2005

Structural geomorphology and paleoseismicity of the Hope Fault

J. Dykstra Eusden
Bates College, deusden@bates.edu

Jarg R. Pettinga
University of Canterbury

Rob Langridge
GNS Science

Recommended Citation
Eusden, J.D., Pettinga, J.R. and Langridge, R., 2005, Structural Geomorphology and paleoseismicity of the Hope Fault: in Field Trip Guides for the Geological Society of New Zealand 50th Annual Conference, J.R. Pettinga and A. M. Wandres, eds., Geological Society of New Zealand Miscellaneous Publication 119B, p. 157-178.

50th Kaikoura05

The Organising Committee extends a warm welcome to all delegates and visitors to Kaikoura, where it all began 50 years ago.

Please note that all information in this publication was correct at the time of going to print. However, due to factors beyond our immediate control, such as weather, road conditions and permission for land access, some unexpected late changes in field trip routes and itineraries may be required.

Bibliographic References:

Programme & Abstracts Volume

A.N. Author (2005) What I did in my holidays. *In:* Pettinga, J.R. and Wandres, A.M. (eds.) Programme and Abstracts, Geological Society of New Zealand 50th Annual Conference, Kaikoura, New Zealand. Geological Society of New Zealand Misc. Publ. 119A, x-y p.

Field Trip Guide Volume

A.F.T. Leader (2005) A tour of my field area. *In:* Pettinga, J.R. and Wandres, A.M. (eds.) Field Trip Guides, Geological Society of New Zealand 50th Annual Conference, Kaikoura, New Zealand. Geological Society of New Zealand Misc. Publ. 119B, xx-yy p.

Geological Society of New Zealand

50th Annual Conference

28 November to 1 December 2005
Kaikoura Memorial Hall and Takahanga Marae
Kaikoura

Field Trip Guides

J. R. Pettinga and A. M. Wandres (Editors)

Organising Committee

Jarg Pettinga and Keith Lewis (Co - Conveners)
Anekant Wandres
Tim Davies
Kari Bassett
Jocelyn Campbell
Malcolm Laird
Margaret Bradshaw
Student Helpers

with administrative assistance from:

Janet Simes (Absolutely Organised Ltd)
Janet Warburton

Geological Society of New Zealand Miscellaneous Publication 119B
ISBN 0-908678-02-9

Field Trip Guides – Contents

Field Trip 7

STRUCTURAL GEOMORPHOLOGY AND PALEOSEISMICITY OF THE HOPE FAULT

J. Dykstra Eusden Jr[1] , Jarg R. Pettinga[2], and Rob Langridge[3]

[1]Department of Geology, Bates College, Lewiston, Maine, 04240, U.S.A.
deusden*bates.edu

[2]Department of Geological Sciences, University of Canterbury,
Private Bag 4800, Christchurch, New Zealand
jarg.pettinga*canterbury.ac.nz

[3]GNS Science, P.O. 30 368, Lower Hutt, New Zealand
R.Langridge*gns.cri.nz

PREAMBLE

The northeast trending dextral-reverse oblique slip Hope Fault is one of the major structures of the Marlborough Fault System and the Australia-Pacific plate boundary zone in the South Island of New Zealand. This fieldtrip presents an analysis of the structural and tectonic geomorphic development of the Hope Fault zone in the vicinity of the Charwell River to understand the near-surface temporal and spatial structural style of deformation and fault zone kinematics along a 10 km section of the fault. The Charwell region is a classic study area with respect to the interplay between active tectonics, tectonic geomorphology and surface processes.

We recognise four distinct types of fault scarps: (1) the main rangefront trace of the Hope Fault defines a releasing bend geometry, with a projected step-over width of c. 1000m; (2) thrust faults at the foot of the rangefront that ramp over the aggradational surfaces in the footwall block; (3) in the toe of the hanging wall block, c. 20 normal fault scarps are mapped near-parallel the main Hope Fault; and 4) more than 100 late normal faults are oblique to the main Hope Fault, and cut obliquely across all other faults. The overall fault pattern outlines an initial fault wedge between the thrust and early normal faults that is 5 km in length and 1 km at its widest point. A secondary wedge defined by the late normal faults is 7 km in length, 2 km at its widest, and it overprints the initial wedge. The structural/geomorphic interactions between the initial and secondary fault wedges developed in a series of at least four successive stages.

Exposures to be visited include the thrust fault ramp, the Main Normal fault and late stage normal faults. Landscape units that will be viewed include: (1) flights of aggradation-degradation terraces in the footwall forming an extensive piedmont; (2) fault dissected, sloping topography in the hanging wall containing 95% of all the faults; and (3) eroded subhorizontal piedmont terrace remnants that indicate the rangefront has repeatedly propagated to the southeast into the footwall block.

INTRODUCTION

This fieldtrip highlights a few of the spectacular features that define the structural development and subsequent wedge collapse of the oblique-slip Hope Fault in the vicinity of the Charwell River in the northeast South Island, New Zealand. The purpose of the fieldtrip is to observe the near-surface temporal and spatial structural style of deformation and fault zone kinematics along the Hope Fault within the context of a collapsing internal fault wedge, and in turn to relate that to the evolving landscape geomorphology in this active plate tectonic setting and unique geomorphic setting. For a complete description of the Charwell region structural geology and landscape geomorphology see Eusden et al. (2005).

Overview of Hope Fault

The Hope Fault of North Canterbury is part of the Marlborough Fault System of northeast-trending oblique strike-slip faults which, together with the Alpine Fault, compose the major features of the Australia-Pacific plate boundary zone in the South Island of New Zealand (Fig. 1). In the northern South Island, the Marlborough Fault System effectively acts as the plate boundary strike-slip transfer zone, linking the west-facing Hikurangi subduction margin in the northeast with the east-dipping oblique-slip Alpine Fault to the southwest (Pettinga & Wise 1994; Little & Jones 1998; Little et al. 1998; Pettinga et al. 1998; Nicol & Van Dissen

2002). The active deformation in the Marlborough Fault System is characterised by complex patterns of strain partitioning occurring in the upper crust dominated by four principal oblique-slip structures, which are, from northwest to southeast, the Wairau, Awatere, Clarence and Hope Faults. There has been a gradual temporal southeastward migration in the loci of strike-slip displacement across these faults in the late Quaternary, with the Hope Fault currently carrying the highest slip rates (Pettinga et al., 2001). This is a response to the southeastward development of the Marlborough Fault System over time.

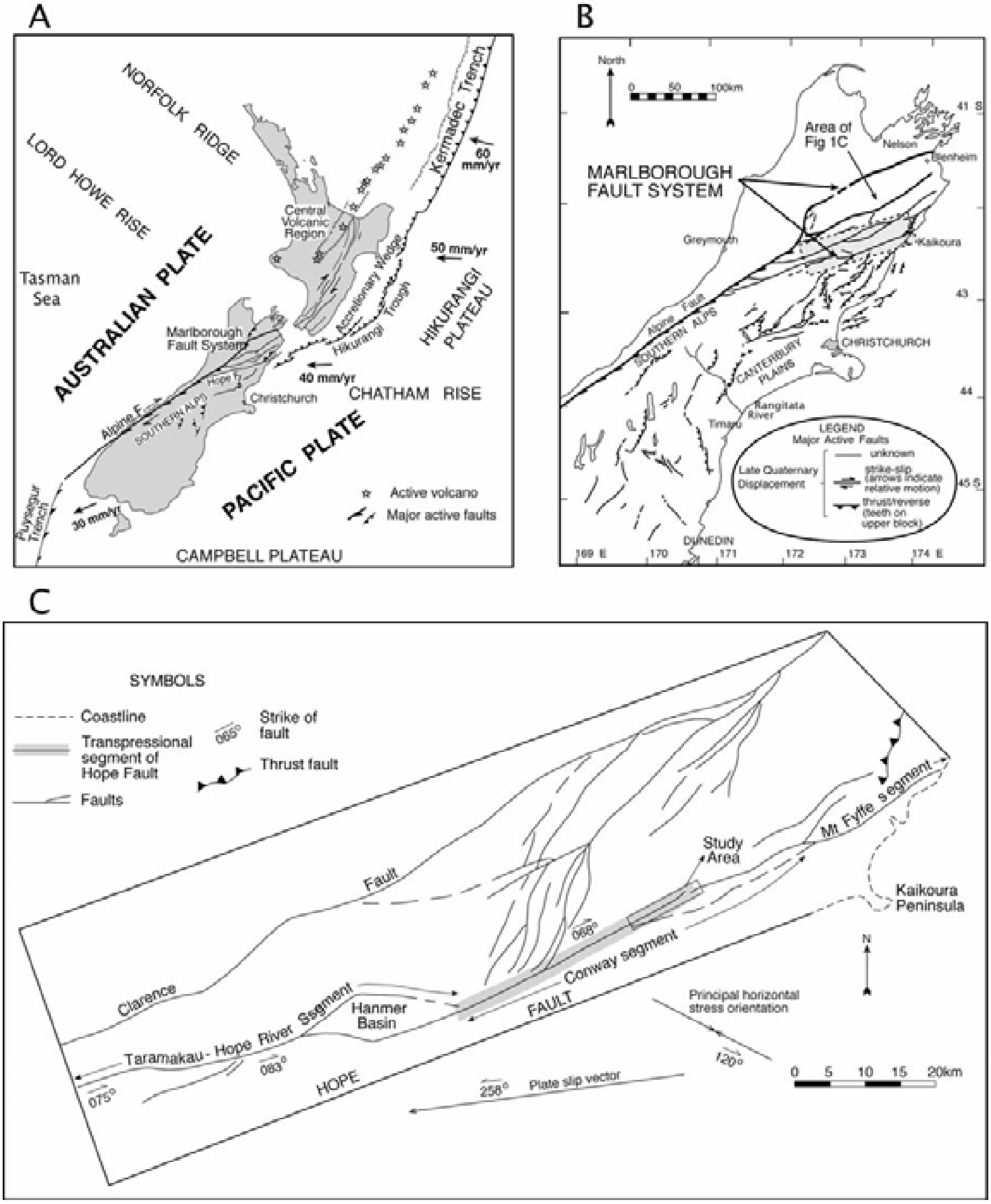


Figure 1: Location of the study area and general tectonic setting of the Hope Fault; A, Regional tectonic setting of New Zealand. B, Marlborough Fault System in the South Island. C, Hope Fault showing the strike of various segments of the fault, the Pacific plate motion vector, and principal horizontal stress orientation from Pettinga & Wise (1994) and Nicol & Van Dissen (2002).

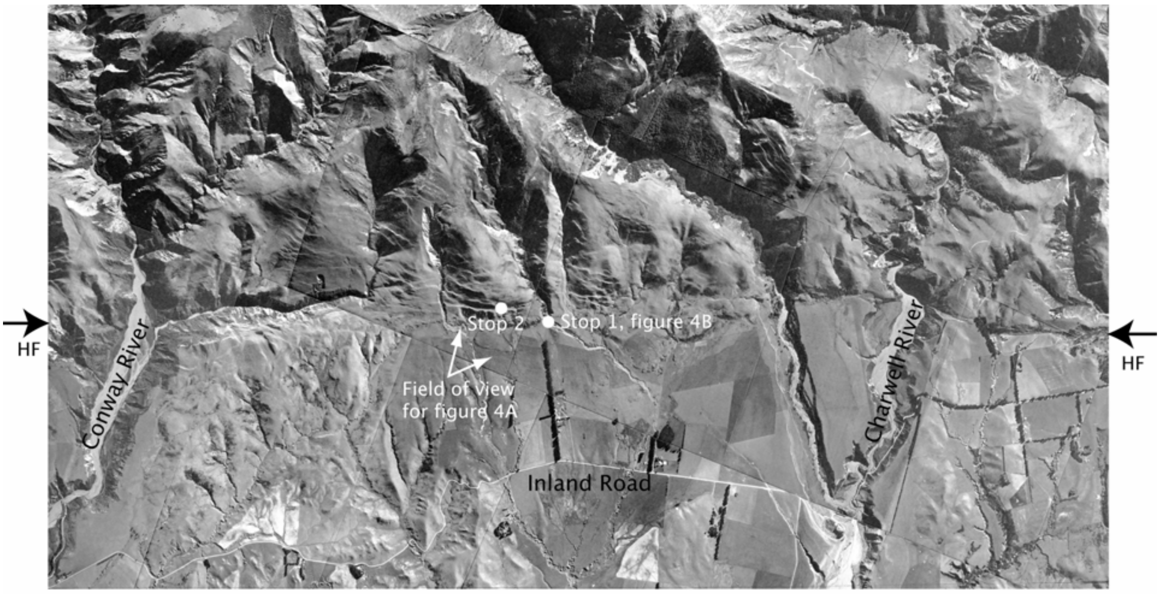
Charwell River Region

The Charwell River region of the Conway segment of the Hope Fault has a rich history of interdisciplinary study by soil scientists, geologists, biologists and geomorphologists and is a classic study area with respect to the interplay between active tectonics, tectonic geomorphology and surface processes. There has been considerable work done on: (1) slip rate calculations (Knuepfer 1984, 1992); (2) the relationships between tectonic uplift, climate change, and geomorphology (Bull & Knuepfer 1987; Bull 1991); (3) estimating ages of aggradation-degradation stream terraces using weathering rind dating (Knuepfer 1988); (4) lichen dating of earthquake generated rockfalls (Bull & Brandon 1998); (5) soil loess stratigraphic controls on piedmont development (Tonkin & Almond, 1998; Roering et al. 2002); and (6) structural development and landscape geomorphology (Eusden et al., 2005). Weathering-rind ages from greywacke cobbles exposed on terrace surfaces have been used to determine slip rates in the Charwell River (Knuepfer 1984; Bull 1991), Robson Creek, 9 km west of the Charwell (McCone 1989), Sawyers Creek, 6 km east of the Charwell (Van Dissen 1989) and Greenburn Stream , 4 km east of Charwell (Pope 1994; Langridge et al 2003). These slip rate calculations range from 33-23 mm/yr of horizontal displacement and 2.5 mm/yr vertical displacement over the past 40,000 yr for the Charwell River region of the Hope Fault. A conservative estimate of the ratio of strike-slip to dip-slip on this segment of the Hope Fault is c. 10:1.

INTERNAL FAULT WEDGE EFFECT

Integral to the structural analysis of this region is a model describing the stages of development of an internal fault wedge that attempts to explain what has always been an apparent paradox to field geologists working in the oblique structures of Canterbury. The paradox is that despite the known transpressive and predominately strike-slip nature of many of the oblique-slip faults, where one would predict that reverse fault geometries should exist, normal faults are commonly found in addition to the observed reverse and strike-slip faults. In many cases normal faults are far more common than reverse faults in these transpressive regions. The first stage of evolution in the wedge is dominated by reverse faults in a transpressive duplex (the internal fault wedge). Accompanying the development of the thrust faults are normal faults. The simplest geometric form of the internal fault wedge is one where the basal fault is the thrust and the roof fault is the normal fault. These two normally disparate fault types develop simultaneously as the wedge extrudes out of the oblique strike-slip fault zone. The next stage of development is characterised by collapse of the extruded fault wedge whereupon thrusts change slip direction to become normal faults and early normal faults continue to slip.

Because the oblique strike-slip faults are neither vertical nor purely strike-slip but have moderately steep dips toward the hanging wall and a component of reverse-slip, the development of the wedge leaves an unsupported region in the hanging wall which then undergoes gravitational collapse. As the fault continues to slip, newly propagating reverse and normal faults will develop and another wedge forms, leaving behind the collapsed portion of the fault. The newly propagating faults will develop principally into the footwall block, which effectively continually moves the range front position over time.



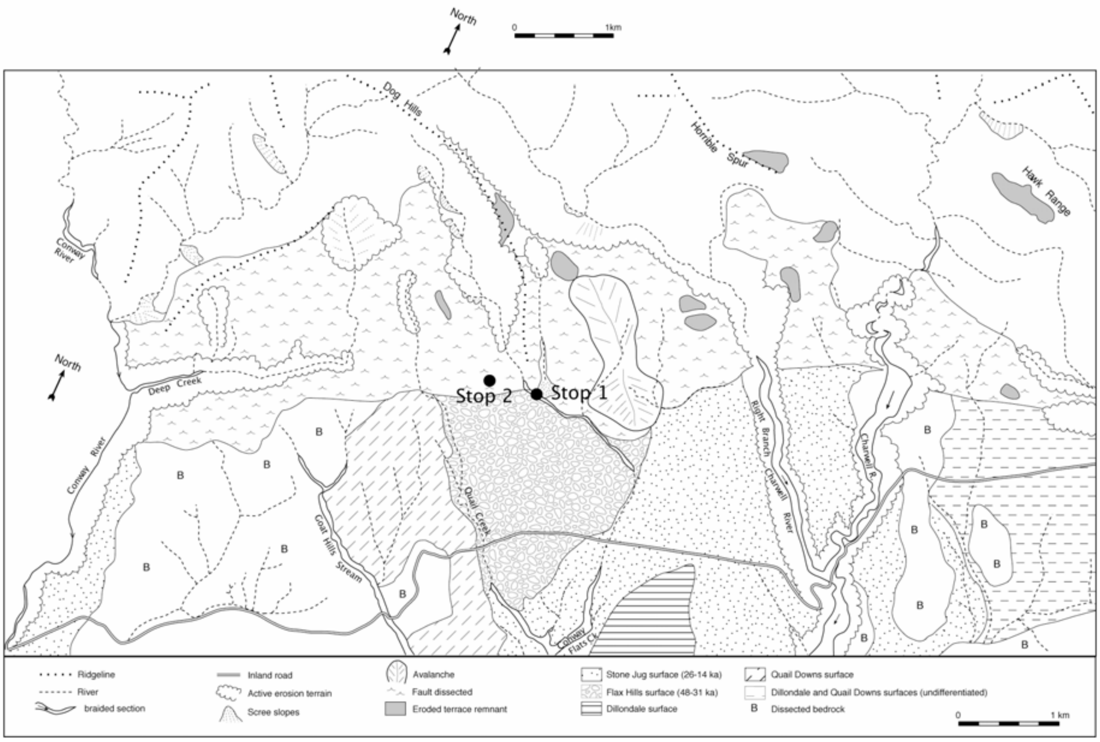


Figure 2 - top above: Airphoto mosaic of the study area. The Hope Fault strikes southwest-northeast through the study area. Principal drainages are the Conway River (major braided drainage in the southwest), and Left (west) Branch and main branch of the Charwell River (northeast portion of photo). Locations of ground level and aerial photographs shown with white arrows and letters/numbers.

Figure 3 - lower above: Landscape geomorphology map of the study area. (after Eusden et al. 2005)

BEDROCK GEOLOGY AND CHARWELL LANDSCAPE

The bedrock geology throughout the fieldtrip is composed of early Cretaceous Torlesse sandstone and argillite assigned to the Pahau Subterrane (Bradshaw 1989). The remainder of the geology consists of Quaternary-Recent deposits. These deposits are characterised by flights of aggradation/degradation surfaces and associated loess sheets deposited in former piedmont valleys of the Charwell River. The strike-slip displacements along the Hope Fault coupled with the climatically induced aggradation-degradation cycles left a relatively complete set of terrace surfaces that are well constrained temporally by radiocarbon, lichen and weathering-rind dating as well as soil loess stratigraphy. Figure 2 shows an airphoto mosaic of the study area and Fig. 3 shows the resulting landscape geomorphology map. For a complete discussion of each landscape unit in the Charwell region see Eusden et al. (2005).

FAULT SCARPS

On this field trip we will see all four designations of fault scarps that have been made in the Charwell region. These include : (1) those that are part of the main trace of the dextral reverse slip Hope Fault; (2) a small number of reverse and thrust faults; (3) normal fault scarps that parallel the main Hope Fault trace; and (4) numerous normal fault scarps that cut all other faults scarps and extend well into the hanging wall and footwall blocks. Figure 4 shows a map of all the fault scarps and a sequence of events diagram that illustrates the various developmental stages. For a full description of each fault scarp type please see Eusden et al. (2005).

DEVELOPMENT AND COLLAPSE OF THE FAULT WEDGE

The three main traces (western, central, and eastern sections) of the Hope Fault in the study area define a transpressional 23° releasing bend geometry. The thrust faults are close to (c. 10° off) what would be considered the predicted strike orientation for reverse-slip structures given the known direction of the principal horizontal stress (c. 120°, see Fig. 1) in the region (Pettinga & Wise 1994; Nicol & Van Dissen 2002). The normal faults parallel to the central section of the Hope Fault represent a paradox in that they are nearly in the same orientation as the thrust faults. The Main Normal Fault and the thrust faults outline an internal fault wedge located near the central section of the Hope Fault.

These faults are also obliquely cut by the late normal faults suggesting that some of the normal faults parallel to the central section of the Hope Fault may have developed simultaneously with the thrust faults. The late normal faults cut obliquely across all other faults and are the youngest faults to form in this system.

The overall pattern of the faults also defines a complex wedge-like geometry. There appears to have been an initial fault wedge located between the western and central sections of the Hope Fault. The outline of the initial fault wedge is shown on Fig.4A and is bracketed between the Main Normal Fault and the thrust faults. This wedge is c. 5 km in length and c. 1 km at its widest point. It tapers in both a westerly and easterly direction to c. 200 m in width. This geometry is consistent with an internal fault wedge model for an oblique strike-slip fault.

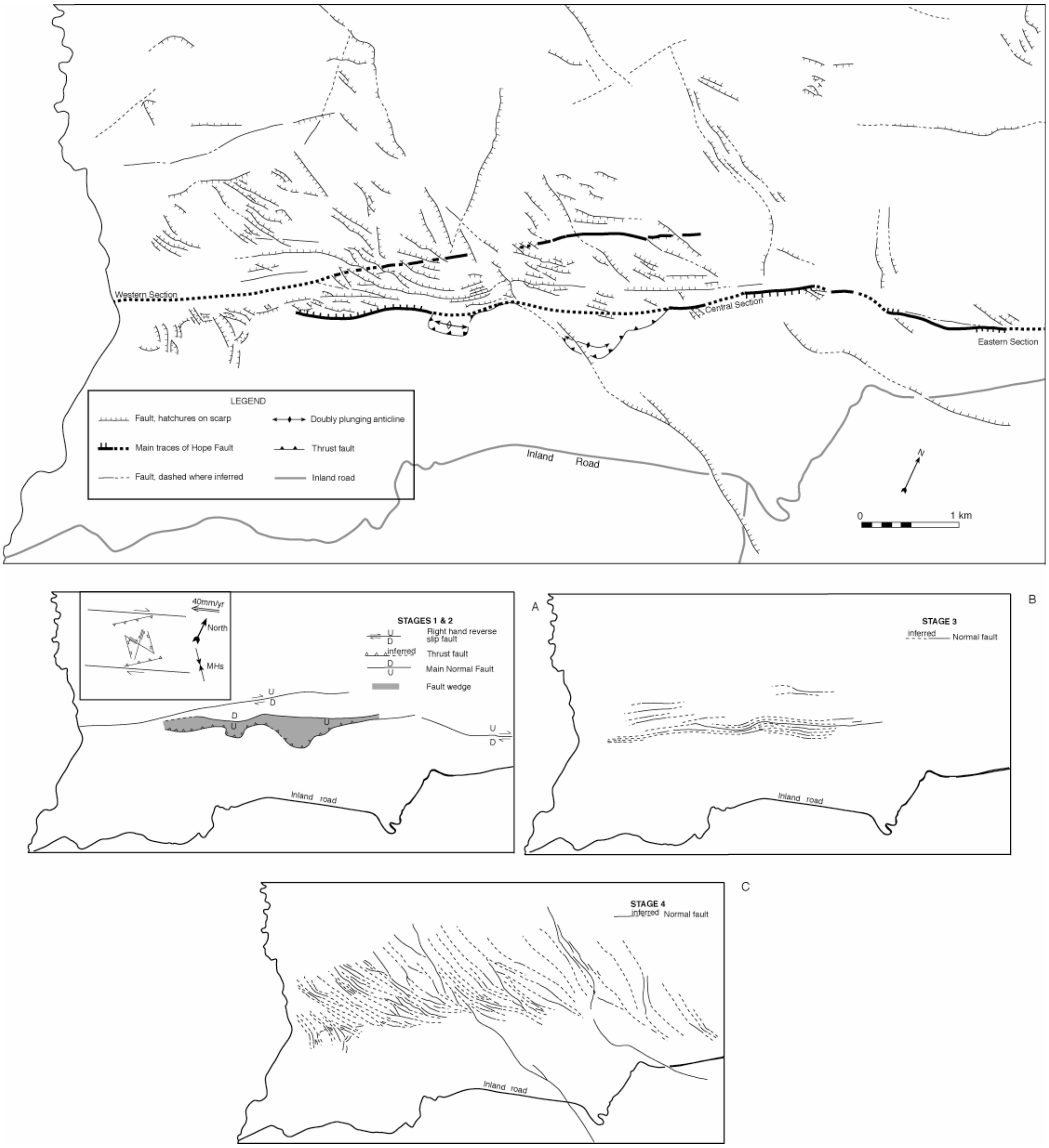


Figure 4: Main map shows the fault scarps of the study area. Three smaller maps show the reconstructed fault geometries in map view. A, Stage 1 and 2 fault pattern. Stage 1 includes the development of the western and eastern sections of the Hope Fault. Stage 2 is characterised by the development of the central section of the Hope Fault and the internal fault wedge between the thrust and Main Normal Fault as delineated by the diagonal line pattern. Insert shows the plate vector, mean horizontal stress (MHS), and expected thrust and normal fault orientations within a strike-slip system. B, Stage 3 fault pattern is characterised by normal faults that parallel the central section of the Hope Fault. These developed as the internal fault wedge collapsed gravitationally. C, Stage 4 fault pattern is dominated by numerous late normal faults that cut obliquely across all other faults. This region of late faulting defines the secondary wedge that formed as the entire hanging wall block collapsed (from Eusden et al. 2005)

Another wedge is also apparent and appears to have overprinted the initial wedge. This secondary wedge is loosely defined by the mapped extent of the late normal faults as shown on Fig.4C. This wedge begins along the central section of the Hope Fault and extends well up into the hanging wall block beyond the western section of the Hope Fault. It is c. 7 km in length and c. 2 km at its widest. This secondary fault wedge has a slight eastward-tapering geometry in both the intensity and width of late normal faults (Fig. 4C).

All of these observations suggest to us that the fault developed in a series of at least four stages (Fig 5) where the initial internal fault wedge was later overprinted by the secondary fault wedge. In Stage 1, the western section of the Hope Fault had developed and formed the range front position at the time (Fig. 5A). In Stage 2, the central section of the Hope Fault develops as a footwall propagating oblique-slip fault with accompanying thrusts and normal faults. The central section now becomes the active rangefront fault and the initial internal fault wedge is created between the thrust fault and the Main Normal Fault (Fig. 5A). In Stage 3, the initial wedge created between the thrust fault and Main Normal Fault in Stage 2 became unsupported and underwent gravitational collapse (Fig. 5B). The 10 or so normal fault scarps immediately next to and on the piedmont side of the Main Normal Fault developed during the collapse. The Main Normal Fault likely continued to slip in a normal fashion, which may explain why it has the longest and tallest scarp of all normal faults in the area. Stage 4 represents the final phase of development in this fault system and is characterised by a late, more extensive, wedge of collapse structures (Fig. 5C). The late normal faults that make up this secondary wedge responded to an opening of space in the hanging wall due to the motion of the fault blocks around the releasing bend. For more details concerning this model see Eusden et al. (2005).

FIELD STOP DESCRIPTIONS

Please note that we are crossing private lands owned by Geoff and Kath Jopp of Conway Downs Station. Permission must be obtained before visiting these localities. Access to the property is about 3 km SW of the Charwell River bridge on the Inland Road and about 40 km SW of Kaikoura.

Stop 1

As we approach the first stop, the obvious range front landscape marks what we have called the central section of the Hope Fault (Fig 6A). It has a strike of 060°, dips between 59° and 71°NW, is 5 km long and poorly defined because curved thrust faults, extending out into the footwall block, have significantly modified it. Of greater interest is a thrust that is curved, convex toward the footwall block, and surrounding small, rounded hills, extending 20-60 m above the Flax Hills aggradational surface. The hills are made of the deformed Flax Hills gravels that have been folded into doubly plunging, domal structures. The thrust fault is shown at the base of these hills due to the presence of very subdued, 0.25-2.0 m high scarps and numerous springs issuing from the base of the hills. These hills extend 200-600 m out into the footwall block. The thrust faults merge at depth with the central section of the Hope Fault . The thrust fault marks the base of the internal fault wedge that formed during Stage 2 and collapsed during Stage 3.

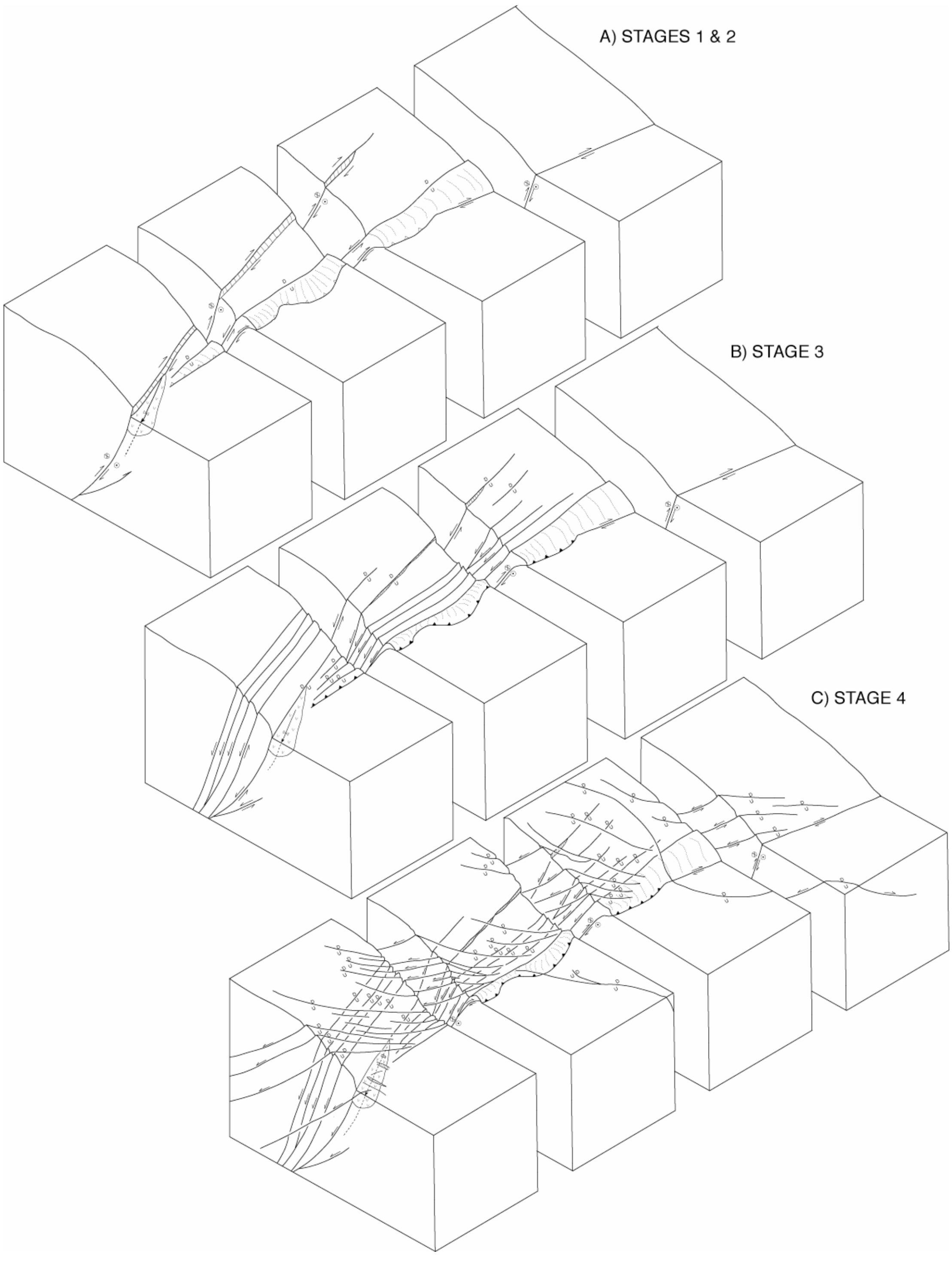


Figure 5: Three-dimensional schematic model for the development and modification of the Hope Fault in the Charwell River area. A, Stage 1 and 2 formation of the initial fault wedge. B, Stage 3, collapse of the initial wedge along normal faults parallel to the central segment of the Hope Fault. C, Initiation of the secondary fault wedge and late normal faults due to collapse of the entire hanging wall (from Eusden et al. 2005).

The thrust fault is exposed in the gravel bank of the Conway Flats Creek (Fig 6B). At the base of the outcrop, the fault cuts through shattered Torlesse Formation with a dip of 57°NW. It then shallows to a dip of 22°NW as it extends up through the overlying gravels. The dip separation in the gravels along the fault is 2.5 m. The gravels above the fault are folded into an asymmetric anticline and also dissected by three late normal faults and one back thrust.

Looking NE down the Hope Fault you can see one or more of the eroded sub-horizontal terrace remnants offset by the western section of the Hope Fault which formed during Stage 1. The interesting aspect of these eroded terrace remnants for this fieldtrip is that they exist in the hanging wall. Some of these were likely once piedmont, or footwall block, aggradation surfaces that have subsequently been uplifted and are now found in the hanging wall. Their presence suggests that the range front position, delineated by the active Hope Fault trace, has migrated over time, moving southeast towards the piedmont into the footwall block.

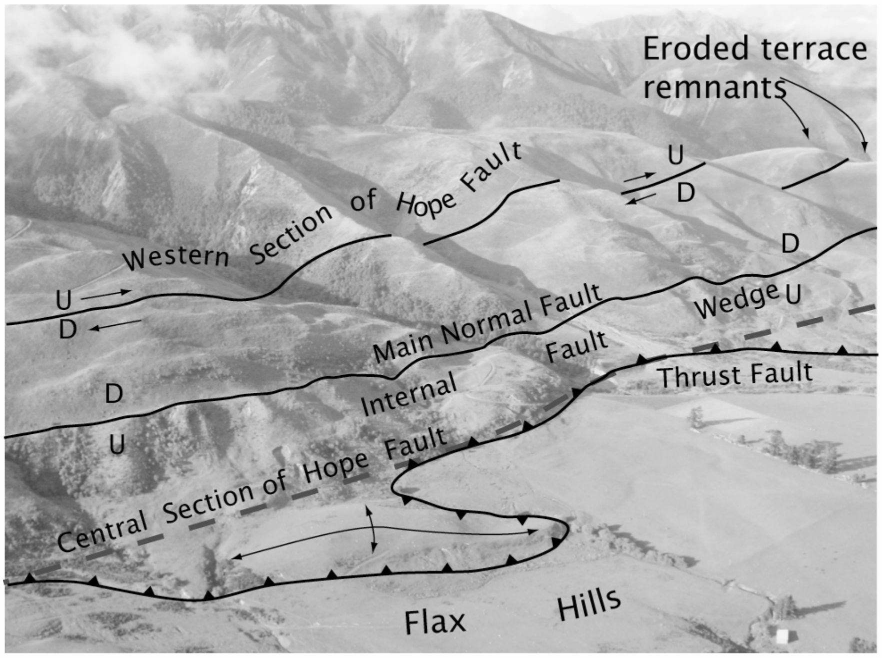
Stop 2

We continue uphill along the farm track to the Main Normal Fault which marks the top boundary of the internal fault wedge. This is one of about 20 normal fault scarps formed during Stages 2 and 3 that generally parallel the strike and dip of the central segment of the Hope Fault. The Main Normal Fault is the second longest continuous fault scarp in the study area, extending 4.2 km with a strike of 062°. This scarp consistently faces uphill with heights between 2 and 10 m. Four different exposures of faults in this category show shattered and or bedded Torlesse in the footwall and Quaternary-Recent gravels, tilted toward the piedmont, in the hanging wall. Dips average 70° NW and no strike-slip offsets of ridgelines, drainages, or any other geomorphic features have been observed along these faults.

Late normal faults formed during Stage 4 can be seen in the hanging wall above the Maine Normal Fault. Approximately 110 normal fault scarps have been mapped. These faults are the youngest in the area as they crosscut all other fault scarps described above. Many examples of this relationship can be seen on the airphoto mosaic (Fig. 3) The majority of these scarps are northwest of the central section of the Hope Fault. Their strikes systematically vary from c. 130° farthest from the Hope Fault, to c. 080° adjacent to the central section of the Hope Fault (Fig. 5A). Scarp heights are generally low, averaging c. 1 m or less. Scarp lengths are variable and range between 2 km and tens of metres. The majority (90%) of scarps in this category face uphill toward the north. Exposures of faults in this category show Torlesse in the footwall, and Quaternary-Recent gravels tilted toward the piedmont, in the hanging wall, confirming the normal slip separation. Dips on the faults range from 55° to 80°.

Looking east across the piedmont there are two late normal faults that extend well into the piedmont reach of the footwall block cutting across the Stone Jug aggradational surface. These are the longest and third-longest fault scarps in the study area with lengths of 4.5 and 3.1 km. Directly below is a good view of one of the doubly plunging antiformal hills formed by thrust faulting in Stage 2.

A



B

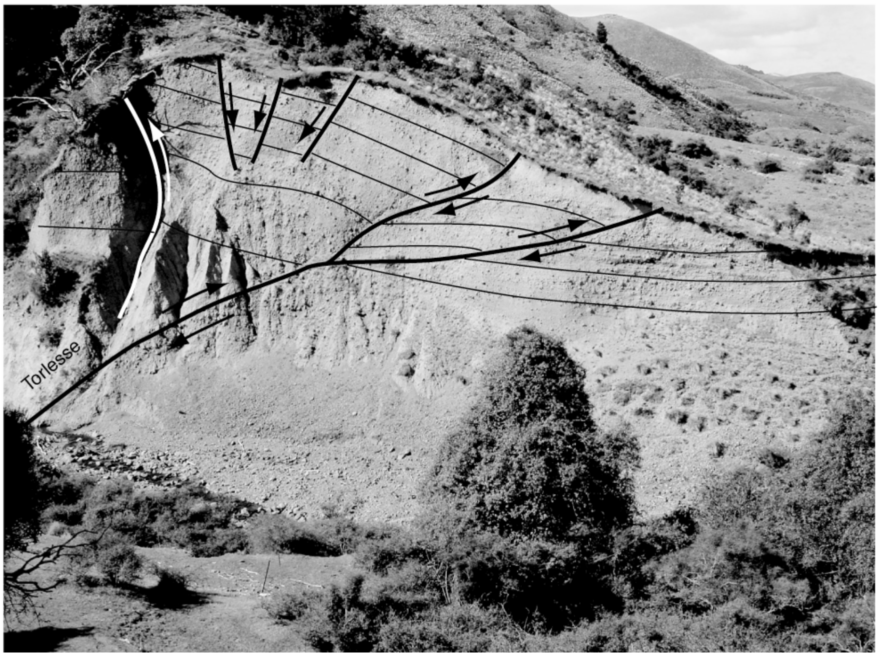


Figure 6: A, Oblique aerial photograph looking north across the Hope Fault. The western and central sections of the Hope Fault and the Main Normal and thrust faults are highlighted. A doubly plunging anticline floored by the thrust is seen overlapping the footwall block. The internal fault wedge is located between the Main Normal and thrust faults. B, Ground level photograph looking northeast of the western thrust fault exposed in deformed Flax Hills gravels. Line drawing of faults exposed in showing the thrust, several normal faults and one back thrust through the gravels (after Eusden et al. 2005).

THE GREENBURN STREAM SITE

In the valley of Greenburn Stream the Hope Fault has a clear mappable geomorphic trace visible in aerial photographs. The fault trace at Greenburn Stream is characterised by a linear uphill-facing scarp located at the base of the prominent rangefront of the Hawk Range, with an average strike of 072°. The Greenburn Stream trench site (NZMS 260 031/423678) is located c. 2 km west of Clarence Reserve (Pope 1994) and can be viewed from above at a highway turnout directly south of the site.

We will wander up the farm track on the true left bank of Greenburn Stream to the trench site to discuss the site geomorphology and surficial units, followed by an in-depth discussion of the results from two trench excavations. From there we will go down into Urquhart Stream to view the pug zone of the Hope Fault, 1-2 event dextral displacements and to consider the age of these last two events. We will finish up at Greenburn by walking up to another potential trench site.

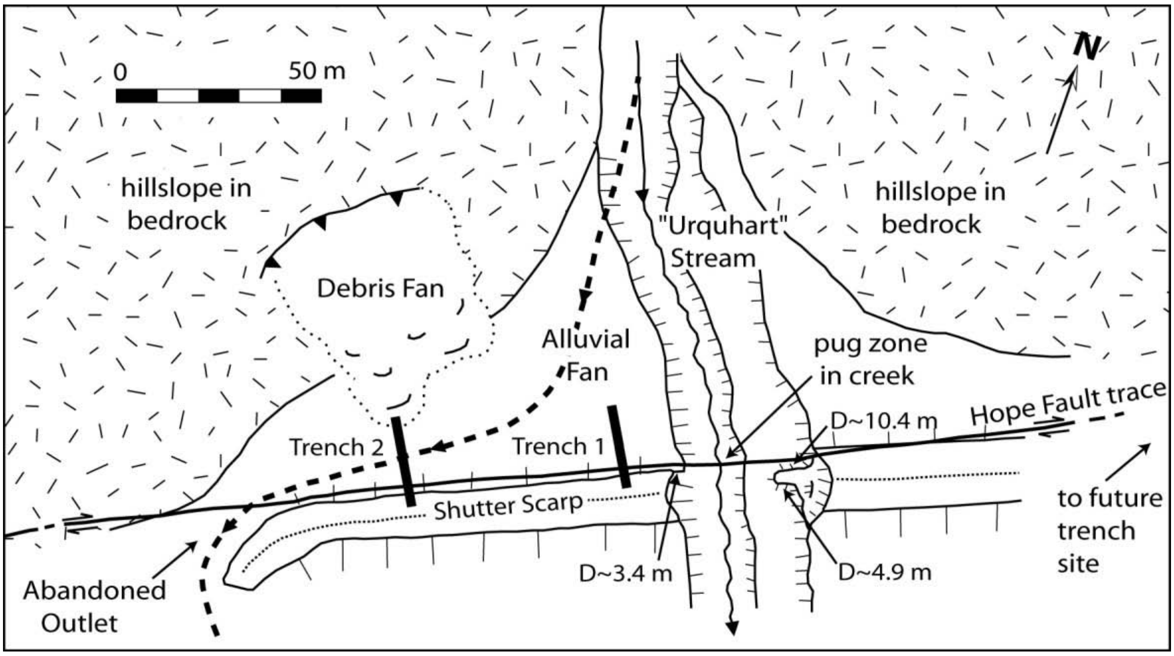


Figure. 7: Geomorphic map of the Greenburn Stream trench site (modified after Pope 1994). Modern incised Urquhart Stream crosses the fault but was formally dextrally deflected by 100-130 m and drained through the abandoned outlet. Small dextral displacements and the pug zone of the fault can be observed in the floor of the modern stream.

Two paleoseismic trenches were opened in 2001 at this site c. 700 m upstream from the Highway 70 bridge over Greenburn Stream. The trenches were excavated normal to the shutter scarp and adjacent trough formed along the fault trace, beside Urquhart Stream. The trenches and paleoseismic interpretation were previously described in Langridge et al (2003). The shutter scarp is cored by sheared greywacke basement (Torlesse Group), while the trough behind it had a fan-shaped morphology (Pope 1994)(Figure 7). Thus it was inferred that sediments in the trough were derived from the now-incised Urquhart Stream, which formerly had an outlet at the western end of the trough and shutter ridge. Near Trench 1, a number of greywacke sandstone clasts occur on the surface of the trough. A series of dextral displacements were measured between Greenburn and Sawyers Creek by Pope (1994) and an estimate of 5-6 m was derived for a single-event dextral displacement for the Hope Fault in this vicinity. This range is consistent with values at the site, in Urquhart Stream.

Trench 1 - Stratigraphy and slip rate

Paleoseismic trenches provide not only a record of young faulting and earthquake events, but also a record of young sedimentation and chronology. Before discussing the faulting, it is worth introducing Trench 1 in terms of the geomorphic setting that is described and the actual stratigraphy that was observed (Figure 8a).

Trench 1 (T1) was located c. 10 m from the west bank of Urquhart Stream, i.e. near the valley axis (Figure 7). T1 was 17 m long and up to 5 m deep from the top of the shutter scarp to the bottom of the trough exposure. The east wall of T1 was presented in Langridge et al (2003) (Figure 9). Subsequently a log of the west wall was completed and additional radiocarbon dates were undertaken (Langridge 2004). The trough deposits filled and were faulted against sheared scarp units. Trough fill consisted of moderately sorted and sub-angular fan gravels and interbedded sand to silt beds.

The beds appear to fine upward and fan toward the scarp, implying scarp-normal flow. However, the uppermost sequence (Channel Package; C1-C3) have channel cross-sections that are scarp-parallel. The maximum age of deposits in T1 comes from fine-grained charcoal in the lowest fine bed (Fs1) on the east wall (4409 ± 60 radiocarbon yr BP). One further radiocarbon date was undertaken on fan gravels above Fs1 in the east wall to confirm this date and the fan succession, yielding an age of 4168 ± 40 yr BP. No dateable material was found in the middle and upper "South Fan" deposits (MFs and UFs). Two other charcoal samples from near the top of the trench were dated. These come from the east and west walls within a paleosol developed on gravels underlying the young "Channel Package" units, and gave ages of 686 ± 40 and 809 ± 40 radiocarbon yr BP, respectively (Langridge 2004). Using the method of weathering rind thickness to determine the age of the surface cobbles above the modern soil yields an estimated age of 220 ± 60 yr BP (Pope 1994; Langridge et al 2003)(Figure 8a).

The 2-sigma calibrated age on Fs1 (4844-5288 cal yr BP) has been used in conjunction with the measured length of the shutter scarp (presumed deflection of paleo-Urquhart Stream) of 115 ± 15 m to calculate a slip rate for the Conway segment of the Hope Fault. Though the value of 23 ± 4 mm/yr is a maximum dextral slip rate, i.e. the date represents only a minimum age for the beginning of fan deposition against the shutter scarp, it is the first slip rate from this part of the Hope Fault that is derived using a radiocarbon date, as opposed to weathering rind determinations, e.g. Van Dissen (1989).

Trench 1 – faulting

The pattern of faults in T1 resembles an extensional fan, graben, or half-graben structure. These faults were clearly visible by the offset of the fine-grained interbeds within the fan gravel sequence (Figure 9). Faults in the shutter scarp are generally high-angle and dip to the northwest, toward the rangefront. When observed in cross-section such shutter scarps commonly have through-going faults that propagate to the outside of the shutter ridge (Campbell 2001), therefore, making the shutter ridge a kind of strike-sliver.

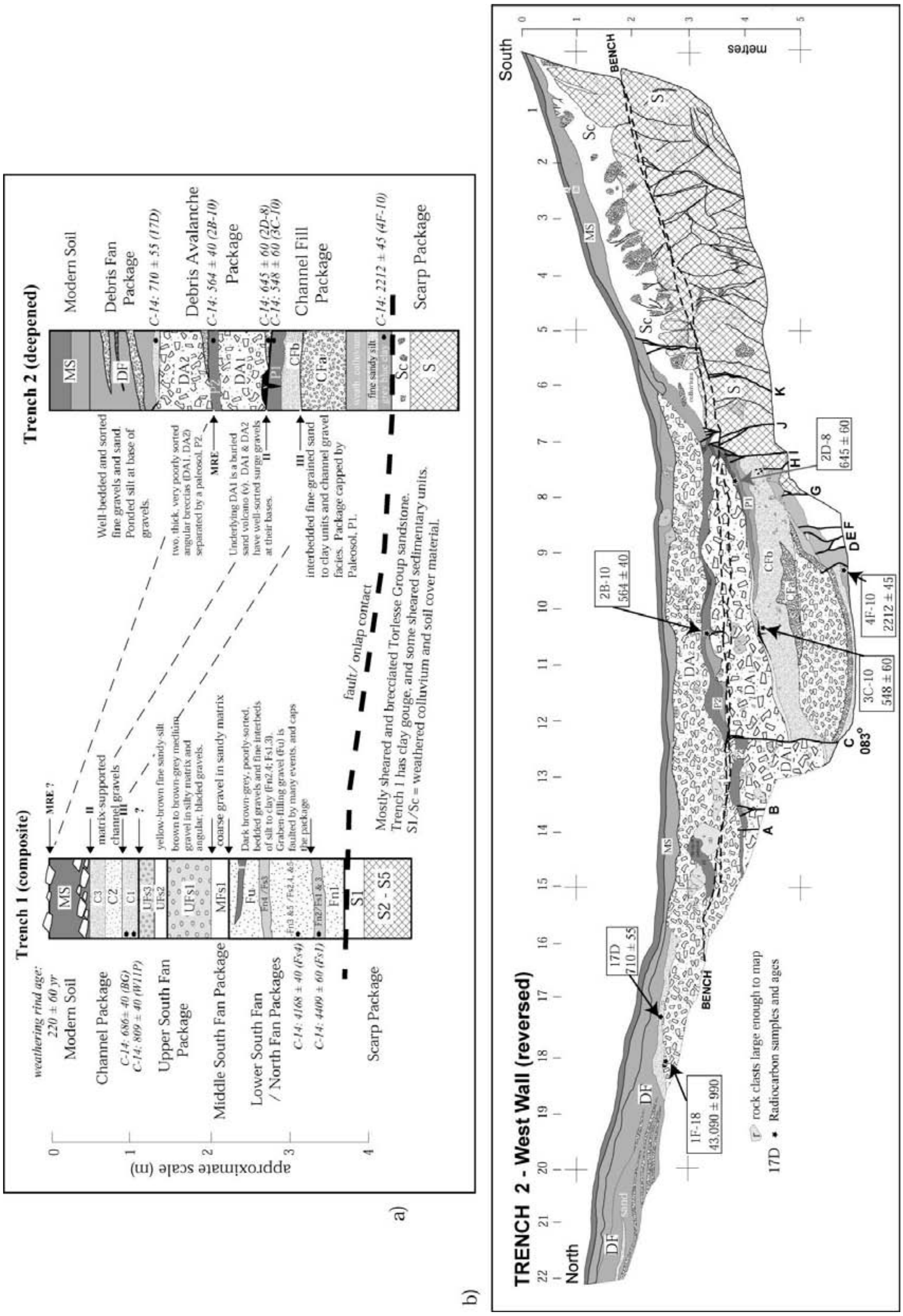


Figure 8: a) Summary of stratigraphy and dates from Trenches 1 and 2 at Greenburn Stream. Arrows and Roman numbers refer to earthquake event horizon positions. b) log of West wall of Trench 2 (modified after Langridge et al 2003). After deepening within the central fault zone and basin, further event horizon, age control and a liquefaction sand source were discovered.

However, the greatest amount of deformation observed in T1 occurs in the late Holocene sediments of the shutter basin. Northwest-dipping faults predominate from metres 1-11. Some of these faults cut the lower South Fan deposits, but not those units above this level, thus providing some structural and paleoseismic control. Northwest of metre-11, faults dip to the southeast with medium to high dip angles (40-70º).

The most recent faulting event (MRE) is observed by the truncation of units C1/C2 and the modern soil by fault B. (Fig. – a). This event is bracketed by the age of the surface clasts near mtr-8 (if they arrived on the ground surface from an event-related debris avalanche) and the youngest radiocarbon age in the trench (684 ± 40 yr BP). This places the MRE in T1 at AD 1269-1840.

There is further evidence for bending and faulting of the Channel Package that may have all occurred before the development of the modern soil. If correct, this implies there have been two or three rupture events in T1 since the burial of the P1 paleosol (809 ± 40; AD 1163-1284) on the west wall, or 686 ± 40 (AD 1269-1394) on the east wall. Without doubt, faulting relations show there have been at least two events since AD 1269.

Trench 2 - stratigraphy

Trench 2 was excavated c. 60 m west of T1 near the outlet of the formerly deflected Urquhart Stream (Langridge et al 2003). There is a significant contrast in the styles of sedimentation (and structure) between the two trenches (Figure 8a). The presence of landslide geomorphology in the land surface is mirrored by the occurrence of three major debris deposits in the upper part of the trench stratigraphy that are derived, not from the shutter scarp, but from the rangefront hillslope facing the shutter ridge.

The uppermost (DF) deposits in the north are bedded debris fan deposits of the surficial debris lobe. Underlying this is a thick debris avalanche unit (DA_2). A modern soil overlies DF and DA_2. Another soil/silt (P2) and debris avalanche (DA_1) pair underlie DA_2. DA_1 overlies a ponded silt to soil transition (paleosol 1; P1) that has formed on fine to medium scarp-parallel channel deposits. Deepening of T2 in 2002 exposed a thick cobble channel gravel at the base of this channel sequence, overlying fine-grained units (Figure 8b). The morphology of these units and the radiocarbon dates above (e.g. 645 ± 80 yr BP) and below them, imply that this is the same channel package as observed in T1. If so, the channel package has thickened, coarsened and deepened along the length of the shutter basin and has been completely buried at T2 by the DA and DF deposits. Using the survey data and stratigraphy suggests that a gradient of only 0.5-1.5º would be necessary to correspond the scarp-parallel channels from T1 to T2. The basal units in the deepened T2 were a grey blue clay and a fine sand deposit. Wood from the lowest unit in the trench gave a radiocarbon age of 2212 ± 45 yr BP.

No deposits with the texture and angularity of the fan deposits, or with an age of >4000 yr, were exposed in T2. Presumably, these occur below the level of our trench. The implications of several exposures along the shutter basin are that: (i) the paleo-gradient of the channel package can be estimated (0.5-1.5°); (ii) the outlet must have been lower than at present, and (iii) that the first of two large debris avalanches must have blocked the exit of the deflected stream.

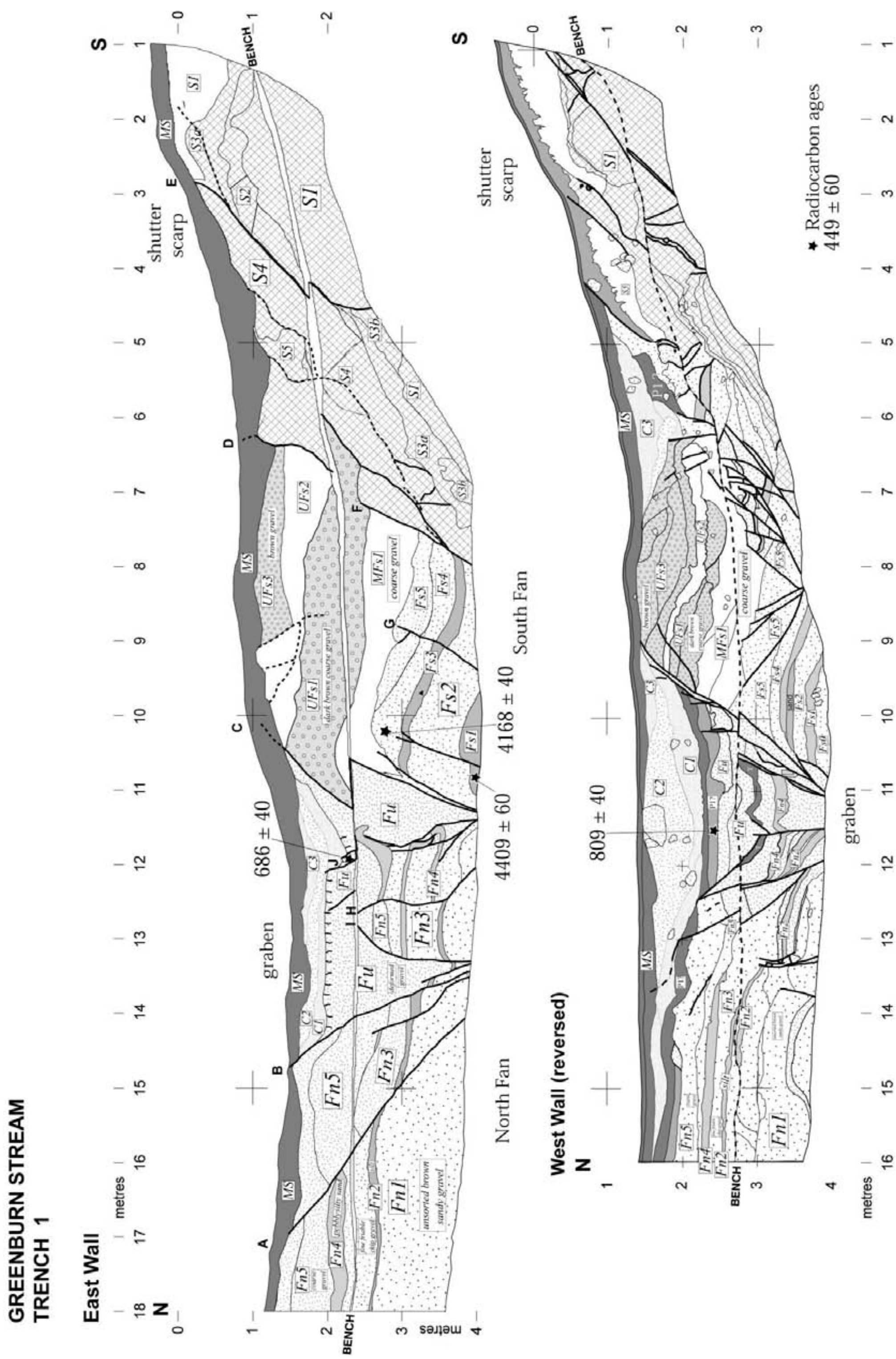


Figure 9: Logs of the east and west wall of Trench 1. The east wall is presented in Langridge et al (2003). The west wall and new radiocarbon dates are presented here. The trench shows a record of c. 4500 yr of faulting on the Hope Fault. See stratigraphic column for unit descriptions.

Trench 2 – faulting

Faulting in T2 is considerably less complex than in T1 due in large part to the younger sequence of deposits encountered within the range of excavation (Figure 8b). The thick units, separated by soils or ponded silts and the coseismic nature of deposits make the identification of earthquake events straightforward.

The most recent event (MRE) faulting cuts all units below and including paleosol 2 (P2). The faulted ground surface was rapidly overlain by debris avalanche DA_2 and more gradually by deposits of the debris fan, DF. There are some problems with using the radiocarbon dates in this trench due to reworking and residence time of charcoal. However, regardless of these issues we can state that a weakly nutty modern soil has developed over DA_2 and DF since the MRE. The amount of soil development is consistent with the fact that there is no documented surface faulting or large earthquakes in this part of NZ since AD 1840.

The penultimate event (PE) faulting has a similar set of structural relations. Fault I clearly cuts Paleosol 1 (P1), but not DA_1. P1 is overlain near mtr-10 by a suite of coseismic deposits. Immediately above the organic ponded sediment (P1 equivalent) is a dome-shaped sand interpreted as a remnant sand volcano derived from liquefaction (Langridge et al 2003). Overlying the sand volcano are surge gravels and the debris avalanche DA_1. Charcoal taken from P1 has an age of 548 ± 60 radiocarbon yr BP (AD 1279-1407). Several other samples from this trench have overlapping calibrated age ranges with this sample suggesting significant residence of charcoal in this time period, or that big old trees have been burned close to the site. However, being both the youngest and lowest of the C-14 samples, this date implies that two events have occurred since c. AD 1295.

The antepenultimate (APE) event faults units up to and including the base of the cobble channel gravel. The lower limiting age on this event is 2212 ± 45 yr BP. This event probably correlates to the third event back in T1.

Conclusions – Seismic hazard

An in-depth discussion on how the dextral slip rate (<23 ± 4 mm/yr) was derived is outlined in Langridge et al (2003). In combination with the single-event displacement estimate of 5-6 m (Pope 1994), the average recurrence time of large surface faulting events observed at the Greenburn Stream site is at least 180-310 yr (Langridge et al 2003). These authors also suggest an age of AD 1780 ± 60 yr for the MRE faulting, i.e. immediately prior to the European colonisation of South Island. There are no reports of large earthquakes in historical accounts of Kaikoura, despite it being a whaling station before 1840 (Sherrard, 1966). Bull (2003) suggests that large earthquakes occurred on the Hope fault around AD 1742 ± 10 yr and AD 1834 ± 10 yr. Nevertheless, the current recurrence interval should be at least 165 yr (i.e. from AD 1840). It has not been possible to confidently date either the exact number of events in the last c. 700 yr and the age of the penultimate event. Depending on whether there are two or three events during this period, i.e. from AD 1295 to 1840, the recurrence time from paleoseismic data is up to 277-555 yr. Using the Wells and Coppersmith (1994) relations in association with the rupture length (70 km Kahutara River to Waiau River) and displacement estimates results in an earthquake magnitude estimate of M 7.2-7.3. Though this magnitude seems low compared to other NZ earthquakes, in association with the short repeat times for the Conway segment it implies that this region will experience strong ground motions at relatively short intervals, from the Conway segment, other segments of the Hope Fault, or from other nearby earthquake sources in Marlborough and North Canterbury.

REFERENCES

Aydin, A.; Nur, A. 1982: Evolution of pull-apart basins and their scale independence. *Tectonics 1*: 95-105.

Armstrong, M. J. 2000: Geomorphological and geophysical investigation of the effects of active tectonic deformation on the hydrogeology of North Culverden Basin, North Canterbury. Unpublished Geology Ph.D. thesis, University of Canterbury Library, Christchurch, New Zealand.

Barnes, P.; Audru, J. C., 1999: The offshore Hope Fault and related structures between Marlborough and the southern Hikurangi margin. *In*: Subduction systems and process in New Zealand: Programme and Abstract Volumes, New Zealand Geophysical Society Symposium.

Berryman, K. R.; Beanland, S.; Cooper, A. F.; Cutten, H. N.; Norris, R. J.; Wood, P. R. 1992: The Alpine fault, New Zealand: variation in Quaternary structural style and geomorphic expression: *Annales Tectonicae, VI*: 126-163.

Bradshaw, J. D. 1989: Cretaceous geotectonic patterns in the New Zealand region. *Tectonics 8*: 803-820.

Bull, W. B. 1991: Geomorphic responses to climate change. Oxford University Press, New York. 326 p.

Bull, W. B. 2003: Lichenometry dating of coseismic changes to a New Zealand landslide complex. *Annals of Geophysics 46,* 1155-1168.

Bull, W. B., Knuepfer, P. L. K. 1987: Adjustments by the Charwell River, New Zealand, to uplift and climatic changes: *Geomorphology, v. 1*: 15-32

Bull, W. B., Brandon, M. T. 1998: Lichen dating of earthquake generated regional rockfall events, Southern Alps, New Zealand. *Geological Society of America Bulletin 110*: 60-84.

Campbell, J. 2001: The Hope Fault. Field Trip Guide, International Lithosphere Program, Ten Years in Paleoseismology in the ILP, Kaikoura, New Zealand, December 2001, 31 pp.

Clayton, L. 1966: Tectonic depressions along the Hope Fault, a transcurrent fault in north Canterbury. *New Zealand Journal of Geology and Geophysics 9*: 95-104.

Clayton, L. 1968: Late Pleistocene glaciations of the Waiau valley, north Canterbury. *New Zealand Journal of Geology and Geophysics 11*: 753-767.

Cowan, H. A. 1989: An evaluation of the Late Quaternary displacements and seismic hazard associated with the Hope and Kakapo Faults, Amuri District, north Canterbury. Unpublished MSc Engineering Geology Thesis, University of Canterbury Library, Christchurch, New Zealand.

Cowan, H. A. 1990: Late Quaternary displacements on the Hope Fault at Glynn Wye, North Canterbury. *New Zealand Journal of Geology and Geophysics 33*: 285-293.

Cowan, H. A. 1991: The North Canterbury earthquake of 1 September, 1888. *Journal of the Royal Society of New Zealand 21*: 1-12.

Cowan, H. A.; McGlone, M. S. 1991: Late Holocene displacements and characteristic earthquakes on the Hope River segment of the Hope Fault, New Zealand. *Journal of the Royal Society of New Zealand 21*: 373-384.

Cowan, H. A.; Nicol, A.; Tonkin, P. 1996: A comparison of historical and paleoseismicity in a newly formed fault zone and a mature fault zone, North Canterbury, New Zealand. *Journal of Geophysical Research 101*: 6021-6036.

DeMets, C.; Gordon, R. G.; Argus, D.; Stein, S. 1990: Current plate motions. *Geophysical Journal International 101*: 425-478.

DeMets, C.; Gordon, R.G.; Argus, D.; Stein, S. 1994: Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions. *Geophysical Research Letters 21*: 2191-2194.

Eusden, J. D.; Pettinga, J. R.; Campbell, J. K. 2000: Structural evolution and landscape development of a collapsed transpressive duplex on the Hope Fault, North Canterbury, New Zealand: *New Zealand Journal of Geology and Geophysics 43*: 391-404.

Freund, R. 1971: The Hope Fault: a strike-slip fault in New Zealand. New Zealand Geological Survey Bulletin 86.

Knuepfer, P. L. K. 1984: Tectonic geomorphology and present-day tectonics of the Alpine shear system, South Island, New Zealand. Unpublished Ph.D. thesis, Univ. of Arizona, U.S.A.

Knuepfer, P. L. K. 1988: Estimating ages of late Quaternary stream terraces from analysis of weathering rinds and soils: *Geological Society of America Bulletin 100*: 1224-1236.

Knuepfer, P. L. K. 1992: Temporal variations in latest Quaternary slip across the Australian-Pacific plate boundary, northeastern South Island, New Zealand. *Tectonics 11*: 449-464.

Langridge, R.M. 2004: How is tectonic slip partitioned from the Alpine Fault to the Marlborough Fault System? – Results from a FRST Post-Doctoral Fellowship, *Institute of Geological & Nuclear Sciences science report* 2004/32. 18 p.

Langridge, R. M.; Campbell, J.; Hill, N.; Pere, V.; Pope, J.; Pettinga, J.; Estrada, B.; Berryman, K. 2003: Paleoseismology and slip rate of the Conway segment of the Hope Fault at Greenburn Stream, South Island, New Zealand. *Annals of Geophysics 46*: 1119-1140.

Lensen, G. J. 1963: Geological Map of New Zealand 1:250,000. Sheet 16, "Kaikoura". N.Z. DSIR, Wellington.

Little, T. A.; Jones, A. 1998: Seven million years of strike-slip and related off-fault deformation, northeastern Marlborough fault system, South Island, New Zealand. *Tectonics 17:* 285-302.

Little, T. A.; Grapes, R. H.; Berger, GW. 1998: Late Quaternary strike-slip on the eastern part of the Awatere Fault, South Island, New Zealand. *Geological Society of America Bulletin 110*: 127-148.

Mann, P.; Hempton, M. R.; Bradley, D. C.; Burke, K. 1983: Development of pull-apart basins. *Journal of Geology 91*: 529-554.

McCalpin, J. 1996: *Paleoseismicity*, Academic Press, 588 p.

McCone, R. J. 1989: Aspects of deformation and secondary structures associated with the Hope Fault, inland Kaikoura. Unpublished MSc thesis, University of Canterbury

Library, Christchurch, New Zealand.

McMorran, T. J. 1991: The Hope Fault at Hossack Station east of Hanmer Basin, North Canterbury. Unpublished MSc thesis, University of Canterbury Library, Christchurch, N.Z.

Nash, D. B. 1986: Morphologic dating and modeling degradation of fault scarps, In *Active Tectonics*: National Academy Press,Washington, D.C., p. 181-194.

Nicol, A.; Van Dissen, R. 2002: Up-dip partitioning of displacement components on the oblique-slip Clarence Fault, New Zealand: *Journal of Structural Geology 24*: 1521-1535.

Norris, R. J; Cooper, A. F. 2001: Late Quaternary slip rates and slip partitioning on the Alpine Fault, New Zealand. *Journal of Structural Geology 23*: 507-520.

Pettinga, J. R. 2002: Active tectonics and landscape evolution in the Australia-Pacific plate boundary zone, northern South Island, New Zealand: Field Trip Guide for trip Mid 4, Gondwana 11 Conference, Canterbury University, Christchurch, New Zealand, 25 p.

Pettinga, J. R.; Wise, D. U. 1994: Paleostress orientation adjacent to the Alpine Fault of New Zealand: broader implications from fault analysis near Nelson, South Island, N.Z.. *Journal of Geophysical Research, 99/B*: 2727-2736.

Pettinga, J. R.; Chamberlain, C. G.; Yetton, M. D.; Van Dissen, R. J.; Downes, G. 1998: Earthquake source identification and characterization: Report for the Canterbury Regional Council, Rivers and Coastal Resources, and Hazards Section, CRC Publ. No. U98/10.

Pettinga, J. R.; Yetton, M. D.; Van Dissen, R. J.; Downes, G. 2001: Earthquake source identification and characterization for the Canterbury Region, South Island, New Zealand. *Bulletin of the New Zealand Society for Earthquake Engineering 34*: 282-317.

Pope, J. G. 1994: Secondary structures, Holocene displacements and paleoseismicity of the Conway segment of the Hope Fault, Greenburn Stream to Sawyers Creek. Unpublished BSc(Hons) project, Geological Sciences Library, University of Canterbury, Christchurch, New Zealand.

Roering, J. J.; Almond, P.; Tonkin, P.; McKean, J. 2002: Soil transport driven by biological processes over millenial timescales. *Geology 30*: 1115-1118.

Simpson, R. J. 1995: The Seaward segment of the Hope Fault, Seaward Kaikoura Ranges, Southeast Marlborough. Unpublished BSc(Hons) project, Geological Sciences Library, University of Canterbury, Christchurch, New Zealand.

Sherrard, JM 1966. Kaikoura – A History of the District. Kaikoura County Coucil, Kaikoura, New Zealand, 373 p.

Sylvester, A. G. 1988: Strike-slip faults:*Geological Society of America Bulletin, 100,* 1666-1703.

Tonkin, P.; Almond, P. 1998: Using loess soil stratigraphy to reconstruct the Late Quaternary history of piedmonts adjacent to large strike-slip faults, South Island, New Zealand. *Geological Society of New Zealand Miscellaneous Publication 101A*: 227.

Van Dissen, R. J. 1989: Late Quaternary faulting in the Kaikoura region, southeastern Marlborough, New Zealand. Unpublished MS thesis, Oregon State Univ., USA: 72p.

Van Dissen, R. J. 1991: An evaluation of seismic hazard in the Kaikoura region, Southeastern

Marlborough. *New Zealand Geological Survey Record 43*: 93-99.

Van Dissen, R. J.; Yeats, R. S. 1991: Hope Fault, Jordan thrust, and uplift of the Seaward Kaikoura Range, New Zealand. *Geology 19*: 393-396.

Wells DL, Coppersmith, KJ 1994. New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. Bulletin of the Seismological Society of America 84: 974-1002.

Wood, R.; Pettinga, J. R.; Bannister, S.; Lamarche, G.; McMorran, T. 1994: Structure of the Hanmer strike-slip basin, Hope Fault, New Zealand. *Geological Society of America Bulletin, 106*:1459-1473.