DFDP-2 GEOTHERMAL DISCOVERY IN WESTLAND, NEW ZEALAND

Rupert Sutherland[1], John Townend[1], Virginia Toy[2]

[1]Victoria University of Wellington, PO Box 600, Wellington, New Zealand

[2] University of Otago, PO Box 56, Dunedin, New Zealand

rupert.sutherland@vuw.ac.nz

Keywords: *earthquake, tectonics, geothermal, Alpine Fault, hydrogeology.*

ABSTRACT

Boreholes drilled as part of the Deep Fault Drilling Project (DFDP) reveal a geothermal system in the hanging-wall of the Alpine Fault. The DFDP-2B discovery of 100°C water at 600 m depth beneath farmland adjacent to State Highway 6 near Whataroa has led to local interest in geothermal energy, and whether other Westland valleys also have resource potential. The hot temperatures are caused by a combination of fault slip, which moves rock and heat from depth, and topographically-driven fluid flow through fractured rocks that concentrates heat into valleys. Additional technical work is required to assess the size, quality and safety of the geothermal system, but the discovery provides an exciting opportunity for regional development based on clean sustainable energy that can directly leverage existing plant and people employed in a mining industry that is in long-term decline.

1. INTRODUCTION

The Deep Fault Drilling Project (DFDP) is a multi-stage scientific investigation of the Alpine Fault in western South Island, New Zealand (Townend et al., 2009). The first stage of the project (DFDP-1) drilled to 152 m depth at Gaunt Creek (Cooper and Norris, 1994) and was completed in 2011 (Boulton et al., 2014; Carpenter et al., 2014; Niemeijer et al., 2016; Schleicher et al., 2015; Sutherland et al., 2011; Sutherland et al., 2012; Townend et al., 2013; Toy et al., 2015). The second stage of the project (DFDP-2) was completed nearby in the Whataroa valley (Fig. 1) in January 2015 and reached a drilled depth of 893 m (Sutherland et al., 2015).

The science questions that DFDP originally aimed to address are related to fault zone processes. How and why do earthquakes happen? How does slip on a large geological fault occur? What are the ambient conditions and physical properties on and around an active fault in its pre-earthquake state?

The DFDP-2B borehole did not achieve all of its technical objectives, due to a casing failure during a cementing operation, but yielded a remarkable discovery. The geothermal gradient was much higher than expected and comparable to geothermal boreholes that have been drilled in the Taupo Volcanic Zone (Sutherland et al., 2017). There is no evidence for Neogene volcanic activity anywhere near the DFDP-2 site. This paper presents a summary of what was discovered, an explanation for the extreme hydrothermal conditions, and discussion of potential implications for geothermal energy resources in the western South Island.

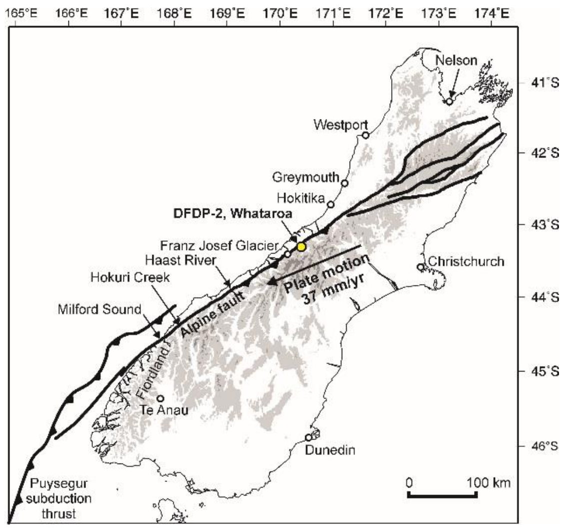

Figure 1: Location of the DFDP-2 site at Whataroa. DFDP-1 was completed at Gaunt Creek, 7 km southwest of DFDP-2.

2. THE ALPINE FAULT

The Alpine Fault (Fig. 1) is a mature plate-bounding transpressive structure that has accommodated >460 km of dextral offset since 24 Ma (Sutherland, 1999), and has a late Quaternary average slip rate of 27+/-5 mm/yr (Norris and Cooper, 2001). The hanging-wall is Mesozoic amphibolite facies meta-greywacke that has been deformed into protomylonite, mylonite, and cataclasite with increasing proximity to the principal slip zone (Norris and Cooper, 2007). The foot-wall is composed of Paleozoic granitoids that intrude quartzose metasediments.

The Alpine Fault fails in large earthquakes (MW 7.6–8.2) every 200–400 years and last ruptured in AD 1717, so is close to rupturing again (Sutherland et al., 2007). Oblique-reverse motion has exhumed a suite of fault rocks from depths of 30 km over the past 3-5 million years (Norris and Cooper, 2007). Numerical models indicate that rapid rock exhumation advects isotherms to relatively shallow depths, and this has been used to explain the occurrence of many hot (<58°C) springs in the hanging-wall of the central Alpine Fault (Allis and Shi, 1995; Allis, 1981; Koons, 1987).

3. DFDP RESULTS

The DFDP-1A and DFDP-1B boreholes penetrated fractured protomylonite, cataclasite, fault gouge, and Quaternary sediments (Sutherland et al., 2011; Sutherland et al., 2012; Toy et al., 2015). The principal slip zone fault gouge is a through-going, planar, thin (1-50 cm, mostly <10 cm) layer of extremely fine-grained

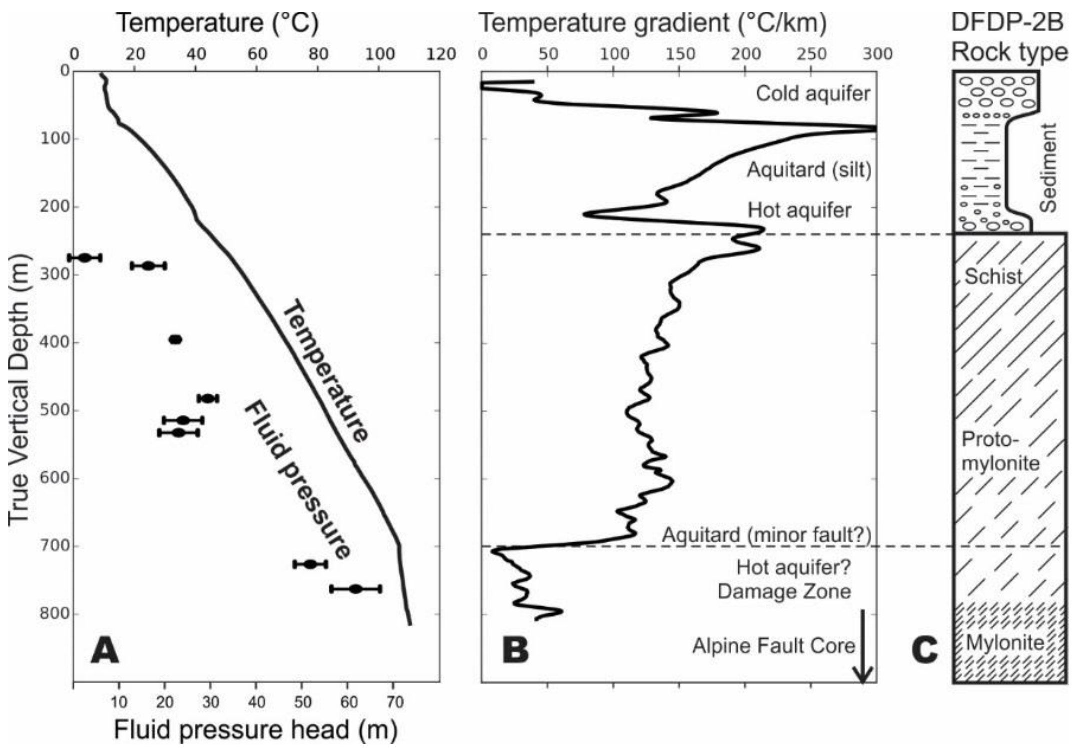

Figure 2. DFDP-2B drilling results. Fluid pressure observations made during breaks in drilling (A). Long-term post-drilling temperature profile measured using distributed temperature sensing on a fibre optic cable (A). Temperature gradient (B). Simplified geologic log and interpretation (C). After Sutherland et al. (2017)

rock generated by slip during repeated earthquakes. The gouge and cemented cataclasite represent a continuous and impermeable layer of variable thickness that plays a major role in governing how fluids move within the fault zone (Sutherland et al., 2012). The DFDP-1B borehole (152 m depth) has a geothermal gradient of 62.6 ± 2.1 °C/km. Wireline geophysical logs reveal a complex pattern of fracturing and alteration that is asymmetric across the fault zone (Townend et al., 2013).

Hydraulic observations and laboratory experiments reveal that cataclasite and the principal-slip-zone gouge (which probably forms a near-continuous layer for hundreds of km along strike and extends to a few km depth) have permeability $<10^{-19}$ m^2 and form an aquitard, whereas fractured protomylonite that is found in the fault hanging-wall (i.e. a continuous tabular zone overlying and parallel to the low-permeability gouge layer) has much higher permeability of $>10^{-15}$ m^2 (Boulton et al., 2012; Sutherland et al., 2012).

The DFDP-2B borehole penetrated a sequence of Quaternary gravel and lake silt, schist, protomylonite, and mylonite (Fig. 2) (Sutherland et al., 2017; Toy et al., 2017). The base of the borehole is estimated to be within 200–400 m of the principal slip zone (PSZ) gouge, based on site surveys and measurement of quartz grain sizes and microstructures in drill cuttings that are similar to mylonitic fault rocks exposed nearby. Comprehensive rock, mud, wireline, and seismological observations were collected, and a fibre-optic cable was installed after drilling to acquire repeated precise temperature measurements.

Post-drilling equilibrated temperatures in the borehole reveal a zone above 700 m depth (true vertical; 740 m drilled depth) characterized by a thermal gradient of 100–200°C/km, and a deeper zone with a gradient of 30–50°C/km (Fig. 2). The fluid pressure gradient in the borehole below the sedimentary layers is 8–10% above hydrostatic, but an aquifer at the base of the sediments (230–240 m) is only slightly over-pressured (<5 m head). This means that, unlike the PSZ gouge mentioned above, the Quaternary silts do not form an effective hydraulic seal (Fig. 2).

The geothermal gradient in the upper 700 m of the DFDP-2B borehole is unusual by global standards: 99% of geothermal gradients measured in deep (>500 m) boreholes elsewhere are <80°C/km (Pollack et al., 1993). Values exceeding 80°C/km are typically associated with volcanic regions, such as the Taupo Volcanic Zone, but there is no evidence for Neogene volcanism near the DFDP-2B site. The regional value determined from petroleum boreholes west of DFDP-2B is c. 30°C/km (Townend, 1999).

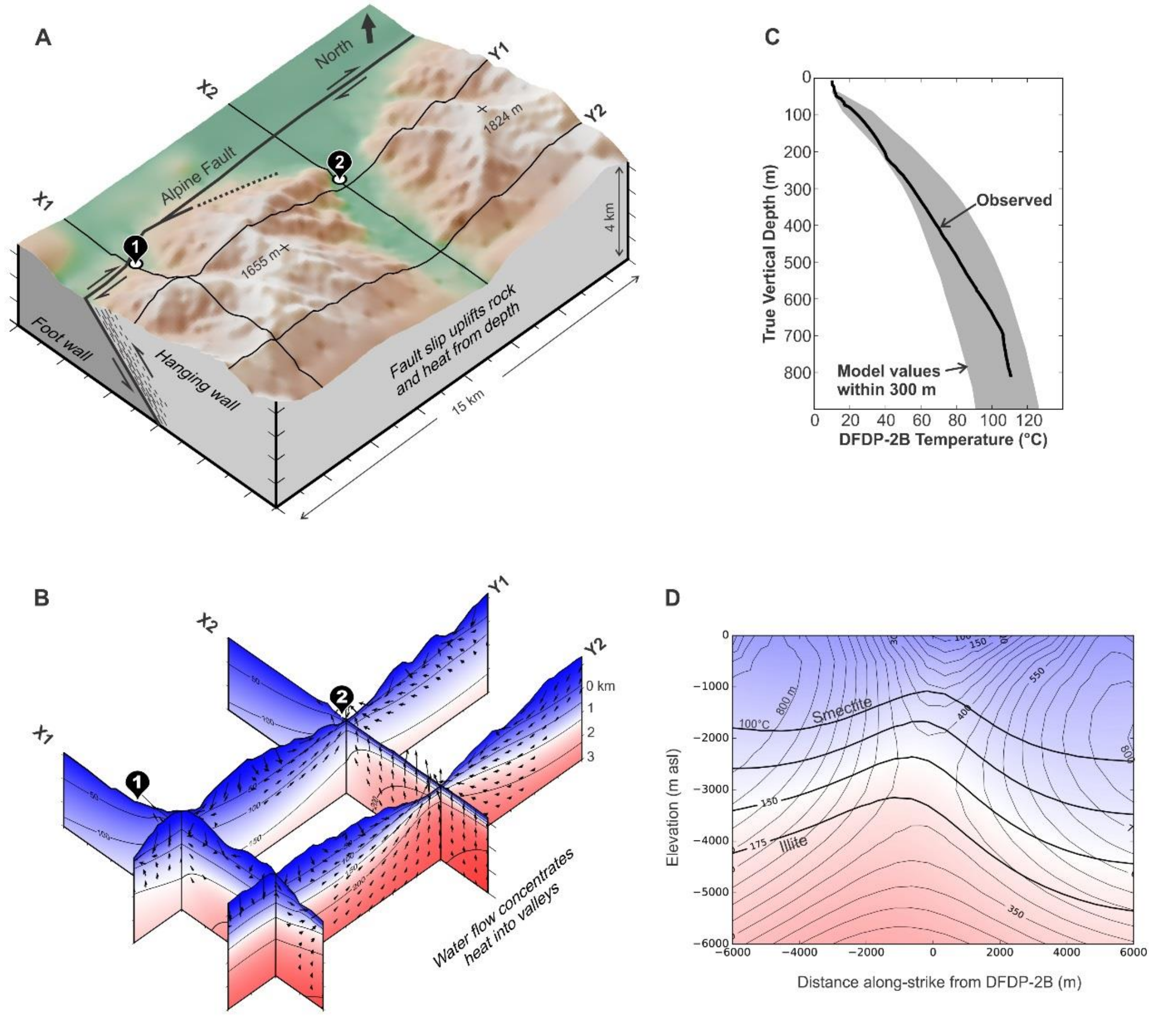

Figure 3. Thermal and fluid flow models, after Sutherland et al. (2017). (A) DFDP-1 and DFDP-2 locations (marked 1 and 2, respectively). (B) Temperature cross-sections with contours in °C and fluid fluxes (arrows show fluxes >0.15 m/yr) extracted from a 3D numerical model with 200 m horizontal resolution near DFDP-2. Parameters for model shown are: (1) dip-slip rate of 8 mm/yr; and (2) uniform permeability of 5.0×10^{-16} m^2 in a layer above 5 km bsl within the Alpine Fault hanging-wall. (C) Comparison of model values (as shown in B), extracted from within 300 m of DFDP-2B, with borehole observations. (D) Fluid pressure and temperature inferred on the Alpine Fault plane: thin lines are fluid pressure head (m, reference fluid density at surface); and bold lines are temperature contours approximately equivalent to the temperature of illite-smectite transitions (100–175°C).

4. GEOTHERMAL STATE

Sutherland et al. (2017) modelled the thermal state near DFDP sites by considering heat transport via:
(1) conduction;
(2) rock advection driven by fault slip; and
(3) fluid advection driven by local topography (Fig. 3). We assumed uniform high permeability to some fixed depth (3 or 5 km) above the principal slip zone of the Alpine Fault and low permeability beneath it. Adjustable parameters were the maximum value of permeability, and the rate of reverse dip-slip fault movement, which is constrained by geological observations of late Quaternary offsets to lie within the range 6–14 mm/yr near the drill-site (Norris and Cooper, 2007). Drilling-related temperature anomalies were modelled separately and excluded from our analysis by selecting observations made >6 months after drilling. There is little variability in thermal diffusivity within the borehole. The 3D model domain is much larger than the specific region of interest.

We aimed to fit temperature observations from DFDP-2B (Fig. 2) and the geothermal gradient of 62±2°C/km measured in the 150 m-deep DFDP-1B borehole (Fig. 3) (Sutherland et al., 2012). Our models are intentionally simplified, because they are under-constrained by observations, and intended only to gain general insight into hydrothermal structure in and around the fault zone. The best fit to DFDP-2B temperature observations is obtained with a fault dip-slip rate of 14 mm/yr and low permeability, but this solution does not fit DFDP-1B observations. The relatively low average curvature of the thermal profile, combined with the over-simplified hydrological structure, leads to the conclusion that rock advection and thermal diffusion are the primary heat transport mechanisms at 240–740 m depth in DFDP-2B. However, but the large difference in geothermal gradient between DFDP-1B and DFDP-2B requires that fluid advection plays an important heat transfer role between sites and requires a regional value of permeability $>5\times10^{-16}$ m^2. The DFDP-2B fluid pressure gradient indicates upward flow through the fractured rock mass near the borehole (Fig. 2A). The large difference in geothermal gradient between sites is explained by along-strike variations in topography that drive fluid flow and hence advection of heat (Fig. 3).

The model results are broadly consistent with existing knowledge of fault slip rate and heterogeneous rock permeability in the hanging-wall of the Alpine Fault. We expect permeability to be low within cataclasites near the principal slip zone and minor fault splays (Sutherland et al., 2012), and for them to be barriers to fault-normal flow. We expect high permeability within the damage zone, producing an aquifer that enhances fault-parallel flow, and beneath mountains of the hanging wall where warm springs are common (Cox et al., 2015). The region of relatively-low geothermal gradient at the base of DFDP-2B (Fig. 2) is a discrete hydrological domain and interpreted as an aquifer associated with the damage zone, but we were unable to verify its properties due to engineering difficulties. Fluid pressure equilibration experiments ("slug tests") conducted during drilling of DFDP-2B indicate bulk-rock permeability around the borehole of order 10^{-15} m^2. However, these estimated values are significantly affected (reduced) by the bentonite mud system that was used during drilling.

In summary, we infer that fault slip moves rock and heat from depth, and topographically-driven fluid flow through fractured rocks concentrates heat into valleys (Fig. 3).

5. ECONOMIC POTENTIAL

The discovery of 100°C water at 600 m depth beneath farmland adjacent to State Highway 6 near Whataroa has led to a great deal of local interest into whether geothermal energy could be commercialized, and whether other Westland valleys may also contain geothermal resources. There are natural warm springs in most valleys.

Commercial success will depend on several factors:
(1) size and sustainability of the resource, i.e. how much heat can be extracted;
(2) quality of the resource, i.e. how rapidly that heat can be extracted;
(3) value of the commercial end-use; and
(4) if the extraction of hot water can be done safely with minimal environmental risk, i.e. regulation and social license.

Additional drilling is required to assess the spatial and depth extent of the geothermal system. However, the very large number of wireline logging runs that we carried out during the DFDP-2 experiment may already allow us to estimate hydraulic conductivities of individual fractured zones, and hence we may be able to construct preliminary reservoir models and estimate the rate at which fluid could be produced. This is a work in progress that we would value input into.

The value of commercial end use is hard to assess without better information regarding characteristics of the resource (size, quality, safety). Models predict that maximum temperatures available may be about 180-240°C. The region is remote and would benefit from local electricity supply for domestic use, tourism, and agriculture; but the total size of demand is relatively small. Resilience may be improved by local supply, if infrastructure is built to withstand earthquake effects. It is likely that earthquakes would enhance permeability and hence increase fluid production rates and 'quality' of the resource. It may be that the direct use of heat, e.g. for milk processing, tourism, and agriculture, could provide greater value than electricity production. Further work is required to assess the value proposition of the resource.

The safety of geothermal production is a significant concern, because the system is bound by the Alpine Fault, which is one of the most hazardous faults in New Zealand. Geothermal production is known to induce earthquakes in some locations. We are in a good position to monitor and model this process at DFDP-2, with good instrumentation in place, a catalogue of background earthquake activity (Chamberlain et al., 2017), and a large research team that specializes in earthquake science. The chemistry of deep geothermal fluids is unknown at present, but is likely to be predictable and relatively benign, based on existing knowledge of hot spring chemistry (Menzies et al., 2014).

The size and quality of the total Westland resource remains highly uncertain. It was previously known that many valleys have minor hot springs with typical temperatures of 20-40°C, and the low temperatures and flow rates provided little encouragement for geothermal exploration. Our discovery reveals that temperatures beneath major valleys may be much higher at moderate depths than previously thought; but that this heat is masked by thick gravel aquifers with active cold groundwater systems.

Additional technical work is required to assess the size, quality and safety of the geothermal system, but the discovery opens up an exciting opportunity for regional development based on clean sustainable energy. Of particular appeal is that the engineering required to develop this resource can directly leverage off existing plant and people that are employed in a local mining industry that is in long-term decline. It is surely worth further investigation.

ACKNOWLEDGEMENTS

This paper is based heavily on the publication of Sutherland et al. (2017) and work of the broader DFDP-2 Science Team, particularly the hydrological models produced by Phaedra Upton and Jamie Coussens. We thank: the Friend family for land access and the Westland community for support; Schlumberger for assistance with optical fibre technology; Benson, Conze, Marx, Pooley, Pyne, and Yeo for engineering and site support; the CNRS University of Montpellier wireline logging group of Pezard, Henry, Nitsch, and Paris; Arnold Contracting; Eco Drilling; and Webster Drilling. Funding was provided by the International Continental Scientific Drilling Program (ICDP), NZ Marsden Fund, GNS Science, Victoria University of Wellington, University of Otago, NZ Ministry for Business Innovation and Employment, NERC grants NE/J022128/1 and NE/J024449/1, and Netherlands Organization for Scientific Research VIDI grant 854.12.011 and ERC starting grant SEISMIC 335915. ICDP provided expert review, staff training, and technical guidance.

REFERENCES

Allis, R., and Shi, Y., 1995, New insights to temperature and pressure beneath the central Southern Alps, New Zealand: New Zealand Journal of Geology and Geophysics, v. 38, no. 4, p. 585-592.

Allis, R. G., 1981, Continental underthrusting beneath the Southern Alps of New Zealand: Geology, v. 9, p. 303-307.

Boulton, C., Carpenter, B. M., Toy, V., and Marone, C., 2012, Physical properties of surface outcrop cataclastic fault rocks, Alpine Fault, New Zealand: Geochemistry Geophysics Geosystems v. Q01018, p. doi:10.1029/2011GC003872.

Boulton, C., Moore, D. E., Lockner, D. A., Toy, V. G., Townend, J., and Sutherland, R., 2014, Frictional properties of exhumed fault gouges in DFDP-1 cores, Alpine Fault, New Zealand: Geophysical Research Letters, v. 41, no. 2, p. 356-362.

Carpenter, B., Kitajima, H., Sutherland, R., Townend, J., Toy, V., and Saffer, D., 2014, Hydraulic and acoustic properties of the active Alpine Fault, New Zealand: Laboratory measurements on DFDP-1 drill core: Earth and Planetary Science Letters, v. 390, p. 45-51.

Chamberlain, C. J., Boese, C. M., Eccles, J. D., Savage, M. K., Baratin, L. M., Townend, J., Gulley, A. K., Jacobs, K. M., Benson, A., Taylor-Offord, S., Thurber, C., Guo, B., Okada, T., Takagi, R., Yoshida, K., Sutherland, R., and Toy, V. G., 2017, Real-Time Earthquake Monitoring during the Second Phase of the Deep Fault Drilling Project, Alpine Fault, New Zealand: Seismological Research Letters, v. 88, p. 1443-1454.

Cooper, A. F., and Norris, R. J., 1994, Anatomy, structural evolution, and slip rate of a plate-boundary thrust: The Alpine fault at Gaunt Creek, Westland, New Zealand: Geological Society of America Bulletin, v. 106, p. 627-633.

Cox, S., Menzies, C., Sutherland, R., Denys, P., Chamberlain, C., and Teagle, D., 2015, Changes in hot spring temperature and hydrogeology of the Alpine Fault hanging wall, New Zealand, induced by distal South Island earthquakes: Geofluids, v. 15, no. 1-2, p. 216-239.

Koons, P. O., 1987, Some thermal and mechanical consequences of rapid uplift; an example from the Southern Alps, New Zealand: Earth and Planetary Science Letters, v. 86, no. 2, p. 307-319.

Menzies, C. D., Teagle, D. A., Craw, D., Cox, S. C., Boyce, A. J., Barrie, C. D., and Roberts, S., 2014, Incursion of meteoric waters into the ductile regime in an active orogen: Earth and Planetary Science Letters, v. 399, p. 1-13.

Niemeijer, A., Boulton, C., Toy, V., Townend, J., and Sutherland, R., 2016, Large-displacement, hydrothermal frictional properties of DFDP-1 fault rocks, Alpine Fault, New Zealand: Implications for deep rupture propagation: Journal of Geophysical Research: Solid Earth, v. 121, no. 2, p. 624-647.

Norris, R. J., and Cooper, A. F., 2001, Late Quaternary slip rates and slip partitioning on the Alpine Fault, New Zealand: Journal of Structural Geology, v. 23, no. 2-3, p. 507-520.

Norris, R. J., and Cooper, A. F., 2007, The Alpine Fault, New Zealand: surface geology and field relationships, *in* Okaya, D., Stern, T. A., and Davey, F., eds., A Continental Plate Boundary: Tectonics at South Island, New Zealand, American Geophysical Union, p. 157–175.

Pollack, H. N., Hurter, S. J., and Johnson, J. R., 1993, Heat flow from the Earth's interior: analysis of the global data set: Reviews of Geophysics, v. 31, no. 3, p. 267-280.

Schleicher, A., Sutherland, R., Townend, J., Toy, V., and van der Pluijm, B., 2015, Clay mineral formation and fabric development in the DFDP-1B borehole, central Alpine Fault, New Zealand: New Zealand Journal of Geology and Geophysics, v. 58, no. 1, p. 13-21.

Sutherland, R., 1999, Cenozoic bending of New Zealand basement terranes and Alpine Fault displacement: a brief review: New Zealand journal of geology and geophysics, v. 42, p. 295-301.

Sutherland, R., Eberhart-Phillips, D., Harris, R. A., Stern, T., Beavan, J., Ellis, S., Henrys, S., Cox, S., Norris, R. J., Berryman, K. R., Townend, J., Bannister, S., Pettinga, J., Leitner, B., Wallace, L., Little, T. A., Cooper, A. F., Yetton, M., and Stirling, M., 2007, Do great earthquakes occur on the Alpine fault in central South Island, New Zealand?, *in* Okaya, D., Stern, T. A., and Davey, F., eds., A Continental Plate Boundary: Tectonics at South Island, New Zealand, American Geophysical Union, p. 235–251.

Sutherland, R., Townend, J., Toy, V., Allen, M., Baratin, L., Barth, N., Beacroft., Benson, l., Boese, C., Boles, A., Boulton, C., Capova, l., Carpenter, B., Celerier, B., Chamberlain, C., Conze, R., Cooper, A., Coussens, J., Coutts, A., Cox, S., Craw, L., Doan, M., Eccles, J., Faulkner, D., Grieve, J., Grochowski, J., Gulley, A., Henry, G., Howarth, J., Jacobs, K., Jeppson, T., Kato, N., Keys, S., Kirilova, M., Kometani, Y., Kovacs, A., Langridge, R., Lin, W., Little, T., Mallyon, D., Mariani, B., Marx, R., Massiot, C., Mathewson, L., Melosh, B., Menzies, C., Moore, J., Morales, L., Morgan, C., Mori, H., Niemeijera, A., Nishikawa, O., Nitsch, O., Paris Cavailhès, J., Pooley, B., Prior, D., Pyne, A., Sauer, K., Savage, M., Schleicher, A., Schmitt, D., Shigematsu, N., Taylor-Offord, S., Tobin, H., Upton, P., Valdez, R., Weaver, K., Wiersberg, T., Williams J., Yeo, S., and Zimmer, M., 2015, Deep Fault Drilling Project (DFDP), Alpine Fault boreholes DFDP-2A and DFDP-2B technical completion report: GNS Science Report, v. 2015/50, p. 1-269.

Sutherland, R., Townend, J., Toy, V., Upton, P., Coussens, J., Allen, M., Baratin, L. M., Barth, N., Becroft, L., Boese, C., Boles, A., Boulton, C., Broderick, N. G. R., Janku-Capova, L., Carpenter, B. M., Célérier, B., Chamberlain, C., Cooper, A., Coutts, A., Cox, S., Craw, L., Doan, M. L., Eccles, J., Faulkner, D., Grieve, J., Grochowski, J., Gulley, A., Hartog, A., Howarth, J., Jacobs, K., Jeppson, T., Kato, N., Keys, S., Kirilova, M., Kometani, Y., Langridge, R., Lin, W., Little, T., Lukacs, A., Mallyon, D., Mariani, E., Massiot, C., Mathewson, L., Melosh, B., Menzies, C., Moore, J., Morales, L., Morgan, C., Mori, H., Niemeijer, A., Nishikawa, O., Prior, D., Sauer, K., Savage, M., Schleicher, A., Schmitt, D. R., Shigematsu, N., Taylor-Offord, S., Teagle, D., Tobin, H., Valdez, R., Weaver, K., Wiersberg, T., Williams, J., Woodman, N., and Zimmer, M., 2017, Extreme hydrothermal conditions at an active plate-bounding fault: Nature, v. 546, no. 7656, p. 137-140.

Sutherland, R., Toy, V., Townend, J., Eccles, J., Prior, D. J., Norris, R. J., Mariani, E., Faulkner, D. R., DePascale, G., Carpenter, B. M., Boulton, C., Menzies, C. D., Cox, S., Little, T., Hasting, M., Cole-Baker, J., Langridge, R., Scott, H. R., Reid-Lindroos, Z. R., Fleming, B., and Wing, R., 2011, Operations and well completion report for boreholes DFDP-1A and DFDP-1B, Deep Fault Drilling Project, Alpine Fault, Gaunt Creek, New Zealand: GNS Science Report, v. 2011/48, p. 70.

Sutherland, R., Toy, V. G., Townend, J., Cox, S. C., Eccles, J. D., Faulkner, D. R., Prior, D. J., Norris, R. J., Mariani, E., Boulton, C., Carpenter, B. M., Menzies, C. D., Little, T. A., Hasting, M., De Pascale, G. P., Langridge, R. M., Scott, H. R., Lindroos, Z. R., Fleming, B., and Kopf, A. J., 2012, Drilling reveals fluid control on architecture and rupture of the Alpine fault, New Zealand: Geology, v. 40, no. 12, p. 1143-1146.

Townend, J., 1999, Heat flow through the West Coast, South Island, New Zealand: New Zealand Journal of Geology and Geophysics, v. 42, p. 21–31.

Townend, J., Sutherland, R., and Toy, V., 2009, Deep Fault Drilling Project—Alpine Fault, New Zealand: Scientific Drilling, v. 8, p. 75-82.

Townend, J., Sutherland, R., Toy, V., Eccles, J., Boulton, C., Cox, S., and 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, v. 14, no. 9, p. 3801-3820.

Toy, V. G., Boulton, C. J., Sutherland, R., Townend, J., Norris, R. J., Little, T. A., Prior, D. J., Mariani, E., Faulkner, D., Menzies, C. D., Scott, H., and Carpenter, B., 2015, Fault rock lithologies and architecture of the central Alpine fault, New Zealand, revealed by DFDP-1 drilling: Lithosphere, v. 7, no. 2, p. 155-173.

Toy, V. G., Sutherland, R., Townend, J., Allen, M. J., Becroft, L., Boles, A., Boulton, C., Carpenter, B., Cooper, A., and Cox, S. C., 2017, Bedrock geology of DFDP-2B, central Alpine Fault, New Zealand: New Zealand Journal of Geology and Geophysics, p. 1-22.