Article

A window into thousands of earthquakes:
Results from the Deep Fault Drilling Project (DFDP)

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In 1941, two geologists, Harold Wellman and Richard Willett, traversed the length of Westland, mapping what would become one of the most influential continental faults in the world, New Zealand's Alpine Fault (Wellman & Willet 1942). The Alpine Fault strikes down the western edge of the Southern Alps, a youthful mountain range on New Zealand's South Island (Fig 1). Here, collision between the Australian and Pacific Plates forms peaks over 3000 m in elevation which trap rain-laden clouds, resulting in 5–15 m of precipitation a year in central and south Westland. Driven by gravity, the rain and snow migrate into fractures and voids along the Alpine Fault, becoming heated and saturated with reactive ions along the way. Within the fault zone, these fluids play a fundamental role in the processes that drive earthquake nucleation and rupture propagation. Measurements made, and rocks recovered, from boreholes drilled during phases one and two of the Deep Fault Drilling Project (DFDP) have enabled scientists to document and quantify these processes for the first time.

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Background

The Alpine Fault is an 850 km-long plate boundary fault that represents the largest known onshore seismic hazard in New

Carolyn Boulton is a Royal Society of New Zealand Rutherford Postdoctoral Fellow at Victoria University of Wellington. Carolyn was awarded a PhD from the University of Canterbury in 2014, and she spent three years at the University of Liverpool as a Postdoctoral Research Associate. She participated on-site during DFDP-1 and DFDP-2 drilling. Her academic research focuses on experimental rock deformation, physical controls on earthquake cycle processes, and geochemical and microstructural indicators of deformation and fluid flow. She has either authored or co-authored fourteen publications on the Alpine Fault.

Lucie Janku-Capova did her MSc in Applied Geophysics at Charles University in Prague, Czech Republic. She is currently completing her PhD at Victoria University of Wellington. Her PhD thesis research has involved participating on-site during DFDP-2 drilling, post-drilling temperature monitoring, and laboratory measurements. Lucie's research uses temperature measurements from the DFDP-2B borehole to identify groundwater flow through fractures and the thermal properties of deformed rocks; together, these datasets are being used to help quantify the overall heat budget in the central Southern Alps.

Jack Williams has a PhD from the University of Otago, during which he investigated fracture damage induced by Alpine Fault earthquakes. As a part of his PhD research, Jack participated on-site during DFDP-2 drilling and in detailed analysis of DFDP-1 cores and downhole images. In addition to Alpine Fault research, he has worked on factors that may allow deformation to localise in the mid-crust (depths 10–20 km), and he contributed to recording the unusually complex surface ruptures that were generated by the 2016 Kaikoura Earthquake.

Jamie Coussens has an MSc in Earth Sciences from Oxford University and recently submitted his PhD thesis at the National Oceanography Centre at the University of Southampton. Jamie's PhD research used models of fluid and heat flow in the Southern Alps to understand how hot fluids modulate the Alpine Fault's seismic cycle. He participated on-site during DFDP-2 drilling and is well known for his dedication to obtaining borehole measurements through rain and gale-force winds.

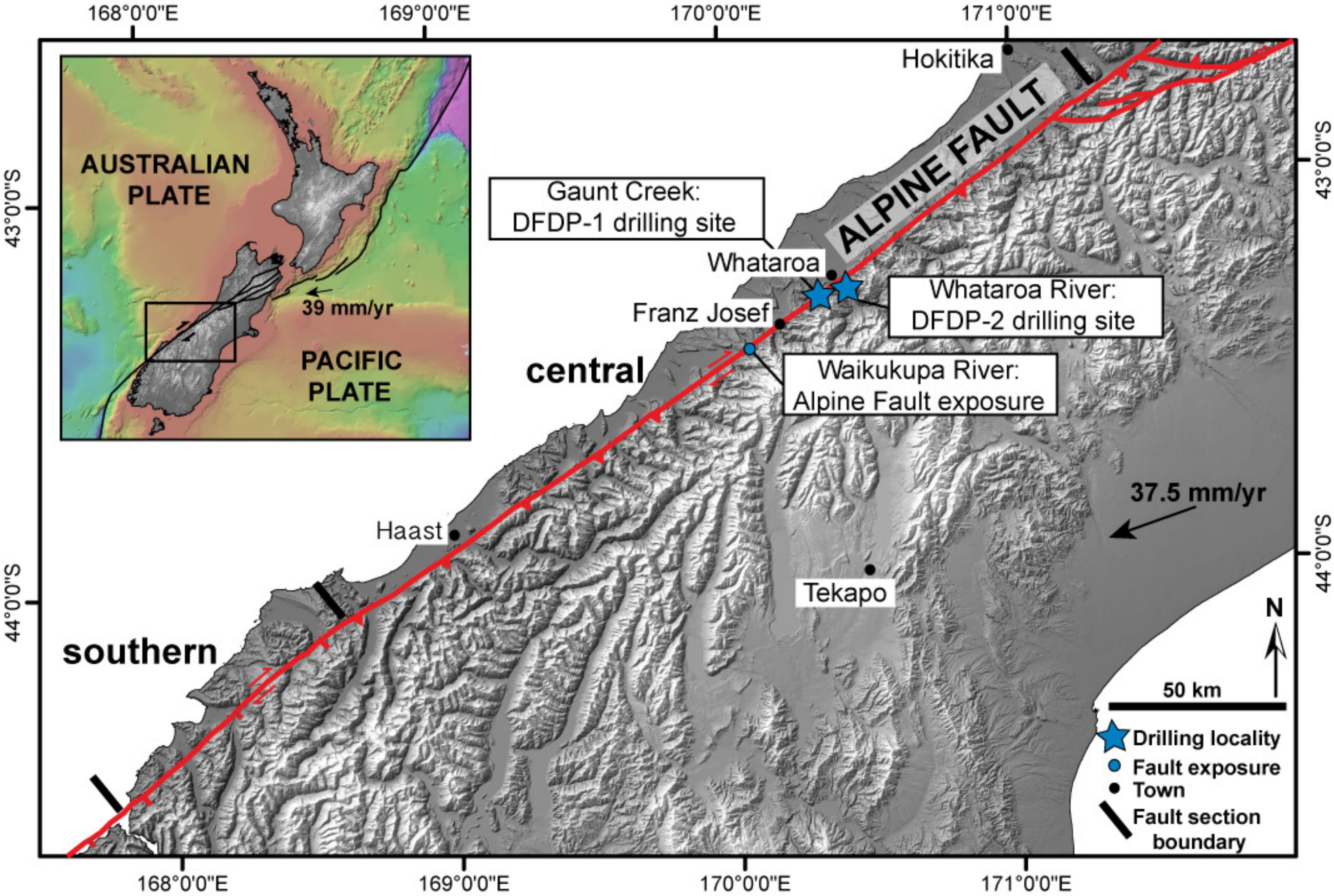

Figure 1. The tectonic setting of New Zealand's South Island, which sits astride the Australian and Pacific Plates (inset). The larger greyscale map is a digital elevation model (DEM) that depicts the trace of the Alpine Fault along with the location of the Deep Fault Drilling Project boreholes at Gaunt Creek and the Whataroa River (blue stars). On the DEM, the boundary between the southern and central Alpine Fault is shown by bold black lines (after Boulton *et al*. 2017a).

Zealand (Fig 1). Years before the advent of plate tectonic theory, Harold Wellman recognised that the Alpine Fault displaces once-contiguous basement rocks in Nelson and Otago by 480 km (Wellman 1953). Today, through the work of Wellman, Evison, Norris, and many others, we know that displacement along the fault occurs during large earthquakes ($M_w \approx 7$–8) that repeat cyclically every 200–400 years as a result of relative motion between the Australian and Pacific Plates (Evison 1971; Norris & Cooper 2007; Berryman *et al.* 2012; Cochran *et al.* 2017). Since the last Alpine Fault earthquake occurred in 1717 CE, current estimates suggest that there is around a 30% probability of an Alpine Fault earthquake in the next 50 years (Cochran *et al.* 2017).

The earthquake cycle is a theoretical framework used by earth scientists to describe the repeating processes of tectonic stress accumulation between earthquakes and stress release during earthquakes (Fig 2). On time-scales of decades to centuries between earthquakes (the 'interseismic period'), the crust surrounding a fault accumulates elastic strain and the driving stresses acting on the fault increase. When the driving stresses exceed the frictional strength of the fault, the stored elastic strain energy is released on time-scales of milliseconds to minutes in the form of an earthquake (the 'coseismic period'). Earthquakes force the fault to slip, fracture rocks around the fault, and generate seismic waves (e.g. Reid 1910; Scholz 2002). After an earthquake (during the 'postseismic period'), any remaining energy is gradually released during smaller earthquakes ('aftershocks'), whose magnitudes decrease with time (e.g. Scholz 2002).

The green fractured rocks exposed in large landslides and warm springs emanating upslope from these crush zones have long hinted at the crucial role fractures and fluids play in the processes that govern the Alpine Fault's earthquake cycle (e.g. Barnes *et al.* 1978; Koons *et al.* 1998; Norris & Cooper 2007).

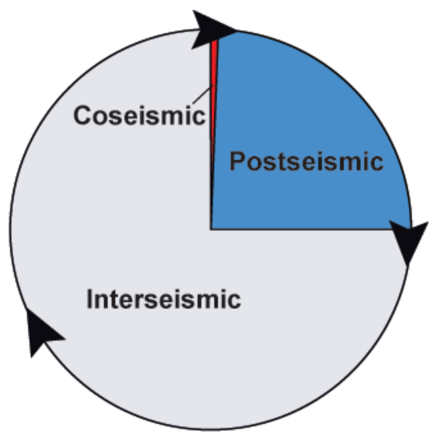

Figure 2. Schematic figure of the earthquake cycle, wherein the process of interseismic strain accumulation and tectonic stress build-up is repeatedly followed by earthquake nucleation and coseismic slip. Coseismic slip often promotes large-scale fluid migration and stress re-adjustments, which can trigger aftershocks in the postseismic period; this phase of the Alpine Fault's earthquake cycle is still poorly understood.

Ongoing uplift has exhumed deformed rocks from around 35 km depth, giving earth scientists the opportunity to study the origins of Alpine Fault earthquakes (e.g. Little *et al.* 2005). However, until recently, poor exposure in the forested terrane had kept researchers from gathering the measurements and continuous rock record necessary to quantify physical processes at work in the 'earthquake factory' beneath the Southern Alps. The first two phases of the Deep Fault Drilling Project (DFDP), in 2011 and 2014, drilled, sampled, and monitored the Alpine Fault to better understand earthquake cycle processes.

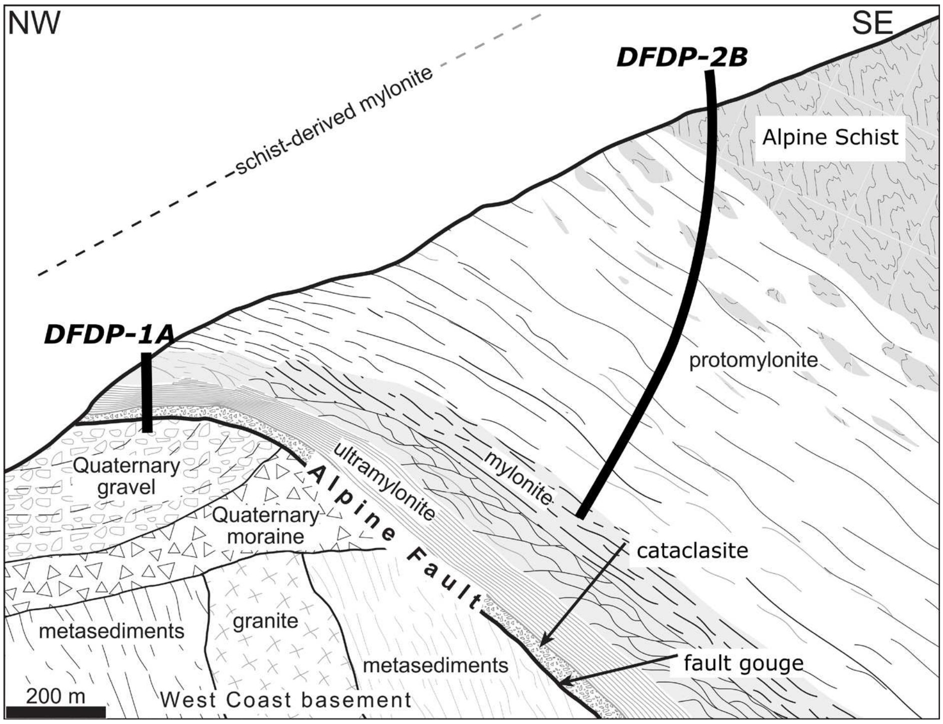

Figure 3. A simplified cross-section of the central Alpine Fault, which accommodates both strike-slip and thrust (top-to-the-northwest) movement. Thrusting brings Pacific Plate rocks deformed at high temperatures and pressures (such as schists, protomylonites, mylonites, and ultramylonites) to the surface more rapidly than they cool. In the brittle part of the fault, the exhuming schists and mylonites are broken up and altered by fluids, forming cataclasites, breccias, and gouges. Sometimes, so much heat is generated during an earthquake that the rocks melt and form pseudotachylytes. Thick, bold lines schematically show the sequences of rocks sampled in DFDP-1 and DFDP-2 (after Norris & Cooper 2007).

Deep Fault Drilling Project Phases 1 and 2

Phase 1 of the Deep Fault Drilling Project occurred in January and February 2011 when two boreholes were drilled at Gaunt Creek, about 20 km northeast of Franz Josef Glacier (Cooper & Norris 1994) (Fig 1). The two vertical boreholes were drilled to depths of 100.6 m (DFDP-1A) and 151.4 m (DFDP-1B) and yielded the first continuous set of rock cores and geophysical measurements from the Pacific Plate to the Australian Plate through the Alpine Fault (Fig 3). In addition, *in situ* measurements of fluid flow in and around the fault were made, and an observatory was installed to provide long-term monitoring of temperatures, fluid pressures and chemistry, and seismic activity near the fault (Sutherland *et al.* 2012; Townend *et al.* 2013; Toy *et al.* 2015).

During Phase 2 of the Deep Fault Drilling Project, initial (DFDP-2A, 212.6 m depth) and primary (DFDP-2B, 893.2 m depth) boreholes were drilled in late August to December 2014. Situated on the banks of the Whataroa River, about 5 km southeast of Whataroa township, DFDP-2 boreholes intersected sediments and fault rocks entirely within the Pacific Plate (*Front cover*; Figs 1, 3). Achieving the original goal of drilling through the Alpine Fault, into the Australian Plate, proved impossible due to technical problems (Sutherland *et al.* 2015). Nevertheless, outstanding geophysical measurements were obtained in DFDP-2B using downhole sensors and geochemical and hydrological indicators of fluid flow within the borehole. Data collected from DFDP-2B complemented results from DFDP-1 and highlighted the intriguing interplay between fluids and fractures in rocks just above the plate-boundary contact (Sutherland *et al.* 2017).

Alpine Fault rocks are exhumed from mid-crustal depths more rapidly than they can cool (e.g. Koons 1987; Little *et al.* 2005; Beyssac *et al.* 2016). As a result, fluids migrating through the uplifted fault rocks are heated and forced to the surface by the combined effects of topography and fault zone structure (e.g. Koons *et al.* 1998; Menzies *et al.* 2014, 2016; Sutherland *et al.* 2017). Along their flow paths, the variably heated fluids play a critical role in: (1) controlling the type and abundance of minerals present, (2) governing the strength of the fault when it slips during an earthquake, and (3) re-strengthening the fault after a slip event. Fluids play such diverse roles because of their ability to both dissolve and precipitate minerals *and* become pressurised when confined within layers of rock. Recent insights into these earthquake cycle processes are described further below.

Borehole measurements

Measurements made within DFDP boreholes provide fundamental information on the fluid flow and temperature regimes around and within the Alpine Fault (Fig. 4). In contrast to laboratory measurements, which are typically made on small (cm-sized) rock samples, borehole measurements reflect system-scale processes, meaning that the integrated effects of topography, fracture sets, and different rock types can be quantified. Downhole measurements of permeability* in DFDP-1B returned a fascinating result: within the borehole – and in the laboratory – plate-boundary contact materials have the same low permeability (Boulton *et al.* 2012; Sutherland *et al.* 2012; Carpenter *et al.* 2014). At Gaunt Creek, permeability decreases up to 6 orders of magnitude within a few tens of metres of the plate boundary, reaching extremely low values at the contact with the Australian Plate. These low values indicate that most open spaces within Alpine Fault rocks immediately above the plate boundary, from the cm-scale to the km-scale, have been sealed, inhibiting fluid movement. Furthermore, fluid movement

*Permeability is a measure of the ease with which a fluid (or gas) moves through a medium: the lower the permeability, the more slowly this migration occurs.

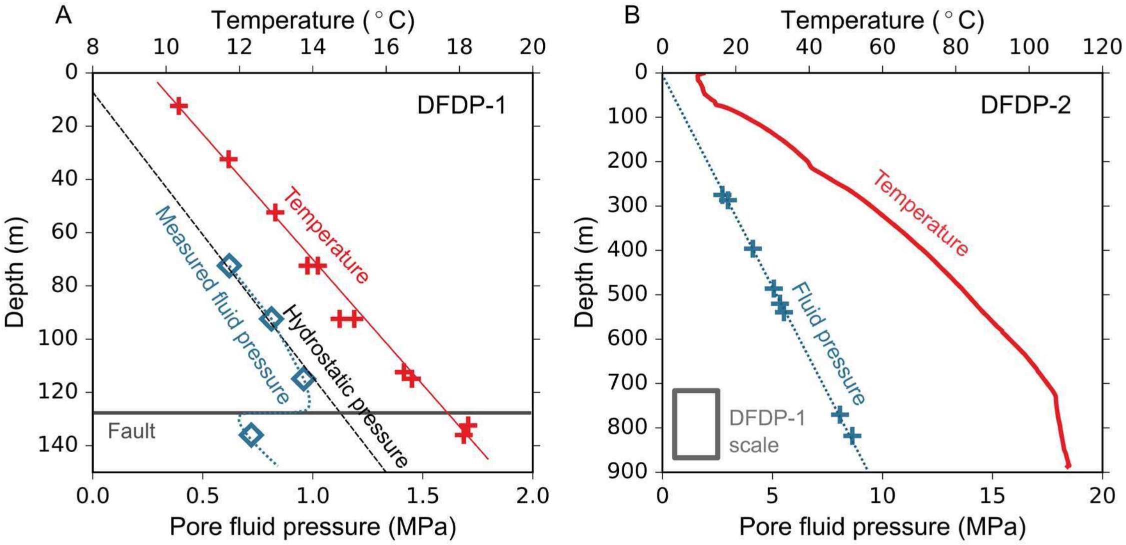

Figure 4. Temperature and pressure measurements from DFDP-1B and DFDP-2B boreholes. (a) DFDP-1B is a shallow borehole drilled through the damage zone of the fault at Gaunt Creek, a minor tributary to the Waitangi-taona River. In the DFDP-1B borehole, fault rock permeability is very low, and very little fluid movement is allowed. Therefore, temperature rises linearly with depth, as does the fluid pressure. Fluid pressure decreases within 20 m of the fault in rocks which have been almost completely sealed by clay and calcite precipitation, and pressure drops dramatically in the Australian Plate rocks below the fault. The line labelled 'hydrostatic pressure' is for reference. Hydrostatic fluid pressure is the pressure created by the weight of the volume of water at a given depth: a hydrostatically pressured fluid is in equilibrium. (b) In DFDP-2B, fault-related fractures are not sealed. Groundwater flows in great volumes and becomes overpressured as it is concentrated under the major Whataroa River valley (i.e. its pressure is greater than hydrostatic). The fluid pressure increases with depth more steeply than in DFDP-1B, and if the borehole was not cased and cemented, the pressurised fluid would have created a column of water 60 m high (similar to a geyser). The upward flow of water is also causing the concave shape of the temperature profile because the water is bringing heat with it. The bottom part of the borehole, where the temperature gradient suddenly drops from > 100°C/km to < 50°C/km, is probably associated with a 'reservoir' where water flows so vigorously that it gets mixed, effectively having almost the same temperature over a hundred metres (after Sutherland *et al.* 2012, 2017).

is particularly sluggish within the layer of clay-rich plate-boundary rocks called *gouges*, within which the slip occurs during earthquakes (Figs 3, 4, 5).

The DFDP-2B borehole penetrated rocks 1000 m to 100 m from the impermeable plate-boundary gouges (Fig 3). At these distances, fluids move rapidly through fault-related fractures that have not been sealed. Normally, thick layers of river sediments keep these pressurised fluids underground, but most keen locals know where they can dig a natural hotpool along a braided river. In DFDP-2B, keeping the fluids from overflowing at the wellhead was a significant drilling-related challenge. The high specific heat capacity of water makes it a very efficient medium for heat transport in the geological environment. Temperatures of fluids surrounding the fault, though, depend on their flow rate through the rocks and the amount of heat that is available to be transferred from the rocks themselves.

Scientists have often tried to calculate the temperature of the rocks surrounding the Alpine Fault. However, past attempts to model the geothermal gradient* differed markedly because of uncertainties related mainly to the influence of topography and fault zone permeability structure (e.g. Koons 1987; Allis & Shi 1995; Upton *et al.* 1995; Batt & Braun 1999). Accurate measurements of the geothermal gradient adjacent to the Alpine Fault were made for the first time in the DFDP-1B borehole, yielding a gradient of 62.6 ± 2.1°C/km (Sutherland *et al.* 2012). In the DFDP-2B borehole, temperature increases even more markedly between the surface and 700 m vertical depth (730 m drilled depth) by a gradient of 100–200°C/km. Below 700 m, the geothermal gradient decreases to 30–50°C/km. The extremely high gradient measured in DFDP-2B (125°C/km on average) is higher than 99% of all other deep boreholes in continental crust (Sutherland *et al.* 2017).

Revised models that combine these temperature measurements and our new understanding that the Alpine Fault forms an impermeable barrier to fluid flow show that: (1) hot upwelling fluids are concentrated into major river valleys (like the Whataroa River) on the West Coast, and (2) the average temperature of the fluids varies with depth along the length of the fault, in response to the changing style and rate of fault movement (Sutherland *et al.* 2017). Temperature is a major control on the way rocks accommodate deformation and the type of minerals that can form within a fault zone.

Rocks recovered

Mineralogy

Between Haast and Hokitika, the Alpine Fault accommodates over 70% of the total relative motion between the Australian and Pacific Plates (27 ± 5 mm/yr horizontally and 6–9 mm/yr vertically) (Norris & Cooper 2001, 2007; Beavan *et al.* 2010). This figure suggests that, compared to all the other faults in the Southern Alps, the Alpine Fault is relatively weak and mechanically efficient at accommodating tectonic motion. There are multiple reasons for the fault's relative weakness, including its longevity, geometric simplicity, and the high temperature of the rocks within it at depth (e.g. Koons 1987; Norris & Toy 2014). Earthquakes, however, only originate in the cooler portions of

*The geothermal gradient is a measure of how much temperature increases with depth below the surface of the earth, and stable continents generally have a geothermal gradient of 20 to 40 °C/km.

the fault at temperatures less than 350 to 450 °C. Here, the dominant fault-forming minerals quartz and feldspar cannot deform aseismically (*without earthquakes*) by ductile creep mechanisms (like worked metal in a forge) (Sibson 1977; Scholz 2002). Instead, deformation occurs frictionally. Frictional behaviour is usually characterised by a locked interseismic period, followed by a rapidly sliding coseismic period.

A special group of hydrous, platy minerals termed phyllosilicates (loosely called clays here) rarely become locked and instead relieve tectonic stress by sliding steadily due to the easily broken bonds between the platy mineral surfaces (e.g. Moore & Lockner 2004). When sufficient clay enrichment occurs, faults are weak, creep continuously, and accumulate less stored elastic strain energy. Thus, weak faults pose a lower seismic risk. In rock mechanics, 'weak' and 'strong' are adjectives used to denote how easily rocks break or slide when pressure is applied. A famous example of a weak, clay-rich creeping fault is the San Andreas Fault near Parkfield in California, USA (Hickman & Zoback 2004; Lockner *et al.* 2011).

Unlike the San Andreas Fault, the weakness of the Alpine Fault cannot be easily explained by an abundance of low-strength clay. Rocks recovered from the core of the Alpine Fault in DFDP-1 yielded an intriguing result: most rocks near the plate boundary are not markedly enriched in clay minerals relative to more distal portions of the fault zone (e.g. Boulton *et al*. 2017a). In fact, the frictionally weak clay montmorillonite only occurs within a narrow, <10 cm-wide, layer immediately adjacent to the Australian Plate (Fig. 5) (Boulton *et al*. 2012, 2014, 2017a; Schleicher *et al.* 2015). Montmorillonite is thermodynamically stable at temperatures less than 150°C, and it requires small reactive particles and fluids with the right chemistry to form. By the time it reaches the surface, the frictional part of the Alpine Fault has experienced between five and ten thousand earthquakes. However, because most of these earthquakes happen where the fault is hotter than 150°C, and the rocks are exhumed so quickly, the weak mineral montmorillonite does not have enough time to form. Instead, montmorillonite only exists in the near surface (upper ~2–4 km) and scarcely influences the interseismic behaviour of the fault zone, which has been completely locked during recorded history (e.g. Sutherland *et al.* 2007).

Earthquake-simulation experiments

In the past twenty years, scientists working in experimental rock deformation have developed extraordinary machines capable of simulating frictional sliding during earthquakes (e.g. Di Toro *et al.* 2011; Ma *et al.* 2014). Earthquake-simulation experiments were conducted on a complete suite of faulting-related rocks recovered from DFDP-1 boreholes (Boulton *et al.* 2017b). These experiments tested how Alpine Fault rocks would behave during an earthquake. During each experiment, powdered rocks were forced to slide at 1 m/s, typical of coseismic slip rates. Instruments recorded the rock's resistance to shear during the sliding, which can be converted into a friction coefficient*. Results showed that all Alpine Fault rocks tested, both wet and dry, have exceedingly low friction coefficients during earthquakes (Fig. 6). Low-permeability, water-saturated gouges containing montmorillonite exhibited the weakest behaviours because pressurised fluids within them are unable to escape during sliding. Planes containing these clay-rich gouges offer little resistance to slip during an earthquake, helping to explain the long history of large-displacement, surface-rupturing earthquakes observed on the Alpine Fault (e.g. Sutherland *et al.* 2007; Berryman *et al.* 2012; Cochran *et al.* 2017). The earthquake-simulation experiments also demonstrated another reason for the Alpine

*The coefficient of friction is a measure of the strength of a rock. Most rocks have a coefficient of friction in the range of 0.60 to 0.85.

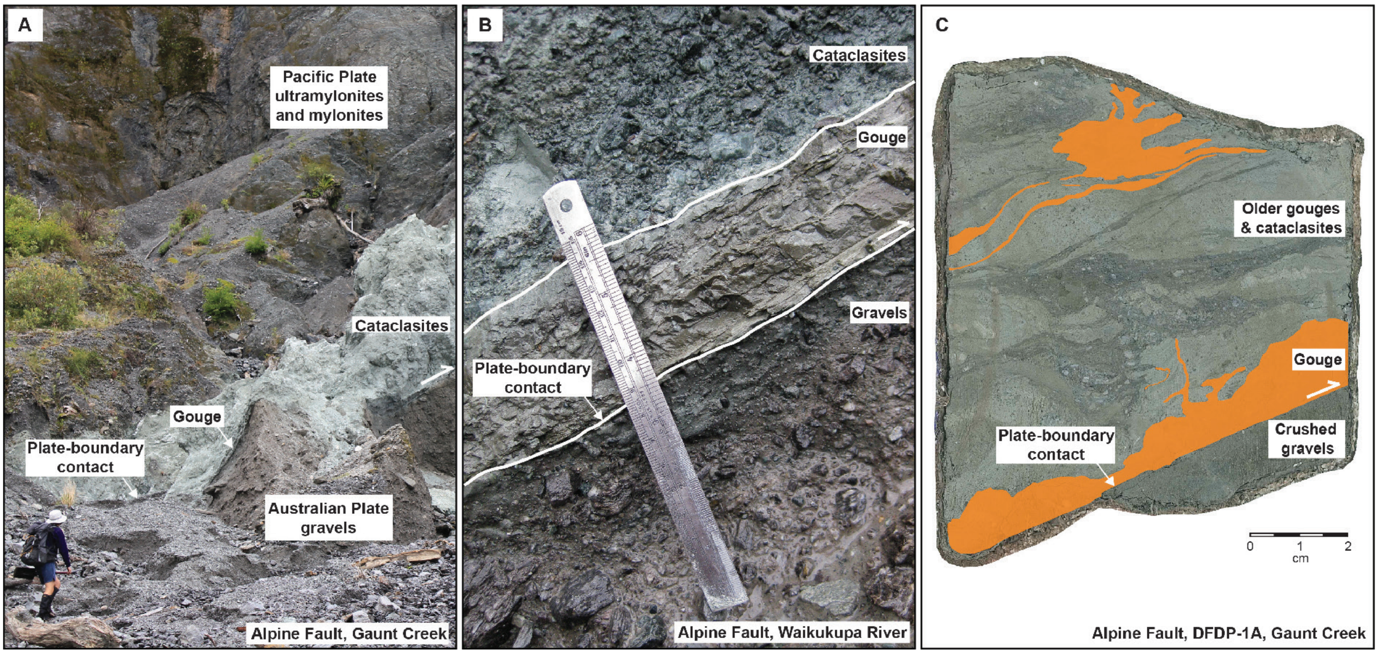

Figure 5. Images of Alpine Fault plate-boundary gouges. (a) The contact between exhumed Pacific-Plate mylonites, cataclasites, and gouges and Australian Plate gravels exposed in a scarp at Gaunt Creek (figure for scale). (b) The same contact exposed in a scarp at the Waikukupa River. The brown-coloured gouges at the plate-boundary contain the weak mineral montmorillonite (ruler for scale). (c) In DFDP-1A drill core, multiple generations of gouges containing montmorillonite are seen (shaded in orange). Older generations are deformed in the rocks above the plate-boundary contact. The most recent generation occurs as a thin layer along the boundary. The orientation of all images is southeast–northwest (L–R) (figures a and b after Boulton *et al.* 2012).

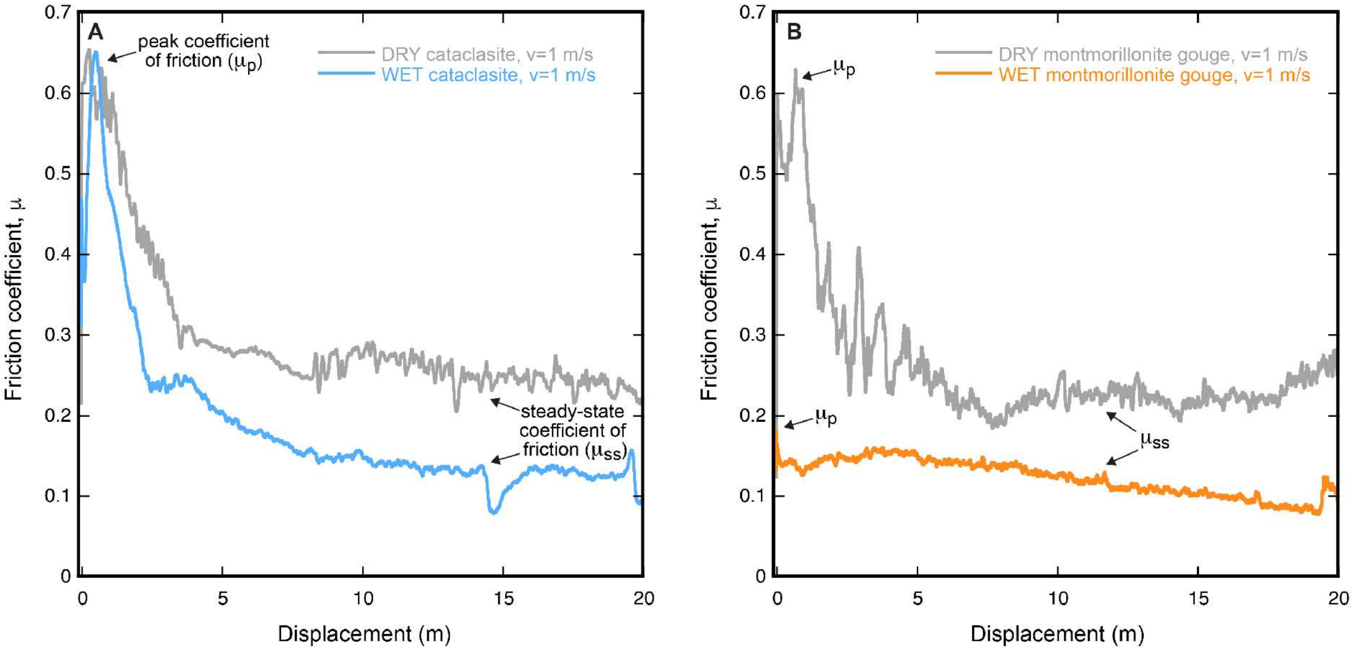

Figure 6. Earthquake-simulation experiment results show the extraordinarily weak frictional behaviour of Alpine Fault rocks at coseismic slip rates. (a) Typical data obtained during dry and wet simulation experiments on Alpine Fault cataclasites, where the coefficient of friction is plotted against displacement, or slip. The coefficient of friction is the ratio of shear stress, the resistance to sliding, to normal stress, the pressure applied to the rock. Note the high peak, but low steady-state friction coefficients. (b) Typical data obtained during dry and wet simulation experiments on Alpine Fault montmorillonite gouges. Note the extremely low peak and steady-state friction coefficients of the wet gouge (orange line) (see Boulton *et al.* 2017b for a complete description of experimental methods).

Fault's relative weakness: frictional heat generated during a large earthquake activates numerous mechanisms that collectively and concurrently reduce the strength of the fault (Boulton *et al.* 2017b).

Images of interseismic strengthening

When an earthquake occurs, rocks surrounding the fault break. Imagine trying to squeeze a fractured rock: it crumbles. For the brittle rocks surrounding a fault to re-accumulate elastic strain energy, and re-start the earthquake cycle, the fractures must heal. Rocks recovered during DFDP-1 drilling record thousands of earthquakes. X-ray images of entire rock cores, along with optical and electron images of smaller polished rock samples, show that circulating fluids above the Alpine Fault heal the damage done during earthquakes (Figs 7, 8) (Williams *et al.* 2016, 2017; Boulton *et al*. 2017a).

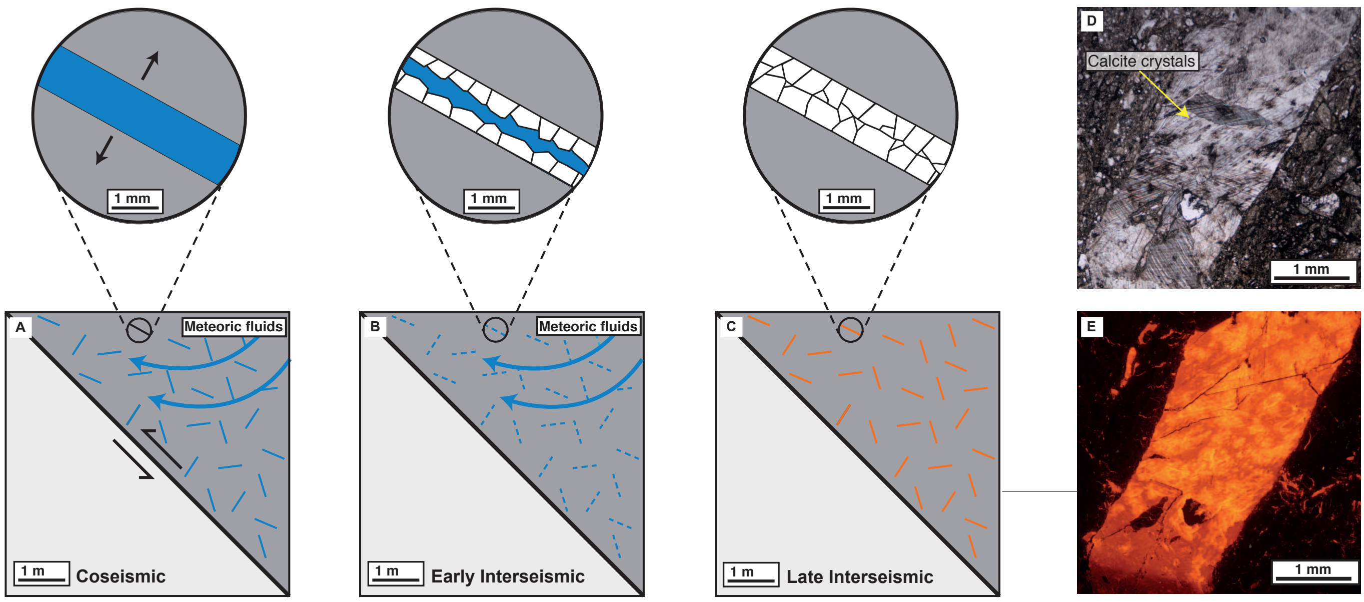

Figure 7. The important role calcite plays in sealing fractures and reducing permeability near the plate-boundary fault. (a) During an earthquake, rocks adjacent to the Alpine Fault are fractured, creating pathways for fluids saturated with calcium and carbonate ions. (b) Fluids (blue arrows) that originated as rain and snow on the Southern Alps migrate through the fractures, precipitating calcite crystals along fracture margins. The fluids are effectively trapped in the Pacific Plate by the impermeable clay-rich gouges. (c) The calcite crystals grow until they meet other crystals, sealing the fracture and reducing the permeability of the rock. (d) A plane-polarised light microscope image of a calcite vein in cataclasite recovered during DFDP-1. (e) The same vein imaged in cathodoluminescence, showing the orange and yellow excitation colours of calcite (after Boulton *et al.* 2017b and Williams *et al.* 2017).

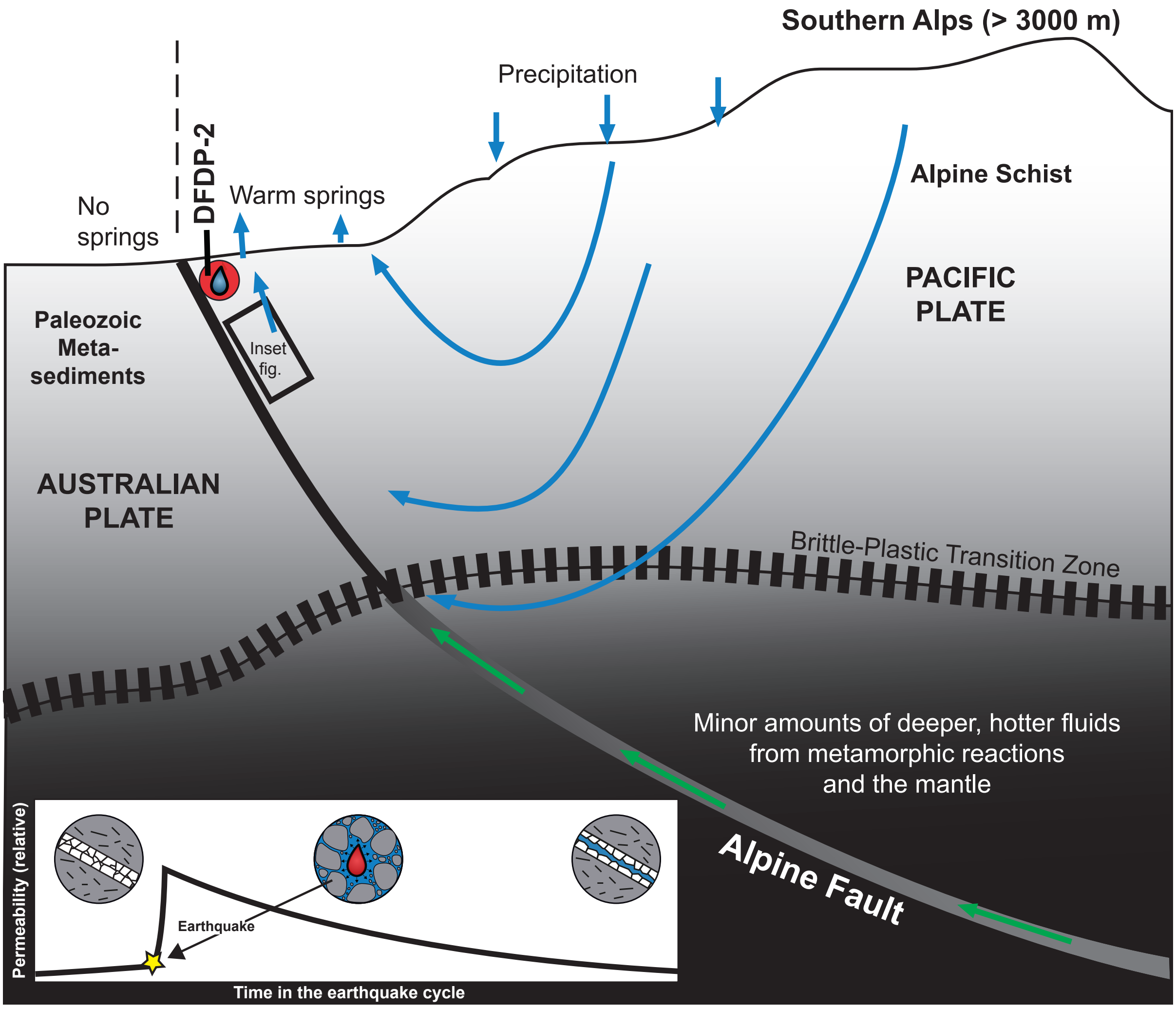

Figure 8. Plate boundary cross-section based on field observations and data collected during the Deep Fault Drilling Project (modified from Menzies *et al.* 2016 and Boulton *et al.* 2017a). The Alpine Fault forms an impermeable barrier throughout the earthquake cycle (bold diagonal line). While there are several fluid sources within the Alpine Fault Zone, meteoric water is volumetrically dominant within the brittle crust. (*Inset*) A plot of relative fault-zone permeability against time in the earthquake cycle, showing the increase in permeability expected during and immediately after an earthquake. Icons illustrate the progressive infilling of fractures with calcite precipitated from hot fluids during the interseismic period. The sealing of open fractures decreases permeability, potentially creating pockets of highly pressured pore fluids which can trigger another earthquake and/or become further pressurised during frictional sliding.

Earthquake-generated fractures are a haven for hot fluids. After an earthquake, these open fractures create permeable pathways through the crushed rocks above the plate-boundary fault (e.g. Sibson 1992). In the upper ~ 6–8 km of the fault, migrating fluids are saturated with reactive calcium and carbonate ions, the principal components of the mineral calcite (e.g. Menzies *et al.* 2014, 2016). In Alpine Fault rocks located closest to the plate-boundary, calcite invariably fills fractures, appearing white in whole-rock samples and optical microscope images, and stunning oranges, reds and yellows in cathodoluminescence (CL) images (Fig 7). At deeper levels, fractures are sealed mainly with a combination of calcite, quartz, and other minerals (Upton *et al*. 1995; Toy *et al*. 2010; Menzies *et al.* 2014).

The net effect of fluid migration and associated calcite (± quartz) precipitation is a gradual decrease in permeability during the interseismic part of the earthquake cycle (Figs 7, 8). At the same time, rock competency increases, promoting interseismic strain build-up. Numerical models of these processes show that as permeability decreases, fluids trapped within the fault zone can become highly pressured, a way of decreasing fault strength and triggering earthquakes (e.g. Gratier *et al.* 2003; see also Sibson 1992). This triggering, or *nucleation*, of a large-magnitude earthquake with a rupture area that spans much of the Alpine Fault marks the start of a new earthquake cycle (Fig. 2; inset, Fig. 8).

Key results

The Deep Fault Drilling Project (DFDP) has provided researchers with unparalleled opportunities to understand the mechanisms that generate earthquakes on the Alpine Fault. Results show that fluids play a fundamental role in explaining the weakness during earthquakes. When fault slip occurs during an earthquake, trapped fluids become pressurised, allowing slip to occur easily. Between earthquakes, fluids circulate through fractures located above the impermeable plate-boundary fault gouge. These circulating fluids carry tremendous amounts of heat, as well as the building blocks of fracture-sealing minerals. Following an earthquake, the gradual precipitation of calcite into open fractures strengthens the fault and primes it for a future seismic event.

Geophysical observations made in the DFDP-1 and DFDP-2 boreholes, along with geological observations made in the laboratory, provide vital information for models of seismic radiation and strong ground motion. Furthermore, the drilling project has enabled over 40 international undergraduate, postgraduate, and early career researchers to collaborate on borehole measurements as well as rocks exposed in the West Coast's rivers and valleys, recovered from the DFDP boreholes, and sent to laboratories worldwide. Just as Harold Wellman's career was inspired by surface observations of the Alpine Fault's astonishing and then-inexplicable movement, our new underground observations are motivating researchers to discover the physics that underpin these dramatic displacements and the as-yet unpredictable earthquakes that accompany them.

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