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122

123 **Abstract**

124 During the second phase of the Alpine Fault, Deep Fault Drilling Project (DFDP) in the Whataroa
125 River, South Westland, New Zealand, bedrock was encountered in the DFDP-2B borehole from 238.5
126 – 893.2 m Measured Depth (MD). Continuous sampling and meso- to microscale characterization of
127 whole rock cuttings established that, in sequence, the borehole sampled amphibolite facies, Torlesse
128 Composite Terrane-derived schists, protomylonites, and mylonites, terminating 200-400 m above an
129 Alpine Fault Principal Slip Zone (PSZ) with a maximum dip of 62°. The most diagnostic structural
130 features of increasing PSZ proximity were the occurrence of shear bands and reduction in mean quartz
131 grain sizes. A change in composition to greater mica:quartz+feldspar, most markedly below ~ 700 m MD,
132 is inferred to result from either heterogeneous sampling or a change in lithology related to alteration.
133 Major oxide variations suggest the fault-proximal Alpine Fault alteration zone, as previously defined in
134 DFDP-1 core, was not sampled.

135

136 **Key words:** Alpine Fault, New Zealand, scientific drilling, mylonite, cataclasite.

137

138

139 **Introduction**

140 ***The Alpine Fault, Deep Fault Drilling Project (DFDP)***

141 The Alpine Fault, Deep Fault Drilling Project (DFDP; Townend et al. 2009) aims to drill into New
142 Zealand's Alpine Fault zone at a range of depths along an exhumation trajectory. At the drill sites, in
143 the Whataroa and Waitangi-taona River areas (Fig. 1), this seismically active structure (Sutherland et
144 al. 2007) accommodates around 70% of the 37 mm yr⁻¹ of obliquely convergent relative Pacific-
145 Australian Plate motions by dextral-reverse shear (Norris & Cooper 2001; DeMets et al. 2010). Uplift
146 of the Pacific Plate hanging wall at rates of 6-9 mm yr⁻¹ (Little et al. 2005; Beavan et al. 2010) coupled
147 with rapid erosion in response to abundant orographic rainfall results in exposure of dominantly
148 Mesozoic metasedimentary and metavolcanic rocks that have a polyphase metamorphic fabric that
149 was subject to peak pressures and temperatures in the oligoclase zone of the amphibolite facies (Vry
150 et al. 2004; Beyssac et al. 2016). Although complex in detail, the structural and metamorphic fabrics,
151 as well as the kinematic history of these rocks is simpler than that of any other similar structure
152 worldwide (Townend et al. 2009), so study of the fault rocks promises a globally unique opportunity
153 to determine how they progressively evolved.

154 A first phase of drilling, DFDP-1, undertaken in 2011 at Gaunt Creek, tributary to the Waitangi-taona
155 River, successfully sampled smectite-rich gouges inferred to be active or recently active Principal
156 Slip Zones (PSZ) in two boreholes at depths of 90.75 m in DFDP-1A and 128.10 m and 143.85 m in
157 DFDP-1B. Observations during and after drilling allowed description of fault zone architecture
158 appropriate for the <100 m thickness of fault rocks drilled immediately around the PSZs (Sutherland
159 et al. 2012), measurement and correlation of petrophysical properties, (Townend et al. 2013) and a
160 definition of a characteristic suite of lithologies (Toy et al. 2015).

161 The second phase of drilling, DFDP-2, (Sutherland et al. 2017) was carried out from August 2014 –
162 January 2015 in the Whataroa Valley (Figs. 1, 2, see also reference frames and corrections section of
163 the supplementary data to this contribution). Two boreholes were drilled: DFDP-2A penetrated to
164 212.6 m MD (where MD, Measured Depth, is the length of drill string from the top of the drill rig
165 table, at an elevation of 98.14 m, to the bit) and DFDP-2B penetrated to 893.1 m MD. Three main
166 types of samples were recovered from DFDP-2A during the preliminary stages of drilling (Table 2).
167 Due to a greater than anticipated thickness of Quaternary sediments encountered in this borehole
168 (Sutherland et al. 2015), a second borehole (DFDP-2B) was spudded nearby. The aim to penetrate
169 the active PSZ of the fault at a depth of approximately 1 km, was not realised in either hole due to
170 scientific and technical difficulties further explained by Sutherland et al. (2015). Nevertheless, a
171 substantial set of samples, continuous measurements, and wireline geophysical logs were collected,
172 and an optical fibre cable was installed that provides longer term monitoring capability (Sutherland
173 et al. 2015; 2017).

174 DFDP-2 was initially drilled as an open hole through the basement rocks, using a polycrystalline
175 diamond composite (PDC) bit (but other types of drillbits were sometimes used at depths <547 m, as
176 further explained in the supplementary data). This generated small (millimetre-sized) chips of rock
177 known as 'cuttings'. The technical plan was to change drilling methods to recover intact rock cores
178 at a distance of up to 300 m above the PSZ. The subsurface structure at the drillsite could not be
179 unequivocally defined from geophysical surveys or by projection of surface structure to depth, so
180 additional interpretation of proximity to the PSZ was based on observations of the cuttings and

181 correlation to lithological definitions based on past outcrop mapping (e.g. Little et al. 2002; Toy et al.
182 2012b) and from DFDP-1 (Toy et al. 2015). The sequence was expected to be lithologically part of
183 the Aspiring Lithologic Association, a subdivision of the Torlesse Composite Terrane – i.e.
184 quartzofeldspathic metasediments (pelite and psammite) with minor metabasite (amphibolite) and
185 metachert, typically in metre to decimetre thick layers (Cox & Barrell 2007; Craw 1984). The
186 maximum metamorphic grade was expected to be the K-feldspar zone of the amphibolite facies (Cox
187 & Barrell 2007). Close to the Alpine Fault PSZ we anticipated mylonite or cataclasite-series rocks
188 comparable to one of the eight lithological units observed in DFDP-1 boreholes (Table 1; cf. Toy et
189 al. 2015), but first we expected to encounter lower shear strain equivalents such as mylonites,
190 protomylonites, and the non-mylonitic precursors to these mylonitic rocks, the Alpine Schists (Norris
191 & Cooper 2007; Toy et al. 2008). Hand samples are commonly categorised as one or other of these
192 tectonites based on foliation characteristics at mm to cm-scale, as well as the presence of cm-spaced
193 shear bands, and the preservation of cm-scale fold hinges, as explained by Toy et al. (2012b).

194 The cuttings sampling method typically only yields chips smaller than a few mm in diameter, and it
195 mixes chips derived over many drilled metres. Nevertheless, this aspect of the DFDP-2 project was
196 successful, because our collaborative onsite descriptions were carefully tailored to obtain information
197 that would be diagnostic of fault rock lithology. Before drilling commenced, a ‘synthetic cuttings
198 experiment’ was carried out. In this, microstructural and mineralogical variations were documented
199 in outcrop-derived samples transecting the mylonite zone that had been crushed to resemble drilled
200 cuttings. An onsite thin section laboratory allowed comparable information to be obtained from
201 cuttings samples. The synthetic cuttings data indicated microstructural information – particularly
202 observations of high temperature ductile fabrics and measurements of quartz grain size – would be
203 most easily correlated to the fault rock sequence established from outcrop and thus diagnostic of
204 proximity to the PSZ. Onsite descriptions focused on obtaining this information at the same rate as
205 drilling progressed.

206 A range of lab-based analyses have subsequently been carried out at lower resolution to complement
207 onsite data and to better inform us of bulk rock compositional variations that might serve as an
208 indicator of the overall fault rock protolith.

209 The purpose of this paper is fourfold;

210 (i) To summarise the geological samples recovered from the drilled bedrock sequence onsite
211 during DFDP-2B, as well as descriptions and analyses made on- and offsite during the Operational
212 Period of DFDP-2B, which lasted from January – December 2015.

213 (ii) To assess variations in these datasets and interpret these variations by comparison with
214 previous studies,

215 (iii) To assess whether the methods employed allowed us to assess accurately the structural and
216 lithological character of the drilled sequence, and

217 (iv) To document and evaluate use of geological data gathered during drilling to guide real-time
218 operational decisions.

219 The key outcome we report is a definitive lithological profile of mineralogical and structural
220 variations across a continuous section from Alpine Schist protolith to mylonite. This provides a
221 contextual frame of reference in which to interpret and correlate other continuous datasets (e.g.
222 wireline geophysical logs, mud-derived gases, temperature measurements), and to guide future

223 targeted analytical programs and investigations. This contribution should be considered as a
224 companion to discussions of measurements of fluid pressure and temperature in the borehole
225 (Sutherland et al. 2017) and datasets arising from wireline geophysical surveys.

226 **Methods**

227 *Drilling data collection*

228 Synopses of protocols for sample and data collection are presented here and in the methods section
229 of the supplementary data to this contribution. Full versions of the onsite protocols (both undertaken
230 or planned) are included as appendices to the Borehole Completion Report (Sutherland et al. 2015)
231 and full versions of protocols for subsequent laboratory analyses are included in the supplementary
232 data.

233 The main types of samples recovered were cuttings (i.e. rock chips), drilling muds, cores and gases
234 dissolved in the drilling muds.

235 *Cuttings and mud sampling*

236 During both DFDP-2A and DFDP-2B, cuttings and mud samples brought to the surface in the mud
237 recirculation system were collected at the outlet pipe. Sampling depths of cuttings are reported as
238 metres MD in accordance with international best practice in Scientific Drilling – which is designed
239 to minimise errors in records in the long term (Harms et al. 2007). True depth, and elevations from
240 which these samples were derived require correction of MD for elevation of the datum these were
241 measured with respect to, as well as delay in transport of cuttings from the drillbit to the surface (lag
242 depth), and borehole inclination. These corrections are discussed further in the reference frames and
243 corrections section of the supplementary data.

244 Best practices and sampling methodologies were initially established based on our experiences on
245 previous similar projects (such as DFDP-1), then refined to achieve the best possible balance of
246 scientific rigour and practical application at the specific operating conditions of DFDP-2. As we were
247 developing these methods simultaneously with drilling, initial samples were collected less
248 systematically than later ones. However, by ~450 m MD, cuttings and mud collection from DFDP-
249 2B had become routine and a consistent methodology was in place. At this stage a cuttings (CU)
250 sample was taken every 2 m and a mud (MU) sample every 3 m. Thin sections were made onsite from
251 every third washed cuttings sample, ie. every 6 metres drilled depth. Further details of sampling
252 procedures and thin section methodology are included in the methods sections of the supplementary
253 data.

254 *Core sampling*

255 Because the technical plan at the start of drilling included collection of up to 300 m of bedrock cores
256 proximal to the Alpine Fault's PSZ, facilities and rigorous and comprehensive collection protocols
257 were prepared to handle these cores. In the end, the only cores collected were of Quaternary material
258 (silts) in the upper 212.6 m of DFDP-2A, and of concrete and slivers of wall rock around the depth
259 of a casing break in DFDP-2B (Sutherland et al. 2015; Tables 2 and 3). Further details of sampling
260 procedures, core orientation conventions, and descriptive methodology are included in the methods
261 sections of the supplementary data.

262 ***Samples and data***

263 Samples were registered in a project-specific version of the International Continental Scientific
264 Drilling Program (ICDP)'s Drilling Information System (DIS) database at time of collection, or at
265 time of separation in the case of subsamples. Sample collection from DFDP-2B was more systematic
266 than from DFDP-2A, and a wide range of materials were collected from the entire depth range drilled,
267 as summarised in Table 3 and demonstrated in Figs 2 and 3. Further details of sample and data
268 availability are included in the methods section of the supplementary data.

269 ***Sample descriptions and analyses***

270 During DFDP-2B, geological team members carried out hand specimen and microscopic descriptions
271 of mineralogy and structure on the drillsite. Subsequently, subsamples were taken and analysed by
272 electron beam methods such as energy dispersive spectroscopy (EDS) – to further quantify
273 mineralogy, and electron backscatter diffraction (EBSD) – to further map and quantify
274 microstructures. Mineralogical and geochemical information was also acquired, respectively, by X-
275 ray fluorescence spectroscopy (XRF) and X-ray diffraction (XRD). Further details of these
276 descriptions and analyses can be found in the methods section of the supplementary data.

277 ***Compositional information***

278 An estimate of composition of each cutting sample was determined by measuring the weight
279 proportion of quartz+feldspar:mica-rich chips onsite. Proxies to these estimates were derived from
280 these compositional data. For the XRD data, we compared the proportion of
281 quartz+feldspar:muscovite+biotite+chlorite. For the XRF data, we compared the Al_2O_3 : SiO_2 ratio
282 (Fig. 3). We chose these oxides rather than K_2O (which should be common in micas) because Al_2O_3
283 and SiO_2 are comparatively immobile in crustal fault zones (Gresens 1967; Grant 1986). The plot of
284 of major element oxides in Fig. 3 does not distinguish whether Al_2O_3 is present in plagioclase or
285 phyllosilicates, but simply reflects the relative abundance of quartz compared to these other major
286 phases.

287 ***Structural information***

288 Structural and microstructural characteristics that we considered would be diagnostic of our position
289 within the typical Alpine Fault Zone fault rock sequence (Toy et al., 2015) were documented in hand
290 specimen and thin section. Additionally, the mean grain size of quartz in cuttings fragments was
291 measured onsite using a petrographic microscope and the linear intercept method (Exner 1972).
292 Structural descriptions of drill cores were also undertaken. Further details about these analytical
293 methods and the types of data recorded can be found in the methods section of the supplementary
294 data.

295 Electron backscatter diffraction data were also collected from offsite thin sections. These data were
296 processed using both CHANNEL5 HKL software (see Bestmann & Prior 2003) and the MTEX
297 crystallographic texture analysis and modelling toolbox for Matlab (Bachmann et al. 2010;
298 <http://mtex-toolbox.github.io>). Again, further details of these analyses are provided in the methods
299 section of the supplementary data.

300 **Results**

301 **Cuttings descriptions**

302 The cuttings samples mostly comprise sub-angular to angular chips. Chip grain size (not the size of
303 constituent mineral grains) was visually estimated as a percentage of gravel (>2 mm), sand (>60
304 micrometres and <2 mm), and clay (<60 micrometres) (Fig. 3b). Silt-sized cuttings were not
305 differentiated because particles of this size would have been introduced by the circulating drilling
306 mud. Clay fractions were almost never identified in the washed basement cuttings samples because
307 they were removed during the washing process. Ratios of gravel:sand average 52:48% but there are
308 substantial variation with ratios ranging from 0:100% to 100:0%. For example, particularly fine-
309 grained cuttings (>90% sand) were recovered between 493 and 502 m MD, while the majority of
310 cuttings recovered between 300 and 400 m MD are >90% gravel sized.

311 In each washed and dried bulk cuttings sample we differentiated distinct types of chips, based on their
312 colour and mineralogy. Common chip types that we described and were available for use in the DIS
313 database were ‘quartz’, ‘muscovite-biotite-quartz schist’, ‘biotite-muscovite-quartz schist’, ‘grey
314 fine-grained schist (QFSP mica schist)’, ‘sugary quartz-feldspar (QFSP mica schist)’, and ‘carbonate’
315 (illustrated in the Example VCutD form in the supplementary data; QFSP = quartzofeldspathic). Chip
316 colours (again selected from descriptive terms we defined in the DIS) are typically shades of cream,
317 grey to black, and more rarely brown or orange. Examination of the described chip sizes and colours
318 against depth over the > 600 m of drilled bedrock sequence reveals no systematic variations that could
319 be interpreted to reflect protolith or structural grade. Proportions of common minerals were also
320 estimated. Structural characteristics documented include: the nature of tectonite foliation – which is
321 typically either planar or undulating, and hairline to mm-spaced, continuous, or absent; the presence
322 of vein fragments; and the presence of striated and undulating surfaces, shear bands, and rarely mica
323 streak or shear band intersection lineations (as defined by Toy et al. 2012b).

324 Thin section descriptions confirmed a mineral phase composition dominated by quartz, with
325 plagioclase feldspar, muscovite, biotite, and more rarely chlorite, garnet, calcite, with accessory
326 minerals including apatite, graphite, ilmenite, rutile, titanite, zircon and unidentified opaques.

327 Quartz microstructures typically comprise remnant grains hundreds to thousands of micrometres in
328 length, with undulose extinction and interlobate grain boundaries. Polygonal aggregates comprising
329 smaller (mostly <100 micrometres), more equant grains lacking undulose extinction, which we infer
330 are ‘recrystallised’ grains, were increasingly noted with increasing depth, as were highly elongated
331 grain shapes commonly referred to as “ribbon grains” (Passchier & Trouw 2006). A Crystallographic
332 Preferred Orientation (CPO) was noted in many of these polygonal aggregates. Plagioclase crystals
333 are mostly a few hundred micrometres in size, but could be larger (e.g. 1000 micrometres in DFDP-
334 2B_618-620_CU [ICDP5052EXIM601] *). They are mostly intermixed with quartz in foliation
335 domains in schists and protomylonites.

336 In non-mylonitic Alpine Schists and protomylonites, biotite and muscovite are generally ‘elongated’
337 grains, clustered in planar, millimetre-thick foliation domains. Graphite grains are distributed along

* Numbers in brackets are International Geological Sample Numbers, IGSN, as further described in the methods sections of the supplementary material.

338 muscovite basal planes. Biotite porphyroclasts 1-2 mm long typically contain inclusions of opaque
339 minerals (graphite), fine mica and quartz. These define inclusion trails, commonly with curved habit
340 like the form surface of microfolds, but elsewhere planar. Muscovite and biotite fish were typically
341 recognized at MD \geq 532 m. There is no systematic change in the maximum size of muscovite and
342 biotite grains, but fine 'recrystallised biotite' grains were increasingly noted at MD >775 m. Large
343 (>1 mm diameter) biotite porphyroblasts prevail throughout the drilled depth range but become less
344 common with increasing depth, presumably because they are more extensively recrystallised.
345 Chlorite was first observed in thin sections at 460 m MD, and at greater depths was described as
346 'replacing' or 'in association with' biotite or infilling cracks in garnet. Garnets are variably present
347 throughout the drilled bedrock sequence.

348 Mineralogy was documented onsite, but mineral abundances were not recorded, so the thin section
349 analyses did not result in a systematic dataset that highlights mineralogical variation. This decision
350 was motivated by the observation that in nearby outcrops (e.g. Stony Creek, Gaunt Creek; Fig. 1.), in
351 DFDP-1 core, and in synthetic cuttings, structural character of the sequence changes systematically
352 with distance from the PSZ, whereas modal mineralogy does not (Little et al. 2002; 2015; Toy 2008;
353 Toy et al. 2008; 2015). Our primary aim was to identify proximity to the PSZ. At the rate of drilling,
354 this aim was best addressed by using the time available for microscopic work to make systematic
355 microstructural descriptions and measurements. Chips comprising altered (to chlorite and epidote)
356 amphibolite were observed in DFDP-2B_492-494_CU [ICDP5052EXEL601] (Fig. 6e,f), and
357 cataclasite in DFDP-2B_878-880_CU [ICDP5052EXQP601] (described further below), but in
358 general the same minerals were found to be present in each sample.

359 ***Notable structural features and variations***

360 Significant mesostructural characteristics included gradual reduction in the thickness of foliation
361 domains (from mm to hairline spaced) with increasing drilled depth, and the presence of striated or
362 undulating surfaces. These were first noted in cuttings samples at 546 m MD, and became
363 increasingly common from 590 m MD (Fig. 3g). A cataclasite fragment was sampled at 878-880 m
364 MD [ICDP5052EXPP601]. This fragment is probably derived from one of the numerous minor faults
365 and fracture zones commonly seen in surface exposures within the hanging wall of the Alpine Fault.
366 As we were collecting only a small proportion of the total cuttings created by the drilling process, it
367 is unlikely that we would have been able to sample all such structures from the cuttings alone.
368 However, they are readily identifiable in borehole televiewer imagery (Massiot 2017).

369 DFDP-2 wall rock drill cores from MD = 475.5-476.9 m consist of a dark grey, mica-rich,
370 quartzofeldspathic protomylonite with an average grain size of 2-3 mm. Quartz porphyroclasts
371 display recrystallisation textures while plagioclases have largely brittle fabrics. Shear bands are
372 abundant. Biotite and muscovite grains are approximately 3-5 mm in length and are aligned on
373 foliation and shear band surfaces. Rare garnets are up to 2 mm in diameter. Quartz pods and ribbons
374 occur sub-parallel to the mylonitic foliation with thicknesses of 0.5-1 cm (Fig. 3g, 4b).

375 In microstructural descriptions of onsite thin sections of cuttings samples, shear bands were noted
376 throughout the drilled sequence. Shear band density increased with depth, and they were first
377 qualitatively described as 'abundant' at MD = 494 m. Foliation domain spacing and shear band
378 spacings were irregularly noted in descriptions but not documented in a systematic way, so it is
379 difficult to assess how these vary with increasing depth and inferred mylonite grade (Fig. 3f).

380 Analysis and description of wall rock drill cores reveals closely spaced mylonitic foliations and shear
381 band surfaces. Foliation spacing is approximately 2-4 mm (Fig. 5b). Shear bands are generally spaced
382 at a sub-centimetre scale and form an average angle of $30 \pm 4^\circ$ with the mylonitic foliation. Quartz
383 pods display ductile textures including rare intrafolial isoclinal folds and a dynamically recrystallised
384 matrix. In some locations, quartz pods define the mylonitic foliation. Foliation and shear bands are
385 overprinted by brittle fractures, generally at a low angle to the foliation. These fractures may be
386 natural or drilling-induced. Linear fabrics are defined by aligned mica on both foliation and shear
387 surfaces. Brittle slickenlines were not observed.

388 ***Indicators of ductile simple shear strain***

389 Exhumed Alpine Fault mylonites accommodated progressively higher finite ductile shear strains
390 toward the principal slip zone (Norris & Cooper 2003), resulting in progressive changes in structure,
391 microstructure, and proportion of dynamically recrystallised material. Some of the changes most
392 prominent in outcrop, such as phase mixing and reducing intensity of a spaced foliation (Toy et al.
393 2011) were not specifically noted in the cuttings samples. This is probably because most of the chips
394 are smaller than the spacing of the foliation domains. However, there is sufficient observational
395 evidence to correlate the cuttings with the previously-defined ductile fault rock sequence. Features
396 indicative of ductile shear strain that were noted include: the number of chip surfaces showing
397 undulating habit with grooved/striated shiny surfaces increased with depth (Fig. 3g); and in thin
398 section, the proportion of inherited pre-mylonitic porphyroblasts, i.e., >1 mm long primarily biotite
399 grains containing graphitic inclusion trails, reduced with increasing depth in the borehole (Fig. 3g).
400 The average grain size of the largest muscovites and biotites also gradually decreased with depth (Fig.
401 3e), as did the spacing of shear bands (Fig. 3f). Graphite was found to be redistributed onto grain
402 boundaries, albeit still as small (typically 1-5 micrometre), dispersed grains. Sporadic sigmoidal
403 quartz domains and micaceous layers deflected into shear bands were also observed (Fig. 3g).

404 The most quantitative indicator of increasing ductile shear strain that could be correlated to outcrop
405 samples was the mean quartz grain size measured in nearly pure quartz fragments by the linear
406 intercept method. As demonstrated in Fig. 3d., this measured grain size showed a slight reduction
407 throughout the sequence interpreted as protomylonite, then a fairly dramatic reduction below 100
408 micrometres at the inferred protomylonite-mylonite boundary at 830 m MD. The same numerical
409 change had been previously observed in synthetic cuttings from Stony Creek (Fig. 1).

410 The shear band and foliation spacings and relative orientations documented in the DFDP-2B cores
411 are consistent with those previously described in outcrops in proximity to the Alpine Fault. Norris &
412 Cooper (2003) and Toy et al. (2013) estimate an order of magnitude increase in shear strain through
413 the mylonite zone of the Alpine Fault in the central and southern Alps, with simple shear strains
414 increasing from $\gamma \sim 12$ in protomylonites to $\gamma \sim 150$ in ultramylonites (for pure shear stretches
415 perpendicular to the fault zone of $S_3 \sim 0.29$). Gillam et al. (2013) report that only a proportion of these
416 strains, $\gamma \sim 0.6-0.8$, results from cumulative slip on shear bands in the distal mylonite zone at Tartare
417 Stream, but the authors also demonstrate that the shear bands become more closely spaced toward the
418 Alpine Fault and the foliation orientation coincides with the shear zone boundary. A shear strain
419 gradient could not be detected in the short length of Whataroa DFDP-2 core. However, the 2-4 mm
420 shear band spacing observed is fairly consistent with the 3-4 mm spacing in the distal mylonite zone
421 of the Tartare Stream (Gillam et al. 2013).

422 Shear band and foliation spacing can also be affected by lithologic heterogeneities, particularly the
423 thickness and strength of layered material or rigid porphyroclasts. For example, shear bands are more
424 widely spaced and thus each accommodates higher slip in thick, stiff foliation domains (Gillam et al.
425 2013). In well-layered protomylonites of the DFDP-2 cores, foliation parallel quartz pods and ribbons
426 are the stiffest material in these otherwise mica-rich rocks. Shear bands were not observed in the stiff
427 quartz layers in the cores, and this is likely an artefact of a wide shear band spacing and a limited
428 observable area presented by drill cores, rather than a lack of shear bands, which were able to be
429 measured in the intervening microlithons (Fig. 5). These measurements demonstrate a dihedral angle
430 between shear bands and foliation in the borehole at Whataroa ($30 \pm 4^\circ$) that is the same as was
431 recorded by Gillam et al. (2013) ($30 \pm 1^\circ$), who report little variation in this angle through the mylonite
432 shear strain gradient. Toy et al. (2012b) found that the angle between the mean foliation and mean
433 shear band plane in a geographically broader area, using datasets from outcrops at Gaunt Creek, Stony
434 Creek and around the Waikukupa River (Fig. 1), is 26° , which is again consistent with both
435 measurements from DFDP-2B cores and the findings of Gillam et al. (2013).

436 Late stage brittle fractures are predominantly sub-parallel to the mylonitic foliation (Fig. 5; Massiot
437 2017), suggesting that the anisotropic strength of the ductile fabric in the DFDP-2 cores influenced
438 later brittle deformation patterns. Does this anisotropy have an influence on the orientations of all
439 brittle structures that form in layered mylonites and ultramylonites adjacent to the Alpine Fault? In
440 cores recovered from the DFDP-1A borehole and in DFDP-1B at depths 94-128.2 m (i.e. entirely
441 within the hanging wall), Williams et al. (2016) and Williams (2017) observed that foliation-parallel
442 fractures account for only 11% of fractures in units where a foliation exists (i.e. not including
443 mechanically homogenous cataclasites). They concluded that fracture orientations non-parallel to
444 foliation are symptomatic of the Alpine Fault damage zone, which has a nearly constant thickness of
445 160 m in this area.

446 ***Significant compositional variations***

447 Major element analyses (XRF) and mineralogy (XRD) (Table 4, Figs. 3,7) indicate that the cuttings
448 are derived from amphibolite facies Alpine Schist (Pitcairn et al. 2006). However, the full spectrum
449 of Alpine Fault rock types observed elsewhere in outcrops and in DFDP-1 core was not recognised
450 in the cuttings samples. Most of the rock types observed in the cuttings were mineralogically
451 comparable to Unit 1 (ie. grey and dark green Alpine Schist-derived ultramylonites) from DFDP-1
452 (Table 1), but displayed less well-developed microstructural indicators of ductile shear strain, as
453 discussed below. There was also one chip sample of cataclasite similar to Unit 3 or 4 from DFDP-1.

454 ***Variations in mineralogy***

455 Most cuttings samples are quartzofeldspathic in composition, i.e., primarily quartz, plagioclase,
456 muscovite and biotite with rarer calcite, garnet, and chlorite plus accessory phases, corresponding to
457 the grey variant of Unit 1 (Table 1). The protolith is inferred to be the Torlesse Composite Terrane
458 (Cox & Barrell 2007), mostly because the structural and transport history requires it, but also because
459 distinctive minerals that would be diagnostic of other possible protoliths (e.g. abundant allanite or K-
460 feldspar porphyroclasts would suggest Western Province granitoid as a protolith, while a high
461 quartz:plagioclase ratio would suggest Greenland Group metasediments) are not observed. Only one
462 cuttings thin section, in the sample recovered from 494-496 m MD [ICDP5052EXIK601], contains
463 an epidote-chlorite-amphibole-rich clast. This mineralogy is similar to that of retrogressed

464 amphibolite – the dark green variant of Unit 1 (Table 1). Amphibolite, generally in association with
465 high pelite:psammite ratios, is a common constituent of the Aspiring Lithologic Association (Craw,
466 1984), which is mapped at the drillsite in QMAP:Aoraki by Cox & Barrell (2007).

467 At nearby Gaunt Creek, Toy et al. (2008) determined amphibolite comprises >5% of the mylonite
468 sequence. However, its comparative scarcity in DFDP-2B samples indicates that most of the schist
469 we sampled has a ‘normal Torlesse’ quartzofeldspathic protolith, namely trench-fill sediments
470 deposited on the Mesozoic Gondwana margin (Mortimer 2004). Similarly, although the drillsite is
471 mapped in the K-feldspar zone of the amphibolite facies, no K-feldspar was observed either in thin
472 section or in XRD. These observations indicate that revisions of the QMAP:Aoraki (Cox & Barrell
473 2007) may be locally required.

474 The mineralogy, chemistry, and structure of the cuttings samples mostly change slowly and
475 progressively with depth. The most obvious change occurs below ~700 m MD where the overall ratio
476 of quartz+feldspar:mica chips subtly decreases (Fig. 3i). XRD data also suggest that
477 chlorite+muscovite become more abundant compared to biotite beneath this depth (Table 5, Fig. 3k).
478 However, we are wary about making interpretations of the nature of lithological change from the
479 XRD data, because the proportion of chlorite indicated is greater than we qualitatively observed in
480 thin sections of the same samples. Notably, chlorite was only described in thin sections below 460 m
481 MD, but the XRD data suggest it is present by 405.7 m MD in similar abundance to deeper samples.
482 The thin sections sample only a few chips while the XRD data are measured on powders made by
483 crushing at least 20g of chips, so this may reflect a heterogeneous distribution of the mineral in the
484 rock chips or a inhomogeneous mixing of cuttings.

485 These mineralogical changes should be reflected in chemical variations. We examined their potential
486 significance based on major element oxide proportions derived by XRF, specifically considering the
487 ratio of $\text{Al}_2\text{O}_3/\text{SiO}_2$ to $\text{Fe}_2\text{O}_3+\text{MgO}$ (Fig. 7), which is an indicator of primary sedimentary protolith
488 variation. This allowed assessment of whether these changes are the result of a change in protolith,
489 or reflect chemical mass change. The possible protoliths, namely Alpine Schist, the Torlesse and
490 Caples Terranes, and the Aspiring Lithologic Association, are best fit by, and lie around a trendline
491 labelled as the ‘protolith array’ (Pitcairn 2004). Samples that lie substantially away from this protolith
492 array have experienced secondary mobility of silica. Rocks lying above the trendline have
493 experienced silica removal and those lying below the trendline have experienced silica addition. On
494 this plot, psammites have $\text{Fe}_2\text{O}_3+\text{MgO}$ values of <6 wt.%; pelites >6 wt.% and metabasic rocks >10
495 wt.%. DFDP-1 “alteration zone” samples are defined as those taken from within 50 m of the fault
496 PSZ in that drillcore (Boulton et al. 2017), and these plot below the protolith array indicating silica
497 addition. DFDP-2 data from this study (Table 4) show two distinct trends. Shallower than 720 m,
498 cuttings samples lie along a similar array as the Torlesse Terrane (including its Aspiring Lithologic
499 Association) protoliths and deeper than 720 m, cuttings samples lie above this trend indicating a
500 decrease in quartz and/or increase in muscovite.

501 Amphibolite facies, oligoclase-bearing Alpine Schist have average loss on ignition (LOI) of 1.4 ± 0.6
502 wt.% (Pitcairn et al. 2006), our measurements for the top ~700 m of the borehole are above this range
503 (2.7 ± 0.4 wt.%) indicating that the protomylonite cuttings of the Alpine Fault zone in the Whataroa
504 Valley have higher volatile contents than the background, non-mylonitic Alpine Schist. Below 700
505 m, the LOI measurements made of cuttings from the borehole increase to 3.6 ± 0.6 wt.% (Fig. 3) which
506 likely reflects greater amounts of CO_2 from carbonate minerals, or of H_2O or OH from phyllosilicate

507 minerals, which commonly increase in modal proportion with proximity to the Alpine Fault, as noted
508 in DFDP-1 boreholes (Sutherland et al. 2012; Townend et al. 2013, Toy et al. 2015). Petrographic
509 evidence suggests the latter as the dominant source of this chemical signature because carbonate
510 minerals are uncommon in the cuttings (Fig. 3h). There is a sharp increase in LOI to 4.4% at 716 m
511 MD, coincident with the change in the trend towards increasing $\text{Al}_2\text{O}_3/\text{SiO}_2$ ratios (Figs. 3l, 7).

512 **Discussion**

513 ***Interpretation of DFDP-2B cuttings data***

514 A significant variation observed in DFDP-2B cuttings was in the quartz+feldspar:mica ratio, or
515 proxies for this ratio derived from major element analyses (XRF) and mineralogical analyses (XRD)
516 (Tables 4, 5, and Figs. 3, 7). In general, the ratio of quartz+feldspar:mica, or its proxies, decreases
517 with depth. However, some discrepancies between the compositional analyses are also apparent.
518 Notably, (i) the XRD data show a continued gradual decrease in quartz+feldspar:mica toward the
519 base of the borehole, (ii) TIMA (TESCAN Integrated Mineral Analyzer) and weight proportion of
520 chip data show a trend reversal, i.e. a slight increase in quartz+feldspar:mica below 780 m MD (Fig.
521 3i,j,k), and (iii) TIMA and XRD data suggest much greater proportions of quartz+feldspar:mica
522 overall than the weight proportion of chips analysis.

523 The ratios of Al_2O_3 to SiO_2 and LOI to SiO_2 increase down hole, alluding to a decrease in SiO_2 from
524 quartz and an increase in Al_2O_3 in micas and water associated with phyllosilicates (Figs. 3j,k, 7). The
525 XRD, TIMA, and XRF data (Fig. 3l,7) strongly indicate that compositionally distinctive samples
526 recovered below ~700-720 m MD are not a sliver of either Aspiring Lithologic Association, or Alpine
527 Fault alteration zone. Instead, we suggest these samples lie on a mixing line consistent with increasing
528 proportions of muscovite and chlorite and that the variation may either reflect a slight increase in
529 pelite:psammite ratio, depletion of silica by fluids circulating in late fractures, or heterogeneous
530 sampling of cuttings rich in phyllosilicates due to variations in borehole circulation parameters and
531 chip size (Fig. S1; Fig. 3b).

532 The modal compositions of cuttings samples are affected by the mineralogy of rock being drilled, the
533 type of drill bit used, and the sampling process. The increase in lag correction toward the base of the
534 hole (Fig. S1) reflects the increase in depth over which mud and entrained cuttings were transported
535 to the surface, but the lag depth is relatively minor and there is no evidence for cuttings storage within
536 the borehole. The sampling process, in which cuttings are sieved from drilling mud, may have resulted
537 in under-sampling of small cuttings, introducing bias into our inference of rock type where certain
538 components are more finely cut. In washed cuttings samples, pure quartzo-feldspathic cuttings tended
539 to be the smaller particles, so an apparent increase in mica with depth could be interpreted as under-
540 sampling of the quartzo-feldspathic component. However, in some samples, coarse-grained quartzo-
541 feldspathic cuttings dominated (Fig. 4) and the two thickest quartz-dominant layers were identified
542 when coarse cuttings samples were collected at 300-350 m MD (shown as grey horizontal bands on
543 Fig. 3, panels b and i). The lack of independent constraints on overall mineralogy mean that
544 hypotheses about sampling bias due to sieving cannot be verified. There were no major changes in
545 drill bit type or sampling process below 547 m MD (Sutherland et al., 2015), so we are confident that
546 relative changes in cuttings samples reflect changes in the rock type being drilled.

547 It is also important to note that identification of chips as quartz+feldspar or mica in the visual chip
548 analysis only means that those minerals dominate the macroscopic appearance of that particular chip
549 during its visual examination under the binocular microscope. These are not quantitative
550 measurements of the modal mineralogy of the sample. The visual chip analyses is biased towards
551 mica because the cuttings chips tended to lie flat on muscovite layers (Fig. 3i). Quartz segregations
552 commonly lie between muscovite layers, but these were not accurately quantified because the chips
553 had to be turned on their side under the microscope to see the quartz. Manipulating each cutting was
554 often too time consuming to be done at the rate that new samples were acquired.

555 ***Testing methods for data processing and analysis***

556 One of the advantages of such large datasets is that they are ideal for testing methodologies for
557 automated data collection to determine consistency across the different datasets and also allow for
558 evaluation of the various analytical methods. We tested (i) methods for calculating recrystallised grain
559 size of quartz, and (ii) methods to determine modal mineralogy and broad mineralogical variation
560 from EDS, XRD and XRF analyses.

561 ***Quartz grain size analysis from EBSD data***

562 In EBSD datasets there is a high probability that grains comprising only a few pixels are indexing
563 errors, and so it is common to filter out the finest fraction from the dataset before a mean is
564 calculated. Halfpenny et al. (2006) suggested that a statistically robust grain size data can only be
565 obtained from CHANNEL software if grains containing fewer than 5 pixels are removed, which we
566 have done by setting a minimum pixel size of 13 when detecting grains. Consequently, the smallest
567 grains included in the CHANNEL grain size distribution (Fig. 8c) are 9.8 micrometers in
568 diameter. MTEX uses a more computationally robust method (Cross et al. 2015) that removes both
569 grains comprising 4 or fewer pixels and those that are poorly constrained based on the fraction of
570 their area indexed. The grain size distribution illustrated in Fig. 8d uses this filtering method. The
571 mean grain size from the MTEX dataset (35.8 ± 53 micrometers) is larger than that determined by
572 CHANNEL (26.7 ± 33 micrometers). Kidder et al. (2014) determined a dominant quartz grain size in
573 central Alpine Fault mylonites of approximately 40-60 micrometers based on analysis of 250
574 mylonite samples. The grain size determined by MTEX is most consistent with this, suggesting that
575 its filtering method is more robust than CHANNEL's. We thus propose that noise reduction in
576 CHANNEL followed by grain segmentation and analysis in MTEX will produce the best outcome
577 for grain size measurements. Procedurally, it is also important to output a map of the detected grains
578 and visually compare this to the input data to verify that processing artefacts have not been introduced
579 in any such analysis.

580 We generally find that grain sizes measured by a linear intercept method onsite (and previously on
581 synthetic cuttings) are dissimilar to those determined by subsequent EBSD mapping – the latter are
582 generally much smaller. However, the two datasets show local increases at comparable depths (Fig.
583 3d). This could be because we analysed more quartz grains that are found in mineralogically mixed
584 layers in the EBSD data than in the chips, where we focused on nearly pure quartz chips. Grain
585 boundary pinning (e.g., Herwegh & Burger 2004) generally results in a smaller grain size in
586 polyphase domains compared with monophase (“pure”) mineralogical layers (Little et al. 2015). It is
587 also likely that the smallest grains were not easily visible in the thin sections by the geologist carrying
588 out the linear intercept analysis, so these results are weighted toward larger grains. Overall, we do not

589 recommend that any of our methods are used for stress determinations by recrystallised grain size
590 piezometry (e.g. Holyoke & Kronenberg 2010). However, the methods employed in this study are
591 appropriate for tracking variations that result from accommodation of ductile strain provided they are
592 properly calibrated to similar measurements made in outcrop samples.

593 *Modal mineralogy*

594 In EDS maps, the AZtec software version 3.1 (Oxford Instruments Nanoanalysis 2013) available
595 during these analyses automatically segmented quantitative oxide proportion maps into a set of
596 minerals not recognized in thin sections. For example, large areas of each map were assigned to be
597 SiO₂, leaving only high concentrations of typically more minor elements, such as Fe, from which to
598 construct other minerals. In the TIMA maps, the Mineral Liberation Analysis (MLA) method
599 described in the methods section of the supplementary data yielded substantial areas of clays and
600 zeolites (e.g. ferrosapponite, schorl, three types of allanite, nepheline; Fig. S2b). Automated PhaseID
601 was only recently implemented in AZtec, and the TIMA instrument and the associated software were
602 only recently developed. As with any automated routine (cf. EBSD; Prior et al. 1999), rapid advances
603 in the quality of the output are expected in the next few years. In these particular datasets, it is likely
604 that more careful examination of the automatically detected minerals by the software operator, then
605 introduction of appropriate corrections to the software, would yield more realistic results, consistent
606 with other geochemical data. Note that operator-informed software corrections were not possible in
607 the version of AZtec available during acquisition and processing of DFDP-2B datasets, but this
608 functionality has been implemented in the most recent AZtec versions (versions 3.2 and 3.3).

609 Do these analytical methods nevertheless provide reasonable estimates of the bulk composition? If
610 they do, we expect the sum of the area of minerals automatically assigned as micas should show
611 similar variation to the areas rich in potassium (K). We carried out this analysis for the TIMA maps,
612 demonstrating a fairly good correlation (the shapes of the curves in Fig. 3j are similar). However, the
613 area rich in K within TIMA maps shows a gradual decrease throughout the borehole, whereas the
614 sum of minerals automatically indexed as mica gradually increases below 700m MD, which could
615 reflect chloritisation of biotite. In summary, the onsite analysis of quartz+feldspar:mica ratios yields
616 similar variations down hole to those indicated by the proxies to this derived from EDS, XRF, and
617 XRD, notably a gradual decrease in the quartz+feldspar:mica ratio with depth, and a very similar
618 shape to the moving window average curves for mica proportion from the onsite analysis of chips
619 (Fig. 3i), and both mica, and K-rich areas (Fig. 3j) derived from the TIMA maps. This suggests all
620 these methods are appropriate indicators of compositional variation.

621 *Implications for interpretation of other continuous datasets*

622 Both the estimates of quartz+feldspar:mica proportion made on the drill site, and the subsequent XRD
623 and XRF analyses (Fig. 3i,k,l) indicate a general decrease in quartz+feldspar:mica with depth in the
624 borehole. This gradual change should be detected in variations in the wireline geophysical logs.
625 Higher resolution variations in composition, unaffected by cuttings mixing and lag, may also be
626 resolved in the wireline data.

627 In DFDP-1, Townend et al. (2013) identified that the geophysical parameters most strongly correlated
628 to lithological variations were bulk electrical properties, and natural gamma. They noted they
629 expected electrical properties to be sensitive to phyllosilicate content, while natural gamma

630 particularly varies in response to the proportion of K⁺ ions, which mostly reflects phyllosilicate
631 content but is also sensitive to the presence of K-feldspar.

632 It is also possible that the strength of the developed tectonite fabrics, which reflects the strain they
633 have accommodated, particularly the distribution of micas within the samples, will affect the rate,
634 and anisotropy, of elastic wave propagation through the borehole wall rocks (e.g. Christensen &
635 Okaya 2007; Dempsey et al. 2011). We strongly recommend that comparisons be made between the
636 microstructural proxies to strain and tectonite fabric intensity, such as quartz grain size, and downhole
637 measurements of elastic properties in future.

638 A rigorous comparison among the geological, geochemical and wireline geophysical logs is beyond
639 the scope of this contribution, but such analysis is underway by others (e.g. Massiot 2017). The
640 datasets presented here, particularly those demonstrating, or acting as proxies to, variation in
641 quartz+feldspar:mica proportion with depth provide an important baseline for those researchers.

642 ***Prediction of fault rock sequence with further drilling.***

643 Observations made during the DFDP-2B geology study suggest that this borehole terminated after
644 having penetrated ~63 m (MD) of Alpine Fault mylonites based on interpretation of the change in
645 quartz grain size. In nearby outcrops mylonites + ultramylonites + cataclasites have mapped true
646 structural thicknesses of 530 m (Gaunt Creek), 430 m (Stony Creek), and 550 m (Parker Creek) but
647 elsewhere, such as Hare Mare and Doughboy Creeks (Fig. 1), late brittle faults cause excision of parts
648 of the sequence so there are only 100-250 m of mylonites + ultramylonites + cataclasites (Toy 2008).
649 We interpret that by 893 m MD, DFDP-2B had drilled to a structural distance (perpendicular to
650 foliation) of 200-400 m from the PSZ of the Alpine Fault Zone. Since the hole was not vertical and
651 the foliation dips steeply SE, the vertical distance would be greater. This allows us to tentatively
652 position a PSZ at a depth of 1100 m MD on Figs. 3 and 9, and by back-calculating distance from a
653 PSZ, correlate between borehole measurements and those from other outcrops, such as quartz grain
654 size data from Stony Creek illustrated in Fig. 3d. This interpretation of structural position is supported
655 by the geochemical indications (Fig. 7 and section 4.2) that the fault's alteration zone, which has a
656 thickness of < 50 m in DFDP-1 cores, and less than this in most outcrops (Toy et al. 2012a), was not
657 sampled. This is a minimum estimate of the PSZ depth, which could range up to 1300 m MD.

658 The DFDP-2B borehole terminated further from the Alpine Fault's PSZ than the the uppermost
659 (cataclasite) rocks encountered in the DFDP-1A and DFDP-1B boreholes. We infer that further
660 drilling in DFDP-2B would have yielded progressively more fractured and incohesive mylonite, then
661 ultramylonite comparable to Units 1 and 2 in DFDP-1 (Toy et al. 2015), followed by cataclasites and
662 then PSZ gouges. A composite log demonstrating our preferred correlation of the sequences
663 encountered in the two phases of drilling is illustrated in Fig. 9. This reveals a missing (undrilled)
664 section between the base of DFDP-2B and the uppermost core recovered from DFDP-1 of at least
665 120 m and possibly as much as 320 m. More accurate estimates of the position of the base of DFDP-
666 2B with respect to the PSZ may be derivable from analysis of fracture orientations and fillings. Based
667 on observations made in the DFDP-1 boreholes and in outcrop, Williams (2017) defined the Alpine
668 Fault damage zone as a 100–160 m-wide interval of relatively dense clay-filled fractures of a broad
669 range of orientations, rather than subparallel to foliation. We considered whether we could derive this
670 information from the DFDP-2B logging data, but these do not yield distinctive petrophysical or
671 structural features, so such analysis is unlikely to be fruitful, and additional drilling seems required

672 to log and core the entire hanging-wall transect, and calibrate the mineralogical, geochemical, and
673 petrophysical data sets. Future analyses of the records gathered on three borehole seismometers
674 arrayed within a 1km radius of DFDP-2B may also allow resolution of fault zone structure through
675 tomographic and fault zone guided wave analyses (cf. Eccles et al. 2015).

676 As well as allowing correlation to DFDP-1 and outcrop, the estimate of the depth at which the PSZ
677 might have been intercepted if DFDP-2B had continued provides a constraint on fault dip. In general,
678 the Alpine Fault PSZ is inferred to be parallel to the mean mylonitic foliation (e.g. Norris & Cooper
679 2007; Toy et al. 2012b). The average mylonitic foliation in the area surrounding the Whataroa Valley
680 (Fig. 2) is shallow-dipping (26°), but this is inferred to be a result of collapse onto the unsupported
681 footwall during overthrusting, as is typically observed in outcrops to the north of the Whataroa River.
682 Foliation dip probably steepens with increasing depth to match a mean dip of 50° of distal hanging
683 wall mylonitic foliation attitudes along this section of the Alpine Fault (Toy et al. 2012b; Gillam et
684 al. 2013). The average hanging wall schist foliation in outcrops in this area dips 59° (Fig. 2b), and
685 analysis of borehole televiewer data in DFDP-2B reveals an average schist and protomylonite
686 foliation dip of 60° (Massiot 2017), but elsewhere along the central Alpine Fault these foliations
687 typically dip more steeply than those of the mylonites, so we do not think these data constrain the
688 PSZ dip. A PSZ with a dip of 50° is illustrated by the black dashed line in Fig. 2b. If this interpretation
689 is correct, DFDP-2B should have intercepted the fault PSZ just before 1100 m MD. During planning
690 of DFDP-2, it was considered possible that the fault PSZ dips more steeply than this, either because
691 there is a strike-slip segment of the Alpine Fault crossing the Whataroa River (Barth et al. 2012;
692 Norris et al. 2012), or because the mean dip of the Alpine Fault at depth in this area is particularly
693 steep (Little et al. 2006). Linking a fault position in the near-surface consistent with the observed
694 steepening of foliation dips a short distance into the hangingwall, with a maximum PSZ intercept at
695 1300 m MD, now allows us to constrain a maximum feasible fault PSZ dip of 62° (Fig. 2b).

696 **Conclusions and future directions**

697 The onsite lab and procedures carried out during DFDP-2B yielded a rich array of samples,
698 descriptions and datasets. These data were usefully compared to the offsite analyses to better
699 understand the ability of various analytical methods to document true variation in the fault rock
700 sequence. Our routine analyses have also yielded baseline datasets that provide a framework of
701 lithological and structural information within which to interpret and provide a geologic context for
702 the wide variety of continuous datasets that were gathered during DFDP-2B.

703 The drilled sequence comprises Alpine Schist, protomylonite and mylonite derived from a
704 metasedimentary Torlesse Composite Terrane protolith. No samples were returned from Alpine Fault
705 ultramylonites, cataclasites, or alteration zone in DFDP-2 (Units 2-5 in Toy et al. 2015).

706 Structural features of cuttings chips could be correlated with outcropping sequences of schist-
707 protomylonite-mylonite from nearby natural exposures. When considered in the context of
708 complementary outcrop mapping, there is a high level of confidence in the inference of the proximity
709 to the fault reached by the DFDP-2B drill hole. The Alpine Fault PSZ target is estimated to have been
710 within 200-400 m of the end of hole. This estimate also constrains the maximum dip of the Alpine
711 Fault in the Whataroa Valley to be 62° .

712 The combined sample sets from DFDP-1 and DFDP-2B do not yet offer a complete sample of the
713 Alpine Fault Zone rocks and their protolith. We recommend that the drilled samples should be

714 supplemented from outcrops in future targeted studies addressing scientific hypotheses about ductile
715 shear zones, and ductile-brittle fault zone architecture. Ideally, further drilling of the fault zone will
716 be able to address this deficit.

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728 **Author contributions**

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904 **Figures:**

- 905 1. (a) Overall tectonic setting and location map. Seafloor topography after Smith and Sandwell (1997)
906 (b) Location of DFDP boreholes within the central Alpine Fault Zone (AFZ). This is an enlargement

907 of the orange box in (a). (c) Summary of the expected geological sequence in the Alpine Fault Zone
908 hanging wall. Typical Alpine Fault Zone outcrops can be observed at Harold, Stony, and Hare Mare
909 Creeks, and the Waikukupa River, modified from Norris & Cooper (2007). Coordinate system is NZ
910 Transverse Mercator, NZGD2010.

911 2. (a) Bedrock Geology Map and (b) Cross Section of the area surrounding the DFDP-2 drillsite. The
912 cross section scale is twice that of the map. The geological information is derived from the QMAP
913 database and supplemented by additional field data (Little et al. 2002, and Little unpublished;
914 Howarth unpublished.). Hillslope topography is schematic and illustrates the maximum NW extent
915 in this map area. Alpine Fault Zone mylonites are illustrated even where they are obscured by
916 Quaternary units at the surface; these mylonites are inferred to extend NW of the zone illustrated in
917 QMAP:Aoraki (Cox & Barrell 2007) as far as the most recent trace of the Alpine Fault across the
918 Whataroa River flats – the location of which was constrained by trenching in 2016. Only bedrock
919 foliation data from creeks immediately NW and SE of the Whataroa River were projected onto the
920 cross section. Some mylonitic foliations (purple) project outside this zone due to geometric variations
921 along fault strike. Coordinate system is NZ Transverse Mercator, NZGD2010.

922 3. Compilation of samples, and structural and chemical datasets collected from the DFDP-2B
923 Borehole, bracketed by inferred lithological unit. (a) Sample profile, wherein each dot represents a 2
924 m interval over which cuttings were collected. (b)-(g) summarise structural features noted during
925 onsite logging, and compiled then extracted from the DIS. In particular, note that (d) is a comparison
926 of quartz recrystallised grain sizes obtained onsite by the linear intercept method with those
927 subsequently obtained by EBSD-based methods, and that surface data were projected onto this figure
928 assuming the Alpine Fault would have been intercepted at 1100 m MD in DFDP-2B. The
929 microstructural data illustrated in (f) were only gathered below 500 m MD because onsite protocols
930 developed with time. (h) General lithological profile, constructed as a summary during the onsite
931 operation, with compositional subdivision of bedrock units from the “weight proportion of chips
932 analysis” carried out onsite. (i) Chip proportions. Quartz-rich is >40 wt% quartz+feldspar chips, mica-
933 rich is >40 wt% mica chips. Horizontal grey bands extending across the entire figure coincide with
934 intervals that were identified as quartz-rich. Note inversion of scale for wt% mica. Mismatches of the
935 quartz+feldspar curves are the proportion of chips with intermediate compositions (from 40-60 wt%
936 mica). (j) to (l) are compositional data derived from analyses of subsamples, as labelled at the top of
937 each column. Again, note the %mica scales increase toward the left. For (d), (e), and (i) to (l),
938 weighted averages, mostly calculated over a 50m moving window, as noted near the top of each panel,
939 demonstrate broad/general trends. Notable structural and lithological features compiled from drill
940 logs are indicated in (g) and (h), respectively. Data sources: (a)-(i) – datapack provided with
941 Sutherland et al., (2015); (j) – supplementary data Table S2; (k) – Table 5; (l) – Table 4; (d) also
942 includes EBSD data from supplementary data Table S3.

943 4. Photographs of selected cuttings samples collected on the drillsite, from a range of depths through
944 the borehole. The background grid is spaced at 1 cm. (a) is the shallowest sample confidently
945 interpreted as bedrock. (b) is a typical of samples collected at intermediate depths through the bedrock
946 sequence. (c) and (d) highlight the typical range of compositions and particle sizes. (c) is mica-rich
947 and fine-grained while (d) is quartz-rich and coarse-grained.

948 5. Key structures from one of the wall rock core sections (23_Z_2; 475.5-476 m MD
949 [ICDP5052ES06HU2]) illustrated through (a) scan of the core, and (b) tracing of the outer surface of

950 the core. (c)-(e) Relative orientations of foliations (black dashed great circles), shear bands (yellow
951 great circles), and prominent quartz veins (red great circles) and their associated poles for all three
952 main core sections demonstrated on lower hemisphere equal area projections. Note that, because the
953 cores were not oriented, these plots are in a reference frame fixed to that core section only. In each
954 case, the top of the stereonet is parallel to the arbitrary reference line scribed along the length of each
955 section, and the core axis plots in the centre of the stereonet.

956 6. (a) and (b) scans of thin sections made on the drillsite. (a) DFDP-2B_213-215 m MD
957 [ICDP5052EX3L601] displays typical characteristics of Alpine Schist, such as graphitic inclusions
958 in porphyroblasts - in biotite (purple arrowed chip) these are distinct bands reflecting a Mesozoic
959 spaced foliation (Little et al., 2002), while in plagioclases they are more distributed but still represent
960 intersection of a planar foliation and the section surface (pink arrowed chip), whereas (b) DFDP-
961 2B_812-814 m MD [ICDP5052EX0P601] displays evidence of mylonitic deformation, particularly
962 sigmoidal clasts (indicated by purple arrows), whose overall shape has been affected by operation of
963 C-type shear bands (e.g. between the pink/red arrows). (c) and (d) are K₂O maps of the surfaces of
964 pucks from which these thin sections were cut. These also demonstrate textural differences between
965 (c) Alpine Schist sample DFDP-2B_266-268_CU [ICDP5052EX1G601] and (d) mylonite DFDP-
966 2B_852-854 m MD [ICDP5052EXXP601]. (e) and (f) illustrate an amphibolite chip observed in
967 DFDP-2B_492-494_CU [ICDP5052EXIK601] in plane polarised and cross polarised light
968 respectively. The latter highlights a crenulated foliation.

969 7. Discriminatory plot based on variations in the major element oxide proportions Fe₂O₃+MgO and
970 Al₂O₃/SiO₂. Whole rock data from the Alpine Schist, Torlesse and Caples Terranes and the Aspiring
971 Lithologic Association include analyses by Coombs et al. (1985); Fagereng & Cooper (2010);
972 McClintock (2000) and other open file data from the Petlab database <http://pet.gns.cri.nz> (Strong et
973 al., 2016). DFDP-1 “alteration zone” samples are defined as those taken from within 50 m of the fault
974 PSZ in that drillcore (Boulton et al. 2017). DFDP-2B data are from cuttings samples analysed in this
975 study (Table 4).

976 8. EBSD maps. All parts of the figure relate to DFDP-2B_520-532_CU [ICDP5052EX7L601]. (a)
977 EBSD-derived phase map generated in CHANNEL software. (b) EBSD-derived phase map generated
978 in MTEX software. In both cases colouring is related to orientation. (c) Grain size distribution for
979 this sample generated in CHANNEL software, for all grains >9.8 micrometers diameter. Note x-axis
980 labels are at the centres of 5 micrometre wide bins; (d) grain size distribution determined by MTEX.

981 9. Composite summary lithological log of DFDP-1 and DFDP-2, demonstrating the proportion of the
982 Alpine Fault Zone sequence able to be accessed for future research through these two sample sets.
983 We have simplified the range of lithologies identified in DFDP-1 by Toy et al. (2015) in order to
984 display them at this scale and to best demonstrate relationships to DFDP-2 samples. Major structural
985 and chemical features are highlighted by annotations at right of the column. DFDP-1 was positioned
986 on this column based on the assumption that the Alpine Fault PSZ would have been encountered after
987 a further 200 m of drilling in DFDP-2B. As discussed in the text, this is a minimum estimate. A
988 maximum of 400 m would yield a PSZ at 1300 m MD. A simplified schematic version of the
989 lithological log is presented at lower right.

990

991 **Tables:**

992

993 **Table 1: Characteristic Alpine Fault lithologies defined by Toy et al. (2015) from outcrop and**
994 **DFDP-1 core samples.**

Unit number	Description	
		995
		996
1	Grey and dark green ultramylonites	997
		998
2	Brown-green-black ultramylonites	999
		1000
3	Upper unfoliated cataclasites	1001
		1002
4	Upper foliated cataclasites	1002
5	Gouges	1003
6	Lower cataclasites	1004
7	Breccias	1005
8	Sedimentary gravels	1006

1007

1008

1009 **Table 2: Summary of samples collected from DFDP-2A.**

Type of sample	On/Offsite	Age or affinity	Purpose	Total #	Depth range (m)		Spacing (m)	Notes
					Top	Bottom		
Cuttings	Onsite	Quaternary	Geological description	127	0	126	1.0	
Fossil	Onsite	Quaternary	Dating	4	58	61.5	0.9	Spacing is an average
Core	Onsite	Quaternary	Geological description	37	125.5	212.6		Total core length = 88.3 m

1010

1011 **Table 3: Summary of samples collected from DFDP-2B.**

Type of sample	On/Offsite	Age or affinity	Purpose	Total #	Depth range (m)		Spacing (m)	Notes
					Top	Bottom		
Cuttings	Onsite	Quat.	Geological description	80	0	238.5	3.0	
Fossil	Onsite	Quat.	Dating	24	19.9	238.0	9.1	Spacing is an average
Cuttings	Onsite	Basement	Geological description	334	238.5	893.2	2.0	
Drilling mud	Onsite	Quat.+ basement	Geological analyses	153	47.0	893.2	5.5	
Fossil	Onsite	Quat.	Dating	1	235.9	236.0		
Core	Onsite	Basement	Geological description	80	437.0	478.3		Total core length = 32.22 m. Mostly concrete. 1.4 m of rock.
Cuttings	Onsite	Basement	Thin section	265	238.5	893.2	4.9	One quartz-rich separate and one whole rock sample at each depth
Unwashed cuttings	Offsite	Basement	Thin section or geochemical analysis	22	280.1	893.2		Unwashed cutting samples were mostly only taken when insufficient washed sample was available for the analyses so the depth interval is not systematic.
Unwashed cuttings	Offsite	Basement	Mechanical tests	4	299.0	886.0		299, 814, 866, 886 m.
Washed cuttings	Offsite	Basement	Thin section or geochemical analysis	202	243.5	884.0	3.2	
Carbonaceous material	Offsite	Quat.	Dating	23	20.0	233.0	9.3	Spacing is an average
Gas extracted from drill mud	Onsite	Quat. + basement	Chemical analysis	36	236.0	892.0	18.2	Average spacing; it actually ranges from 0 to 65 m

1012

1013

Table 4: Major element data measured by XRF.

Top depth of sample (m MD)*	IGSN	SiO ₂ %	TiO ₂ %	Al ₂ O ₃ %	Fe ₂ O ₃ %	MnO %	MgO %	CaO %	Na ₂ O %	K ₂ O %	P ₂ O ₅ %	SO ₃ %	LOI %	Total
243.5	ICDP5052EXGY601	75.52	0.39	11.41	2.90	0.03	1.03	1.29	2.85	1.47	0.10	0.19	2.7	99.86
256.0	ICDP5052EXOY601	74.46	0.40	12.18	3.13	0.05	1.10	1.45	3.27	1.63	0.11	0.08	2.0	99.85
262.0	ICDP5052EXLY601	65.43	0.65	15.57	4.76	0.07	1.88	1.89	3.07	3.00	0.17	0.16	3.2	99.84
291.3	ICDP5052EXRY601	70.93	0.47	13.53	3.81	0.04	1.23	1.62	3.12	2.15	0.13	0.21	2.6	99.84
305.0	ICDP5052EX2V601	70.86	0.51	13.88	3.76	0.04	1.33	1.53	3.25	2.18	0.12	0.18	2.2	99.81
311.0**	ICDP5052EXAY601	68.88	0.55	14.43	4.13	0.03	1.36	1.56	3.30	2.29	0.14	0.34	2.8	99.81
335.0	ICDP5052EX9V601	66.76	0.63	15.65	4.23	0.03	1.50	1.58	3.25	2.79	0.16	0.13	3.1	99.80
359.0	ICDP5052EXBV601	68.37	0.58	14.63	4.27	0.03	1.49	1.62	3.17	2.57	0.15	0.22	2.7	99.80
481.0 (479.0)	ICDP5052EXPV601	66.29	0.71	15.50	4.99	0.06	1.57	1.75	3.32	2.87	0.15	0.20	2.4	99.81
514.0 (512.0)	ICDP5052EX2T601	69.32	0.72	13.93	5.17	0.14	1.31	1.74	3.00	2.01	0.15	0.33	2.0	99.82
532.0	ICDP5052EXWV601	66.61	0.63	15.90	4.44	0.05	1.56	1.62	3.15	2.78	0.18	0.20	2.7	99.82
546.0 (542.0)	ICDP5052EXYV601	68.44	0.74	14.39	4.96	0.12	1.40	1.72	3.05	2.28	0.16	0.26	2.3	99.82
586.0 (584.0)	ICDP5052EX2W601	64.49	0.72	16.27	4.96	0.06	1.65	1.65	3.26	3.06	0.17	0.20	3.3	99.79
628.0 (632.0)	ICDP5052EXAW601	65.34	0.92	15.54	5.52	0.09	1.53	1.60	3.18	2.88	0.16	0.31	2.7	99.77
644.0**	ICDP5052EXXX601	66.52	0.86	14.56	5.39	0.10	1.40	1.69	3.17	2.44	0.17	0.43	3.0	99.73
662.0**	ICDP5052EX0Y601	69.87	0.87	13.07	4.55	0.12	1.11	1.65	3.17	2.04	0.15	0.43	2.7	99.73
694.0 (698.0)	ICDP5052EXNT601	67.46	0.77	14.64	4.73	0.09	1.36	1.62	3.15	2.59	0.15	0.41	2.7	99.67
716.0	ICDP5052EXMW601	62.74	0.78	16.43	5.09	0.06	1.77	1.86	3.31	2.91	0.21	0.20	4.4	99.76
728.0	ICDP5052EXOW601	65.89	0.68	15.81	4.64	0.06	1.63	1.93	3.37	2.72	0.20	0.23	2.6	99.76
746.0	ICDP5052EXRW601	63.50	0.65	18.25	4.01	0.03	1.57	1.45	3.12	3.76	0.19	0.15	3.1	99.78
757.4	ICDP5052EXUW601	67.13	0.53	15.29	3.50	0.03	1.23	1.59	3.68	2.72	0.16	0.18	3.7	99.74
764.0	ICDP5052EXYW601	66.01	0.70	15.93	4.13	0.05	1.29	1.50	3.33	2.62	0.17	0.16	3.9	99.79
782.0	ICDP5052EX0X601	61.05	0.86	18.27	4.89	0.05	1.73	1.48	3.24	3.83	0.23	0.13	4.0	99.76
794.0	ICDP5052EX2X601	63.41	1.03	15.72	4.97	0.08	1.41	1.61	3.82	3.45	0.17	0.21	3.7	99.58
806.0	ICDP5052EX2Y601	59.12	0.79	19.57	4.72	0.05	1.63	1.37	3.09	4.52	0.23	0.12	4.5	99.71
824.0	ICDP5052EXDU601	64.39	1.31	14.44	6.18	0.13	1.45	2.08	3.90	2.35	0.16	0.36	2.6	99.35
842.0	ICDP5052EXHU601	59.63	0.78	18.31	4.77	0.03	1.83	1.64	3.85	4.30	0.22	0.21	3.9	99.47
880.0 (878.0)	ICDP5052EXKU601	61.38	0.76	18.63	4.48	0.04	1.82	1.62	3.61	3.76	0.21	0.23	3.2	99.74
884.0	ICDP5052EXPX601	61.62	0.71	18.88	4.19	0.03	1.73	1.51	3.43	3.66	0.20	0.20	3.6	99.76

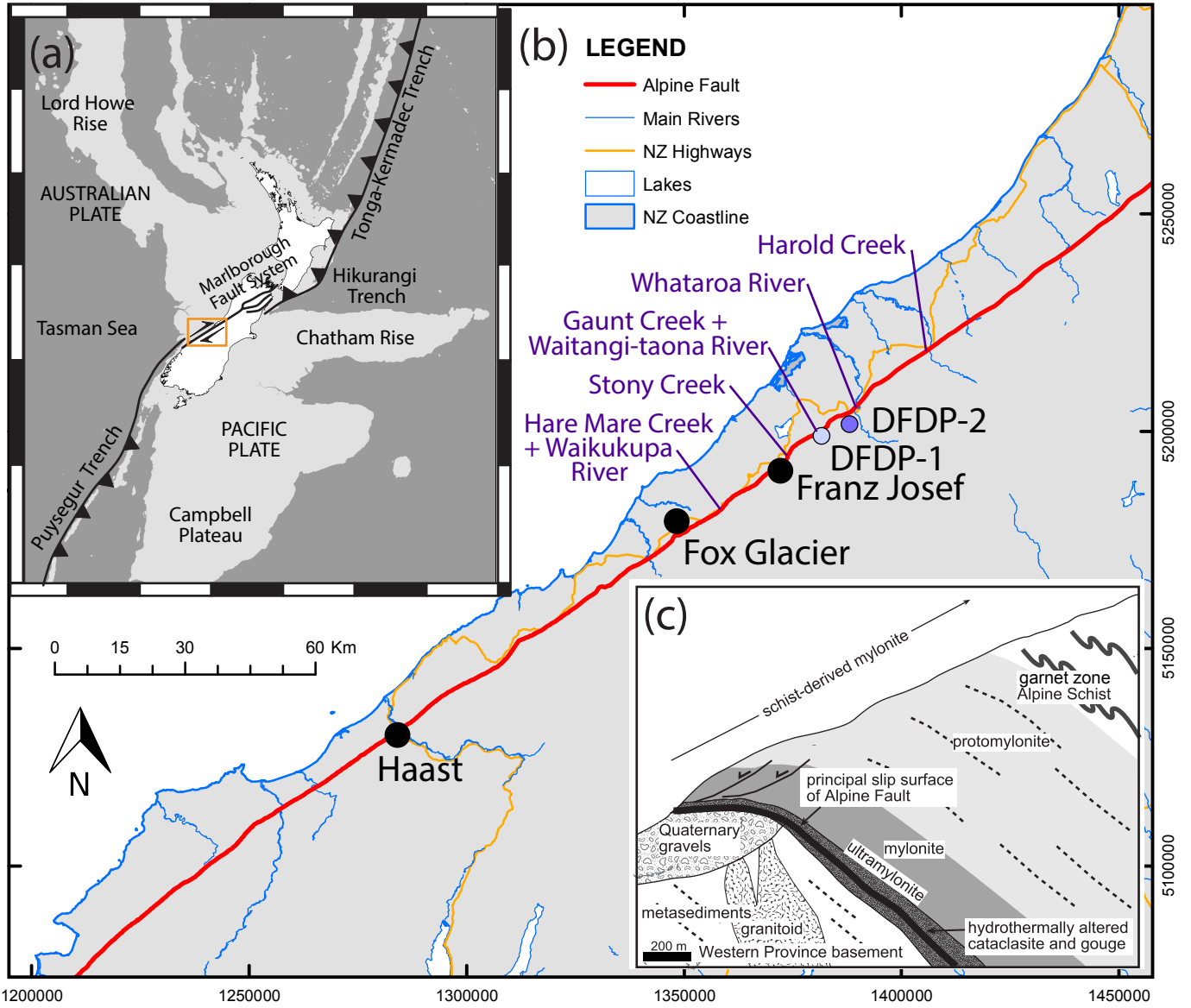
*Depths in parentheses are the closest onsite thin section to this sample.

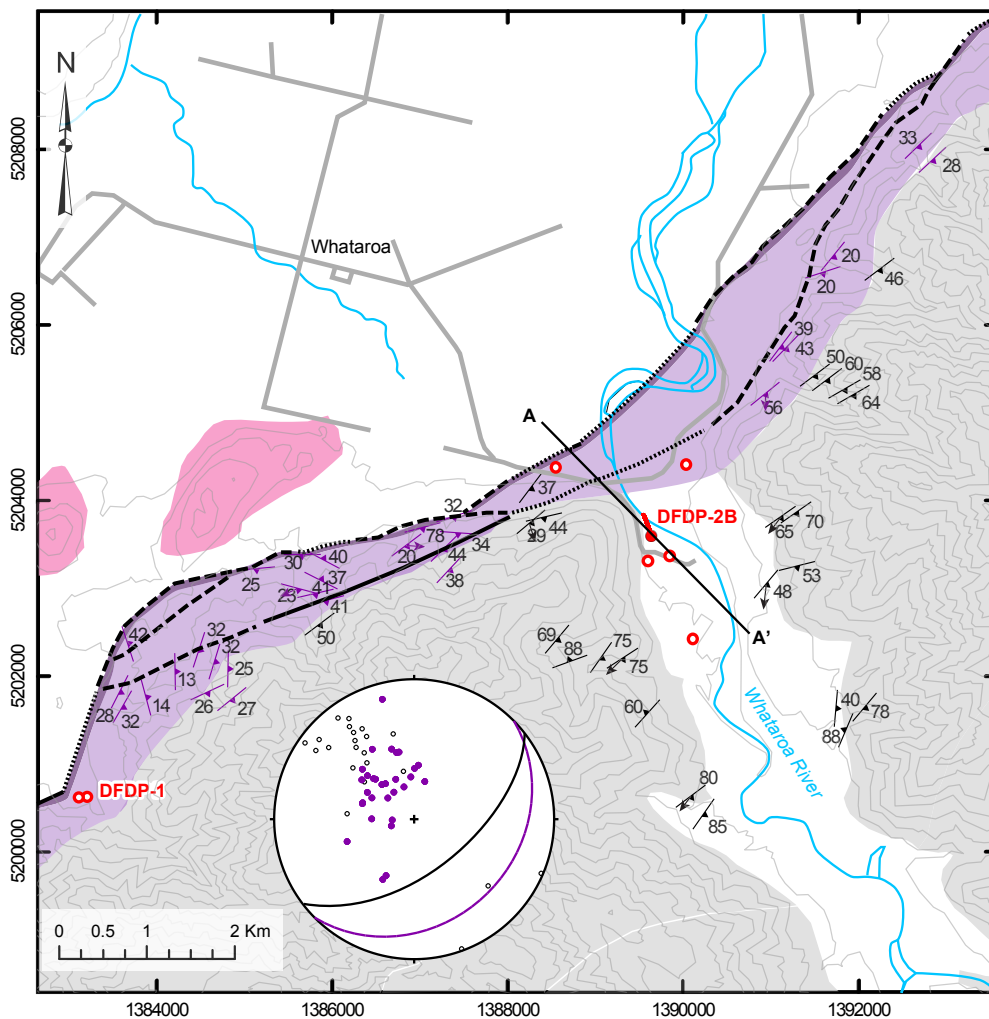
**These analyses were performed on cuttings samples that were not washed before curation on the drillsite, as insufficient washed sample was available.

1018 **Table 5: Mineralogical data measured by XRD.**

Top depth of sample (m MD)	IGSN	Quartz (wt%)	Plagioclase (wt%)	Biotite (wt%)	Muscovite (wt%)	Chlorite (wt%)	Mica (wt%)
405.7	ICDP5052EXGV601	35	32	10	16	7	33
430.2**	ICDP5052EXKV601	35	36	10	12	7	30
454.5	ICDP5052EXMV601	37.1	32	13	14	4	31
479.0	ICDP5052EXQV601	38	32	10	14	6	30
506.0	ICDP5052EXTV601	39	30	11	15	5	31
532.0	ICDP5052EXXV601	36	31	11	18	5	33
554.0	ICDP5052EX1W601	29	32	10	23	6	40
584.0	ICDP5052EX3W601	39	34	10	14	4	28
632.0	ICDP5052EXBW601	34	34	10	17	5	32
662.0**	ICDP5052EX1Y601	37	30	9	20	4	33
686.0	ICDP5052EXHW601	41	34	9	12	4	25
716.0	ICDP5052EXNW601	33	35	11	16	6	32
746.0	ICDP5052EXSW601	29	33	9	24	6	39
764.0	ICDP5052EXZW601	37	30	9	20	4	33
794.0	ICDP5052EX3X601	32	34	7	20	7	35
818.0	ICDP5052EX9X601	39	33	9	13	7	29
836.0	ICDP5052EXFX601	38	34	7	15	6	28
860.0	ICDP5052EXNX601	38	30	8	16	8	32
893.2**	ICDP5052EX7Y601	22	28	9	34	7	50

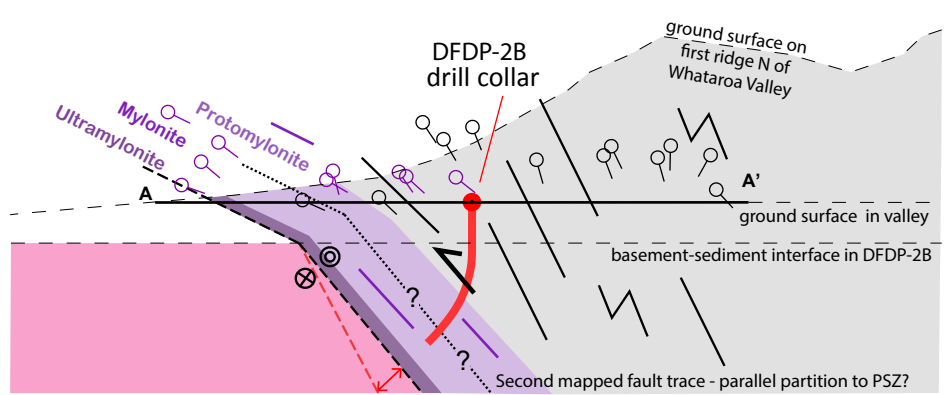
1019 **These analyses were performed on cuttings samples that were not washed before curation on the drillsite, as insufficient washed sample was available.





LEGEND

- DFDP-2B borehole and subsurface trace
- Other boreholes (DFDP-1, SAMBA, DFDP-2 monitoring)
- Roads
- River
- 100m contours
- Foliation**
 - mylonite foliation
 - schist foliation
 - lineation
- Alpine Fault**
 - Accurate
 - Approximate
 - Concealed
- Geological Units**
 - Cover sediments: Late Quaternary alluvium and glacial deposits
 - Garnet zone Alpine Schist
 - Protomylonite and mylonite
 - Ultramylonite
 - Western Province basement: granitoid with minor Greenland Group metasediment
- Stereonet**
 - Mean mylonitic foliation
 - Mean schist foliation
 - Pole to mylonitic foliation
 - Pole to schist foliation

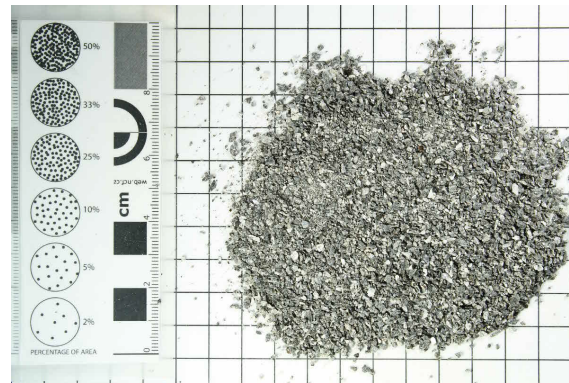


Cross section

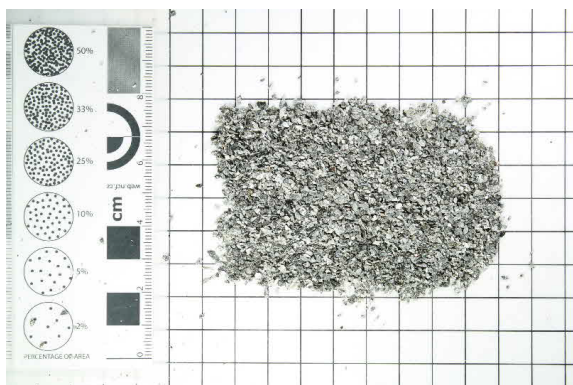
- Foliation dips projected onto cross section
 - Mylonite
 - Alpine Schist
 - Range of possible PSZ intercepts if drilling had continued
 - Steepest possible PSZ
 - Foliation form lines
- 0km 1km
No vertical exaggeration.



(a) 265-267 m MD



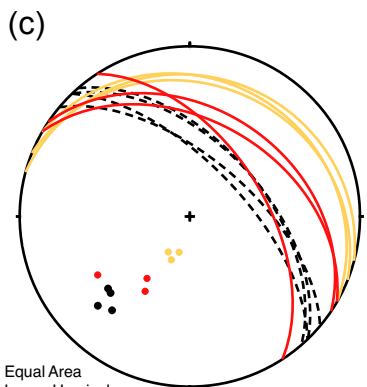
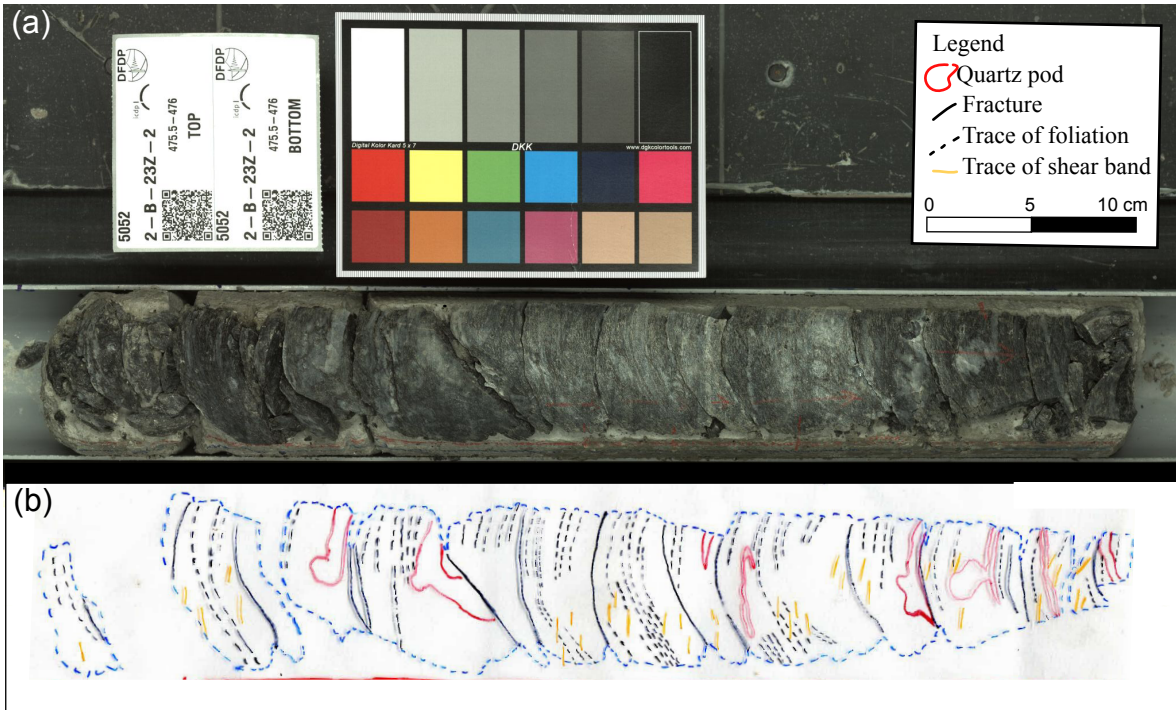
(c) 708-710 m MD



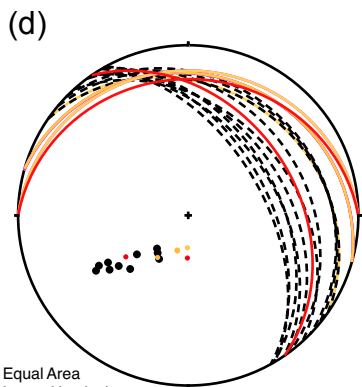
(b) 624-626 m MD



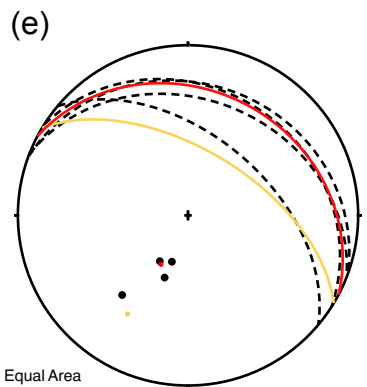
(d) 890-892 m MD



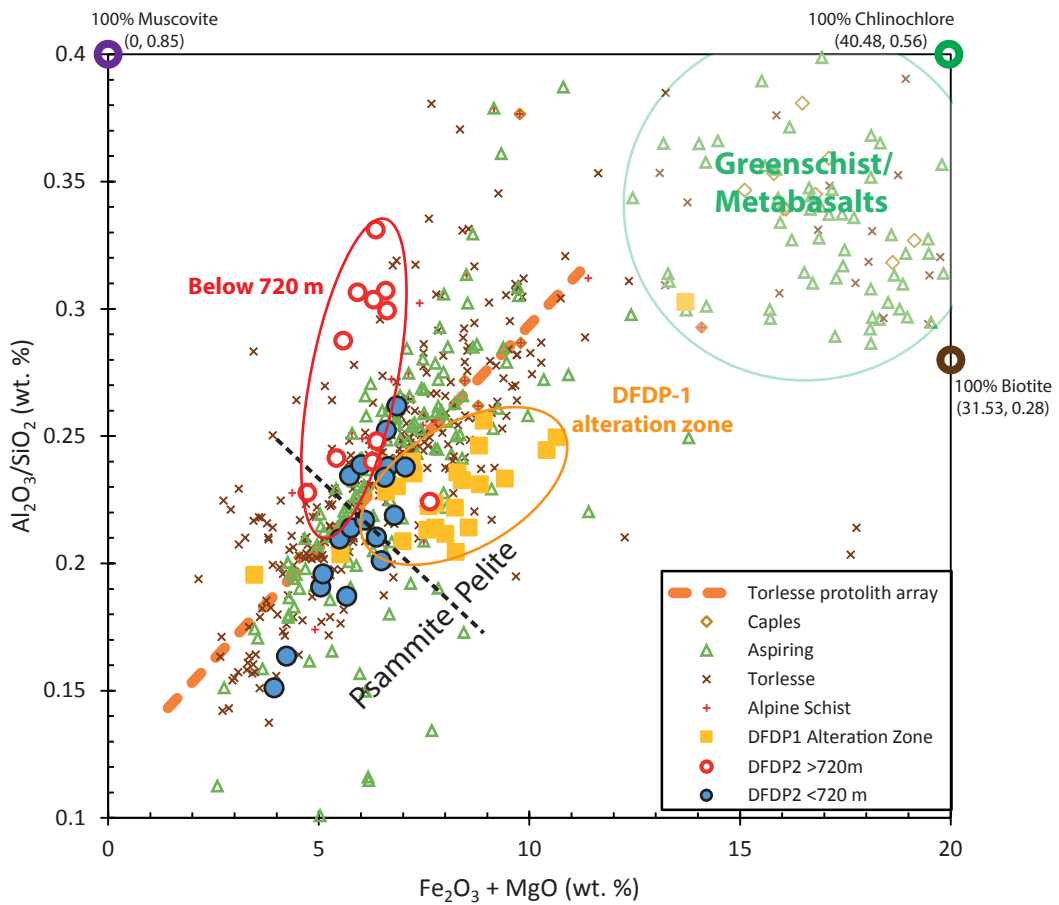
Equal Area
Lower Hemisphere
DFDP-2B_22Z_1



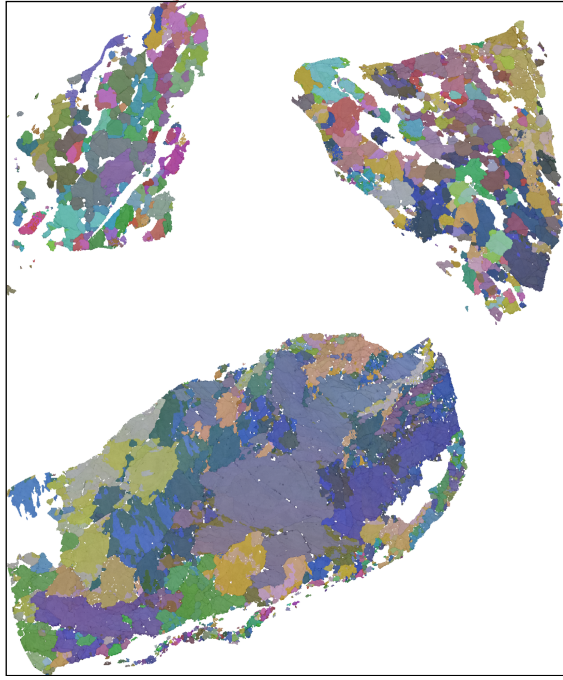
Equal Area
Lower Hemisphere
DFDP-2B_23Z_2



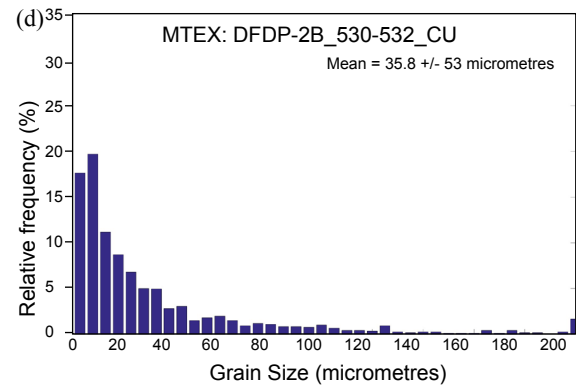
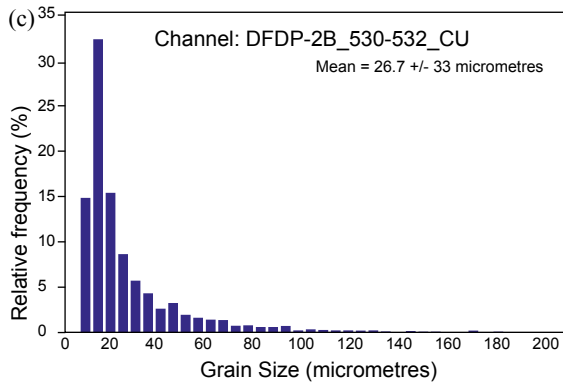
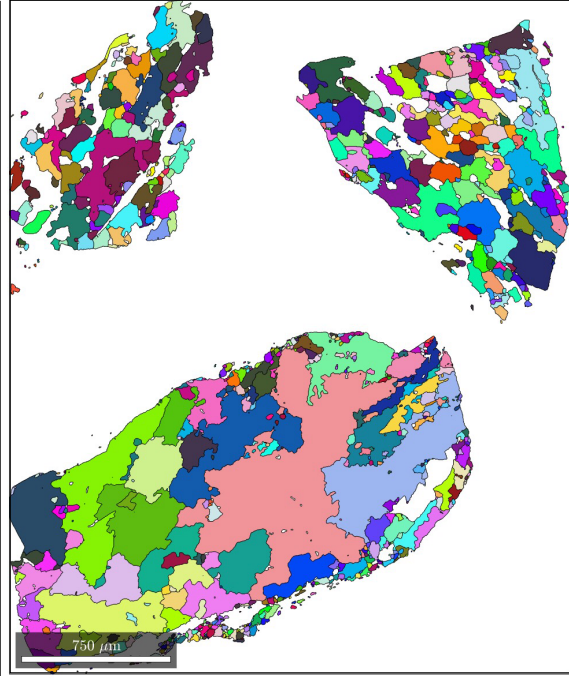
Equal Area
Lower Hemisphere
DFDP-2B_23Z_3

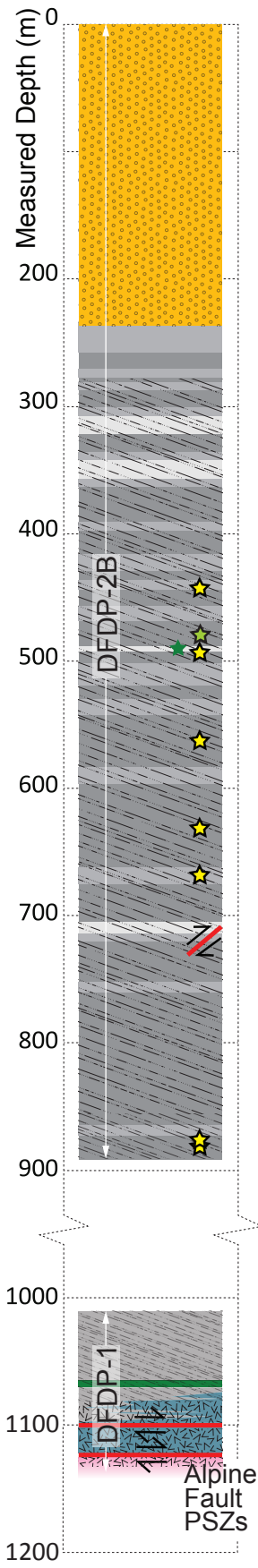


(a) Channel Quartz Orientation Map



(b) MTEX Quartz Orientation Map





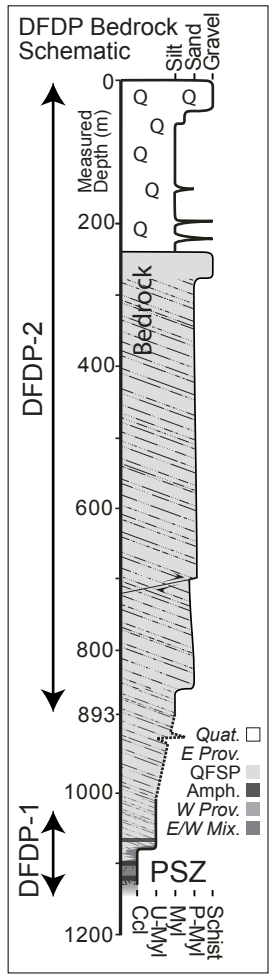
LEGEND

Petrological Features

- Quaternary sequence
- Basement**
- Torlesse protolith
 - Quartz-rich (psammitic)
 - Quartz = mica
 - Mica-rich (pelitic)
 - Metabasic
 - Torlesse-granitoid mix
- Granitoid or gneiss
- Carbonate
- Amphibolite

Structural Features

- Alpine Schist
- Protomylonite
- Mylonite
- Ultramylonite
- Cataclasite
- Gouge
- Fault or fracture zone
- DFDP-2B wall rock cores



Alpine Fault
PSZs