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Fractures in an Andesite Lava Flow at Mt Ruapehu and its Implications for Fracture Modelling in the Rotokawa Geothermal Reservoir, New Zealand

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Abstract

Fluid flow in the high-temperature (320°C), andesite-hosted Rotokawa geothermal reservoir (New Zealand) is largely controlled by fractures and faults. In preparation for developing fracture models and aid with the targeting of permeable fractures, this paper presents the analysis of fractures in a surface analogue on the Mt Ruapehu volcano, New Zealand, using two complementary datasets: (1) a 100 m long scanline where fracture location, orientation, and length were measured by hand, and (2) a terrestrial laser scanner (TLS) survey acquired over the entire outcrop. The majority of fractures form weakly clustered sub-vertical cooling joints, with six dominant dip directions identified on the TLS survey, suggesting the hexagonal shape typical of columnar joints in basaltic lava flows. The scanline survey presents only three of these orientations, which is inferred to be due to the sampling of different fractures. Preliminary analysis of fracture length on the scanline survey highlights the high degree of fracture connectivity and suggests a log-normal distribution. A subset of sub-horizontal, highly clustered fractured is observed only on the scanline and may be linked to intra-flow layering.

This paper also summarises findings from the statistical analysis of fractures observed in acoustic borehole televiewer (BHTV) logs and drill-cores from the Rotokawa andesites. There, fractures are predominantly steeply dipping and striking NE–SW, parallel to the maximum horizontal compressive stress direction and the regional structural trend. Fracture width is best fitted by an exponential distribution. The fracture spacing of the main fracture sets follow a log-normal, power-exponential or gamma distribution, apart from the N-S striking fracture set which is best modelled by a power-law. A change of fracture spacing distribution is noted at c. 1–5 m, with exponential and log-normal best fitting lower and higher spacing, respectively, and may correspond to the threshold at which fracture interaction occurs. The spacing and width distributions differ from the power-law distribution found in crystalline-hosted geothermal fields. These distributions indicates the presence of mechanical layers within the Rotokawa andesites, either associated with unidentified faults, or with the intercalation of permeable, mechanically heterogeneous breccia layers and massive lava flow interior. Though fractures display a preferred strike consistent with them being of tectonic origin, their geometries are likely to have been affected by fractures formed during the emplacement and cooling of the lava flow. Integrating these observations will be fundamental for developing reliable fracture models at the Rotokawa Geothermal Field, and in other volcanic-hosted geothermal reservoirs.

Introduction

Fluid flow is inferred to be controlled by fractures and faults in a number of geothermal systems but the identification of permeable fracture networks often remains problematic, and reservoir-scale faults can act as both fluid flow pathways or barriers within reservoirs [Rowland and Simmons, 2012]. Twenty-three large high temperature hydrothermal systems occur in the Taupo Volcanic Zone (TVZ), New Zealand, with an estimated total of 4.2 GW thermal output [Bibby et al., 1995]. The electrical production capacity from TVZ geothermal resources is currently 980 MW, 14–16% of New Zealand’s electricity production, and is set to increase to 21-29% by 2040 (New Zealand Energy Outlook 2013).
Improving the targeting of permeable zones which locally promote the flow of hot fluids is of primary importance for developing geothermal resources in the TVZ.

Fracture models, such as discrete fracture networks (DFNs), offer a predictive tool for evaluating the fracture distribution and the associated permeability in a reservoir based on the knowledge of the statistical distributions of fracture’s geometrical attributes (orientation, length, spacing and aperture) across a range of scales [Chilès, 2005]. DFNs can be constrained by structural, lithological, geomechanical and seismological data [Barton et al., 2013, Bonneau et al., 2013, Pochet et al., 2013]. To date, few fracture models have been developed in geothermal reservoirs [see Sausse et al., 2010, Maffucci et al., 2013, Barton et al., 2013, Marakchi et al., 2013]. These projects were performed for enhanced geothermal systems (EGS) applications where the host formations are sedimentary or crystalline, and the thermal stress control on the fracture processes is limited compared to high temperature reservoirs (> 200°C).

High temperature geothermal systems hosted in lava flows are common in the TVZ and worldwide [Rae, 2007, Bertani, 2012, Sepulveda et al., 2012]. In these reservoirs, porosity is low and fluid flow is structurally controlled [e.g. Rosenberg et al., 2009, Siratovich et al., 2014]. Fracture networks result from the emplacement of the lava flow, and due to tectonic, thermal and hydrothermal processes [Fournier, 1998, Gudmundsson et al., 2001, Hetényi et al., 2012, Siratovich et al., 2014]. Undeformed lava flows typically have a heterogeneous permeability distribution with high permeability units composed of the densely fractured upper colonnades and rubbly flow margins, and low permeability flow interiors [Pollyea and Fairley, 2012]. High permeability has been related to brecciated rhyolites at the Wairakei-Tauhara Geothermal Field, TVZ [Rosenberg et al., 2009, Milloy and Lim, 2012]. Columnar joints provide vertical flow pathways which result in an anisotropic permeability tensor and have an impact on the distribution of fractures in geothermal systems hosted in lava flows [Brathwaite et al., 2001, Zuquim and Rowland, 2013].

This work aims to evaluate the fracture distribution in the high temperature (320°C), Rotokawa Geothermal Field located in the TVZ, which has a 174 MW installed electricity production capacity [Quinao and Sirad-Azwar, 2012]. The deep aquifer is hosted in a 800 to 2100 m thick unit of andesite lavas and breccias, where fluid flow is mostly controlled by fractures and faults. The reservoir has a heterogeneous permeability distribution, and pressure drawdown analysis reveals that it contains a barrier to flow related to one of the three main inferred NE–SW striking normal faults [Quinao and Sirad-Azwar, 2012, Wallis et al., 2013]. Heterogeneity in the orientation and density of fractures and the orientation of the horizontal stresses is also observed at the borehole scale [McNamara et al., submitted]. Textural and mineralogical variations of the andesite lavas and breccia at the nearby Ngatamariki Geothermal Field are consistent with products of a complex composite volcano, such as Mt Ruapehu located at the southern tip of the TVZ, with the main edifice forming the Rotokawa Andesite [Chambefort et al., 2014]. Andesite flows at Mt Ruapehu are thus chemically and morphologically good analogues of the Rotokawa andesites prior to their burial.

An andesite lava flow of the Whakapapa Formation [Price et al., 2012] located at Iwikau Village, on the west slope of Mt Ruapehu, has been selected to evaluate the distribution of fractures related to the emplacement and cooling of a lava flow prior to its burial. This outcrop, here referred to as “Happy Valley”, presents the interior of a single andesite lava flow with the lower and upper auto-brecicciated zones apparent in places (Figure 1A, 2D). This paper presents the preliminary findings on the orientation, length and density of fractures evaluated from scanlines and terrestrial laser scanner (TLS) surveys. The results from the scanline and TLS surveys are compared to evaluate reliability of the measurements for each technique. Findings of a statistical analysis of fracture orientation, width and spacing from BHTV logs acquired in three wells in the Rotokawa andesites are also summarised. The implications for the generation of reliable and predictive DFNs models at Rotokawa are discussed.
1 Data and Methods: scanline and terrestrial laser scanner surveys

Fracture attributes are commonly manually described in outcrops using one dimension (1D) scanline surveys, where fracture characteristics are measured along a line, or 2D window surveys where fractures are described within a fixed rectangular area [Priest, 1993; Mauldon et al., 2001]. This work uses a combination of (1) standard scanline samplings and (2) TLS surveys. TLSs emit and receive laser pulses at predefined vertical and horizontal angular intervals. The resulting high density 3D point cloud is a measurement of the location (x, y, z) and backscattered energy reflectivity of each reflected pulse [Pfeifer and Briese, 2007; Buckley et al., 2008]. Scanlines allow the detailed measurement of small fractures (> 1 mm wide in this study) but are only in 1D. TLS surveys allow a comprehensive fracture analysis of an entire outcrop, which is therefore less subject to observation biases than scanlines or window surveys of limited sizes.

The location, orientation, length, and abutting relationships of 200 fractures were measured along a 99.5 m scanline (Figure 1A). The scanline has a varying trend along the profile, usually with a low plunge. To mitigate the systematic under-sampling of fractures sub-parallel to the scanline trajectory, a weighting derived from the angle between the fracture plane and the scanline trajectory is applied to the raw dataset, forming the “Terzaghi corrected” dataset [Terzaghi, 1965]. The reading error of compass hand measurement is 2–3° and a maximum allowable correction weight of 10 is applied [Massiot et al., 2015]. Three clustered zones of sub-horizontal fractures were measured (yellow stars on Figure 1A, Figure 2E). The first cluster (at 7–8 m along the scanline) intersects the scanline and is included into the analysis. The two other clusters (at 87 and 99.5 m) occur close to the scanline and were measured separately. Changes of facies of the andesite lava flow, i.e. either massive lava or breccia, were also noted. The upper breccia is mostly covered by vegetation and the lower breccia is intermittently observed at the bottom of the outcrop (Figure 1A).

TLS scans and photographs were acquired using the Riegl LMS-Z420i instrument from three positions precisely located by GPS measurements. The acquisitions from several locations limit the blind areas that the laser rays cannot directly access (e.g. behind a building). Scans acquired from different locations were merged using the GPS measurements resulting in a point cloud of > 2 million points. The merging was adjusted with a plane patch filter algorithm in the RiScanPro software resulting in a precision of 2 cm. Few blind areas remained in the final dataset (Figure 2C). The zones where the point cloud captured vegetation or buildings were manually deleted in the CloudCompare software [Brodu and Lague, 2012]. The merged scan was sub-sampled to c.a. 450 000 points with a point every 4 cm. The normals were calculated using a local quadratic approximation on local planes of 0.15 m radius. The orientation of the normals were then transformed into the dip magnitude and dip direction of the local plane for each point (Figure 1B-F). A single fracture plane is represented by numerous points. The spatially regular distribution of points in the point cloud ensures that the number of normals of specific orientation is proportional to the area of the fractures of this orientation.

The highest values of the local curvature and roughness scalar fields calculated on the point cloud correlate to the contacts between contiguous fracture faces (Figure 1G-H). These scalar fields will be analysed in the following of this project with an edge detection algorithm to individualise fracture planes, and evaluate the fracture orientation and length distribution more precisely.

2 Results: geometrical characteristics of fractures at the Happy Valley andesitic lava flow

2.1 Fracture orientation

Stereonets of the poles to planes of fractures are displayed in Figure 5 with a density contouring generated by a kernel density function in R [R Development Core Team, 2008] capable of handling the large TLS dataset. This contouring method is based on the number of poles per area and provides similar contours as a standard Fisher density method.
Figure 1: Scanline and TLS survey at the Happy Valley outcrop, Iwikau Village, Mt Ruapehu.

A) Panoramic view of the outcrop showing the breccia layers, the trace of the scanline (dark blue line), the sub-horizontal fracture zones and sub-vertical cooling joints. Black squares show the location of enlarged sections in Figure 1B and C-H. Arrows labelled ‘1’ and ‘2’ indicate the same features present in all diagrams as a reference point. B) Oblique view of the TLS point cloud looking upwards, coloured according to the dip direction. C-D): Photographs of the outcrop where the orientation of a rock face and fractures measured by hand are compared to results from the TLS in E). F) TLS point cloud coloured according to the local dip direction. G) Areas of the TLS point cloud with high curvature values. H) Areas of the TLS point cloud with high roughness values.
Figure 2: A-B) Photograph of the base of the flow showing a brecciated area. B) Photograph A with a facies overlay: breccia in yellow, lenses of massive lava within the breccia in red. A fracture propagating through massive lava and breccia is indicated (blue line). C) TLS point cloud of the area shown in A. The red star indicates a blind area. D) Photograph of a rock face intersected by sub-horizontal fractures. Black square represents the area shown in E. E) Photograph of a cluster of sub-horizontal fractures (white arrows) intersected by a sub-vertical open fracture (yellow dotted line). F) TLS point cloud of the area shown in D. Numbered arrows in figures A-C and D-F mark features for points of reference.

Figure 3: Lithologies observed in cores from the Rotokawa Andesite. a) Moderately altered lava with low fracture density. b) Strongly altered lava, low to high fracture density. Fractures mostly consist of epidote veins. c) Moderately altered breccia with low fracture density. d) Breccia with vein intersecting a clast. (NF: natural fractures, Cl: clast).

Figure 4: BHTV log with travel-time and amplitude images, and interpretative diagram showing four fractures of varying width (w) and normal spacing (s). BHTV logs are displayed unwrapped with north on the left and right, and south in the middle.
The scanline dataset shows two fracture populations: the main population (82%) of fractures are moderately to steeply dipping (≥ 30°), and a subordinate population (FSs1) is gently dipping (< 30°; Figure 5 A). The under-sampling of the sub-horizontal fractures is mitigated by the Terzaghi correction (Figure 5 D). The steeply dipping fractures (≥ 30°) of the Terzaghi-corrected dataset form three fracture sets: the dominant fracture set 2 ‘FSs2’ striking NW–SE (pole to planes trending NE and SW), and subordinate fracture sets ‘FSs3’ and ‘FSs4’ striking NE–SW and ENE–WSW, respectively (Figure 5 E). A k-means clustering algorithm applied to the Terzaghi corrected dataset confirms the visual assessment of the delineation of fracture sets FSs1 and FSs2, but cannot confirm if fracture sets FSs3 and FSs4 are individual sets or form a single group.

The TLS dataset indicates a similar distribution for the steeply dipping fractures (≥ 30°) with fracture sets Fst2 and Fst4 corresponding to fracture sets FSs2 and FSs4 on the scanline (Figure 5 C). Subordinate fracture set FSs3 striking NE–SW observed on the scanline is not present on the TLS dataset. Instead, a subordinate group striking NNE–SSW is delineated (fracture set Fst5). Sub-horizontal fractures are rare on the TLS dataset (2.5% dipping < 30°).

Figure 5: Stereonets of pole to fractures at the Happy Valley andesite lava flow. A) Scanline survey, raw dataset. B) Scanline survey, raw dataset, fractures dipping ≥ 30°. C) TLS survey. D) Scanline survey, corrected for orientation bias. E) Scanline survey, corrected for orientation bias, fracture dipping ≥ 30°. F) Synthetic stereonet representing columns with rectangular, pentagonal, and hexagonal section. All stereonets are Schmidt lower hemisphere projections, with density contouring using the k2de R package.
2.2 Fracture terminations and length distribution

Fracture length is analysed using the scanline dataset and is subject to several observation biases [Priest 2004]. As a preliminary analysis, the ‘i-bias’, related to the high- and low- measurement cut-offs, is ignored by focusing on fractures where both terminations were identified. The treatment of the ‘f-bias’ and ‘g-bias’, related to the preferential intersection of the long fractures by the outcrop and by the scanline, respectively, will be accounted for in future work. Each fracture termination was noted according to the following classification: 1): the fracture tip is observed, 2): the fracture terminates against another fracture, 3): the fracture tip is observed and occurs within a breccia facies (particular case of 1). A double digit code indicates the type of both termination for each fracture. A profile of the fracture length and termination classification along the scanline is displayed in Figure A. The outcrop has a high proportion of fractures that terminate against other fractures (termination type 2). Of the 117 fractures where both terminations were visible, 37% of fractures have both terminations against other fractures (types 2–2), and an additional 44% have at least one termination against another fracture (types 1–2 and 2–3).

The distribution of fracture length reflects the high proportion of fractures terminating against other fractures (Figure B). All fractures, bar one, are < 5.5 m long. The exception, a 11.6 m long fracture, is a sub-horizontal fracture in the middle of the lava flow. Two sub-vertical fractures, of 5 and 6.5 m long, did not intersect the scanline (and are not included into the scanline dataset) but were measured as indicators of long fractures. The median fracture length is 0.54 m and 79% of fractures are ≤ 1 m long (Table 1). The length of fractures where one or both terminations could not be determined are censored, i.e. the measurement is a lower bound. These censored fractures are longer than the fractures where both terminations are observed (1.06 m median length).

<table>
<thead>
<tr>
<th>n</th>
<th>min</th>
<th>median</th>
<th>mean</th>
<th>sd</th>
<th>Cv</th>
<th>max</th>
</tr>
</thead>
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<tr>
<td>Length of full fractures (m)</td>
<td>117</td>
<td>0.48</td>
<td>0.78</td>
<td>1.21</td>
<td>1.55</td>
<td>11.6</td>
</tr>
<tr>
<td></td>
<td>(292)</td>
<td>(1.03)</td>
<td>(1.90)</td>
<td>(1.84)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length of censored fractures (m)</td>
<td>74</td>
<td>1.28</td>
<td>1.51</td>
<td>1.14</td>
<td>0.75</td>
<td>5.3</td>
</tr>
<tr>
<td></td>
<td>(177)</td>
<td>(1.34)</td>
<td>(0.99)</td>
<td>(0.74)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Summary of fracture length and linear density statistics for the scanline dataset. The parameters obtained from the Terzaghi corrected dataset are indicated in brackets; n = number of fractures; min = minimum; sd = standard deviation; Cv = coefficient of variation; max = maximum.

2.3 Linear fracture density

A systematic analysis of the spacing distribution of each fracture set is necessary before firm conclusions can be made on the fracture density and spacing. As a preliminary step, the linear fracture density is described here, i.e. the number of fracture occurring in successive metre-long intervals along the scanline, measured in fractures per metre (f.m$^{-1}$). The mean linear density indicates a moderate level of fracturing (2 f.m$^{-1}$), although 15 individual metre-long intervals of scanline are not intersected by any fracture (Table 1, Figure C).

The coefficient of variation $C_v$ ($C_v$=standard deviation/mean) indicates the dispersion of the distribution around the mean. The density of sub-horizontal fractures (dip < 30°) has a high coefficient of variation ($C_v = 2.9$) indicating that there are strongly clustered. Steeply dipping fractures are weakly...
clustered (Cv = 1.09). The sub-horizontal fractures are the most subject to the orientation bias given their relative orientation to the scanline, and thus are less likely to be sampled. However, visual inspection of the outcrop confirms the presence of these clusters of sub-horizontal fractures (Figure 1). Three zones of closely spaced sub-horizontal, slightly opened fractures are observed (Figure 2). The density measured orthogonally to their mean orientation is 22.7 f.m⁻¹, 30 f.m⁻¹, and 40 f.m⁻¹ with 17, 9, and 40 fractures measured, respectively (Figure 2E).

Figure 6: Fracture length, density and spacing along the scanline. A) Profile along the scanline showing linear fracture density, fracture length and termination type, and intervals of breccia. The fractures where the length was not measured are in grey below the profile. See text for the termination code. B) Histogram of fracture length, corrected dataset, coloured by the termination characteristics. Inset: synthetic log-normal distribution. C) Histograms of fracture linear density for the raw and corrected datasets. D) Histogram of linear fracture density by categories of dip magnitude, corrected dataset.

3 Summary of findings from the statistical analysis of fractures from BHTV logs in the Rotokawa andesites

The analysis and results of the statistical analysis of fractures observed on BHTV logs at the Rotokawa Geothermal Field are detailed in Massiot et al. (in review). As it is of significance for the development of the DFNs, the main results are reported herein.
3.1 Reservoir data: drill cores and BHTV logs

A total of 33 m of core has been sampled from andesitic formations in 14 wells. The cores exhibit a wide range of alteration intensities (Figure 3a-b) and have two facies: massive lava (Figure 3a-b) and breccia (Figure 3c-d). 310 fractures were logged from 21 m of core in massive lava and 35 fractures from 12 m of core in breccia. Fracture width in the cores is between 0.5–3 mm, with two fractures being 5 mm wide. The fracture frequency is five times greater in lavas than in breccias in which veins tend to surround clasts (Figure 3e). Veins also cross the breccia clasts in some occasions (Figure 3f).

BHTV logging yields an image of the inside of a borehole generated by the transmission and reception of ultrasonic pulses. Planar fractures appear as sinusoids on BHTV logs, which are automatically oriented to geographic North using inbuilt magnetometers (Figure 4). BHTV logs have been acquired at the Rotokawa Geothermal field in three wells (RK18L2, RK30L1 and RK32) with the high-temperature (<300°C) ABI-85 tool. The BHTV log resolution is c. 5 mm horizontally and c. 10 mm vertically, and is decreased locally by artefacts such as stick-and-pull and poor borehole or logging conditions [Lofts and Bourke, 1999]. Fractures are analysed following the methodology detailed in Massiot et al. [2015]. Fracture width is the fracture-normal distance between fracture walls, i.e. measurements have been corrected for fracture dip. A total of 1217 fractures have been identified within the 2345 m of the BHTV logs acquired in andesitic formations, as defined from cuttings or inferred from nearby wells and 3D modelling [Rae, 2007, Wallis et al., 2013].

Statistical distributions are fitted to the fracture width and spacing data using a maximum likelihood estimation algorithm [Stasinopoulos and Rigby, 2007]. Five distribution types are evaluated: exponential, gamma, log-normal, power-exponential and power-law, the latter evaluated using a pareto distribution. The truncated versions of these distribution families are used to account for data truncation and censoring. The model selection is based on the relative penalised likelihood of the distributions (deviance) using the Schwarz Bayesian Criterion (SBC; Schwarz [1978], Kolyukhin and Torabi [2012]). The most likely distributions have the lowest SBC deviance. The difference between the lowest deviance $SBS_{\text{min}}$ and the deviance of the studied distribution $SBS_i$ is evaluated for each dataset: $\Delta(SBS_i) = SBS_{\text{min}} - SBS_i$. Fitted distributions with $\Delta(SBS_i) < 2$ are likely, and goodness-of-fit is evaluated with quantile-quantile plots.

3.2 Fracture orientation

Four fracture sets are identified by visual assessment of Fisher density on stereonets (Figure 7). The majority of fractures (FS1) are steeply dipping (>70°) and strike NE–SW, parallel to the maximum horizontal stress (025° ± 11° to 045° ± 15°) ($S_{\text{Hmax}}$; confidence intervals are standard deviations; McNamara et al., submitted). Fracture set FS2 is a subordinate cluster striking N–S, observed in wells RK18L2 and RK30L1. Subordinate fracture sets strike NW–SE (FS3), and NE–SW (FS4) with more gentle dips (37°–63°) than FS1, and are only observed in wells RK30L1 and RK32, respectively (Table 2).

<table>
<thead>
<tr>
<th>Fracture set</th>
<th>All</th>
<th>FS1</th>
<th>FS2</th>
<th>FS3</th>
<th>FS4</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>1217</td>
<td>791</td>
<td>128</td>
<td>58</td>
<td>70</td>
</tr>
<tr>
<td>Well</td>
<td>all</td>
<td>all</td>
<td>RK18L2, RK30L1</td>
<td>RK30L1</td>
<td>RK32</td>
</tr>
<tr>
<td>Mean orientation (dip/dip direction)</td>
<td>81/125</td>
<td>90/310</td>
<td>83/085</td>
<td>76/209</td>
<td>52/308</td>
</tr>
<tr>
<td>Mean width (mm)</td>
<td>11.1±7.2</td>
<td>11.5±7.8</td>
<td>8.8±4.8</td>
<td>7.5±3.1</td>
<td>15.3±7.5</td>
</tr>
<tr>
<td>Mean spacing (m)</td>
<td>1.7±8.4</td>
<td>3.3±15.5</td>
<td>17.3±52.1</td>
<td>11.4±41.4</td>
<td>12.6±25.0</td>
</tr>
</tbody>
</table>

Table 2: Summary of fracture orientation, width and spacing in BHTV logs of the andesite intervals of the Rotokawa Geothermal Field. n: number of fractures. Confidence intervals are one standard deviation.
3.3 Statistical analysis of fracture width and spacing

After considering observation bias and data from the core description, the fracture width is found to be best modelled by an exponential distribution \( f_y(y|\lambda) = \lambda \exp(-\lambda y) \) with \( \lambda \) coefficients between 0.13±0.01 and 0.29±0.02, which should be treated as a lower bound.

The normal spacing, estimated orthogonal to the mean fracture set orientation, varies between 0–58 m with an arithmetic mean of 1.6 m (Table 2). The best fit of each fracture set over the 0.01–50 m spacing range is indicated in Figure 7 and is found to be log-normal, gamma or power-exponential distribution for all fracture sets except FS2. These distributions have a characteristic scale which has not been observed in other geothermal reservoirs hosted in crystalline formations [Barton and Zoback, 1992; Ledesert et al., 1993; Barton et al., 2013]. The characteristic scale may be associated with internal processes or mechanical interfaces linked with stratigraphic layering, cooling joints, flow-banding or faults [Huang and Angelier, 1989; Bonnet et al., 2001]. The subordinate fracture set FS2 striking N–S is best modelled by a power-law distribution, similar to the classic distribution of earthquake magnitudes [Hurst et al., 2008], which suggests that the spacing of this fracture is more likely to be controlled by tectonic processes than by layering [Gillespie et al., 1993].

Low fracture spacings (0.5–5 m) are best modelled by an exponential distribution whereas higher spacings are best fitted by log-normal or power-law distributions, except for the N–S striking dataset and the NE–SW striking fracture set in well RK32. The change of distribution model at different scales may be linked to the threshold at which fractures start interacting with each other.
4 Discussion

4.1 Fracture Orientation

The scanline and TLS analyses show two main fracture populations in the andesite lava flow, that either dip gently (≤ 30°) or moderately to steeply (> 30°). Moderately to steeply dipping fractures form columnar joints. Sub-horizontal fractures appear to represent planes of weakness at intra-flow interfaces which may be related to variations of crystallinity or viscosity, sometimes appearing as flow banding [Schaefer and Kattenhorn, 2004]. Sub-horizontal fractures exert a significant control on the propagation of posterior fractures, as seen on figure 2E where a vertical fracture propagates with successive jogs at each sub-horizontal fracture interface.

Steeply-dipping fractures measured on the scanline can be separated into three or four subsets. The TLS analysis indicates that fractures have six dominant dip directions, which is in agreement with the classic model of pentagonal to hexagonal cooling columns (Hetényi et al. [2012], Figure 5D-F). This difference may be linked to different observation biases affecting the two methods of data collection:

1. Direction of observation: the scanline preferentially samples fractures orthogonal to the scanline (i.e. striking NE–SW on this outcrop oriented NW–SE) and is mitigated by applying the Terzaghi correction. On the other hand, the outcrop presents numerous faces oriented parallel to the outcrop, i.e. striking NW–SE, which are preferentially sampled by the TLS. This orientation bias may explain the highest proportion of fractures belonging to fracture set FSt2 (Figure 5D). However, the TLS survey is less likely to be affected by the direction of observation than the scanline because of the largest coverage of the outcrop and the 3D character of the points cloud.

2. Resolution: the TLS survey samples the main fracture planes presenting a face of at least 10 cm², while the scanline survey also samples smaller features (> 1 mm width).

3. Dimensionality of the fractures: the TLS survey only samples fractures presenting a face, while fractures located within a fracture surface are also sampled on the scanline survey. This impacts particularly the sub-horizontal fractures appearing as slightly opened fractures within a high angle fracture plane (Figure 2D-F, Figure 8).

A number of conchoidal (curved) fractures are observed (e.g. fracture F1 in Figure 1D, F and Figure 8). While a single average measurement is taken for each fracture for the scanline survey, the TLS point cloud offers the possibility of evaluating the curvature of the fractures, which may impact the connectivity of the modelled fracture network [Bonneau et al., 2013]. The study of low and intermediate values of roughness and curvature scalar fields, not related to the contact between two adjacent fractures, may help in quantifying the fracture curvature.

The TLS survey provides a more complete representation of the fractures at the Happy Valley outcrop, and opportunities for studying non-planar features which are common on andesite lava flow. It is however crucial to complement the TLS survey by inferences on fracture populations sampled uniquely by the scanline survey.

Fracture orientation analysis using BHTV logs from the Rotokawa andesites indicates that the current in-situ stresses are likely to control the modern structural expression (at least in terms of slipping and open fractures) with the dominant fracture strike parallel to the orientation of $S_{Hmax}$ (McNamara et al., submitted). However, these fractures may have utilised parts of fractures formed during the emplacement and cooling of the lava flow (e.g. columnar joints). Sub-horizontal fractures are rare on the BHTV logs, which could be due to a resolution issue (aperture too small to be detected). The impact of tectonic stresses during burial and faulting on the aperture of these sub-horizontal fracture requires further investigation.

4.2 Fracture length

The analysis of fracture lengths measured from the scanline survey highlights the high connectivity of the fractures, with a high proportion of fractures terminating against other fractures, and is reflected in
Figure 8: Photograph showing the differences between fracture length measurements using the TLS (L-TLS) and the scanline (L-sc) surveys where growth increment subdivide the columnar joint. A conchoidal fracture is shown, as well as a thin fracture orthogonal to the columnar joint measured on the scanline survey but not visible on the TLS. The white bar is a 1-m long tape measure.

the low number of fractures longer than 1 m. The integration of censored fractures in the analysis will increase the mean fracture length. If an observation bias can be ruled out for the shortest fractures, the histogram shape suggests that the fracture length distribution may be log-normal, which will be thoroughly evaluated in the next step of this project.

The analysis of fracture length on the TLS point cloud will be performed in the next phase of this project. It is envisioned that the fracture lengths from the TLS will be higher than those recorded from the scanline survey and will contain a lower proportion of fractures terminating against other fractures. Indeed, the fracture lengths on the scanline survey were measured to where they first intersect another fracture, and in some cases are a growth increment, i.e. a portion of the entire columnar joint length (Figure 8, Degraff and Aydin [1993]). The fracture lengths obtained from the TLS analysis will be more representative of entire columnar joints than the scanline, while the scanline survey will provide information on fracture growth and propagation processes not available on the TLS.

4.3 Fracture density

The fracture density analysis of the scanline survey is characterised by the difference between the strong clustering of the sub-horizontal fractures, and the weak clustering of sub-vertical fractures. The shape of the histogram for the sub-horizontal fractures, and the high $C_v$, suggest an exponential or power-law type density distribution for the sub-horizontal fractures. The presence of metre-long intervals along the scanline without any fracture, and the shape of the histogram for the steeply dipping fractures, suggest that the fracture density of the steeply dipping fractures follows a log-normal type distribution. However, this analysis requires the subdivision of the steeply dipping fractures into individual clusters of similar orientation, and will be preferentially made on the TLS survey where the clusters are more clearly defined.

Pre-existing topography has a strong impact on the development of cooling joints [Hetényi et al., 2012]. As the Happy Valley lava flow formed over a gentle slope (Figure 1A), fracture density and spacing observed in this outcrop will be treated as a lower bound. The effect of the emplacement configuration of the rock on fracture spacing will be studied by comparing the findings at Happy
Valley with a similar analysis of two nearby outcrops: a thin (2–5 m wide) sub-vertical dyke, and an older lava flow.

The best-fit of exponential, and either log-normal or gamma distribution to fracture width and spacing, respectively, highlights the presence of characteristic scales and associated mechanical layers in the 800–1200 m thick Rotokawa Andesite. It is proposed that these mechanical layers are made of a combination of the intercalation of breccia zones between individual lava flows, columnar jointing, sub-horizontal fractures inherent to the lava flow architecture, and faults (as inferred in McNamara et al., submitted).

4.4 Facies variations in the andesite lavas: implications for permeability

The lava flow studied at the Happy Valley outcrop is mostly composed of massive lava facies. Rubbly, brecciated zones at the base of the lava flow have a strong impact on the fracture propagation. Some columnar joints terminate at the massive lava/breccia interface. Fractures in breccia tend to be of higher tortuosity than in the massive lava (Figure 2), probably due to the mechanical heterogeneity of the breccia. Columnar joints partially propagating through the breccia levels provide a direct connection to the rest of the fracture network in the lava flow. The breccia is not recognisable on the TLS survey due to the point density (4 cm) being of similar size as the size of the breccia clasts (Figure 2), and the impact of lithology on fracture characteristics at the Happy Valley outcrop will be performed using the scanline survey.

The lower frequency of fractures in drill-cores of andesite breccia from the Rotokawa Geothermal Field, associated with intense veining surrounding the clasts, indicates that these breccias have had a high permeability. The integration of breccia layers in a fracture model of the Rotokawa Geothermal Field will thus be of great importance at several levels: (1) the direct impact of increased permeability within the breccia, (2) the potential lateral connection between lava flows, (3) the vertical connection between the breccias and the columnar joints of the massive flow interiors, and the structures associated with the normal faulting regime and (4) the modification of the fracture propagation mechanisms.

Conclusion

The combination of standard scanline survey and TLS scans of an outcrop located on Mt Ruapehu, New Zealand, provided information on the geometry and fracture processes that occur during the emplacement of an andesitic lava flow. Two types of fractures are observed: steeply dipping fractures forming columnar joints, and sub-horizontal fractures which are likely associated with lithological layering within the lava flow. The columnar joints sampled by the TLS have six main dip directions which suggests they have hexagonal plan-view shape. The scanline survey, even after correction for orientation sampling bias, does not fully sample these six dip directions. The columnar joints have a moderate fracture density with a high degree of connectivity to nearby fractures. Preliminary investigations suggest that fracture density and length of the columnar joints follow a log-normal distribution. The integration of censored fractures will increase the mean length. The TLS scans do not sample the sub-horizontal fractures as they do not form specific fracture faces, which highlights the need to confirm the findings from the TLS analysis with manual scanline measurements. Contrary to the columnar joints, the sub-horizontal fractures are strongly clustered. These sub-horizontal fractures have a strong impact on the fracture connectivity and on the propagation of subsequent fractures across these zones. The statistical analysis of three BHTV logs at the Rotokawa Geothermal Field provides input data for developing fracture models of this andesite-hosted reservoir. The impact of breccia layers, intrinsic to the lava flow or developed during sedimentary and hydrothermal processes, will be critical to the success of fracture network modelling, and targeting permeable zones at the Rotokawa Geothermal Field.
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