Extreme hydrothermal conditions at an active plate-bounding fault

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Temperature and fluid pressure conditions control rock deformation and mineralization on geological faults, and hence the distribution of earthquakes [1](#_ENREF_1). Typical intraplate continental crust has hydrostatic fluid pressure and a near-surface thermal gradient of 31±15°C/km [2](#_ENREF_2),[3](#_ENREF_3). At temperatures >300–450°C, found at >10–15 km depth, intra-crystalline plasticity of quartz and feldspar relieves stress by aseismic creep and earthquakes are infrequent. Hydrothermal conditions control the stability of mineral phases and hence frictional-mechanical processes associated with earthquake rupture cycles, but there are few data from active plate-bounding faults. Here, we report results from a scientific borehole drilled into the upper part of the Alpine Fault, which is late in its cycle of stress accumulation and expected to rupture in a magnitude 8 earthquake during coming decades [4](#_ENREF_4),[5](#_ENREF_5). The DFDP-2B borehole (893 m depth) revealed a pore fluid pressure gradient >9±1% above hydrostatic and an average geothermal gradient of 125±55°C/km within the hanging-wall of the fault. These extreme conditions result from rapid fault movement, which transports rock and heat from depth, and topographically-driven fluid movement that concentrates heat into valleys. Shear heating may occur within the fault but is not required to explain our observations. Our data and models show that interactions between fault slip, rock fracturing and alteration, and geomorphic processes on active faults can produce highly-anomalous fluid pressure and temperature gradients in the upper part of the seismogenic zone that affect mineralization and fault slip processes at plate boundaries.

Borehole measurements from intraplate regions reveal near-hydrostatic fluid pressures and linear increases in effective stress with depth that are consistent with the crust being close to brittle failure and containing faults with friction coefficients of 0.6–1.0 and low cohesive strengths [3](#_ENREF_3). Laboratory measurements for many natural rocks have a similar (Byerlee) range of frictional strengths [6](#_ENREF_6). However, major active faults at plate boundaries appear anomalously weak. For example, the maximum horizontal stress adjacent to the San Andreas Fault in California is oriented at a high angle (65–85°) to the fault and, despite ambient stress magnitudes similar to those in intra-plate regions, the geometry of the stress field yields a low shear stress resolved onto the fault, and hence a lower inferred frictional strength than that predicted by Byerlee friction [7](#_ENREF_7). There is mounting evidence that this is true for many faults [8](#_ENREF_8).

The lack of significant heat flow anomalies adjacent to large plate boundary faults, most famously the San Andreas Fault [9](#_ENREF_9), also demonstrates that less work is done on faults than predicted if Byerlee frictional failure dissipated energy as heat. Drilling has revealed that heat generated by >50 m of slip during the Mw 9.0 Tohoku-Oki 2011 earthquake produced only a small temperature anomaly, requiring an average friction coefficient during slip of <0.1 [10](#_ENREF_10); similar results were found after the Wenchuan 2008 and Chi-Chi 1999 earthquakes [11](#_ENREF_11),[12](#_ENREF_12). Plate boundary faults must, therefore, be composed of materials that are mechanically weak on long time-scales, even if weakness is a transient phenomenon during movement.

Brittle fault rocks form within the seismogenic zone via physical comminution of rock and temperature-sensitive chemical reactions with pore fluids. Experimental studies of dynamic friction confirm that slip-weakening by up to one order of magnitude is common as the slip rate approaches values inferred for large earthquakes, though the mechanisms of weakening are debated [13](#_ENREF_13),[14](#_ENREF_14). The evolution of the coefficient of friction on a fault surface during and after an earthquake is time-dependent [15](#_ENREF_15). Of particular significance is the stability of phyllosilicate phases with low dynamic friction [16](#_ENREF_16), thermal expansion and the generation of physicochemical reaction products produced during slip [13](#_ENREF_13), and the presence of low-permeability mineral cements that enhance dynamic fluid pressurization mechanisms [17](#_ENREF_17). Temperature and fluids within fault zones are primary controls on material properties and slip-weakening mechanisms, and hence strongly influence earthquake processes.

Scientific drilling is the only way to directly determine ambient conditions and measure physical and chemical properties within active fault zones [8](#_ENREF_8). Drilling studies have taken place in response to Mw 6.9 to 9.0 earthquakes in Japan, Taiwan, China and USA [8](#_ENREF_8),[10-12](#_ENREF_10),[18-21](#_ENREF_18), and the results do not reveal anomalous temperatures or fluid pressures (Figure 1). Borehole injection experiments, earthquake aftershock studies, and laboratory experiments on fault zone materials reveal that the earthquake process perturbs the fault zone, which then heals during the post-seismic period [22-26](#_ENREF_22" \o "Kitagawa, 2007 #22).

The Alpine Fault of southern New Zealand is a major plate boundary fault (Figure 1) that produces large earthquakes every 291 ± 23 years and last ruptured in AD 1717 [4](#_ENREF_4),[5](#_ENREF_5). It has a Quaternary oblique dextral-reverse slip rate of 26±5 mm/yr [27](#_ENREF_27). The oblique dextral-reverse slip has exhumed a suite of fault rocks from depths of 30 km in the past few million years [27](#_ENREF_27). The primary motivation of the Deep Fault Drilling Project (DFDP) is to understand ambient conditions, rock properties, and geophysical phenomena immediately before a large earthquake, because initial conditions affect earthquake nucleation, rupture, and seismic radiation; and little is known about active geological faults before they slip.

Drilling of the DFDP-2B borehole was completed on 8 December 2014. We penetrated a sequence of Quaternary gravel and lake silt, schist, protomylonite, and mylonite (Figure 2). The base of the borehole is estimated to be within 200–400 m of the principal-slip-zone gouge, based on site surveys and measurement of quartz grain sizes and textures 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 gradient of 100–200°C/km, and a deeper zone with a gradient of 30–50°C/km (Figure 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), meaning that the silts do not constitute a total hydraulic seal (Figure 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 [2](#_ENREF_2) (Figure 1). Values exceeding 80°C/km are typically associated with volcanic regions, 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 [28](#_ENREF_28).

We model the thermal state near DFDP sites by considering simultaneous heat transport via (1) conduction, (2) rock advection driven by fault slip, and (3) fluid advection driven by local topography (Figure 3). We assume 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 are the value of high 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 [27](#_ENREF_27). Drilling-related temperature anomalies are modelled separately and excluded from our analysis by selecting observations made >6 months after drilling (Extended DataFigures 1 & 2). There is little variability in thermal diffusivity within the borehole (Extended Data Figure 3). The 3D model domain (Extended Data Figure 4) is much larger than the specific region of interest. See Methods for details.

We aim to fit temperature observations from DFDP-2B (Figure 2) and the geothermal gradient of 62±2°C/km measured in the 150 m-deep DFDP-1B borehole (Figure 3)[29](#_ENREF_29). 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 (Extended Data Figure 5). The relatively low average curvature of the thermal profile, combined with the over-simplified hydrological structure, leads to an inference that rock advection and thermal diffusion are the primary heat transport mechanisms at 240–740 m depth in DFDP-2B; 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 >5×10–16 m2 (Extended Data Figure 5). The DFDP-2B fluid pressure gradient indicates upward flow through the fractured rock mass near the borehole (Figure 2A).

The models 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 [29](#_ENREF_29), 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 [30](#_ENREF_30). The region of relatively-low geothermal gradient at the base of DFDP-2B (Figure 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 m2 (Extended Data Tables 1 & 2). 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 (Figure 3).

Our results have broad implications for understanding earthquakes and fault zone geology, because temperature and fluid pressure anomalies inferred close to the principal slip zone are significant. Lateral changes in temperature and fluid pressure may be >50°C and >4 MPa, respectively (Figure 3D), and this must affect chemical, mineralogical, and seismogenic processes. Our models predict considerable along-strike variations in the depth of smectite alteration (<100–175°C), which may influence dynamic fault strength at shallow depths during earthquakes. In some hanging-wall valley locations, our models predict pore fluid temperatures could exceed 200°C at only 1 km depth, and nearby potential drill sites could sample the principal slip zone beneath smectite alteration. Large along-strike temperature anomalies cause pore fluid density and viscosity variations that influence fluid-rock interactions and provide a mechanism for deeper fluid convection, even though heat transport by fluids in low-permeability deeper rocks may be minor. Mineralogical evidence from near the Alpine Fault confirms that boiling occurs in the upper and mid-crust [31](#_ENREF_31) and that meteoric fluids circulate through the entire seismogenic zone [32](#_ENREF_32).

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# Author contributions

The drilling experiment and this paper were led by Sutherland, Townend, and Toy. Thermal and hydraulic models and pre-drill planning: Upton, Coussens, Woodman, Teagle, Menzies, Hartog. All authors except Broderick, Woodman and Teagle contributed to science goals on-site during drilling. Post-drill optical fibre temperature measurements and analysis: Sutherland, Broderick, Capova, Chamberlain, Baratin, Hartog.

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# Figure legends

**Figure 1.**  (A) Geothermal gradient measured in DFDP-2B compared to global continental measurements (black curve) and previous active fault drilling measurements (circles) (International Heat Flow Commission, v. 2010). (**B**) Location on the Australia-Pacific tectonic plate boundary of borehole DFDP-2B at 43.29065°S (WGS84), 170.40646°E, with local depth datum at 94.84 m (NZGD2009).

**Figure 2.** DFDP-2B borehole results. (A) Observed mean temperature 7-14 months after drilling (solid line; Source Data); and equilibrated fluid pressure estimates (circles) determined from mud pressure equilibration experiments carried out during breaks in drilling (Extended Data Table 1). (B) Temperature gradient and inferred locations of aquifers and aquitards. (C) Geological summary.

**Figure 3.** Thermal and fluid flow models. (A) DFDP-1 and DFDP-2 locations (marked 1 and 2, respectively), the Alpine Fault, and topography. The hanging wall is Mesozoic amphibolite facies meta-greywacke, with a transition through protomylonite to mylonite to cataclasite in proximity to the principal slip zone [27](#_ENREF_27). The foot wall is composed of Paleozoic granitoids that intrude quartzose metasediments. (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 (Extended Data Figure 4). Parameters for model shown are: (1) dip-slip rate of 8 mm/yr; and (2) uniform permeability of 5.0×10–16 m2 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 illite-smectite transitions (100–175°C).

# Methods

Temperature observations were made using wireline logging tools before borehole completion, and an optic-fibre cable after completion. The optic-fibre cable was installed and cemented outside steel casing, and interrogated by distributed temperature sensing (DTS) analysis based on Raman scattering of laser light from a source at the surface [33](#_ENREF_33). A summary of temperature measurements is shown in Extended Data Figure 1.

Details of drilling operations, scientific equipment and protocols are published elsewhere [34](#_ENREF_34) and the borehole geometry is provided in a supplemental data file. Drilling ended on 8 December 2014 and steel casing was cemented on 17 December 2014. Residual cement was drilled out from within casing to 400 m depth on 8 January 2015 (<4 hours operations).

Temperatures measured by logging tools were influenced by the history of drilling fluid circulation in the borehole, but this drilling-related temperature anomaly diffused away and was small (c. 1°C) by January 2015. There is a high level of repeatability between later measurements (Extended Data Figure 2), and the very small temperature variation of c. 0.3°C observed between March 2015 and February 2016 is not converging exponentially on a single value with time. We interpret these changes to represent a non-drilling-related phenomenon. The supplemental data table contains an average value of the four latest profiles, which were measured between July 2015 and February 2016 and are not affected by borehole operations. Observed thermal equilibration times of several weeks are consistent with the bulk thermal diffusivity profile in the borehole that was inferred from mineralogical analysis of rock cuttings (Extended Data Figure 3).

Pore fluid pressure values (Figure 1) were derived from analyses of mud level equilibration during breaks in drilling. Equilibrium borehole hydraulic heads were estimated at a range of borehole lengths (Extended Data Tables 1 and 2). These observations were modeled with an exponential function (R2 >0.93 for all tests) by adjusting three parameters: initial mud level perturbation, decay constant, and equilibrium mud level, *M*. Hydraulic head, *H*, was then calculated using the measured mud density, *D,* and the vertical length of the borehole at the time of the test, *L*, using the equation *H = D(L+M) – L*.

Thermal and hydrological models were constructed and solved using FLAC3D (finite difference method, Itasca Consulting Group) and FEFLOW (finite element method, MIKE Powered by DHI). The numerical solution was computed in two steps. In the first step, a 2D crustal exhumation model, similar to previous geodynamic models that predict localization of slip on the Alpine Fault [35](#_ENREF_35), was simulated using FLAC3D to 30 km depth for 10 Ma. The rate of dip-slip movement was treated as a variable parameter. The 2D result was then used to apply a basal temperature boundary condition to a 3D model with topography (Extended Data Figure 4; FLAC3D and FEFLOW solutions). No-flow boundary conditions were applied for fluid and heat at the sides of the model. At the basal surface, a no-fluid-flow condition was imposed. An atmospheric temperature and pore pressure condition was applied at the top surface. A low permeability of 10–18 m2 was imposed beneath the fault. The heat equation solved is   
*∂T/∂t = H/Cb + κb*∇⋅∇*T − (Cf /Cb )***u***f* ⋅∇*T − (Cr /Cb )***u***r* ⋅∇*T = 0 ,*where *H* is internal heat productivity, *κb* is bulk thermal diffusivity, *T* is temperature, *Cf* , *Cr* and *Cb* are volumetric heat capacities of fluid, rock, and the bulk mixture, respectively, **u***f* and **u***r* are vector fluxes of fluid and rock respectively, and ∇ = (*∂/∂x, ∂/∂y, ∂/∂z)* is the gradient operator.

Uniform permeability above the fault was treated as a variable parameter. In initial simulations using FLAC3D the permeability extended to 5 km below sealevel (bsl). A hanging-wall permeability of (5.5±2.0)×10–16 m2 and a fault dip-slip rate of 7.7±2.7 mm/yr produced an adequate fit to DFDP-2 observations, but with a strong trade-off between the two parameters: faster dip-slip rates require lower permeabilities. Model runs were then completed using FEFLOW with uniform permeability to 3 km bsl and temperature-dependent fluid density. Results are shown in Extended Data Figures 5, 6, and 7. Because density was temperature-dependent in FEFLOW model runs, we report hydraulic conductivity (factor of c. 10-7 conversion in near-surface).

We did not limit fluid recharge rate or allow the piezometric surface to adjust. If we had, then even higher values of permeability could fit our data and may be more realistic: the piezometric surface and lateral fluid pressure gradients would be lowered. It is likely that permeability is both anisotropic and localized e.g. within and near the damage zone, along lithologic layers, or within fractured zones. However, such models are under-constrained by observations, so were not constructed. Minor faults may also create local seals that compartmentalize flow.

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# Data figure and table legends

**Extended Data Figure 1**. Borehole temperature measurements taken on successive dates (grey lines by logging tools, colour lines by DTS).

**Extended Data Figure 2**. Enlargement of borehole temperature measurements to show magnitude of DTS temperature changes with time.

**Extended Data Figure 3**. Bulk mean thermal diffusivity profile for borehole DFDP-2B inferred from quantitative x-ray diffraction analysis of rock cuttings (geometric mean of mineral-specific diffusivities).

**Extended Data Figure 4**. 3D model mesh geometry with variable node spacing of 200, 500, or 1000 m.

**Extended Data Figure 5**. Fit of FEFLOW models to observations at DFDP-2B by varying parameters of uniform hanging-wall permeability to 3 km bsl, and variable dip-slip rate on the Alpine Fault. White dots indicate the parameter combinations of specific models.

**Extended Data Figure 6**. Temperature profiles predicted by models (colour) compared to observations at DFDP-2B (black).

**Extended Data Figure 7**. Shallow temperature gradient predicted by models at DFDP-1B. Note that the temperature gradient may be slightly over-estimated by the model, because local fault curvature is not accurately resolved by our model and the DFDP-1B location is placed slightly farther into the base of the hanging-wall in the model than it is in reality.

**Extended Data Table 1.** Pore fluid pressure head, *H,* determined from borehole length, *L*, equilibrium mud level, *M*, and mud density, *D*. Estimated standard errors are labelled using the symbol *S*. Mud levels and hydraulic heads are relative to the local ground surface.

**Extended Data Table 2.** Mean pore fluid pressure heads, *H,* and standard errors, *SH*, determined for each borehole length, *L,* and true vertical depth, *TVD*. See data in Extended DataTable 1. Hydraulic heads are relative to the local ground surface.

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