TIMING AND MAGNITUDE OF LATEST PLEISTOCENE AND HOLOCENE DEEP-SEATED LANDSLIDES IN THE WAIPAOA SEDIMENTARY SYSTEM, NEW ZEALAND

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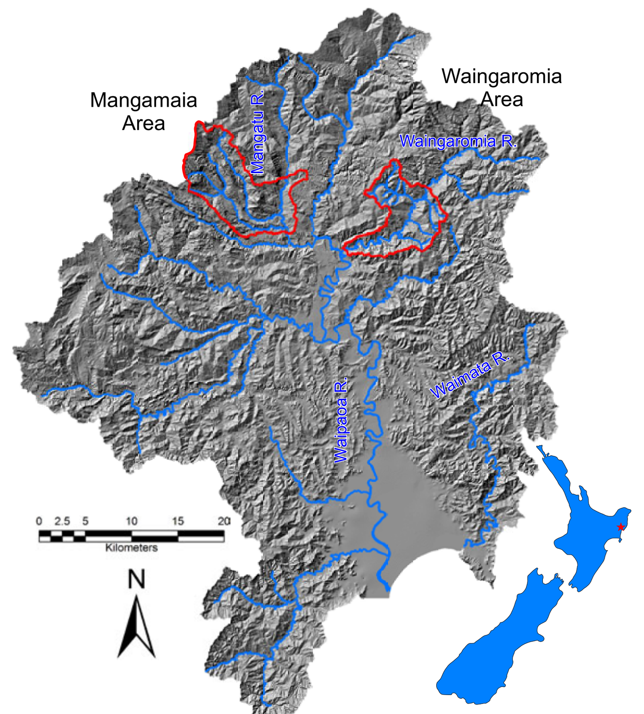
Abstract

Deep-seated landslides are pervasive in the non-glacial Waipaoa River catchment, New Zealand and are an indication of a landscape in transition. Landslides are important agents of local mass wasting, but their overall role in sedimentary systems is generally poorly understood. Using new high resolution topographic data sets, tephrochronology, and field mapping, we investigate the spatial and temporal relationship between river incision and deep-seated landslides and approximate the sediment flux from post 18 ka deep-seated landslides.

In the Waipaoa, and for much of the eastern North Island, the shift from the LGM to the current interglacial resulted in catchment-wide channel incision (Berryman et al., 2000; Litchfield and Berryman, 2005). Incision was accomplished by knickpoint retreat that had progressed into most of the major tributaries to the Waipaoa by the early Holocene (Crosby and Whipple, 2006; Berryman et al., 2010). Channel incision, although one of the most widespread and effective erosive processes in the catchment, only contributed ~25% of the total post 18 ka sediment yield (Orpin et al., 2006; Marden et al., 2008). Our analysis shows that deep-seated landslides are unlikely to make up this apparent source area sediment deficit.

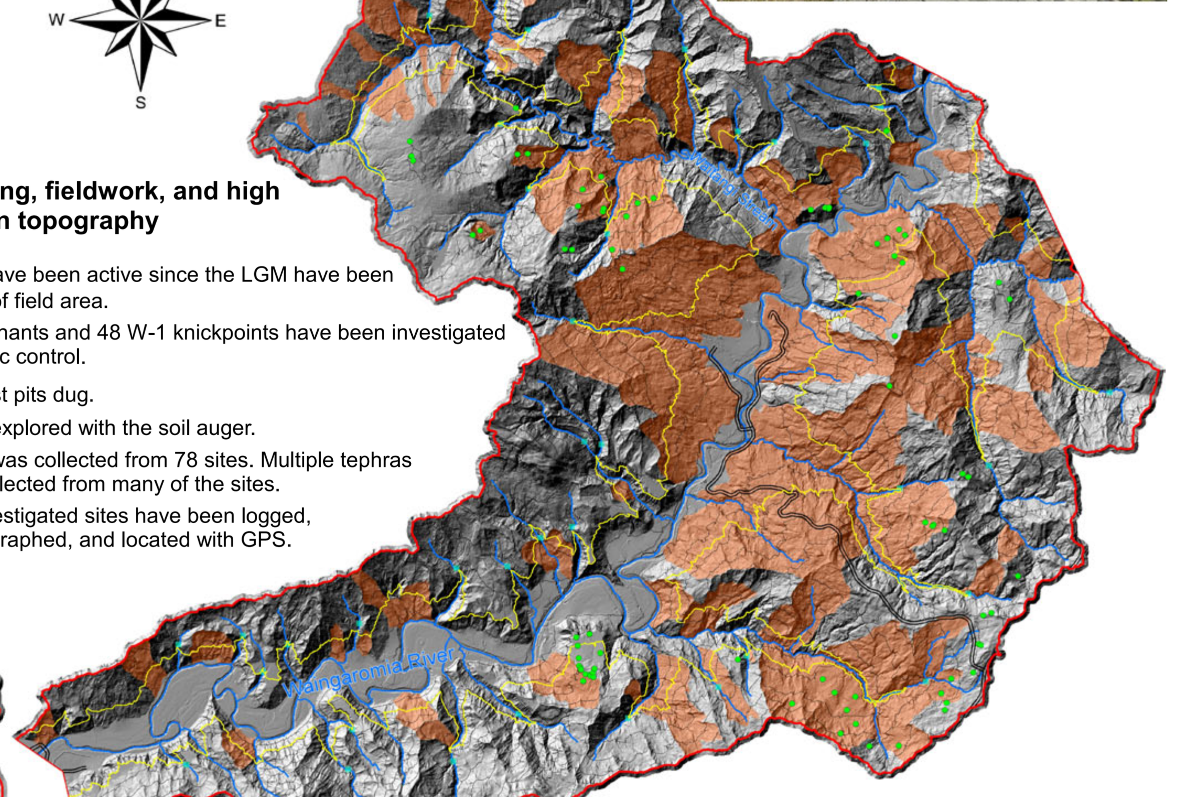
Geomorphic mapping and tephrochronology in the upper Waipaoa indicate that hillslopes adjusted to rapid incision through deep-seated landslides, which occupy over 30% of the surface area of portions of the catchment. Tephra cover bed ages determined by microprobe analysis suggest that hillslope adjustment in these upper reaches started between the deposition of the ca. 13,600 yr BP Waiohau tephra and the ca. 9,500 yr BP Rotoma tephra. Tephrochronology further shows that many slopes have continued to adjust to channel incision into the late Holocene. Volumetric estimates indicate that the sediment delivered to the offshore sink from these upper Waipaoa landslides is likely to be less than 20% of the sediment volume calculated for channel incision. This analysis raises questions about erosive processes and our ability to balance large scale sediment budgets. For example, does coastal erosion contribute a significant volume to the offshore sink? Was sediment from other catchments trapped in the Poverty Bay post-glacial shelf basin? Understanding the role of deep-seated landslides in the Waipaoa Sedimentary System has advanced our knowledge about land to ocean sediment transfer and will inform future land-use, environmental and ecological planning decisions, and hazard management.



Location
The Waipaoa River catchment with some major rivers labeled. Red outlined areas are the two tributary areas where the timing and magnitude of the deep-seated landslides in the sedimentary system are currently being investigated. The Waingaromia area on the east side of the catchment is underlain by mostly Miocene mudstones of the Tolaga group and some Miocene melange (Mazengarb and Speden, 2000). The Mangamaia area on the west side of the catchment is underlain by Oligocene to Early Miocene allochthonous mudstones and limestones of the Tolaga and Mangatu groups (Mazengarb and Speden, 2000).

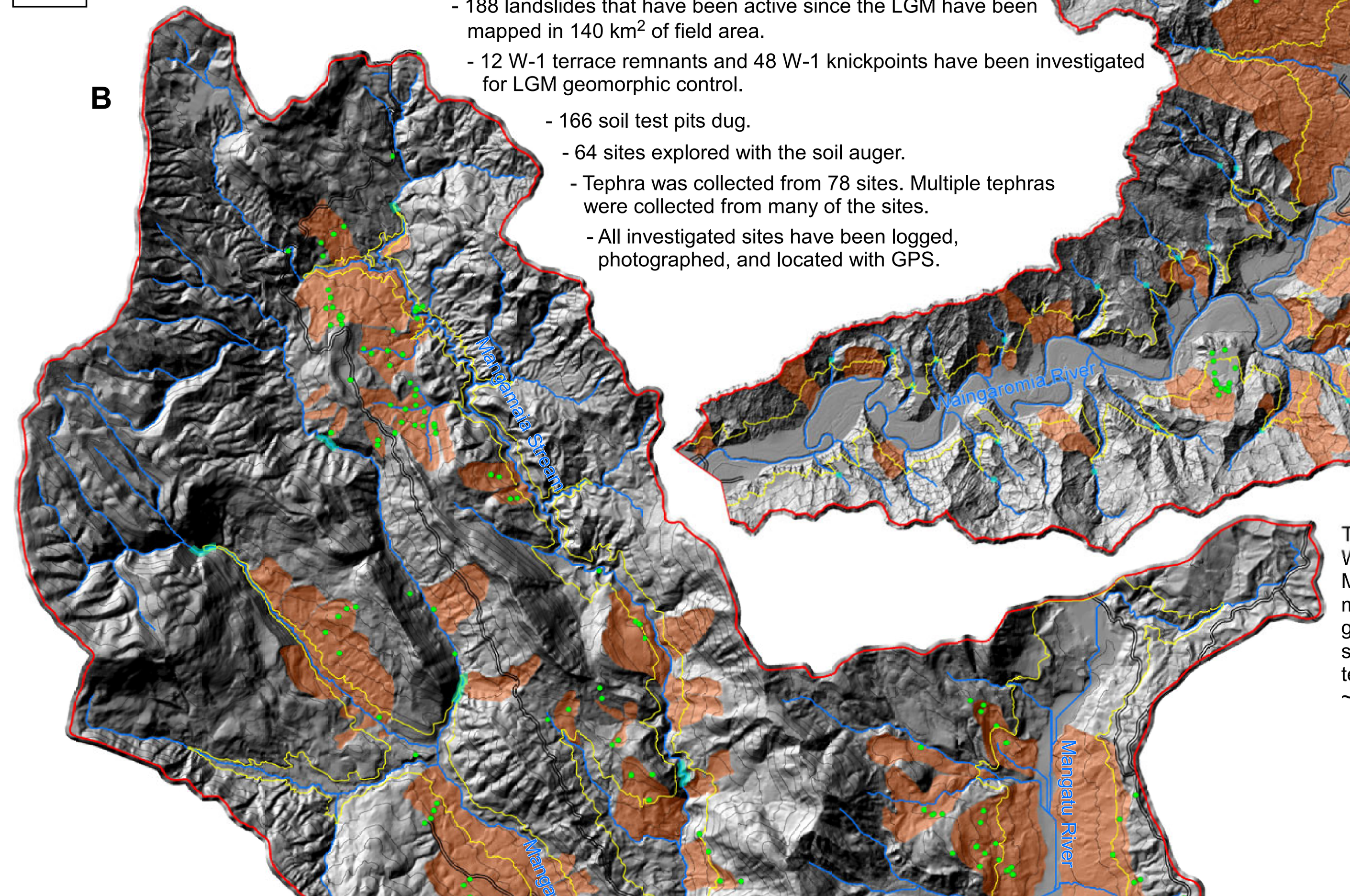
0 1 2 4 6 8
Kilometers

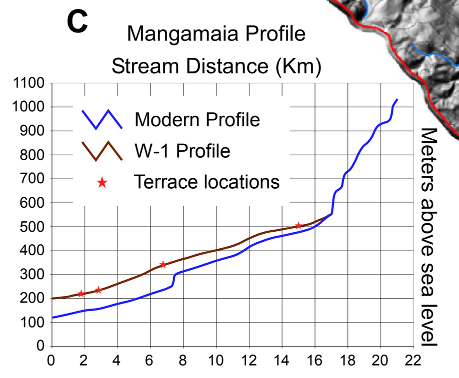
- Area boundaries
- Rivers and streams
- Modelled Waipaoa-1 aggradation surface extent
- Roads
- Deep-seated landslides
- Knickpoints or knickzones
- Test pit and auger locations



Geomorphic mapping, fieldwork, and high resolution topography

- 188 landslides that have been active since the LGM have been mapped in 140 km^2 of field area.
- 12 W-1 terrace remnants and 48 W-1 knickpoints have been investigated for LGM geomorphic control.
- 166 soil test pits dug.
- 64 sites explored with the soil auger.
- Tephra was collected from 78 sites. Multiple tephras were collected from many of the sites.
- All investigated sites have been logged, photographed, and located with GPS.





The two tributary research areas. **A)** The Waingaromia area - lidar base map. **B)** The Mangamaia area - photogrammetric base map. **C)** Mangamaia stream profile. **D)** W-1 gravels and cover sequence above bedrock strath. **E)** Cover sequence on the W-1 terrace shown in D. The basal tephra is the ~17,500 cal. yr BP Rerewhakaaitu tephra.

Outline of project methods

Field
- Identify landslides by air photo interpretation and field mapping.
- Identify Waipaoa-1 terrace remnants and knickpoints by air photo interpretation and field mapping.

Timing
- Target only landslides that cut the Waipaoa-1 surface. Concentrate on upslope post glacial sedimentation.
- Investigate the timing of landslide activity with tephrochronology and C^{14} dates where possible.

Magnitude
- Use high resolution topography and GIS to produce a first-order volumetric estimate for the postglacial sediment delivered to the Waipaoa Sedimentary System from deep-seated landslides in the representative test areas (topographic reconstructions).
- Expand the first-order volumetric estimate in the representative test areas to the Waipaoa catchment as a whole.

Tephras that are probably present in the Waipaoa catchment

Tephra	Mid point of age range cal. yr BP	error +/-
Kaharoa	636	12
Taupo	1717	13
Waimihia	3410	40
Unit-K	5120	150
Whakatane	5530	60
Tuhua	7005	155
Mamaku	8005	45
Rotoma	9505	25
Opepe	10075	155
Poronui	11190	80
Karapiti	11410	190
Okupata	11620	190
Konini	11720	220
Waiohau	13635	165
Rotorua	15425	325
Rerewhakaaitu	17625	425
Okareka	21800	500
TeRere	25271	779
Kawakawa/Oruanui	27097	957
Unit L	31500	
Omataroa	32500	
Awakeri	32800	
Mangaone	33000	
Rotoehu	c.55000	

Kaipo Bog
~70 km, 235°
Lowe et al. 1999

Ages:
Lowe et al. 2008

Smith et al. 2005

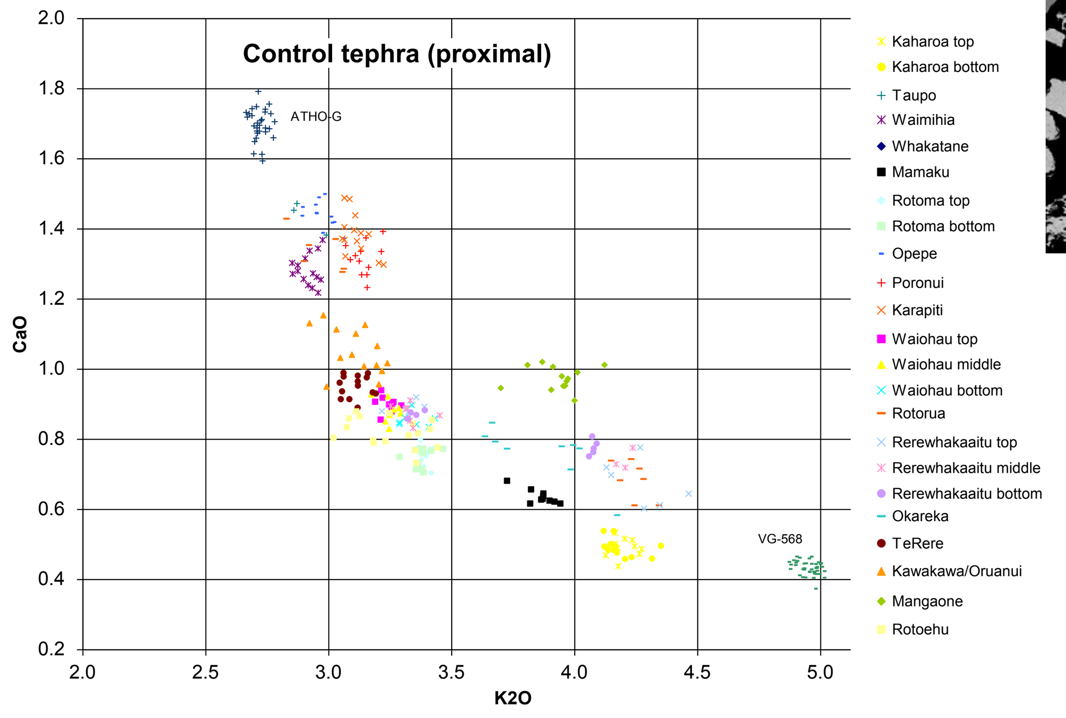
Tephrochronology

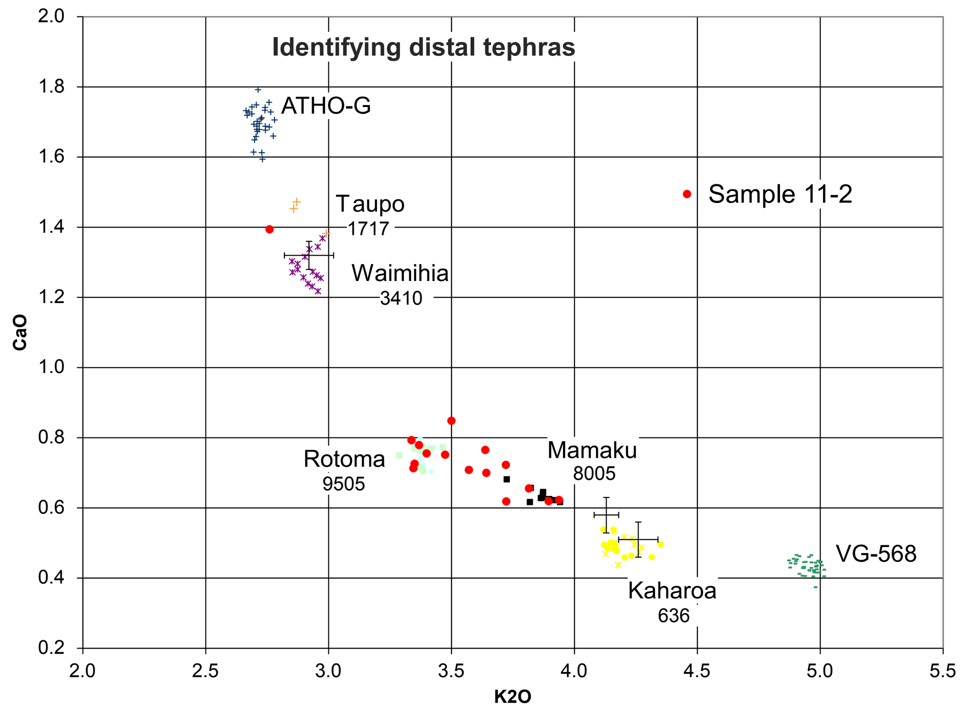
Many of the tephras are not distinguishable in the field by visual identification alone.

Tephras are identified by a combination of:

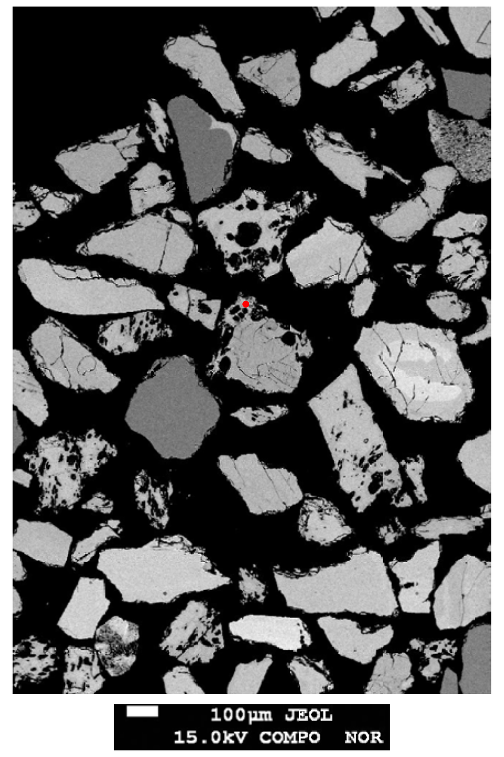
- stratigraphic position
- ferromagnesian mineral assemblage
- glass chemistry

Rerewhakaaitu to present.....
16 tephras?

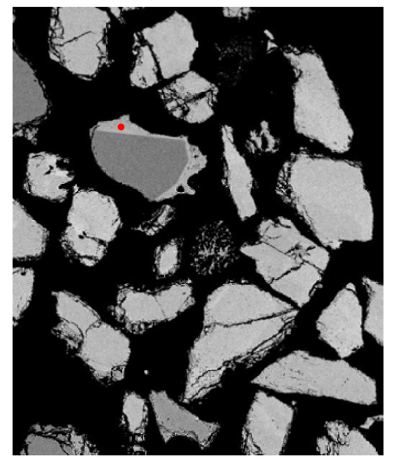




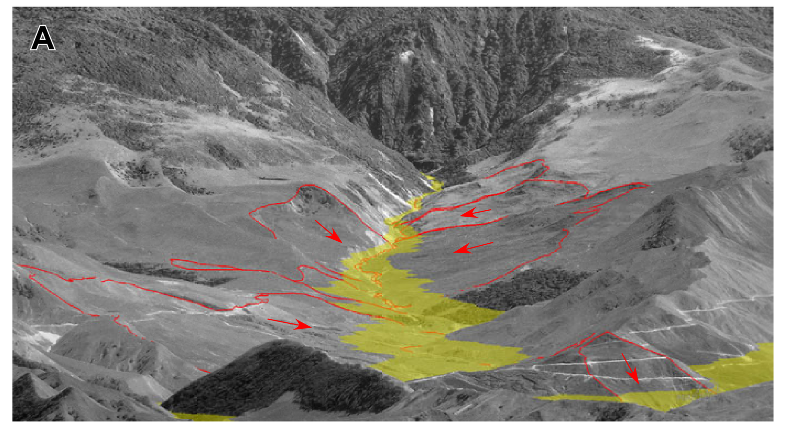
Tephra glass chemistry microanalysis completed on the Victoria University of Wellington JEOL JXA-8230 SuperProbe Electron Probe.

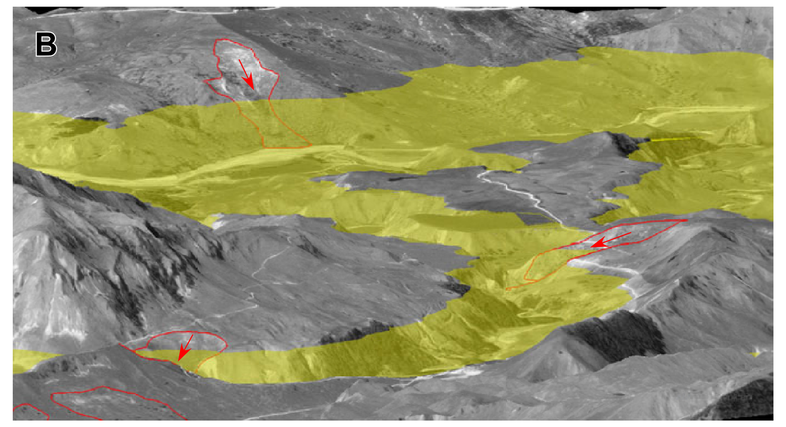


Electron probe microanalysis setup:
- Accelerator voltage: 15 kV
- Probe Current: 8 nA
- Spot size: 20 microns



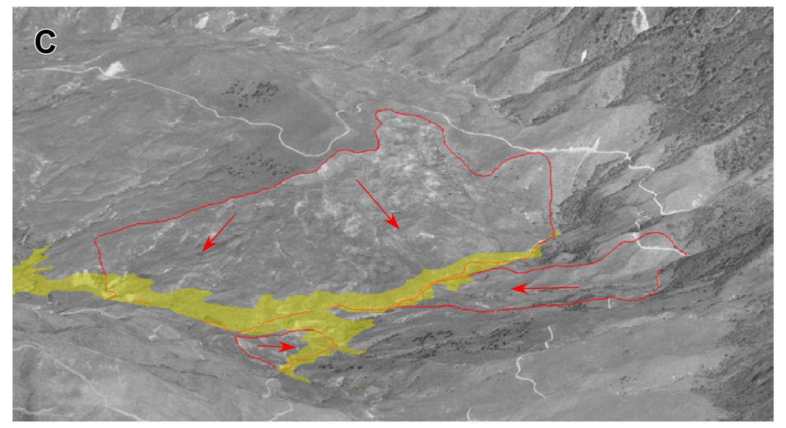
Analyses of tephra cover suggests that hillslope adjustment in the upper reaches of the Waipaoa started between the deposition of the ca. 13,600 yr BP Waiohau tephra and the ca. 9,500 yr BP Rotoma tephra. Tephra cover further shows that many slopes have continued to adjust to channel incision into the late Holocene.





- Deep-seated landslides
- Reconstructed Waipaoa-1 aggradation surface

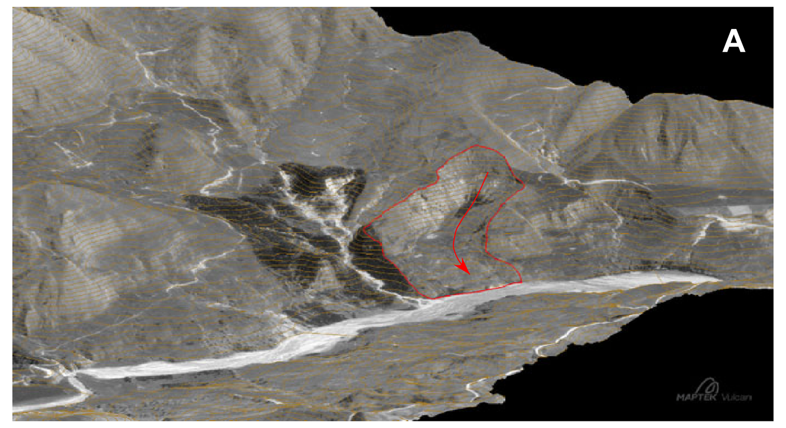
A, B, and C are orthophotography draped 5 m DTM images of the Mangamaia area showing landslides and the reconstructed Waipaoa-1 aggradation surface. **A)** View up the upper Mangapapa tributary. **B)** View down to the confluence of the Mangamaia tributary and the Mangatu River showing extensive Waipaoa-1 aggradation terraces. **C)** View of the upper Mangamaia tributary.

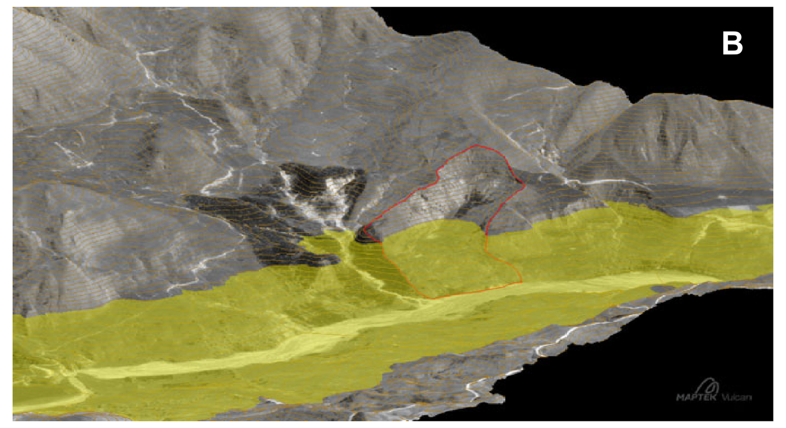


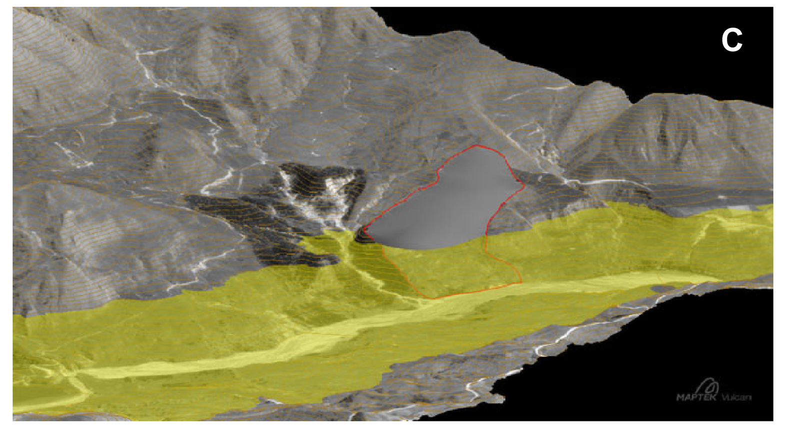
Magnitude

Recognized deep-seated landslides that are directly connected with the fluvial system comprise 20-35 percent of the surface area of the two sections under study. One mechanism for such widespread instability is removal of an effective hillslope toe buttress system by the widespread post-18 ka channel incision. Field work and mapping indicates that many of these large landslides are downstream of knickpoints in their respective tributaries and, based on tephra cover on landslide debris, have been active in the Holocene.

The software Maptek Vulcan™ 3-D was used for terrain modeling and the reconstruction of the Waipaoa-1 aggradation surface and will be instrumental in reconstructing pre-hillslope mass movement topography, calculating landslide-derived sediment volumes for the two tributary study areas, and modeling the evolution of the landscape through the last approximately 18 ka. The volume of sediment removed by channel incision in the two study areas is ~ 1.5 km^3.



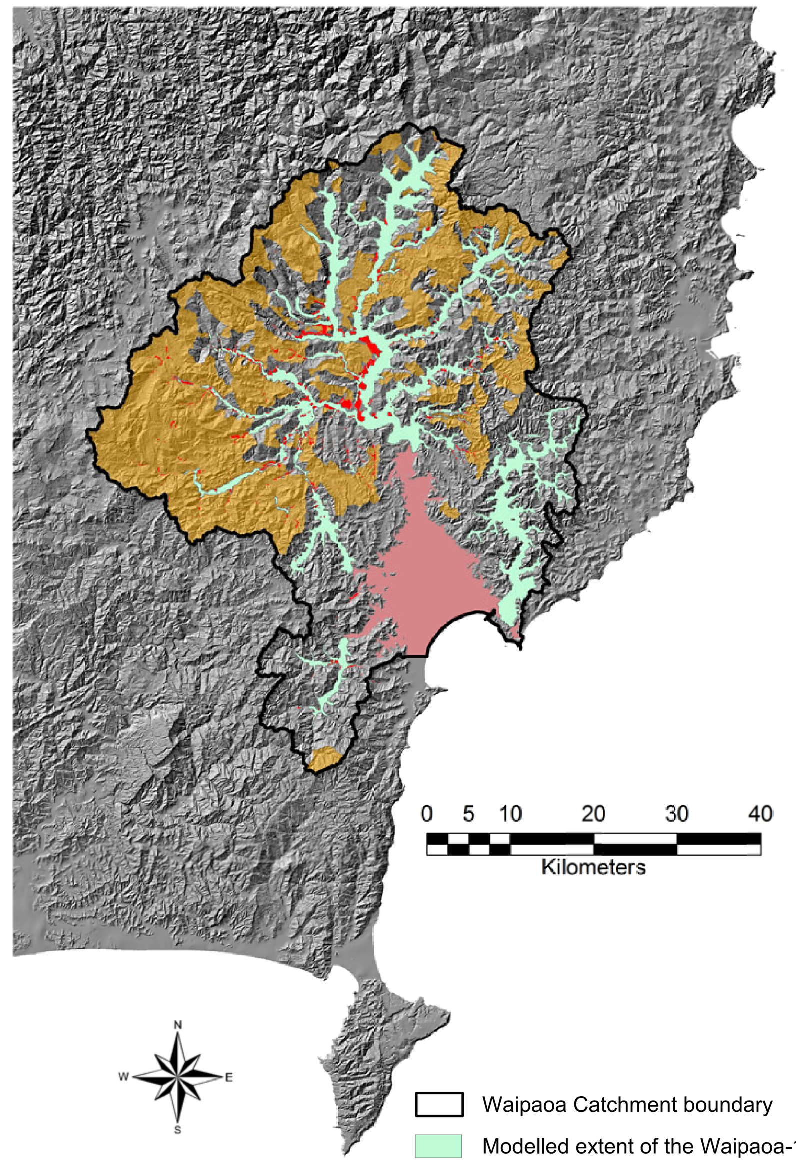




Paleotopographic Reconstructions

Using the results of the mapping and geomorphic age control it is possible to credibly reconstruct pre 18 ka paleotopography. The first step in the reconstruction is to model the pre 18 ka aggradation surface by using terrace remnants and base level controlled knickpoints as model control. The next step is to reconstruct pre- landslide hillslope topography using scarps and stable geomorphic features for control.

The figures above illustrate this process. The landslide mapped in **A** exhibits very little tephra cover anywhere on its scarps or body; however, outside the mapped scarp, tephra cover is over a meter thick. The slide clearly cuts across the Waipaoa-1 aggradation surface shown by the terrace remnant seen in the far right of the image. **B** shows the reconstructed Waipaoa-1 aggradation surface for this stretch of the Mangatu River using terrace remnants both upstream and downstream of the landslide. **C** shows the modeled pre-slide slope topography based on the morphology of the slope outside the scarp. In this case the volume for the portion of the landslide that is upslope from the aggradation surface is 7,228,080 m^3.



- Waipaoa Catchment boundary
- Modelled extent of the Waipaoa-1 surface from Marden et al., 2008
- Waipaoa-1 terraces from Marden et al., 2008
- Areas above significant knickpoints (Waipaoa-1 and/or Lithologic). Knickpoints from Crosby and Whipple, 2006.
- Poverty Flat

Discussion

Only ~25% of the total post 18 ka sediment yield for the Waipaoa Catchment can be accounted for by channel incision, one of the most widespread and most effective erosive processes in the catchment (Orpin et al., 2006; Marden et al., 2008). We find that deep-seated landslides, which are pervasive features, cannot make up this apparent source area sediment deficit. This presents a challenge to our current understanding of the Waipaoa Sedimentary System.

New high resolution topographic data sets (lidar and photogrammetry) combined with tephrochronology and field mapping have enabled us to approximate the sediment flux from post 18 ka deep-seated landslides. The sediment delivered to the offshore sink from these upper Waipaoa landslides is likely to be less than 20% of the sediment volume calculated for channel incision. A further GIS analysis of the ~2500 km2 Waipaoa catchment (**left**) taking into account previous work delineating relict topography (Crosby and Whipple, 2006) and accounting for river incision and slopes stabilized behind terrace remnants (Marden et al., 2008), indicates that only about half of the available catchment area could have contributed additional large volumes of sediment to the offshore post 18 ka sink. The presence of tephra older than 18 ka on landforms ranging from flat ridgelines to steep (>30 degree) slopes (**right**) in this remaining terrestrial source area suggests these landforms have not been eroded en masse. The apparent source deficit remains even with many of the major erosive processes considered and the source area with potential to contribute sediment effectively reduced.

This analysis raises questions about erosive processes and our ability to balance large scale sediment budgets. Does coastal erosion contribute a significant volume to the offshore sink? Was sediment from other catchments trapped in the Poverty Bay post-glacial shelf basin? Are the uncertainties in any of the source and sink calculations large enough to make the previous questions essentially irrelevant? We believe that it is an achievable goal to account for the major processes that generate sediment in the Waipaoa Sedimentary System and that this budget analysis can inform our understanding of active landscapes.

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