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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 earthquakes1. Typical intraplate continental crust has hydrostatic fluid pressure and a near-surface thermal gradient of 31 ± 15 degrees Celsius per kilometre3,4. At temperatures above 300–450 degrees Celsius, usually found at depths greater than 10–15 kilometres, the 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 temperature and fluid pressure data from active plate-bounding faults. Here we report results from a 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 in the coming decades4,5. The borehole (depth 893 metres) revealed a pore fluid pressure gradient exceeding 9 ± 1 per cent above hydrostatic levels and an average geothermal gradient of 125 ± 55 degrees Celsius per kilometre within the hanging wall of the fault. These extreme hydrothermal 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 highly anomalous fluid pressure and temperature gradients in the upper part of the seismogenic zone can be created by positive feedbacks between processes of fault slip, rock fracturing and alteration, and landscape development at plate-bounding faults.

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 strengths9. Laboratory measurements for many natural rocks have a similar (Byerlee) range of frictional strengths6. 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 friction7. There is mounting evidence that this is true for many faults8.

The lack of noticeable heat flow anomalies adjacent to large plate boundary faults, most famously the San Andreas Fault9, 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 Tohoku-Oki 2011 earthquake (moment magnitude Mw = 9.0) produced only a small temperature anomaly, requiring an average friction coefficient during slip of <0.1 (ref. 10); similar results were found after the Wenchuan 2008 and Chi-Chi 1999 earthquakes11,12. Plate boundary faults must, therefore, be composed of materials that are mechanically weak on long timescales, even if weakness is a transient phenomenon during movement. Brittle fault rocks form within the seismogenic zone via the physical comminution of rock and via 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 debated13–15. The evolution of the coefficient of friction on a fault surface during and after an earthquake is time-dependent15. Of particular importance is the stability of phyllosilicate phases with low dynamic friction16, thermal expansion and the generation of physicochemical reaction products produced during slip17, and the presence of low-permeability mineral cements.
that enhance dynamic fluid pressurization mechanisms. Temperature and fluids within fault zones are primary controls on material properties and slip-weakening mechanisms, and hence they strongly influence earthquake processes.

Scientific drilling is the only way to determine ambient conditions directly and to measure physical and chemical properties within active fault zones. Drilling studies have taken place in response to earthquakes of $M_w = 6.9–9.0$ in Japan, Taiwan, China and the USA, and the results do not reveal anomalous temperatures or fluid pressures. 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.

The Alpine Fault of southern New Zealand is a major plate boundary fault (Fig. 1) that produces large earthquakes every 291 ± 23 years and last ruptured in AD 1717. It has a Quaternary oblique dextral-reverse slip rate of 26 ± 5 mm yr$^{-1}$. The oblique dextral-reverse slip has exhumed a suite of fault rocks from depths of 30 km in the past few million years. 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 little is known about active geological faults before they slip, experiments carried out during breaks in drilling (Extended Data Tables 1 and 2).

Figure 1 | Global context and regional setting. a, Geothermal gradient measured in DFDP-2B compared to global continental measurements (black curve) and previous active fault drilling measurements (circles). Data are taken from the Global Heat Flow Database of the International Heat Flow Commission, version 2010, http://www.heatflow.und.edu. SAFOD, the San Andreas Fault Observatory at Depth, USA; TCDP, the Taiwan Chelungpu-Fault Drilling Project; WFSD, the Wenchuan Earthquake Fault Scientific Drilling, China. b, Location on the Australia-Pacific tectonic plate boundary of borehole DFDP-2B at 43.29065° S (WGS84 datum), 170.40646° E, with local depth datum at 94.84 m (NZGD2009 datum).

Figure 2 | DFDP-2B borehole results. a, Observed mean temperature 7–14 months after drilling (solid line; see Source Data for this figure online); and equilibrated fluid pressure estimates (circles, error bars show two standard errors) determined from mud pressure equilibration experiments carried out during breaks in drilling (Extended Data Tables 1 and 2). b, Temperature gradient and inferred locations of aquifers and aquitards. c, Geological summary. Source Data for Fig. 2 is available online.
and initial conditions are assumed to affect earthquake nucleation, rupture and seismic radiation. 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 (Fig. 2). The base of the borehole is estimated to be within 200–400 m of the principal slip-zone gouge, on the basis of 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 (that is, downhole geophysical), 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 of true vertical depth (740 m drilled depth) characterized by a gradient of 100–200 °C km⁻¹, and a deeper zone with a gradient of 30–50 °C km⁻¹ (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), meaning that the silts do not constitute a total 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 less than 80 °C km⁻¹ (ref. 2; Fig. 1). Values exceeding 80 °C km⁻¹ 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 about 30 °C km⁻¹ (ref. 28).

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Fig. 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 is important in heat transfer between sites and also requires a regional value of permeability >5 × 10^-16 m² (Extended Data Fig. 5). The DFDP-2B fluid pressure gradient indicates upward flow through the fractured rock mass near the borehole (Fig. 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 spays39, and that these cataclasites and spays will be barriers to fault-normal flow. We expect high permeability within the damage zone, producing an aquifer that enhances fault-parallel flow, and Bennett et al.31 and that meteoric fluids circulate through the damage zone. Evidence from near the Alpine Fault confirms that boiling occurs in the slip zone at temperatures above the smectite–illite transition. Large and nearby future boreholes could sample the Alpine Fault principal earthquakes in the continental crust of the United States. Geology 142, 1143–1146 (2012).


12. Li, H. et al. Long-term temperature records following the Mw 7.9 Wenchuan (China) earthquake are consistent with low friction. Geology 43, 163–166 (2015).


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Author Contributions The drilling experiment and this paper were led by R.S., J.T. and V.T. Modelling and borehole drilling were done by P.U., J.C., N.W., D.T., C.M. and A.H. All authors except N.G.R.B., N.W. and D.T. contributed to science goals on-site during drilling. Post-drill optical fibre temperature measurements and analysis were performed by R.S., N.G.R.B., L.J.-C., C.C., L.-M.B. and A.H.

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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\(^{35}\). A summary of temperature measurements is shown in Extended Data Fig. 1.

Details of drilling operations, scientific equipment and protocols are published elsewhere\(^{33}\) and the borehole geometry is provided in the Source Data for Fig. 2. Drilling ended on 8 December 2014 and the steel casing was cemented on 17 December 2014. Residual cement was drilled out from within the casing to a depth of 400 m depth on 8 January 2015 (<4 h 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 (about 1 °C) by January 2015. There is a drilling fluid circulation in the borehole, but this drilling-related temperature boundary condition to a three-dimensional model with topography (Extended parameter. The two-dimensional result was then used to apply a basal temperature localization of slip on the Alpine Fault\(^{35}\), was simulated using FLAC3D to a depth of 5 km below sea level. A hanging-wall permeability of \((5.5 \pm 2.0) \times 10^{-16} \text{ m}^2\) and a fault dip-slip rate of \(7.7 \pm 2.7 \text{ mm yr}^{-1}\) 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 below sea level and temperature-dependent fluid density. Results are shown in Extended Data Figs 5, 6 and 7. Because density was temperature-dependent in FEFLOW model runs, we report hydraulic conductivity (factor of about \(10^{-2}\) conversion at the 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, for example, 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.

Data availability. Data that support the findings of this study are available as Extended Data Tables 1 and 2 and Source Data for Fig. 1. Additional relevant data (for example, individual temperature logs shown in Extended Data Fig. 1) will be made available online\(^{35}\), in forthcoming publications, or data are available from the corresponding author upon reasonable request.

Extended Data Figure 1 | Borehole temperature measurements taken on successive dates (year/month/day). Grey lines indicate measurements using logging tools; coloured lines those taken using DTS.
Extended Data Figure 2 | Enlargement of borehole temperature measurements, showing that the magnitude of DTS temperature changes with time.
Extended Data Figure 3 | Bulk mean thermal diffusivity profile for borehole DFDP-2B. Data inferred from quantitative X-ray diffraction analysis of rock cuttings (geometric mean of mineral-specific diffusivities).
Extended Data Figure 4 | Three-dimensional model mesh geometry with variable node spacing of 200 m, 500 m or 1,000 m.
Extended Data Figure 5 | Fit of FEFLOW models to observations at DFDP-2B by varying parameters. Variable parameters are the (uniform) hanging-wall permeability to 3 km below sea level, and the dip-slip rate on the Alpine Fault. White dots indicate the parameter combinations of specific models. RMS, root mean square.
Extended Data Figure 6 | Temperature profiles predicted by models (colour) compared to observations at DFDP-2B (black). (m asl, metres above sea level.)
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, $D$

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$S_M = 0.05$ m.

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, $S_H$, determined for each borehole length, $L$, and true vertical depth, TVD

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See data in Extended Data Table 1. Hydraulic heads are relative to the local ground surface.