Discontinuity orientation in jigsaw clasts from volcanic debris avalanche deposits and implications for emplacement mechanism

GEOQuébec 2015
Challenges from North to South
Des défis du Nord au Sud

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ABSTRACT
Jigsaw fractures in clasts have been noted in the deposit of large (>1 Mm^3) volcanic debris avalanches and non-volcanic rock avalanches at numerous locations around the world but they have rarely been systematically studied. This project applied terrestrial photogrammetry techniques to characterize the discontinuity orientation of jigsaw clasts found in the debris avalanche deposits around Mt. Taranaki. Mt. Taranaki is a stratovolcano located on the North Island of New Zealand. The orientation of 355 discontinuities was obtained from clasts at 7 stations on the west side of Mt. Taranaki. The constant discontinuity orientation in clasts from stations separated by approximately 10 km has implications on the landslide debris transport and emplacement mechanisms. Two emplacement mechanisms that could result in a consistent orientation pattern in the jigsaw clasts at all 7 stations are discussed and compared with the field observations at Mt. Taranaki.

RÉSUMÉ
Les fractures avec des textures d'assemblage de casse-tête ont été noté dans les clastes des dépôts de grandes (> 1 Mm^3) avalanches de débris volcaniques et d'avalanches de roches non volcaniques à de nombreux endroits dans le monde, mais elles ont rarement été étudiés systématiquement. Ce projet applique les techniques de photogrammétrie terrestre pour caractériser l'orientation des discontinuités présentent dans des fragments avec des texture d'assemblage de casse-tête à l'intérieur des dépôts d'avalanche de débris autour du Mont Taranaki. Le Mont Taranaki est un stratovolcan qui se trouve sur l'Ile Nord de la Nouvelle Zélande. L'information sur l'orientation de 355 discontinuités fut acquise dans les clastes à 7 stations sur le côté ouest du Mont Taranaki. L'orientation constante de discontinuité dans les clastes à des stations séparer par d'environ 10 km a des implications sur les mécanismes de transport et de la mise en place des débris de glissement de terrain. Deux mécanismes de mise en place qui pourraient résulter en des d'orientation de discontinuités similaires dans les clastes avec des textures d'assemblage de casse-tête dans tous les 7 stations sont présenté et comparé avec les observations de terrain au Mont Taranaki.

1 INTRODUCTION

Mt. Taranaki, which is also referred to as Mt. Egmont or Egmont Volcano, is a 2518 m stratovolcano that has been active for at least the last 115 ka (Alloway et al., 1992). It is located on the North Island of New Zealand (Fig. 1). The last volcanic event occurring from Mt. Taranaki was the 1755 eruption, which resulted in dome collapse, block-and -ash-flows, and related deposition. The last recorded significant mass movement (lahars) was in 1999 and 2009, both were the result of rain-induced remobilization of eroding volcaniclastics material. Mt. Taranaki is the youngest of 4 volcanic centres in the Taranaki region. The volcanoes form a NW-SE trending lineament with volcanism becoming progressively younger towards the SE. The three main geological units present at Mt. Taranaki are: massive flow, pyroclastic material, block and ash (Fig. 2).

The Mt. Taranaki edifice is geomorphically the dominant feature of the Taranaki Peninsula and is surrounded by a near circular ring plain expanding up to 30 km from the volcano. The surrounding plain consists of a range of deposits that record numerous mass movement events with sedimentological features recoding a spectrum of rock-water rheologies. The most distinctive feature is the surface mounds (hummocks) that were originally called conical hills (Fig. 3). They were initially thought to be volcanic blisters of lava flow or related to glacial outwash deposits (Grange, 1931).

Figure 1: Overview of Mt. Taranaki looking northeast.

The 1980 Mt. St. Helens eruption was the first occasion when a large volcanic debris-avalanche was observed and documented at the time of emplacement (e.g., Glicken, 1986) providing a model for the interpretation of similar deposits elsewhere (e.g. Crandell et al., 1984).

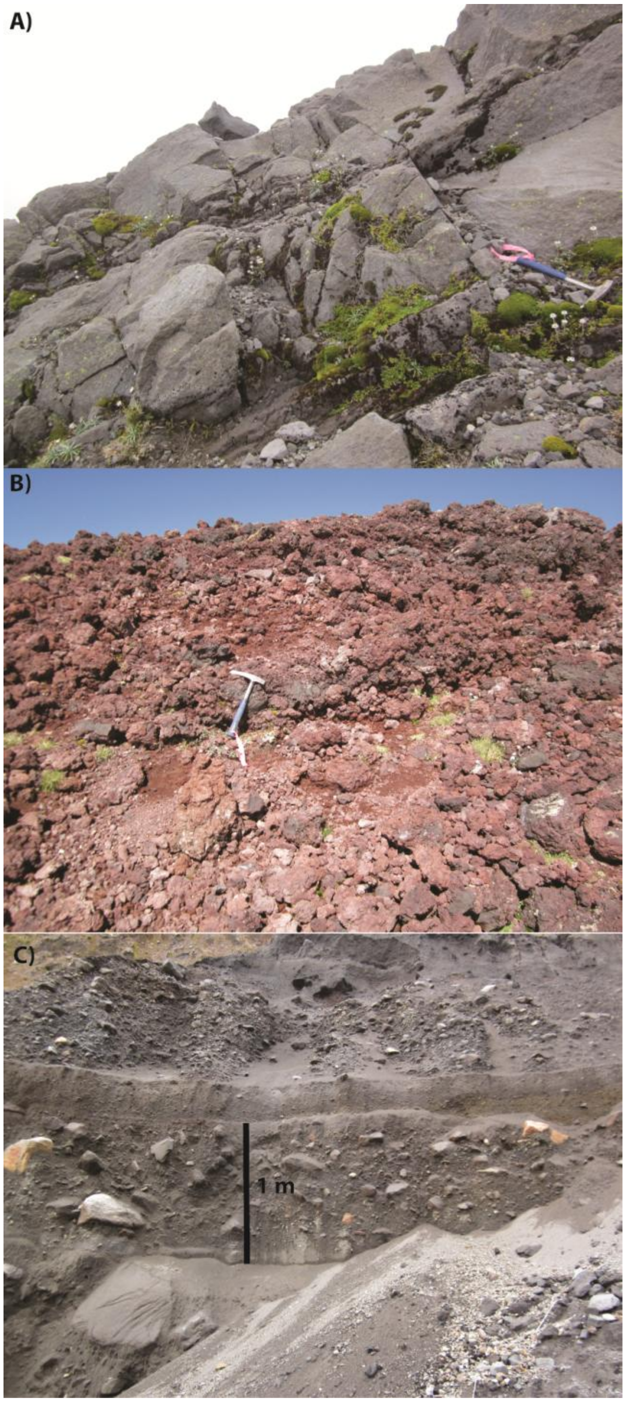

Figure 2: Three main geological units present at Mt. Taranaki. A) Massive flow, B) Pyroclastic flow, C) Block and ash flow.

1.1 Hummocks

The existence of hummocky mounds has now been reported in large landslide deposits around the world. They are particularly common in association with slope failures of volcanic edifices (e.g. Guthrie et al. 2012) but they have also been reported in non-volcanic slope failure deposits (e.g. McConnell and Brock, 1904). A wide range of mechanisms has been proposed to explain their formation. Recent proposed mechanisms regarding the genesis of hummocks concentrate on the transport/deposition dynamics of debris and rock avalanche and the post-depositional landscape responses:

- They form when finer deposits accumulate around a large boulder that acts as an anchor (Goguel and Pachould, 1972).
- They form due to vibratory movement concurrent with landslide events which segregate clasts within the deposit (Cassie et al., 1988).
- They form due to the presence of cohesive and frictional units which create different deformation rates (Shea and van Wyk de Vries, 2008).
- They represent large scale dewatering structures similar to sand-volcanoes (Evans et al., 2009).
- They represent conditions where the velocity of the debris in the flow direction is less than velocity perpendicular to flow direction (Dufresne and Davies, 2009).
- They represent the morphological expression of brittle layer deformation associated with spreading during a debris avalanche (Paguican et al., 2014).

1.2 Jigsaw clasts

Jigsaw fractures in clasts have also been noted in volcanic debris avalanches (e.g. Ui and Glicken, 1986; Roverato et al., 2011; Tost et al. 2014) and rock avalanches (e.g. Shreeve, 1959; Betran and Texier, 1999; Pollet and Schneider, 2004) at numerous locations around the world but their systematic orientation mapping has rarely been undertaken. In general, the jigsaw fractures are interpreted to be the result of fracturing associated with the transport of large landslide debris (Barth, 2014). Weidinger et al. (2014) showed that jigsaw fractures were also observed at the mm-scale in thin sections of clasts in rock avalanche deposits.

2 PREVIOUS WORK

Three late Quaternary laharic breccia deposits extending west and south-west from Mt. Taranaki were mapped by Neall (1979). These deposits with their characteristic mounds or “conical hills” (Morgan & Gibson 1927), were named Opua, Warea and Pungarehu formations; later to be identified as debris-avalanche deposits. The most spectacular of the three is the Pungarehu Formation, which has an estimated minimum volume of 7.5 km^3. The Punagrehu Formation is the best-exposed debris avalanche deposit of the volcanic ring plain which dominates the landscape with distinctive mounds ranging in average height from 5 m near the coast to 30 m near the base of Mt. Taranaki (Neall, 1979). The deposit overlies the 22.1 ka Kawakawa Tephra.

The main internal structure of debris avalanche deposits is comprised of two major components: 1) fragmental rock clasts, and 2) matrix. A fragmental rock clast is defined as a fragmented or deformed piece of lava or layered volcaniclastic material commonly preserving stratification and/or intrusive contacts formed within the original volcanic edifice (Alloway et al., 2005). The internal structure of the Mt. Taranaki debris avalanche deposits is characterised by fragmental rock clasts (FRC) and matrix. The matrix is unsorted and unstratified and may contain rip-up clasts of plastically distorted soil, peat and tephra layers as well as wood fragments entrained from the terrain beneath. Intra-clast matrix is a separate entity that occurs between fragmental rock clasts and megaclasts of the original lithologies from the edifice (Alloway et al., 2005). The clasts can be large coherent fragments of rock, intact portions of the original edifice strata, fragmented clasts that have been partially disaggregated and those that have completely disaggregated to form a "domain" of rock fragments that are recognisably related and could represent a jigsaw puzzle. The lithology and ratio of matrix to FRCs can vary within each debris-avalanche deposit depending on the characteristics of the source area, related volcanic activity, as well as flow rheology and interaction with paleo-topography. (Fig. 3).

Ui et al. (1986) provided one of the first studies that quantified the variations in block or clast size and jigsaw fractures within the deposit and spatially across the extent of the deposit. The data showed a pattern of decreasing block size with distance from the source zone (Mt. Taranaki) as a result of collision and transport. In contrast, the number of jigsaw fracture clasts were more common closer to the source zone. It was also noted that abrasion and other clast-to-clast contact resulted in distinctive impact features (Ui et al., 1986).

Zernack et al. (2012) further characterised the sedimentology of the Mt. Taranaki debris avalanche deposits and redefined the stratigraphy of the ring plain volcaniclastics with the discovery of 5 new debris avalanche events (Fig. 4). From this study, a clear relationship between the evolution of the volcanic centre and the growth of a cone and destruction of the cone was established, confirming a cyclical process. The results from the work by Zernak et al. (2012) suggest that large edifice collapses tend to occur with a frequency of one event per 16 ka while the expected volume of these large slope failures is estimated to be 7.5 km^3, similar to the Pungarehu Fm.

Using a scanning electron microscope (SEM), Procter (2009) examined rock fragments, pyroxene and hornblende crystals within the Opua Fm. (a debris avalanche deposit located south of the Pungarehu Fm. see Fig. 4) matrix that typically showed micro cracks from impacts and splitting of the particles. The rock fragments were subrounded to subangular with curved conjugate pairs of micro cracks visible at 90- 350x magnification, yet very little jointing was observed or evidence of surface friction or scratching from other grains with only a small number of grains exhibiting hackles in one or two locations on the grain. Micro cracks that were present were typically one or two cracks that migrated across the entire shard. The greatest impacts on the surface of the glass shards may not be attributed to a decompression or explosion during initiation of the debris avalanche but rather to the relative softness of the glass. Procter (2009) suggested that since hackles are concentrated in localized areas (on the grain) they must result from grain to grain contact during flow. Procter (2009) also determined that the proportion of fragments displaying micro cracks in samples from longitudinal and lateral cross-sections showed few consistent variations or a spatial pattern of distribution. Overall, axial deposits show the highest proportions of micro cracked crystal grains compared to those from marginal areas of the deposit.

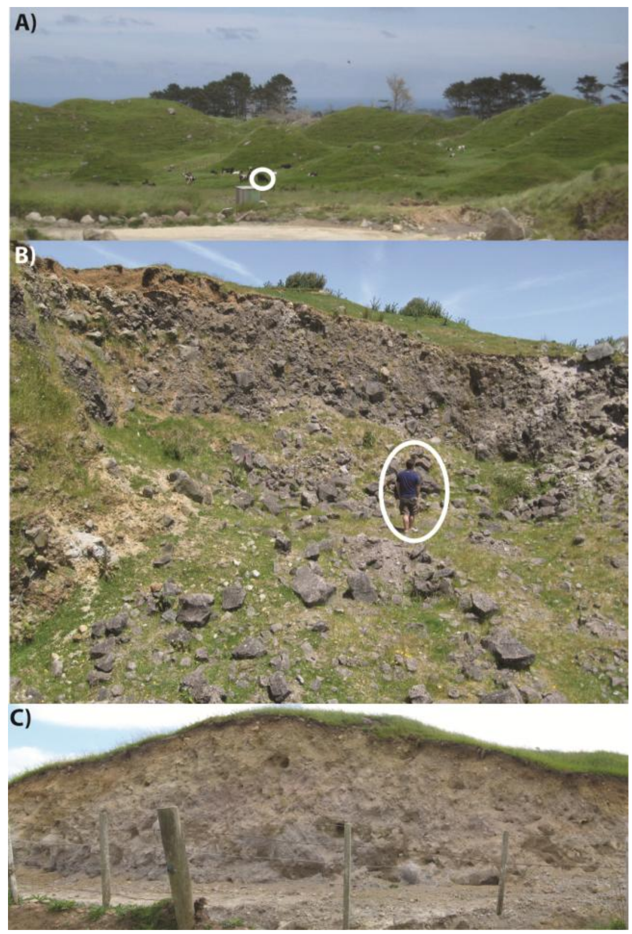

Figure 3: A) Overview of hummocks in the debris avalanche deposits to the west of Mt. Taranaki (cow circled for scale), B) Clast-rich hummock exposure in a borrow pit (person circled for scale), C) Matrix-rich hummock exposure through an irrigation channel.

A recent study of Roverato et al. (2015) showed similar spatial distribution patterns of micro-cracks throughout the Pungarehu Fm. However, Roverato et al. (2015) also identified clusters of fractured clasts and micro cracks within the deposits and attributed this chaotic distribution to be more related to mega-clasts or shear zones within the flowing mass. It is considered that the more regular occurrence of the matrix at distal locations is a result of collisional and frictional regimes influencing transport and emplacement.

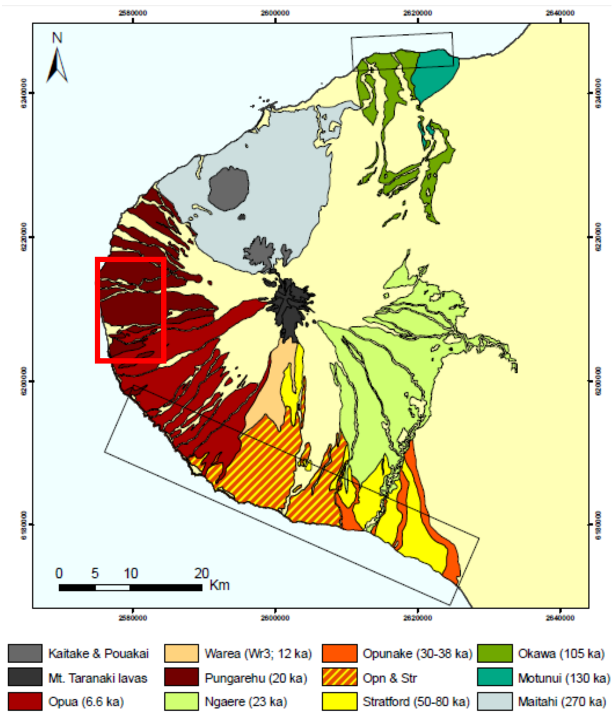

Figure 4: Map of identified debris avalanches on Mt. Taranaki (Zernack, 2008). Study area for this project outlined in red.

3 METHODOLOGY

In this study, terrestrial photogrammetry techniques were used to characterise the orientation of jigsaw fractures. This method allows for measurements to be obtained from clasts that are difficult to access safely and minimises disturbing the clasts. The application of terrestrial photogrammetry to get information on the orientation, persistence and roughness of discontinuities has a long history (e.g. More, 1974) but the technique has gained in popularity recently with the implementation of the photogrammetric and georeferencing operations in software to create three-dimensional models (e.g. Sturzenegger and Stead 2009).

Fractured clasts at seven field stations were investigated as part of this project. All stations studied were outcrops from the Pungarehu Fm. debris avalanche deposit on the west side of Mt Taranaki. Cross-sectional exposures through the debris avalanche deposit were provided by coastal cliffs, road cuts, gravel quarries and borrow pits. Digital imagery of the fractured clasts was acquired using a Nikon 300s digital SLR camera with a 105 mm focal length lens (Fig. 5A). The images were processed using the software Sirovision (CAE Mining, 2012) to create 3D models of the clasts (Fig. 5B). This software has previously been used successfully to collect orientation data at natural cliffs in New Zealand (Brideau et al. 2012).

The 3D models were georeferenced using the position of the camera (determined in the field using a handheld GPS), the distance between the camera and the outcrop (measured with a rangefinder), and the bearing of the line of sight of the camera to the outcrop (measured with a compass). This methodology has been demonstrated by Maconochie et al. (2010) to provide reliable discontinuity orientation measurements. The orientation was extracted from the 3D models by defining the plane or trace corresponding to a discontinuity (Fig. 5B). Based on their morphology and appearance, the discontinuity were characterised where possible into fractures (rough and fresh surfaces without staining) and joints (smoother surfaces with weathering stain).

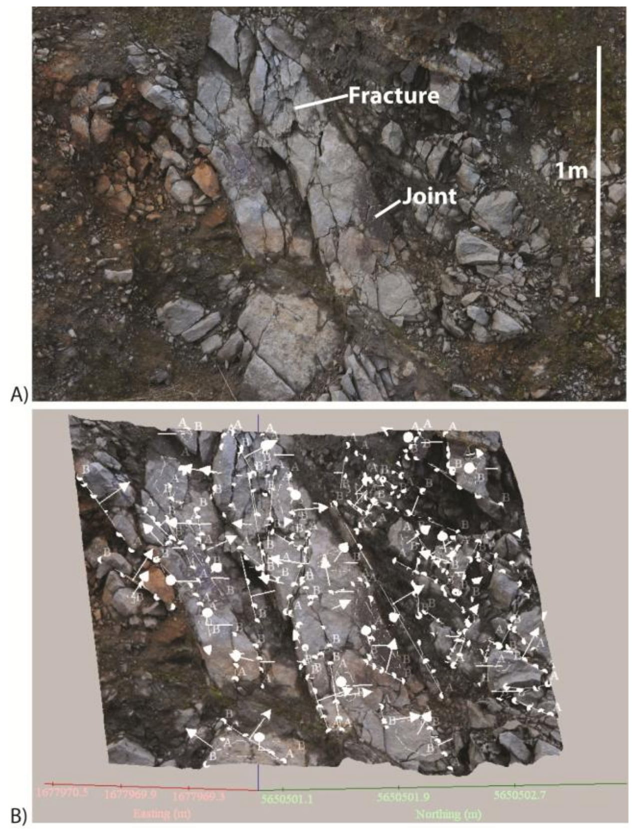

Figure 5: Photograph of a clast in the debris avalanche at site 3, A) Example of fracture and joint discontinuities, B) 3D model with discontinuity surfaces and traces identified.

4 RESULTS

A total of seven distinct clasts located within 4 m depth of the present day ground surface and between 0.5 and 3 m in diameter were investigated. In all but one instance, the jig-saw clasts occurred as a single feature (i.e. no clusters).

The locations of the station visited and associated stereonets of the pole to the discontinuity identified are presented in Figure 6. A total of 355 discontinuities were

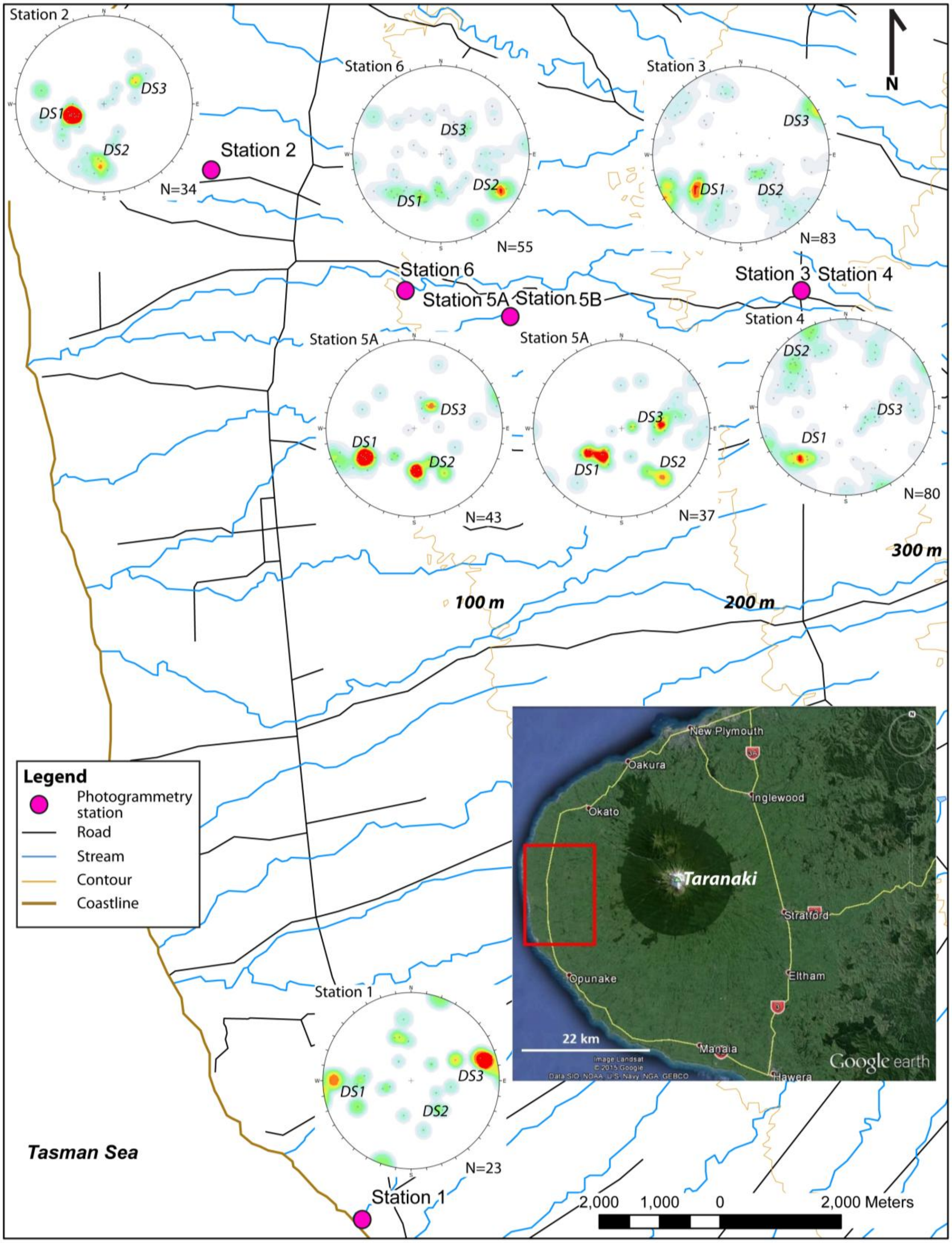

Figure 6: Location of station where terrestrial photogrammetry models were generated and the stereonets of the associated discontinuity orientations.

identified at seven stations. Because the fractured clasts investigated were found in outcrops with various orientations, the Terzaghi weighting (Terzaghi, 1965) for a planar surface was used in the software DIPS (Rocscience, 2012) to minimize the sampling bias in density contouring the datasets. The discontinuity pattern (Fig. 6) at all seven stations was consistent with a dominant concentration of discontinuities (DS1) with a dip direction between 045-080° (NE-ENE), a secondary concentration (DS2) with a dip direction between 315-350° (NW-NNW), and a third grouping (DS3) with a dip direction between 215-240° (SW-WSW). In his engineering geology characterization of the Taranaki volcanic edifice, Deutschle (2013) also found three dominant discontinuity sets in the rock masses.

A symbolic pole plot of the discontinuity types (Fig. 7) reveals the dominant discontinuity set with the NE-ENE dip direction is sometimes associated with discontinuities interpreted as joints (Fig. 7A) while at other stations the dominant discontinuity set is associated with interpreted fractures (Fig. 7B). This is attributed to the variability in clast texture and structure (i.e. homogenous vesicular vs. jointed massive andesite) with discontinuities occurring preferentially along a pre-existing plane of weakness.

5 DISCUSSION

The orientation of discontinuities in landslide debris is not typically investigated. In deep-seated gravitation slope deformation discontinuity orientations in and out of the moving mass are sometimes characterised to provide constraints on the modelled failure mechanism (e.g. Pritchard and Savigny, 1991). In rapid rock slope failures, the authors know only of the study by Carpenter (2002) that investigated the discontinuity orientation in and out of the deposit of a large rockslide in the Himalaya. The orientation of discontinuity sets between clasts in different sections of the deposit was found to be consistent. A similar orientation between the discontinuity orientation pattern of the clasts in the deposit and the in-situ rock mass at the base of the initiation zone was also observed (Carpenter, 2002). While the constant orientation within the deposit by Carpenter (2002) is similar to the results presented in this paper, the rockslide deposit from the Himalayan example consist of one (or a few) intact block(s) that travelled en-masse with most of the deformation occurring at a relatively thin basal zone.

The constant discontinuity orientation in clasts at stations separated by approximately 10 km may be explained by the two emplacement mechanisms. However, neither mechanism explains all the features observed in the debris avalanche deposits at Mt. Taranaki. In the first model, the clasts are located in hummocks near the top of the deposit, they could be part of the non-fragmenting carapace of a large landslide as suggested by Dunning and Armitage (2011) and Davies and McSaveney (2011). The discontinuities recorded in this study would then be joints and fractures already present in the clasts or fracturing of the rock mass during the initial detachment (failure) from Mt. Taranaki. This model implies that the upper layer of the failed mass underwent no fracturing during transport and little to no reorientation of the clasts, which is consistent with a laminar flow of the debris. Two-dimensional discrete element modelling by Thompson et al. (2010) of volcanic edifice collapse supports this emplacement model. A shortcoming of this mechanism is that it can't explain why the fractured clasts are surrounded by a homogeneous gravelly matrix that does not resemble the rock mass conditions in the initiation zone (Fig. 3 vs. Fig. 4).

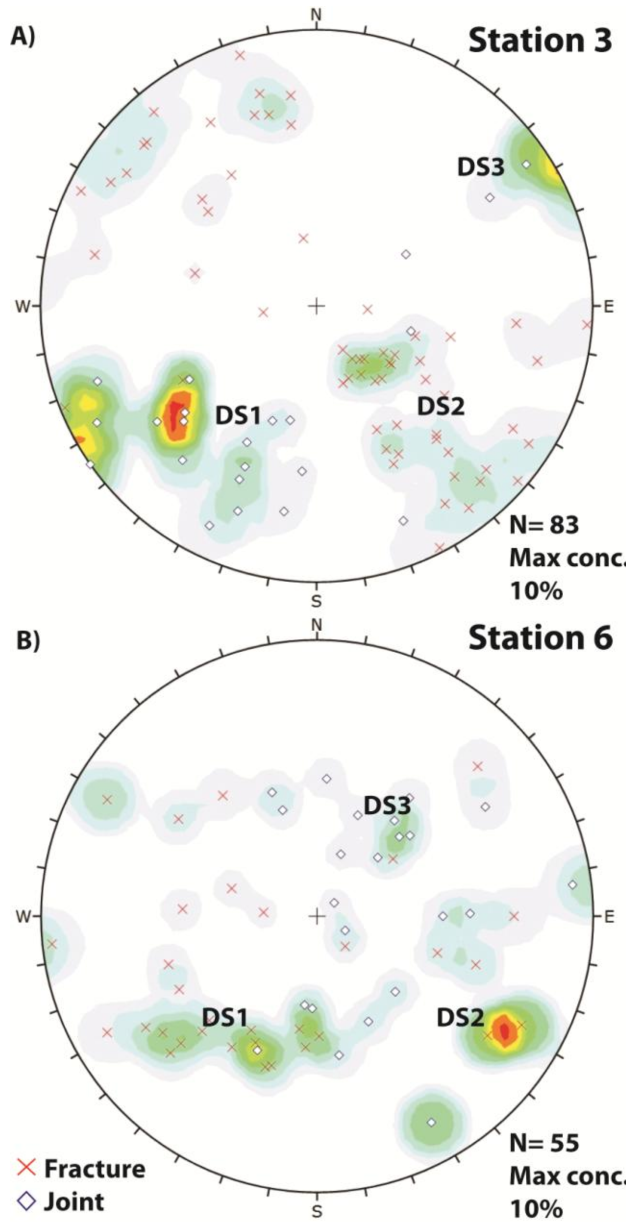

Figure 7: Symbolic pole plot showing the orientation of the fractures and joints observed at station A) 3 and B) 6. See figure 6 for the location of the sites. Terzaghi weighting applied to contouring and maximum contour set at 10% by the user.

In the alternate model, the fracturing of the clasts occurs in the late stages of the emplacement mechanism to prevent the infilling of the fracture with matrix and the disintegration and subsequent mixing of the clast fragments (Dunning and Armitage, 2011). Shea and van Wyk de Vries (2008) compiled sedimentological and geomorphological features of several volcanic debris avalanche deposits around the work and compared them with the results of physical models. They found that the central and distal portion of the deposits contain late emplacement compressive structures (Shea and van Wyk de Vries, 2008). Recent three-dimensional discrete element modelling by Rait et al., 2012 has demonstrated that dynamic fragmentation of rock clasts can occur at high compressive strain rate. This implies that rapid loading can result in rock damage with relatively small strain. Currently the model by Rait et al., (2012) is thought to only represent the conditions at the base of large debris and rock avalanches and the mechanism has not demonstrated to be applicable to clasts near the top of the deposit surrounded by gravelly material.

The first mechanism, which suggests that the upper level of a debris avalanche travels as a laminar flow, is considered to be the most applicable because while some impacts between clasts is expected in a large debris avalanche travelling up to 25 km from its source zone (as documented by Ui et al., 1986, Procter 2009 and Roverto et al., 2014), the discontinuity pattern documented in this study from the Pungarehu Fm. is similar to the pattern recorded by Deutschle (2013) for the in-situ source material on the flanks of Mt. Taranaki suggesting that intense comminution is not occurring in the upper level of the debris avalanche during transport and emplacement. This first model is also consistent with other field observations around the world that found evidence that little mixing occurs during the travel and emplacement of debris from large rock slope failures (e.g. Strom, 2006).

6 CONCLUSIONS

Terrestrial photogrammetry techniques were used to characterize the discontinuity orientation pattern in a large debris avalanche deposit that initiated from Mt. Taranaki on the North Island of New Zealand. The discontinuity orientation pattern from jigsaw mega-clasts (>1 m) in the upper part of the deposit at seven stations separated by more than 10 km was found to be remarkably consistent. Based on this result, a laminar flow in the upper part of the travelling failed mass is considered to be the most likely emplacement mechanism.

ACKNOWLEDGEMENTS

The authors would like to thank E. Fea for comments on the manuscript and T. Davies for discussions on fracturing during large rock slope failures and their subsequent emplacement mechanisms.

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