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Controls on fault zone structure and brittle fracturing in the foliated hanging wall of the Alpine Fault

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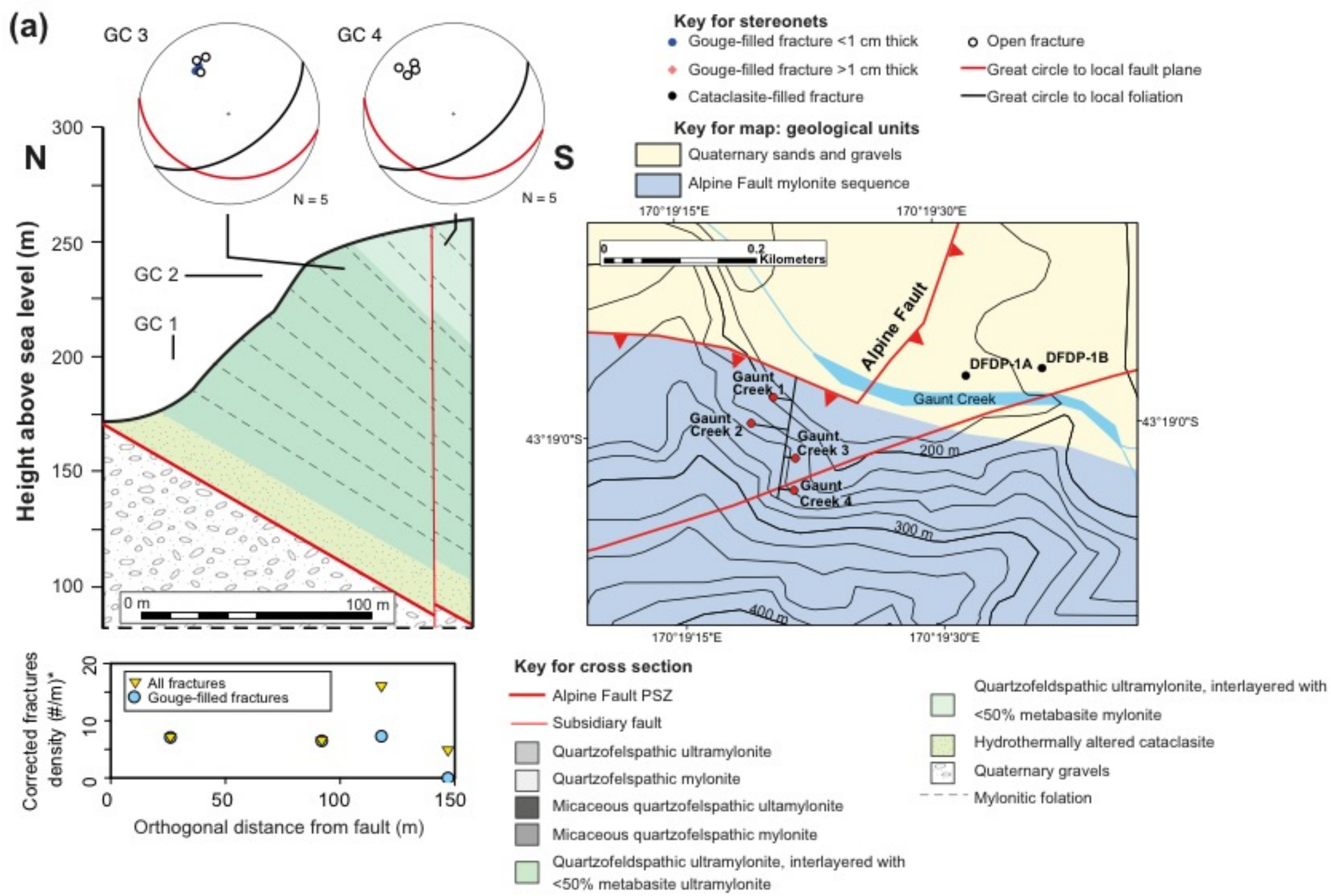
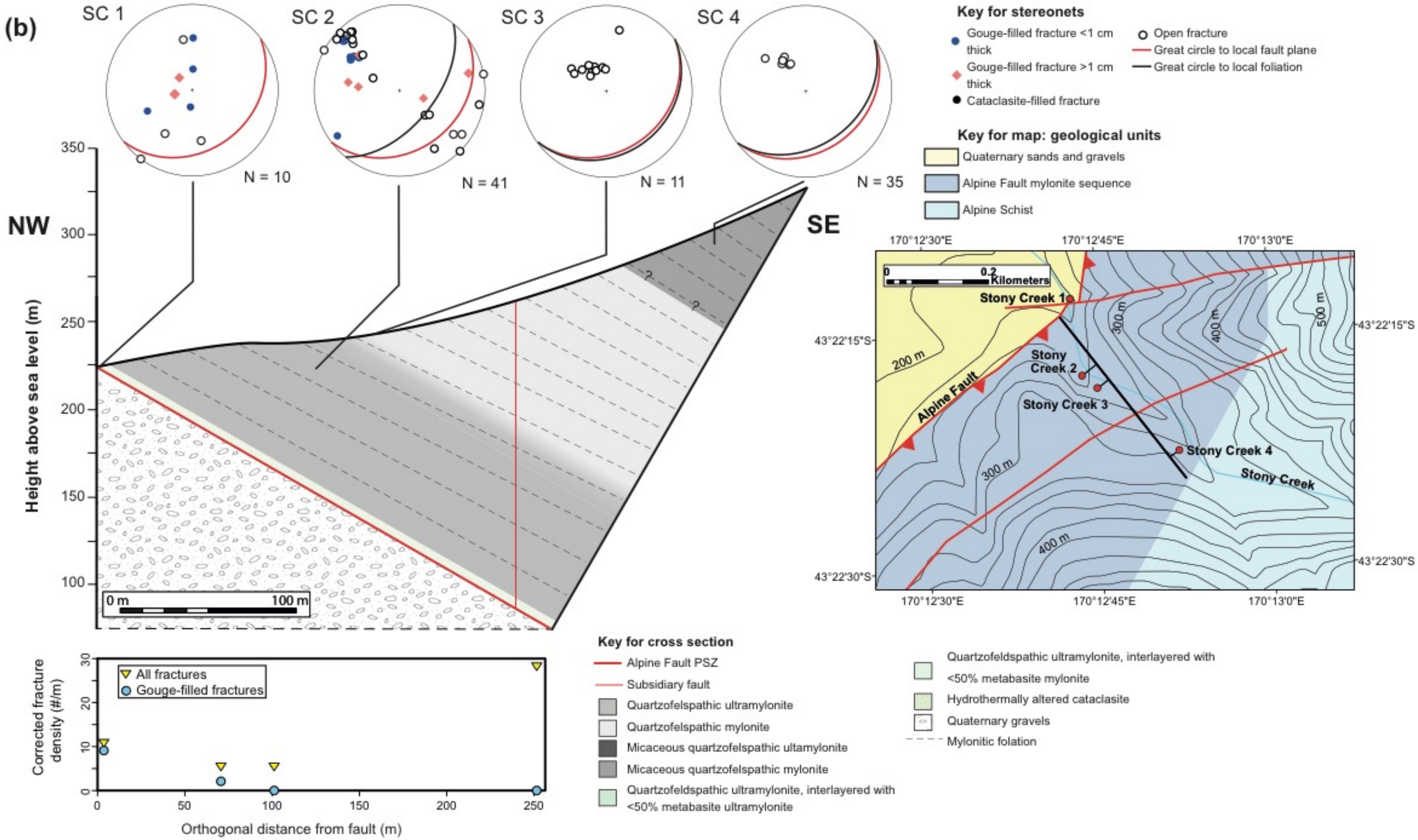
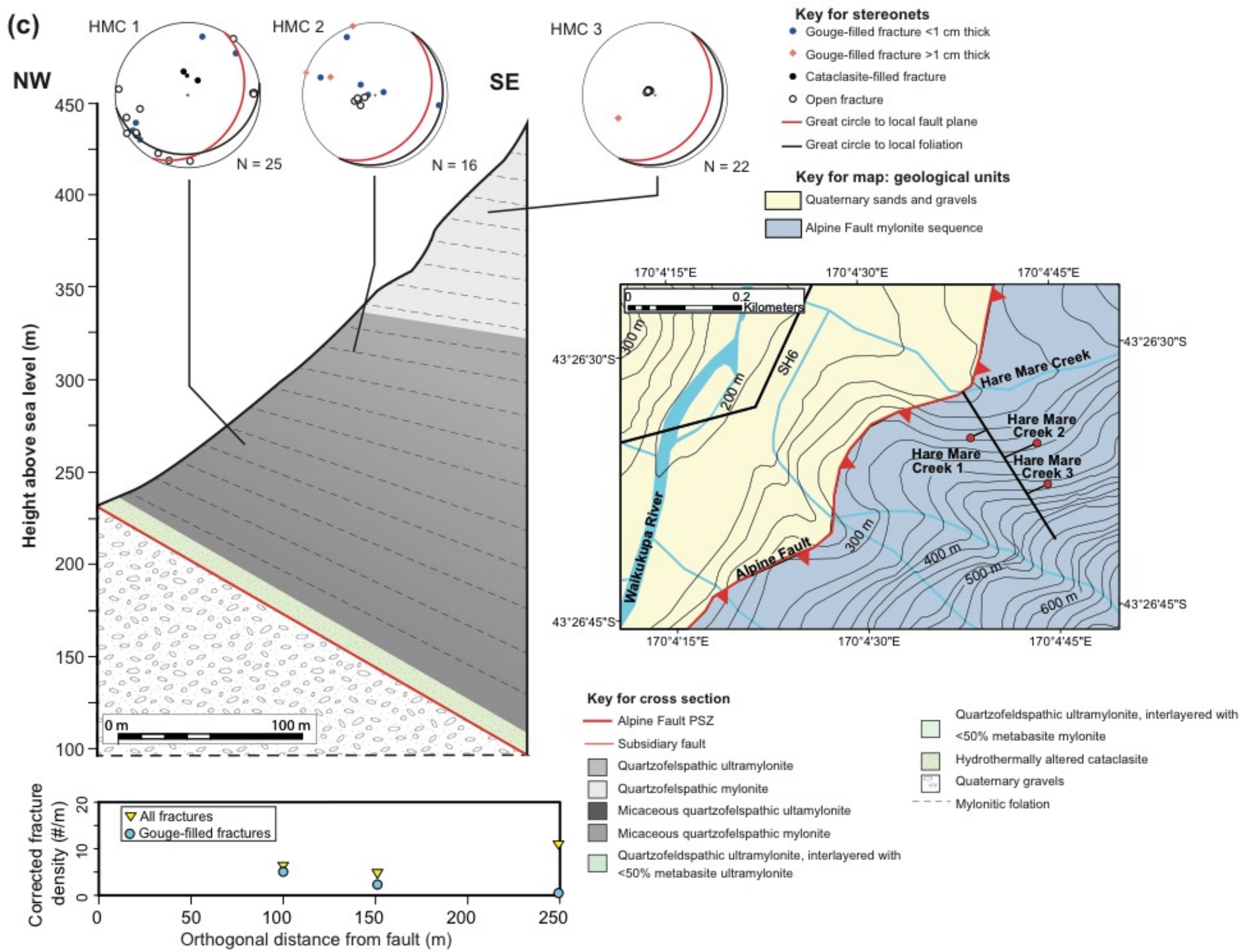
Supplementary Material

Figure S1




(b)
SC 1
SC 2
SC 3
SC 4
N = 10
N = 41
N = 11
N = 35
NW
SE
Height above sea level (m)
350
300
250
200
150
100
0 m
100 m
?
Key for stereonets
Gouge-filled fracture <1 cm thick
Gouge-filled fracture >1 cm thick
Cataclasite-filled fracture
Open fracture
Great circle to local fault plane
Great circle to local foliation
Key for map: geological units
Quaternary sands and gravels
Alpine Fault mylonite sequence
Alpine Schist
170°12'30"E
170°12'45"E
170°13'0"E
43°22'15"S
43°22'30"S
0
0.2
Kilometers
Stony Creek 1
Stony Creek 2
Stony Creek 3
Stony Creek 4
Stony Creek
Alpine Fault
200 m
300 m
400 m
500 m
Corrected fracture density (#/m)
All fractures
Gouge-filled fractures
0
10
20
30
50
150
250
Orthogonal distance from fault (m)
Key for cross section
Alpine Fault PSZ
Subsidiary fault
Quartzofelspathic ultramylonite
Quartzofelspathic mylonite
Micaceous quartzofelspathic ultamylonite
Micaceous quartzofelspathic mylonite
Quartzofeldspathic ultramylonite, interlayered with <50% metabasite ultramylonite
Quartzofeldspathic ultramylonite, interlayered with <50% metabasite mylonite
Hydrothermally altered cataclasite
Quaternary gravels
Mylonitic folation


(c)
HMC 1
HMC 2
HMC 3
N = 25
N = 16
N = 22
NW
SE
Height above sea level (m)
Key for stereonets
Gouge-filled fracture <1 cm thick
Gouge-filled fracture >1 cm thick
Cataclasite-filled fracture
Open fracture
Great circle to local fault plane
Great circle to local foliation
Key for map: geological units
Quaternary sands and gravels
Alpine Fault mylonite sequence
Hare Mare Creek
Hare Mare Creek 1
Hare Mare Creek 2
Hare Mare Creek 3
Alpine Fault
Waikukupa River
SH6
Kilometers
Key for cross section
Alpine Fault PSZ
Subsidiary fault
Quartzofelspathic ultramylonite
Quartzofelspathic mylonite
Micaceous quartzofelspathic ultamylonite
Micaceous quartzofelspathic mylonite
Quartzofeldspathic ultramylonite, interlayered with <50% metabasite ultramylonite
Quartzofeldspathic ultramylonite, interlayered with <50% metabasite mylonite
Hydrothermally altered cataclasite
Quaternary gravels
Mylonitic foliation
All fractures
Gouge-filled fractures
Corrected fracture density (#/m)
Orthogonal distance from fault (m)

5

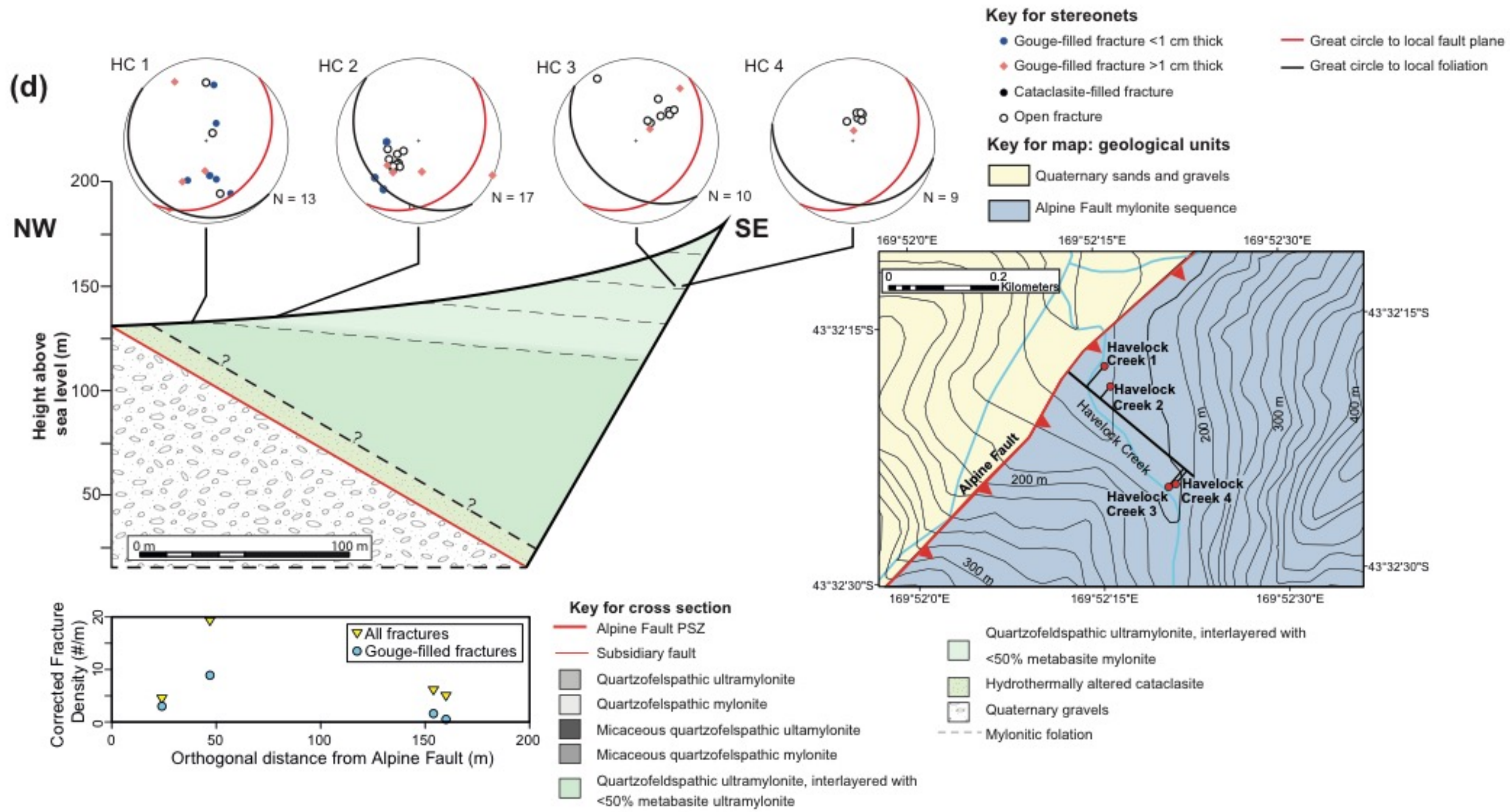


Figure S1: Cross sections showing varying intensity and style of damage with distance from the Alpine Fault principal slip zones (PSZ) for: (a) Gaunt Creek, (b) Stony Creek, (c) Hare Mare Creek and (d) Havelock Creek. Alpine Fault location as mapped during the University of Otago's Department of Geology fault zone mapping program (http://www.otago.ac.nz/geology/research/structural-geology/alpine-fault/af-maps.html). Each cross section also presents: (1) the corrected density of fractures at all stations as a function of the orthogonal distance from the fault, (2) fracture orientations at each station, and (3) a map of the stations with respect to the fault and cross section. Location of these sites shown in Figure 1b and Table S2. Fault rock lithologies previously described by Toy, (2008). SH-6 in (c), State Highway 6. *Density of fractures calculated from two perpendicular transects at Gaunt Creek stations 1 and 2.

Figure S2

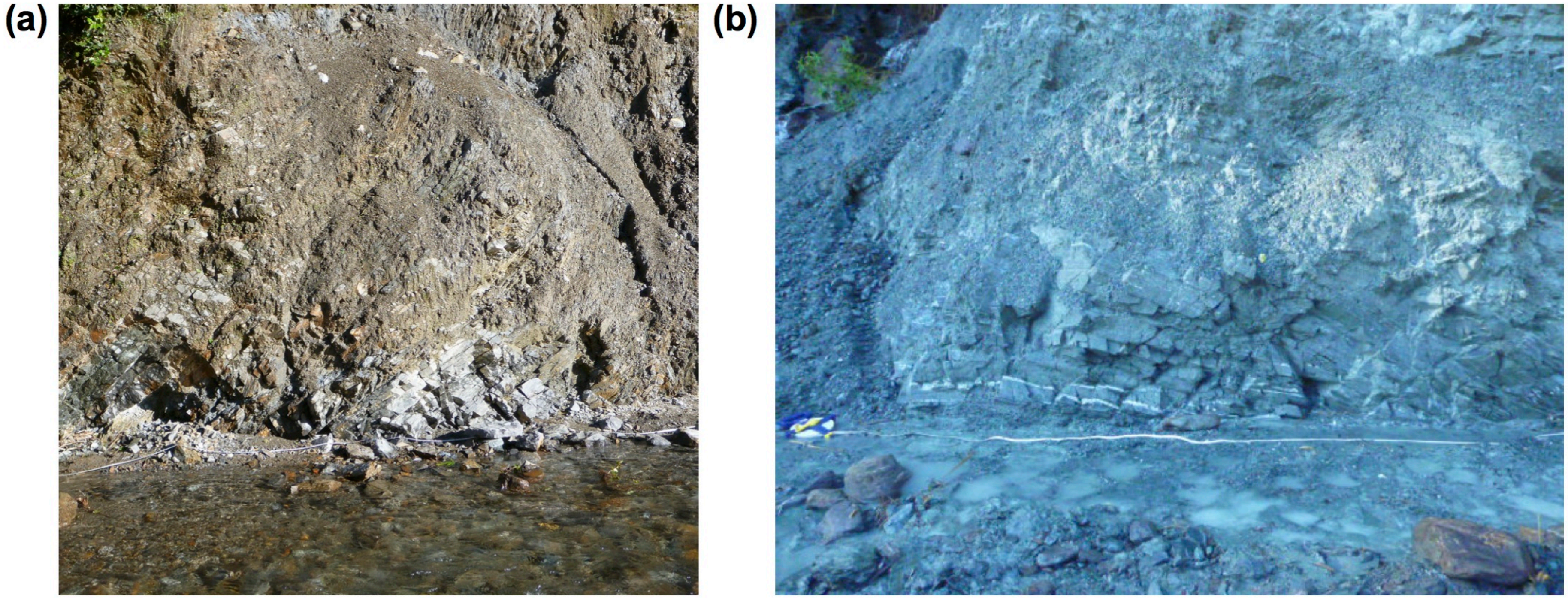


Figure S2: Exposure used for (a) Stony Creek 2 and (b) Havelock Creek 1 transects (Figure S1). This illustrates the sub-vertical nature of the outcrops used in this study, with the highest quality exposure at its base. Hence a linear transect provides the best method for quantitatively assessing fracture density. Field of view: (a) 10 m, (b) 6 m.

Figure S3

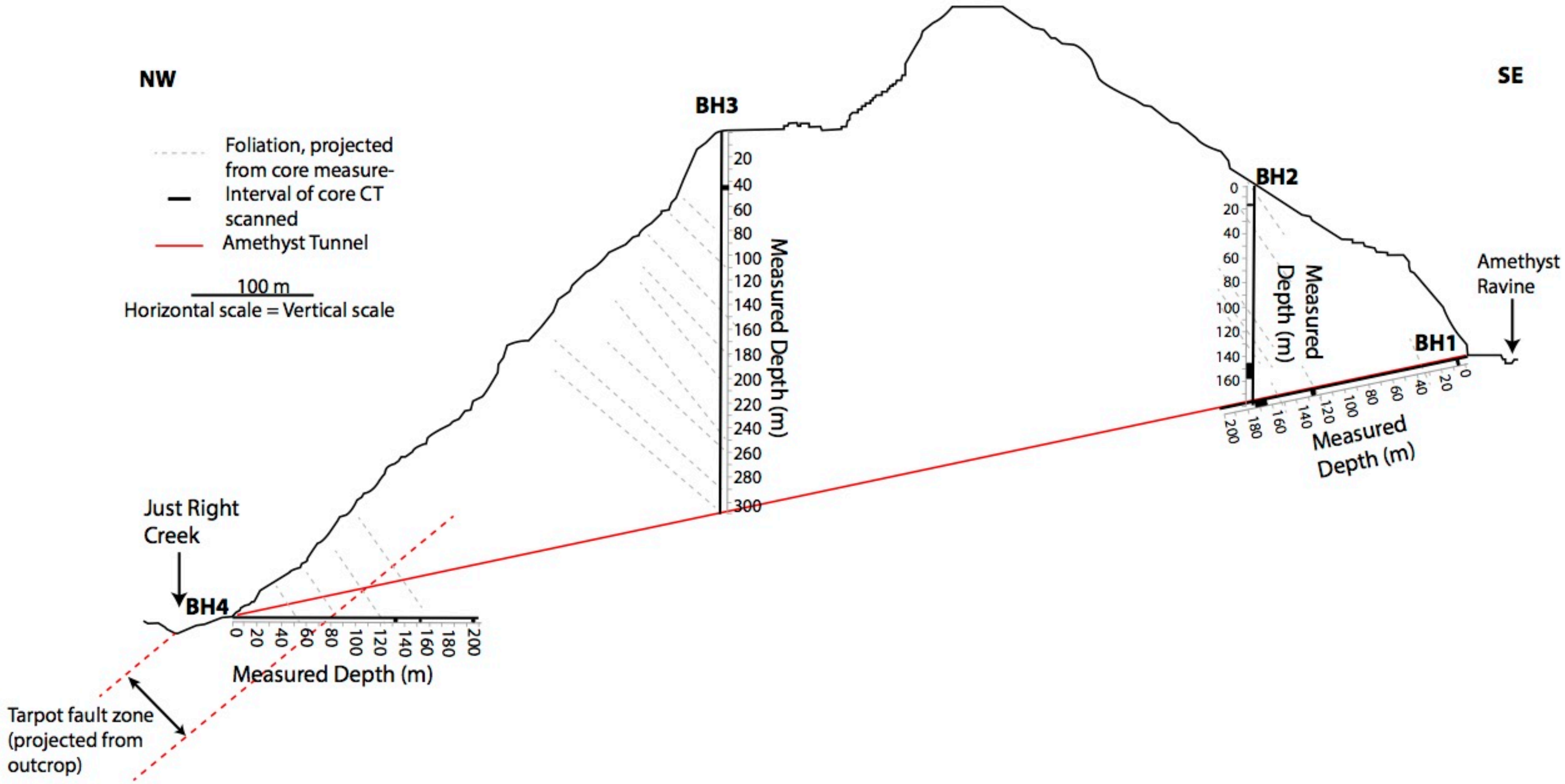


Figure S3: Cross section through the Amethyst Tunnel and its four exploratory boreholes (B1-4), Hari Hari, Westland, New Zealand. See Figure 1b for location. Modified from Geotech Consulting Limited (2006), to show where intervals of drill-core that were CT scanned are located.

Figure S4

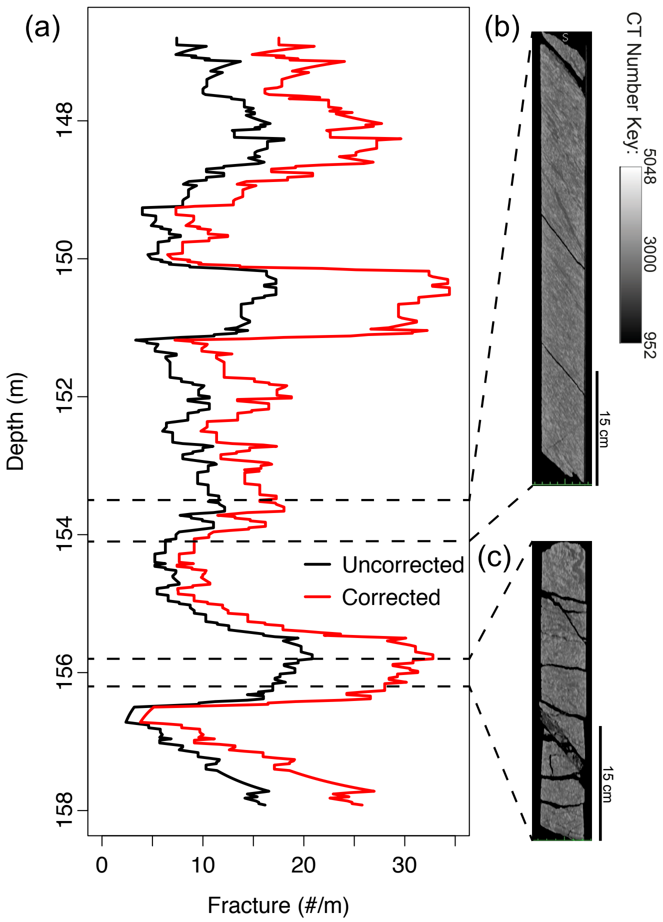


Figure S4: Fracture density variations measured within CT scans of AHP drill-core from BH2, depth interval 146.8-157.9 m. (a) Fracture density calculated using a moving average (uncorrected for orientation bias) and weighted moving average (corrected), for intervals of 2 cm with 1 m moving window. Full description and justification of this technique for measuring fracture density is presented in Williams et al., (2016). Since it is not possible to reliably differentiate between natural and induced fractures in this core, the fracture densities should be regarded as a maximum estimate. Core-axial parallel CT scans of representative core sections with (b) low, and (c) high fracture density that surrounds a minor fault are also given. (b) Core section (borehole-core run-core section-depth interval) BH2-74-3-153.5-154,1 (c) BH2-75-2-155.8-156.2.

Table S1

Core Section	**Depth of matched structure (m)**	**Counterclockwise rotation to match BHTV (°)**	**Rotation applied (°)**	**Quality of match**
29-1	94.75	313	310	Good
	94.90	307		
31-1	96.70	319	319	Poor
31-2	97.35	16	20	Good
	97.45	24		
32-1	98.51	124	124	Poor
33-2	**99.45**	**164**	170	Good
	99.50	186		
	100.00	158		
34-1	100.90	349	330	Good
	101.30	333		
	101.35	**326**		
34-2	101.65	199	199	Poor
35-1	102.15	294	287	Moderate
	102.20	281		
35-2	102.85	307	307	Good
	103.15	306		
36-1	103.65	93	85	Good
	103.75	77		
	104.30	**94**		
36-2	104.40	204	211	Moderate
	104.85	217		

Core Section	Depth of matched structure (m)	Counterclockwise rotation to match BHTV (°)	Rotation applied (°)	Quality of match
37-1	105.6	246	245	Good
	105.95	244		
37-2	106.16	198	202	Moderate
	106.30	219		
	106.55	189		
38-1	107.25	3	11	Moderate
	107.30	27		
	107.34	5		
39-1	107.65	114	110	Good
	107.70	111		
	108.15	106		
39-3/40-1	108.70	116	109	Moderate
	108.80	102		
41-1	110.05	155	148	Good
	110.10	144		
	110.25	145		
41-2	110.60	101	106	Moderate
	110.70	111		
43-1	111.65	229	223	Moderate
	111.85	235		
	112.15	205		
45-1	113.00	112	96	Moderate
	113.20	89		
	113.65	87		

Core Section	Depth of matched structure (m)	Counterclockwise rotation to match BHTV (°)	Rotation applied (°)	Quality of match
46-1	114.00	17	21	Good
	114.10	25		
48-1	114.70	10	8	Good
	114.95	5		
	115.00	8		
49-1	115.70	108	110	Good
	116.25	112		
52-1	118.65	132	135	Good
	118.95	134		
	119.05	140		
53-1	120.70	338	338	Poor
53-2	121.40	267	267	Poor
54-1	122.15	47	40	Moderate
	122.30	45		
	122.40	28		
54-2	122.85	279	280	Good
	122.90	281		
55-1	123.40	325	317	Moderate
	123.75	309		
56-1	124.95	340	333	Moderate
	125.35	327		
56-2	126.00	313	328	Good
	126.10	**325**		
	126.20	**331**		

Table S1: Summary of rotations applied to DFDP-1B core sections to rotate drill-core back into a geographic reference frame. Numbers in bold indicate matching between prominent structures in the drill-core and so the rotation applied is weighted towards them. Quality of matching refers to classification scheme outlined Appendix A.

Table S2

Transect	Latitude	Longitude	Orthogonal distance from Alpine Fault (m)	Lithology	Length of Scanline (m)	Orientation of scanline	Total fracture density (#/m)	Corrected total fracture density (weighted #/m)	Gouge filled fracture density (#/m)	Corrected gouge filled fracture density (weighted #/m)
Gaunt Creek-1	43° 18’ 59.49” S	170° 19’ 20.54” E	27	Protocataclasite-ultramylonite transition	2.4	*	7.1		7.1	
Gaunt Creek 2	43° 18’ 59.56” S	170° 19’ 19.20” E	90	Q-Fs ultramylonites with <50% metabasics	1.7	*	6.5		6.5	

Gaunt Creek 3	43° 19’ 01.11” S	170° 19’ 21.71” E	118	Q-Fs ultramylonites with <50% metabasics	1	00/034	5.0	16.0	2.0	7.3
Gaunt Creek 4	43° 19’ 02.46” S	170° 19’ 21.56” E	147	Q-Fs mylonites with <50% metabasics	2.2	22/023	2.3	4.6	0	0
Stony Creek 1	43° 22’ 12.77” S	170° 12’ 42.99” E	7	Q-Fs ultramylonite	2	Vertical	5.2	11	4.0	9.1
Stony Creek 2	43° 22’ 17.68” S	170° 12’ 43.83” E	73	Q-Fs mylonite	9.4	00/301	4.4	5.6	1.5	2.1
Stony Creek 3	43° 22’ 18.49” S	170° 12’ 45.12” E	103	Q-Fs mylonite	2.4	Vertical	4.6	5.6	0	0

Stony Creek 4	43° 22’ 22.62” S	170° 12’ 52.09” E	251	Micaceous mylonite	1.6	Vertical	22	28.4	0	0
Hare Mare Creek 1	43° 26’ 35.24” S	170° 04’ 38.72” E	101	Micaceous ultramylonite	6.4	00/146, 00/52	3.6	6.6	0.8	5.3
Hare Mare Creek 2	43° 26’ 35.67” S	170° 04’ 43.91” E	151	Micaceous mylonite	7.7	20/339	2.5	5.0	1.4	2.6
Hare Mare Creek 3	43° 26’ 38.02” S	170° 04’ 44.64” E	250	Q-Fs mylonite	2	Vertical	10.7	11.1	0.5	0.8
Havelock Creek 1	43° 32’ 17.63” S	169° 49 15.98” E	24	Q-Fs ultramylonites	5.8	00/020	2.8	4.5	1.7	3.0

				with <50% metabasics						
Havelock Creek 2	43° 32’ 18.84” S	169° 52’ 16.42” E	48	Q-Fs and micaceous ultramylonites with <50% metabasics	2.1	Vertical	14.2	19.3	3.8	8.9
Havelock Creek 3	43° 32’ 24.89” S	169° 52’ 20.82” E	154	Q-Fs mylonite with <50% metabasics	3.7	00/005	2.7	6.1	0.3	1.6
Havelock Creek 4	43° 32’ 24.74” S	169° 52’ 21.41” E	160	Q-Fs mylonite with <50% metabasics	1.95	Vertical	4.6	5	0.5	0.5

Bullock Creek	43° 30’ 42.33” S	169° 56’ 41.85” E	517	Q-Fs mylonite	17	00/008	1.65	3.7	0.3	0.9

Table S2: Compilation of results from scanline fracture analysis around the Alpine Fault. Fracture densities are given to 1 decimal place. Q-Fs, quartzofeldspathic. *At Gaunt Creek stations 1 and 2, a horizontal and vertical scanline was used to collect fracture information at each station. Orientation were not collected so no ‘corrected’ fracture density was calculated. Orthogonal distance from the fault calculated assuming a fault dip of 30° (Norris and Cooper 1995). See Table S3 for comparison to estimates made assuming a fault dip of 45°.

Table S3

Station	**Distance from Alpine Fault dipping at 30° (m)**	**Distance from Alpine Fault dipping at 45° (m)**
Gaunt Creek 1	**27**	**33**
Gaunt Creek 2	**92**	**99**
Gaunt Creek 3	**118**	**126**
Gaunt Creek 4	147	161
Stony Creek 1	**7**	**7**
Stony Creek 2	**73**	**95**
Stony Creek 3	103	131
Stony Creek 4	251	311
Hare Mare Creek 1	**101**	**106**
Hare Mare Creek 2	**151**	**170**
Hare Mare Creek 3	250	269
Havelock Creek 1	**24**	**34**
Havelock Creek 2	**48**	**62**
Havelock Creek 3	**154**	**205**
Havelock Creek 4	160	213
Bullock Creek	517	721

Table S3: Range of estimates of orthogonal distances between field stations and the Alpine Fault, assuming it dips either 30 to 45°. Based on the observations of Norris and Cooper, (1995), our preferred estimates are for the Alpine Fault dipping at 30°. Those stations considered to be part of the inner damage zone (i.e. >1 gouge-filled fractures per metre, as defined section 5.2) are in bold.