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Previously Unknown Fault Shakes New Zealand's South Island

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At 4:35 A.M. local time on 4 September (1635 UTC, 3 September), a previously unrecognized fault system ruptured in the Canterbury region of New Zealand's South Island, producing a moment magnitude (M_w) 7.1 earthquake that caused widespread damage throughout the area. In stark contrast to the 2010 M_w 7.0 Haiti earthquake, no deaths occurred and only two injuries were reported despite the epicenter's location about 40 kilometers west of Christchurch (population ~386,000). The Canterbury region now faces a rebuilding estimated to cost more than NZ$4 billion (US$2.95 billion).

On the positive side, this earthquake has provided an opportunity to document the dynamics and effects of a major strike-slip fault rupture in the absence of death or serious injury. The low-relief and well-maintained agricultural landscape of the Canterbury Plains helped scientists characterize very subtle earthquake-related ground deformation at high resolution, helping to classify the earthquake's basic geological features [*Quigley et al.,* 2010]. The prompt mobilization of collaborating scientific teams allowed for rapid data capture immediately after the earthquake, and new scientific programs directed at developing a greater understanding of this event are under way.

The September 2010 Darfield (Canterbury) Earthquake

The epicenter of the earthquake was approximately 10 kilometers southeast of the town of Darfield (Figure 1a) with a focal depth of 10.8 kilometers [*Gledhill et al.,* 2010] within the Canterbury Plains, an area of moderately low historical seismicity just east of the Southern Alps foothills. The previous largest earthquake to affect Christchurch was the 1888 *M* 7–7.3 North Canterbury earthquake, which ruptured the Hope Fault about 100 kilometers north of the city. Moment tensor solutions indicate that the Darfield earthquake main shock is associated with almost purely dextral strike-slip displacement on a subvertical, nearly east-west striking fault plane. The event produced a dextral strike-slip surface rupture trace greater than 29 kilometers long (Figure 1a). Using data from New Zealand national and strong-motion seismic networks, New Zealand seismologists have identified a reverse faulting component in the overall rupture sequence [*Gledhill et al.,* 2010]. As of mid-November, the region has experienced thousands of aftershocks of local magnitude (M_L) greater than 2, including 12 aftershocks of M_L greater than 5.0, with decreasing frequency in approximate accordance with current theories of aftershock decay.

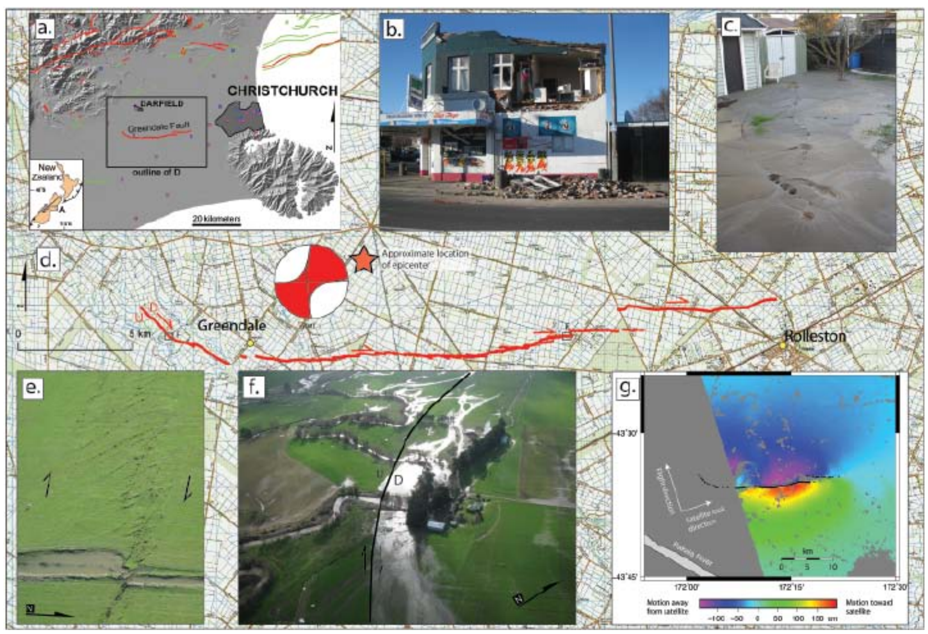

Fig. 1. (a) Digital elevation map of Canterbury region showing location of Greendale Fault and other tectonically active structures relative to selected urban centers. Red lines are active faults, and green lines are active folds (data from Forsyth et al. *[2008] (see www.gns.cri.nz, search word "QMAP Christchurch") and GNS Science Active Faults Database). Blue squares are GeoNet national strong-motion network sites, and purple squares are Canterbury regional strong-motion network sites. Locations of sites in Figures 1e and 1f are shown on map. A PDF of the fault map is available at http://www.drquigs.com and http://www.geonet.org.nz. (b) Failure of an unsupported wall in Christchurch. (c) Linear trend of sand boils in a liquefaction-affected part of Christchurch. (d) Mapped location of Greendale Fault, showing a pattern of similarly oriented faults and relative fault movement (arrows denote relative motion of area north of fault, with U representing up (the hanging wall of the secondary thrust component) and D representing down (the footwall of the secondary thrust component), although the centroid moment tensor "beachball" diagram for this earthquake (http://www.globalcmt.org) shows that the majority of motion on the fault is strike-slip). (e) Greendale Fault surface rupture patterns and dextral offset of irrigation channels. (f) Partial diversion of the Hororata River because the northeast side of the Greendale Fault has moved down at this location. (g) Unwrapped differential interferometric synthetic aperture radar (InSAR) image of coseismic ground deformation from Advanced Land Observing Satellite phased array type L-band synthetic aperture radar (ALOS/PALSAR) ascending track 336 between 11 March 2010 and 11 September 2010, with the mapped surface rupture overlaid. ALOS processing by Sergey Samsonov, University of Western Ontario, London, Canada. ALOS data used with permission.*

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The shallow depth and proximity of the earthquake to Christchurch resulted in felt intensities of as much as IX on the Modified Mercalli (MM) Intensity Scale, although most were MM VIII or less. Extensive damage occurred to unreinforced masonry buildings throughout the region (Figure 1b), but no buildings totally collapsed. The earthquake struck early in the morning, minimizing human exposure to hazards such as exterior wall and parapet collapses onto normally busy sidewalks. Nonetheless, many thousands of brick chimneys collapsed throughout the region. Extensive liquefaction, differential subsidence, and lateral spreading occurred in areas close to major streams and rivers throughout Christchurch, Kaiapoi, and Tai Tapu (Figure 1c). In these areas, as well as near the fault trace, some homes were rendered uninhabitable by the earthquake and resulting liquefaction. Parts of the city were without water and power for several days following. Slow ground settlement has continued to affect liquefaction-prone areas.

An M_L 5.1 aftershock on 8 September located about 7 kilometers southeast of the city center at a depth of approximately 6 kilometers caused further damage to previously compromised structures.

A Rapid and Coordinated Scientific Response

Immediately following the earthquake, Earth scientists from the University of Canterbury (UC) in Christchurch rushed to inspect earthquake damage in the city and provide immediate information to the public via media. Within 3 hours of the earthquake a reconnaissance and response team led by scientists from the UC Active Tectonics team and GNS Science (GNS) had been deployed. By 9:30 A.M. the UC reconnaissance team located the first evidence for ground surface fault rupture and began to assess local hazards and conduct detailed measurements of fault offsets across roads and fences. GNS scientists undertook a helicopter reconnaissance flight to define the limits of obvious surface deformation and photograph key features. Another team of UC staff and students, aided later by colleagues from other organizations, began mapping liquefaction features in and around Christchurch. By the end of the day, a first approximation of the surface rupture length and general damage patterns had been established throughout the region, which formed the basis for planning the scientific documentation of the event.

The rapid collaborative scientific response ensured that fault deformation features were accurately documented before they were removed by land remediation. The fault was mapped in detail over the following 2 weeks using a variety of methods, ranging from tape and compass to Global Positioning System (GPS) surveys and terrestrial laser scanning. The fault rupture occurred entirely in a region with numerous linear features such as roads, fences, hedgerows, and irrigation channels, which provided an invaluable wealth of fault displacement markers. Progressive iterations of maps of the surface rupture features were made available to the public online and presented to local and regional councils and landowners. Airborne lidar (light detection and ranging) was flown over a roughly 20-kilometer-long section of the fault rupture (Figure 2) 6 days after the event. As a consequence, a spectacular data set of fault displacement, buckling, and detailed fracture patterns was captured over the full length of the surface rupture. Fault data continue to be analyzed by GNS and UC personnel.

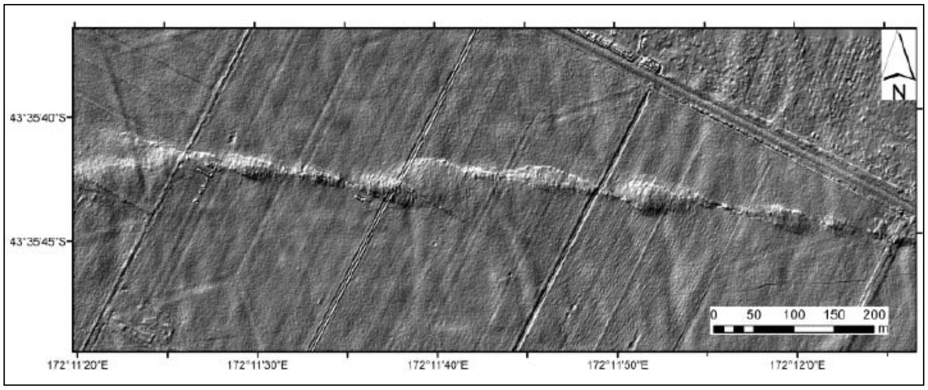

Fig. 2. Lidar (light detection and ranging) hillshade (illuminated from the northwest) digital elevation map of a short section of the central Greendale Fault, showing characteristic left stepping rupture pattern and right-lateral offsets of farm roads and fences. Lidar from NZ Aerial Mapping Limited.

Scientists working on GeoNet, a New Zealand–based geological hazard monitoring system operated by GNS for New Zealand's Earthquake Commission (EQC), deployed portable earthquake recorders the day after the main shock and have been continuously processing seismological data since the event. A GNS-led team used GPS to resurvey more than 80 existing survey marks within 80 kilometers of the rupture starting 3 days after the event; the 45 marks closest to the main shock were resurveyed 2 weeks later. GNS is working with overseas colleagues to collect and process interferometric synthetic aperture radar (InSAR) data from both Japanese and European satellites; some of the early images have produced very high quality maps of surface displacements (Figure 1f) [*Beavan et al.*, 2010]. The InSAR data are being combined with GPS, geological, and seismological data to develop rupture models.

Characteristics of the Surface Fault Rupture

The zone of identified surface rupture extends from about 4 kilometers west-northwest (WNW) of the hamlet of Greendale for about 29 kilometers to an eastern tip roughly 2 kilometers NW of the town of Rolleston (Figures 1a and 1d). The fault, not previously recognized, has been named the Greendale Fault. High-quality observations and measures of offsets and fracture patterns reveal more than 4 meters of right-lateral displacement (Figures 1e and 2). Vertical offsets of up to approximately 1 meter occur at constraining or releasing bends. Oblique northeast-side down slip on the NW striking western portion of the fault resulted in partial diversion of the Hororata River (Figure 1f). The gross morphology of the fault is that of a series of EW striking, NE stepping surface traces (Figure 1d) that in detail consist of ESE trending fractures with right-lateral displacements, SE trending extensional fractures, SSE to south trending fractures with left-lateral displacements, and NE striking thrusts and folds (Figure 1e). Offsets as small as 1–5 centimeters were mapped due to the numerous straight features (e.g., roads, fences) crossing the fault. Ongoing research and mapping of deformation will provide additional constraints on the spatial pattern of surface rupture.

The Greendale Fault ruptured primarily across gravelly alluvial plains abandoned by rivers at the end of the last glaciation, about 16,000 years ago [*Forsyth et al.*, 2008]. No evidence of previous faulting had been recognized, either prior to the earthquake or in retrospective examination of pre-earthquake aerial photographs. However, thorough cultivation of the Canterbury Plains following the arrival of Europeans in the mid-1800s has subdued some detail of the original river channel form. Coupled with the possibility that previous earthquakes may not have produced significant surface rupture, the long-term earthquake history of the Greendale Fault is difficult to assess.

What Are Earth Scientists Doing Now?

Together with research partners in New Zealand and abroad, several UC- and GNS-led research programs have been initiated following the earthquake. High-precision GPS surveying and measurement of fault offsets continues, with an emphasis on refining the characteristics of the surface rupture. Structural analysis of fault fracture arrays is providing insights into fault behavior and kinematics. Repeat surveying of markers across the Greendale Fault, conducted at weekly intervals, helps document postrupture relaxation and/or ongoing fault growth. Reoccupation of pre-earthquake survey points, combined with GPS and InSAR studies, will provide high-resolution data sets relevant to characterizing the earthquake source.

The earthquake has provided seismologists with an exceptional set of near-source strong-motion data from the GeoNet national strong-motion network and the Canterbury regional strong-motion network (Figure 1a). The station nearest the rupture recorded peak ground accelerations greater than those of gravity [*Cousins and McVerry*, 2010], and understanding why accelerations diminished over small distances is important for understanding the future seismic hazard throughout this region.

Seismologists are currently working on better defining the rupture's evolution using inversion methods and recently developed source-tracking methods. Landslide mapping and monitoring programs are in place. Geophysical surveys (seismic and ground-penetrating radar), fault trenching, and excavations of areas that experienced liquefaction during this earthquake are being conducted to investigate the subsurface geometry and earthquake history of the newly discovered Greendale Fault. Mapping of tree damage is providing insights into the extent to which coseismic shaking, changes in water table, and damage by faulting of root systems played a role in generating observed patterns of forest destruction. Mapping of displaced boulders is providing data relevant to understanding the factors influencing peak ground acceleration variability. Collaborative efforts to link remote sensing, seismological, and geological data to fault rupture propagation models are providing intriguing insights into the rupture dynamics of this earthquake and continental strike-slip earthquakes in general.

Acknowledgments

Field mapping in the weeks following the earthquake would not have been possible without the dedicated efforts of many GNS Science staff and students and staff at the University of Canterbury's Department of Geological Sciences. GeoNet provided an invaluable resource of rapid information on earthquake for researchers and the public. We would also like to thank the landowners for gracious access to the fault trace and other field sites during this stressful period. Personnel from GNS Science, Land Information New Zealand, University of Otago, and Victoria University participated in postearthquake GPS surveys. We thank Duncan Agnew for reviewing this article.

References

Beavan, J., S. Samsonov, M. Motagh, L. Wallace, S. Ellis, and N. Palmer (2010), The M_w 7.1 Darfield (Canterbury) earthquake: Geodetic observations and preliminary source model, *Bull. N. Z. Soc. Earthquake Eng.*, in press.

Cousins, J., and G. McVerry (2010), Overview of strong-motion data from the Darfield earthquake, *Bull. N. Z. Soc. Earthquake Eng.*, in press.

Forsyth, P. J., D. J. A. Barrell, and R. Jongens (2008), Geology of the Christchurch area, *Geol. Map 16*, 1 sheet + 67 pp., 1:250,000, GNS Sci., Lower Hutt, New Zealand.

Gledhill, K., et al. (2010), The Darfield (Canterbury) M_w 7.1 earthquake of September 2010: Preliminary seismological report, *Bull. N. Z. Soc. Earthquake Eng.*, in press.

Quigley, M., et al. (2010), Surface rupture of the Greendale Fault during the M_w 7.1 Darfield (Canterbury) earthquake, New Zealand: Initial findings, *Bull. N. Z. Soc. Earthquake Eng.*, in press.

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NEWS

New Type of Bacterium Expands Possibilities of Life, Scientists Indicate

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Leading up to NASA's 2 December news briefing about a new astrobiology finding, segments of the blogosphere had run wild with speculation that the agency would announce that it has found life elsewhere. Although some bloggers and readers may have been disappointed in the actual announcement, scientists at the briefing at NASA headquarters in Washington, D. C., said the finding of a bacterium that can grow by using arsenic instead of phosphorus is "phenomenal," with broad implications for searching for life on Earth and elsewhere and for other areas of research on Earth.

Felisa Wolfe-Simon, a NASA Astrobiology Research Fellow in residence at the U.S. Geological Survey in Menlo Park, Calif., led a team that discovered and experimented on the microbe, known as strain GFAJ-1 of the common bacteria group Gammaproteobacteria. Noting that life is mostly composed of carbon, hydrogen, nitrogen, oxygen, sulfur, and phosphorus, she said, "If there is an organism on Earth doing something different, we've cracked open the door to what is possible for life elsewhere."

Wolfe-Simon said she had come up with the idea of testing the substitution of arsenic for phosphorus used by an organism by thinking about the periodic table, where arsenic lies just below phosphorus and is similar to it in some ways. The research team isolated the bacterium from mud from Mono Lake, Calif., and substituted arsenic for phosphorus. "Exchange of one of the major bio-elements may have profound evolutionary and geochemical significance," the team indicates in a paper published online by *Science* on 2 December (*Science Express*, doi:10.1126/science.1197258).

At the briefing, James Elser, professor, Arizona State University, Tempe, said the finding of an organism that thrives on arsenic could lead to research that could have practical implications on Earth, including looking into the possibility of whether such an organism could be useful in wastewater treatment, in the development of an alternative bioenergy, and in serving as a replacement for dwindling phosphorus supplies.

Pamela Conrad, an astrobiologist with NASA's Goddard Space Flight Center, Greenbelt, Md., and deputy principal investigator of an investigation flying on the Mars Science Laboratory in 2011, said the finding "is delightful because it makes me have to expand my notions of what environmental constituents might enable inhabitability."

However, Steven Benner, distinguished fellow at the Foundation for Applied Molecular Evolution, Gainesville, Fla., said at the briefing that the evidence presented in the paper has not yet won him over. He said it is an exceptional result that "will require exceptional evidence to support it." Benner said he would like to see further research, including radioactive isotope labeling experiments.

NASA Astrobiology Institute director Carl Pilcher, who was not on the briefing panel, told *Eos* the finding is "huge. It's not finding silicon-based life, and it's not finding non-carbon-based life, but it is finding life in which one of the six essential elements has been replaced," he said, adding that he is even more excited about where the finding might lead. "When you make a discovery that is this profound about the nature of life, you are going to learn all kinds of other things as the scientific community follows up."

"While certainly being able to announce the discovery of an extraterrestrial would be an incredible announcement, we feel that from our perspective and our understanding of biology here on Earth," said Mary Voytek, director of NASA's Astrobiology Program, "this is a a phenomenal finding. We are talking about taking the fundamental building blocks of life and replacing one of them with a perhaps not unpredicted, but another, compound."

Voytek added that she is sorry if those hoping for ET are disappointed. "But there are lots of other people who see this as a huge finding and a significant finding that is going to lead to new areas of reseach and will fundamentally change how we define life and therefore how we will look for it. Maybe we will be able to find ET now, because we have more information about what we might be looking for."

—Randy Showstack, Staff Writer