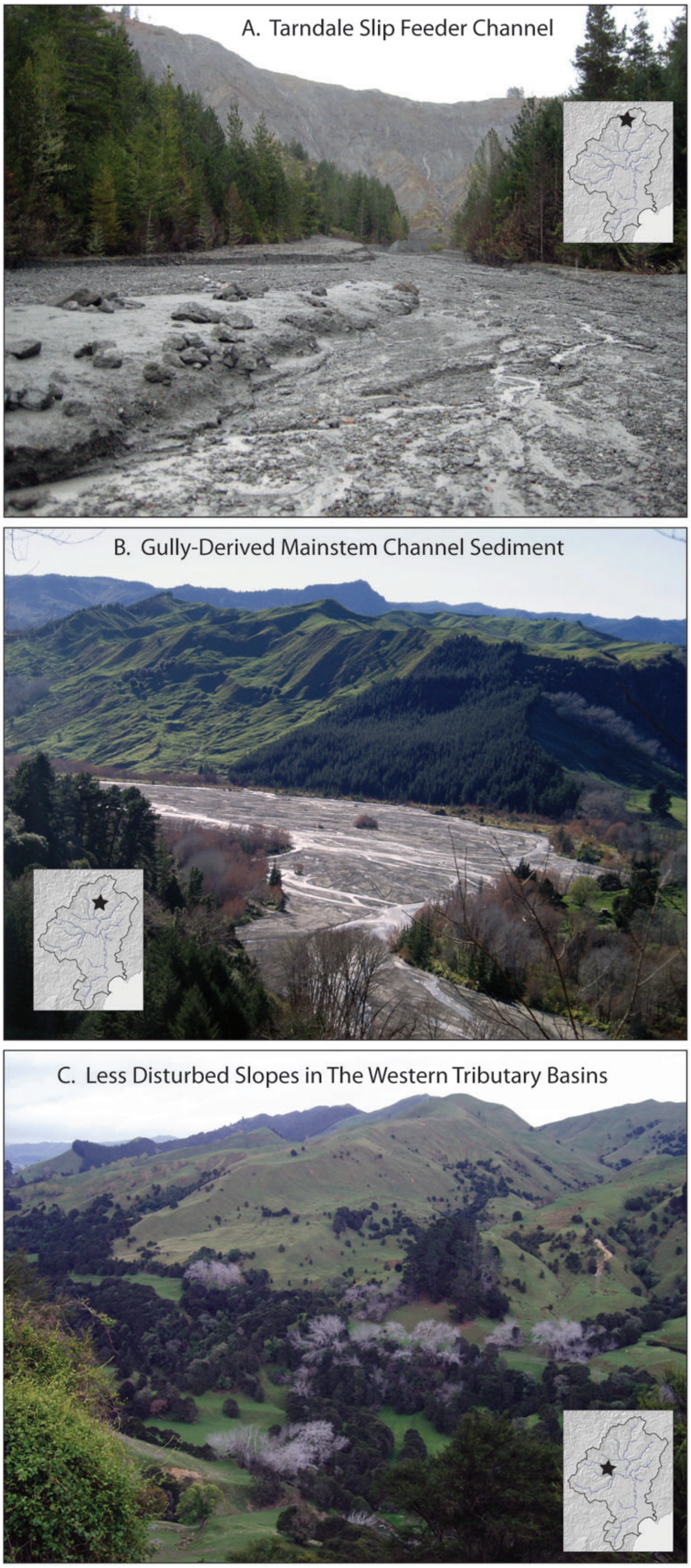

Figure 3 - Field photos

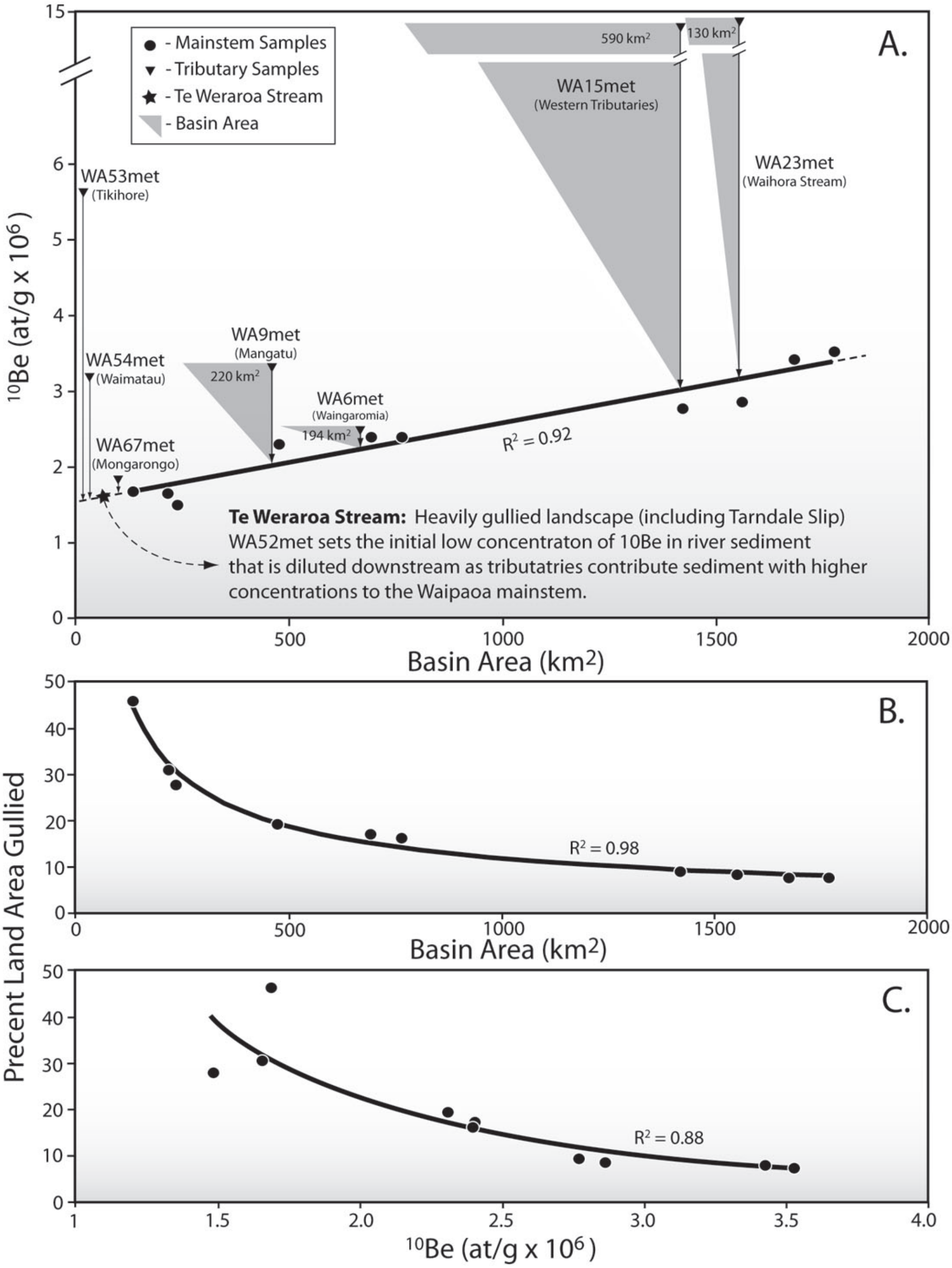

Figure 4 - Data Plots

TO BE INCLUDED AS SUPPLEMENTAL MATERIAL:

Table 1. Summary information for all samples

Sample ID*	Collection Date	Type†	Basin	Dominant Lithologies§	Basin Area (km^2)	Area After Mix (km^2)#	Gullied Area (km^2)**	Percent Gullied Area	Easting††	Northing††	^{10}Be (at/g x 10^6)§§	Percent Analytic Error (±)	Laboratory Percent Difference	Temporal Percent Difference
wa55metis	March 2005	Mainstem	Waipaoa	Mix	135	-	62.7	46.6	2934482	6313167	1.68 ± 0.07	4.1	-	-
wa17metis	March 2005	Mainstem	Waipaoa	Mix	215	-	66.3	30.8	2932852	6307866	1.66 ± 0.07	4.4	-	-
wa8metis	May 2004	Mainstem	Waipaoa	Mix	237	-	66.3	28.0	2931309	6303207	1.52 ± 0.07	4.4	-	-
wa19metis	March 2005	Mainstem	Waipaoa	Mix	237	-	66.3	28.0	2931320	6303196	1.44 ± 0.06	4.1	-	-
wa8/19met_ave##	na	Mainstem	Waipaoa	Mix	237	-	66.3	28.0	2931315	6303202	1.48 ± 0.06	4.2	-	2.7
wa7metis	May 2004	Mainstem	Waipaoa	Mix	476	-	92.6	19.5	2933052	6302712	2.31 ± 0.08	3.5	-	-
wa14metis	May 2004	Mainstem	Waipaoa	Mix	692	-	119.4	17.2	2933907	6299582	2.40 ± 0.08	3.5	-	-
wa3metis	May 2004	Mainstem	Waipaoa	Mix	765	-	125.2	16.4	2932576	6292861	2.40 ± 0.09	3.6	-	-
wa4metis	May 2004	Mainstem	Waipaoa	Mix	1422	-	133.3	9.4	2934089	6292248	2.77 ± 0.09	3.4	-	-
wa1metis	May 2004	Mainstem	Waipaoa	Mix	1560	-	133.3	8.5	2935404	6293113	2.89 ± 0.10	3.4	-	-
wa21metis	March 2005	Mainstem	Waipaoa	Mix	1560	-	133.3	8.5	2935397	6293012	2.83 ± 0.10	3.4	-	-
wa1/21met_ave	na	Mainstem	Waipaoa	Mix	1560	-	133.3	8.5	2935401	6293063	2.86 ± 0.10	3.4	-	1.2
wa11metuw	May 2004	Mainstem	Waipaoa	Mix	1682	-	133.3	7.9	2937417	6286506	3.43 ± 0.11	3.1	-	-
wa10metis	May 2004	Mainstem	Waipaoa	Mix	1777	-	133.3	7.5	2937490	6275586	3.53 ± 0.13	3.8	-	-
											±			
wa53metuw	March 2005	Prom Trib	Tikihore	Gullied ss	18	18	14	79.1	2935834	6320513	5.65 ± 0.17	3.1	-	-
wa54metis	March 2005	Prom Trib	Waimatau	Gullied ss	15	33	11.7	76.0	2938264	6322674	3.28 ± 0.10	3.0	-	-
wa54metvt	March 2005	Prom Trib	Waimatau	Gullied ss	15	33	11.7	76.0	2938264	6322674	3.14 ± 0.18	5.8	-	-
wa54met_ave	March 2005	Prom Trib	Waimatau	Gullied ss	15	33	11.7	76.0	2938264	6322674	3.21 ± 0.14	4.4	2.2	-
wa52metuw	March 2005	Prom Trib	Te Weraroa	Gullied ms	29	62	12.6	43.2	2934448	6315280	1.62 ± 0.05	3.3	-	-
wa67metis	March 2005	Prom Trib	Mongoarongo	Gullied ms, ss, mel	38	100	1.1	2.9	2935332	6312973	1.86 ± 0.07	3.6	-	-
wa9metis	May 2004	Prom Trib	Mangatu	Gullied ms, lm	220	451	26.4	12.0	2931396	6302380	3.34 ± 0.14	4.1	-	-
wa6metis	May 2004	Prom Trib	Waingaromia	Gullied ms	194	667	26.9	13.9	2934984	6301871	2.51 ± 0.09	3.7	-	-
wa15metuw	May 2004	Prom Trib	Waikohu	Ungullied ms, ss	587	1397	7.4	1.3	2927098	6294320	14.72 ± 0.45	3.0	-	-
wa15metvt	May 2004	Prom Trib	Waikohu	Ungullied ms, ss	587	1397	7.4	1.3	2927098	6294320	13.50 ± 0.45	3.3	-	-
wa15met_ave	May 2004	Prom Trib	Waikohu	Ungullied ms, ss	587	1397	7.4	1.3	2927098	6294320	14.11 ± 0.45	3.2	4.3	-
wa2metuw	May 2004	Prom Trib	Waihora	Ungullied ms	130	1535	0	0.0	2935145	6294576	12.01 ± 0.37	3.1	-	-
wa2metvt	May 2004	Prom Trib	Waihora	Ungullied ms	130	1535	0	0.0	2935145	6294576	11.70 ± 0.37	3.2	-	-
wa2met_ave	May 2004	Prom Trib	Waihora	Ungullied ms	130	1535	0	0.0	2935145	6294576	11.85 ± 0.37	3.1	1.3	-
wa23metis	March 2005	Prom Trib	Waihora	Ungullied ms	130	1535	0	0.0	2935145	6294576	17.43 ± 0.56	3.2	-	-
wa2/23met_ave	na	Prom Trib	Waihora	Ungullied ms	130	1535	0	0.0	2935145	6294576	14.64 ± 0.46	3.2	-	19.1

* The last two letters on sample IDs indicate the lab in which they were prepared; vt = University of Vermont, uw = University of Washington, and is = Hebrew University.
† Mainstem = samples collected along the mainstem Waipaoa channel. Prom trib = samples collected from prominent tributaries mixing into the mainstem Waipaoa channel.
§ Lithology abbreviations are as follows: ss = sandstone, ms = mudstone, lm = limestone, and mel = melange.
# Area after mix is the total basin area after a given tributary has mixed with the mainstem channel.
** Gullied areas were calculated in ArcGIS® using the East Cape Terraine Geographic coverage (REF).
†† All coordinates are listed in NZ Grid, 1949.
§§ Errors in nuclide concentrations include propagated laboratory and measurement uncertainties. Measured ratios of 10/9 Be normailized to the new 07KNSTD3110 standard (Nishiizumi, et al., 2007).
IDs ending in "ave" are the average of the indicated process or temporal replicates.