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Map of the 2010 Greendale Fault surface rupture, Canterbury, New Zealand: application to land use planning[1]

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Rupture of the Greendale Fault during the 4 September 2010, M_W7.1 Darfield (Canterbury) earthquake produced a zone of ground-surface rupture that severely damaged several houses, buildings and lifelines. Immediately after the earthquake, surface rupture features were mapped in the field and from digital terrain models developed from airborne Light Detection and Ranging (lidar) data. To enable rebuild decisions to be made and for future land use planning, a fault avoidance zone was defined for the Greendale Fault following the Ministry for the Environment guidelines on 'Planning for the Development of Land on or Close to Active Faults'. We present here the most detailed map to date of the fault trace and describe how this was used to define and characterise the fault avoidance zone for land use planning purposes.

Keywords: active fault; surface fault rupture map; fault avoidance zone; strike-slip fault; Darfield earthquake; Canterbury earthquake sequence; land use planning

Introduction

Rupture of the Greendale Fault during the 4 September 2010, M_W7.1 Darfield (Canterbury) earthquake produced a 29.5 ± 0.5-km-long, 30 to 300-m-wide zone of ground-surface rupture and deformation, involving 5.2 ± 0.2 m maximum horizontal, 1.45 ± 0.2 m maximum vertical and 2.5 ± 0.1 m average net displacement (Quigley et al. 2010a, 2012) (Fig. 1). Information from the Greendale Fault rupture has contributed significantly to calibrating international and national fault scaling relationships (Quigley et al. 2012) and, together with seismic and geodetic data, has helped define the complex rupture mechanism of the Darfield earthquake (Beavan et al. 2010; Gledhill et al. 2010, 2011; Holden et al. 2011).

As well as advancing the scientific knowledge of fault rupture mechanics, the surface rupture data acquired is essential for the recovery of the local community and future planning. Deformation associated with ground-surface rupture along the Greendale Fault severely damaged several houses, buildings and infrastructure to the extent that they need to be rebuilt or repaired (Quigley et al. 2010a,b; Van Dissen et al. 2011). Our study aims to assist local authorities in deciding where and what structures can be built or repaired now that there is a known active fault in this area.

Specifically, we use field mapping, surveying, analysis of aerial photographs and an airborne Light Detection and Ranging (lidar) dataset of the 2010 surface rupture to precisely locate the fault rupture and define the types of surface deformation associated with the rupture. We then apply the guidelines for mitigating fault surface rupture hazard (Kerr et al. 2003) to define a fault avoidance zone (FAZ). These guidelines were established by a joint working group of the New Zealand Society for Earthquake Engineering and the Geological Society of New Zealand under the auspices of the Ministry for the Environment (MfE) to assist resource management planners to avoid and/or mitigate fault rupture hazard. Our FAZ mapping illustrates major elements of the MfE guidelines, and provides an example of their application.

Geological setting

The Greendale Fault is situated near the outer edge of the broad zone of deformation marking the boundary between the Australian and Pacific Plates (Figs. 1A, 1B). In the central South Island, the Pacific Plate is moving west–southwest relative to the Australian Plate at c. 38 mm yr^{-1} (Wallace et al. 2007). Approximately 25% of the plate boundary deformation is distributed across numerous reverse and strike-slip faults within and east of the Southern

[1]Supplementary data available online at www.tandfonline.com/10.1080/00288306.2012.680473. **Supplementary File 1:** Data supplement to Map of the 2010 Greendale Fault surface rupture, Canterbury, New Zealand: Application to land use planning.

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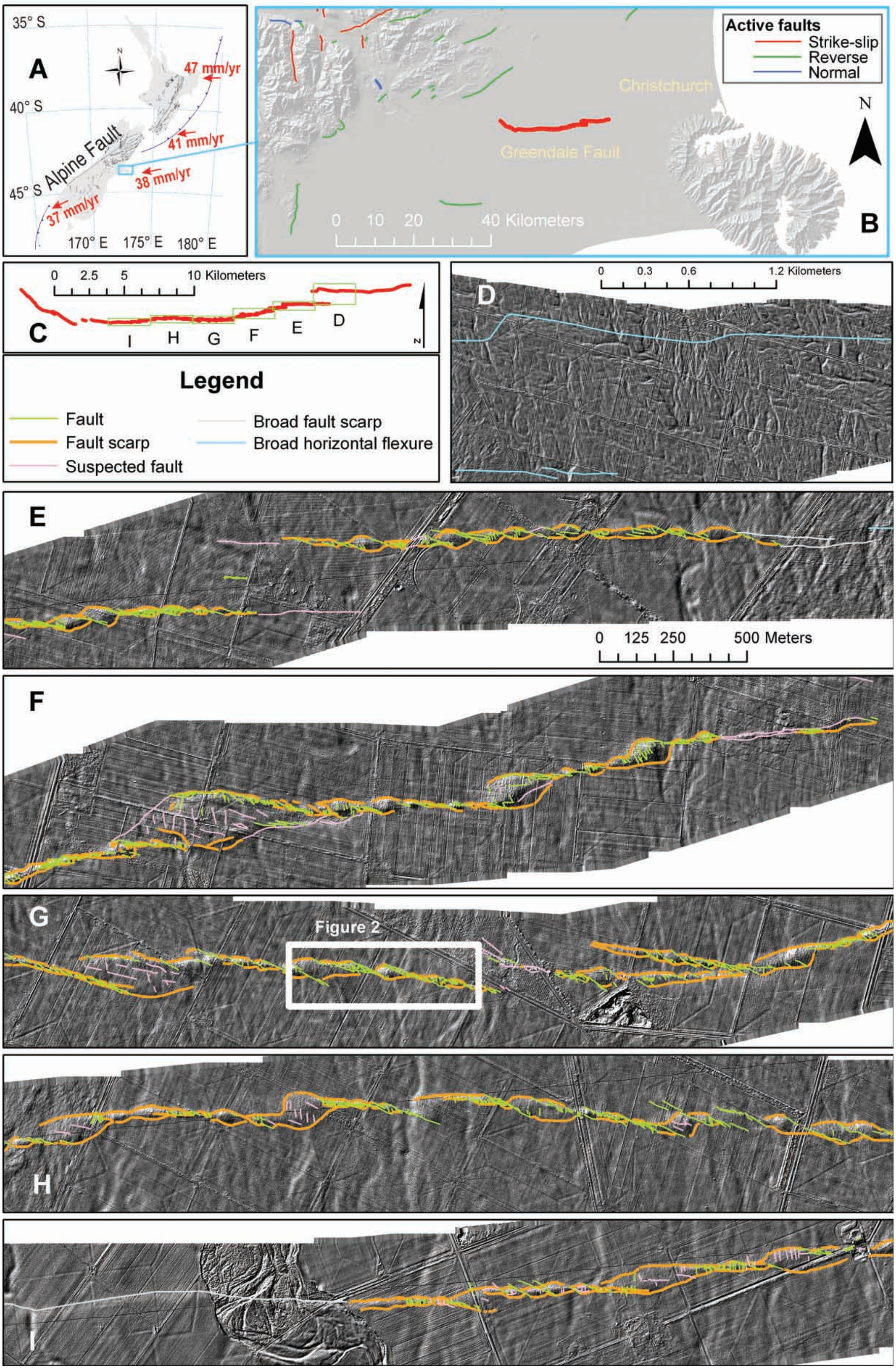

Figure 1 A, Plate tectonic context of New Zealand. **B**, Location of Greendale Fault. **C–I**, Ground-surface rupture features mapped along the Greendale Fault. The basemap is a shaded hill relief produced from the lidar data.

Alps (Norris & Cooper 2001; Pettinga et al. 2001), including the Greendale Fault.

The Greendale Fault lies in the Rakaia to Waimakariri sector of the Canterbury Plains. In the central part of the plains, the braided river beds of the Rakaia, Selwyn and Waimakariri rivers coalesced during the last ice age, between c. 28 kyr and c. 18 kyr ago (Forsyth et al. 2008 and references therein). During that time, alluvial deposits (the Burnham and Windwhistle Formations; Forsyth et al. 2008 and references therein) accumulated to thicknesses of tens to hundreds of metres in some areas, burying, or at least obscuring, the geomorphic expression of slow slip rate active faults crossing the plains, in particular strike-slip faults, such as the Greendale Fault. Estimated slip rates on active faults in this part of Canterbury are $<< 2$ mm yr^{-1} (Pettinga et al. 2001; New Zealand Active Fault Database, http://data.gns.cri.nz/af/), consistent with the relatively low (c. 2 mm yr^{-1}) geodetic rate of deformation across the entire Canterbury Plains (Wallace et al. 2007). Also, seismic reflection studies prior to 2010 (e.g., Jongens et al. 2012) had not identified a subsurface expression of the Greendale Fault.

Fault mapping

Datasets used for fault mapping

The datasets used in our fault mapping comprise detailed field mapping, oblique aerial and ground-based photographs (e.g., Barrell et al. 2011), and survey measurements obtained during the weeks after the 4 September earthquake. We also used lidar images and corresponding aerial orthophotographs acquired 1 week after the earthquake (see examples in Fig. 2).

Our field measurements (Quigley et al. 2010a, 2012) (e.g., Fig. 2G) have been essential to assess the true width of deformation and fault extent that, in some cases, is not constrained by the lidar data. We mapped as many individual faults and fissures as possible in a few areas to assess the types of structures in the deformation zone before they were removed by recovery operations. However, due to recovery having been rapid, only a small proportion of the thousands of Greendale Fault surface rupture deformation features were accurately surveyed in the field. Instead, we relied upon the detailed aerial photography and lidar imagery to capture these features during subsequent desktop mapping. The resolution of the airborne datasets and the quality of the orthophotographs (Fig. 2) was not ideal and thus features with displacements < 0.3 m are likely to have been missed.

Fault features

We have classified the various mapped fault features according to their geomorphic expression as 'faults', 'fault scarps', 'suspected faults', 'broad fault scarps' and 'broad horizontal flexures' (Figs. 1D–1I). The term 'faults' includes features in which the ground was clearly opened such as fissures and strike-slip faults. The category 'fault scarp' refers to vertical step-like warps of the ground surface. These steps, or changes in elevation, may be purely the result of folding of the ground, or may include some folding in conjunction with discrete offsets along one or several faults. 'Suspected faults' include fissures and faults that we noted during the field mapping campaign, but did not examine in detail. Also within the 'suspected fault' category are subtle lineaments visible on the post-earthquake aerial photography or lidar imagery, but not obvious in the field. The 'broad fault scarp' category includes very wide (tens of metres) or very subtle (amplitude of less than c. 1 m vertical) vertical bends in the ground surface. The 'broad horizontal flexure' refers to distributed horizontal shearing over a wide band without the presence of individual surface faults. Most of these broad horizontal flexures were only revealed on account of human-constructed straight lines, such as roads, fences, etc., that were measurably bent.

The Greendale Fault surface rupture displays three sections of different geomorphic character (Figs. 1C–1I). The westernmost 7-km-long section is dominated by a single 'broad fault scarp' that changes in trend from N125°E to E–W (Figs. 1C, 1I). Along the section from 7 to 23 km (Figs. 1E–1H), most of the features mapped as 'faults', as well as some of the 'fault scarps', have three trends: N110–130°E, N161–180°E and N70–92°E. Other fault scarps are either reverse faults or folds (N29–65°E). Part of the deformation along the eastern and central sections was expressed as a 'broad horizontal flexure', as well as discrete faults and folds. The easternmost section (23–29 km) is defined uniquely by a single 'broad horizontal flexure' (Figs. 1C, 1D).

Defining the fault avoidance zone

In the MfE guidelines (Kerr et al. 2003), the hazard posed by fault rupture is quantified using two parameters: (1) fault location (extent of deformation), and (2) the average recurrence interval of surface rupture faulting. In this study, we focus only on the fault location. Two concepts are relevant for mapping the extent of the deformation, 'fault avoidance zone' (FAZ) and 'fault complexity'. A FAZ is defined in the MfE guidelines as 'an area created by establishing a buffer zone either side of the known fault trace'. The MfE guidelines recommend a minimum buffer zone width of 20 m either side of the fault trace. Fault complexity refers to the width and distribution of the deformed land defining the fault trace. The final FAZ includes the fault complexity area plus the 20 m setback. The FAZ concept encompasses and allows for the avoidance of minor distributed deformation in the vicinity of the fault.

The MfE guidelines recommend differing limitations on land development depending on the specific type of fault complexity. The fault complexity categories are given below:

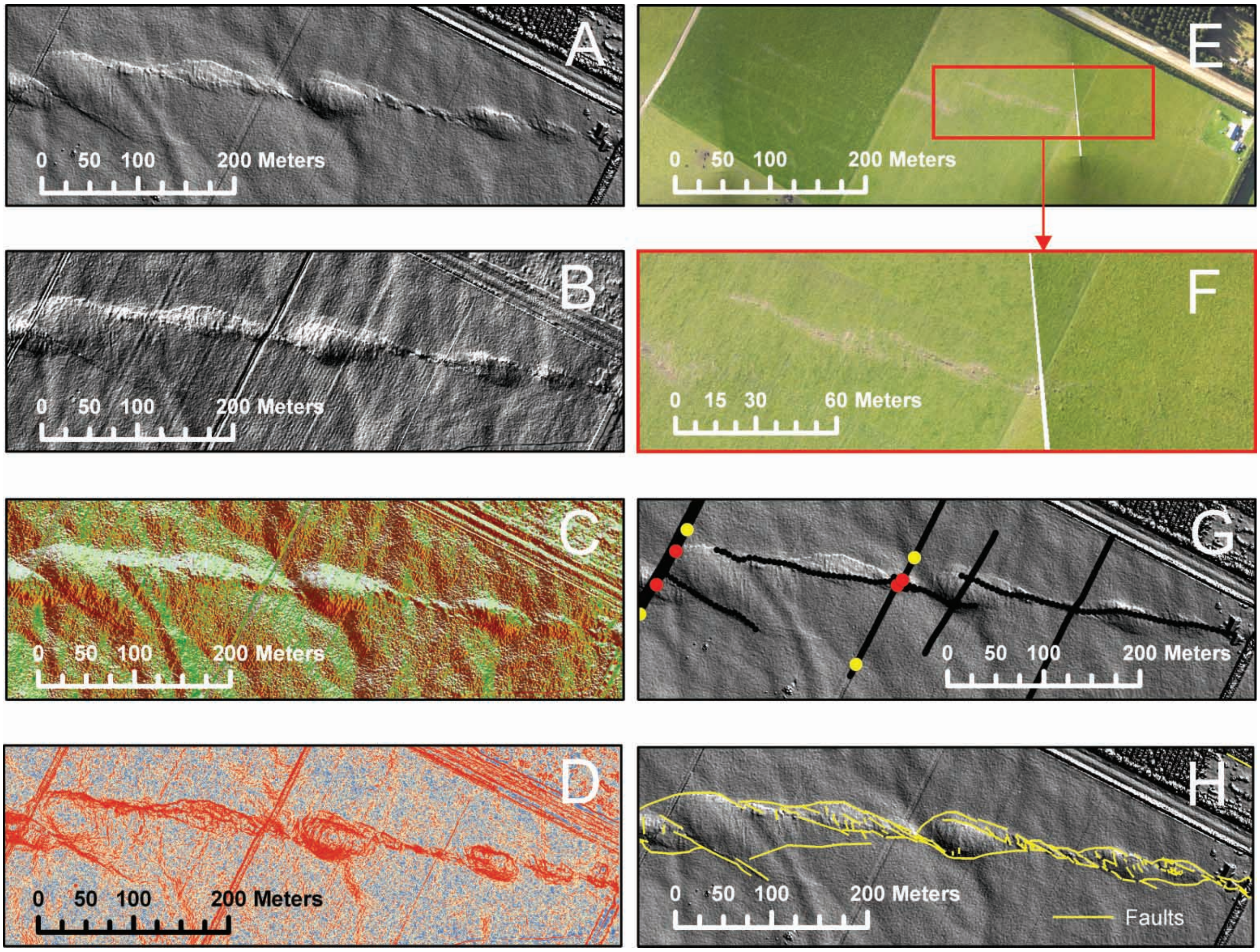

Figure 2 Orthophotographs and images obtained from the post-earthquake Digital Elevation Model produced with lidar data (0.5 m spatial resolution), and used to map ground features associated with rupture of the Greendale Fault. **A**, Hill-shaded relief image with illumination from the N45°E. **B**, Hill-shaded relief image with illumination from the N335°E. **C**, Aspect (orientation of the slope with respect to the north) image. **D**, Slope angle image. **E**, Orthophotographs (arrows indicate faults). **F**, Detail of 2E (arrows indicate faults). The quality of aerial photographs, acquired simultaneously with the lidar, was poor. Considerable ground shading by the plane and clouds resulted in many photographs being dark and of low contrast. A further disadvantage was that the direction of the sunlight enhanced only those features oriented north–south. **G**, Data collected in the field. Black lines are GPS surveys of man-made structures such as fences, roads and lifelines with real-time kinematic GPS equipment (Leica 550; resolution c. 2 cm) along the whole trace, as well as detailed surveys of most features at specific locations. Yellow and red dots indicate the 50% and 100% deformation, respectively, across each perpendicular profile. These were subsequently used to assess fault deformation width. **H**, Ground-surface features mapped using all datasets (A–G).

- Class A: Well defined: a well-defined fault trace of limited geographic width (typically metres to tens of metres wide).
- Class B: Distributed: deformation is distributed over a relatively broad geographic area (typically tens to hundreds of metres wide). Usually comprises multiple fault traces and/or folds.
- Class C: Uncertain: the fault trace has either not been mapped in detail or cannot be identified. This is typically a result of gaps in the trace(s), caused by erosion, or coverage of the trace(s).

We consider that the features categorised in our datasets as faults, fault scarps and broad fault scarps are sufficiently well delineated to qualify as 'well defined' fault complexity, whereas our broad horizontal flexures qualify as 'distributed' fault complexity. In addition, we have mapped some areas of 'distributed' or 'uncertain' fault complexity in zones where broad bulges were noted during fieldwork, and at some of the step-over areas along the fault trace (Fig. 3).

To define the FAZ, we first assigned an uncertainty in the location of the feature, and deformation associated with it. Many of the features that we represent as a single line

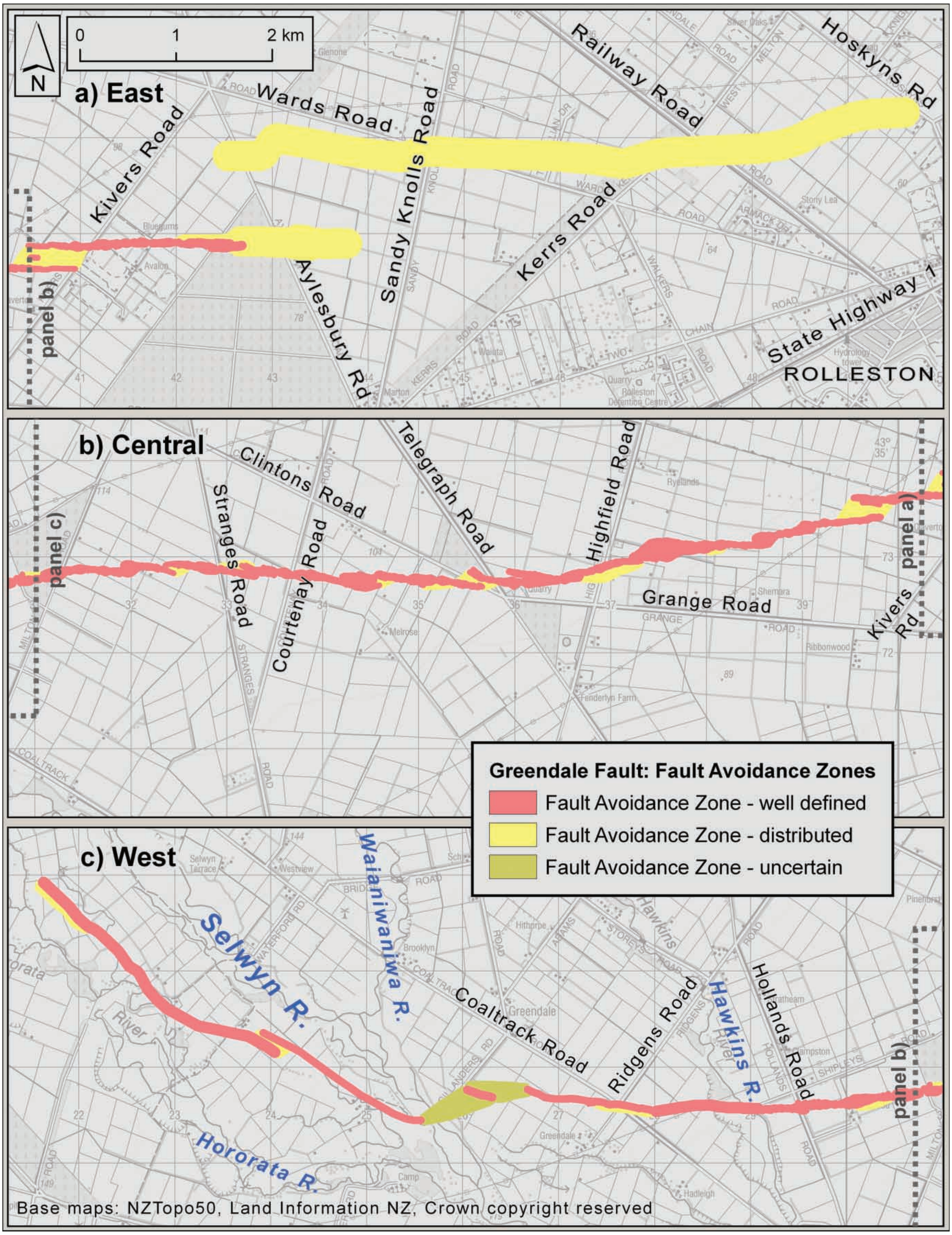

Figure 3 Fault avoidance zones (FAZ) defined for the Greendale Fault. See text for description of the FAZ types. The FAZ for the Greendale Fault consists of an eastern section c. 300-m wide that is characterised by moderately distributed deformation. The central section of the FAZ is narrower because many of the rupture features are well-defined. The western section is similar to the central section except for an uncertain zone around the step-over feature between the Selwyn River and Coaltrack Road.

actually have some width. For example a fault, in detail, is really an array of interlocking small fractures over a zone up to several metres wide (e.g., Ando & Yamashita, 2007). Because of resolution limitations of the lidar and aerial photographs, we consider that the locations of lines in our dataset are, at best, accurate to only ± 2 m, and in some cases, they may only be accurate to ± 5 m. For this reason, we generated a 10-m-wide envelope of uncertainty around the periphery of all our mapped 'well-defined' features. This envelope allows for the uncertainty in the mapping, as well as encompassing: (1) small features seen during the field campaign but which were not resolvable in the aerial photographs or lidar; and (2) broad deformation which extended beyond the mapped faults and bulges. For the broad scarps and broad horizontal flexures we used our field data to define the width of the deformation (e.g., Fig. 2G). After the location uncertainly zone was defined, we added 20 m of recommended setback to each of our mapped features to create the FAZ. Field measurements were then used to check that our delineated FAZs are wide enough to encompass all the observed deformation.

Discussion and conclusion

Fault kinematics

From a kinematics perspective, the mapped surface rupture presents typical tectonic structures associated with transpressional strike-slip faulting (e.g., Schreurs & Colletta 1998; Dooley et al. 1999). These features closely resemble those formed by sand box models (e.g., Dooley et al. 1999) and other historic strike-slip surface ruptures (Petersen et al. 2011). The three geomorphic sections (Fig. 1C) are a consequence of kinematic differences. The western 7-km-long section is a releasing bend, which suggests that the N125°E 'broad scarp' is an oblique normal and right lateral fault and the E–W one is a predominantly strike-slip fault with an oblique reverse component (Duffy et al. 2011). The section from 7 to 23 km is very complex, displaying several left steps with corresponding push-up structures. Along this section there are Riedel shears (N110–130°E), conjugate Riedel shears (N161–180°E), normal faults and fissures (N120–140°E) and some P thrusts (N70–92°E). Other faults scarps are either reverse faults or folds (N29–65°E) commonly associated with left steps. The eastern section is defined by a single broad horizontal flexure that is a monocline with a vertical axis.

Application to other faults

Several lessons learnt from the Greendale Fault rupture and detailed mapping can be used to aid in defining FAZs for other active faults. The lessons are particularly applicable to strike-slip faults that have not ruptured for thousands to tens of thousands of years, especially if they rupture through similarly thick alluvial gravel-rich deposits. First, the deformation widths mapped here provide an analogue for uncertainty of deformation width that could be expected elsewhere. Many of the mapped Greendale Fault features will become progressively less visible because of natural erosion, burial or human modification. However, the potential location of deformation features needs to be considered in fault avoidance maps. The geomorphic and kinematic analyses documented here can be applied elsewhere to assess potential locations of obscured deformation features, especially in areas of potential high fault complexity such as step overs.

Second, the true length of Greendale Fault surface rupture was only discovered because of the quick scientific response and careful field mapping. For example, the eastern section of the fault (Fig. 1) was only detected in the field as it is not visible on lidar images or aerial photographs. This implies that the length of fault ruptures that are thousands to tens of thousands of years old is likely to be underestimated. For those faults, assessment of the potential fault length beyond what is observable is justified, not only for definition of FAZ (this study) but also when earthquake magnitudes are derived from fault length (Quigley et al. 2010a,b, 2012).

Although detailed mapping of fresh surface ruptures is essential to improve knowledge on fault rupture and inform planners, not all features of the Greendale Fault rupture could be mapped due to insufficient field time or resolutional limitations of airborne imagery. For future surface-rupture earthquakes, in order to gain maximum knowledge benefit, we strongly recommend acquiring traditional high-resolution, low-altitude stereo-paired aerial photography immediately after the event, as well as higher altitude orthophotograph coverage, lidar and satellite images (e.g., Barnhart et al. 2011).

Land use planning

The precisely delineated FAZ in conjunction with the recurrence interval of the fault is currently being used to guide reinstatement of damaged buildings and he construction of new buildings in the area deformed by the Greendale Fault. A preliminary assessment suggests a recurrence interval for the Greendale Fault of ≥ 8000 yr based on review of pre-2010 aerial photography and lidar (Villamor et al. 2011). Applying the MfE guidelines, construction of residential buildings within the FAZ would be a permitted activity, but critical facilities such as buildings with post-emergency functions would be a non-complying activity and require resource consent (i.e., permission required for an activity that might affect the environment, and that is not allowed 'as of right' in the district or regional plan; http://www.legislation.govt.nz/act/public/1991/0069/latest/DLM230265.html). On-going studies of the recurrence interval of the fault may help to refine this further.

We hope that the example of fault rupture hazard mapping of the Greendale Fault presented in this paper will help promote and inform similar hazard mapping of other active faults in comparable settings elsewhere in New Zealand. FAZ mapping, in combination with thoughtful land use planning and engineering, not only facilitates life safety, but also has the potential to improve post-event functionality of important structures, including lifelines, where the consequences of surface fault rupture can be incorporated into resilient design (e.g., Honegger et al. 2004; Bray & Kelson 2006; Faccioli et al. 2008).

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