Structural control on rockfall: a geolithological and geomechanical characterization of Miocene volcanics[1],[2]

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[2] Figures and Tables attached separately.

ABSTRACT
The February 22 and June 13, 2011 events of the Canterbury Earthquake Sequence triggered widespread rockfall within Lyttelton volcanic group deposits. This study attempts to isolate primary structural controls on rockfall in volcanic rock by characterizing the geomechanical and geolithological properties of a single rockfall source above Rapaki village. The source rock is inaccessible due to the continuing seismic hazard, so a scanline was conducted on an exposed outcrop behind the source cliff face. Scanline data characterized the orientation and persistence of discontinuities within a coherent lava unit. Rock mass characterization was completed for both the coherent and brecciated lava flows found at or above the scanline. Images of the cliff face taken by an Unmanned Aerial Vehicle (UAV) were collated into a single orthomosaic image used to map the rockfall source. The source cliff contains both coherent and brecciated lava flows, which are not equally distributed on the face and show unique joint patterns and rock strengths. Detachment zones were classified based on the lithologies with the zone, the presence of visible joint release, and lithologic contacts at the boundaries of the detachment zone. Though the coherent lava has a higher compressive strength, it is more likely to detach than the brecciated lava due to higher joint intensity. Lithologic contacts are the strongest control on rockfall detachment zones, possibly due to changes in the primary joint pattern of the lava flows as the units near contacts.

Keywords: UAV mapping, detachment zones, Lyttelton volcanics, Canterbury Earthquake Sequence, rock mass characterization

1. INTRODUCTION

Rockfall releases, or detachment zones, are controlled by planes of weakness in a rock mass such as bedding planes, faults, foliation, joints, cleavage or schistosity (Wyllie and Mah, 2004). Failures occur on these planes of weakness due to earthquakes, intense rain, freeze-thaw cycles, planar failures in fractured rock, and 10 more rare causes (Wyllie and Mah, 2004). Little work has been done to examine the relationship between primary structures (cooling joints and bedding) and detachment zones in volcanic rock. It is well known that joint sets can vary over short distances in volcanic rock (Wyllie and Mah, 2004), so characterizations of primary structures must acknowledge the non-uniform nature of the jointing.

The 2010-2011 Canterbury Earthquake Sequence (CES) generated over 5,719 rockfall boulders (Massey et al. 2014) from sources cliffs of Lyttelton volcanic group deposits. These basaltic, Miocene deposits form the western part of Banks Peninsula, south of Christchurch, New Zealand (Fig. 1A). The study cliff above Rapaki village (Fig. 1B) released rockfall boulders during the February 22 and 13 July 2011 events.

This study used a geomechanical survey and images from an Unmanned Aerial Vehicle (UAV) in an attempt to isolate primary structural controls on rockfall detachment zones. We suggest that rockfall detachment zones are strongly controlled by contacts between deposits due to a change in primary cooling joint patterns near lithologic boundaries. An understanding of the structural control on rockfall is necessary because of the continuing rockfall hazard that impacts many residents of the greater Christchurch area. Mitigation methods such as land zoning, scaling cliffs, creating bunds, and stepping cliffs attempt to lessen the impact of the hazard, but the primary structures of the rock that contribute to rockfall have not been examined in great detail in volcanic rock. This study is the first to map individual detachment zones and characterize how each zone relates to primary structures such as bedding and cooling joints. Additionally, the detailed UAV orthomosaic image provides a baseline for comparison if continuing CES aftershocks or an Alpine Fault rupture cause future rockfall events at Rapaki.

2. GEOLOGIC SETTING

2. 1 Lyttelton Volcanic Sequence

The large basaltic Miocene Lyttelton volcanic complex (11 - 9.7 Ma) (Sewell et al., 1992, Forsyth et al., 2008) is preserved as an eroded crater rim ridgeline known as the Port Hills region. The Lyttelton volcanic group is largely composed of ridge forming lava flows (both columnar jointed and blocky with surrounding autobreccia) and scoriaceous material interlayered with minor ash horizons, pyroclastic flows, paleosols and conglomerates intruded by dykes and domes, and overlain by loess (Sewell et al., 1992, Forsyth et al., 2008, Hampton, 2010).

Rapaki Peak is a preserved cone fragment of Hampton's (2010) eruptive package IV of the Governor's Bay Cone (Fig. 2). The cliff face exposes lava flows roughly perpendicular to flow direction, with flows dipping back into the slope (see Hampton, 2010 for further explanation of the Lyttelton volcanic evolution and structure). Lava flows are both coherent and brecciated.

2. 2 Co-seismic rockfall

Rockfall in the Port Hills has not been isolated to CES events, as hundreds of paleorockfall boulders have been identified (Mackey and Quigley, 2014). While there have not been any major historic rockfall events in the Port Hills, cosmogenic nucleotide dating of paleoboulders at sites that experienced rockfall during the CES suggest an extensive rockfall event ca. 8-6 ka, with a potential preceding event ca. 14-13 ka (Mackey and Quigley, 2014).

Between 2010 and 2011, the CES triggered 5,719 mapped boulders from roughly 4,800 source areas (Massey et al., 2014). The 22 February 2011 earthquake released 3542 mapped boulders (Massey et al., 2014, Heron et al., 2014, Quigley et al., 2016) and the 13 June 2011 earthquake released 1474 mapped boulders.

During the 22 February and 13 June events, more than 650 boulders were released from the source cliff above Rapaki village (Massey et al., 2014, Mackey and Quigley, 2014, Vick, 2015). Two house were hit in the village during the February event (Massey, et. al., 2012) and 10 residential properties were zoned against future development due to an unacceptably high life safety risk.

3. METHODS

3. 1 Geologic Mapping

Due to the inaccessibility of the cliff face, this study used a UAV to collect over 1,200 images in order to map the face itself. The UAV was a Phantom 3 Professional, outfitted with a Sony EXMOR 1/2.3" camera (effective pixels 12.4 million, lens FOV 94^{o}, focal length 3.61mm, f/2.8). Images were processed by the Agisoft 3D modeling software, which constructed the 3D model and output an orthomosaic image of the cliff face. The model was run twice with different quantities and groups of images and the best quality image was created using 258 images with a ground resolution of 2.35cm/pixel.

Detachment zones, zones of coherent lava, and breccia contacts were mapped over the orthomosaic image in Adobe Illustrator. Raw images from the UAV were consulted when additional detail was needed due to the limited resolution of the orthomosaic image itself.

Detachment zones were identified by color changes (redder fresh surface), the lack of lichen cover, and a smoother surface weathering profile. They were further classified by visible joint control as "definite," "not apparent," "mixed" or "inconclusive." Detachment zones with definite joint control showed releases on clear, planar surfaces, and most often subvertical and subhorizontal cooling joints. Detachment zones with definite joint control may show angular releases or blocky patterns. Detachments with not apparent joint control were often pockets in the source rock, absent of planar surfaces and visibly irregular. Mixed zones contained areas of definite and not apparent joint control, while the inconclusive designation reflected detachment zones were the judgment was dubious due to image angle or resolution. Relative surface area of detachments and the coherent lava unit was calculated using an area tool within Illustrator.

The coherent lava showed blockier patterns, smoother planar joints, smooth lichen cover, prevalent subhorizontal joints, and a platy fracture pattern. Breccia contacts were mapped with varying degrees of confidence based on breaks in slope, changes in fracture patterns, or preferential weathering of contacts.

Additional polygons were drawn to exclude unlikely rockfall source areas. Rockfall sources are usually greater that 35^{o}, so grassy areas of low slope were judged not to be source rock when calculating relative detachment areas (Fig. 3).

3.2 Geomechanical Survey

A scan line survey of a coherent lava layer in an outcrop exposed on the backside of the cliff face (Fig. 4) was completed. The outcrop is roughly 3 meters tall and it dips 80^{o} to 346^{o}. A total of 48 joints and one lithologic contact were measured across a 9-meter scan line within a coherent lava unit. These features were surveyed at roughly waist height across the section, with additional measurements taken outside of waist height if they were representative at outcrop scale, but absent from the predefined survey level. For each discontinuity, we recorded the feature type, dip, dip direction, trace length, aperture, infilling, infilling strength, roughness, and asperity amplitude. Few trace lengths under 0.25m were measured due to their unlikely contribution to rockfall detachment. A full breccia unit could not be located in the field and exposures were incomplete, so we did not complete a scanline.

At the same outcrop, separate evaluations were completed to quantify the fracture patterns and rock strength of the coherent and brecciated sections. To calculate rock mass rating (RMR), numbers were assigned to parameters including: estimated uniaxial compression strength (UCS), joint volume, joint spacing, roughness, persistence, aperture, infilling, and weathering. These parameters produced a rock mass rating (after Bieniawski, 1989) for each lithology. Additionally, each rock mass was given a Geological Strength Index (GSI) number reflecting joint structure and surface conditions (after Hoek and Marinos, 2000).

4. RESULTS

4. 1 Geologic Mapping

Detailed mapping on the orthomosaic image of the cliff face revealed that 86% of the exposed bedrock is breccia, while 14% is coherent lava (Fig. 5A). The lava layers are not laterally continuous across the face and coherent lava deposits are smaller than brecciated units. 7% of all exposed breccia was released during the CES while 20% of the coherent lava released. By surface area, 69% of the detachment zones were breccia and 31% were coherent lava.

60 detachment zones resulting from the CES (representing 9% of the source rock surface area) were mapped and subdivided based on lithologies within each detachment, visible joint control on the detachment, and the presence of lithologic boundaries around the detachment (Fig. 5 and Table 1). Detachment zones were distributed fairly randomly across much of the outcrop. However, there were fewer detachments in the lower northern (right side of image) segment of the cliff.

4.2 Geomechanical Survey

4.2.1 Joint Characteristics in the Coherent Lava Scanline

Joint patterns varied widely through the survey in the coherent lava – the southern section was dominated by curvilinear joints that asymptotically crosscut the entire unit, while the northern section contained several sub-vertical, very persistent (up to 2 meters) joint sets spaced 15 to 50cm apart (Fig. 6) Dip and dip direction data for 47 discontinuities aligned in four sets, one subvertical and three subhorizontal (Fig. 7 and Table 2)

Some discontinuities continued through the whole unit while others were not as persistent. A few discontinuities propagated into the overlying breccia unit. The average trace length was 1.1 meters, but the measurements ranged from 0.1m to 2.4m. Traces recorded in the scanline show a bimodal distribution (Fig. 8)

Most joints had very narrow (0-2mm) to moderately narrow (6-20mm) apertures. Joint surfaces were predominantly undulating and smooth, but some were planar and rough, undulating and rough, or stepped and rough in declining frequency. Asperity varied from 1mm to 25mm, but was most often 4mm.

Many joints in the coherent lava trend subparallel to the contact and become more tightly spaced near the transition to brecciated lava flows (Fig. 9) The top breccia to coherent lava contact showed increased subhorizontal jointing near the contact, but this was not present at the bottom contact. There were no safely reached breccia-breccia contacts in the field, so is it unclear how the cooling joints behave towards that boundary.

4.2.2 Rock Mass Characterization

Neither the coherent lava or breccia in the outcrop showed recent rockfall release, but the coherent lava showed more signs of kinematic instability leading to block release. Deep etching in the breccia unit exposed precariously attached clasts. The breccia unit was more highly weathered, with exposed apertures up to 1m into the face. Joints in the coherent lava unit were not visible more than 10cm into the face, typically around 1-2cm. Neither unit showed infilling of the joints and groundwater was not a factor. Further rock mass information is summarized in Table 3.

5. DISCUSSION

5.1 Rock Strength vs. Joint Patterns Causing Detachment Zones

Laboratory testing conducted by Carey et al. (2014) showed that Lyttelton coherent lavas have a UCS of 100-243 (average 180 MPa) and the breccia units have a UCS of 0.9-15.8 (average 3.5) MPa. Our field estimates differ slightly (breccia strength is 20-100MPa, coherent lava strength is 50-250 MPa) but the laboratory-tested samples were taken from more distal sea cliff deposits. As such, values are comparable but not precisely representative of the units at Rapaki. Both methods show that the breccia has a lower UCS and the strength of the coherent lava varies more widely than the breccia. Our differences may be explained by the imprecise nature of field estimating or it is possible that our breccia unit was stronger than those tested in the laboratory. In the absence of any jointing, we assume that a seismic event would lead to more detachment in the weaker breccia unit.

Our study found that by surface area, only 7% of the total breccia detached during the CES, while 20% of the coherent lava detached. We explain this due to the tighter joint spacing of the coherent unit and the lower GSI values. In this case, primary joint patterns contribute to rockfall detachment more than rock strength.

5.2 Distribution of Detachment Zones

The distribution of detachment zones is fairly random across the source cliff, with notable absences on the lower northern (right side of the image) section (Fig. 5A). The grassy areas in the section have a lower slope, but that does not explain the lack of releases in the visible, subvertical bedrock. Some spots in this area sit back nearly concave into the slope, suggesting there may have been a large paleo-release. Due to the relative lack of tectonically induced joints visible in the orthomosaic image, it is possible that large detachments leave the source rock behind the detachment more stable, and thus less vulnerable to release in future events.

5.3 Primary Structural Controls on Detachment in Volcanic Rock

Differing primary joint patterns cause a larger portion of the stronger coherent lava to detach than the weaker breccia unit, but detachment zones are also influenced by lithologic boundaries. 68% of detachment zones are bounded by at least one lithologic contact, accounting for 83% of total detachment surface area. When detachment zones were subdivided based on visible joint control, 48% of zones (49% of surface area) showed release on visible planar joints. A significant portion of detachment zones are defined by joints, but a larger percentage of detachment zones are related to a lithologic boundary.

The strong lithologic boundary control may be due to primary cooling behavior in the coherent lava as it transitions into breccia. At this contact transitional area, more subhorizontal, closely spaced joints are seen, so the coherent lava rock mass could be less stable near lithologic contacts. It is difficult to distinguish if the lithologic contact control on detachments is due to the change in joint patterns, or simply the plane of weakness that occurs between two different units. Evidence suggests that there is a change in primary cooling joint patterns, which would decrease the strength of the rock mass in that concentrated area.

We find that unit thickness is not a limit for rockfall block size, as the largest detachment zones contain both lithologies. This suggests that lithologic boundaries can be cut within some (18%) detachment zones. There is no significant difference in detachment zones sizes within the coherent lava or breccia units (both lithologic units average 5 area units per detachment zone), although detachment zones may release multiple blocks of different sizes. Blocks will fragment on descent differently, due to joint structure and rock strength.

5.4 Variations in Joint Patterns within Lyttelton Volcanic Deposits

This study identified four joint sets, with three subvertical sets and one subhorizontal set. Previous work by Brideau et al. (Brideau et al., 2012) in Lyttelton volcanic deposits identified 3-4 steeply dipping sets along with a subhorizontal set. The difference in subvertical joint sets may be due to the lesser amount of joints measured in our study, or it could be due to differing cooling behaviors in vent proximal (ours) and distal (Brideau et al., 2012) lava flows. The distal deposits show a decrease in frequency as trace lengths increase, opposed to our bimodal distribution of trace lengths.

Massey et al. (2014) claimed that Lyttelton volcanics breccia had well spaced (>40m) discontinuities and little primary structure, but our detailed mapping suggests that much of the breccia above Rapaki has columnar joints. The joints in the breccia are more regular and planar than previously discussed (Fig. 10) This highlights the complex nature of volcanic rock units due to discrete differences within different units depending on their primary emplacement mechanism (i.e. rheology of flow, proximity to vent, flow direction, dip). Additional differences arise depending on how units are exposed in the landscape such as erosion or environments (like coastal cliffs at Sumner or ridge cliffs along the crater rim).

5.5 Variations in Failure Mechanisms within Lyttelton Volcanic Deposits

Massey et al. (2014) classifies volcanic units of the Lyttelton Volcanic Group primarily considering the coastal cliff sections of Redcliffs, Sumner, and Taylors Mistake. While the classifications are thorough and present a comparable data set to Rapaki, variances in deposit characteristics exist, as briefly discussed in relation to joint patterns in the breccia, which are due to proximity to eruptive source. Another major control is the dip of units; in coastal sections the overall dip of lava flows is approximately at right angles to the cliff face and dipping seaward. In a columnar jointed lava flow, joints form perpendicular to the cooling surface, which is a sloped surface in this case, resulting in the promotion of toppling failure. At Rapaki this relation is not as simplistic due to the complexities of being closer to vent regions (such as larger variations in flow directions within a smaller area) and the greater influence of erosion, which produces varying orientations of ridges and cliff faces.

At Rapaki, increased subhorizontal joint frequency near contacts acts as a plane of weakness. Tabular blocks formed by the columnar joints in the coherent lava and brecciated lava can be undercut by preferential erosion of breccia contacts and are thus more prone to rotational failure. Curvilinear joints seen in the scanline could have the same effect, encouraging rotational failure. Toppling style failure is unlikely, because the units are not dipping towards their release direction.

5.6 Using Surface Area as a Proxy for Rockfall Boulders at Rapaki

Of all detachment zone surface area, 69% was in the breccia compared to 31% in the coherent lava. Surface area cannot be used as a direct comparison with rockfall volume in the boulder field, because 96% of mapped CES boulders (by volume) were breccia (Borella et al., *in prep*). This may be due to the extent of the boulder field mapping area, because some blocks fell from the face without travelling into the boulder field. The tighter joint spacing of the coherent lava likely created smaller, platier blocks that behaved in this way. By mapping on the orthophoto, we could not account for any potential overhangs that caused larger volumes to release from detachment zones.

6. FUTURE WORK

More work must be done to confirm that lithologic boundaries are the strongest primary structural control on rockfall detachments in all volcanic rock. This could be explored within the Lyttleton volcanic group, in both proximal and distal deposits. Comparing joint sets at the proximal Rapaki deposits and the distal Sumner deposits (Brideau et al., 2012) suggests that joint patterns may differ, but this must be supported with additional measurements from other distal and proximal deposits.

Variations in lava flow direction and the presence of other volcanic deposits such as ignimbrite or ash may also act as controls on rockfall detachments in volcanic rocks. The mechanisms for rockfall in Lyttelton volcanic deposits could be explored further, as flow dip directions in relation to the cliff face can promote or discourage toppling behavior. Preferential erosion of weaker units could encourage undercutting and create overhangs that cause blocks to drop from the cliff due to lack of support. Future study sites could consider how lithologic units and flow direction impact the mechanisms for rockfall in the greater Christchurch area.

Further work either at Rapaki or other Lyttelton volcanic group deposits could help constrain the joint pattern behavior in the coherent lava unit. Within UAV images of the source rock at Rapaki, there are variable joint patterns that occasionally change near contacts, but without additional study sites and field observations, it is hard to know the extent of variability within Lyttelton coherent lava deposits. The theory that coherent lava jointing changes to more tightly spaced, subhorizontal blocks near the contact with breccia unit appears true from the scanline outcrop, but more field observations are needed to prove this is representative for all deposits.

The 3D model can be run through semi-automated software that can extract discontinuity information such as orientation and trace length. While the software could not be attained for this study, joint information across the cliff face could better characterize the sets and eventually estimate block sizes. If joint orientations were extracted across the entire cliff face rather than from our isolated scanline, block sizes could be estimated. The boulder data set for paleo and CES rockfall is thorough, so comparison with estimated block sizes could help constrain fragmentation on descent.

7. CONCLUSIONS

The rockfall source above Rapaki is predominantly brecciated lava with columnar cooling joints and minor coherent lavas appearing randomly across the outcrop as pockets. While the coherent lava has a strong compressive strength, its higher joint volume makes it more susceptible to rockfall release. During the 2010-2011 Canterbury Earthquake Sequence, roughly 9% of volcanic cliff above Rapaki detached as rockfall boulders. The detachment zones are semi-randomly distributed across the cliff face, with notable absences where the slopes are shallow or the cliff face is concave into the slope. Detachments are often defined by lithologic boundaries, which is in part due to a drop in GSI values and more tightly spaced subhorizontal joints. Changes in primary cooling joints in both coherent and brecciated lava flows near lithologic contacts are the strongest control on rockfall detachment zones. This study provides more information for the greater Christchurch region as mitigation methods are being put in place to reduce impact of co-seismic rockfall. Understanding the primary structures can inform mechanisms of failure, as they are inherent to the rock mass regardless of mitigation measures.

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