Study of the fluvial and environmental processes affected by the Calbuco eruption, April 2015

18th July -18th August 2016

Newcastle University

Alexandra McKee, Rebecca Leitch and Diana Luke

Abstract

The Calbuco Volcano is located in southern Chile in the Southern Volcanic Zone and until 2015, this volcano had not erupted for over 40 years. Prior eruptions have featured volcanic hazards such as lahars and pyroclastic flows. Both of which, have resulted from the 2015 eruption and as a result they have altered the fluvial, geomorphological and environmental processes. The main findings revolved around the possibility that the Rio Blanco Este cannot return to its pre-eruptive state, lahars are common feature of this environment and that topography has influenced the loses to vegetation.

Contents

Acknowledgements

Firstly, we wish to express our sincere thanks to The Royal Geographical Society (with IBG), The Jeremy Willson Charitable Trust, The Gilchrist Educational Trust and The Newcastle Expeditions Committee for supporting this project.

Our sincere thanks goes to Professor A. Iroumé from the Universidad Austral de Chile and his team from the Forestry Department, including Professor R. Batalla, Manuel Cartagena, Izzat Montero, Enrique Hipp, Guillermo Barrientos and Luisa Villablanca, who extended their generosity by providing equipment, laboratories for sediment analysis, transport to Valdivia and excellent conversation.

The kindness and hospitality of the Chilean people will never be forgotten, especially Nico and Alejandra, owners of the beautiful Quila Hostal. We were not only welcomed as guests, but as part of the family. We would like to extend my thanks to Rodrigo, transport operator extraordinaire, who projected his friendship and consideration through the language barrier. We are also grateful to Carolyn McCarthy and Richard Carrier for making us feel at home and showing us the beauty of the region.

Finally, we would like to take this opportunity to express my gratitude to all the Geography Department faculty members for their help and support, and for providing me with all the necessary facilities for the research, especially Professor A. Russell, Dr S. Dunning, Dr R. Carr, Dr M. Perks and Professor A. Nayak, as well as the Physical Geography Technicians.

1. Introduction

Despite being one of the most active volcanoes in Chile the Calbuco volcano was not actively being monitored prior to the eruption in 2015. One of the main reasons this opportunity came about was as a result of Professor Russell undertaking research at the Calbuco Volcano. This research related to post-eruption contemporary data both primary and secondary and involved several field visits to the location. As this data was available for us to use, it gave us the unique opportunity to study the fluvial and environmental processes affected by the Calbuco eruption along the Rio Blanco-Este.

We had three main objectives. Firstly, analysing the geomorphic change of the Rio Blanco Este and determining whether the river would return to its pre-eruptive state. This was done using secondary data such as aerial imagery and primary data regarding clast size and primary surveys.

The next objective was to understand lahar activity and chronology by logging individual columns along the western bank of the Rio Blanco where lateral units were recognised and characterised according to different parameters (sorting, roundness and colour). Grain size distribution was also carried out from samples collected in order to understand flow behaviour and rheology.

The last objective was to analyse the impact of volcanic disturbance (lahars and pyroclastic flows) on vegetation and topography using Digital Elevation Models (DEMs), aerial imagery, GPS points and bark removal data as well as comparing photographs.

Swanson *et al.* (2013) discussed volcanic and hydrologic processes on forest vegetation in relation to a nearby volcano. This study was useful as it linked all the objectives and various processes together. Therefore, this could be used to compare with Calbuco. Furthermore, Pierson (2004) also provided insight into the mechanics of a lahar type flow, which helped determine what kind of flow the lahar was.

1.1. The April 2015 Calbuco Eruption

On 23nd April 2015, the Calbuco volcano erupted with the ash cloud reaching some parts of Argentina (Romero *et al*., 2016). According to Castruccio *et al.* (2016), the eruption involved two sub-Plinian stages, where pyroclastic density currents travelled 6km away from the source on most of the flanks as well as ash columns that reached over 15km in height. Furthermore, lahars both primary and secondary occurred on the south, northern and north eastern flanks of the volcano both during and after the eruptions (Castruccio *et al.*, 2016; Reckziegel *et al*., 2016). Therefore, this is similar to the volcanic products from previous eruptions.

2. Methods

2.1. Study Site

Figure 1 identifies the different types of volcanic products produced as a result of the 2015 Calbuco eruption and the location they affected. The fallout deposit resulting from the ash cloud, travelled north-eastwards, therefore effecting the area surrounding the Rio Blanco-Este. The eruption caused pyroclastic flows to form down all river catchments. However, the pyroclastic flows that occurred in the Rio Blanco-Frio Valley travelled the furthest. As a result, the Pyroclastic flow reached the upper site which is just over 5km away from the summit. However, the pyroclastic flow did not reach the lower site which is nearly 9km away. Lahars on the other hand affected both sites and unlike the pyroclastic flows reached the mouth of the river catchments. Similarly, to the pyroclastic flows, they effected all river catchments surrounding the volcano.

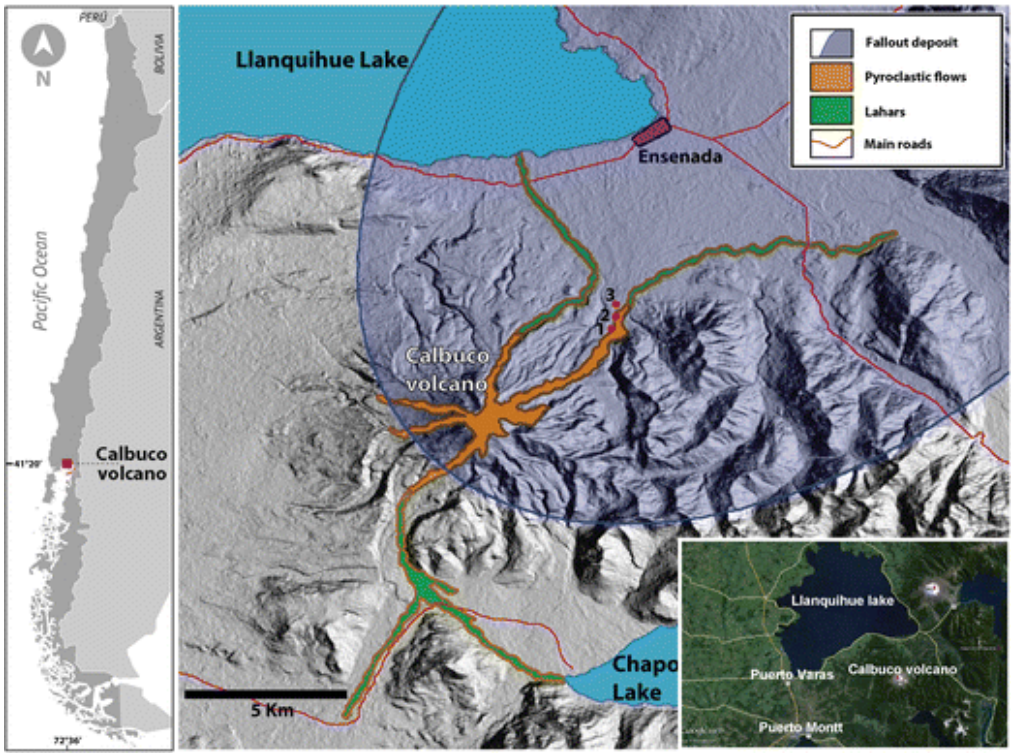

Figure 1	*Distribution of lahars, Pyroclastic flows and fallout deposit as a result of the eruption. Yellow circle represents the location of the upper site and the red circle represents the location of the lower site (adapted from Castruccio* et al.*, 2016).*

2.2. 1st Objective

The satellite imagery from a number of sources was imported into a GIS software programme, called QGIS, which allowed a time-series of geomorphic maps to be created. From these maps, a number of deductions could be made, such as rates of sedimentation and erosion, linking these to causes, such as rainfall, snowmelt or logjams, and which site sustained the most damage.

Several Digital Elevation Models (DEMs) were layered in QGIS, then several cross profiles were created to understand the elevation changes since the eruption.

A chronology of geomorphic events since the eruption was created using photographs from the study sites, satellite imagery and DEMs.

To understand the timing and effects of the volcanic processes, several facies were identified at each study site, then stratigraphic columns were completed.

Secondary information from the Chilean meteorological department provided monthly and daily rainfall values for the study period (April 2015 – Aug 2016).

2.3. 2nd Objective

A handheld GPS device was used to obtain the coordinates of prominent features and geomorphic landforms in the landscape, i.e. the active river channel, river banks and rock fall tallus', boulder clusters etc., at both proximal and distal reaches of the Rio Blanco Este. These were imported into QGIS software where 300m (approx.) stretches of the channel were delineated and a range of features and landforms were digitised. A systematic sampling technique was employed to choose sites for sedimentological analysis, by using a fixed interval of approximately 100 m between each site at both stretches, resulting in a total of four sites. Additional tools in QGIS allowed for the extraction of elevation profiles and topographical analysis from several Digital Elevation Models (DEMs).

Random large clasts deposited at the base of the river banks were selected along each stretch and measurements of the 3 main axes (a-, b-, c-) were taken. This allowed identification of volcanically derived- or fluvial derived- clasts to further assess the depositional environment.

A total of eight columns were selected across both locations for sedimentological logging, closely following the format outlined by Tucker (2009). Working from the base upwards, layers of strata were identified and characterised laterally based on several observations (e.g. matrix composition, clast size,

roundness/sharpness, colour, etc.) Detailed hand-drawn versions of these logs were constructed directly from photographs taken in the field. These were scanned into the drawing package CorelDraw Photopaint and converted from bitmaps into 'line art'.

Samples of the finer grained matrix were collected at each stratigraphic column analysed and were dried out in the laboratory. Each sample was weighed to approximately 200g, before being emptied into a stack of thirteen sieves, with aperture sizes ranging from 63 – 20000 microns. Using both lateral and vertical motion, the sieves were manually agitated to keep the sample moving continuously over the surface. The results were processed using Microsoft Excel and the computer program GRADISTAT (Version 4.0) to present cumulative plots for each sample, on a base-10 logarithmic scale.

2.4. 3rd objective

The height of bark removal on trees were measured using a tape measure to assess the damage to vegetation in relation to their proximity to the current river channel. GPS points were taken to record the vegetation boundary in 2016 at both sites on the northern side. This was done by following the vegetation limit and recording GPS points every 30m. The southern side could not be reached as the river flow was to rapid, therefore vegetation boundary on this side was done via secondary data. The river location was also mapped using GPS points at both sites, therefore this could be used to compare 2016 location with the years previously to help assess whether river location has altered the distribution of vegetation.

Secondary data was mainly sourced from Google Earth, particularly for satellite imagery prior to 2015. Data regarding topography was gathered using LiDAR imagery where a map of relief was then created for both sites using QGIS. This was to compare the topography at both sites. Furthermore, Digital Elevation Models (DEMs) from the US Embassy and the Lidar data were used to compare topographical changes before and after the eruption.

3. Results

3.1. 1st Objective

Figure 2 shows how the Rio Blanco Este has changed at Site 2 over more than a year after the eruption. The river, which was very widespread in July 2015 and covered the entire floodplain, became very subdued by a year later, diverting water from the outer bank to an inner channel. A month later, there was again more water in the outer channel, before joining to the main channel again. In July 2015, the top of a house is visible although not a year later.

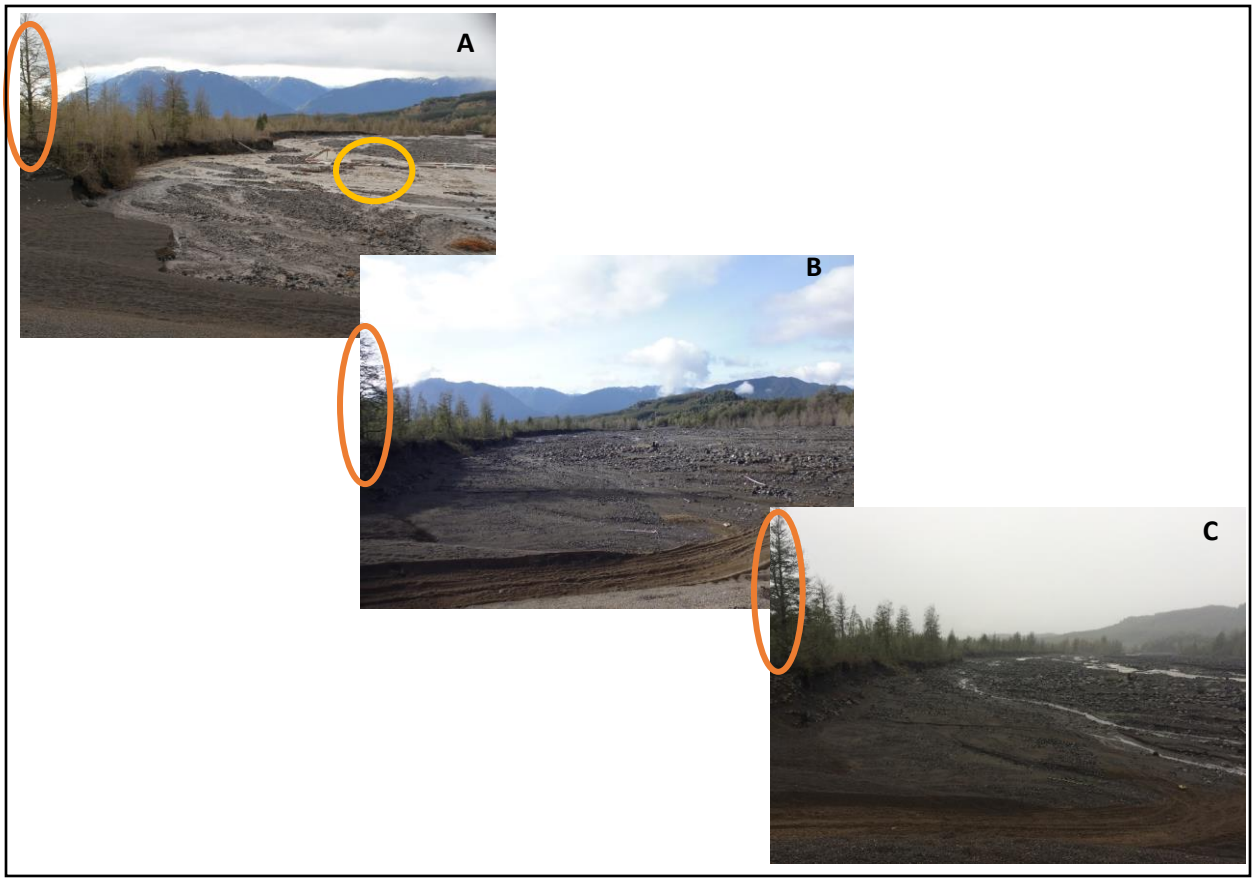

Figure 2 *Photographs of Site 2 taken on: A) July 2015; B) July 2016; C) August 2016.*

Average rock size is 32.7cm and 19.1cm at Site 1 and 2 respectively (Fig. 3) At Site 1, the rock size does not alter with distance from the eruptive centre, however average rock size decreased with distance from the eruptive centre at Site 2.

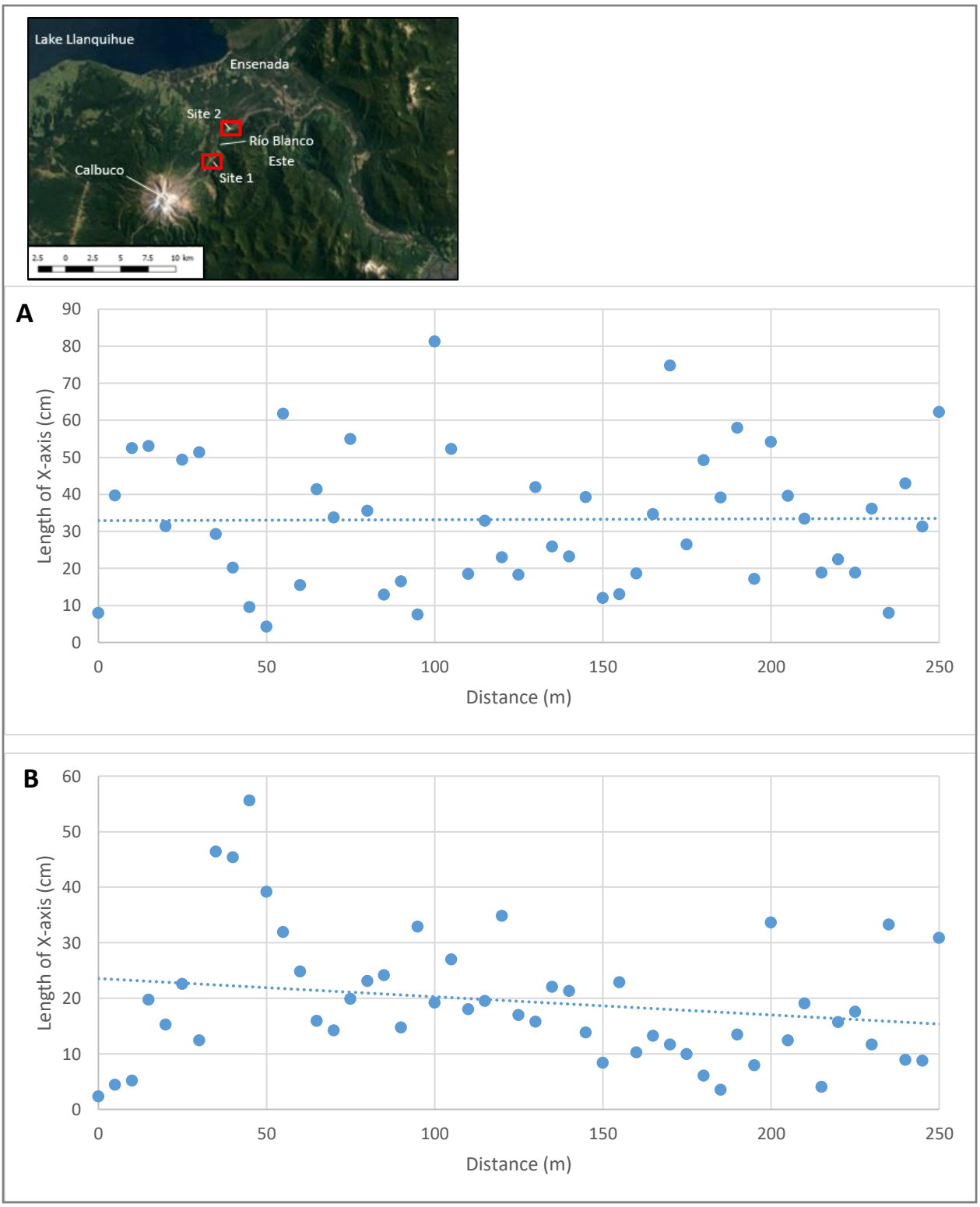

Figure 3 *Rock size averages plotted against increasing distance from the eruptive centre at: A) Site 1; and B) Site 2. The inset map shows the location of the study sites in relation to each other.*

Between March 2015 to November 2016, the elevation at Site 1 has decreased below pre-eruptive levels (Fig. 4.1). The profiles display increasing elevation values as distance from the eruptive centre increases.

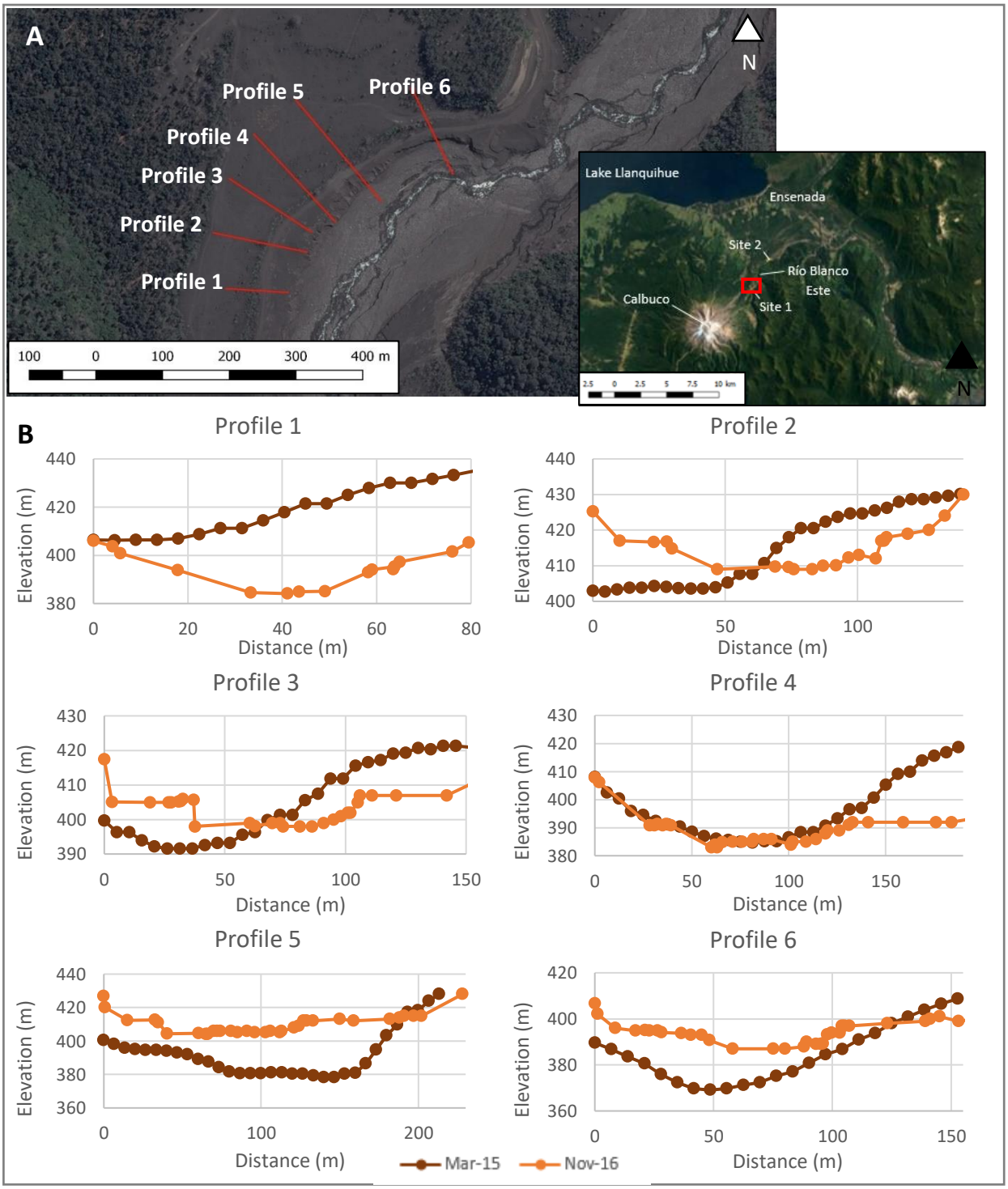

Figure 4.1 *A) Map of cross-profiles at Site 1 (inset shows location of Site 1); B) Cross-profiles showing elevation change. USA Embassy DEM provided the March 2015 data (primary axis), handheld laser range finder provided the November 2016 data (credited to Professor A. Russell).*

Sixteen months following the eruption, elevation at Site 2 has increased above pre-eruptive levels by an average of 10m (Fig. 4.2).

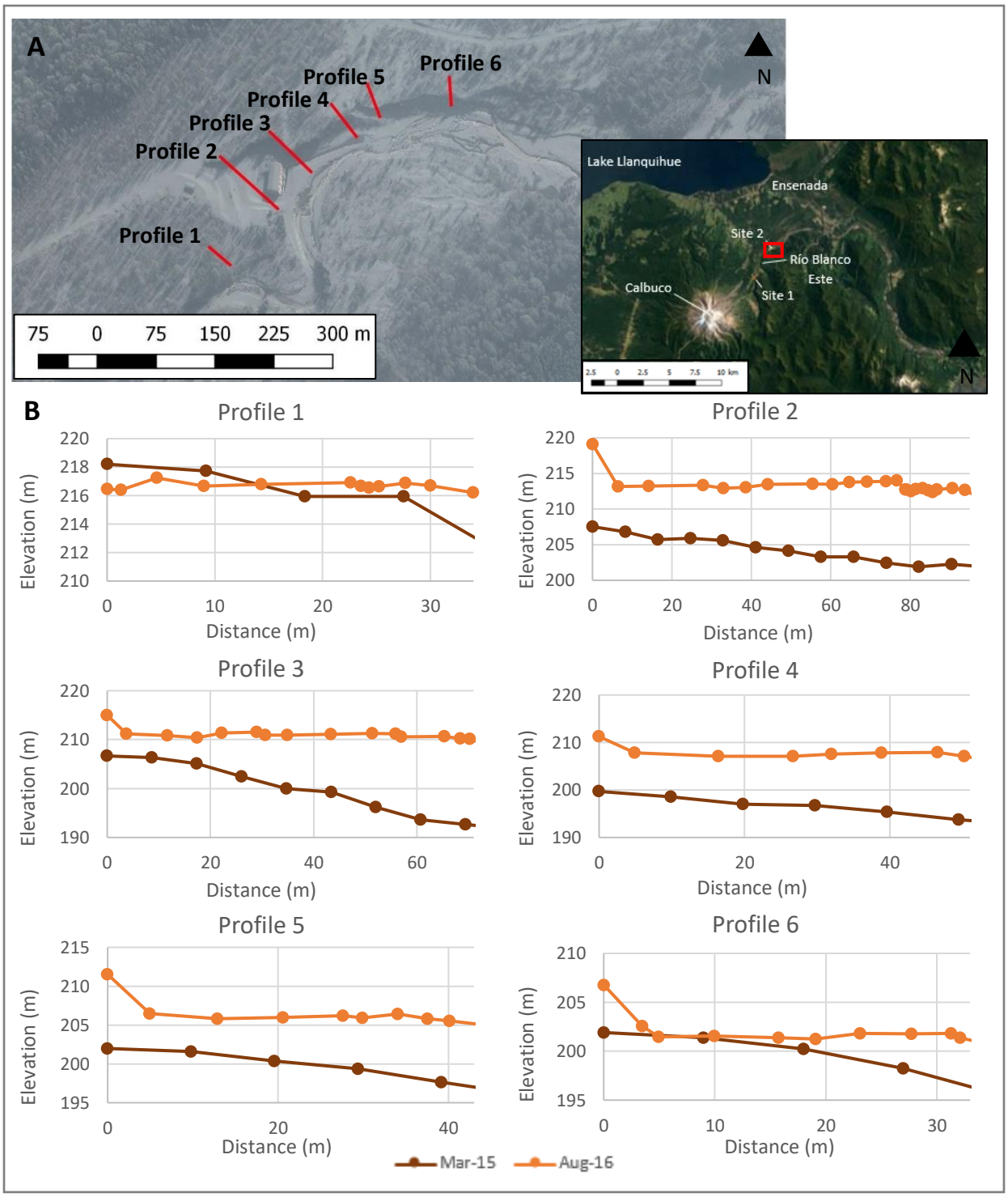

Figure 4.2 *A) Map of cross-profiles (inset shows location of Site 2); B) Cross-profiles of Site 2 showing elevation change. USA Embassy DEM provided the March 2015 data, Trimble R2 dGPS provided the August 2016 data.*

3.2. 2nd Objective

Figure 5 is a geomorphological representation of the three sites that were selected at the upper Rio Blanco Este valley (one site was discarded due to lack of stratigraphy present in bank). Unstable banks that measured heights of ~12 m on average were evident, which were prone to significant amounts of slumping. A series of unconsolidated terraces consisting of very poorly sorted, coarse gravel, sand and various boulder sizes are present in this upper area. These displayed surficial streamlined boulder clusters and flow marks, indicating previous palaeo-channels. Whilst most deposits are unconsolidated and therefore subject to remobilisation and burial by fluvial activity, large and supported blocks were also abundant across these terraces. This is suggestive that this is an environment subject to sudden changes in discharge and the channel will respond by abruptly avulsing.

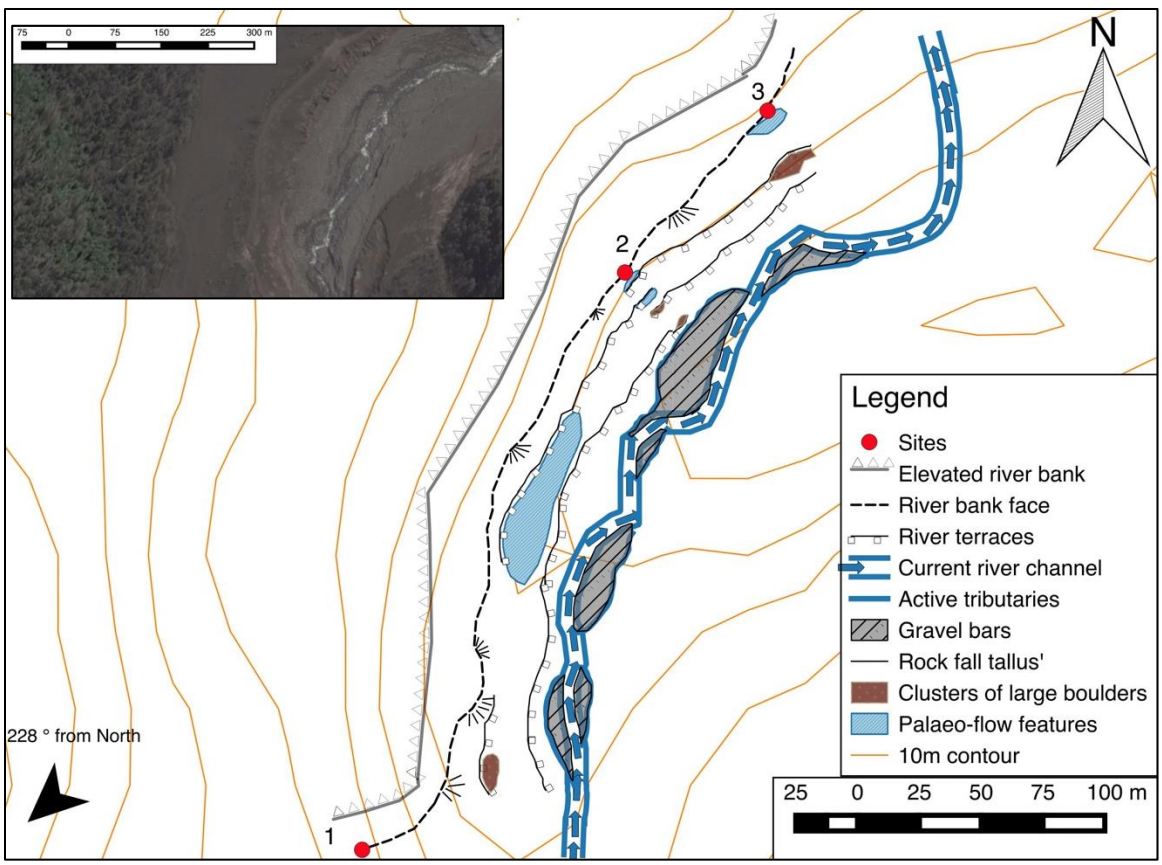

Figure 5	*Geomorphological map created from GPS data collected from the field during the period 20/08/16 – 12/09/16. Inset; screen grab of Google Satellite imagery of the area. Includes N bearing to Calbuco crater.*

(a) **(b)**

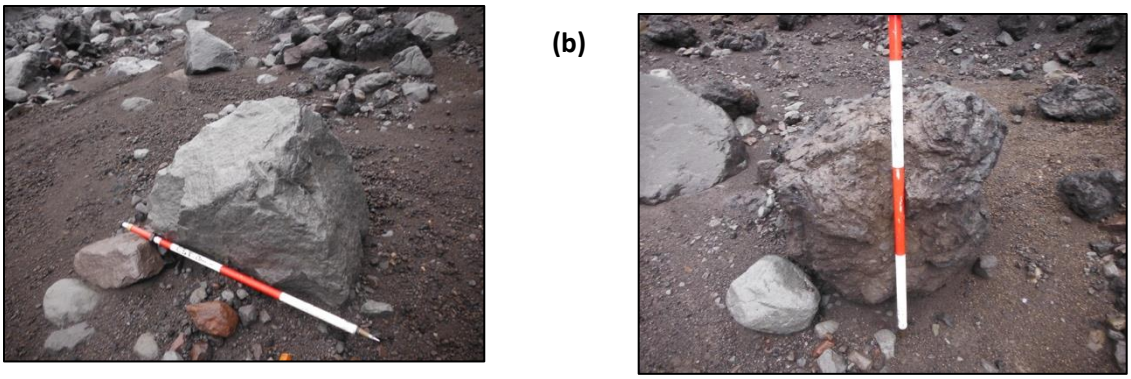

Figure 6	*Large boulders identified at the upper Rio Blanco Este. (a) light-grey angular boulder, fluvial-originated, partially buried by finer sediment. a-axis measured ~1161 mm. (b) dark-grey/brown dense spherical bomb; c-axis measured ~745 mm, more rounded shape.*

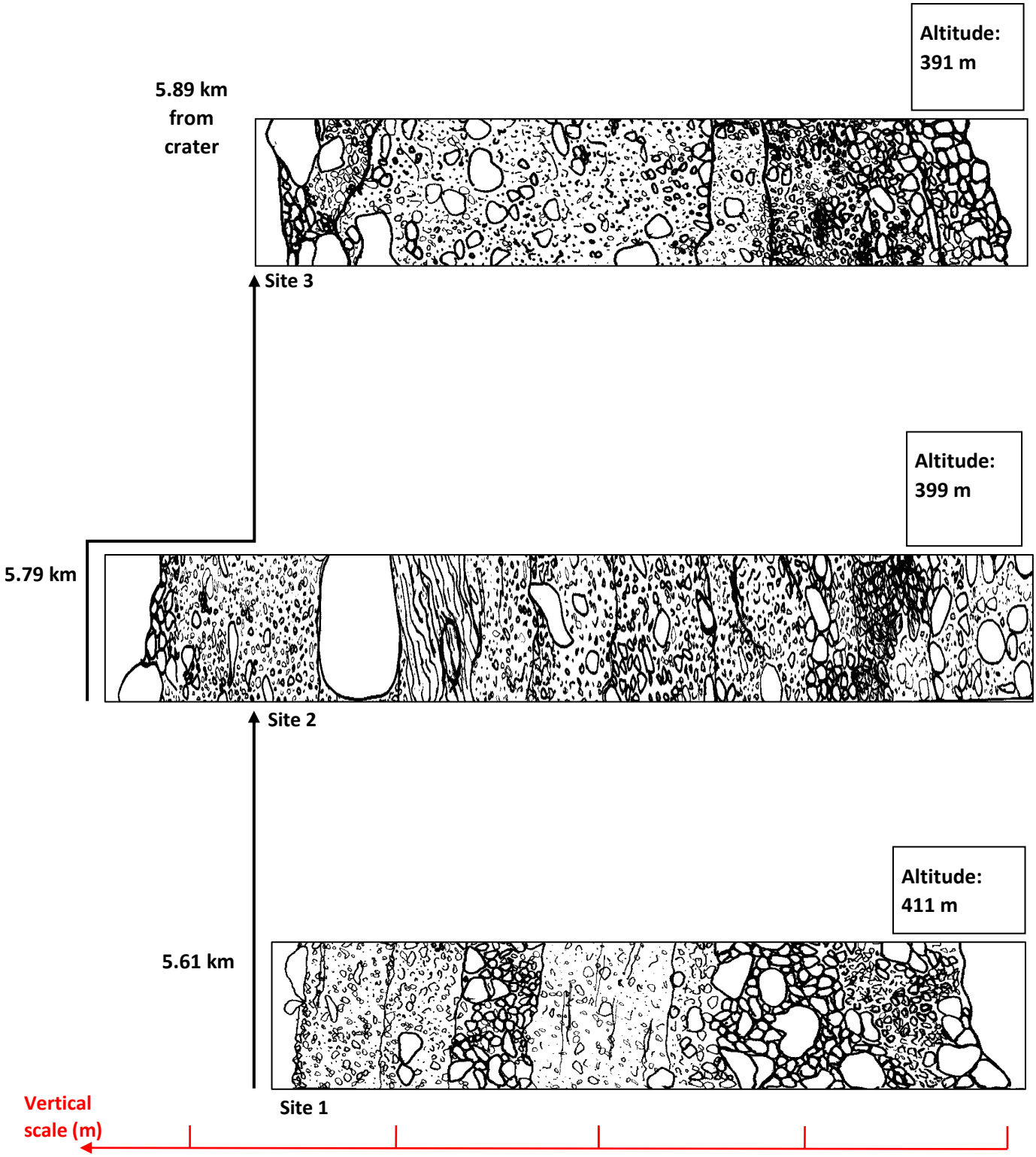

Figure 7 *Stratigraphic sketches of deposits from Site 1, 2 and 3 at their respective distances from the crater source and height above sea level.*

3.3. 3rd Objective

Figure 8 identifies the topography at both sites, whereby 10m contour lines emphasize the change in height. This is in order to analyse whether the topography at both sites would have had an influence on how vegetation was affected by the eruption. The contours are spread further apart at the lower site, indicating that this section is gently sloping downstream with a 30m drop from the top of the site to the bottom. Furthermore, the floodplain at its widest is in excess of 300m. The upper site on the other hand has a much steeper topography either side of the river as the contours are much closer together. Furthermore, the downstream gradient is also steeper and the floodplain is only 200m wide. Therefore, there are contrasts between topography at both sites.

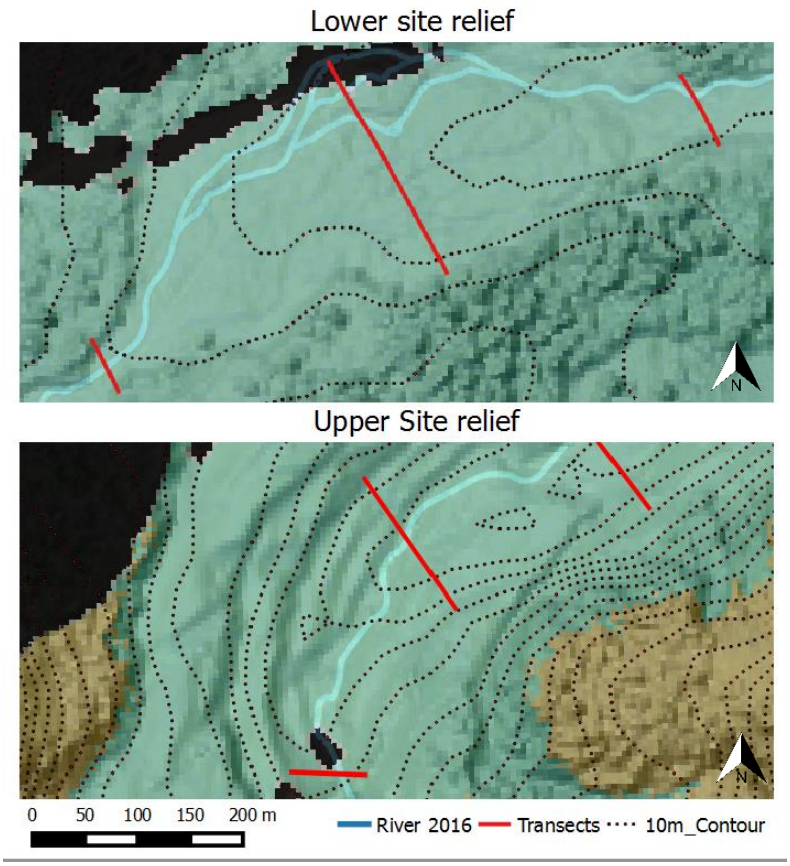

Figure 8	*Comparing the relief at the lower and upper site using LiDAR imagery (2016). Location of cross sections (from left to right: 1, 2 and 3). to analyse the topographical changes post eruption are identified.*

In figure 9, the changes in topography between 2015 and 2016 are analysed. In order to see how the topography was affected as a result of the eruption and how this may reflect the distribution of vegetation. After analysis of the Digital Elevation Models from 2015 and 2016, it is evident that both sites have increased in height. However, the Upper site has areas with an increase in height of 20m whereas the lower site has areas which have increased by 10m at the most.

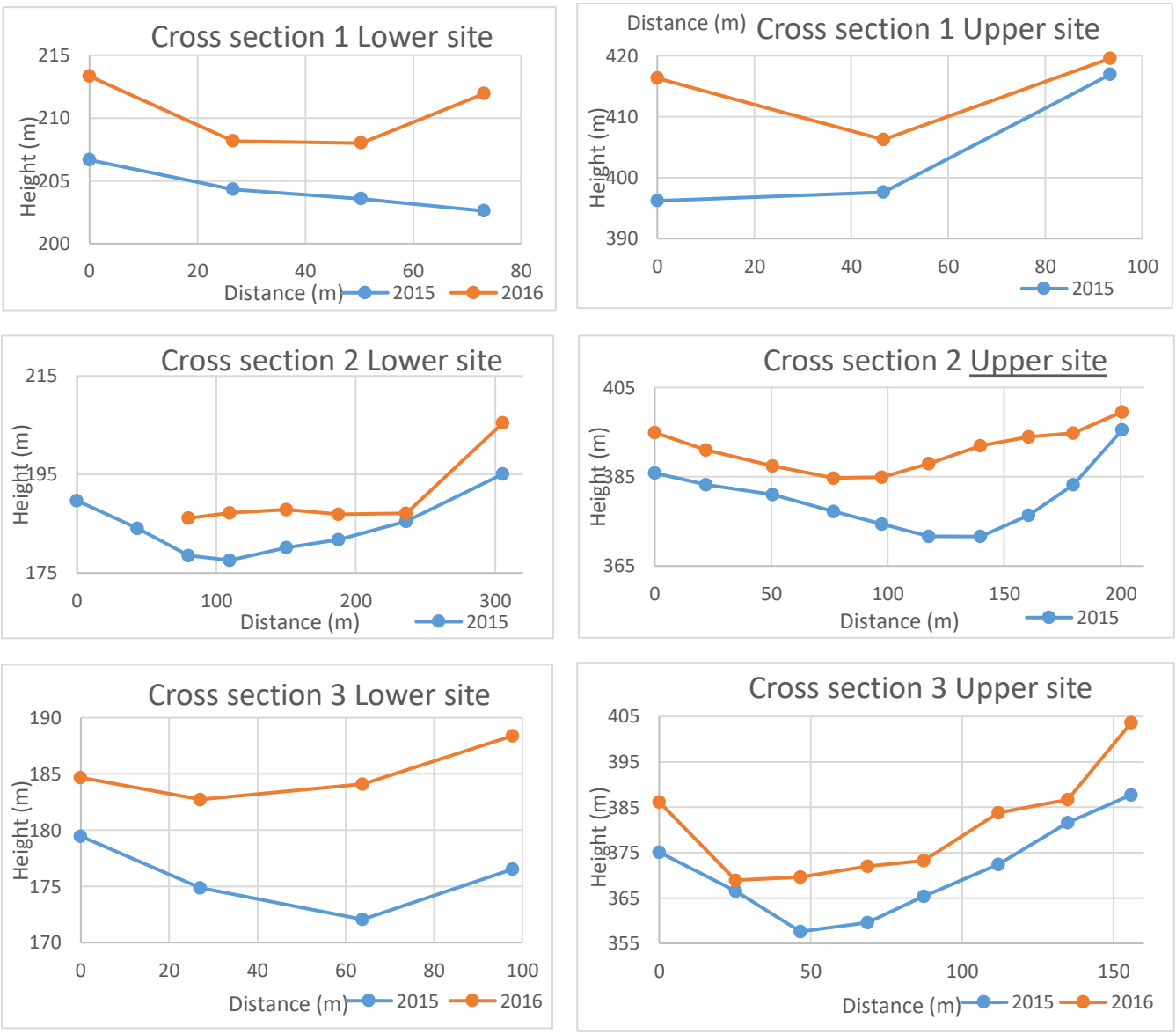

Figure 9	*Cross sections of the transects identified in figure 2.A DEM from the US Embassy is used to analyse the elevation in 2015 and LIDAR data is used to analyse the elevation in 2016. (USA Embassy DEM, 2016; Lidar, 2016).*

Figure 10 and 11 identify the regions at the upper and lower site where vegetation has been lost between 2015 and 2016. The vegetation boundary at the lower site has altered much more between 2015 and 2016 than at the upper site.

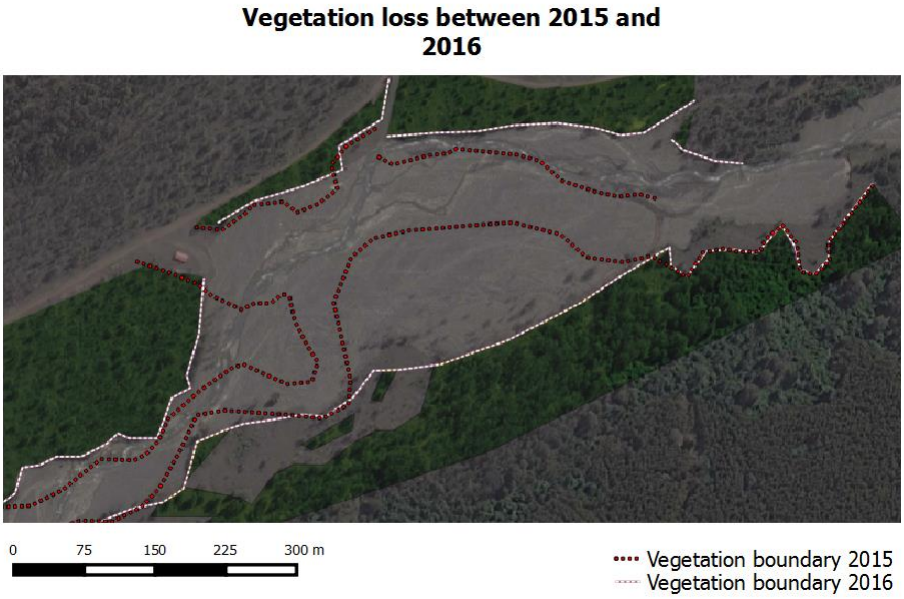

Figure 10	*Vegetation loss at lower site (Google Earth, 2016). © 2015 Google Inc, used with permission. Google and the Google logo are registered trademarks of Google Inc. ©2016 DigitalGlobe.*

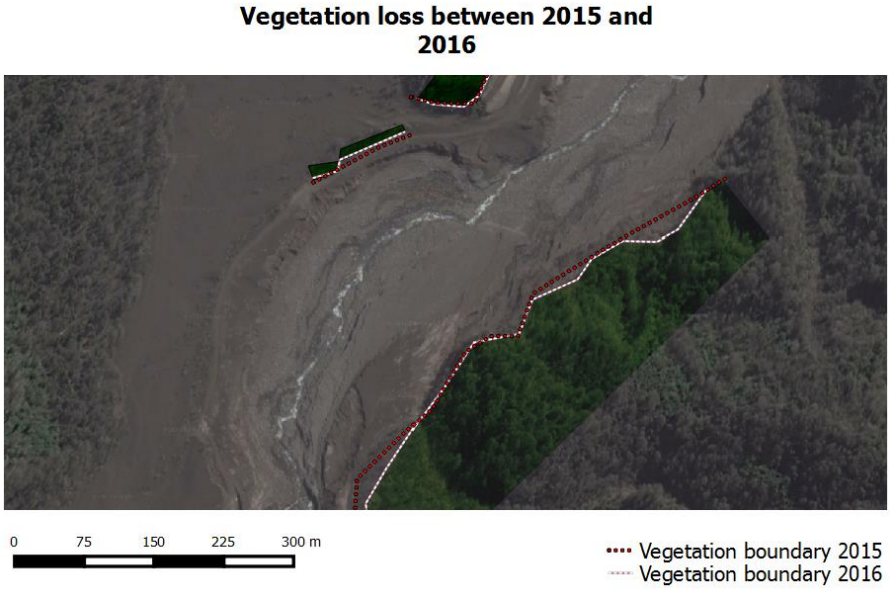

Figure 11	*Vegetation loss at upper site (Google Earth, 2016a). © 2015 Google Inc, used with permission. Google and the Google logo are registered trademarks of Google Inc. ©2016 DigitalGlobe*

In relation to the amount of vegetation loss figure 12 and 13 show the extent to which the vegetation has been affected at both sites. In figure 12, the northern side of the river in 2015 has only 39% of vegetation remaining at the lower site and only 6% at the upper site in relation to the amount of vegetation in 2014. In 2016, further reductions occurred as only 25.5% remained at the lower site and only 4.7% at the upper site.

In figure 13, the southern side of the river in 2015 had only 39% and 26% of the vegetation remaining at the lower site and upper site from the 2014 values. In 2016 a further reduction meant only 27.6% and 23.8% of vegetation is remaining from the 2014 values at the lower and upper sites. Therefore, these figures identify that the main changes to vegetation loss at the upper site occur immediately after the eruption in 2015. However, at the lower site, there are big losses to vegetation after the eruption in 2015, but there are continuing changes between 2015 and 2016.

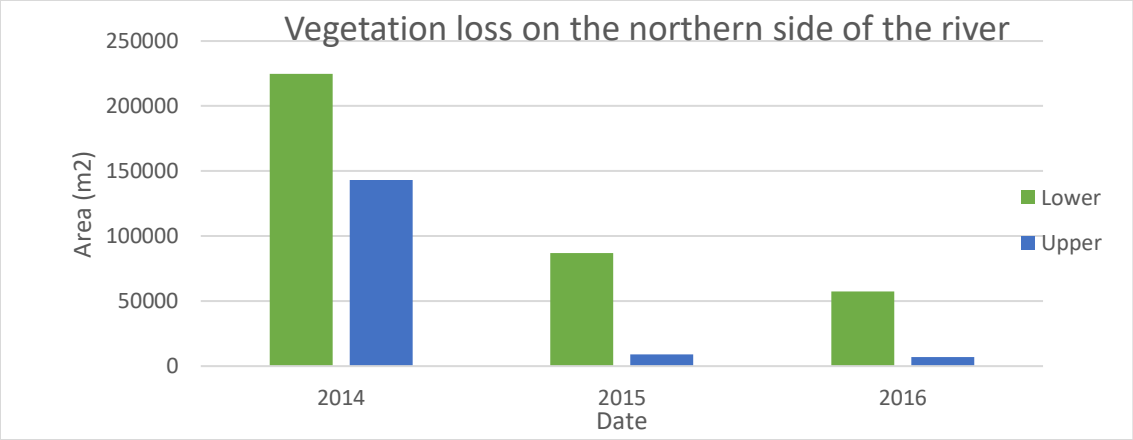

Figure 12 *Vegetation loss from northern side of the lower and upper sites.*

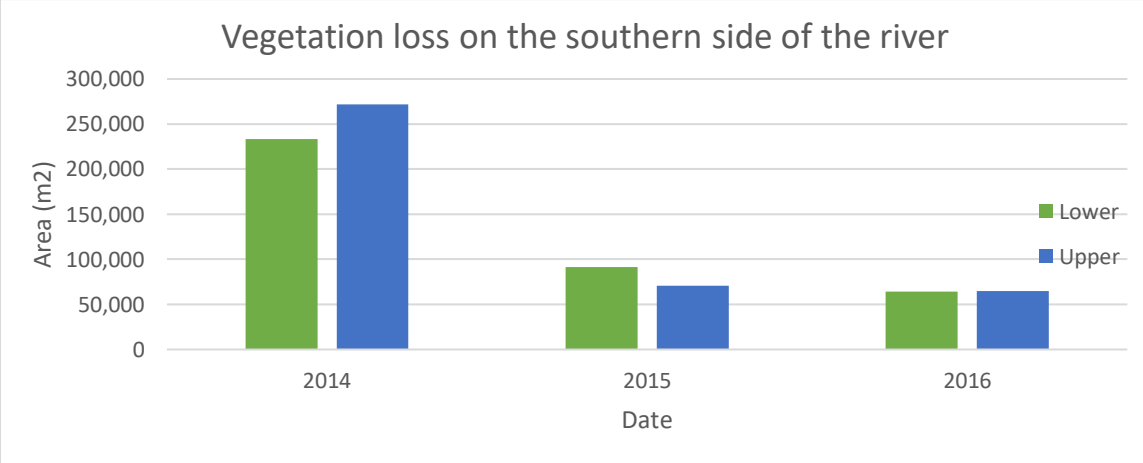

Figure 13 *Vegetation loss from the southern side of the lower and the upper sites.*

The lower site featured some vegetation that remained standing unlike at the upper site, where no vegetation remained up to 100m away from the river channel. Subsequently, this vegetation featured evidence of erosion as a result of the lahars, where the height could then be measured. This can be seen in figures 14 and 15, whereby 15 identifies the relationship between bark removal and the proximity to the river channel.

Figure 14 *Bark removal at lower site.*

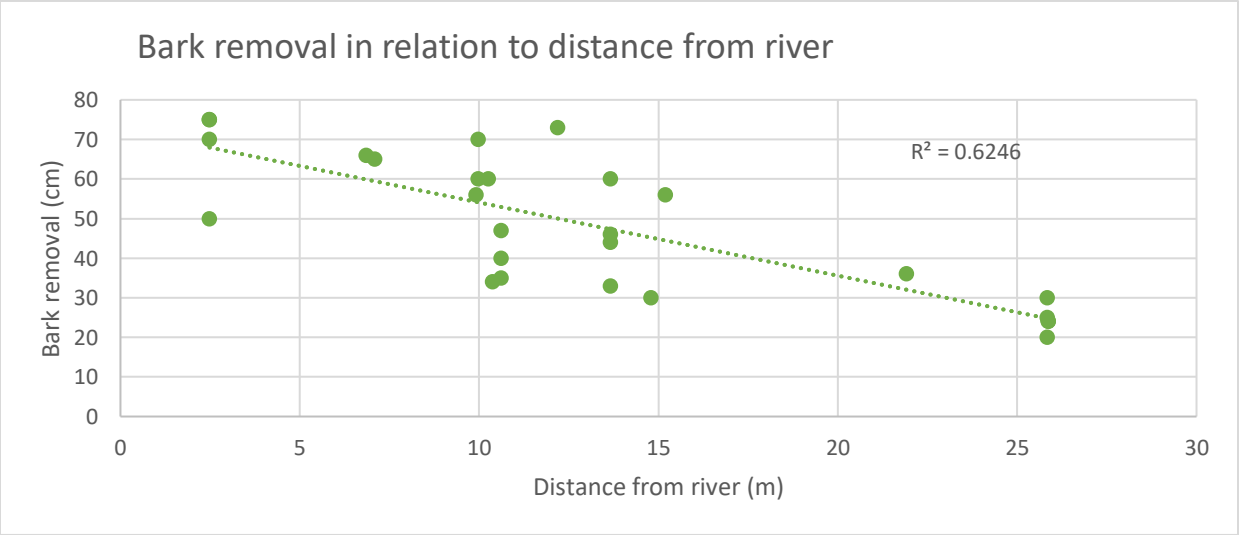

Figure 15 *Bark removal and distance from river.*

4. Discussion

4.1. 1st Objective

It can be shown that extreme geomorphological change has occurred at Site 2 as over 12m of sediment was added to the site since March 2015. While Site 1 was temporarily buried by pyroclastic and lahar flows during and immediately after the eruption, Site 2 was not severely altered until several months post-eruption. The increase in elevation, which inundated a small house (Fig. 2), was caused by the fluvial processes that dominate mountainous areas. These processes have been identified by Pierson *et al*. (2011) to be more geomorphologically important than lahars, causing extreme changes further downstream than lahar extent.

Site 1 is exhibiting signs of fluvial recovery ~18 months after the April 2015 eruption. Within 1m of the active river channel, average rock size is 32.7cm at Site 1 compared to 19.1cm at Site 2 (Fig. 3). The river channel is still highly changeable, however, as Figure 24.1 shows the series of channel planform change between July – August 2016. Bed armouring is a product of selective transport which allows finer volcaniclastic sediment to be transported downstream, leaving coarser rocks and boulders behind (Gran and Montgomery, 2005). The larger clasts resist incision better than finer-grained material, so the river cannot remobilise volcaniclastic sediment beneath the clasts. Therefore, bed armouring stabilises the channel and promotes fluvial recovery. At Mount Pinatubo, bed armouring occurred during the first dry season following the eruption and eventually developed a year-round armour, which reduced the sediment yield downstream (Gran and Montgomery, 2005). Despite this indication of fluvial recovery of the Río Blanco Este, Pierson and Major (2014) warn that the appearance of several isolated features does not confirm that a fluvial system is recovering from a volcanic eruption.

The Calbuco eruption ejected large quantities of volcaniclastic sediment onto the surrounding landscape (Fig. 4.1 and 4.2) which triggered severe geomorphological and fluvial adjustment in the affected drainage basin (Gob *et al*., 2016; Major *et al*., 2000). Between April 2015 and November 2016, elevations at Site 1 decreased below pre-eruption levels (Fig. 4.1), while at Site 2, elevation increased above pre-eruption levels (Fig. 4.2). The elevation fluctuation portrays the fluvial regime at a given time and illustrates how the system is adjusting to the major influx of sediment (Pierson and Major, 2014). An increase in elevation indicates that the hydrological system is deficient in the energy required to transport the volcaniclastic material downstream, while a decrease in elevation indicates that the system has excess energy to incise into the banks (Gran and Montgomery, 2005). Zheng *et al.* (2014) suggested that the pattern of

degradation upstream and aggradation downstream is typical behaviour of fluvial systems which have been disturbed by large influxes of sediment, indicating that the Río Blanco Este is responding normally to major sediment input following an eruption.

4.2. 2nd Objective

The stratigraphic sketches for Site 1, 2 and 3 are displayed in Figure 7 with their relative distances from Calbuco's crater and elevation height from the floodplain level, therefore providing an illustration of the variation in grain sizes and sedimentary patterns of deposits along this stretch of river. Across all sites, the deposits display evidence of several features that indicate a lahar flow source, as outlined by Pierson (2004). Most of the lower units were indistinguishable stratigraphically due to fine layers of sand/silty material covering the surface of the deposits, which is indicative of the cohesive solid-fluid mixtures of a debris-flow phase (Middleton & Hampton, 1973; Scott et al., 1995; Vallance & Scott, 1997; Vallance & Iverson, 2015). Both normal- and inverse- grading is apparent within the horizontal layers displayed in Figure 7, which is an additional characteristic feature of debris-flow deposits, as originally proposed by Pierson & Scott's (1995) analysis following the 1982 eruption of Mount St. Helens. Individual clasts show great variation in size and display a random orientation as they are supported within the matrix.

All the deposits belong to the same textural group of 'Sandy Gravel', however they show internal variation in further sediment classification between 'Sandy Fine-'and 'Sandy Coarse Gravel' groups. Patterns of very poorly to poorly sorted were deduced from graphic standard deviation values for all samples at the proximal sites. These patterns can also clearly be observed in Figure 3 when visually compared to a sorting classification diagram. Most of the samples exhibit a trimodal distribution of grain-sizes, with very high concentrations of Gravel and Sand concentrations and lesser of Silt and Clay concentrations.

Similar undulating patterns can be observed across most of the samples, with a gradual incline in mass retained at the larger sieve sizes (20000 – 4000 µm), followed by a small plateau for the intermediate sieve sizes (2000 - 1000 µm), immediately followed by steeper inclines for the smaller sieve sizes (425 – 63 µm). All samples, except for Sample 4 (from Site 3), had 10% or less of their total mass retained at the largest sieve size of 20000 µm (or 20 mm). This suggests that the deposits collected in Sample 4 have a higher proportion of gravel-sized clasts, per Wentworth's (1922) size classes.

GRADISTAT-derived values of 'Skewness' and 'Kurtosis', which are both examples of statistical measures that determine the symmetry of a distribution and how flat or peaked a data set is relative to a normal

distribution, respectively (Harris & Jarvis, 2013). Both data sets show a general increasing trend with Sample number, i.e. distance from the crater. Therefore, skewness is increasing from a finely skewed to a coarser skewed distribution and kurtosis is increasing from very platykurtic nearer to the source to mesokurtic distributions further away. However, Sample 3 provides an anomalous result with peaks in both skewness and kurtosis values.

4.3. *3rd Objective*

The results show that the topography varies at both sites, with the upper site being considerably narrower and steeper than the lower site which features a more gently sloping terrain with a wider floodplain. Furthermore, after the eruption, both sites increased in height, with the upper site experiencing higher deposition than the lower site. There are also differences in regards to vegetation loses with the lower site experiencing continual change both immediately after the eruption and a year later. However, it appears that the majority of the vegetation loss at the upper site occurred immediately following the eruption, with very little occurring in the following year.

The differences in the vegetation remaining at both sites after the 2015 eruption can be explained initially by the volcanic products that affected both areas. As Castruccio *et al.* (2016) indicated, pyroclastic flows then lahars affected the upper site, whereas the lower site was only affected by lahars. Therefore, the majority of existing vegetation close to the river would have been destroyed at the upper site as Del Moral and Grishin (1999) indicate the severity of pyroclastic flows is too high, resulting in rare survival. In contrast, there can be survival along the perimeters of a lahar. Therefore, this also explains why at the lower site, there is some standing vegetation.

In addition to this, the bark removal photographed in figure 14 relates to debris-flow damage identified by Pierson (2004) as only bark remained on downstream side of the trunk. Therefore, depositional and erosional processes can be evidenced at the lower site as indicated by the bark removal, the retreat in the vegetation boundary and the increase in height of the floodplain as shown in figure 2. In regards to the upper site, similar processes have also affected the site as evidenced by the formation of debris or boulder levees and a large increase in height of the channel (Figure 9). Pierson, (1995) and Schürch *et al*. (2011) indicate that higher rates of deposition usually occur when the channel is wider and of lower relief (Pierson, 1995; Schürch *et al*., 2011). Therefore, this explains why there was lots of deposition at the lower site as the topography is wider and flatter. However, figure 9 also indicates that the upper site had areas with substantially more deposition, which is surprising considering it is narrow and steeper. This could

either be as a result of other factors which restrict flow therefore allowing for deposition or it could be down to errors in the Digital Elevation Models which permitted the evaluation of the change in topography between 2015 and 2016.

5. Conclusion

Overall, there is no question that the fluvial and environmental processes have been altered and affected as a result of the 2015 Calbuco eruption. In regards to the first objective, fluvial and geomorphological processes have resulted in the Rio Blanco Este undergoing vast amount of geomorphic change. Subsequently, this means that it is unlikely the Rio Blanco Este will return to its pre-eruptive state. However, there are signs at one of the sites that it may be trying to do this. Concerning the second objective, sediment log analysis, identified deposits relating to lahars. Lastly, for the third objective, vegetation loss initially was as a result of the different volcanic products that affected both sites. However, the upper site had a more immediate change while the lower site had a longer response time and at both sites the topography influenced the vegetation that survived and ultimately resulted in a more severe impact to vegetation at the upper site.

In regards to reliability, assessing the topographical changes via Digital Elevation Models, can be subject to error. Particularly, as they were from different sources. There was an attempt to adjust for these errors, but the actual height increase at both sites could be out by a few metres above and below what is indicated. Grain size analysis can also produce errors in regards to the weighing of sediment and also when removing the sieves from each other, finer sediment can escape.

Further work is important as there are communities living in close proximity and as indicated lahars are a hazard which are common product of this volcano. Further work analysing the river channel and its response in years to come would be good to assess whether the Rio Blanco Este does return to its pre-eruptive state. Lastly, further studies involving succession rates of vegetation would be important as there are species of plant which are endemic to Chile.

Bibliography

Blott, S. J. and Pye, K. (2001) GRADISTAT: A Grain Size Distribution and Statistics Package for the Analysis of Uncnsolidated Sediments. *Earth Surface Processes and Landforms,* Vol.26, pp.1237 – 1248.

Castruccio, A., Clavero, J., Segura, A., Samaniego, P., Roche, O., Le Pennec and Droguett, B. (2016) Eruptive parameters and dynamics of the April 2015 sub-Plinian eruptions of Calbuco Volcano (southern Chile). *Bulletin of Volcanology*, Vol.78 (9), pp.1 – 19.

Del Moral, R and Grishin, S, Yu. (1999) 'Volcanic Disturbances and Ecosystem Recovery' in Walker L, R. (ed.) *Ecosystems of Disturbed Ground*. Amsterdam: Elsevier Science B.V.,pp.137 – 155.

Gob, F., Gautier, E., Virmoux, C., Grancher, D., Tamisier, V., Primanda, K., Wibowo, S., Sarrazin, C., de Belizal, E., Ville, A., Lavigne, F. (2016) River responses to the 2010 major eruption of the Merapi volcano, central Java, Indonesia. *Geomorphology*, Vol.273, pp.244 – 257.

Gran, K., Montgomery, D. (2005) Spatial and temporal patterns in fluvial recovery following volcanic eruptions: Channel response to basin-wide sediment loading at Mount Pinatubo, Philippines. *Geological Society of America Bulletin*, Vol.117 (1), pp.195 – 211.

Harris, R. & Jarvis, C. (2013) *Statistics in Geography and Environmental Science*. 2nd Edition. Abingdon (New York): Routledge.

Hickey-Vargas, R., Abdollahi, M, J., Parada, M, A., López-Escobar, L and Frey, F, A. (1995) Crustal xenoliths from Calbuco Volcano, Andean Southern Volcanic Zone: implications for crustal composition and magma-crust interaction. *Contributions to Mineralogy and Petrology,* Vol.119 (4), pp.331 – 344.

Klohn, E. (1963) The February 1961 eruption of Calbuco volcano, Bulletin of the Seismological Society of America, Vol.53 (6), pp.1435-1436.

López-Escobar, l., Parada, M, A., Hickey-Vargas, R., Frey, F, A., Kempton, P, D and Moreno, H. (1995) Calbuco Volcano and minor eruptive centers distributed along the Liquiñe-Ofqui Fault Zone, Chile (41°-42° S): contrasting origin of andesitic and basaltic magma in the Southern Volcanic Zone of the Andes. *Contributions to Mineralogy and Petrology,* Vol.119 (4), pp.345 – 361.

Major, J., Pierson, T., Dinehart, R., Costa, J. (2000) Sediment yield following severe volcanic disturbance—a two-decade perspective from Mount St. Helens. *Geology*, Vol.28 (9), pp.819 – 822.

Middleton, G. V. & Hampton, M. A. (1973) Sediment Gravity Flows: Mechanics of Flow and Deposition. Los Angeles: *Society of Economic Paleontologists and Mineralogists*.

Pelto, M. (2015) *American Geophysical Union*. Available at: http://blogs.agu.org/fromaglaciersperspective /2015/04/25/calbuco-volcano-glaciers-chile/. (Accessed: 7th March 2016).

Pierson, T. (1995) Flow characteristics of large eruption-triggered debris flows at snow-clad volcanoes: constraints for debris-flow models. *Journal of Volcanology and Geothermal Research*, Vol.66 (1), pp.283 – 294.

Pierson, T. and Major, J. (2014) Hydrogeomorphic effects of explosive volcanic eruptions on drainage basins. *Annual Review of Earth and Planetary Sciences*, Vol.42, pp.469 – 507.

Pierson, T. C. & Scott, K. M. (1985) Downstream Dilution of a Lahar: Transition From Debris Flow to Hyperconcentrated Streamflow. *Water Resources Research,* Vol.21 (10), pp.1511 – 1524.

Pierson, T. C. (2004). Distinguishing between Debris Flows and Floods from Field Evidence in Small Watersheds, *Reducing Risk from Volcanic Hazards*. USGS Fact Sheet, pp.20014 – 3142.

Pierson, T., Pringle, P., Cameron, K. (2011) Magnitude and timing of downstream channel aggradation and degradation in response to a dome-building eruption at Mount Hood, Oregon. Bulletin of the *Geological Society of America*, Vol.123, pp.3 – 20.

Romero, J, E., Morgavi, D., Arzilli, F., Daga, R., Caselli, A., Reckziegel, F., Viramonte, J., Diaz-Alvarado, J., Polacci, M., Burton, M and Perugini, D. (2016) Eruption dynamics of the 22-23 April 2015 Calbuco Volcano (Southern Chile): Analyses of tephra fall deposits. *Journal of Volcanology and Geothermal Research*, Vol.317, pp.15 – 29.

Schurch., P., Densmore, A, L., Rosser, N, J and McArdell, B, W. (2011) 'Dynamic controls on erosion and deposition on debris-flow fans'. *Geology,* Vol.39 (9), pp.827 – 830.

Scott, K. M., Vallance, J. W. & Pringle , P. T. (1995) Sedimentology, behavior, and hazards of debris-flows at Mount Rainier, Washington. *USGS Professional Paper,* pp.1547.

Sernageomin (2014) *Volcán Calbuco*. Available at: http://www.sernageomin.cl/archivosVolcanes/2012 0613111604955FichaVnCalbuco.pdf. (Accessed: 20th February 2016).

Stern, C, R. (2004) Active Andean volcanism: its geologic and tectonic setting. *Revista geológica de Chile*, Vol.31 (2), pp.161 – 206.

Stern, C, R., Moreno, H., López-Escobar, L., Clavero, J, E., Lara, L, E., Naranjo, J, A., Parada, M, A and Skewes, M, A. (2007) 'Chilean Volcanoes' in *The Geology of Chile* by Moreno, T and Gibbons, W (eds.). London: The Geological Society of London.

Swanson, F., Jones, J., Crisafulli, C., Lara, A. (2013) Effects of volcanic and hydrologic processes on forest vegetation: Chaitén Volcano, Chile. *Andean Geology*, Vol.40 (2), pp.359 – 391.

Tucker, M., (2009) *Sedimentary Petrology: An Introduction to the Origin of Sedimentary Rocks*. 3rd edition, Oxford: Blackwell Science.

Vallance, J. W. & Scott, K. M., (1997) The Osceola Mudflow from Mount Rainier: Sedimentology and hazard implications of a huge clay-rich debris flow. *Geological Society of America Bulletin,* Vol.109, pp.143 – 163.

Vallance, J.W. and Iverson, R.M. (2015) 'Lahars and Their Deposits', in Sigurdsson, H. (ed.) *The Encyclopaedia of Volcanoes*, 2nd edition, New York: Elsevier Inc.

Watt, S, F, L., Pyle, D, M., Naranjo, J, A., Rosqvist, G., Mella, M., Mather, T, A and Moreno, H. (2011) Holocene tephrochronology of the Hualaihue region (Andean southern volcanic zone, ~42° S), southern Chile. *Quaternary International*, Vol.246 (1), pp.324 – 343.

Wentworth, C. K., (1922) A scale of grade and class terms for clastic sediments.. *Journal of Geology,* Vol.30, pp.377 – 392.

Zheng, S., Wu, B., Thorne, C., Simon, A. (2014) Morphological evolution of the North Fork Toutle river following the eruption of Mount St. Helens, Washington. *Geomorphology*, Vol.208, pp.102 – 116.

Appendices

Images

Image 1	*Rocks lining the Río Blanco Este in the foreground and the Calbuco volcano in the background.*

Image 2	*Rocks lining the braided channel at Site 2 (foreground), the Osorno volcano (background).*

Image 3 *The snow-covered Calbuco volcano as seen from the Osorno volcano.*

Image 4 *The Chile Expedition Team at Site 2: Becky, Diana and Alex (from left to right).*

Image 5	*Site 1 showing river terraces and the active channel of the Río Blanco Este.*

Image 6	*En route to Site 2.*

Final Budget

Incoming

The Newcastle Expeditions Committee	£3,000.00
The Royal Geographical Society	£1,000.00
The Gilchrist Educational Trust	£1,000.00
Personal contributions (£1,103.55 each)	£3,310.65

Outgoing

UK Travel	
Flight	£166.98
Train	£61.30
International Travel	
International flights to Chile	£2,782.53
Internal flights in Chile	£531.00
Travel in Chile	£286.89
Accommodation in Chile	£1,814.70
Food	£471.33
Equipment and Other	
Vaccinations	£540.00
Dry liner 60L	£13.99
Waterproof notepads	£36.51
Waterproof ponchos	£13.32
Map for project	£20.38
Personal Spending (some food, purchases and essentials, £600 each)	£1,800.00
Total	**£8,310.65**

Presentations, Publications and Other Outputs

The Chile Expedition Team were selected by the Newcastle Expeditions Committee from over 115 students to deliver a presentation at the annual Celebrating Student Research Scholarships and Expeditions presentation evening was held on 23rd November 2016. Over 300 students, staff and members of the public heard about our experiences and findings from Chile: https://research.ncl.ac.uk/expeditionresearchscholarships/celebratingresearchscholarshipsexpeditions/2016presentations/.

The presentation can be heard at: https://research.ncl.ac.uk/expeditionresearchscholarships/celebratingresearchscholarshipsexpeditions/2016presentations/alexandramckeerebeccaleitchdianaluke/.

The Newcastle University Press Office wrote an article which summarises the main presentations from the main presentations from the evening in an article titled "Students take on global research issues". This can be found at: http://www.ncl.ac.uk/press/news/2016/11/studentstakeonglobalresearchissues/.

Alongside the presentation, the Chile Team also produced a poster for the evening, which can be found at: http://research.ncl.ac.uk/expeditionresearchscholarships/postergalleries/Alexandra%20Mckee.pdf.

A regional newspaper, The Chronicle, wrote an article titled "Newcastle University students risk yellow warning to complete Chile volcano expedition" about this expedition. This article can be found at: http://www.chroniclelive.co.uk/news/north-east-news/newcastle-university-students-risk-yellow-12228456.

The majority of the research has been accumulated to create three distinct undergraduate dissertations. For more information about the projects, please contact:

- Alexandra McKee (A.G.McKee1@ncl.ac.uk) for information about the response and recovery of the Río Blanco Este after the April 2015 Calbuco eruption.
- Rebecca Leitch (R.Leitch1@newcastle.ac.uk) for information about understanding lahar activity and characterising the chronology of recent deposits.
- Diana Luke (D.Luke@newcastle.ac.uk) for information about the volcanic disturbance on vegetation and topography.