Damaged beyond repair? Characterising the damage zone of a fault late in its interseismic cycle, the Alpine Fault, New Zealand

Jack N. Williams\textsuperscript{a*}, Virginia G. Toy\textsuperscript{a}, Cécile Massiot\textsuperscript{b}, David D. McNamara\textsuperscript{c}, Ting Wang\textsuperscript{d}

Affiliations:

\textsuperscript{a}Department of Geology, University of Otago, PO Box 56, Dunedin 9054, New Zealand

\textsuperscript{b}School of Geography, Environment, and Earth Sciences, Victoria University of Wellington, PO Box 600, Wellington 6012, New Zealand

\textsuperscript{c}GNS Science, PO Box 30-368, Lower Hutt 5040, New Zealand

\textsuperscript{d}Department of Mathematics and Statistics, University of Otago, PO Box 56, Dunedin 9054, New Zealand

Email addresses:

Jack Williams: jack.williams@otago.ac.nz

Virginia G. Toy: virginia.toy@otago.ac.nz

Cécile Massiot: Cecile.Massiot@vuw.ac.nz

David D. McNamara: D.McNamara@gns.cri.nz

Ting Wang: ting.wang@otago.ac.nz

*Corresponding Author: Jack Williams\textsuperscript{a} (email: jack.williams@otago.ac.nz, Ph: +64 275271455)
Abstract

X-ray computed tomography (CT) scans of drill-core, recovered from the first phase of the Deep Fault Drilling Project (DFDP-1) through New Zealand’s Alpine Fault, provide an excellent opportunity to study the damage zone of a plate-bounding continental scale fault, late in its interseismic cycle. Documentation of the intermediate-macro scale damage zone structures observed in the CT images show that there is no increase in the density of these structures towards the fault’s principal slip zones (PSZs), at least within the interval sampled, which is 30 m above and below the PSZs. This is in agreement with independent analysis using borehole televiewer data. Instead, we conclude the density of damage zone structures to correspond to lithology. We find that 72% of fractures are fully healed, by a combination of clays, calcite and quartz, with an additional 24% partially healed. This fracture healing is consistent with the Alpine Fault’s late interseismic state, and the fact that the interval of damage zone sampled coincides with an alteration zone, an interval of extensive fluid-rock interaction. These fractures do not impose a reduction of P-wave velocity, as measured by wireline methods. Outside the alteration zone there is indirect evidence of less extensive fracture healing.

1. Introduction

Fault zone structure analysis concerns the three dimensional manifestations of a fault, such as its thickness, geometry, and continuity of slip surfaces (Chester and Logan, 1986; Faulkner et al., 2008; Wibberley et al., 2008). These features are classically
described with reference to a ‘fault core’ and ‘damage zone’ (Caine et al., 1996). Under this terminology, the fault core accommodated the majority of brittle strain and generally consists of cataclasites and gouges. The surrounding damage zone is typically a zone of enhanced fracturing, subsidiary faulting, and other deformation related features (Anders and Wiltshire, 1994; Vermilye and Scholz, 1998; Schulz and Evans, 2000; Wilson et al., 2003; Mitchell and Faulkner, 2009; Johri et al., 2014; Jeppson and Tobin, 2015). The damage zone is significantly wider than the fault core and may host single (Figure 1a) or multiple anastomosing fault cores (Figure 1b) (Faulkner et al., 2008).

Fault zones are the product of the subtle interplay between and within different components of their system such as their structure, mechanical properties, and composition (Faulkner et al., 2010). Thus, though damage zones accommodate only a small amount of displacement relative to the fault core, they are strongly coupled with many other fault zone properties. In particular, there exist feedback relationships between the damage zone and the stress state around the fault (Faulkner et al., 2006), its permeability (Wibberley and Shimamoto, 2003; Lockner et al., 2009; Mitchell and Faulkner, 2012), elastic properties (Griffith et al., 2009; Gudmundsson et al., 2010), and the dynamics of earthquake rupture (Andrews, 2005; Rice et al., 2005; Weng et al., 2016).

However, the exact nature of these relationships is liable to change with time since damage zones evolve through the seismic cycle. In this cycle, fractures are opened by coseismic faulting and then progressively healed during the interseismic period by
closing or precipitation of secondary minerals (Sibson, 1990; Chester et al., 1993; Li and Vidale, 2001; Tenthorey and Cox, 2006; Lin et al., 2007; Wästeby et al., 2014). By using the example of New Zealand’s Alpine Fault, we are able to report on a fault that is understood to be late in its interseismic cycle (Berryman et al., 2012; Townend et al., 2013), and so can investigate how fault healing since the last major Alpine Fault rupture has influenced its damage zone.

The Alpine Fault is also an attractive target for damage zone characterisation as off-fault processes are occurring within a rock mass that contains lithological variations (Toy et al., 2015). This allows for assessment of how lithology competes with other influences on damage zone formation, such as distance from the fault core (Chester et al., 2005; Savage and Brodsky, 2011; Johri et al., 2014), the displacement the fault has accommodated (Beach et al., 1999; Fossen and Hesthammer, 2000; Faulkner et al., 2011; Savage and Brodsky, 2011) and variations in confining pressure (Ben-Zion and Shi, 2005; Lund Snee et al., 2014; Ishii, 2015), fault geometry (Chester and Chester, 2000; Childs et al., 2009; Finzi et al., 2009; Bistacchi et al., 2010; Lin and Yamashita, 2013) and frictional properties (Savage and Cooke, 2010).

Here we examine a record of the Alpine Fault’s damage zone provided by X-ray computed tomography scans of drill core from the first phase of the Alpine Fault, Deep Fault Drilling Project (DFDP-1, http://alpine.icdp-online.org). Results are then combined with lithological characterisation of the drill-core (Toy et al., 2015) and wireline logs of the DFDP-1 boreholes (Townend et al., 2013) to: (1) provide an assessment of the spatial distribution of damage zone structures around the DFDP-1
boreholes, (2) offer direct evidence of how, for a fault late in its interseismic cycle, the damage zone has healed, and (3) explore what effect this healing has on the elastic properties of the surrounding rock mass.

2. Geological setting of the Alpine Fault

2.1 Tectonic setting

The Alpine Fault is a major transpressive structure that extends for 850 km (~660 km onshore) along the west side of the South Island of New Zealand. Here it is the main structure forming the boundary between the Pacific and Australian plates (Figure 2a), accommodating slip at ~70% of the rates indicated by the NUVEL-1A interplate velocity vectors (DeMets et al., 1994; Norris and Cooper, 2001). This study focuses on the central section of the Alpine Fault between Hokitika and Haast (Figure 2b), which has been the focus of DFDP, a multiphase scientific drilling programme that aims to directly sample the structure and ambient conditions of the Alpine Fault at depth (Townend et al., 2009).

Paleoseismic, geodetic and seismological observations indicate that the Alpine Fault is locked above depths of 12-18 km (Wallace et al., 2007) and that it fails in large (Mw>7) and possibly great (Mw>8) earthquakes (Sutherland et al., 2007; De Pascale and Langridge, 2012). A stratigraphic record of past earthquakes, spanning 8000 years on the southern section of the Alpine Fault, indicate that the fault has a recurrence interval of 329 ± 68 years (Berryman et al., 2012). Since the last large/great earthquake occurred in 1717 AD (Wells et al., 1999; De Pascale and
Langridge, 2012) the Alpine Fault is statistically in the late phase of its interseismic cycle. This makes it a globally significant site for the study of tectonic deformation (Townend et al., 2009), particularly in the case of fault damage zones that evolve over the seismic cycle (Chester et al., 1993; Lin et al., 2007; Wästeby et al., 2014).

2.2 Alpine Fault zone structure

At the regional scale, the central section of the Alpine Fault is approximately a moderately southeast dipping, dextral-reverse, planar fault. It separates basement, granitic, and gneissic Australian plate rocks in the footwall - that in places are overlain by Quaternary gravels - from Pacific plate, amphibolite facies (oligoclase-zone) quartzofeldspathic Alpine Schist in the hanging wall (Norris and Cooper, 2007). Adjacent to the principal slip zones (PSZs) of the fault in the hanging wall (Figure 2c), the schist grades into protomylonites, mylonites, and ultramylonites (Reed, 1964; Sibson et al., 1981; Cooper and Norris, 1994; Norris and Cooper, 1997, 2007; Toy, 2008). These units are considered to be accommodating motion along the Alpine Fault by a combination of dislocation creep and grain-size-sensitive creep in a 1-2 km thick shear zone below the seismogenic portion of the Alpine Fault (Norris and Cooper, 2007; Toy et al., 2015). Immediately overlaying the PSZs is an interval of cataclasite derived from the adjacent mylonites (Figure 2c). This is interpreted to have been generated through brittle deformation and pressure solution-accommodated grain-size sensitive creep, occurring towards the base of the seismogenic zone (Warr and Cox, 2001; Toy et al., 2015).
This same sequence was also encountered in the first phase of DFDP drilling (DFDP-1) that took place at the extensively studied Alpine Fault exposure at Gaunt Creek (Sutherland et al., (2012); Toy et al., (2015), Figure 2b). This site saw the completion of two vertical boreholes: DFDP-1A to a depth of ~100 m and DFDP-1B to a depth of ~152 m. Interpretations from the wireline suites in DFDP-1A and DFDP-1B (Townend et al., 2013) were integrated with drill-core descriptions to provide a classification scheme for the DFDP-1 lithologies (Toy et al., 2015).

The structurally reworked rocks that Toy et al. (2015) described are compatible with the Caine et al. (1996) conceptual fault zone model. The fault core consists of the cataclasites and gouges (units 3-6 of Toy et al., 2015) that demonstrably accommodated the majority of brittle displacement along the Alpine Fault. Surrounding these units are heavily fractured ultramylonites and breccias (units 1, 2 and 7 of Toy et al., 2015) that constitute the damage zone.

Defining the boundary between the fault core and damage zone for the DFDP-1 drill-core is problematic. Firstly the rocks that span the damage zone-fault core transition are overprinted by a pervasive “alteration zone.” This is broadly defined by Sutherland et al. (2012) as a zone of enhanced fluid-rock interaction within which there has been extensive carbonate and phyllosilicate neomineralisation.

Secondly, in the depth interval of ~69-80 m in DFDP-1A, and ~96-116 m in DFDP-1B, damage zone mylonites and fault core cataclasites are interlayered (Toy et al., 2015). It is only below these depth intervals that the DFDP-1 drill-core consistently
comprises cataclasites (units 3-6), and it is these depths that we define as the boundary between the fault core and damage zone (i.e. 80 m in DFDP-1A, 116 m in DFDP-1B).

Finally, strain within the fault core has been further localised to <0.5 m thick gouges that comprise the PSZs and were interpreted to define active or recently abandoned slip surfaces. These were intercepted at measured depths (MD) of 90.75 m in DFDP-1A and 128.20 and 143.85 m in DFDP-1B. The gouges have a distinct set of geophysical properties: low resistivity, density, and P wave velocity, and high spontaneous potential (Townend et al., 2013). They have a finer grain size and distinct mineralogy (particularly the presence of smectite) compared to the surrounding cataclasites (Boulton et al., 2014). Furthermore they have comparably low permeability ($10^{-20} \text{ m}^2$) (Boulton et al., 2012) and under fluid-saturated conditions, low frictional strength (Ikari et al., 2014). These properties set up the conditions necessary for dynamic hydrologic processes, such as thermal pressurisation (Sibson, 1973; Lachenbruch, 1980), that facilitates localisation of co-seismic slip at shallow depths onto the PSZs (Carpenter et al., 2014; Ikari et al., 2014; Mitchell and Toy, 2014). Therefore, herein we consider the spatial distribution of damage around the boreholes with regards to proximity to the fault core and to the PSZs.
3. Methods

3.1 X-ray Computed Tomography

A qualitative and quantitative analysis of the Alpine Fault damage zone was performed using X-ray Computed Tomography (CT) scan images of the DFDP-1 drill-core. Drill-core was retrieved from ~31% and ~36% of the DFDP-1A and DFDP-1B boreholes respectively (Toy et al., 2015). Drill-core recovery was focused around the PSZs and so a near continuous record of rocks extending distances of <35 m from the PSZs exists. Since an alteration zone extends <50 m from the PSZs in the DFDP-1 boreholes (Sutherland et al., 2012), the drill-core analysed in this study lies substantially within this zone.

CT scanning provides a quick, non-destructive means to three-dimensionally image objects based on the extent to which they attenuate X-rays passing through them. Attenuation is a function of the material’s atomic number (Z) and density; though the extent to which either one of these properties attenuates X-rays is also a factor of the X-ray energy (Ketcham and Carlson, 2001).

During CT scanning, the raw intensity data of the detected X-rays are converted linearly to a CT number, which in this study corresponds to the 12-bit Hounsfield Unit (HU) scale. Two-dimensional, transverse image slices of the object are constructed with the CT numbers represented by a greyscale. Under the HU scale, air is assigned a CT number of -1000 and is black, whereas materials with anomalously high density or Z values, such as calcite, are assigned higher CT numbers and appear
Further information about CT scanning and its application to geosciences is outlined by Ketcham and Carlson (2001).

A total of 23.2 m of drill-core from DFDP-1A and 50.5 m from DFDP-1B, that covered all lithological units described by Toy et al., 2015, except unit 7 breccias, was scanned at the Oncology Department of Dunedin Hospital. The Phillips Accolade scanner was operated at 200 mA, with a Beam Quality of 8.4 mm, and a Half Value Layer of 120 kVp. The horizontal slice spacing was 1 mm, field of view was 50 mm, and the image size was 1024 x 1024 pixels. This results in a voxel size of 0.244 x 0.244 x 1 mm in the x, y and z directions respectively. Reconstruction of two-dimensional CT slices into three-dimensional images of the drill-core was performed using OsiriX Imaging Software (http://www.osirix-viewer.com/).

3.2 Classification of damage zone structures in CT images

We documented all damage zone structures observed in the CT images. We note that damage zones do not necessarily include just fractures, but host a continuum of features that form as the fault accommodates displacement, such as subsidiary faults, and a gradual change (i.e. a rotation) of foliation orientation (Schulz and Evans, 1998; Faulkner et al., 2010; Savage and Brodsky, 2011). Therefore, we use the umbrella term ‘damage zone structure’ to define any feature recognised in the CT images that constitutes the Alpine Fault damage zone (Table 1).

In the CT images, damage zone structures are represented by an aligned group of voxels or pixels with anomalous CT numbers relative to the surrounding matrix.
(Wennberg et al., 2009), and with a distinct edge so that it is possible to differentiate them from the mylonitic foliation also apparent in the CT images (Figure 3a). Given the dimensions of a voxel in the acquired CT data, only structures with an aperture >1 mm (i.e. larger than one pixel in the z direction) are considered. Thus this study is primarily concerned with intermediate to macroscale damage around the Alpine Fault.

Damage zone structures were manually picked and categorised into different types based on their aperture, the CT number of their fill and its texture (Table 1). The colours used to label the different structures relate to the greyscale that was used to visualise the CT scan images (with a CT number window of 500-4000). In the damage zone structure classification used in this study (Table 1), the filling of gouge and cataclasite in type i and ii structures respectively, indicates that they have accommodated some localised strain and so represent subsidiary faults.

Lithological units 3, 4 and 6 of Toy et al., (2015) are defined by the presence of cataclasite implying that they have been previously extensively fractured (Sibson, 1977; Chester and Chester, 1998) during accommodation of delocalised shear strain in the fault core. We note, however, that the cataclasite fabric has been cross cut by a later generation of damage zone structures, and it is these structures that we account for in this study (Figure 3b and c).

Damage zone structures (type iii - viii) represent different types of fractures (Table 1). By correlation to visual core logs, dark grey and grey fractures (type iii and iv) are observed to be clay filled fractures. The low CT numbers (<0) in type v fractures
indicate densities similar to air and so represent open fractures, whilst fractures that contain a range of low and moderate CT numbers (type vi and vii) signify partially open fractures. Quartz and calcite veins are represented by white fractures (type viii). Other features associated with fault damage zones, such as rotation of foliation or mineralogical changes (Schulz and Evans, 1998, 2000) were not recognised in the CT images.

3.3 Differentiation of natural and induced fractures in DFDP-1 drill-core

In distinguishing damage zone structures in drill-core, we need to take account of, and remove fractures that may have been induced during drilling, coring or handling processes. Fractures reported as handling-induced were identified from visual core logs and removed from this analysis (Figure 3a). To identify fractures induced by drilling or coring we apply the frameworks developed by Kulander et al., (1990) and Keren and Kirkpatrick, (2016). Kulander et al., (1990) proposes that all fractures with a fill are natural. Therefore only black/open fractures (type v, Table 1) may represent induced fractures. Drill-core was washed immediately after recovery (Sutherland et al., 2011), so that the chance of any induced fractures being filled with drilling mud was minimal. Nevertheless, we cannot be certain that drilling mud was removed from all induced fractures.

Of the induced fractures types described by Kulander et al., (1990), some form with a distinct morphology. In this way, we identified disc fractures that tend to be sub-horizontal and contain convex tops and concave bottoms (Figure 3d), and that form in response to a vertical tension imposed by removal of the overlaying drilled rock
column (Kulander et al., 1990; Keren and Kirkpatrick, 2016). In foliated rocks, disc fractures may be inclined with respect to the foliation (Kulander et al., 1990).

Therefore, where we see black/open (type v) fractures parallel to the foliation in the mylonites, we also consider these to be induced structures (Figure 3a).

Some intervals of DFDP-1 drill-core show significant brecciation (Figure 3e and f). The presence of slickenslides on individual clasts is typically used to determine if this is natural or induced (Keren and Kirkpatrick, 2016). Unfortunately DFDP-1 drill-core has been sub-sampled to the extent that it is not possible to make these observations. However, we consider that natural brecciation in DFDP-1 drill-core typically results in the development of a cataclasite fabric with rounded clasts, (Figure 3f), since they have been sheared (Storti et al., 2007; Bjørk et al., 2009). Some intervals of breccia within the mylonite units show evidence of *in situ* fragmentation with angular clasts (Figure 3e). These breccias are interpreted to have been induced by drilling.

There are also some open fractures that occur in triangular sets and in which the apex of the triangle points towards the centre of the core (Figure 3g). These are interpreted as per Keren and Kirkpatrick, (2016) to be induced fractures, formed due to vertical flexure of the core. Finally, open fractures with mineralised surfaces were not omitted from this analysis, since they represent natural permeable fractures or fractures that opened during core recovery. Despite the careful approach described above, we cannot categorically rule out that some induced fractures were not removed from this analysis; also some induced fractures may have exploited pre-existing fractures.
3.4 Quantitative analysis of the density and distribution of damage zone structures

To measure how damage zone structures are distributed around the Alpine Fault, we measured the intersection depth of any structure along a 1D core-axial scan line within a 2D CT image slice of DFDP-1 drill-core (Figure 4). The DFDP-1 boreholes are vertical and so this scan line represents a vertical line. We then applied a weighted moving average to this dataset, to illustrate the distribution and density of damage zone structures. Our justification for using this statistical measure is twofold as explained in the following.

3.4.1 Accurate representation of the distribution of damage zone structures

Previous studies of fault damage zones sampled by boreholes typically represent the distribution of damage zone structures by binning them into depth intervals (e.g. Barton and Zoback, 1992; Yeh et al., 2007; Johri et al., 2014). The frequency of fractures within each depth bin is then represented in a histogram. However, these histograms are based on disjoint bins, and thus may fail to capture intervals of anomalously high or low structure density that exist across the boundary of two consecutive bins. For example, for the hypothetical fracture dataset shown in Figure 5a there is an interval of high fracture density at ~10 m depth. If fractures are binned into 5 m intervals (Figure 5b), the 10 m depth acts as a boundary between two bins thus splitting high fracture density across two bins (i.e. the bins at 5-10 m and 10-15 m) and obscuring its observation. This can be partially addressed by reducing the bin size (Figure 5c). However, this will increase the amount of noise in the data resulting in a “jagged histogram” (Wand, 1997).
In this study, we performed a moving average calculation to determine the distribution of damage zone structures. In this calculation, the density is calculated within a window of a predetermined depth interval centred on each depth. For example for depth \( i \), and a moving window size \( 2x+1 \), the moving average (\( MA \)) is calculated as:

\[
MA(i) = \frac{1}{2x + 1} \sum_{i-x}^{i+x} \frac{n_{\text{damage zone structures}}}{n}
\]  

(1)

In this way, a continuous measurement of density is made, which more adequately captures variations in the depth distribution of the damage zone structures. When applied to the fracture dataset in Figure 5a, the region of high fracture density at \(~10\) m depth is well represented (Figure 5d). Caution must be applied when selecting the size of the moving window to ensure an appropriate size is used, otherwise this method can excessively smooth the data. Furthermore, if there was a boundary across which there was an abrupt change in the density of damage zone structures, this may be more effectively represented by a discrete binning method with an appropriate bin size.

3.4.2 Correction for orientation sampling bias

The density of structures derived from the number of their intersections along a 1D scan line should account for an orientation bias in which structures (sub) parallel to the scan line are under-sampled (Terzaghi, 1965; Barton and Zoback, 1992; Priest, 1993). In order to account for this, each damage zone structure was assigned a statistical weight, \( w \), (Terzaghi, 1965):
\[ w = \frac{1}{\cos \delta} \] 

where \( \delta \) is the acute angle between the normal plane to a structure and the scan line, with a maximum value of \( w=10 \), which corresponds to an angle of \( \delta = 84.3^\circ \), to limit the overestimation of \( w \) (Priest, 1993; Massiot et al., 2015). Since the scan line represents a vertical line, \( \delta \) is equivalent to the true dip of the damage zone structure. DFDP-1 drill-core is not oriented (Sutherland et al., 2011) and so the orientation of structures was measured within a local drill-core reference frame applying the convention described in Figure 4. A weighted moving average (WMA) was then calculated in which the density of damage zone structures for a given depth \( (i) \) is calculated from the sum of \( w \) of all damage zone structures found within a moving window \( 2x+1 \), divided by the length of the window as expressed by:

\[ WMA(i) = \frac{1}{2x + 1} \sum_{i-x}^{i+x} w_{\text{damage zone structures}} \]  

This correction for orientation bias was also applied to the hypothetical dataset in Figure 5a to illustrate its effect on the calculation of fracture density. The corrected fracture population was represented by both binning into depth intervals (represented by weighted histograms, where the frequency of each bin is the sum of ‘\( w \’) of all fractures within each bin, Figure 5b and c), and by using a weighted moving average (Figure 5d). In both cases a higher fracture density is calculated at intervals where steeply dipping fractures intersect the vertical scan line. This more accurately reflects the density of steeply dipping fractures that are not accounted for in the uncorrected calculations.
However, the weighting does add a bias, since it is only applied to the intervals where a steeply dipping fracture has been sampled. This implies that all the unsampled steeply dipping fractures, which are required for the correction, are located at the same depths as where they were sampled in the borehole. This could consequently overestimate the fracture density for these depths. In short, applying a weighted moving average will provide information on the density of poorly oriented fractures within a rock mass, but not their distribution across the rock mass. For this reason, we show results for cases where the Terzaghi weighting correction has, and has not been applied to damage zone structure distribution in the DFDP-1 boreholes. To fully account for density and distribution of fractures in a rock mass, ideally two mutually perpendicular scan lines or a circular scan line should be employed (Mauldon et al., 2001; Watkins et al., 2015).

For this study a weighted moving average was calculated at intervals of 2 cm depth. A moving window of 1 m was used unless otherwise stated. Where there was incomplete drill-core recovery, the size of the moving window was reduced by the length of the interval of missing drill-core.

We also apply the weighted and non-weighted moving averages techniques to the documented density of damage zone structures picked in the acoustic borehole televiewer (BHTV) logs of the DFDP-1B borehole (McNamara, 2015). BHTV data are continuously recorded with depth and the acquired image has a consistent quality throughout (Townend et al., 2013), removing the need to normalise for missing
intervals or zones of variable quality. However, a BHTV log has a lower resolution than CT images; it reveals structures only with an aperture of >5 mm and with a significant acoustic contrast with the rock hosting the structure (Figure 6). Thus a moving window of 5 m was used and the density of damage zone structures was calculated at 10 cm intervals.

4. Results

4.1 Density and distribution of damage zone structures

The densities of damage zone structures, which are apparent from CT images of DFDP-1A and 1B drill-core, are shown in Figure 7 and Figure 8 respectively. The CT images show no increase in the density of damage zone structures towards either the fault core or the PSZs. Indeed the core sections with the highest density of structures are those at depths of 39-45 m from DFDP-1B, which have the greatest distance (<89 m) from PSZ-1 sampled in DFDP-1.

Initial interpretations of BHTV data for the DFDP-1B borehole indicate no increase in the density of damage zone structures towards either the fault core or the PSZ (Townend et al., 2013). A revision of these data (McNamara, 2015), which is included in Figure 8, does indicate a small degree of non-monotonic increasing damage immediately above PSZ-1 (105-125 m), regardless of whether a correction for orientation bias is added. The overall lower density of damage zone structures in the BHTV dataset compared to the drill-core CT images reflects its lower resolution as described above. The damage zone structures most consistently sampled by the
BHTV are type i, ii and type v structures (Table 1), which tend to be the structures
with the highest aperture.

Though we note no, or very little, control on damage zone structure density with
proximity to the PSZs, it is apparent that some noticeable trends in the damage zone
structure density profiles coincide with lithological changes (Figure 7 and Figure 8).
For example at ~100, 106 and 116 m in DFDP-1B, a drop in the density of damage
zone structures corresponds to a transition from unit 3 cataclasites to unit 2
ultramylonites. This is qualitatively observed in the CT images (Figure 9). Damage
zone structure density is low below PSZ-1 in DFDP-1B (128.2 m depth) within the
footwall cataclasites, and below 81 m in DFDP-1A in an interval dominated by
hanging-wall foliated cataclasites.

The profile for the corrected density of damage zone structures (calculated using a
weighted moving average) tends to follow the uncorrected profile (calculated using a
moving average, Figure 7 and Figure 8). This suggests that the distribution of steeply
dipping damage zone structures, that are poorly oriented for intersection by the
DFDP-1 boreholes, is fairly homogenous. The interval 43-45 m in DFDP-1B is an
exception to this. This reflects the fact that it has a particularly high density of steeply
dipping structures, which is not accounted for in the uncorrected profile.

4.2 Effect of damage zone structures on the elastic properties of the rock mass

Of the damage zone structures observed in the CT images of DFDP-1 drill-core that
are located within the alteration zone of the Alpine Fault (that is all DFDP-1A drill-
core and all DFDP-1B drill-core at depths >94 m), 96% of fractures were healed to some extent (i.e. only 4% exhibited no evidence of filling, and so were classed as open type v structures) and 72% were fully healed (i.e. only 28% were open or partially open, type v-vii structures, Table 1).

In order to constrain the influence of damage zone structures on the elastic properties of the rock mass surrounding the Alpine Fault, we compare the density of damage zone structures in the DFDP-1 boreholes to the P-wave velocity ($V_P$) of the boreholes. These were obtained by wireline logging and previously presented in Townend et al. (2013). Previous studies have shown that the presence of damage zone fractures may reduce $V_P$ around a fault at a range of scales (e.g. Stierman and Kovach, 1979; Jeppson et al., 2010; Jeanne et al., 2012; Rempe et al., 2013; Jeppson and Tobin, 2015). Qualitative comparisons of $V_P$ logs to damage zone structure density (Figure 7 and Figure 8) show that intervals of high damage zone structure density (e.g. 125-127 m, DFDP-1B) do not show corresponding reductions in $V_P$ and vice versa (e.g. 135-140 m, DFDP-1B).

We explore this further using the following approach. In DFDP-1, $V_P$ was measured at 2 cm intervals using a single-source dual receiver logging sonde that estimates $V_P$ over a 30 cm interval (Townend et al., 2013). Therefore, by calculating the density of damage zone structures using a moving average with a window size of 30 cm, we can directly compare $V_P$ to damage zone structure density for the DFDP-1 boreholes at depth intervals of 2 cm. We follow the convention of Townend et al., (2013) who noted that the resistivity anomaly associated with PSZ-1 in the DFDP-1B borehole is
at 128.4 m (Figure 8), which is 0.2 m below that measured in the drill-core. Therefore the DFDP-1B drill-core depths are adjusted by 0.2 m downward. No correction is required for DFDP-1A drill-core depths. It is noted that due to uncertainty in the core depths, for example where there are intervals of no drill-core recovery, there may still be a <30 cm difference between the corrected core depths and wireline log depths.

Cross-plots for all depths, and for depths separated by lithological unit, are shown in Figure 10. Also shown is the 95% confidence interval (CI) for the slope of the best-fit line to describe any correlation between damage zone structure density and $V_p$. In cases where the CI’s are both close to zero and positive (Figure 10a, b and e-g), a very weak positive correlation exists. Where the CI’s are either side of zero, there is no statistically significant correlation between damage zone structure density and $V_p$ (Figure 10c and d). If we account for damage zone structures that are open or partially open, only, then no significant correlation is also observed (Figure 10h). Thus we find no systematic and consistent correlation between the elastic moduli of the fault rocks, as measured by the $V_p$ wireline logs of the DFDP-1 boreholes, and the density of damage zone structures.

5. Discussion

An analysis of the distribution of damage zone structures around the Alpine Fault, measured from DFDP-1 drill-core CT images and BHTV log data from the DFDP-1B borehole (Townend et al., 2013; McNamara, 2015), is made here. These results are then discussed in the context of other datasets gathered from the DFDP-1 project and their interpretations (Sutherland et al., 2012; Townend et al., 2013; Carpenter et al.,
2014; Eccles et al., 2015; Toy et al., 2015), to inform how the damage zone may influence various aspects of fault zone behaviour.

5.1 On the density of damage zone structures with proximity to the fault core and PSZs

We find the highest density of damage zone structures in the shallowest core intervals (39-45 m) in DFDP-1B (Figures 8). This is attributed to a high proportion of steeply-dipping foliation-parallel fractures, relative to the rest of DFDP-1B core (Figure 11). However, these fractures could conceivably have been generated from unloading effects (Engelder, 1985; Zangerl et al., 2006), during the rapid exhumation of the Alpine Fault hanging wall (Norris and Cooper, 2007). For this interval, their presence could therefore mask a trend of increasing damage zone structure density towards the fault.

For all other intervals sampled in DFDP-1, foliation-parallel fractures account for only 11% of all damage zone structures. Consequently, uncertainty in whether this fracture set reflects fault damage or unloading, will not affect our conclusion that the density of damage zone structures does not increase with proximity to the PSZ or fault core, within the scale of these intervals of DFDP-1 (30 m vertical distance in the borehole both above and below the PSZs). It is still possible, though, that the density of damage zone structures decays over a larger scale. Field studies, and coring from deeper wells, which would provide a continued record of fracturing around the Alpine Fault and span the transition from inside to outside the damage zone, would help elucidate these observations.
The lack of decay in the density of damage zones sampled in the DFDP-1 CT images is dissimilar to previous studies of fault damage zones that find clear decays in fracture density with increasing distance from the fault core. Logarithmic (Chester et al., 2005), exponential (Mitchell and Faulkner, 2009), and power law (Savage and Brodsky, 2011; Johri et al., 2014) relationships have all been invoked to describe this decay. Although McNamara, (2015) recognises a small degree of increasing damage towards PSZ-1 in the BHTV logs of DFDP-1B (Figure 8), it is not as marked as has been reported elsewhere.

5.2 Lithological role on the Alpine Fault damage zone

5.2.1 Influence of lithology on the intensity of damage

Though no relationship is found between the density of damage zone structures and proximity to the PSZs within the scale of DFDP-1, we note some trends can be modulated by lithology. For each of the lithological units defined by Toy et al., (2015), a representative example CT image of the unit and the density of damage zone structures section is given in Figure 12. Unit 1 ultramylonites and the ‘2-4 mixture unit’ contain the most damage zone structures. Unit 2 ultramylonites, which tend to be sampled closer to the PSZs, contain fewer damage zone structures than unit 1 ultramylonites. The footwall cataclasite (unit 6) is cross cut by noticeably fewer damage zone structures than the hanging wall cataclasites (unit 3 and 4). A link between lithology and the intensity of damage zone structures has been described elsewhere for faults in mixed sedimentary sequences (e.g. Chester & Logan 1986, Peacock & Xing 1994, Berg & Skar 2005).
A lithological control on fracture density can be explained by the following. Ishii et al., 2010 and Ishii, 2015 invoke that fractures are induced in damage zones during fault slip by increasing differential stresses and/or decreasing effective normal stresses, so that the Griffith-Coulomb failure criterion is met. Tensional strength ($T_0$), frictional strength ($\mu$) and cohesion ($c$) are fundamental constitutive properties of lithology (Twiss and Moores, 2007; Ishii, 2015). Therefore, if variations existed in these properties for the different units sampled in DFDP-1, the stresses (yield strength) necessary for tensional, hybrid and/or shear fractures to form in each of these units will also differ. Rheological variations associated with lithology will also control fracturing since less competent rocks are more likely to respond to failure by ductile shear deformation than by fracturing (Peacock and Xing, 1994; Fagereng and Sibson, 2010; Rowe et al., 2013). Further aspects of damage zone formation may also be influenced by lithology, such as the asymmetry of damage either side of a fault (Ben-Zion and Shi, 2005; Dor et al., 2006), and the width of the damage zone (Beach et al., 1999; Heynekamp et al., 1999).

5.2.2 Lithological influence on the spatial distribution of damage zone structures around DFDP-1

Given our finding that lithology is systematically related to the density of damage zone structures within the vicinity of the DFDP-1 boreholes, the distribution of the lithologies will in turn control the distribution of damage zone structures. We find that unit 1 ultramylonites that lie furthest from the Alpine Fault are the most heavily damaged (Figure 13), though the degree with which this reflects seismic damage or exhumation is unclear. With increasing proximity to the PSZs, a zone of interlayered
unit 2 ultramylonites, and unit 3 cataclasite units are encountered, as observed in Figure 9. The PSZ itself is overlain by a ~10 m thick unit of foliated cataclasite (unit 4), in which the structures that define the damage zone are infrequent compared to units 1-3. These observations indicate that with respect to Figure 1, the Alpine Fault represents a composite of the two models. It has a central thick (~10 m) fault core with well-defined PSZs (c.f. Figure 1a), but at its margins, fault core cataclasites anastomose with damage zone units (c.f. Figure 1b). Below PSZ-1, lies unit 6 footwall cataclasite that exhibit few damage zone structures cross cutting the initial cataclasite fabric (Figure 13).

Since damage zone structures are present within the fault core cataclasite units, where they cross-cut its fabric (Figures 3b, c, 7, 8 and 11), the fault core and fault damage zone spatially overlap. Damage is generated around the plane that accommodates shear displacement (Cowie and Scholz, 1992; Andrews, 2005; Ben-Zion and Shi, 2005); thus at shallow depths where the frictional properties of the PSZ facilitate the localisation of coseismic slip (Ikari et al., 2014), fracturing can occur within the surrounding well-cemented cataclasites.

5.3 Extent of fault zone healing

As discussed in section 4.2, we find no consistent relationship between the density of damage zone structures around the DFDP-1 boreholes and $V_p$ as measured by wireline logs of the DFDP-1 boreholes (Figure 10). This observation may be interpreted in two ways: (1) in this study we only consider intermediate-macroscopic damage zone structures (aperture >1 mm), thus $V_p$ may instead be controlled by
microfracture damage around the fault (e.g. Rempe et al. 2013), or (2) from healing of fractures, at all scales since the last Alpine Fault earthquake, resulting in a negligible effect of the fractures on the elastic moduli of the fault rocks and thus $V_P$.

We favour the latter explanation since evidence of widespread fracture healing is found at both the macroscale in the CT images, and at the microscale, where a pervasive calcite and clay cement, and relatively few open microfractures are noted (Toy et al., 2015). Furthermore, laboratory elastic wave speed tests on cylindrical samples from the DFDP-1 drill-core, whose dimensions (25 mm in diameter, <36 mm long) dictate that they sample microfractures only, did not demonstrate a reduction in $V_P$ associated with microscale fracture density (Tatham et al., 2012; Carpenter et al., 2014).

Even where open and partially open fractures are observed, they are not found to exert an influence on $V_P$ (Figure 10h); although it should be acknowledged that the lack of filling in these fractures may not necessarily result from a lack of healing, but instead from disturbance and opening during drilling. Nonetheless, it is clear that variations in the elastic properties -and other petrophysical properties- of the rock mass surrounding the DFDP-1 boreholes do not reflect fracturing, but instead changes in the extent of alteration and comminution superimposed on differences in primary lithology (Townend et al., 2013; Carpenter et al., 2014). This is in contrast to the San Andreas Observatory at Depth borehole, where it is inferred that macro scale fractures contribute to the development of a low velocity zone around the fault (Jeppson and Tobin, 2015).
The concept of fault and fracture healing within the timescale of seismic cycles ($10^1$-$10^4$ years) has gathered much attention owing to its fundamental role in many models for earthquake generation (Sibson, 1990; Rice, 1992; Chester et al., 1993). Monitoring of fault zones immediately after an earthquake by seismic surveys (Li and Vidale, 2001; Hiramatsu et al., 2005), or by studies of groundwater flow in boreholes (Xue et al., 2013; Wästeby et al., 2014) report hydrochemical recovery initiating immediately following an earthquake and that healing is complete within 2-10 years of an earthquake. Laboratory measurements of permeability on drill-core recovered approximately a year after the 1995 $M_w$ 7.2 Kobe in Japan, show that despite fracture filling noted in the drill-core itself (Lin et al., 2007), the damage zone is still an interval of enhanced permeability (Lockner et al., 2009). This indicates that within a year of an earthquake the damage zone is only partially healed. Laboratory studies, which aim to recreate healing within natural fault zones, find these processes are effective on timescales that range from days to tens of years, depending on the temperature and the chemistry of the pore fluid (Morrow et al., 2001; Tenthorey and Cox, 2006). Field observations have also identified fracture sealing within the recurrence intervals of large earthquakes (Woodcock et al., 2007). Since the Alpine Fault last hosted a major rupture in 1717 AD (Wells et al., 1999; De Pascale and Langridge, 2012), we conclude that in the intervening ~300 years, there has been ample time for fracture healing to occur.

However, it is significant that this study considers the damage zone immediately around the fault only (<30 m orthogonal distance from the PSZs). This interval lies within the alteration zone, that is noted as a zone within which fractures have been
extensively healed (Sutherland et al., 2012). Outside the <50 m thick alteration zone, drill-core recovery was low (Sutherland et al., 2011) with only 1.6 m of drill-core recovered over a depth range of 7 m. This means we cannot directly compare fracture healing inside and outside of the alteration zone using CT scans of DFDP-1 drill-core.

Nonetheless, the low drill-core recovery does indicate that this rock mass has low geotechnical strength. This is an indicator that it contains more open fractures. However, as noted in section 5.1, some of these fractures may have been generated by mechanisms other than seismic damage. Further indirect evidence of less extensive fracture healing outside the alteration zone comes from downhole permeability measurements that record the highest permeability (~$10^{-14}$ m$^{-2}$) in the damage zone above the alteration zone (Sutherland et al., 2012), again suggesting the presence of more open fractures in this interval. Thus, in the case of the Alpine Fault in its current late interseismic state, the damage zone immediately adjacent to the fault core is not the interval with the highest permeability.

This discrepancy in the extent to which fractures are healed inside and outside the alteration zone of the Alpine Fault can contribute to our understanding of the inconsistency between studies that report fracture healing and strength recovery through seismic cycles (Moore et al., 1994; Morrow et al., 2001; Tenthorey et al., 2003), and geophysical studies that find evidence of long-lived fracture induced damage around faults (Cochran et al., 2009; Ellsworth and Malin, 2011). In the case of the Alpine Fault, although fracture healing has occurred in the immediate vicinity of the fault (within the alteration zone), healing did not universally affect the entire
damage zone. This allows damage-induced reduction in the elastic rigidity of rocks to persist even though the Alpine Fault is late in its interseismic cycle, which thus permits the propagation of Fault Zone Guided Waves, as reported within the Alpine Fault by Eccles et al. (2015).

Determining the extent of fracture healing within a fault damage zone and its effect on the elastic properties of the rock mass is important as unhealed fractures can rotate the stress field around the fault (Faulkner et al., 2006; Gudmundsson et al., 2010), increase the extent of seismic ruptures (Weng et al., 2016), and increase fault zone compressibility which suppresses its ability to accommodate thermal pressurisation (Griffith et al., 2009). In DFDP-1, interseismic healing has yielded a damage zone that, immediately above (<50 m) the PSZs, has low permeability and high rigidity. Coupled with a particular low PSZ permeability (Boulton et al., 2012; Sutherland et al., 2012) this suggests that the conditions around the Alpine Fault are favourable for thermal pressurisation to occur.

5.4 Alpine Fault damage zone asymmetry

Higher fracture densities have been observed in the hanging wall of a fault relative to the footwall in several drilling projects into dipping thrust faults (Heermance et al., 2003; Lin et al., 2007; Yeh et al., 2007; Li et al., 2013). Based on the relative compliance of the rocks across the PSZs (Ben-Zion and Shi, 2005; Dor et al., 2006) and its setting as a dipping thrust fault (Ma and Beroza, 2008; Ma, 2009), Townend et al., (2013) predict that the extent of damage in the Alpine Fault will be greater in the hanging wall, as it is relatively stiffer than the footwall.
Based on the CT images, we note that the unit 6 footwall cataclasites exhibit relatively few damage zone structures that cross cut the cataclasite fabric compared to the hanging wall units (Figure 12, Figure 13). This is consistent with the observations of (Townend et al., 2013) and the analysis of fractures identified in the BHTV images (McNamara, 2015).

Below the footwall cataclasites in DFDP-1B (i.e. at depths >143.85 m MD) a ~7 m thick sequence of uncemented breccias were encountered; however it is not possible to discriminate if brecciation was tectonic or drilling induced (Toy et al., 2015). As they were not CT scanned these rocks have not been considered in this study. Consequently, the full extent of the damage in the Alpine Fault footwall is still poorly constrained and we cannot categorically state that the hanging wall is more damaged than the footwall. Accounting for the bi-material effects on rupture dynamics and damage zone asymmetry (Ben-Zion and Shi, 2005; Ma and Beroza, 2008) for the Alpine Fault will require, but is worthy of, further study.

Finally, we note that these observations are based on two 1-D transects through a heterogeneous fault system that exhibits variability along strike and with depth. Future work characterising the Alpine Fault in the field will account for along strike variation. A more complete assessment of damage at depth and damage in the footwall would be particularly possible in future scientific drilling projects into the Alpine Fault.
6. Conclusions

Qualitative and quantitative characterisation of structures that define the Alpine Fault damage zone has been conducted using X-ray Computed Tomography (CT) scans of drill-core recovered from the first phase of the Deep Fault Drilling Project (DFDP-1). Statistical analysis of the density and distribution of these structures was performed using a moving average that provides a more reliable measure of their distribution. A weighting was also added that accounts for orientation bias. Our major findings, listed below, are broadly consistent with independent analysis of damage zone structures picked in BHTV logs of the DFDP-1B borehole (Townend et al., 2013; McNamara, 2015).

1. The density of damage zone structures does not increase with proximity to the PSZs, within the scale of the DFDP-1 boreholes. Instead there is a lithological influence on the density and distribution of damage zone structures.

2. Damage zone structures extends into the fault core cataclasites where they cross cut the fabric. This is consistent with slip at shallow depths on Alpine Fault occurring on the PSZs.

3. We find that the majority of the damage zone structures sampled in this study are cemented/healed (72% fully, an additional 24% at least partially) by a combination of clays, calcite and quartz. This is consistent with the fact that the Alpine Fault is late in its interseismic cycle and has resulted in the structures imparting no influence on the stiffness of the rocks as evidenced by
their P-wave velocity. This facilitates the conditions necessary for thermal pressurisation to occur within the PSZ during earthquake rupture.

4. However, direct evidence of such damage zone healing is localised to within <50 m of the Alpine Fault in the alteration zone. Outside this interval, there is indirect evidence that fracture induced damage persists. Thus in the outer damage zone, damage maybe a permanent feature of the Alpine Fault throughout the seismic cycle.

Acknowledgements

DFDP-1 was funded by: GNS Science; Victoria University of Wellington; the University of Otago; the University of Auckland; the University of Canterbury; Deutsche Forschungsgemeinschaft and the University of Bremen; Natural Environment Research Council grants NE/J024449/1, NE/ G524160/1 and NE/H012486/1 and the University of Liverpool; and the Marsden Fund of the Royal Society of New Zealand. The International Continental Scientific Drilling Program, ICDP (www.icdp-online.org) provided extensive support. JW was supported by a University of Otago Doctoral Scholarship. We thank Steven Mills for his help in the generation of unrolled CT images and Matthew Paris and the Oncology Department at Dunedin Hospital for the use of a CT scanner. Reviews from James Kirkpatrick and Marieke Rempe greatly improved this manuscript.
References


Bjørk, T.E., Mair, K., Austrheim, H., 2009. Quantifying granular material and


Chester, J.S., Chester, F.M., Kronenberg, A.K., 2005. Fracture surface energy of the

Childs, C., Manzocchi, T., Walsh, J.J., Bonson, C.G., Nicol, A., Schöpfer, M.P.J.,
2009. A geometric model of fault zone and fault rock thickness variations. J.

Cochran, E.S., Li, Y.-G., Shearer, P.M., Barbot, S., Fialko, Y., Vidale, J.E., 2009.
Seismic and geodetic evidence for extensive, long-lived fault damage zones.
Geology 37, 315–318. doi:10.1130/G25306A.1

Columbus, J., Sirguey, P., Tenzer, R., 2011. A free fully assessed 15 metre digital
elevation model for New Zealand. Surv. Q. 300, 16.

Cooper, A.F., Norris, R.J., 1994. Anatomy, structural evolution, and slip rate of a
plate-boundary thrust: The Alpine fault at Gaunt Creek, Westland, New Zealand.

Geol. 14, 1133–1148.

earthquake in A.D. 1717, central Alpine fault, New Zealand. Geology.
doi:10.1130/g33363.1

the geomagnetic reversal time scale on estimates of current plate motions.

Dor, O., Rockwell, T.K., Ben-Zion, Y., 2006. Geological observations of damage
asymmetry in the structure of the San Jacinto, San Andreas and Punchbowl faults
in southern California: A possible indicator for preferred rupture propagation

Eccles, J.D., Gulley, A.K., Malin, P.E., Boese, C.M., Townend, J., Sutherland, R.,
2015. Fault Zone Guided Wave Generation on the Locked, Late Interseismic

Ellsworth, W.L., Malin, P.E., 2011. Deep rock damage in the San Andreas Fault
Publ. 359, 39–53.

Engelder, T., 1985. Loading paths to joint propagation during a tectonic cycle: an
example from the Appalachian Plateau, USA. J. Struct. Geol. 7, 459–476.

Fagereng, Å., Sibson, R.H., 2010. Melange rheology and seismic style. Geology 38,
751–754.

Faulkner, D.R., Jackson, C.A.L., Lunn, R.J., Schlische, R.W., Shipton, Z.K.,
2010. A review of recent developments concerning the structure, mechanics and fluid flow properties of fault zones. J.
Struct. Geol. 32, 1557–1575.


damage zones with displacement and the implications for fault growth processes.

Publ. 299, 139–150.


Ikari, M.J., Carpenter, B.M., Kopf, A.J., Marone, C., 2014. Frictional strength, rate-dependence, and healing in DFDP-1 borehole samples from the Alpine Fault,
New Zealand. Tectonophysics.


Rowe, C.D., Moore, J.C., Remitti, F., 2013. The thickness of subduction plate
boundary faults from the seafloor into the seismogenic zone. Geology 41, 991–
994.

of fracture distribution and secondary fault strands in fault damage zones. J.

Savage, H.M., Cooke, M.L., 2010. Unlocking the effects of friction on fault damage

Schulz, S.E., Evans, J.P., 2000. Mesoscopic structure of the Punchbowl Fault,
Southern California and the geologic and geophysical structure of active strike-

Schulz, S.E., Evans, J.P., 1998. Spatial variability in microscopic deformation and
composition of the Punchbowl fault, southern California: Implications for
mechanisms, fluid-rock interaction, and fault morphology. Tectonophysics 295,
223–244. doi:10.1016/S0040-1951(98)00122-X

Publ. 54, 15–28.

191–213. doi:10.1144/gsjgs.133.3.0191

Earthquake Faulting and a Mechanism for Partial or Total Stress Relief. Nat.

rocks in the Alpine Fault Zone, New Zealand. Geol. Soc. London, Spec. Publ. 9,


Sutherland, R., Eberhart-Phillips, D., Harris, R.A., Stern, T., Bevan, J., Ellis, S.,

Henrys, D., Cox, S., Norris, R.J., Berryman, K.R., Townend, J., Bannister, S.,

Pettinga, J., Leitner, B., Wallace, L., Little, T.A., Cooper, A.F., Yetton, M.,


Sutherland, R., Toy, V., Townend, J., Eccles, J., Prior, D.J., Norris, R.J., Mariani, E.,

Faulkner, D.R., de Pascale, G., Carpenter, B.M., Boulton, C., Menzies, C.D.,


Sutherland, R., Toy, V.G., Townend, J., Cox, S.C., Eccles, J.D., Faulkner, D.R., Prior, D.J., Norris, R.J., Mariano, R., Boulton, C., Carpenter, B.M., Menzies, C.D.,


Tatham, D.J., Faulkner, D.R., Mariani, E., Toy, V.G., 2012. Laboratory measurements of the permeability and P and S wave velocity and anisotropy of


Figure 1: Conceptual models of fault zone architecture with different configurations of damage zone and fault core: (a) single fault core, and (b) multiple anastomosing fault cores bounded by lenses of damaged rock. A schematic representation of how brittle strain may be distributed across these faults is also shown. Diagram intentionally has no scale. Modified from Mitchell and Faulkner (2009).
Figure 2: Location map. (a) Map of South Island, New Zealand showing extent of Alpine Fault and all other onshore active faults for South Island (GNS Active Fault Database, http://data.gns.cri.nz/af/). Black box illustrates extent of (b), a locality map for the DFDP-1 site at Gaunt Creek in the context of the central section of the Alpine Fault (red line) that extends roughly between Hokitika and Haast. Hills illuminated using greyscale from 15 m digital elevation model (Columbus et al., 2011), illumination is from the northwest, yellow lines are roads. (c) Composite schematic
section of rock sequence typically encountered in an oblique thrust segment of the central Alpine Fault, modified after Norris and Cooper (2007).
Figure 3: Distinction between damage zone structures and other features in 2D X-ray computed tomography (CT) images. (a) CT drill-core axial parallel image of DFDP-1 drill-core (1B-34-1 101.97-102.13 m). Whilst foliation and fractures both appear as linear arrangement of anomalous CT values, fractures have more distinct boundaries and greater anomalies of CT values. The foliation-parallel black fracture is interpreted to have formed from the release of confining pressure during the drilling itself, whilst the sub-horizontal black fracture is noted in the core-log as being handling induced. (b) CT image and (c) equivalent section in 180º core scan, to show examples of damage zone structures in a cataclasite unit (DFDP-1B 66-1 138.38-138.56 m), in
which fractures and subsidiary faults cross cut the initial cataclasite fabric. (d) Disc fracture in DFDP-1A 60-2 81.50-81.70 m. Example of core sections with induced (e, DFDP-1A 49-1 67.7-67.95 m) and natural (f, DFDP-1B 31-1 96.75-96.95 m) brecciation. Induced brecciation is characterised by angular fragmentation of the core, during drilling, whereas natural brecciation leads to the rounding of clasts. (g) Two open fractures dipping in opposite directions to define a triangular set whose apex points at the centre of the drill-core (DFDP-1A 54-1 73.7-73.83 m). CT numbers refer to greyscale as shown. This greyscale is used in all subsequent CT images.
Figure 4: (a) Example of how the depth of a dipping damage zone structure was measured by recording the depth at which the structure intersected a scan-line parallel to the core axis in a 2D CT image (1B-37-2 105.96-106.15 m). Depth is measured relative to the top of the core section; these sections are registered to absolute depths so from them the depth of the structure within the borehole can be calculated. (b) To measure the orientation of a damage zone structure within a local core reference frame; strike was measured in a CT axial slice image of the core (which represents a horizontal plane since the DFDP-1 boreholes were vertical) relative to the right hand edge of the core container, which was denoted ‘north.’ An apparent dip of the structure was measured from the angle between the damage zone structure and a line 90° to the core axis in a core axial parallel 2D CT scan image as shown in (a). Using the strike, a true dip can then be calculated from apparent dip.
Figure 5: (a) A hypothetical fractured rock mass intersected by a vertical borehole, illustrating how fracture density and distribution may be calculated in a borehole. The rock mass contains two fracture sets: (1) dipping at 03° (red) and (2) dipping at 70° (black). These intersect the borehole at a randomly generated set of depths using the ‘sample’ function in the statistical programming language R (https://stat.ethz.ch/R-manual/R-devel/library/base/html/sample.html). (b&c) Fracture distribution around the borehole represented using a histogram with frequency calculated in (b) 5 m bins and (c) 2.5 m bins. Blue boxes in histograms represent fracture density calculated using the Terzaghi correction for orientation bias as explained in text. (d) Fracture set depicted using a (black) moving and (red) weighted moving average calculation, which are uncorrected and corrected orientation bias respectively. Moving average
has been calculated using a moving window of 2.5 m and at intervals of 25 cm. When fracture density is represented using a moving average it gives a better representation of intervals of high fracture density that are split across two bins (such as at ~10 m) than when fracture density is represented on a histogram. Introducing a weighting to correct for orientation bias gives a better representation of the density of steeply dipping fractures in the rock mass but does not inform us further on their distribution.
Figure 6: A comparison between borehole televiewer (BHTV) statically normalised data (two way travel time (TWTT) and amplitude) and an ‘unrolled’ CT image, which depicts an image of the outer surface of the drill-core, for the depth interval 107.57-108.56 m in DFDP-1B. This demonstrates that, because the resolution of the BHTV is less than that of the CT images, damage zone structures picked in the CT images may not be picked in the BHTV data.
Figure 7

**Core Lithologies Key**

- **1** Green and dark grey ultramylonites
- **2** Brown-green-black ultramylonites
- **3** Hanging wall unfoliated cataclasites
- **4** Hanging-wall foliated cataclasites
- **5** Gouges
- **6** Footwall cataclasites
- **7** Breccias
- **8** Sedimentary gravels

**Figure 7**

Damage zone structures #/m

- Depth (m): 0, 40, 80
- Damage zone

**$V_p$ (m/s)**

- Depth (m): 2000, 4000, 6000
- Uncorrected, Corrected

**Resistivity (Ωm)**

- Depth (m): 200, 600, 1000

Legend:

- Green and dark grey ultramylonites
- Brown-green-black ultramylonites
- Hanging wall unfoliated cataclasites
- Hanging-wall foliated cataclasites
- Gouges
- Footwall cataclasites
- Breccias
- Sedimentary gravels

**PSZ**
Figure 7: Density of damage zone structures within CT scan images of DFDP-1A drill-core calculated using a moving average and weighted moving average with a 1 m window size. Results are shown for cases in which a weighting has, and has not, been applied to correct for orientation bias. Colours adjacent to plots reflect the DFDP-1 lithologies defined by Toy et al. (2015). Wireline logging data previously presented in Townend et al. (2013).
Figure 8: As for Figure 7, but for the DFDP-1B borehole. Additionally we show the density of damage zone structures picked in BHTV data (McNamara, 2015), calculated with a moving average at intervals of 10 cm and with a 5 m moving window to reflect the lower resolution of these data. Note that the resistivity anomaly associated with PSZ-1 is 0.2 m below that measured in the drill-core.
Figure 9: CT image slice of drill-core section DFDP-1B 49-1, 115.50-116.05 m. This section exemplifies the disparity between unit 3 cataclasite that exhibits a relatively high amount of fault damage zone (denoted by vertical white arrows), compared to unit 2 ultramylonites that contain relatively few damage zone structures, even though
it is only ~12 m vertical distance from PSZ-1 sampled in DFDP-1B. Horizontal green arrows and ellipse indicate areas of induced damage in the drill-core.
Figure 10: Cross-plots of damage zone structure density, calculated using a moving average with a window size of 30 cm, against P-wave velocity ($V_P$) obtained from wireline logging (Townend et al., 2013). CI refers to the 95% confidence interval of, b, the slope of the best-fit line between the damage zone structure density and $V_P$, to four decimal places. If the CI values are close to, but both above zero, it suggests a very weak positive correlation and vice versa. Values either side of zero indicate that, statistically, there is no significant correlation between these parameters. (a) For all data points in the DFDP-1 boreholes. (b)-(g) are selected from (a) by lithological unit: (b) unit 1 ultramylonites, (c) unit 2 ultramylonites, (d) unit 2-4 mixture, (e) unit 3 cataclasites, (f) unit 4 cataclasites, (g) unit 6 cataclasites. (h) Cross plot calculated as for all depths, but accounting for open and partially open fractures only (type v, vi and vii structures, Table 1).
Figure 11: CT image of heavily fractured mylonite that was amongst the drill-core recovered furthest from PSZ-1 in DFDP-1B (core section 1B-25-2, depth 44.8-45.2 m). Green (horizontal) arrows identify foliation parallel filled fractures. It is unclear whether this fracture set formed as a result of seismic damage or from unloading during exhumation. White (vertical) arrows identify a non-foliation parallel set of fractures that continue to be identified in this interval.
Figure 12: A representative drill-core axial parallel CT image of each DFDP-1 lithology (Toy et al., 2015) to qualitatively show how damage zone structure density varies across lithology. (b) Density of damage zone structures for each lithological unit, corrected for orientation bias. Error bars show the interquartile range of damage zone structure density calculated using a weighted moving average for each lithology.
Figure 13: A schematic representation of the distribution of damage zone structures in a cross section around the Alpine Fault, which was sampled in DFDP-1.
<table>
<thead>
<tr>
<th>Type</th>
<th>CT Number Range</th>
<th>Aperture (mm)</th>
<th>Interpretation and Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i) Gouge Filled</td>
<td>1400-1900</td>
<td>&gt;3</td>
<td>Small fault, clasts, 1-50 mm in size, of high CT (1900-3000) values, surrounded by low CT values</td>
</tr>
<tr>
<td>(ii) Cataclasite</td>
<td>1300-3000</td>
<td>&gt;3</td>
<td>Cataclasite filled fault, clasts, 1-50 mm in size, of high CT (1900-3000) values, surrounded by low CT values</td>
</tr>
</tbody>
</table>

Table 1
<table>
<thead>
<tr>
<th>2000 values</th>
<th>Clay filled fracture</th>
<th>Clay filled fracture</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1-2</td>
<td>1-30</td>
<td></td>
</tr>
<tr>
<td>1600-2200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(iii) Dark grey</td>
<td></td>
<td>(iv) Grey</td>
</tr>
</tbody>
</table>

- 2000 values:
  - (i) 1600 - 2200
  - (ii) <1
  - (iii) Dark grey
  - (iv) Grey

- Clay filled fractures:
  - 10 cm
  - 5 cm

- Image captions:
  - 10 cm
  - 5 cm
<table>
<thead>
<tr>
<th>Open fracture</th>
<th>Partially open fracture. Gradual change in CT number along length</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1-3</td>
<td>&lt;1-3</td>
</tr>
<tr>
<td>-1024-1200</td>
<td>-1024-2200</td>
</tr>
</tbody>
</table>

(v) Black  
(vi) Black-dark grey
<table>
<thead>
<tr>
<th>(vii) Black and dark grey</th>
<th>-1024-2200</th>
<th>&lt;1-5</th>
<th>Partially open fracture. Abrupt change in CT number along length</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>(viii) White</td>
<td>2300-3000</td>
<td>&lt;1-5</td>
<td>Quartz or calcite vein</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 1: Classification scheme for describing damage zone structures observed in CT scans of DFDP-1 drill-core. Percentage of damage zone structures applies to those recognised within the alteration zone only, i.e. it excludes structures recognised in the interval of 39-45 m in the DFDP-1B borehole.