2	wall of the Alpine Fault
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15	
16	Abstract
17	The orientations and densities of fractures in the foliated hanging-wall of the Alpine Fault
18	provide insights into the role of a mechanical anisotropy in upper crustal deformation, and the
19	extent to which existing models of fault zone structure can be applied to active plate-
20	boundary faults. Three datasets were used to quantify fracture damage at different distances
21	from the Alpine Fault principal slip zones (PSZs): (1) X-ray computed tomography (CT)
22	images of drill-core collected within 25 m of the PSZs during the first phase of the Deep Fault
23	Drilling Project that were reoriented with respect to borehole televiewer images, (2) field
24	measurements from creek sections at <500 m from the PSZs, and (3) CT images of oriented

Controls on fault zone structure and brittle fracturing in the foliated hanging-

25 drill-core collected during the Amethyst Hydro Project at distances of ~500-1400 m from the 26 PSZs. Results show that within 160 m of the PSZs in foliated cataclasites and ultramylonites, 27 gouge-filled fractures exhibit a wide range of orientations. At these distances, fractures are 28 interpreted to form at high confining pressures and/or in rocks that have a weak mechanical 29 anisotropy. Conversely, at distances greater than 160 m from the PSZs, fractures are typically 30 open and subparallel to the mylonitic foliation or schistosity, implying that fracturing 31 occurred at low confining pressures and/or in rocks that are mechanically anisotropic. 32 Fracture density is similar across the ~500 m width of the hanging-wall datasets, indicating 33 that the Alpine Fault does not have a typical "damage zone" defined by decreasing fracture 34 density with distance. Instead, we conclude that the ~160 m-wide zone of intensive gouge-35 filled fractures provides the best estimate for the width of brittle fault-related damage. This 36 estimate is similar to the 60-200 m wide Alpine Fault low-velocity zone detected through 37 fault zone guided waves, indicating that a majority of its brittle damage occurs within its 38 hanging-wall.

39 Keywords: fractures, anisotropy, Alpine Fault, Deep Fault Drilling Project, damage zone

## 40 **1. Introduction**

41 Conceptual models of fault zone structure in the upper crust often invoke a relatively narrow 42 "fault core" that accommodates most displacement, surrounded by a halo of heavily fractured 43 rock termed the "damage zone" (Caine et al., 1996; Chester et al., 1993; Chester and Logan, 44 1986; Faulkner et al., 2010). These models have been successfully applied in a variety of 45 tectonic settings and for a wide range of fault displacements and exhumation depths (e.g. 46 Choi et al., 2016; Faulkner et al., 2010; Kim et al., 2004; Mitchell and Faulkner, 2009; 47 Savage and Brodsky, 2011). However, the term "damage zone" has been applied by 48 geologists and geophysicists to describe a range of fault-related features in a fairly 49 inconsistent way (Choi et al., 2016; Cochran et al., 2009; Peacock et al., 2016). For example, 50 the term has been used to describe fractures and faults at stepovers and bends (Chester and

51 Chester, 2000; Kim et al., 2004; Mitchell and Faulkner, 2009; Wilson et al., 2003), the 52 volume of inelastic deformation that is induced by dynamic off-fault stresses during fault-53 tip/earthquake rupture propagation (Andrews, 2005; Cowie and Scholz, 1992; Rice et al., 54 2005; Templeton and Rice, 2008; Vermilye and Scholz, 1998), and the volume of rock in 55 which earthquake swarms or foreshock and aftershock sequences are localised (Kim and 56 Sanderson, 2008; Savage et al., 2017; Sibson, 1989; Yukutake et al., 2011). Furthermore, 57 whereas damage zones are typically reported to be <5 km in width (Faulkner et al., 2011; 58 Savage and Brodsky, 2011), co-seismic ground shaking can modify fracture permeability at 59 distances many hundreds of kilometres from the fault source (Cox et al., 2015; Muir-Wood 60 and King, 1993; O'Brien et al., 2016).

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62 Brittle faults often develop in mylonite sequences or other (e.g. jointed) rocks that contain 63 compositional and mechanical anisotropies (Bistacchi et al., 2012; Chester and Fletcher, 64 1997; Massironi et al., 2011). Evidence from field studies (Bistacchi et al., 2010; Peacock and 65 Sanderson, 1992), experiments (Donath, 1961; Misra et al., 2015; Paterson and Wong, 2005), 66 and numerical modelling (Chester and Fletcher, 1997) demonstrates that such anisotropy can 67 significantly affect the orientation and densities of brittle fractures. Despite this, "fault core-68 damage zone" models are based largely on field observations from relatively isotropic and 69 homogenous host rocks, and there have been comparatively few field studies (Bistacchi et al., 70 (2010) being a notable exception) that document the influence of mechanical anisotropy on 71 patterns of brittle fracture damage in large-displacement faults.

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In this contribution, we present a comprehensive study of fracture densities, orientations, and mineral fills across the hanging-wall of the Alpine Fault' central section. In doing so, we critically assess the application of "damage zone" models to a plate-boundary-scale structure. In addition, the Alpine Fault is an active fault that rapidly exhumes ductile-to-brittle fault rock sequences from depths of up to 35 km (Little et al., 2005; Norris and Toy, 2014;

78 Sutherland et al., 2007). Brittle fracturing in its hanging-wall therefore overprints a 1-2 km 79 wide mylonite sequence containing a pervasive foliation sub-parallel to the main fault surface 80 (Cooper and Norris, 1994; Norris and Cooper, 1997, 2007; Toy, 2008), which provides an 81 opportunity to assess the influence of rock anisotropy on fracturing. Observations of 82 fracturing have been made from multiple datasets and across a range of scales. Measurements 83 from within 25 m of the Alpine Fault principal slip zones (PSZs) were made from shallow 84 (depths <130 m) drill-cores and wireline logs obtained during the first phase of the Deep 85 Fault Drilling Project (DFDP-1). These are combined with field studies at distances <500 m 86 from the PSZs and analyses of drill-core recovered at 500-1400 m from the PSZs during the 87 Amethyst Hydro Project (AHP). Results are then compared to geophysical studies (Boese et 88 al., 2012; Chamberlain et al., 2017; Eccles et al., 2015) to improve our understanding of the 89 structure of the Alpine Fault, and to provide new insights into the relationships between 90 fracturing and mechanical anisotropy.

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## 92 **2. Tectonic setting of the Alpine Fault**

93 The Alpine Fault is a crustal-scale (along strike extent ~850 km, depth ~35 km) transpressive 94 discontinuity accommodating ~70% of Pacific-Australian plate motion in the South Island of 95 New Zealand (DeMets et al., 1994; Norris and Cooper, 2001, Figure 1a). Slip rates vary along 96 strike such that it can be broadly divided into three sections: (1) a northern section between 97 Lake Rotoiti and its intersection with the Hope Fault near Hokitika, (2) a central section 98 between Hokitika and Haast (Figure 1a), and (3) a southern section between Haast and its 99 offshore termination near the Puysegur subduction zone (Norris and Cooper, 2007; 100 Sutherland et al., 2007). This study focuses on the central section where the fault currently 101 accommodates dextral strike-slip at a rate of  $27 \pm 5$  mm/yr and dip-slip at a rate of 6-10 102 mm/yr (Little et al., 2005; Norris and Cooper, 2001).

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104 In the central section at depths greater than 8-12 km, the Alpine Fault accommodates motion 105 via viscous creep across a > 1 km wide ductile shear zone in which the hanging wall "Alpine 106 Schist" protolith is progressively mylonitised (Norris and Cooper, 2007; Toy et al., 2010). 107 Shear strains increase with proximity to the Alpine Fault so that a sequence of 108 protomylonites, mylonites and ultramylonites form (Figure 2), which are exhumed to the 109 surface in the Alpine Fault's hanging-wall (Norris and Cooper, 2003; Reed, 1964; Toy et al., 110 2008). Foliation in the mylonite sequence is mainly defined by alternating quartzofeldspathic 111 layers and mica-rich layers (Figure 2). Bottle-green hornblende-rich metabasic mylonites or 112 purple-dark grey mylonites that are comparatively mica rich are also present, and reflect 113 variations in protolith lithology (Cooper and Norris, 2011; Norris and Cooper, 2007; Sibson 114 et al., 1981; Toy, 2008). As the mylonite sequences are exhumed to depths of less than 8-12 115 km, temperatures drop below those at which quartz plasticity occurs and brittle deformation 116 starts to overprint the mylonitic shear zone (Norris and Cooper, 2007; Toy et al., 2010, 2015). 117 This is reflected in the formation of a  $\sim 20$  m thick layer of green, inducated and frequently 118 foliated cataclasite (Allen et al., 2017; Toy et al., 2015), and a 10-50 cm thick clav-rich 119 principal slip zone (PSZ) that is preserved adjacent to the currently-active fault trace (Boulton 120 et al., 2017, 2012; Ikari et al., 2014; Mitchell and Toy, 2014).

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122 Projections of outcrop-derived measurements (Norris and Cooper, 1995, 2007) and 123 geophysical imaging (Stern et al., 2007) indicate that at depths >4 km the central section of 124 the Alpine Fault zone can be considered a single sub-planar structure, which is thought to 125 have the same orientation as the regional mylonitic foliation (055/45 SE). However, at depths 126 of less than 4 km, perturbations in the regional stress field induced by hanging-wall 127 topography results in segmentation of the fault trace into a series of km-long, approximately 128 E-W striking and steeply-dipping strike-slip fault strands and NE-SW striking, gently-dipping 129 (~30°) thrust segments (Barth et al., 2012; Norris and Cooper, 1995, 2007; Simpson et al., 130 1994).

## 131 **3. Methodology**

- 132 3.1 Fracture orientations from DFDP-1 drill-core
- 133 Hanging-wall fracture orientations at less than 25 m orthogonal distance from the PSZ were
- 134 assessed through analysis of datasets arising from the first phase of the Deep Fault Drilling
- 135 Project (DFDP-1, <u>http://alpine.icdp-online.org</u>). DFDP-1 successfully sampled the Alpine
- 136 Fault in two boreholes (DFDP-1A and DFDP-1B, Figure 3) at depths of less than 150 m in
- 137 early 2011 at Gaunt Creek (Figure 1b, Sutherland et al., 2012). The geophysical properties of
- the DFDP-1 boreholes were characterised by a full suite of wireline logs (Townend et al.,
- 139 2013), which were combined with visual core descriptions to construct a lithological
- 140 classification scheme for DFDP-1 drill-core (Figure 3, Toy et al., 2015).

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- 142 Abundant fractures, typically with a gouge-fill, were observed in X-ray computed
- 143 tomography (CT) scans of DFDP-1 drill-core (Williams et al., 2016). The true orientation of
- 144 these fractures was determined for the depth interval 94-126 m in the DFDP-1B borehole
- 145 (Figure 3). True fracture orientations were obtained by generating 'unrolled' CT images of
- 146 individual core sections (Mills and Williams, 2017), which are directly analogous to
- 147 geographically referenced but lower resolution borehole televiewer (BHTV) images.
- 148 Where fractures could be matched between the two images, a rotation could be derived to
- 149 transform all fracture orientations in the CT scans from a local core reference frame to their
- true geographic orientation (Figure 4). Depending on the number of fractures matched, core
- 151 was rotated with a high, moderate, or low degree of confidence. A full methodology is
- 152 provided in Appendix A the rotations applied to DFDP-1 core sections are listed in Table S1,
- and a CT-BHTV image comparison is given in Williams et al., (2017b).

155 3.2 Field observations of fracture orientations and densities

156 At distances up to 150-250 m from the PSZs, fracture orientations and densities were 157 measured in four creeks (Gaunt Creek, Stony Creek, Hare Mare Creek and Havelock Creek, 158 Figure 1b) that cut across the hanging-wall mylonite sequence approximately perpendicular to 159 the main fault trace (Figure S1). Along each creek, fracture orientations and densities were 160 collected at 3 or 4 measuring stations. Additional information was also collected at c. 500 m 161 from the Alpine Fault in Bullock Creek (Figure 1b). Each creek transect cuts across a thrust 162 segment of the Alpine Fault, and thus orthogonal distance between the measuring stations and 163 the PSZs was calculated assuming a fault dip of 30° (Norris and Cooper, 1995, 1997). The 164 mylonite lithology for each station was classified using the scheme presented in Toy, (2008). 165

The density of fractures at each measuring station was calculated following the methodology of Hudson and Priest, (1983) and Schulz and Evans, (2000), where the number and orientation of fractures that intersect a linear transect was recorded. This technique has the tendency to under-sample fractures oriented sub-parallel to the scan-line. Therefore, a weighting (*w*) factor calculated using a modified version of the Terzaghi correction (Massiot et al., 2015; Terzagh 65) was applied to each fracture, and results are shown as 'corrected' fracture density.

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174 3.3 Fracture orientations and densities in the Amethyst Hydro Project boreholes

The Amethyst Hydro Project (AHP) was developed to divert water from the Amethyst Ravine down a 1040 m-long tunnel to a powerhouse on the floodplain of the Wanganui River. Prior to the main phase of tunnelling, four exploratory boreholes (BH1-4; Figure 1b and S2) were completed between 2005-2006, resulting in the recovery of a total of ~890 m of drill-core at depths of 50-200 m. The boreholes are situated 1-2 km east of the surface trace of the Alpine

180 Fault. Below the boreholes, the Alpine Fault dips c. 45° to the east (Norris and Cooper, 1995)

181 meaning that drill-cores are at orthogonal distances of ~0.5-1.4 km from the PSZs.

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183 To provide a dataset analogous to the DFDP-1 CT scans, a total of 31.9 m of drill-core from 184 the AHP boreholes was CT scanned at the Southern Cross Hospital in Wellington, New 185 Zealand. Initial descriptions of the drill-core found that the Rock Quality Designation (RQD, 186 the % of intact core lengths >100 mm/1 m of drill-core) varied considerably. Intervals with 187 RQD values less than 10% are related to intense fracturing adjacent to the Tarpot Fault and other minor faults that intersect the AHP boreholes (Ge h Consulting Limited, 2006; 188 Savage, 2013, Figure S3). To ensure that the description of the fracture network sampled in 189 190 the AHP is unaffected by damage from these minor faults, CT scanning was focussed on 191 intervals of high RQD (Figure S2). The CT scanner was operated at 100 mA and an X-ray 192 tube voltage of 120 kVp. Slice spacing was 1.25 mm, field of view 250 mm, and the image 193 size was 512 x 512 pixels. Therefore, the size of one voxel is 0.488 x 0.488 x 1.25 mm in the x, y, z directions respectively. Reconstruction of two-dimensional CT slices into three-194 195 dimensional images of the drill-core was performed using OsiriX Imaging Software (http://www.osirix-viewer.com/). 196

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AHP drill-core was not oriented. However, the prominent schistosity observed in the drillcores has a known orientation and can be used as a reference to reorient drill-core back into a geographic reference frame. For BH2 and BH3 drill-cores, which are vertical, this required only a single transformation. For the inclined BH1 and BH4 drill-cores, this required first rotating the core with respect to the foliation. These orientations were then corrected for the inclination of the drill core using the Planes from Oriented and Navigated Drillcore (POND) Excel spreadsheet (Stanley and Hooper, 2003).

### 205 **4. Results**

4.1 Fracture orientations in DFDP-1 drill-core within 25 m of the Alpine Fault

207 In the DFDP-1 CT images, a total of 637 fractures were rotated into their true geographic 208 orientation (Figure 5a; Appendix B). In both the CT and BHTV datasets, a set of fractures is 209 observed sub-parallel to the mylonitic foliation and Alpine Fault orientation at Gaunt Creek 210 (015/43 E, Figures 5a and b; Townend et al., 2013). Clustering of this fracture set is stronger 211 in the lower-resolution BHTV images indicating that: (1) fractures observed at the resolution 212 of the BHTV are more likely to be aligned subparallel to the fault plane and foliation than 213 those visible in CT, and/or (2) some of the planar structures identified from the BHTV images 214 were the mylonitic foliation itself. The comparison between CT and BHTV images is 215 discussed further in Appendix B. 216 217 No clear relationships are generally observed between the type of fracture (Williams et al., 218 2016) and fracture orientation (Figure 5a). Plotted separately in Figures 5c and 5d are 219 fractures hosted in foliated ultramylonites and cataclasites (Units 1, 2 and 4 of Toy et al., 220 2015) and fractures hosted in relatively homogenous unfoliated cataclasites (Unit 3 of Toy et 221 al., 2015). It is evident that fractures in the foliated units are more clustered around the local 222 Alpine Fault and foliation orientation than fractures in the homogenous units. However, even 223 within the foliated units there are many fractures that cut across the foliation at a wide range 224 of orientations (Figure 5c and 6).

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4.2 Fracture orientations, densities, and fill in field transects within 500 m of the Alpine Fault
The orientations and densities of fractures observed in the four-main field transects are
summarised in Figure 7. In these transects, similar structures to those observed in the CT
scans of DFDP-1 core are identified (Figure 8). Total fracture density in the transects varies
between 3-30 fractures/metre, and there are no clear decreases in fracture density with

231	increasing distance from the Alpine Fault in any of the transects (Figure 7a). Distinctive
232	gouge-filled fractures (Figure 8a-c) are observed at all distances from the Alpine Fault, but
233	are relatively abundant (>1 fracture/metre, Figure 7a, Table S2) only within approximately
234	100-160 m of the PSZs (Figure 7a). The thicker gouge-filled fractures (> 1cm) commonly
235	juxtapose different lithologies or offset markers (Figure 8g-i). Thinner gouge-filled fractures
236	(< 1cm) are localised within 160 m of the Alpine Fault. Open fractures (Figure 8d-f) are
237	present at all stations, though are most prevalent at those furthest from the fault (Figure 7b).
238	
239	The composition of the mylonites can also affect fracture density. Intervals of micaceous
240	mylonites and ultramylonites are observed to contain relatively high densities of gouge-filled
241	fractures when they are juxtaposed against quartzofeldspathic mylonites and ultramylonites
242	(Figures 9a and b). At Hare Mare Creek station 2, the disappearance of thin gouge-filled
243	fractures coincides with a transition from micaceous-quartzofeldspathic mylonite to
244	quartzofeldspathic mylonites (Figure 9c). Localities that showed the widest range in fracture
245	orientations tend to be less than 160 m from the PSZs within the ultramylonites (Figure 7a).
246	Within mylonite units, fracture orientations tend to be more aligned to the foliation (Figure
247	7a), although gouge-filled fractures can sometimes cut across it (e.g. Bullock Creek, Figure

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7b).

4.3 Fractures in AHP drill-core, 500-1400 m from the Alpine Fault

251 The AHP sampled grey, well-foliated schist bedrock of the Haast Schist Group (textural zone

252 III-IV, Turnbull et al., 2001). Foliation is defined by alternating quartzo-feldspathic and

253 micaceous layers (Figure 10a and b). All 239 fractures measured in the CT scans of drill-core

- are plotted in Figure 11. There is a strong alignment of fractures to the host rock schistosity
- and the regional Alpine Fault orientation, in agreement with the findings during initial drill-
- core descriptions (Geotech Consulting Limited, 2006; Savage, 2013). Fractures that cut across

the schistosity are most frequent in BH4 (Figure 10d and 11). Though fractures are

258 predominantly open, it is conceivable that the original fill may have been lost during the

259 subsequent core handling processes. This means that standard schemes to differentiate

between natural and induced fractures (Kulander et al., 1990) cannot be applied to this

dataset.

## 262 5 Discussion

263 5.1 Fracture orientations in anisotropic wall rocks in the Alpine Fault hanging-wall

264 Two styles of fracturing are evident in the mechanically anisotropic Alpine Fault cataclasite,

265 mylonite and schist sequence. Within DFDP-1 core, fractures are predominantly gouge-filled

and exhibit a range of orientations (Figure 5 and 6) with only a small proportion (11%) of

267 fractures in foliated cataclasites and ultramylonites clearly foliation-parallel (Williams et al.,

268 2016). However, in host rock schists sampled by the AHP drill-core, the fractures are

269 predominantly foliation-parallel (Figure 11). In field transects, open, foliation-parallel

270 fractures are found at all localities, but they are most common at distances greater than 160 m

from the Alpine Fault in the mylonite and protomylonite sequence (Figure 7). Overall, there is

a transition from dominantly open, foliation-parallel fractures at distances greater than 160 m

273 from the PSZs, to gouge-filled fractures with more variable orientations closer to the fault

274 (Figure 12).

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Experimental studies on foliated rocks demonstrate that mechanical anisotropy will exert the greatest control on rock failure when: (1) the angle between  $\sigma_1$  and the anisotropy ( $\alpha$ ) is ~30°, (2) confining pressure is low (<35 MPa), and (3) the mechanical 'strength' of the anisotropy is high (Donath, 1961; Misra et al., 2015; Nasseri et al., 2003; Paterson and Wong, 2005). The first factor can be approximated for the Alpine Fault given the mylonite's average

orientation of 055/45SE (Norris and Cooper, 2007) and stress tensor orientation within the

surrounding crust, determined from focal mechanisms of microseismicity in the Alpine Fault's hanging-wall (Boese et al., 2012). This yields a value of  $\alpha$  of approximately 44°, when measured in the plane containing the maximum and minimum principal stresses ( $\sigma_1$  and  $\sigma_3$ ). This can be considered an intermediate value of  $\alpha$ , since in deformation experiments fractures may form parallel or non-parallel to the foliation depending on the combination of confining pressure and lithology (Donath, 1961; Nasseri et al., 2003; Paterson and Wong, 2005).

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290 Foliation-parallel fractures are generally least common in the ultramylonites and foliated 291 cataclasites. Lithology may control mechanical anisotropy depending on mineralogy, 292 porosity, grain size, and the nature of the foliation surfaces (Donath, 1961; Nasseri et al., 293 2003). It is notable that phase mixing and grain size reduction in the ultramylonites (Figure 294 2a) reduces the intensity of the foliation, compared to the relatively coarse-grained schists, 295 protomylonites, and mylonites (Figure 2b) (Norris and Cooper, 2007; Toy et al., 2010, 2008). 296 This data suggest this lithological change could have a marked effect on the orientation of 297 fracturing. Compositional variations between relatively quartzofeldspathic and relatively 298 micaceous mylonites can also influence the density of foliation-parallel fractures in some 299 cases (Figure 9). For example, at Hare Mare Creek, there is a sharp lithological boundary 300 between micaceous and quartzofeldspathic mylonite, and gouge-filled fractures predominate 301 in the former, while open foliation-parallel fractures predominate in the latter (Figure 9c). 302 These observations highlight that fracturing in the upper crust may be influenced by 303 lithological variations imposed by an underlying linked, and synkinematic, shear zone. 304

However, at other localities (e.g. Stony Creek, Figure 7), variations in dominant fracture characteristics are confined within units of similar composition and texture. This indicates that variations in confining pressure are also important, with foliation-parallel fractures forming at relatively low confining pressures compared to fractures adjacent to the Alpine

309	Fault in the ultramylonites. Indeed, it is likely foliation-parallel fractures formed as confining
310	pressure was released (Engelder, 1985; Price, 1959; Zangerl et al., 2006) during rapid
311	exhumation (6-9 mm/yr) of the hanging-wall along the Alpine Fault (Little et al., 2005;
312	Tippett and Kamp, 1995).

314 5.2 Fracture damage around the Alpine Fault

315 Caine et al., (1996) defined a fault damage zone as "a network of subsidiary structures that 316 bound the fault core and may enhance fault zone permeability relative to the core and 317 undeformed protolith." In applying this definition, most previous work has defined the 318 damage zone as a volume of rock that shows elevated fracture densities compared to a 319 "background" level of fracturing that normally includes widely-spaced regional fracture or 320 joint sets (e.g. Berg and Skar, 2005; Faulkner et al., 2010; Savage and Brodsky, 2011; Schulz 321 and Evans, 2000). Our data from the field transects of the Alpine Fault show that fracture 322 density remains roughly constant (>3.5 fractures/m) for at least 500 m into the hanging-wall 323 (Figure 7a). Furthermore, at distances 200-1500 m from the Alpine Fault an active 324 hydrogeological system was sampled by the DFDP-2B borehole (Sutherland et al., 2017; 325 Townend et al., 2015). Permeability in this rock mass is controlled by open fractures (Cox et 326 al., 2015; Sutherland et al., 2017) that are foliation-parallel (Massiot, 2017), and so directly 327 analogous to the fractures sampled in the field (Figure 8g-i) and in AHP drill-core (Figure 328 10).

329

Despite these observations, we suggest that the damage zone surrounding the Alpine Fault is
most appropriately represented by the localised zone with intensive (>1 fracture/metre)
broadly oriented gouge-filled fractures observed in DFDP-1 drill-core (Figures 5 and 6) and
field transects (Figure 7 and 8). Microstructural and compositional analysis of these fractures
indicates that they form in response to wear and shear of the surrounding of the wall rock

along with silicate mineralisation from hydrothermal fluids (Warr and Cox, 2001; Williams et
al., 2017a). They are considered necessary to the development of near-surface (<4 km) fault</li>
wedges that facilitate complex oblique-slip Alpine Fault movement (Barth et al., 2012; Norris
and Cooper, 1997). They may also reflect the dynamic off-fault stresses associated with M<sub>w</sub>
>7.5 Alpine Fault earthquake ruptures (Sutherland et al., 2007), when the hanging-wall is in
compression assuming up-dip rupture propagation (Ma and Beroza, 2008; Rice et al., 2005).

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342 Gouge-filled fractures are present at all distances in our field transects (Figure 7-9) and within 343 the AHP drill-core (Figure 10c). However, their interval of high density (>1 fracture/metre) is 344 restricted to less than 118-146 m from the PSZs at Gaunt Creek (i.e. between stations 3-4), 345 <73-103 m at Stony Creek (i.e. between stations 2-3), <151 m at Hare Mare Creek (at station 346 2, Figure 8c) and <155-160 m at Havelock Creek (i.e. between stations 3-4). This is 347 consistent with the observations of Norris and Cooper, (2007) who suggested that the Alpine 348 Fault's central section damage zone can be defined by a ~100 m wide zone of intensive 349 gouge-filled fractures. These estimates of damage zone width are also similar to those made 350 elsewhere on the Alpine Fault (e.g. Barth et al., 2013 in the southern section in South 351 Westland; Wright, 1998 at the northern end of the the central section, Figure 13a) and to other 352 predictions for crustal-scale (Figure 13b), rapidly-moving (~few cm/yr) fault zones that have 353 accommodated hundreds of kilometres of displacement (Biegel and Sammis, 2004; Childs et 354 al., 2009; Finzi et al., 2009; Manighetti et al., 2007; Perrin et al., 2016; Savage and Brodsky, 355 2011; Savage and Cooke, 2010).

356

357 5.3 Comparison to geophysical data

358 A relatively narrow (<100-160 m) hanging-wall damage zone is also broadly consistent with

359 the presence of a 60-200 m wide Low Velocity Zone around the Alpine Fault, which extends

360 to depths of 8 km (Eccles et al., 2015). This was detected by Fault Zone Guided Waves

(FZGWs) that are commonly regarded as an *in situ* indicator of fault damage (e.g. Ben-Zion
and Sammis, 2003; Eberhart-Phillips et al., 1995; Ellsworth and Malin, 2011; Li et al., 2014).
If the FZGWs are sampling the zone of intensive gouge-filled fracturing, it therefore indicates
that the >500 m wide interval of open foliation-parallel fractures are a near-surface feature
only. This is consistent with our interpretation that these fractures formed at low confining
pressures during exhumation within the Alpine Fault's hanging wall.

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FZGWs are a measure of total fault zone width. Since our hanging-wall damage zone width measurements are towards the higher end of the Alpine Fault FZGW estimates, much of the damage may be concentrated in the Alpine Fault's hanging wall. This is consistent with other dipping thrust faults (Li et al., 2013; Ma, 2009; Yeh et al., 2007). However, Western Province basement rocks to the west of the Alpine Fault are rarely exposed (Lund Snee et al., 2014; Norris and Cooper, 2007), so it is not possible to examine Alpine Fault footwall damage to confirm this.

375

Pervasive minor faults have been mapped for distances of tens of kilometres from the Alpine Fault (Cox and Barrell, 2007; Cox and Sutherland, 2007). We interpret that the occasional gouge-filled fractures observed here at distances greater than 160 m from the Alpine Fault (e.g. Figure 8e) are equivalent to this set. These fractures may also be the exhumed equivalent of structures that are currently accommodating the diffuse, low-moderate magnitude ( $M_W < 6$ ) seismicity that has been recorded at depths less than 10 km in the Alpine Fault's hanging-wall (Boese et al., 2012; Chamberlain et al., 2017; Eberhart - Phillips, 1995).

## 383 6. Conclusions

Fracture orientations and densities in the foliated hanging-wall of the Alpine Fault's central
section were quantified in drill-core from the Deep Fault Drilling Project (DFDP-1), field

386 transects in four creek sections and drill-core recovered from the Amethyst Hydro Project. At 387 distances greater than approximately 160 m from the Alpine Fault principal slip zones (PSZs), 388 open and foliation-parallel fractures dominate. These are interpreted to form at low confining 389 pressures in Alpine Schists and Alpine Fault mylonites that are mechanically anisotropic. At 390 distances less than c. 160 m from the PSZs, gouge-filled fractures with a wide range of 391 orientations predominate. Fracture density and orientation are locally influenced by changes 392 in host rock lithology, but overall fracture density is approximately constant at distances of up 393 to c. 500 m from the PSZs. We conclude that the Alpine Fault's hanging-wall "damage zone" 394 is most suitably defined by the approximately 160 m-wide zone of gouge-filled fractures. 395 These fractures formed at relatively high confining pressures and/or in relatively 396 mechanically isotropic ultramylonites and foliated cataclasites. They are interpreted to have 397 been generated during the development of fault wedges and/or the dynamic effect of ruptures 398 propagating along the Alpine Fault. Comparison of our field-based estimates of damage zone 399 width (160 m) to the total thickness of the low-velocity zone measured in geophysical data 400 (60-200 m) suggests that the Alpine Fault damage zone is asymmetric, with most brittle fault-401 related damage focussed in its hanging-wall.

## 402 Code availability

- 403 The code to generate 'unrolled' circumferential CT images is available from the GFZ data
- 404 service (http://pmd.gfz-
- 405 potsdam.de/panmetaworks/review/7f1b114f11b67f540bb1360ead692dc578a66e3d0935c7fef

406 6ffe210db285300-icdp/).

## 407 **Data availability**

In the supplementary information, we include detailed field maps and cross sections (Figure
S1), a cross section through the Amethyst Tunnel and location of boreholes (Figure S2), an
example of AHP CT scans (Figure S3), a list of rotations applied to DFDP-1B core (Table

411	S1), and a summary of field transects (Table S2). Lithological distribution and Alpine Fault
412	location as per University of Otago fault zone mapping program, which is available at:
413	http://www.otago.ac.nz/geology/research/structural-geology/alpine-fault/af-maps.html.

414 DFDP-1 and AHP CT scan 'core logs' and CT-BHTV image comparison are available on the

- 415 GFZ data service (http://pmd.gfz-
- 416 potsdam.de/panmetaworks/review/52b75045a30f1bd60f7fd5b841e69c468885e2a10dfc3704e
- 417 50b236df2ef8608-icdp).

418

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#### 431 **Appendix A: DFDP-1B core rotation methodology**

432 The technique employed to reorient core DFDP-1 here is similar to that described in Jarrard et

433 al., (2001), Paulsen et al., (2002) and Shigematsu et al., (2014), however, instead of

434 comparing DFDP-1 BHTV data to DMT CoreScan system® unrolled core scans, we compare

435 BTHV images to 'unrolled' CT core images. The acquisition and interpretation of the DFDP-

436 1 BHTV logs has been previously described by Townend et al., (2013) and McNamara, (2015). DFDP-1 CT scans consist of a stack of core-axial perpendicular image slices with a 437 438 pixel size of 0.244 mm and a spacing of 1 mm. The CT stack for each core section was loaded 439 into Fiji (http://fiji.sc/Fiji) and a circle was manually defined around the irregular boundary of 440 drill-core in a core axial-perpendicular image slice using the code available at Mills and 441 Williams, (2017). This circle was then used to define the path of the image in all other slices. 442 Generation of the unrolled images accounts for the fact that the spacing between individual 443 CT slices (1 mm, i.e. the core-axial parallel pixel size) is greater than the pixel size within the 444 slices (0.244 mm). Unrolled images were then reflected around the borehole axis as an image 445 of the outer surface of the core and a BHTV image are reflections of each other. This 446 technique has benefits over methods using the DMT CoreScan system®, since drill-core does 447 not have to be physically rotated and so can be used without the risk of damaging fragile core 448 sections.

449

Unrolled CT images were imported into the composite log viewing software WellCAD® (http://www.alt.lu/wellcad.htm) along with the BHTV images, where they are placed side-byside to allow matching of structures (Figure 4, see also Williams et al., (2017b)). When correlating the two datasets, it was first necessary to account for possible depth shifts between recorded drill-core depths and BHTV imagery due to factors such as stretching of the logging cable and intervals from which no drill-core was recovered (Haggas et al., 2001; Jarrard et al., 2001). In this study, depth shifts of no more than ±30 cm were allowed.

457

458 The orientation of fractures in the DFDP-1 CT images had previously been measured within a

459 local core reference frame (see Figure 4 in Williams et al., 2016). Since the DFDP-1

460 boreholes were vertical, corrections to reorient the drill-core back into a geographic reference

461 frame required only a single rotation about the core axis to correct for the dip direction. When

462 correlating structures, errors may be introduced by: (1) the internal BHTV magnetometer

463  $(\pm 2^{\circ})$ , (2) the manual picking of sinusoidal curves on BHTV and unrolled CT images that can be  $\pm 10^{\circ}$  for shallowly dipping (<30°) structures (Jarrard et al., 2001), and (3) the fact that the 464 465 DFDP-1B BHTV data imaged the open borehole, which has a larger diameter (127 mm) than 466 the drill-core (85 mm). To mitigate against the cumulative effect of these errors, Jarrard et al., 467 (2001) stitched unrolled images of many different core sections together that spanned 468 intervals of 5-30 m, prior to the matching with BHTV imagery. This meant that only a single 469 rotation was necessary for all core sections across the entire stitched interval, which could be 470 based on identifying ~20-30 matching structures between the BHTV and unrolled core 471 images. 472

473 In DFDP-1 it was not possible to stitch unrolled CT images of core section together as no 474 prominent reference marker across different sections were identified. Consequently each <1 475 m long core section had to be reoriented individually, within which we never identified more 476 than 3 matching structures. Therefore, compared to the methodology described by Jarrard et 477 al., (2001), the degree of confidence on the applied reorientation was strongly dependent on 478 the quality of individual matches for each core section and the range of rotations that they 479 indicated. We recorded this qualitatively for each core section using the scheme outlined 480 below.

481

High degree of confidence: images matched with one very prominent structure (e.g.
Figure 4d), or matched with two or more structures whose range of suggested
rotations are within 10° of each other (Figure 4b and c).

485

Moderate degree of confidence: images matched with one prominent feature or two
 features that indicate rotations that range 10-19° (e.g. Figure 4a) or three features
 whose range of suggested rotations are within 20-30° of each other.

490 • Low degree of confidence: images matched with one feature or two features whose
491 range of suggested rotations are within 20-30° of each other.

492

In this scheme, a core reorientation is deemed unreliable if the range of rotations suggested by different structures is  $\geq 30^{\circ}$ , i.e. equivalent to the cumulative effect of possible errors listed above. For those core sections where more than one matching structure was identified, the rotation that was applied was derived from the average of that required for each match. If one of the matched structures was more prominent, then the applied rotation was biased towards that structure.

## 499 Appendix B: DFDP-1B core rotation validity

500 Based on the criteria presented in Appendix A, of the 40 core sections from DFDP-1B in 501 which there was suitable quality of unrolled CT and BHTV images to attempt reorientation 502 (Figure 3), 31 were reoriented (Table S1). Prior to reorientation, fractures in these sections 503 exhibit no clustering (Figure A1a), however, a weak one does develop after reorientation 504 (Figure 5a). Since fractures in nature typically exhibit non-random orientations, this is 505 evidence that the reorientation of the CT scans was successful (Kulander et al., 1990; Paulsen 506 et al., 2002). In addition, fractures within some individual core sections (Figure A1b), and 507 fractures rotated based on a high degree of confidence (Figure A1c) contain a wide range of

508 orientations.

509

The recognition of fractures in unrolled CT images that are not observed in BHTV can be readily explained by the higher resolution of the CT images. However, structures are also observed in the BHTV logs, but not interpreted as fractures in the CT images (Figure 4). This may represent noise in the BHTV images, or in the case of foliation-parallel structures, the ultramylonitic foliation itself since it can be difficult to differentiate these structures. The subordinate north-dipping set of fractures in the BHTV images (Figure 5b) is not recognised

- 516 in the orientations gathered from CT images (Figure 5a). A similar north dipping fracture set
- 517 was also recognised in DFDP-2B BHTV images (Massiot 2017), and their causation and
- 518 relevance is the focus of ongoing work.

### 519 **Competing Interests**

520 Authors declare that they have no conflict of interest.

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## 851 List of Figures

## 852 Figure 1



853

Figure 1: (a) Location map for Alpine Fault and all other onshore active faults on the South Island of
New Zealand (GNS Science Active Fault Database, http://data.gns.cri.nz/af/). Box shows extent of (b),
a location map for the DFDP-1 and AHP boreholes, and field transects. The generalised underlying
geology is derived from the GNS Science 1:250000 QMAP project (Rattenbury and Isaac, 2012) and
has been draped over a digital elevation model.



Figure 2: (a) Quartzofeldspathic Alpine Fault ultramylonite that gradually grades to mylonite at the
base of the image. A foliation defined by alternating white quartzofeldspathic bands and dark grey
mica bands is hard to distinguish in the ultramylonite, but is more apparent in the mylonite. (b) Well
foliated Alpine Fault protomylonite-mylonite transition at Gaunt Creek. Compass is 5 cm wide. Both
images previously presented in Toy, (2008).



Figure 3: Cross section through the DFDP-1 boreholes, showing interval where reoriented drill-core is
located. Boxes with diagonal lines depict intervals in borehole with no core recovery, grey lines
represent mylonitic foliation. Modified from Sutherland et al., (2012), with lithological units
previously defined by Toy et al., (2015).



Figure 4: Examples of matching structures between BHTV images and unrolled CT images. In each
image, the first two columns are the BHTV amplitude image, without and with interpretations
respectively, whilst the third and fourth columns depict the unrolled CT image over the same interval,
also without and with interpretations. Fractures that have been traced in red indicate those that were
matched to reorientate core.



#### 884

885 Figure 5: Lower hemisphere equal area stereplots depicting orientation of fractures in DFDP-1. 886 Contouring on stereoplots was applied to poles that are weighted depending on their orientation 887 correction w (see Sect. 3.2), and that are rounded to the nearest whole number. Contours were then 888 generated for the weighted poles using a probability distribution calculated by a Kernel function in the 889 RFOC package for R (Lees, 2014). Great circle represents orientation of Alpine Fault plane and 890 foliation at DFDP-1 site (Townend et al., 2013). (a) Orientation of all fractures that were reoriented by 891 matching structures between unrolled CT images and BHTV images, sorted by fracture type (Williams 892 et al., 2016). (b) Orientation of features recognised in the BHTV images over the interval of reoriented 893 core (94-126 m in DFDP-1B). Fracture orientations extracted from reoriented DFDP-1 CT images in 894 (c) foliated units and (d) unfoliated units, using the DFDP-1 lithological classification scheme (Toy et 895 al., 2015).





Figure 6: The relationship between foliation and fracture orientations, as observed in 2D CT image
slices of DFDP-1 core. In (a) and (b) fractures tend to cross-cut the ultramylonitic foliation
(orientation represented by white line in top left corner of each image). (c) Fractures show a greater
preference to be aligned parallel to the foliation. Note that (c) was previously shown in Williams et al.,
(2016), and is not included in the reorientation analysis in Figure 5, as there was no BHTV imagery
for this interval. Intervals are (borehole, core section and run, depth interval): (a) DFDP-1A 55-1
75.45-75.62 m, (b) DFDP-1B 35-1 102.49-102.64 m, and (c) DFDP-1B 25-2, 44.80-45.20 m.



907 Figure 7: (a) Corrected fracture density at all stations for gouge-filled fractures and all fractures.
908 Dashed line indicates a corrected fracture density of 1 fracture/metre. No orientation data was
909 collected at Gaunt Creek stations 1 and 2, so fracture density is calculated from the two perpendicular
910 transects. (b) Compilation of stereoplots for fracture orientations at each field station. Stations have

- 911 been plotted as a function of distance from the fault and distance along-strike (with respect to
- 912 Havelock Creek) along within fault rock lithologies. Dashed lines indicate gradational or obscured
- 913 lithological boundaries. Qfs, Quartzofeldspath; MB, metabasic; Mic, Micaceous. For field cross
- 914 sections and location of stations, see Figure S1. Results are also summarised in Table S2.





917 Figure 8: Examples of different fractures observed in the field around the Alpine Fault, and correlative 918 fractures in DFDP-1 CT scans. (a-c) Thin gouge-filled fractures have a range of orientations and found 919 exclusively within 160 m from the fault. They are equivalent to type iii of fractures from Williams et 920 al., (2016). (d-f) Thicker gouge and cataclasite filled fractures are equivalent to type i and ii fractures 921 of Williams et al. (2016) and may be observed at all distances from the Alpine Fault. (g-i) Open 922 fractures are mainly foliation-parallel. Equivalent to type v fractures of Williams et al., (2016). 923 Location of field photos: (a) Waikukupa thrust, (b) and (g) Stony Creek, (d) and (h) Havelock Creek, 924 (e) Bullock Creek. Compass clinometer 8 cm and yellow notebook 20 cm in length. Measuring tape in (e) 1.1 m long, walking pole in (g) 1 m in length. DFDP-1 CT scan intervals: (c) DFDP-1B 56-2 925 125.35-125.49 m, (f) DFDP-1B 35-1 102.00-102.15 m, (i) DFDP-1B 33-2 99.45-99.60 m 926



![](_page_43_Figure_3.jpeg)

![](_page_44_Figure_1.jpeg)

936

Figure 10: Fracture styles noted in the Amethyst Hydro Project (AHP) drill-core. Unrolled images of
AHP drill-core (BH1 45-2 124.3-124.9 m) taken by (a) DMT core scanner and (b) generated from a
CT image. (1) Identifies fracture cutting across foliation, (2) foliation-parallel fracture with alteration
halo, (3) foliation defined by quartzofeldspathic bands that have low CT numbers. (c&d) Core-axial
parallel CT image slices of AHP drill-core. In (c) white arrows point to a 'crush zone' sub parallel to
foliation (BH2 75-2 155.92-156.04 m). (d) more variable fracture orientations identified in BH4
(Section 70-4 196.62-196.80 m).

![](_page_45_Figure_1.jpeg)

![](_page_45_Figure_2.jpeg)

948 AHP drill-core separated by borehole. Contours plotted with weighted poles (see Figure 5).

![](_page_46_Figure_1.jpeg)

Figure 12: A schematic cross section through a thrust section of the central section of the
Alpine Fault, depicting fracture network, its relationship to foliation, and the distribution of
subsidiary faults. Respective position of DFDP-1 boreholes also shown. Constructed from
cross sections previously presented in Norris and Cooper, (2007) and Sutherland et al.,
(2012).

![](_page_47_Figure_1.jpeg)

959 Figure 13: (a) Compilation of estimates of the extent of intensive gouge-filled fracturing on 960 the Pacific Plate side of the Alpine Fault from four creek sections in this study (Gaunt Creek, 961 Stony Creek, Hare Mare Creek and Havelock Creek), which is considered to be the best 962 indicator of Alpine Fault damage zone width. This is combined with other along-strike estimates of damage zone thickness for the Alpine Fault: McKenzie Creek and Martyr River 963 (Barth et al., 2013) and Kaka Creek (Wright, 1998). (b) Log-log plot of fault zone thickness 964 965 as a function of fault displacement previously presented in Savage and Brodsky, (2011), 966 combined with estimates made for the Alpine Fault assuming footwall damage is no more 967 extensive than in the hanging-wall. Displacement for the Alpine Fault is 480 km (Norris and 968 Cooper, 2007; Wellman, 1953), However, convergence along the Alpine Fault's central 969 section requires that it erodes its own fault rocks so these points are plotted to reflect only the 970 brittle displacement the rocks themselves have accommodated as they are exhumed through 971 the seismogenic zone (22 km, Barth et al., (2012)). Error bars reflect uncertainty in 972 constraining fault zone width (as for example, footwall damage is largely unknown), not 973 necessarily variability in fault zone thickness.

## 975 Figure A1

![](_page_48_Figure_1.jpeg)

![](_page_48_Figure_2.jpeg)

Figure A1: Stereoplots to tests the confidence in reorientations applied to rotate DFDP-1 CT
scan fracture orientations into geographic coordinates. Red great circle and diamond in each
plot represents plane and pole to the Alpine Fault orientation measured in DFDP-1B. Plotted
with Kamb contours with intervals of two standard deviations. (a) Orientation of fractures
shown in Figure 5a before rotation, (b) orientation of reoriented fractures within a single core
section (DFDP-1B 56-2), and (c) orientation of fractures in CT images from core sections that
were oriented with a high degree of confidence with BHTV images.