Reviewer Number 2

This short and concise manuscript describes fractures in the hangingwall of the Alpine fault. It is very well written and illustrated (assuming that the quality of the real images is much better than the ones in the pdf), and contains some useful data. One of the conclusions about the width of the damage zone and how it is defined is well supported by the data.

#1 One question concerns the attribution of the open fractures to low confining pressures. It is argued that the type of fracture varies independently of rock type and therefore that confining pressure must be an additional variable. However, there are other factors that can affect fracture styles, most notably pore fluid pressure. The presence of an open fracture alone does not mean that it formed under low confining pressures (though it is quite possible).

The hypothesis that fractures are kept open by the high pore fluid pressures around the Alpine Fault is an interesting idea; not least as the DFDP-2B boreholes demonstrated that these fractures do transmit fluids (Townend et al 2018). If such a zone existed though, then it would be anticipated that it would be encompassed within the Low Velocity Zone (LVZ) around the Alpine Fault and be detected by FZGW, since pressurised fluids can strongly attenuate seismic velocities (e.g. Nur and Simmons 1969, Jones and Nur 1984, Christensen 1989, Eberhart-Phillips et al 1995). However, this is not the case as the Alpine Fault LVZ is reported to be 60-200 m wide (Eccles et al 2015). Consequently, this network of open fracture cannot have contributed to the LVZ; hence our interpretation that this is a near-surface phenomena (Lines 363-365). Furthermore, if these fractures were kept open by high pore fluid pressure, then one might expect to some evidence of fracture mineralisation. However, extensive mineralisation is only observed within <50 m of the Alpine Fault (Williams et al 2017). See also comment #1 by reviewer #1

#2 This discussion highlights a related issue: what are the kinematics of the fractures? This is one area of weakness in the descriptions. Presumably the gouge filled fractures have a shear displacement, but how much and in what directions? What about the open fractures? Do they have any fractographic features giving information on the fracture type? What do the variety of orientations of the gouge filled fractures mean for paleostress? What is their relation to seismicity? Could the differences between the fractures be simply that the open fractures are mode I and the gouge-filled, othermodes? Would this necessarily imply lower pressures?

The omission of information regarding the kinematics of these fractures can be readily corrected in a revisited manuscript using data collected in this study and previous work. Though offset markers across gouge-filled fractures (particularly those <1 cm thick) are rarely observed in our dataset, where they are present, reverse offset is most frequently noted (Figure 8f). This is comparable to previous field studies (Cooper and Norris 1994, Norris and Cooper 1997) and descriptions of DFDP-1 core (Toy et al 2015). Furthermore, these studies note steeply dipping fractures with strike-slip slickenside lineations (Norris and Cooper 1997) and a small population of gouge-filled shears with normal dip-slip (Cooper and Norris 1994). Using high resolution airborne LiDAR, subsidiary dextral and dextral-normal faults within the Alpine Fault thrust sheets have also been mapped (Barth et al 2012).

These observations thus indicate that these fractures exhibit a range of shear-senses. This may be linked to the complex interaction between the transpressional strain accommodated across the Alpine Fault and the near-surface topographic stresses (Norris and Cooper 1995, Upton et al 2017). Furthermore, it is quite possible that these fractures formed under a dynamic co-seismic stress state that is quite different to the background static state (see also comment #2 by reviewer #1).

Consequently, though we recognise the value of using gouge-filled fracture orientations to obtain paleostresses orientations around the Alpine Fault, we consider that the range of fracture orientations, shear senses, and a stress state, which varies both spatially and temporally, prohibits such analysis. We also note that previous attempts to use fracture orientations to derive stress orientations around the Alpine Fault have been unsuccessful (Snee et al. 2014). This was interpreted to be because it is: (1) a reactivated structure and (2) hosted in anisotropic rock.

With regards to the open fractures, no evidence of shear across them is observed. This supports the idea that they truly represent extensional Mode I fractures and can be termed joints. However, given that foliation, not *stress, likely governs their orientation (see comment #1 by reviewer #1), these also cannot be used as paleostress indicators*

No doubt some of these questions are answered elsewhere or in the process of being answered, but they are relevant to this manuscript. In general it would, however, be good to have a more description of the fractures.

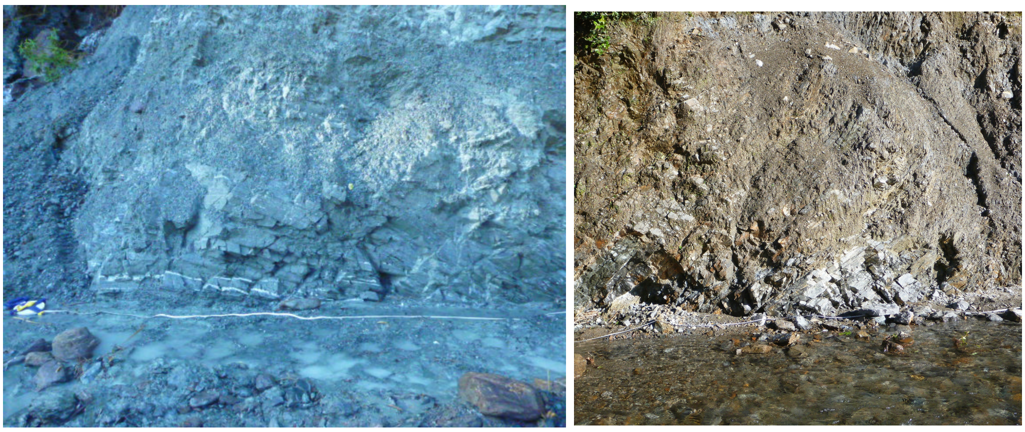
The scan line methodology needs some further justification in the light of recent literature about the circular scan line technique.

We concede that circular scan lines are a superior way of quantitatively assessing fracturing at the outcrop scale (as well document in Watkins et al 2015), however, the outcrops across our stream transects did not lend themselves to this strategy for the following reasons:

1.) *All transects were across (sub) vertical cliff faces, whereas the circular scan line technique is best suited to flat outcrops. If undertaking a circular scan line, the maximum diameter would be 2-3 m, as it is limited by the height with which one could accurately measure fracture orientations and fill from a cliff face. By contrast, a <20 m long scanline along the cliffs base (see figure below) would contain far more information.*

2.) *The cliff faces are themselves covered in debris or highly friable rock. However, the base of the exposures are "cleaned" when the streams are in flood, and so still provide good quality exposure (see figure below). Consequently, a long scan-line along the cliff bases will provide the best information on the fracturing at these outcrops.*

In future, we recognise that quantitative analysis of fracturing may be improved by 3D photogrammetry models or FracPraQ software (Healy et al 2017; n.b. this work flow was not published until after we conducted our fieldwork in 2015-16).



Outcrop used for (left) Havelock Creek transect 2 and (right) Stony Creek transect 2, illustrating that the highest quality exposure lies along the base of the cliff. This illustrates why a linear transect provides the best opportunity for collecting quantitative fracture data at these outcrops.

Comments line by line

Line 189-190: Is this valid? What is the relationship between these faults and the Alpine fault? What is they are also part of the damage zone?

We consider these faults to be representative of regional deformation in the Alpine Faults hanging-wall (discussed at Lines 379-382), not the Alpine Fault damage zone per se (as also addressed at for reviewer 1's comments for lines 269-274 and 379). Although clearly the crust is highly deformed for km's into the Alpine Fault 's hanging-wall (as one would expect for the crust next to a plate boundary fault!!), the density of these structures is particularly high only within 160 m of the fault and it is this zone that represents the damage *zone (or inner damage zone as defined in Townend et al 2018). This can be clarified in the revised manuscript.*

Line 204: Was there any way to check on the validity of these results e.g. compare some nearby surface orientations?

Yes, the orientation of foliation, joints and fractures were subsequently measured in the Amethsyt Tunnel itself (Savage 2013), which was completed after the boreholes, and are broadly consistent with our results (i.e. foliation dips SSE, and fractures and faults are parallel to it). We can include their observation in the revised manuscript.

Line 230: Is this corrected

These measurements have been corrected for orientation bias, and this can be explained in the revised manuscript.

Line 308: How is the confining pressure at which the fractures formed determined?

We apologise that our writing was unclear, this was only meant to be in a qualitative sense. The evidence for this interpretation is discussed in our replies to comment # 1 by reviewer 1 and comment #1 by this reviewer.

Figure 4: I hope that the quality of these images is better than the ones in the pdf, which are so poor that the fractures are entirely unconvincing.

As noted for other comments, the original version of this figure has a much higher resolution, and this will presumably the case at the final publication state.

References

Ampuero, J. P., & Mao, X. (2017). Upper limit on damage zone thickness controlled by seismogenic depth. *Fault Zone Dynamic Processes: Evolution of Fault Properties During Seismic Rupture*, *227*, 243.

Barth, N. C., Toy, V. G., Langridge, R. M., & Norris, R. J. (2012). Scale dependence of oblique plate-boundary partitioning: New insights from LiDAR, central Alpine fault, New Zealand. *Lithosphere*, *4*(5), 435-448.

Barth, N. C., Boulton, C., Carpenter, B. M., Batt, G. E., & Toy, V. G. (2013). Slip localization on the southern Alpine fault, New Zealand. *Tectonics*, *32*(3), 620-640.

Boese, C. M., Townend, J., Smith, E., & Stern, T. (2012). Microseismicity and stress in the vicinity of the Alpine Fault, central Southern Alps, New Zealand. *Journal of Geophysical Research: Solid Earth*, *117*(B2).

Cappa, F., Perrin, C., Manighetti, I., & Delor, E. (2014). Off-fault long-term damage: A condition to account for generic, triangular earthquake slip profiles. *Geochemistry, Geophysics, Geosystems*, *15*(4), 1476-1493.

Chamberlain, C. J., Boese, C. M., & Townend, J. (2017). Cross-correlation-based detection and characterisation of microseismicity adjacent to the locked, late-interseismic Alpine Fault, South Westland, New Zealand. *Earth and Planetary Science Letters*, *457*, 63-72.

Christensen, N. I. (1989). Pore pressure, seismic velocities, and crustal structure. *Geological Society of America Memoirs*, *172*, 783-798.

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*(4), 315-318.

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 Zeal. Geol. Soc. Am. Bull. 106, 627-633.

Donath, F. A. (1961). Experimental study of shear failure in anisotropic rocks. *Geological Society of America Bulletin*, *72*(6), 985-989.

Eberhart-Phillips, D., Stanley, W. D., Rodriguez, B. D., & Lutter, W. J. (1995). Surface seismic and electrical methods to detect fluids related to faulting. *Journal of Geophysical Research: Solid Earth*, *100*(B7), 12919-12936.

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 Alpine Fault, New Zealand. *Geophysical Research Letters*, *42*(14), 5736-5743.

Ellsworth, W. L., & Malin, P. E. (2011). Deep rock damage in the San Andreas Fault revealed by P-and S-type fault-zone-guided waves. *Geological Society, London, Special Publications*, *359*(1), 39-53.

Engelder, T. (1985). Loading paths to joint propagation during a tectonic cycle: an example from the Appalachian Plateau, USA. *Journal of Structural Geology*, *7*(3), 459-476.

Healy, D., Rizzo, R. E., Cornwell, D. G., Farrell, N. J., Watkins, H., Timms, N. E., ... & Smith, M. (2017). FracPaQ: A MATLAB™ toolbox for the quantification of fracture patterns. *Journal of Structural Geology*, *95*, 1-16.

Geotech Consulting Limited: Amethyst Hydro Scheme Drilling Investigation Summary 630 Report., 2006

Huang, Y., Ampuero, J. P., & Helmberger, D. V. (2014). Earthquake ruptures modulated by waves in damaged fault zones. *Journal of Geophysical Research: Solid Earth*, *119*(4), 3133-3154.

Jones, T. D., & Nur, A. (1984). The nature of seismic reflections from deep crustal fault zones. *Journal of Geophysical Research: Solid Earth*, *89*(B5), 3153-3171.

Langridge, R. M., Ries, W. F., Farrier, T., Barth, N. C., Khajavi, N., & De Pascale, G. P. (2014). Developing sub 5-m LiDAR DEMs for forested sections of the Alpine and Hope faults, South Island, New Zealand: Implications for structural interpretations. *Journal of Structural Geology*, *64*, 53-66.

Langridge, R. M., Ries, W. F., Litchfield, N. J., Villamor, P., Van Dissen, R. J., Barrell, D. J. A., ... & Lee, J. M. (2016). The New Zealand active faults database. *New Zealand Journal of Geology and Geophysics*, *59*(1), 86-96.

Ma, S., & Beroza, G. C. (2008). Rupture dynamics on a bimaterial interface for dipping faults. *Bulletin of the Seismological Society of America*, *98*(4), 1642-1658.

Mitchell, T. M., & Faulkner, D. R. (2009). The nature and origin of off-fault damage surrounding strike-slip fault zones with a wide range of displacements: a field study from the Atacama fault system, northern Chile. *Journal of Structural Geology*, *31*(8), 802-816.

Mitchell, T. M., & Faulkner, D. R. (2012). Towards quantifying the matrix permeability of fault damage zones in low porosity rocks. *Earth and Planetary Science Letters*, *339*, 24-31.

Norris, R. J., & Cooper, A. F. (2007). The Alpine Fault, New Zealand: surface geology and field relationships. *A Continental Plate Boundary: Tectonics at South Island, New Zealand*, 157-175.

Nasseri, M. H. B., Rao, K. S., & Ramamurthy, T. (2003). Anisotropic strength and deformational behavior of Himalayan schists. *International Journal of Rock Mechanics and Mining Sciences*, *40*(1), 3-23.

Norris, R. J., & Cooper, A. F. (1995). Origin of small-scale segmentation and transpressional thrusting along the Alpine fault, New Zealand. *Geological Society of America Bulletin*, *107*(2), 231-240.

Norris, R. J., & Cooper, A. F. (1997). Erosional control on the structural evolution of a transpressional thrust complex on the Alpine Fault, New Zealand. *Journal of Structural Geology*, *19*(10), 1323-1342.

Nur, A., & Simmons, G. (1969). The effect of saturation on velocity in low porosity rocks. *Earth and Planetary Science Letters*, *7*(2), 183-193.

Perrin, C., Manighetti, I., Ampuero, J. P., Cappa, F., & Gaudemer, Y. (2016). Location of largest earthquake slip and fast rupture controlled by along-strike change in fault structural maturity due to fault growth. *Journal of Geophysical Research: Solid Earth*, *121*(5), 3666-3685.

Paterson, M. S., & Wong, T. F. (2005). Experimental rock deformation-the brittle field. *Springer Science & Business Media.*

Priest, S. D. (1993). Discontinuity analysis for rock engineering. *Springer Science & Business Media.*

Upton, P., Song, B. R., & Koons, P. O. (2017). Topographic control on shallow fault structure and strain partitioning near Whataroa, New Zealand demonstrates weak Alpine Fault. *New Zealand Journal of Geology and Geophysics*, 1-8.

Savage, E. (2013). Investigating Rock Mass Conditions and Implications for Tunnelling and Construction of the Amethyst Hydro Project, Harihari.

Sibson, R. H., White, S. H., & Atkinson, B. K. (1981). Structure and distribution of fault rocks in the Alpine Fault Zone, New Zealand. *Geological Society, London, Special Publications*, *9*(1), 197-210.

Simpson, G. D., Cooper, A. F., & Norris, R. J. (1994). Late quaternary evolution of the Alpine fault zone at Paringa, South Westland, New Zealand. *New Zealand journal of geology and geophysics*, *37*(1), 49-58.

Snee, J. E. L., Toy, V. G., & Gessner, K. (2014). Significance of brittle deformation in the footwall of the Alpine Fault, New Zealand: Smithy Creek Fault zone. *Journal of Structural Geology*, 64, 79-98.

Stern, T., Okaya, D., Kleffmann, S., Scherwath, M., Henrys, S., & Davey, F. (2007). Geophysical exploration and dynamics of the Alpine fault zone. *A Continental Plate Boundary: Tectonics at South Island, New Zealand*, 207-233.

Sutherland, R., Eberhart-Phillips, D., Harris, R. A., Stern, T., Beavan, J., Ellis, S., ... & Townend, J. (2007). Do great earthquakes occur on the Alpine fault in central South Island, New Zealand?. *A continental plate boundary: tectonics at South Island, New Zealand*, 235-251.

Townend, J., Sutherland, R., Toy, V. G., Eccles, J. D., Boulton, C., Cox, S. C., & McNamara, D. (2013). Late-interseismic state of a continental plate-bounding fault: Petrophysical results from DFDP-1 wireline logging and core analysis, Alpine Fault, New Zealand. *Geochemistry, Geophysics, Geosystems*, *14*(9), 3801-3820.

Townend, J., Sutherland, R., Toy, V. G., Doan, M. L., Célérier, B., Massiot, C, et al. (2018). Petrophysical, Geochemical, and Hydrological Evidence for Extensive Fracture-Mediated Fluid and Heat Transport in the Alpine Fault's Hanging-Wall Damage Zone. *Geochemistry, Geophysics, Geosystems.*

Toy, V. G., Boulton, C. J., Sutherland, R., Townend, J., Norris, R. J., Little, T. A., ... & Scott, H. (2015). Fault rock lithologies and architecture of the central Alpine fault, New Zealand, revealed by DFDP-1 drilling. *Lithosphere*, *7*(2), 155-173.

Toy, V. G., Sutherland, R., Townend, J., Allen, M. J., Becroft, L., Boles, A., ... & Daube, C. (2017). Bedrock geology of DFDP-2B, central Alpine Fault, New Zealand. New Zealand Journal of Geology and Geophysics, 60(4), 497-518.

Watkins, H., Bond, C. E., Healy, D., & Butler, R. W. (2015). Appraisal of fracture sampling methods and a new workflow to characterise heterogeneous fracture networks at outcrop. *Journal of Structural Geology*, *72*, 67-82.

Weng, H., Yang, H., Zhang, Z., & Chen, X. (2016). Earthquake rupture extents and coseismic slips promoted by damaged fault zones. *Journal of Geophysical Research: Solid Earth*, *121*(6), 4446-4457.

Williams, J. N., Toy, V. G., Massiot, C., McNamara, D. D., & Wang, T. (2016). Damaged beyond repair? Characterising the damage zone of a fault late in its interseismic cycle, the Alpine Fault, New Zealand. *Journal of Structural Geology*, *90*, 76-94.

Williams, J. N., Toy, V. G., Smith, S. A., & Boulton, C. (2017). Fracturing, fluid-rock interaction and mineralisation during the seismic cycle along the Alpine Fault. *Journal of Structural Geology*, *103*, 151-166.