Deep Fault Drilling Project—Alpine Fault, New Zealand

by John Townend, Rupert Sutherland, and Virginia Toy

doi:10.2204/iodp.sd.8.12.2009

The Alpine Fault, South Island, New Zealand, constitutes a globally significant natural laboratory for research into how active plate-bounding continental faults work and, in particular, how rocks exposed at the surface today relate to deep-seated processes of tectonic deformation, seismogenesis, and mineralization. The along-strike homogeneity of the hanging wall, rapid rate of dextral-reverse slip on an inclined fault plane, and relatively shallow depths to mechanical and chemical transitions make the Alpine Fault and the broader South Island plate boundary an important international site for multi-disciplinary research and a realistic target for an ambitious long-term program of scientific drilling investigations.

Introduction

The mid-crust is the locus of several fundamental geological and geophysical phenomena. These include the transitions from brittle to ductile behavior and from unstable to stable frictional sliding; earthquake nucleation and predominant moment release; the peak in the crustal stress envelope; the transition from predominantly cataclastic to mylonitic fault rocks; and mineralization associated with fracture permeability. Current understanding of faulting, seismogenesis, and mineralization in this tectonically important zone is largely based on remote geophysical observations of active faults and direct geological observations of fossil faults.

The Alpine Fault, New Zealand, is a major dextral-reverse fault that is thought to fail in large earthquakes (M_w ~7.9) every 200–400 years and to have last ruptured in the year 1717. Ongoing uplift has rapidly exhumed a crustal section from depths of as much as 30 km, yielding a young (<~1Ma), well-preserved sample of mid-crustal structures comparable to those currently active at depth. Surface studies and geophysical experiments have provided valuable images of structures and associated deformation mechanisms, and contributed to archetypal models of continental faulting and orogenesis.

An International Continental Scientific Drilling Program-funded workshop attended by sixty-one researchers from seven countries was held on 22–28 March 2009 at Franz Josef, adjacent to the central portion of the Alpine Fault. The workshop addressed the state of knowledge of the Alpine Fault; the significance and feasibility of a multi-national program of drilling and allied science; and the preliminary steps required for site characterization, preparatory drilling, and longer-term science planning. The program involved seventeen technical presentations on the Alpine Fault, earthquake physics and faulting, and scientific drilling, as well as fourteen talks addressing related subjects and intended to stimulate discussion. The program also contained field trips to sites along the Alpine Fault to view fault rocks and geomorphic features as well as potential drill sites.

Three principal scientific themes emerged from the workshop: (1) evolution of a transpressive orogenic system; (2) ductile and brittle deformation mechanisms, and their interaction; and (3) seismogenesis and the habitat of earthquakes. The remarkable along-strike homogeneity of the Alpine Fault's hanging wall, the rapid rate of slip, and the dextral-reverse kinematics enable the progressive evolution of fault zone materials to be examined by linking rocks exposed at the surface to their *in situ* protoliths at depth along common exhumation trajectories. In the central portion of the fault, where exhumation rates and thermal gradients are highest,

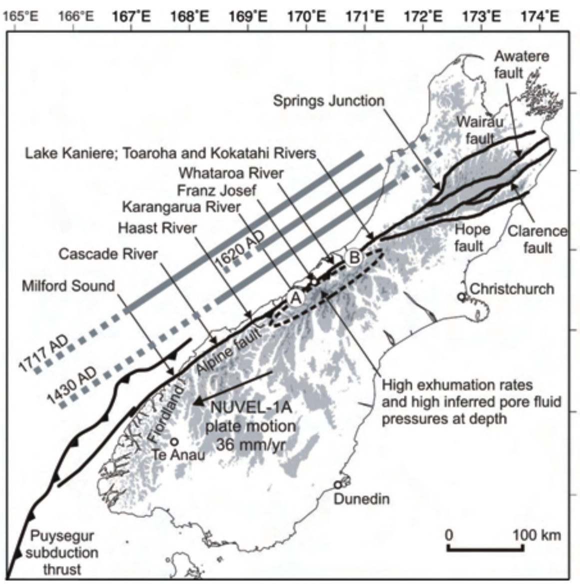

Figure 1. Map of the South Island of New Zealand showing principal features of the Australia–Pacific plate boundary and key locations referred to in the text. "A" and "B" mark the ends of the along-fault illustration in Fig. 4. The thick gray lines indicate the inferred extent of past Alpine Fault ruptures during historical times. Light gray shading demarcates topography higher than 800 m. Reproduced by permission of the American Geophysical Union after Sutherland et al., 2007. Copyright 2007 American Geophysical Union.

several sites can be identified at which rocks encountered at depth in boreholes would correspond to well-studied outcrops, enabling progressive geological deformation and petrological changes to be studied as functions of space and time along the transport path.

The Alpine Fault affords a rare opportunity to study, via scientific drilling and allied research, the physical character of tectonic deformation at depth within a major active continental fault that is late in its seismic cycle and which can be geophysically monitored in the coming decades.

Tectonic Setting

The Alpine Fault is the primary structure accommodating Australia–Pacific plate motion in New Zealand's South Island (Norris et al., 1990; Fig. 1). It is a mature dextral-reverse fault that offsets basement rocks laterally by ~470 km, with estimated late Quaternary horizontal displacement rates of 21–27 mm yr^{-1} (Wellman, 1953; Norris and Cooper, 2001; Sutherland et al., 2006). Paleoseismic evidence near the Alpine Fault identifies earthquakes in the years 1717, 1620, and 1430, with estimated moment magnitudes of 7.9±0.3, 7.6±0.3, and 7.9±0.4, respectively (Sutherland et al., 2007).

In the central South Island, the Alpine Fault is dextral-reverse and bounds the western edge of the Southern Alps (Norris et al., 1990). Rapid exhumation (~6–9 mm yr^{-1}; Little et al., 2005) has also produced rapid cooling, indicated by decreasing metamorphic grade and increasing thermochronological age with distance from the fault (Koons, 1987; Batt et al., 2004; Little et al., 2005). It has produced a spectacular exposure of the crustal section from depths of as much as 20–30 km (Little et al., 2002; Norris and Cooper, 2003). The exposed section may provide a young proxy for material currently deforming at mid-crustal depths, allowing unprecedented ground-truthing of geophysical data and the interpretation of borehole observations in terms of recent fault products—and *vice versa*.

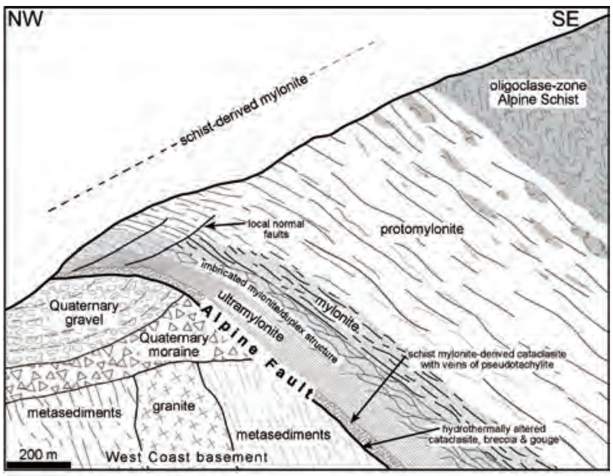

Figure 2. Schematic cross-section of an oblique thrust segment within the central section of the Alpine Fault. Reproduced by permission of the American Geophysical Union after Norris and Cooper, 2007. Copyright 2007 American Geophysical Union.

The exhumed 1–2-km-wide Plio-Pleistocene mylonite zone (illustrated schematically in Fig. 2) demonstrates that localized deformation occurs beneath the brittle part of the Alpine Fault (Sibson et al., 1979; Norris and Cooper, 2001, 2003; Toy et al., 2008 and references therein). Along its central segment, the fault juxtaposes a hanging wall of lithologically rather uniform high-grade (up to garnet-oligoclase facies) foliated Alpine schists against a footwall comprising a basement of Paleozoic greywackes (Greenland Group) intruded by Devonian–Cretaceous granites and overlain by a Cretaceous–Cenozoic cover sequence (see Cox and Barrel, 2007; Cox and Sutherland, 2007). Although portions of the fault zone are exposed in numerous river sections, no exposed complete fault-rock sequence from hard-rock hanging wall to hard-rock footwall has yet been located.

About 7 km structurally above the Alpine Fault lies a brittle-ductile shear array inferred to have formed at >20-km depths, with evidence for complex, transient semi-brittle behavior at high strain-rates and fluid pressure cycling on relatively short, possibly seismic, timescales (Wightman and Little, 2007). The base of the hanging wall seismogenic zone inferred from contemporary seismicity is relatively shallow (~8–12 km; Leitner et al., 2001). Geodetic studies are consistent with a shallow (5–10 km) depth for full fault locking (Beavan et al., 1999), though some degree of interseismic coupling may persist to as deep as ~18 km (Wallace et al., 2007). In the mid-crust, the fault zone exhibits low seismic wave speeds and high attenuation (Stern et al., 2001; Eberhart-Phillips and Bannister, 2002; Stern et al., 2007 and references therein) and high electrical conductivity (Wannamaker et al., 2002), suggesting interconnected saline fluids at high pressures within the ductile regime.

Why the Alpine Fault?

The Alpine Fault is a well-studied active continental fault that, unlike many other similar faults elsewhere, has not produced large earthquakes or measureable creep in historic times; however, paleoseismic data suggest that it has produced large earthquakes in the Holocene and that it is late in the earthquake cycle. The Alpine Fault's dextral-reverse kinematics, non-vertical dip, and rapid slip rates have exhumed to the ground surface a fresh sample of fault rocks inferred to have formed at depths of as much as 30 km within the last few million years. Due to its relatively steep dip, fluid-saturated state, and high near-surface geothermal gradient, the Alpine Fault serves further as an analogue for environments in which economically significant mesothermal mineralization has occurred (Koons and Craw, 1991; Weinberg et al., 2005; Sibson, 2007).

The following factors and related logistical considerations make the Alpine Fault a globally significant target of fundamental research into tectonic deformation, seismic hazard, and mineral resource formation:

- The >300-km along-strike exposure of a relatively uniform-lithology hanging wall and derived fault rocks that formed during the current tectonic regime, providing an exceptional reference for interpreting observations of contemporary processes and structure and older, exhumed structure
- Rapid uplift resulting in advection of crustal isotherms so that brittle-ductile transition processes can be studied at shallower depths than possible in other active transpressional settings
- Sequences of fault rocks developed during unidirectional exhumation on well-determined trajectories over relatively short time periods
- The opportunity to study on an ongoing basis the state of a locked fault thought to be late in the earthquake cycle
- Well-determined, rapid Quaternary slip rates
- An extensive body of geological and geophysical knowledge, and a modern, nationwide geophysical monitoring network (GeoNet; Fig. 3)
- A non-vertical fault orientation enabling fault penetration with either subvertical or incline holes
- A relatively benign political and physical environment in which to operate with existing petroleum industry onshore drilling activity and supporting infrastructure.

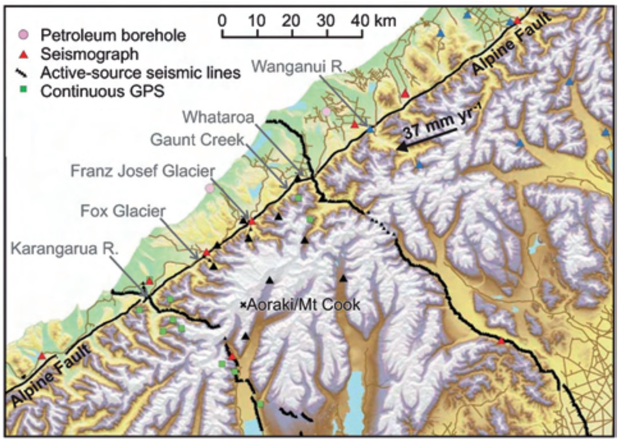

Figure 3. Map of the central section of the Alpine Fault showing existing infrastructure, the onshore portions of the South Island Geophysical Transect (SIGHT) active-source seismic lines, background seismicity, and the locations of possible drill sites.

Why Drill?

Drawing inferences about conditions and processes prevailing at seismogenic or greater depths based on outcrop observations is complicated by the fact that rocks exposed at the surface may have undergone modifications—structural, mineralogical, and geochemical—during their exhumation and at shallow depths.

One way of examining and accounting for the character and extent of upper crustal modifications is to examine a rock mass at depth whose future exhumation trajectory intersects a present-day surface outcrop (i.e., to treat the rock mass at depth as the protolith of the modified rocks now observed at the surface). The Alpine Fault kinematics are such that fault rocks evolve progressively on a path towards the surface, where they exit the system. This allows examination of progressive fault rock development using paired borehole and surface observations that is not possible on purely strike-slip faults where fault rocks may be continuously reworked at the same depth throughout the fault's history.

The second principal reason for drilling into the central Alpine Fault is to address the physics of faulting and seismogenesis by gaining access to the fault zone at depth and determining the temperature, fluid pressure and chemistry, bulk rock properties, and stress conditions prevailing at a late stage in the earthquake cycle, and establishing a long-term monitoring capability. Drilling enables continuous observations to be made of the fault zone in the immediate vicinity of the borehole itself and further afield using fault-zone guided waves, for instance (Li and Malin, 2008). It also provides a mechanism of calibrating and interpreting remote observations, such as those provided by the South Island Geophysical Transect project (SIGHT; Okaya et al., 2002; Stern et al., 2007), and linking these to surface data and rupture models. Laboratory measurements made on samples retrieved from depth, as well as measurements of the conditions under which those samples were collected, are required to more accurately describe the physical characteristics of fault rocks during coseismic rupture, and to account for strong ground motions (Beeler, 2006; Rice and Cocco, 2007).

Figure 4 illustrates the idealized geometry of the Alpine Fault in the central Southern Alps (inset stereogram) and a schematic view of the fault plane (as viewed normal to the plane), with the locations of key surface outcrops and fault-crossing roads marked. The regional fault plane strikes northeast and dips at approximately 50° to the southeast on

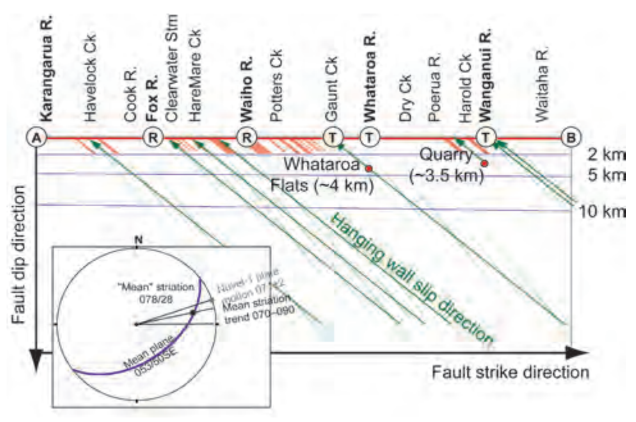

Figure 4. Schematic view normal to the mean fault plane in the central Alpine Fault region showing rock uplift trajectories and key outcrop locations. Place names shown in bold correspond to prospective drill sites. "A" (southwest) and "B" (northeast) are marked on Figure 1 for reference. "T" and "R" denote tracks and roads, respectively, crossing the fault trace. The short red lines mark strike-slip sections of the fault trace. The inset summarizes the mean fault geometry in stereographic projection.

average, and northeast-plunging striations define a mean rake of ~38° NE (Norris and Cooper, 1995; 1997; Little et al., 2002). Figure 4 demonstrates that there are several points along the fault at which several kilometers' access to the hanging wall is possible northeast of known surface outcrops. This means, for example, that a vertical borehole drilled approximately 3.5 km southeast of where the Alpine Fault crosses the Whataroa River would intersect the Alpine Fault at a depth of ~4 km, sampling material expected to breach the surface in ~0.4 Myr. Most importantly, however, the point at which the borehole intersected the fault plane would lie on the exhumation trajectory of the rocks now exposed in the Gaunt Creek outcrop.

Key Discussion Points

During the course of the workshop, three principal scientific themes and associated research goals emerged:

1. *Evolution of an orogenic system*—to determine how an active transpressional plate boundary system interacts with climate, landscape, and hydrological and thermal regimes;
2. *Ductile and brittle deformation mechanisms*—to determine via integrated surface and borehole observations what deformation mechanisms, mineralogical processes and conditions characterize the ductile and brittle regimes, and their interaction;
3. *Seismogenesis and the habitat of earthquakes*—to examine a major, locked, late-stage, continental fault at depth, determine the conditions under which earthquakes occur, and characterize the materials within which ruptures propagate.

The accompanying group discussions identified a number of common scientific issues related to the Alpine Fault and major continental faults in general, which are summarized below.

Ambient Conditions

A key theme to emerge from the group discussions was the vital importance of understanding the thermal and fluid flow regimes surrounding the Alpine Fault. Current thermal and hydrological models of the shallow to mid-crust in the vicinity of the Alpine Fault, particularly on the hanging wall, are limited by sparse data and consequent uncertainties in the maximum depth and pattern of topographically-induced fluid flow, the permeability structure, and shear heating effects.

The present-day shallow thermal regime west of the Alpine Fault can be inferred from petroleum exploration wells (Townend, 1999), but data are scarce in the immediate vicinity of the Alpine Fault's surface trace and further east. Models of the thermal structure of the Southern Alps orogen (Koons, 1987; Allis and Shi, 1995; Upton et al., 1995; Batt and Braun, 1999; Gerbault et al., 2003) differ quite markedly, and further work is required to reconcile these models with geodetic and seismological estimates of interseismic locking depths and the seismogenic thickness.

Temperature, fluid pressure and chemistry, and stress are all likely to be strongly perturbed at shallow depths by the pronounced topographic relief (as is the Alpine Fault's shallow structure itself; see below) and to differ more markedly from conditions prevailing at depth than has been the case in active fault drilling experiments elsewhere (Zoback et al., 2007). Detailed modeling of all three fields to determine how deep these effects persist is a high priority as plans for future drilling evolve.

Fluid and Rock Geochemistry

The full armory of elemental and isotopic techniques has yet to be brought to bear on fluids sampled in hot springs emanating from around the fault and trapped in exhumed veins within the fault zone and hanging wall. It is likely that more complete suites of geochemical data will aid the identification of fluid sources and flow-paths (Upton et al., 1995; Koons et al., 1998), and in particular enable more detailed analysis of progressive fluid-rock interaction. Among the outstanding questions related to fluid discharge are those of what factors control the number of hot springs along the Alpine Fault, their temperatures (<56°C), and the apparent gap in springs between the Cascade and Karangarua Rivers.

Alpine Fault Geometry

Key to the viability of any future drilling operations is improved knowledge of the Alpine Fault's shallow geometry. Seismic data indicate that the fault has a listric structure in the mid- and lower crust, with its southeastward dips decreasing from ~60° at 15 km depth to ~40° at 25 km depth and to almost zero at 30 km (Stern et al., 2007, and references therein). However, the fault's orientation at depths of hundreds of meters to several kilometers is still poorly constrained. Moreover, the central Alpine Fault (between Whataroa and Haast) exhibits "serial partitioning" into oblique thrust and strike-slip segments whose along-strike dimensions (typically <3 km) appear to be controlled by the spacing of major rivers (Norris and Cooper, 1995, 1997). Erosional control on the segmentation suggests that the segments likely merge into a single oblique structure at depths comparable to the topographic relief (~1000–1500 m), but detailed geophysical work is required to image these near-surface structures and determine their geometries at the depths that drilling might target.

Fault Zone Structure

Prevailing models of Alpine Fault zone structure at various depths have been compiled from partial data sets collected at different locations along the surface trace and in the hanging wall (Reid, 1964; Sibson et al., 1979; Sibson et al., 1981; Norris and Cooper, 1995, 1997, 2003, and 2007; Warr et al., 2007; Toy et al., 2008). Deconvolving near-surface or retrogressive effects that develop in response to depressurization, cooling, and interaction with progressively cooler fluids, from those resulting from cataclastic processes and frictional melting during deeper deformation (Warr and Cox, 2001) will be aided by analysis of suites of petrological and structural observations made at different depths along a single exhumation trajectory. Furthermore, borehole measurements are expected to provide information about changes in fault zone geometry and hence strain distribution, at different depths within the brittle and ductile regimes.

Seismogenesis and the Habitat of Continental Earthquakes

The Alpine Fault provides an excellent opportunity for elucidating the rheological properties and constitutive responses of real fault materials and host rocks. The overall mechanical behavior of a fault zone is likely to be controlled coseismically by thermal and hydraulic factors as well as the fault zone's intrinsic structure. Understanding the short- and long-term evolution of fault microstructures and fault zone fluids, their interaction and their temporal evolution should provide new insight into what mechanisms govern rupture propagation and termination (Sibson, 1985; Wesnousky, 2006; Rice and Cocco, 2007). Comparisons of fault rocks now exposed at the surface with samples retrieved from progressively greater depths and coincident measurements of *in situ* stress, fluid pressure, permeability, and elastic parameters would inform laboratory experiments and theoretical modeling. These issues provide a vital link between detailed structural and microstructural studies of fault rocks and rupture physics-based models of seismic radiation, strong ground motion, and transient interseismic processes. Further, they bear directly on questions of what governs the transition between brittle and ductile deformation processes, the generation and significance of pseudotachylytes, and the mechanical characteristics of a locked fault posing a major seismic hazard.

Interaction between Brittle and Ductile Deformation Processes

The transition in both space and time between continuous, temperature-controlled creep deformation at depth and episodic, pressure-sensitive frictional sliding in the upper-crust (commonly although controversially referred to as the "brittle–ductile transition") is fundamental to understanding the mechanics of crustal scale faults (Rutter, 1986). Characterizing this transition relies on being able to distinguish different grain-scale deformation mechanisms in samples of fault rocks, and determining the effects on those mechanisms of strain rate, temperature, pressure, and fluids (chemically and physically; e.g., Craw and Campbell, 2004).

Interaction of Climate, Landscape, and Tectonics

A great deal of scientific attention has focused on the role of tectonic processes in altering the Earth's topography and, more recently, the effects of surface processes on fault behavior (Koons and Kirby, 2007). The Alpine Fault is unusual in that it currently accommodates fault-parallel and fault-normal displacements on a single dipping structure (Norris et al., 1990; Stern et al., 2000). This has been suggested to reflect thermal weakening resulting from the highly asymmetric precipitation and erosion patterns of the Southern Alps (Koons et al., 2003) and serves as one example of the influence that orographic effects may exert on deep-seated faulting behavior (Upton et al., 2003, 2009). Better understanding of the rates and spatial variations in exhumation are required to more fully investigate climatic and physiographic effects on faulting.

Site Selection and Survey

Scientific Criteria

The key scientific factors that render the Alpine Fault a globally important focus for drilling—geometry, kinematics, rates, exposure—mean that the area of most relevance to drilling is the central section of the fault, between the Karangarua and Wanganui Rivers (Fig. 4), where dip-slip rates on the Alpine Fault and hanging wall exhumation rates are greatest. The central section is approximately bounded by the two longest deep-crustal seismic transects studied during the SIGHT project, providing the opportunity to tie various borehole observations to deeper remote measurements.

The key scientific criteria to be considered, therefore, are as follows: scientific relevance, representativeness, and significance; location in the central segment of the Alpine Fault; scope for multiple boreholes at different distances from the fault; and opportunities for aligned research.

Logistical Criteria

Much of the Alpine Fault lies within a region of very high conservation value; indeed, the central segment of the fault is also the area of highest conservation significance. Hence, one key logistical constraint on drilling operations and related surface studies is the need to minimize environmental impact within a high-profile conservation estate.

Steep topography, high rainfall, and active erosion make access to the hanging wall difficult (in fact, only three graded roads extend more than 1 km east of the fault trace in the central region of most rapid uplift), and field conditions are often challenging. In evaluating different potential drill sites, consideration of the following logistical factors will be particularly important: physical access to the hanging wall; permitting requirements; site conditions (e.g., vulnerability to flooding, ground stability); and visibility/impact.

Sites under Consideration

Figure 4 illustrates the five locations in the central segment of the Alpine fault where roads or farm tracks extend more than 1 km into the hanging wall. Also marked are five locations provisionally identified as possible drill sites requiring detailed site characterization studies—the Wanganui, Whataroa, Waiho (Franz Josef), Fox, and Karangarua River valleys. Of these sites, only the Wanganui, Whataroa, Waiho, and Karangarua River locations are closely linked to known surface outcrops along exhumation trajectories. The Waiho, Fox, and Karangarua Rivers are located in high-profile conservation areas, while the Wanganui River is somewhat removed from the northern SIGHT transect and the zone of most rapid uplift.

The experiment outlined here is well-suited to a multi-phase drilling program conducted over several years and involving a number of boreholes accompanied by detailed local and regional surveys and commencing with shallow (50–150-m-deep) core characterization and instrumentation holes and 1–2-km-deep exploratory holes, and going progressively deeper. This would enable the final and technologically most challenging phases of drilling and monitoring to be directly informed by sub-surface measurements in a similar manner to that used in projects elsewhere.

Surveys Required to Characterize and Define Drilling Targets

In order to adequately evaluate the suitability of any particular site for a long-term drilling operation, it will be necessary to conduct a coordinated multi-disciplinary site characterization program at each site. This program will focus on better defining the geometry of the fault and near-surface units, including alluvium; engineering site design, taking into account flood and landslide hazards; borehole design and stability analysis; and borehole instrumentation planning.

To take maximum advantage of downhole measurements and samples, a large program of aligned research that puts drilling results in context will be conducted. Some of this aligned research is being undertaken already (e.g., detailed geological and geomorphological mapping; paleoseismology; fault rock petrography and geochemistry; local seismicity analysis and tomography; active source seismic studies; numerical modeling). Other techniques (e.g., fault-zone guided wave studies; multi-system thermochronology; laboratory rock mechanics; permeability measurements; analysis of core retrieved from shallow boreholes) have yet to be fully applied to the Alpine Fault and will provide essential data for planning future deep boreholes.

Immediate Actions

Three working groups were convened at the March 2009 workshop to undertake preliminary studies in site selection and characterization, shallow drilling for core characterization and technical feasibility tests, and hydrogeological and thermal modeling and sampling. A fourth group will be convened in late 2009 to review and develop sampling protocols and coordinate permitting and funding applications.

The anisotropic, steeply-dipping fabrics of the hanging-wall Alpine Schist and the Alpine Fault mylonites may pose technical obstacles to drilling. Planning has commenced for a pilot drilling program, likely to take place in the 2010/2011 austral summer, during which one or more shallow (~50–150-m-deep) boreholes will be drilled using a mining rig to evaluate technical configurations, retrieve unweathered core from the fault zone, and conduct downhole logging in conjunction with surface measurements.

Ongoing programs of hot spring monitoring will be extended in 2010 with measurements of shallow subsurface flow and permeability in tunnels transecting the Alpine Fault hanging wall, and hot spring gas chemistry experiments. Temporary seismograph arrays currently deployed north and south of the Whataroa River will be augmented in 2010 to ensure that along-strike variations in seismicity near the Wanganui and Whataroa River prospective drill sites are recorded with a relatively homogeneous network with average instrument spacings of ~5 km. Planning will also begin for a higher-density (~1-km-spacing) transportable array with which to resolve fine-scale structures at each potential drill site in conjunction with active-source studies.

To facilitate the scientific and logistical activities, all activities will be coordinated via the project website (http://drill.gns.cri.nz/nzcdp/dfdp/), where up-to-date information regarding the working groups and the site characterization program may be found.

Acknowledgements

We gratefully acknowledge comments received on an earlier draft from Tim Davies, Tim Little, Peter Malin, Richard Norris, Dave Prior, Mark Quigley, Martha Savage, Damon Teagle, and Phaedra Upton. We thank all the workshop participants for their contributions to the discussions.

References

Allis, R.G., and Shi, Y., 1995. New insights to temperature and pressure beneath the central Southern Alps, New Zealand. *N. Z. J. Geol. Geophys.*, 38(4):585–592.

Batt, G.E., and Braun, J., 1999. The tectonic evolution of the Southern Alps, New Zealand: insights from fully thermally coupled dynamical modeling. *Geophys. J. Int.*, 136:403–420, doi:10.1046/j.1365-246X.1999.00730.x.

Batt, G.E., Baldwin, S.L., Cottam, M.A., Fitzgerald, P.G., and Brandon, M.T., 2004. Cenozoic plate boundary evolution in the South Island of New Zealand: new thermochronological constraints. *Tectonics*, 23(4):17, doi:10.1029/2003TC001527.

Beavan, J., Moore, M., Pearson, C., Henderson, M., Parsons, B., Blick, G., Bourne, S., England, P., Walcott, R.I., Darby, D., and Hodgkinson, K., 1999. Crustal deformation during 1994-98 due to oblique continental collision in the central Southern Alps, New Zealand, and implications for seismic potential of the Alpine fault. *J. Geophys. Res.*, 104(B11):25233–25255, doi:10.1029/1999JB900198.

Beeler, N.M., 2006. Inferring earthquake source parameters from laboratory observations and the scope of lab contributions to source physics. In: Abercrombie, R., McGarr, A., Kanamori, H., and Di Toro, G. (Eds.), *Earthquakes: Radiated Energy and the Physics of Earthquake Faulting. Geophysical Monograph Series*. Washington, DC (American Geophysical Union), 99–119.

Cox, S. and Barrel, D.J.A., 2007. Geology of the Aoraki area, Institute of Geological and Nuclear Sciences 1:250000 Geological Map. Lower Hutt, New Zealand (GNS Science), 71.

Cox, S. and Sutherland, R., 2007. Regional geological framework of South Island, New Zealand, and its significance for understanding the active plate boundary. In: D. Okaya, T.A. Stern and F. Davey (Eds.), *A Continental Plate Boundary: Tectonics at South Island, New Zealand. Geophysical Monograph Series*. Washington, DC (American Geoscience Union), 19–46.

Craw, D. and Campbell, J.R., 2004. Tectonic and structural setting for active mesothermal gold vein systems, Southern Alps, New Zealand. *J. Struct. Geol.*, 26(6-7):995–100, doi:10.1016/j.jsg.2003.11.012.

Eberhart-Phillips, D. and Bannister, S., 2002. Three-dimensional crustal structure in the Southern Alps region of New Zealand from inversion of local earthquake and active source data. *J. Geophys. Res.*, 107(10):20, doi:10.1029/2001JB000567.

Gerbault, M., Henrys, S., and Davey, F., 2003. Numerical models of lithospheric deformation forming the Southern Alps of New Zealand. *J. Geophys. Res.*, 108(7):18, doi:10.1029 2001JB001716.

Koons, P.O., 1987. Some thermal and mechanical consequences of rapid uplift; an example from the Southern Alps, New Zealand. *Earth Planet. Sci. Lett.*, 86(2):307–319, doi:10.1016/0012-821X(87)90228-7.

Koons, P.O. and Craw, D., 1991. Gold mineralization as a consequence of continental collision: an example from the Southern Alps, New Zealand. *Earth Planet. Sci. Lett.*, 103(1-4):1–9, doi:10.1016/0012-821X(91)90145-8.

Koons, P.O. and Kirby, E., 2007. Topography, denudation, and deformation: the role of surface processes in fault evolution. In: Handy, M. R., Hirth, G., and Hovius, N. (Eds.), *Tectonic Faults: Agents of Change on a Dynamic Earth. Dahlem Workshop Reports*. Cambridge, Mass. (The MIT Press), 205–230.

Koons, P.O., Craw, D., Cox, S.C., Upton, P., Templeton, A.S., and Chamberlain, C.P., 1998. Fluid flow during active oblique convergence; a Southern Alps model from mechanical and geochemical observations. *Geology*, 26(2):159–162.

Koons, P.O., Norris, R.J., Craw, D., and Cooper, A.F., 2003. Influence of exhumation on the structural evolution of transpressional plate boundaries: an example from the Southern Alps, New Zealand. *Geology*, 31(1):3–6.

Leitner, B., Eberhart-Phillips, D., Anderson, H., and Nabelek, J.L., 2001. A focused look at the Alpine fault, New Zealand: seismicity, focal mechanisms, and stress observations. *J. Geophys. Res.*, 106(B2):2193–2220, doi:10.1029/2000JB900303.

Li, Y.G. and Malin, P.E., 2008. San Andreas Fault damage at SAFOD viewed with fault-guided waves. *Geophys. Res. Lett.*, 35:L08304, doi:10.1029/2007GL032924.

Little, T.A., Cox, S., Vry, J.K., and Batt, G., 2005. Variations in exhumation level and uplift rate along the oblique-slip Alpine Fault, central Southern Alps, New Zealand. *Geol. Soc. Am. Bull.*, 117(5-6):707–723, doi:10.1130/B25500.1.

Little, T.A., Savage, M.K., and Tikoff, B., 2002. Relationship between crustal finite strain and seismic anisotropy in the mantle, Pacific-Australia plate boundary zone, South Island, New Zealand. *Geophys. J. Int.*, 151(1):106–116, doi:10.1046/j.1365-246X.2002.01730.x.

Norris, R.J. and Cooper, A.F., 1995. Origin of small-scale segmentation and transpressional thrusting along the Alpine Fault, New Zealand. *Geol. Soc. Am. Bull.*, 107(2): 231–240.

Norris, R.J. and Cooper, A.F., 1997. Erosional control on the structural evolution of a transpressional thrust complex on the Alpine Fault, New Zealand. *J. Struct. Geol.*, 19(10):1323–1324, doi:10.1016/S0191-8141(97)00036-9.

Norris, R.J. and Cooper, A.F., 2001. Late Quaternary slip rates and slip partitioning on the Alpine Fault, New Zealand. *J. Struct. Geol.*, 23(2-3):507–520, doi:10.1016/S0191-8141(00)00122-X.

Norris, R.J. and Cooper, A.F., 2003. Very high strains recorded in mylonites along the Alpine Fault, New Zealand: implications for the deep structure of plate boundary faults. *J. Struct. Geol.*, 25(12):2141–2157, doi:10.1016/S0191-8141(03) 00045-2.

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. Geophysical Monograph Series*. Washington, DC (American Geophysical Union),157–175.

Norris, R.J., Koons, P.O., and Cooper, A.F., 1990. The obliquely-convergent plate boundary in the South Island of New Zealand: implications for ancient collision zones. *J. Struct. Geol.*, 12(5-6):715–725, doi:10.1016/0191-8141(90)90084-C.

Okaya, D., Henrys, S., and Stern, T., 2002. Double-sided onshore-offshore seismic imaging of a plate boundary: "super-gathers" across South Island, New Zealand. *Tectonophysics*, 355(1–4):247–263, doi:10.1016/S0040-1951(02)00145-2.

Reid, J.J., 1964. Mylonites, cataclasites, and associated rocks along the Alpine Fault, South Island, New Zealand. *N. Z. J. Geol. Geophys.*, 7:645–684.

Rice, J.R. and Cocco, M., 2007. Seismic fault rheology and earthquake dynamics. In: Handy, M. R., Hirth, G., and Hovius, N. (Eds.), *Tectonic Faults: agents of change on a dynamic Earth. Dahlem Workshop Reports*. Cambridge, Mass. (The MIT Press), 99–137.

Rutter, E.H., 1986. On the nomenclature of mode of failure transitions in rocks. *Tectonophysics*, 122(3-4):381–387, doi:10.1016/0040-1951(86)90153-8.

Sibson, R.H., 1985. Stopping of earthquake ruptures at dilational fault jogs. *Nature*, 316(6025):248–251, doi:10.1038/316248a0.

Sibson, R.H., 2007. Au-quartz mineralization near the base of the continental seismogenic zone. *Geol. Soc. London, Special Publ.*, 272(1):519–532.

Sibson, R.H., White, S.H., and Atkinson, B.K., 1979. Fault rock distribution and structure within the Alpine Fault Zone: a preliminary account. In: Walcott, R.I. and Cresswell, M.M. (Eds.), *Roy. Soc. N. Z.*, 18:55–65.

Sibson, R.H., White, S.H., and Atkinson, B.K., 1981. Structure and distribution of fault rocks in the Alpine fault zone, New Zealand. In: McClay, K.R. and Price, N.J. (Eds.), *Thrust and Nappe Tectonics*. London (Geological Society of London), 197–210.

Stern, T., Kleffman, S., Okaya, D., Scherwath, M., and Bannister, S., 2001. Low seismic-wave speeds and enhanced fluid pressure beneath the Southern Alps of New Zealand. *Geology*, 29:679–682.

Stern, T., Molnar, P., Okaya, D., and Eberhart-Phillips, D., 2000. Teleseismic P wave delays and modes of shortening the mantle lithosphere beneath South Island, New Zealand. *J. Geophys. Res.* 105(B9):21615–21631, doi:10.1029/2000JB900166.

Stern, T.A., Okaya, D.A., Kleffmann, S., Scherwath, M., Henrys, S.A., and Davery, F.J., 2007. Geophysical exploration and dynamics of the Alpine fault zone. In: Okaya, D., Stern, T., and Davey, F. (Eds.), *A Continental Plate Boundary: Tectonics at South Island, New Zealand. Geophysical Monograph Series*, Washington, DC (American Geophysical Union), 207–233.

Sutherland, R., Berryman, K., and Norris, R., 2006. Quaternary slip rate and geomorphology of the Alpine fault: implications for kinematics and seismic hazard in southwest New Zealand. *Geol. Soc. Am. Bull.*, 118(3-4):464–474, doi:10.1130/B25627.1.

Sutherland, R., Eberhart-Philllips, D., Harris, R.A., Stern, T.A., Beavan, R.J., Ellis, S.M., Henrys, S.A., Cox, S.C., Norris, R.J., Berryman, K.R., Townend, J., Bannister, S.C., Pettinga, J., Leitner, B., Wallace, L.M., Little, T.A., Cooper, A.F., Yetton, M., and Stirling, M.W., 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. Geophysical Monograph Series*, Washington, DC (American Geophysical Union), 235–251.

Townend, J., 1999. Heat flow through the West Coast, South Island, New Zealand. *N. Z. J. Geol. Geophys.*, 42:21–31.

Toy, V.G., Prior, D.J., and Norris, R.J., 2008. Quartz fabrics in the Alpine Fault mylonites: influence of pre-existing preferred orientations on fabric development during progressive uplift. *J. Struct. Geol.*, 30(5):602-621, doi:10.1016/j.jsg.2008.01.001.

Upton, P., Koons, P.O., and Chamberlain, C.P., 1995. Penetration of deformation-driven meteoric water into ductile rocks: isotopic and model observations from the Southern Alps, New Zealand. *N. Z. J. Geol. Geophys.*, 38(4):535–543.

Upton, P., Koons, P.O., and Eberhart-Phillips, D., 2003. Extension and partitioning in an oblique subduction zone, New Zealand: constraints from three-dimensional numerical modeling. *Tectonics*, 22(6):7–1, doi:10.1029/2002TC001431.

Upton, P., Koons, P.O., Craw, D., Henderson, C.M. and Enlow, R., 2009. Along-strike differences in the Southern Alps of New Zealand: consequences of inherited variation in rheology. *Tectonics*, 28:TC2007, doi:10.1029/2008TC002353.

Wallace, L.M., Beavan, J., McCaffrey, R., Berryman, K., and Denys, P., 2007. Balancing the plate motion budget in the South Island, New Zealand using GPS, geological and seismological data. *Geophys. J. Int.*, 168(1):332–352, doi:10.1111/j.1365-246X.2006.03183.x.

Wannamaker, P.E., Jiracek, G.R., Stodt, J.A., Caldwell, T.G., Gonzalez, V.M., McKnight, J.D., and Porter, A.D., 2002. Fluid generation and pathways beneath an active compressional orogen, the New Zealand Southern Alps, inferred from magnetotelluric data. *J. Geophys. Res.*, 107(B6):2117, doi:10.1029/2001JB000186.

Warr, L.N. and Cox, S., 2001. Clay mineral transformations and weakening mechanisms along the Alpine Fault, New Zealand, *Geol. Soc. London, Special Publ.*, 186:85–101.

Warr, L.N., van der Pluijm, B.A., and Tourscher, S., 2007. The age and depth of exhumed friction melts along the Alpine fault, New Zealand. *Geology*, 35(7):603–606, doi:10.1130/G23541A.1.

Weinberg, R.F., Van der Borgh, P., Bateman, R.J., and Groves, D.I., 2005. Kinematic history of the Boulder-Lefroy shear zone system and controls on associated gold mineralization, Yilgarn Craton, Western Australia. *Econ. Geology*, 100(7):1407–1426, doi:10.2113/100.7.1407.

Wellman, H.W., 1953. Data for the study of Recent and Late Pleistocene faulting in the South Island of New Zealand. *N. Z. J. Sci. Tech.*, 34(4):270–288.

Wesnousky, S.G., 2006. Predicting the endpoints of earthquake ruptures. *Nature*, 444(7117):358–360, doi:10.1038/nature05275.

Wightman, R.H. and Little, T.A., 2007. Deformation of the Pacific Plate above the Alpine Fault ramp and its relationship to expulsion of metamorphic fluids: an array of backshears. In: Okaya, D., Stern, T.A., and Davey, F. (Eds.), *A Continental Plate Boundary: Tectonics at South Island, New Zealand. Geophysical Monograph Series*, Washington, DC, (American Geophysical Union), 177–205.

Zoback, M.D., Hickman, S., and Ellsworth, W., 2007. The role of fault zone drilling. In: Schubert, G. (Ed.), *Treatise on Geophysics*. Amsterdam (Elsevier), 649–674, doi:10.1016/B978-044452748-6.00084-5.

Authors

John Townend, School of Geography, Environment, and Earth Sciences, Victoria University of Wellington, P.O. Box 600, Wellington, New Zealand, e-mail:john.townend@vuw.ac.nz.

Rupert Sutherland, GNS Science, P.O. Box 30368, Lower Hutt, New Zealand, e-mail: r.sutherland@gns.cri.nz.

Virginia Toy, Department of Geology, University of Otago, P.O. Box 56, Dunedin, New Zealand, e-mail: virginia.toy@otago.ac.nz.

Related Web Links

http://drill.gns.cri.nz/nzcdp/dfdp/index.html
http://www.icdp-online.org