A Spatial Analysis of Modern and Paleo Rockfall

Purau, Lyttelton Harbour, New Zealand

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Abstract

Thousands of rockfalls occurred as a result of the Canterbury earthquake sequence in the Port Hills of Christchurch, New Zealand, and nearby Lyttelton Harbour. Specifically, many fell from the source rock above Purau, 15km Southeast of Christchurch. Here we undertake a spatial analysis of both the modern and paleo rockfall in this area to assess differences in distribution of where they come to rest, and to characterize past rockfall phases. Using ArcMap, we calculate shadow angle, and compare the modern and paleo rockfall distributions over a number of observed characteristics. We find the paleo rockfall is typically distributed with the largest boulders closest to the source, while modern rockfall follows an opposite trend. We also find that the paleo rockfall can be separated into three subpopulations based on correlating various observations of the boulders. Lastly, we find that in the overall data, more boulders come to rest further from the source, but that the majority of the boulder volume rests closer to the source.

Introduction

The Canterbury earthquake sequence started on September 4, 2010 with the $M_W$ 7.1 Darfield earthquake. The epicenter occurred about 40 km west of Christchurch, and as such, caused few rockfalls in the Christchurch area\(^1\). This was not the case, however, when the $M_W$ 6.2 Christchurch earthquake occurred on February 22, 2011. The epicenter was directly under the Port Hills, causing extreme

\(^1\) (Massey et al., 2014)
ground motions (exceeding 2 g in some places) and widespread rockfall\(^2\). A further
after shock occurred on June 13, 2011, with \(M_w\) 6.3 and epicenter at Taylor’s
Mistake. Massey et al., 2014 have conducted an in-depth analysis of the Port Hills
rockfall, but no analysis has been done on the rockfall above Purau. (Figure 1).

Purau is a community of ~300 located on Banks Peninsula at the south side
of Lyttelton Harbour. To the northeast, Camp Bay Road extends at the base of a
series of colluvial and alluvial deposits, narrow ridgelines, and valleys, with a series
of vertical, exposed rock bluffs around 20-30m high above them\(^3\) (Figure 2).

Thousands of boulders have fallen from these faces, generally coming to rest in the
gullies (Figure 3). The slopes along the upper part of the hill are around 35°,
decreasing to 15° to 20° along the lower slopes\(^3\).

**Geologic Setting**

New Zealand is situated on the boundary of the Pacific and Australian plates,
and is tectonically very active as result. Specifically, the South Island is dominated
by oblique subduction of the Australian plate beneath the Pacific plate, and the
right-lateral slip along many crustal faults\(^3\). The February 2011 earthquake
occurred on a previously-unknown blind fault that trends northeast to southwest
under Christchurch\(^3\).

Purau is located across Lyttelton Harbour from the Port Hills, on Banks
Peninsula, 15km from Christchurch. The cliffs and hills in the area are the eroded

\(^2\) (Sinclair, 2011)
\(^3\) (Bradely and Cubrinovski, 2011)
remnants of a large Miocene volcanic center. Lyttelton Harbour formed when the
Pacific Ocean breached the volcanic center\(^4\). A number of buried faults lay below the
surface, at least 12 of which ruptured during the Christchurch earthquake
sequence\(^5\). A buried fault is located under Camp Bay Road\(^2\). At nearby Lyttelton,
peak ground accelerations of 0.98 g were recorded from the February 2011
Christchurch earthquake\(^3\).

**Methods**

Boulder recording and measurement were done by hand over the course of
four full days in the field. Only boulders greater than approximately 1 m\(^3\) were
measured, and if there was uncertainty about whether a rock was a fallen boulder or
in situ, it was not recorded. At each boulder, the coordinates were recorded on a
hand-held GPS unit in WGS 1984, and a series of measurements and observations
were made: dimensions along three axes using a tape measure, percent lichen cover
estimated visually, rock type (volcanic breccia or fine crystalline basalt),
characterization as modern or paleo, surface roughness on a one to six scale,
geomorphic location (gully, interfluve, etc.), and the presence and nature of a
sediment wedge behind ranked on a one to four scale (Figure 4). This data was
entered and compiled manually in Excel into the 890-boulder dataset used for
analysis. Analysis was conducted using ArcMap 10.2 to manipulate the dataset in a
number of ways. Primarily, the symbology was changed to display each of the

\(^4\) (Heron, et al., 2014)
\(^5\) Mackey and Quigley, 2014
observations of the boulders. For example we could color the data points based on
the values for a given characteristic, as shown in Figures 5 through 7. This allowed
us to recognize patterns across multiple variables by aligning the maps and
identifying areas that had similar levels of various characteristics. This method led
to a preliminary inference of patterns of past rockfall.

In addition, the symbology in ArcMap was used to color the modern and
paleo populations differently, and to size the data points based on the boulder
volume (Figure 8). This allowed for a qualitative comparative analysis of the spatial
and volume distribution of each population.

ArcMap was also used to calculate the shadow angle of the rockfall. This was
calculated using the Viewshed tool within the Spatial Analyst toolbox. The base of
the source area is established as a line, and the viewshed is a plane projected from
this at a prescribed angle below horizontal (this is the shadow angle itself). Where
this projection intersects the topography, a line is drawn. This process is repeated
at increasing shadow angles, forming a series of lines approaching the source area
(Figure 9). The areas between the lines are established as polygons, and these
zones are then merged with the dataset, allowing individual analysis of each one
based on the number of boulders and the total boulder volume within each one.

**Results**

We present the data in a number of displays beyond the basic display shown
in Figure 3 (basic map). First, Figure 8 shows the distinction between modern and
paleo rockfall, as well as the range of sizes within each subset.
Figures 5, 6, and 7 display the roughness, lichen, and extent of sediment wedge, respectively.

Figure 9 displays the calculated shadow angle zones, with a minimum shadow angle of 21°, increasing to 37°. The area between each line becomes a polygon, and is referred to by the shadow angle value of its lower boundary. An analysis of each individual zone is then undertaken, resulting in Figures 10 and 11, showing the boulder counts and volume distribution in each shadow angle zone.

**Discussion**

Looking at the various displays of data, we can start to recognize patterns and make inferences about the nature of the rockfall. Figure 3, showing the entire data set highlights the tendency of boulders to come to rest in gullies. This indicates that there is a significant topographic control on the spatial distribution, and that gullies act as a mechanism to arrest falling boulders.

Figure 8, showing the distinction between modern and paleo and the volume distribution, indicated differences between the nature of the modern and paleo rockfall. Within the paleo subset, there is a distinct, if imperfect, pattern of larger boulders coming to rest closer to the source rock. This is especially apparent in the middle to upper portion of the figure, where the primary gully is populated almost exclusively by 1 to 5 m³ boulders, whereas the areas near the source rock are populated primarily by >10m³ boulders. However, within the modern subset, this pattern seems to be the opposite, with larger boulders coming to rest further down the hill. Most likely, this change in distribution indicates the absence of an old-
growth forest that was present when the paleo boulders fell. Large trees on the
slopes can arrest a boulder earlier than it otherwise would have come to rest due to
purely boulder-slope interactions. Perhaps smaller boulders, though, can still fall
relatively far down-slope by going between the trees. With that kind of forest no
longer present, the modern rockfall from 2011 could fall down slope with minimal
obstacles obstructing the fall.

Focusing on the southernmost rockfall area, we see that the modern rockfall
appears to fall much further than the paleo rockfall. This introduces a complicating
factor to assessing paleo rockfall on geomorphically active hillsides: sediment
deposition can bury old boulders, thus rendering them invisible and impossible to
measure and observe. Especially in this specific area, this complicates the
inferences that can be made about the nature of the rockfall. There could be fewer
paleo boulders further down slope due to an old-growth forest obstructing their
path, or there could be paleo boulders further down slope that have been buried by
more recent sedimentation.

We were also able to discern patterns in the lichen, roughness, and sediment
wedge data. Increasing values for all three roughly indicates that a boulder has
been on the slope for more time. As a boulder rests on the hill, increased sun
exposure leads to more lichen, more weathering causes the surface roughness to
increase, and more sediment is able to accumulate behind the boulder. As such, we
sought to use these measurements to distinguish between past rockfall events,
hypothesizing that there would be correlation between the three variables and that
the correlations would fall into distinct parameters, indicating separate sub-
populations. Indeed, visual analysis of maps of the three variables showed distinct populations (Figures 12 and 13). As the figures show, this analysis indicated three past sub-populations, along with the recent 2011 event. By separating these events, the source rock involved and the scope of rockfall distribution for each event could be approximated (Figure 12). It is clear that different source areas were more active in certain populations than in others, and that some sources were active in all three populations.

There is a considerable amount of error that should be acknowledged when attempting to determine past sub-populations based solely on lichen, surface roughness, and sediment wedge. All three characteristics are subject to a considerable amount of error, as they are controlled by more than just the amount of time the boulder has spent on the hillside. Lichen growth can be cyclic, which disrupts the proposed linear relationship between lichen amounts and time spent on the hillside, as it does not grow at consistent rates. Surface roughness is a function of the extent of weathering a boulder has been subjected to, and since the weathering rates vary across the hillside, the specific location of a boulder on the hillside affects the extent to which it is eroded. This, too, disrupts the proposed linear relationship between surface roughness and amount of time spent on the hillside. Similarly, the size of the sediment wedge is a function of erosions rates, so because the erosions rates vary at different locations on the hillside, the size of the sediment wedge will vary based on the erosion rates at different locations on the hill, thus disrupting the proposed linear relationship between the size of the sediment wedge and the amount of time spent on the hillside.
Conclusion and Future Work

Spatial analysis and correlation of lichen, surface roughness, and the size of the sediment wedge behind a boulder can be used to separate the data set into three preliminary subpopulations. While this is a very preliminary set of distinctions to make and is subject to multiple sources of error, it can be applied alongside more rigorous and quantitative dating methods in order to define and characterize the paleo rockfall. Some of these methods include cosmogenic $^3$He dating, lichenometry, and cosmogenic dating of the sediments in the wedge.

Much future work can also be performed within ArcMap. The shadow angle analysis allows for a preliminary look at the boulder and mass distributions, but more analyses can be performed, such as runout distance. The shadow angle can also be undertaken for the modern and paleo populations individually, allowing for comparison and analysis of the boulder and volume distributions across the populations. Furthermore, analyses can be performed to determine more about the mechanisms of rockfall, such as total kinetic energy.$^1$

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$^6$ Bull and Brandon, 1998
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Works Cited


Appendix
Figure 1: Map of Banks Peninsula indicating the locations of Christchurch, Taylor’s Mistake, and Purau.

Figure 2: Field photo of the mapping area looking southeast. Source rock cliffs are visible along the skyline.
Figure 3: ArcMap display of the 890-boulder dataset, indicating the base of the source rock, and the spatial distribution showing most boulders have come to rest in gullies.
Figure 4: Example of a paleo volcanic breccia boulder. Highlighted are examples of the observations made at each boulder. Numbers correspond to the scale used for observations. Up-slope is to the upper left corner.
Figure 5: ArcMap display showing the variety of surface roughness observed on a one to six scale. This is one of three characteristics used to separate the paleo rockfall into three subpopulations.
Figure 6: ArcMap display showing the variety of lichen cover, divided into 10% categories. This is one of the three characteristics used to separate the paleo rockfall into three subpopulations.
Figure 7: ArcMap display showing the variety of size and extent of sediment wedge behind each boulder. This is one of the three characteristics used to separate the paleo rockfall into three subpopulations.
Figure 8: ArcMap display distinguishing between modern and paleo boulders, and displaying according to boulder volume. This display shows the pattern of large paleo boulders staying closer to the source, while large modern boulders tend to move further down-slope.
Figure 9: ArcMap display of the nine shadow angle zones. These are mapped by projecting a plane from the base of the source at a prescribed angle below horizontal, and determining where that plane intersects the topography.
Figure 10: Graph produced from the data in Figure 5, displaying the boulder count distribution in each shadow angle zone.

Figure 11: Graph produced from the data in Figure 5, showing the volume distribution within each shadow angle zone.
Figure 12: Map of field area, displaying rockfall source areas, the base of the source area, all 890 boulders, and the three separate paleo events we were able to differentiate. The data points not included in a colored shape are either modern rockfall (see Figure 4), or were not observed over one or more of the contributing characteristics.
Figure 13: Map of field area, displaying rockfall source areas, the base of the source area, all modern boulders, and the zones of modern rockfall. Also displayed are images of the source areas where modern rockfall originated, and the scarps are indicated where they could be confidently located.