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Paleoseimicity of the Ashley and Loburn Faults, North Canterbury, New Zealand.

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Technical Abstract

PALEOSEISMICITY OF THE ASHLEY AND LOBURN FAUTS NORTH CANTERBURY, NEW ZEALAND

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A paleoseismic investigation was carried out in 1999 on the Ashley Fault, known from a 4.5 km long east-west scarp offsetting late Quaternary fluvial surfaces north of the Ashley River. A second, parallel fault scarp was identified approximately 1.5 km to the north, named the Loburn Fault, projecting west in a convex arc to join the Ashley Fault at the confluence of the Ashley and Okuku Rivers.

Cycles of Pleistocene aggradation, together with regional deformation, caused the migration of the local rivers, leaving former channels to be warped and displaced by structures propagating across them. Specifically, three former channels crossed the tilted and elevated wedge between the Ashley and Loburn Faults. These were progressively abandoned from east to west, Loburn 1 being occupied during Waimean to early Otiran times (Woodland - Windwhistle Formations ca 120 - 65 ka B.P), Loburn 2 by late Otiran to early Aranuian (incised into Burnham Formation <18-22 ka B.P.) and Loburn 3 by mid Aranuian (grading to Springston Formation <10 ka B.P.) The Loburn is the older fault, causing uplift to a maximum scarp height of 28 m across the oldest channel, but only forming a 1 m high scarp, derived from two events, across the Loburn 2 channel and with no trace across Loburn 3. Conversely, the Ashley Fault appears to have been propagating eastward much later, generating a 1.5 m scarp across Loburn 3, but fading eastward on contemporaneous Springston surfaces. Propagation may be as young as latest Pleistocene, because a maximum scarp height of 5.5 m on the Burnham aggradation surface is only slightly more than the 5.0 m on the Loburn 2 channel incised into it.

Trench and scarp data suggest increments of between 0.2 to 0.5 m, throw per event along this scarp, plus a component of dextral slip. Four trenches yielded clear stratigraphic evidence of two or more events, but only one, across the 1.5 m scarp in the Loburn 3 channel, provided any radiocarbon datable material. In the trench clear evidence of one undated event during river occupation was followed by one post-abandonment offset, immediately preceding a dated peat at 4,785 ± 255 years BP. Two further cycles of undeformed peat and silt may date scarp activity at 3,765 ± 70 and 3,420 ± 60 years BP, or merely reflect flooding. Higher degradation terrace offsets cumulating to 2.5 m indicate one earlier event during Loburn 3channel incision. Therefore three to five ground rupture events accumulated a 2. 5 m scarp since the onset of channel incision in the early Holocene. An average 0.5 m slip (Wells and Coppersmith, 1994) is indicative of an M6.6 earthquake, a conservative estimate for the following reasons. The throw is only a component of oblique net slip, maximum displacements are not to be expected close to the propagating end of a young fault, and the Ashley Fault is now known to be one segment of a fault zone which stretches for 40 km across the Canterbury Plains. Ruptures of this length generate M 7.0 or greater events. Uncertainties are compounded by the coincidence of the Ashley termination with the strike of the newly discovered northeast-southwest striking Springbank thrust, suggesting interlinked activity and possibly extending the potential seismic source generated by the combined system much closer to Christchurch city.

PALEOSEISMICITY OF THE ASHLEY AND LOBURN FAULTS NORTH CANTERBURY, NEW ZEALAND

Executive Summary

Since 1973 the Ashley Fault has been known and recognised as active by the 4.5 km long fault scarp lying north of the Ashley River and 5 km northwest of Rangiora. The objective of this study, funded by the Earthquake Commission, was to evaluate this structure as a seismic source affecting not only nearby towns, but also metropolitan Christchurch. The basic investigation was undertaken by Richard Sisson as a B.Sc. Honours research project in the Department of Geological Sciences, University of Canterbury, documenting evidence for the past history of ground rupture events. Unfortunately datable organic material is rarely preserved in this gravel environment, and although it is clear that multiple events have occurred within the last 10,000 years, good age constraints were not obtained.

During the course of mapping, a second fault was identified 1.5 km to the north on the same east-west trend, now named the Loburn Fault. Between the two there is a wedge of elevated ground uplifted by late Quaternary activity on both faults. Westward, the Loburn Fault curves southwest, projected to join the Ashley Fault under the confluence of the Ashley and Okuku Rivers. The interaction of these two faults with a number of geomorphic surfaces of different ages indicates that the Loburn is the older of the two structures and is being bypassed by a the newer splay of the Ashley Fault. This is propagating eastward reaching to just short of the Makerikeri River, where the surface expression of both structures dies out. Geologically, this eastward growth is very young and appears to have displaced surface features only within an estimated 10 -15 ka ago. Data derived from this setting are not ideal for quantifying fault activity, which are best applied to the central sections of "well run in" faults. This is where single event displacements, and slip rates are more likely to have settled to a characteristic pattern of events, providing more reliable estimates of past earthquake magnitudes. Conversely, the intensity of ground motion tends to be concentrated at the ends of faults when they rupture, with implications for Rangiora and rural subdivision around Loburn.

The evidence for this pattern of switching activity on the two faults is related to a history of changing river channels. The combined effect of cycles of aggradation during the glacial cycles at the end of the Pleistocene and uplift north of this area, resulted in a general southwestward migration of the rivers. Specifically, three broad, flat-floored, former channels, informally labelled "Loburn 1, 2 and 3", crossed the uplifted block between the two faults, and were progressively abandoned from east to west. The scarp heights on the faults intersecting these channels is an indication of the cumulative displacement on each fault since the time each channel was occupied. Only the Loburn 3 channel has been dated by radiometric methods because of a lack of appropriate materials in the others. Age estimates are therefore dependent on correlating the topography of the drainage to the regional cycles of fluvio- glacial aggradation.

The Loburn 1 channel is not well dated, but appears to have been occupied at the time of the Woodlands and Windwhistle aggradation cycles (ca. 120 -65 ka). Clearly the Loburn Fault has dominated post-channel deformation, tilting the whole block up to the north and creating a maximum 28 m high scarp at Round Hill just west of the channel.

The age of the Loburn 2 channel is more constrained, because it is incised into, and therefore younger than the Burnham Formation aggradation surface (ca. 18-22 ka ago). Here, the Loburn Fault forms only a scant 1 m high scarp, which was trenched to reveal two events of about 0.5 m vertical offset, upthrown to the south. No datable material was recovered. In contract the Ashley Fault forms a 5 m high scarp across this surface, very little lower than the 5.5 m height of the scarp attained across the Burnham surface into which the channel is cut. Either, little time separates the two surfaces, or the fault only became active at about the time the channel was occupied. Trenching of the high scarp at "the Oaks" homestead showed evidence of the last two events, but yielded no datable organic material.

The Loburn 3 channel was occupied by the Okuku River in post-glacial time (<10ka). The projection of the Loburn Fault shows no displacement of this surface, but the Ashley Fault has a sharp 1.5 m high scarp across the floor of the channel increasing in height to 1.7 m and 2.5 m as the scarp crosses a pair of degradation terraces on the west bank of the channel. This is indicative of two cumulative offset events during the cutting of the channel. Tilting of the block has now reversed, up to the south. On the channel floor a small swamp had formed along the eastern end of the scarp, the only really promising site for the recovery of organic material found along either fault. Trenching of this site provided good evidence of one rupture during the channel occupancy, and one immediately after it was abandoned. The latter event was likely to have preceded the 4,785 ± 255 years B.P (calibrated) radiocarbon date from peat formed immediately above the deformed silts recording this event. The earlier event could not be dated. More ambiguously two further cycles of silt and peat formed in the swamp, the base of each peat being dated 3,765 ± 75 and 3,420 ± 60 years BP respectively. These are undeformed and may represent either flushes of sediment associated with activity along the scarp, or merely local flood events. Taking the terrace data, together with that from the trench, implies a minimum of two ruptures during the incision of the channel and one or more after it was abandoned. If three events do post-date the channel, then average uplift on the scarp is close to 0.5 m for each event suggesting a minimum moment magnitude of the earthquake of M 6.6, If the full 1.5 m displacement of the channel bed was a single event this could rise to M 6.9, particularly as there is circumstantial evidence of oblique strike slip, the throw being only the vertical component of a larger net slip.

The elapsed time since the last event is therefore between 3,500 and 5,000 years. No rigorous estimates of likely recurrence intervals can be derived from these ambiguous data, but the cumulation of displacements of this order needed to create the 5.0 m of scarp across Loburn 2 require from 4 to 10+ increments in the last 10 - 15 ka, and possibly less.

Since the beginning of this project events have overtaken the initial assumption of a single isolated fault. Concurrently, in collaboration with Indo Pacific Energy Ltd an amalgamation of regional mapping with recent industry seismic profiles was revealing that the Ashley-Loburn structure is only the last segment on the propagating tip of an east-west striking fault zone, now referred to as the Ashley Fault System (AFS) extending approximately 40 km to the west. This steps through as series of segments marked by the elevated Cust and Starvation Hills Anticlines analagous to, but larger and more evolved than, the Ashley-Loburn structure. The AFS forms the northern boundary to a further system of faults under the Canterbury Plains revealed by the geophysical data; these were suspected, but not previous proven to exist, from subtle geomorphic effects observed on the surface. These faults form sets of northeast-southwest striking thrust faults stepping out from the range front as far as the newly discovered

Hororata and Springbank Faults, extending from close to the eastern tip of the Ashley Fault south past the Malvern Hills, at least as far as the Rakaia River. It is likely that the propagation of the end of the AFS reflects its connection with the emergence of the Springbank Fault and associated growing anticline, and may provide some measure of the general level of activity at this end of the system. The scarcity of datable material and the effect of the setting on long term lack of uniformity of slip rates, recurrence intervals and offsets makes further statistical treatment of the data inappropriate.

These regional developments clearly reflect on the fundamental questions of the characteristics of possible seismic sources with the potential to affect the city of Christchurch and the larger Canterbury area. Fundamental questions, such as whether or not the whole length of the AFS ruptures across the segment boundaries and, if it functions as a transfer fault, is moving synchronously with activity on the major thrusts, have yet to be answered. These clearly impact on interpreting the source characteristics of the maximum credible earthquake and the predicted pattern of areas of high felt-intensity shaking.

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ASHLEY FAULT REPORT

1. INTRODUCTION

1.1 Project conception and organisation

The project was conceived to improve constraints on the character, timing and magnitudes of earthquakes on the poorly documented Ashley Fault, previously considered to be the closest onshore earthquake source structure to Christchurch. The project was undertaken as part of the Active Tectonics and Earthquake Hazard Research Programme at the University of Canterbury (UC). The research documented in this report was principally funded by the Earthquake Commission Research Foundation, with additional funds from the Active Tectonics Research Programme, UC. Research was undertaken over the period of a year, commenced in December 1998 and was principally undertaken by Richard Sisson, a B.Sc. Honours student at UC, under the supervision of J. Campbell and J. Pettinga. D. Milner has been extensively involved in the compilation of this report. This report presents data, interpretations and conclusions which address the principal aim of this project (to determine the character and paleoseismicity of the Ashley and Loburn faults)

1.2 Objectives of study

The main objectives of this study were to:

1. Determine the structural and seismogenic characteristics of the Ashley Fault.

2. Understand the fault and fluvial histories of the area and their inter-relational development.

3. Establish the frequency and magnitude of seismic events on the Ashley Fault to initiate development of a Seismic Hazard Model.

4. Establish the relationship between the Ashley and Loburn faults, the latter unrecognised prior to this study

5. Identify the relationships to the structures surrounding of the Ashley and Loburn faults.

1.3 Scientific background

Structures in North Canterbury can be subdivided into three domains (Fig. 1; Pettinga et al., 1998):

1. Thrust wedge. Thought to represent the eastern most expression of back thrusting off the Alpine Fault, represented by a N-S striking imbricate thrust front. This domain is progressively migrating eastward under the Canterbury Plains.
2. Hybrid strike-slip faulting (Porters Pass-Amberley Fault Zone, PPAFZ). A hybrid zone of strike-slip and thrust faulting sub-parallel to the present day plate boundary.

North Canterbury fold and thrust belt. Folding reflects reverse basement faulting probably combined with a dextral shear component (Nicol, 1991).

3. North Canterbury fold and thrust belt. Folding reflects reverse basement faulting probably combined with a dextral shear component (Nicol, 1991).

The Ashley Fault is located close to the intersection of these three domains.

The Ashley Fault is situated 4.5 km northwest of Rangiora, North Canterbury, is 30 km from metropolitan Christchurch (Fig. 2), and displaces Late Holocene and Late Pleistocene surfaces by up to 1.5 and 6.8 m respectively. The previously unrecognised Loburn Fault displaces both Pliocene-Pleistocene and surficial Pleistocene-Early Holocene deposits by up to 28 m. During this investigation, the sub-parallel Loburn Fault was identified. Over the same period in association with another project, it became evident that the Ashley Fault was only the eastern end of a much more extensive, interconnected system including the Cust and Starvation Hill Faults and extending more than 60 km west to the Springfield Fault (Fig. 3). These are now collectively grouped into the Ashley Fault System (AFS). The system also clearly connects to the newly discovered northeast-striking Springbank Fault south of Rangiora. The AFS functions as some form of oblique transfer system striking east-west and intersecting the Springbank thrust at a high angle. As this study of the Ashley Fault itself was defined prior to recognition of this extended system, to have included a full investigation of these ancillary faults was outside the time and resources allocated to this project.

The Ashley Fault has been recognised as active for nearly 30 years, first appearing on Kaiapoi (Brown, 1973) and Rangiora-Waikuku (Brown, 1977) maps of geology and water wells. Previous descriptions of the fault kinematics have been variable with both oblique-normal (Berryman, 1979; Cowan, 1992) and oblique-thrust proposed (Brown, 1973). Brown documented displacements of 2 m across the fault in the Burnham Formation (upthrown to the north). Berryman (1979) indicated 6.0 m and 2.7 m strike-slip and dip-slip displacements respectively across the fault (based on channel offset that could not be identified in this study) and concluded that the fault plane dipped south indicating a normal component. Cowan (1992) most recently mapped the Ashley Fault interpreting its connection to the PPAFZ. Cowan (1992) also correlated a landslide and strath preserved on the northern side of the Cust Anticline with the youngest surface displaced by the Ashley Fault, calculating an apparent age for the last rupture of between 2100 and 2500 years BP. From analysis in this study the Ashley and Loburn faults are thought to make up a small section of the AFS.

The Ashley Fault has clearly generated repeated earthquakes during the Holocene, but prior to this study no estimates of magnitude or recurrence interval have been made. The character of the fault and its relationship to surrounding structures have also not been previously determined. Based on the cumulative displacement of late Quaternary surfaces, the Ashley Fault and AFS as a whole pose a significant seismic hazard to the North Canterbury area and metropolitan Christchurch. No previous studies have recognised the Loburn Fault or trenched the Ashley Fault. Any figures stating slip rates or timing of last rupture for the Ashley Fault are estimations based entirely on geomorphic correlation and interpretation.

The newly discovered Springbank Fault (IndoPacific, unpublished data) runs to the south of the field area and strikes northeast. The Springbank Fault is thought to exert a controlling influence over other faults (including the Ashley and Loburn Faults) in the area.

1.4 Research methods

Detailed examination of the active Ashley Fault and nearby Loburn Fault was carried out to improve the quantity and quality of data available for past earthquakes on the faults. The objectives were addressed using the following methods:

1. Detailed mapping on aerial photographs at a scale of 1:1000 to 1:4000. Scarp heights were measured using tape measures and levels.
2. Four trenches were excavated (3 across the Ashley Fault and 1 across the Loburn Fault) and logged at a scale 1:20 to determine fault geometry and quantify displacement per earthquake.
3. Datable organic matter was sought from different stratigraphic horizons in order to quantify the timing of successive rupture events, in the event with limited success.
4. Collation and interpretation of earthquake displacement and timing data to with the intention of constraining slip rates for the fault.

The newly available seismic reflection data from IndoPacific Exploration (1998-1999) were also used to appreciate the nature of the Springbank Fault and its relationship to the AFS. These seismic profiles cannot be reproduced here for commercial reasons.

2. GEOLOGY

2.1 Pre-Pleistocene geology

Only the uppermost Pleistocene units of the local stratigraphic succession are exposed at the surface. Geophysical data suggest that the local basement of Mesozoic Torlesse Group sandstones and mudstones descends eastward and lies at approximately 2,000 m below the Ashley area. The Cretaceous-Tertiary basin sediments comprise the Eyre, and Motunau Groups. Full lithologic descriptions and facies relationships are described in Andrews et al. (1987) and Browne and Field (1985). The sequence becomes condensed, with major unconformities and rapid facies changes where it is exposed inland on the basin margins, but seismic profiles (Indo-Pacific unpublished data), suggests that the strong reflectors formed by the Amuri and Weka Pass Limestones in the middle of the sequence and the distinctive Pliocene to Lower Pleistocene Kowai Formation sands and gravels at the top, are uniform in thickness and continuous beneath the Ashley area. The seismic data suggest that the mechanical properties of these units affect the mode of propagation of faults to the surface.

2.2 Surface geology

Displaced lithologies that are exposed in the field area include (Map 1):

Kowai Formation (Pliocene-Pleistocene)
Woodlands Formation (c. 150 ka)
Burnham Formation (c. 15 to 27 ka)
Springston Formation (<14 ka)

The Kowai Formation is the youngest member of the Motunau Group comprising mudstone, sandstones and conglomerates and is the oldest formation exposed in the area. The Woodlands, Burnham and Springston Formations are deposits from various glacial and interglacial periods consisting of gravels with varying silt and sand matrices. Separation of these units is largely based on delineating the relict surfaces produced during episodes of aggradation assumed to coincide with glacial maxima. Beyond the range of radiocarbon dating, none of the modern methods of dating such surfaces (e.g. cosmogenic isotopes and optically stimulated luminescence (OSL)) have been applied to this region. McPherson (1991) produced the most recent map of Pleistocene deposits in this area, assigning ages to the relict surfaces on the basis of relative elevation, preservation, weathering and loess deposits. The ages beyond radiocarbon dating are those in current use for these units throughout Canterbury, based on assumptions of correlation with the most probable $\delta^{18}O$ isotope stages. As there was no counter evidence to suggest an alternative interpretation, McPherson's mapping has been adopted here. However, it should be noted that elsewhere on the Canterbury Plains, the Windwhistle Formation intervenes between the Woodlands and Burnham Formations. This is thought to correlate with isotope stage 4 ca. (60-75ka). McPherson shows remnants of this surface just outside the study area on the north side of the Makerikeri River and it is probable that some of the surfaces referred to as Woodlands in this study are compound surfaces modified during Windwhistle time, particularly where active deformation affects the normal vertical separation. This uncertainty in correlation clearly affects estimates of long term uplift rates.

2.3 River systems in the field area

Map 1 and Figure 4 show that during the late Pleistocene and early Holocene the river systems changed channels repeatedly in response to a combination of cycles of aggradation when rivers coalesced to form broad, braided floodplains and to the influence of active ground deformation. Channels were incised into these surfaces during the intervening periods and can be related stratigraphically to those terrace surfaces preserving remnants of the aggradation events. The changes in the drainage patterns of the main rivers can be related to tectonic activity on various structures. The evolution of the drainage history, therefore, has the potential to constrain the rate of tectonic uplift and relative timing of events. The evolution of the regional drainage pattern in and around the field area is shown in Figure 3, and is described in order to define a geomorphic framework to which the location and activity of the Ashley and Loburn Faults can be related.

2.3.1 Ashley River

The Ashley River is the main drainage channel into which all other smaller tributaries drain, including the Okuku and Makerikeri Rivers. The Ashley River flows out of Lees Valley into the Loburn Basin in a southeasterly direction before being diverted eastward by the presence of the Cust Anticline, now draining along the structure's northern side before exiting to the coast (Figs. 2 and 3).

To the south of the Cust Anticline lies an ancestral channel of the Ashley River that was active during the deposition of the Burnham Formation, the aggradation event coincident with the last glacial maximum of the Otiran Glaciation. Growth of the Cust Anticline, presumably associated with seismic activity on the Ashley Fault System, diverted the Ashley River to the anticline's northern side, where it now erodes the north face and is entrenched due to the continuation of regional uplift. The old Ashley River channel now accommodates the flow of the substantially smaller Cust River (Cowan, 1992).

2.3.2 Makerikeri River

The channel in which the Makerikeri River flows is too large to have been created by water from the current catchment area, but probably once included the Grey River. The dimensions of this paleochannel are similar to those of the Okuku River to the west, while its present flow is considerably less. During deposition of the Woodlands Formation water was flowing in a former channel defined as Loburn 1 (Map 1) for the purposes of this discussion. The warped remnant of this channel is still preserved on the uplifted eastern end of the Ashley–Loburn structure and may have maintained this route through to Windwhistle time. The more obvious lower channel to the north was fully occupied during the deposition of the Burnham Formation, but the subsequent reduction in flow was caused by the later redirection of the Grey River. Evidence of this diversion can be seen where a SSE-oriented paleochannel formerly joined the eastern branch of the Grey River to the Makerikeri (Fig. 4b). The presence of Burnham Formation surface north of the Makerikeri River's point of entry to the Loburn Basin floodplain provides further evidence that the eastern branch of the Grey River once flowed into the Makerikeri River channel. Subsequent westward migration of the Grey River occurred during the deposition of the Burnham Formation. The extent of the remnants of the Burnham surface suggests that at the height of aggradation there was probably an extensive braided system spread over the surface onto which the Grey and Karetu Rivers as well as the Okuku Rivers flowed and resulted in eventual capture of these tributaries by the Okuku River to the west. The Okuku River is now incised into the south side of the Burnham surface and it is likely that this whole process was a consequence of general southward tilting associated with the growth of the Kowai Anticline and general uplift in the hills to the north.

2.3.4 Okuku Grey and Karetu Rivers

As the Okuku River exits the foothills of the Southern Alps onto the plains of the Loburn Basin it is now joined by the Karetu and Grey Rivers. Beyond this intersection the Okuku River flows south to where it joins the Ashley River north of the Cust Anticline at the junction of the Ashley and Loburn Faults. However, other former channels previously occupied flat-floored valleys incised into the low hills now elevated between the two faults shown on Map 1 as Loburn 2 and 3.

This reconstruction of the paleochannels in the field area indicate a progressive westward migration of the Okuku-Grey-Karetu river system in the Loburn Basin over time (Map 1 and Fig. 4). The different orientations and topographic elevations, suggesting a degree of tectonic control. The westward migration of the three former channels crossing the uplifted Ashley-Loburn block (Loburn 1, 2 and 3 on Map1), to the present channel of the Okuku River is attributable to activity on the Ashley and Loburn Faults as well as to the more regional changes described above. The whole area is affected by activity on other structures mapped, but not previously interpreted, as significantly active in the area's fluvial history. While Figure 3 shows a diagrammatic separation of the Grey and the Karetu and Grey Rivers from the Okuku, the size of these channels and the upstream merging of surfaces suggests that some combination of braided floodplain drainage from all three tributaries entered these channels during the migration stages, particularly through the period of occupation of the Loburn 2 and 3 channels.

3. FAULT DESCRIPTION

The New Zealand landmass sits astride the Australian-Pacific Plate boundary zone and the two plates are currently converging obliquely at a rate of ~40mm/yr in the Canterbury region (De Mets et al, 1990; Fig. 1). Results of stress tensor analysis from recently active faults, focal mechanisms of shallow earthquakes and geodetic surveys across the Southern Alps, indicate that the principal compression is oriented WNW-ESE (Walcott 1979; Nicol and Wise, 1992; Pettinga and Wise, 1994).

3.1 Springbank and Ashley Fault System

The recently identified Springbank Fault is listric, dipping 50° to the northwest near the surface with dip decreasing to 10° at depth. It has accommodated ~350 m vertical displacement since the Early Pleistocene (offset determined from displaced Kowai Formation; IndoPacific, unpublished data) and is likely to be the major controlling structure of other faults in the area.

The AFS forms a discontinuous trace that extends to the west from the Ashley and Loburn faults. At intervals it steps to the south and where these steps occur, the uplifted blocks of the Cust Anticline and Starvation Hill suggest that these segments function as restraining bends in a fault system with a significant right-lateral strike-slip displacement. At this time, there is insufficient subsurface information to determine the nature of the junction between the Springbank and the AFS, and whether or not either fault continues past this intersection.

3.2 Ashley and Loburn Faults

The trace of the Ashley Fault is distinguishable for ~4.5 km in the Loburn Basin flanking the eastern foothills of the Southern Alps and is bound to the southwest by the east plunging tail of the Cust Anticline and to the northeast by the uplifted Ashley Forest area. The Ashley Fault strikes between 260° and 300° along its surface rupture length and is readily defined by fault propagated folding and minor ground rupture upthrown to the north with only minor degradation. Given the orientation of the relative plate motion vector of 077°(De Mets et al., 1990; Fig. 1), the resolved regional compressive stress orientation of WNW-ESE (Walcott 1979; Nicol and Wise, 1992; Pettinga and Wise, 1994) in the area encompassing the Ashley Fault would be expected to induce transpression consistent with right-lateral reverse slip. As the fault is situated near the intersection of three structural domains, the complex array of nearby structures and history of deformation means that this structure is unlikely to behave independently of other structures.

Surficial deposits ranging from Upper Pleistocene to Holocene in age are displaced by up to 6.8 m across the Ashley Fault. The height of the scarp on the older surfaces makes this one of the best examples of a surface rupture trace on the Canterbury Plains gravels.

North of the Ashley Fault, and previously unrecognised, lies the Loburn Fault that strikes generally east-west, is up to the south and displaces Pliocene-Pleistocene and Upper Pleistocene aged deposits by up to ~28 m. The Loburn Fault's scarp is highly degraded indicating that much of the activity is probably older and has been exposed for longer to degradational processes than the Ashley Fault scarp. The Loburn Fault branches from the Ashley Fault near the western termination of the definable Ashley

Fault trace, along the axis of the Ashley River. From its westernmost expression, the Loburn Fault strikes east slowly curving to the northeast before resuming an easterly strike, where it is up to 1.5 km from the Ashley Fault (Map 1). Older events are distinguished by the displacement of Woodlands Formation deposits in the Loburn 1 channel. Within the Loburn 1 channel the fault is characterised by the presence of a ~150 m wide zone of deformation, representing the presence of a shallow southward facing wedge formed by a backthrust-splaying off the main Loburn Fault plane (Map 1).

Fluvial reworking of deposits offset by these faults during the late Quaternary has modified the surface expression of both the Ashley and Loburn Faults with the scarps relating only to the most recent events preserved.

The dips of the Ashley and Loburn faults have been approximately determined by the sinuosity of the intersection of the outcrop of the faults with topography as they traverse across terraces of different topographic elevation. The sinuosity is observed best between the eastern side of the Loburn 3 channel at the southern end of 'the Oaks' for the Ashley Fault, and the eastern side of 'the Oaks' for the Loburn Fault. From these traces, it has been estimated that the Ashley fault plane dips to the north at between 30 and 40°. The Loburn Fault dips to the south at a similar angle. Uplift of the intervening area has resulted from the inward convergence of these faults, with differential tilting of the block upward to the north, and the maximum elevation culminating at Round Hill, the point where the Loburn fault reverts from a northeast to more easterly strike. In this respect there are apparent similarities to the curved periclinal form of the much bigger Cust Anticline to the southwest of the Ashley-Loburn structure.

While it is demonstrable that relative uplift is significant on this fault system, no direct evidence of strike-slip motion was found. A component of dextral slip is to be expected from regional stress orientations and is compatible with the coincidence of uplift with restraining step-over geometry on the AFS and with strike-slip displacement on other east-west striking faults in Canterbury.

Aside from the surficial ground displacements, as outlined above, activity on the Ashley Fault System has resulted in the structural control of antecedent drainage patterns crossing this block. Interpretation of the history of rivers within this local area is therefore of importance in the interpretation of its structural development. The fluvial and tectonic development of the field area is discussed in sections 5.3 and 5.4.

4. OTHER STRUCTURES IN THE FIELD AREA

4.1 NNW to NW trending folds

The most regionally pervasive and the oldest folding controls the orientations of the Loburn 1 channel, Makerikeri River, and to a lesser extent the Loburn 2 channel. This phase extends north from Barkers Road to well beyond the trace of the Loburn Fault, and appears to be independent of, and probably older than, the Ashley-Loburn structure.

Shorter wavelength and smaller-scale structures with a similar trend deforms the Loburn 1 channel and traverse the Loburn Fault wedge structure. This folding was therefore active during the evolution and uplift of the Ashley-Loburn structure. These smaller folds are generally monoclinal, verging toward the SW, and have lower amplitude and shorter wavelength than the earlier phase. They have evidently controlled the drainage of streams now incised discordantly into the Loburn 1 channel, emphasised most by the western of the two currently active streams. These smaller wavelength folds do appear to be more local, but are mapped as extending for a few hundred metres beyond the fault traces (Map 1). Neither set is compatible with the orientation of folding to be expected from internal dextral shear of the fault block.

4.2 NE-SW trending folds

Northeast of the field area the Waipara Syncline and Kowai Anticline are large doubly plunging structures that trend NE-SW and are not related to either the Ashley or Loburn Faults, but are part of the deformation associated with the Porters Pass–Amberley Fault Zone (Cowan, 1992). Abandonment of the Makerikeri River channel by the Grey River occurred possibly in response to general uplift and growth of the two folds during the deposition of the Burnham Formation.

4.3 E-W trending folds

Folding that is clearly associated with the faulting is found along the Ashley Fault largely as short, hanging-wall anticlines immediately above scarp segments, and is a reflection of the thrust component. A slight east-west elevation parallel to Barkers Road on the south side of the fault may be related to the structure described below (Section 5.1.1) associated with the WNW swing in strike of the central section of the Ashley Fault across the Loburn 2 channel.

5. FAULT DISPLACEMENTS

Displacements across the Ashley and Loburn faults have been determined by analysis of a number of offset landforms.

Slip on the Ashley Fault is taken up by a component of reverse dip-slip displacements on two fault strands with displacements accruing mainly through repeated moderate to large magnitude earthquakes. Scarp geometry is related to the strike of the fault trace with at least two locations indicating Holocene surface rupture where slip was almost pure thrust. Several step-over structures along the trace of the Ashley Fault have morphologies that indicate the fault also accommodates a component of strike-slip motion (Map 1), but no linear feature intersecting the fault scarp could be shown to have an unequivocal strike-slip offset.

Slip on the Loburn Fault is also assumed to have been right-lateral, reverse. Evidence of the fault's last activity is represented by the presence of a low, visible scarplet across the Loburn 2 channel (Map 1), but not across Loburn 3. Loburn Fault is now relatively inactive with current strain predominantly accommodated by the Ashley Fault. The Loburn Fault may have been the primary structure and the restraining step-over is being by-passed along the Ashley Fault.

5.1 Displacements along the Ashley Fault measured from ground morphology

5.1.1 Vertical displacements

Unequivocal measurement of total net fault displacement is difficult due to the lack of correlatable strata across the Ashley Fault. Older surfaces have experienced more numerous fault rupture events than younger surfaces and are therefore displaced by greater amounts. Along the trace of the Ashley Fault the scarp height varies between 0.5 and 6.8 m depending on the age of the displaced surfaces and changes in fault geometry along strike. Increased vertical displacements with surface age are illustrated by the 5.5 m displacement of the Burnham Formation south of 'the Oaks' with scarps of 4 m measured in the Loburn 2 channel and 1.5 m in the Loburn 3 channel.

Vertical displacements are also directly related to the fault geometry along strike, as shown by four fault step-overs (Map 1) where small scale (200-300m long) restraining and releasing bends result in local increases in cumulative displacement. On a larger scale for approximately 2km along the mid section of the Ashley Fault, the strike swings to WNW between 'the Oaks' to past Swamp Road (in the Loburn 2 channel; Map 1), fault geometry induced offset variation may also be occurring associated with an increased fault scarp height. On this scale the displacement extends into the footwall so that the effects of the 0.5 to 1.0 m increase in vertical relative displacement are distributed over a 750-850 m wide zone to the south, resulting in little obvious evidence of enhanced surface deformation. The height of the fault scarp increases through this section from 4 m at Swamp Rd to ~5 m (but is the combined scarp heights of splays) just east of 'the Oaks'. This dissemination of faulting makes the interpretation of the number and size of ruptures more difficult to distinguish, with the only sections producing reliable measurements being those where the fault trace is singular and not complicated by step-over structures.

5.1.2 Lateral displacements

Previous work on the Ashley Fault documented evidence of a right-lateral displacement of an abandoned stream channel within the Loburn 3 channel (Berryman, 1979). Inspection of this site did not identify any unequivocal evidence that this channel showed any strike-slip displacement. From the trace that the fault makes along strike it appears that the Ashley Fault accommodates a component of right-lateral strike-slip, but the lack of displaced piercing points across the Ashley Fault makes quantification of any strike-slip movement impossible. The implication of a strike-slip component is based on the interpretation of the three fault depressions and one flower structure that occur at step-overs between fault strands and are consistent with right-lateral shear. The lack of offset piercing points in the form of displaced stream channels and degradation terrace margins, suggests that the last one or two ruptures on the fault accommodated shortening and uplift only.

5.1.3 Fault depressions

Three fault-generated depressions are observed along the trace of the Ashley Fault. One is adjacent to "the Oaks" homestead at the site of Trench 3, one is immediately east of Swamp Road and the third is crossed by Barker Road 1.5 km further east from the Swamp Road junction. These all have similar characteristics and occur at right steps in the fault trace. All three are small structures forming depressions approximately 100-200 metres long.

The structures are all formed by the interaction between two E-W striking fault strands, connected by a short NW striking fault, probably accommodating oblique strike-slip motion. The fault connecting the two main E-W striking fault strands acts as a transfer structure. The sense of movement across the connecting fault is up to the northeast, similar to that of the main fault strands. The northern fault strand accommodates the majority of cumulative displacement, evident by its higher topographic elevation. The southern strand also accommodates uplift its northern side as it approaches the transfer fault from the east, but once west of the transfer fault the ground surface is downthrown on the northern side, inconsistent with the usual sense of relative uplift on the Ashley Fault. This is interpreted as either the result of thrusting on a south dipping fault plane (Fig. 5a), or more probably reversal to normal faulting on the existing fault plane resulting from stress release in the extensional zone of the step-over (Fig. 5b). Both of the main strands apparently continue to overlap beyond this step-over section, accommodating further displacement (up to the north) on the original trace.

These small scale structures bear an obvious self-similarity to the larger scale structure produced by the 2km long change in strike described above, which would also have releasing bend geometry in a right-lateral strike-slip environment. Subsidence on the footwall side may account for the increase in scarp height noted above and the slightly elevated warp forming the east-west structure along Barkers Road, aligned with the eastern end of the Ashley Fault, is a possible analogue of the reversal of throw described in the smaller scale structures as illustrated in Figure 5b.

The pattern of throw reversal across a step-over structure indicates that a fault accommodates a strike-slip component (Fig. 6; e.g. Reches, 1987; Emmons, 1969; Richard et al., 1995). During the development of a pure strike-slip system the fault undergoes different stages of development, from initial en echelon Riedel shears to the establishment of the residual fault as a through going structure consisting of an anatomising fault zone defined by shear lenses (Richard et al., 1995). The Ashley Fault probably represents an intermediate stage with the presence of P (thrust) shears connecting the main shear planes. If this interpretation is correct, it would support the view that the Ashley Fault segment is a young and incompletely evolved structure, a view that would be consistent with the observations on its relationship to the Loburn Fault noted earlier.

From the models of compressional oblique-slip proposed by Richards (1995) the similarities between the structural style of the Ashley Fault and the diagram shown for a ratio of 0.6 for strike-slip to dip-slip displacement suggests that this ratio would be a reasonable approximation of the oblique-slip with the orientation of the transfer structures and depressions indicating the direction of relative motion (right-lateral, reverse; Fig. 7).

5.1.4 Flower structure

One flower-type structure is present along the recent fault trace, located on the Burnham Formation terrace west of the Loburn 3 channel (Map 1) and has culminated in an area uplifted by ~6.8 m. Here a left step-over between two north dipping fault strands, results in compression and subsequently causes a faster uplift rate.

The surface expression of the Ashley Fault at this location is dominantly constrained to the southern side of the structure with uplift on the northern side indicating that oblique motion is accommodated on a north dipping fault plane (Fig. 8). Deformation in the hanging wall is represented by folding and surface tilting, along with both north and south directed thrusting. Inhibited drainage has generated a swampy area north of the uplift.

A steep scarp, probably representative of actual surface rupture, is located along the eastern half of the flower structure and coincides with a swamp on the southern side of the trace. The depression in which the swamp has accumulated was formed by down warping of the footwall in response to southeast directed oblique-slip thrusting.

At its eastern extent the flower structure displaces degradational terraces on the western side of the Loburn 3 channel (Fig. 9). Growth of the structure during the occupation of the Loburn 3 channel impeded drainage and forced the eastward slip-off of the Karetu River preserving the two terraces. The displaced terraces indicate that at least one event occurred on the Ashley Fault during the occupation of the Loburn 3 channel, with one or more events post-dating the channel's abandonment. Evidence for these events was found in trenches excavated across the fault in this channel and is discussed below.

5.2 Displacements along the Loburn Fault measured from ground morphology

The Loburn Fault has displaced upper Pleistocene deposits by up to ~28 m. The most recent movements on the Loburn Fault are represented by a low north facing scarp within the Loburn 2 channel. This impedes drainage of remnant streams forming a swampy area north of the fault trace and is marked by springs on the eastern channel margin. At 'the Oaks', Round Hill and east of the Loburn 1 channel the trace of the fault is expressed as a degraded composite scarp on topography higher than the relicts of Burnham surface, a break in slope generated by tectonic and fluvial activity.

The rupture traces preserved in the paleochannels indicate a decrease in activity on the Loburn Fault coincident with the westward migration of the river systems. Activity along the Loburn Fault was producing the greater amount of uplift on the two faults, prior to the abandonment of the Loburn 2 channel, demonstrated by the relative degree of uplift observed within the Loburn 1 channel and the exposing of Kowai Formation deposits at Round Hill.

This activity has resulted in vertical displacements of ~28 m at Round Hill (although complicated by the folding), 7.5 ± 1 m in the Loburn 1 channel and 0.5 m in the Loburn 2 channel.

The last rupture event, preserved in the Loburn 2 channel clearly occurred after abandonment of the channel. Because no similar trace crosses the Loburn 3 channel, it can be argued that this event occurred during occupation of the Loburn 3 channel by the Okuku River. No evidence of a similar scarp is observed across the Loburn 3 channel, and neither is there evidence of displacement on the degradation terraces higher on the Burnham surface, through which this channel was incised. Either the trailing branch-line junction between the Ashley and Loburn Faults does not reach the surface, so that the surface expression of the Loburn Fault terminates before the junction, or strain was being transferred from the western end of the Loburn Fault to the propagating Ashley Fault by the early Holocene. The former option is unlikely, because the well developed fault scarp and uplift of older deposits on the north side of "the Oaks" clearly indicates that significant uplift was occurring on the Loburn Fault prior to Burnham times, at least this far west.

The detail of the surface morphology along the Loburn Fault is therefore confined to east of "the Oaks". West of Loburn, the Loburn Fault strikes E-W across deposits of Woodlands Formation uplifting and exposing deposits of Kowai Formation at Round Hill. Within the Loburn 2 channel, west of Round Hill, the fault changes strike to

WSW-ENE across the eastern half of the channel, resuming its E-W strike before terminating at the western side of 'the Oaks'. Within the Loburn 1 channel, the Loburn Fault is characterised by the presence of the distinctive uplifted wedge, the product of north directed faulting on the main trace with coeval activity on a southward directed 'backthrust'. This created an elevated area approximately 150 m wide, with associated gentle warping and southward tilting of the preserved upper surface (Map 1 and Fig. 10). The backthrusting is not as prominent beyond the limits of the Loburn 1 channel, on the higher surfaces to the east at Loburn and to the west at Round Hill. This suggests the presence of more brittle lithology closer to the surface under the Loburn 1 channel, where fault plane rupture results in a more pronounced fault trace. Westward projection of the strike of the backthrust trace would connect with the E-W striking section of the Loburn Fault within the Loburn 2 channel, but no trace is evident on the channel surface, constraining the minimum time of last rupture. (Map 1).

No horizontal displacement can be determined on the Loburn Fault but is likely, considering the orientation of the fault, and a restraining bend in the fault provides an explanation for the increased uplift and exposure of Kowai Formation deposits at Round Hill. The lack of strike-slip evidence may be an artefact of landscape modification and the limited recent activity, or to strain partitioning and the accommodation of this component of displacement at depth.

5.3 Fluvial activity vs. tectonics in the Loburn 1 channel

The controls on the drainage pattern in the area are complex. The following is a description of the drainage controls using the example of Loburn 1 channel.

The Loburn 1 channel is oriented in a SSE direction, parallel to the orientation of the Makerikeri River to the east and to the fold present at Round Hill, indicating a possible structural control of the channel alignment. This is most dominant through the zone of uplift produced between the Ashley and Loburn Faults.

Two streams cross the whole structure and are presently active inside the bounds of the Loburn 1 channel; these streams have been obstructed by uplift associated with activity on the Loburn Fault, resulting in the formation of an undrained swamp on the eastern side of each channel to the north of the scarp. They follow the trend of folds aligned with the old channel axis, which now warp the broad, relict floor of the Loburn 1 course. The subdued nature of the Loburn Fault's surface expression across the channel suggests that there was significant coeval fluvial activity.

At the eastern end of the wedged up area, across the Loburn 1 channel, an abandoned stream terrace has been preserved, incised into the channel surface (LT1; Fig. 10). The size of this terrace is similar to that of the present stream, indicating little change in flow. The formation of a swamp behind the fault scarp indicates that the stream's activity has only just been able to compete with activity on the fault.

Uplift on the Loburn Fault has not affected the stream on the western side of the Loburn 1 channel as much, being deeply entrenched and defeating fault uplift. To the west of this stream lies a degradational terrace (LT2; Fig. 10), the size of which indicates a stream somewhat larger than that presently flowing. This may have retained a contribution from a remnant stream of the diverted Grey River that at the time contributed to the Okuku River system then occupying the Loburn 2 channel. The terrace has been deformed and tilted slightly to the southeast as a result of activity on the main Loburn Fault. No evidence of activity on the backthrust present just to the east in the Loburn 1 channel is seen on the LT2 surface.

The path of the stream, while occupying the LT2 terrace, exited the zone of deformation produced by the Loburn Fault, then drained southeastward across the Loburn 1 channel to the eastern side (Fig. 10). Growth of the NW-trending fold, which intersects the western end of the uplifted area associated with backthrusting off the Loburn Fault, has diverted the stream flow from its previous drainage channel to its present position.

Active folding of the Loburn 1 channel surface is also evident in more superficial, local drainage flowing off the southeast tilted surface. Propagation of the folds has diverted these small channel leaving relicts courses, now clearly warped across the axial traces.

5.4 Discussion

From geomorphic evidence the relative timing of fault activity can be deduced. The following discussion outlines the activity of the Ashley and Loburn faults.

The Ashley and Loburn faults have been active during the Quaternary, accommodating significant amounts of uplift and creating a broad anticlinal structure between them that exposes Kowai Formation deposits (Map 1). The area has developed in a complex fashion, with the most noticeable effects on the geomorphology being that of the westward migration of the Okuku-Karetu-Grey river system and the deformation associated with activity on the Loburn and Ashley Faults.

The Loburn Fault was probably the most dominant of the two faults in the early stages of activity, indicated by the uplift and preservation of Kowai Formation deposits at Round Hill and 'the Oaks'. Activity on this fault appears to have diminished since the abandonment of the Loburn 2 channel with only one event preserved post the abandonment of the Loburn 2 channel surface, clearly taking place in the latest Pleistocene or early Holocene, as the channel is incised into the Burnham Formation aggradation surface.

The Ashley Fault has been the dominant structure since the cessation of Burnham Formation deposition, by comparison, forming a composite scarp exceeding 5.0m across the Loburn 2 channel and up to   m on the degraded Burnham surfaces. As previously discussed, the Ashley Fault accommodates dip-slip and probably some strike-slip motion along its strike.

Activity on the Ashley Fault, at the time of maximum activity on the Loburn Fault cannot be determined due to the lack of preserved evidence. The Loburn 1 channel surface is trimmed by a river terrace formed at the time the Loburn 2 channel was occupied, and does not extend to intersect the Ashley Fault. The only measurement of comparative fault activity is the uplift and tilting represented at 'the Oaks'. Here the upper surface is tilted $4 \pm 1°$ toward the north, representing an overall greater degree of uplift on the Ashley Fault, but this was not always the case. A deeply incised south-directed drainage system on 'the Oaks' indicates that prior to the recent activity of the Ashley Fault the same surface probably tilted to the south suggesting that uplift on the Loburn Fault dominated during early fault development.

6. TIMING AND CHARACTER OF PALEOEARTHQUAKES

The choice of trench sites likely to produce a datable record of displacement events was very restricted. The majority of Canterbury fluvial gravels tend to be barren of preserved organic material suitable for radiocarbon dating, because the low water table and dry summers result in rapid decomposition. Perpetually wet swamp sites offer the best targets for the accumulation and preservation of organic material, but often promising sites are found to have only thin accumulations of organic material. Older, high scarps, while clearly representing a longer history of events, frequently yield disappointing records because degradation, slumping and the accumulation of a thick regolith mean that trenches often fail to intersect the rupture surface, or they expose a complex stratigraphy of superficial failures with a lack of intercalated datable material.

The criteria for target sites are those where circumstances lead to restricted drainage along a sharply defined scarp and where colluvial debris off the uplifted scarp may be expected to spill into, and bury swamp deposits along the scarp base. Potentially this allows both the buried vegetation, and vegetation re-established over the debris, to be dated and bracket the scarp-forming event. Frequently in practice, this simple stratigraphy is disrupted by deformation and splaying of the fault as it breaks to the surface.

In the case of the Loburn Fault the diffuse and degraded nature of the old scarp, even in the swampy areas where the small streams entered the fault zone, made these unprofitable targets. The only site with the potential for a simple record of the last one, or more, events was the small scarp across the Loburn 2 channel, where uplift against the flow of drainage produced some swamp accumulation on the north side.

The Ashley Fault, with traces on the younger surfaces might be expected to offer more opportunities, but because the scarps face in the direction of drainage flow, there are few sites where ponding is likely to develop along the scarp. Landowner permission to trench one prospective site could not be obtained and only two other sites were identified which fulfilled the criteria.

6.1 Trench 1

Trench 1 was located on the eastern margin of the Loburn 3 channel where the natural formation of a swamp has occurred along the trace of the Ashley Fault, adjacent to an active stream, supplied by a nearby spring system. Excavation was across the swamp's eastern end, extending 6 m on either side of the fault scarp. Significant relationship variations occur between deposits over the width of the trench on the south side of the fault, so both the east and west faces were logged at this end (Fig. 11).

6.1.1 Stratigraphy

On the northern side of the fault, the bottom of the trench exposes slightly sandy yellow-brown silt, extending from the 6 m station to the 11 m station (Fig. 11). This silt layer has been warped by faulting and disappears beneath the floor of the trench at the 11 m station. The yellow-brown silt is overlain and unconformably onlapped by sub-horizontally bedded yellow-brown alluvial gravels that contain lenses of finer gravel in a silty-sand matrix. The bedding in these gravels becomes sub-parallel to the silt layer between the 10 and 12 m stations where both units progressively roll over into the fault zone (Fig. 11). Approximately 0.7 m below the ground surface the colour of the gravel deposits changes from yellow-brown to orange-brown as a result of ground water perched above the impermeable silt. The top 0.3 m of the trench comprises modern soil with gravel inclusions probably derived from excavation of the nearby farm track. The soil/gravel layer extends down the fault scarp face into the swamp where it is overlain by 0.3 m of peat and characterised by a decrease in the proportion of scattered gravel (Fig. 11).

On the south side of the fault scarp, the trench exposes alluvial deposits above which lies a light greyish-green silty-clay at a similar elevation to the yellow-brown silt on the northern side of the fault (Fig. 11). This silty-clay deposit is 0.2 m thick and, on the eastern trench face, is also seen to roll-over toward the fault. Despite the mirror image relationship of the two silty clay units, it is clear that they are stratigraphically separated. At the point of roll-over the southern grey-green silty-clay unit is in contact with the same alluvial deposits that overlie the northern yellow-brown silt layer and the alluvial unit descends into the base of the fault scarp between the two silts. South of the roll-over the grey silt is covered directly by the lowest peats of the same swamp deposits which onlap onto the top of the alluvium.

The peat deposits comprise layers containing numerous rootlets and logs alternating with silty-peat bands. The layered relationship in the peat is best developed on the western trench face where there are clear relationships between the different stratigraphic levels (Fig. 11). Immediately above the grey-green silt-clay layer is a 0.2 m thick layer of peat, which is in-turn is overlain by a silty-peat layer ~0.3 m thick that may represent the influx of sedimentary material resulting from fault rupture. The origin of the silty-peat band cannot, however, be categorically discriminated from a minor flood event as no obvious deformation separates the depositional events. This sequence is repeated again with ~0.2 m and ~0.4 m thick layers of peat and silty-peat respectively and capped by the most recent accumulations of peat material ~0.6 m thick.

6.1.2 Structure

Structure within the trench is complex, expressed dominantly by deformation of the clay and silt layers exposed in the trench floor and their interrelationships with overlying deposits.

On the northern side of the fault zone the subhorizontal yellow-brown silt layer appears in the trench floor at the 6 m station, but by the 7 m station the layer begins to dip to the south at approximately 15° continuing to steepen over the next two metres. Beyond the 9.5 m station it progressively rolls-over into the trench floor, disappearing at the 11 m station (Fig. 11).

The alluvial deposit slightly unconformably overlying the northern yellow-brown silt is in discordant, presumably sheared contact with the deformed grey-green silty-clay layer on the south side of the fault. These gravels are little deformed over the first 9.5 m of the trench, however beyond this there is an incipient roll-over in the crude layering that increases with proximity to the fault (Fig. 11).

The grey-green silty-clay layer at the southern end of the trench is flat lying. At the 13.5 m station on the eastern face the silty-clay unit rolls-over toward the north, dipping at >45° as it disappears into the trench floor at the 12.5 m station. Conversely, on the western face of the trench the deformation of the same grey-green silty-clay layer is reversed and it is warped upward (the dip reaching 60°S), terminating amongst peat deposits (Fig. 11). The disturbed alluvium at the foot of the scarp has not sheared on a discrete plane, and the deformation reversal of the grey-green silty-clay across the trench indicates the complexity of the site. The twisting and warping of the ductile silt with its angular sheared juxtaposition against the alluvial gravels of the northern side and the angular unconformity at the sedimentary contact with the overlying swamp peats and silts is clear indication of a rupture event post-dating the deposition of the southern silt unit.

6.1.3 Interpretation

Based on the their different lithologies, similar topographic elevation and the absence of alluvial deposits above the southern unit, the yellow-brown silt and grey-green silty-clay layers exposed on opposite sides of the fault are not related; the former must be stratigraphically older and relatively uplifted. The amount of deformation accommodated by these two layers suggests that they have been subjected to multiple rupture events. Onlap of alluvial deposits onto the northern silt indicates that the silt layer was deformed by events prior to the abandonment of the Loburn 3 channel surface and the deposits in the trench record at least two, and possibly as many as 4 fault rupture events.

The first event is preserved as deformation of the northern silt layer, this event occurring during the occupation of the Loburn 3 channel surface by the Okuku River, evident in the onlap of alluvial gravels on to this silt layer.

The second definable event was that which resulted in the downwarped depression that allowed formation of the swamp. This is the first datable event in the trench and apart from defining the timing of this rupture, indicates the minimum age for the river's abandonment of the Loburn 3 channel as there is no subsequent alluvial infilling.

On the evidence of minimum bed lengths of both folded silt units, it is evident that there has been a net convergence across what must have been a wider depression, perhaps a structure similar to those described in section 5.1.3, forming a trap for still water deposits both during and after abandonment by the active river. The swamp itself is in a narrow trench formed on the footwall downwarp generated by the thrust component. The anomalous twisting and uplift of the truncated end of the grey silt layer on the western face of the trench may be indicative of strike-slip movement or a footwall splay.

The other two possible events are represented by the influx of silt into the swamp during two separate intervals. The lack of deformation of the silty-peat layers makes it debatable whether they represent fluvial (minor flood event) or tectonic activity. The combined thicknesses of paired peat and silty-peat peat layers are ~0.5 and ~0.6 m which are close to event displacements discussed in a following section, suggesting that the influx of silt could be caused by fault movement.

6.1.4 Results of radiocarbon dating

Three potentially datable events are preserved in the silty-peat layers of Trench 1, the oldest of which is unequivocally associated with fault rupture. Of twelve samples collected from this site, four were prepared and dated to constrain the elapsed time between events and estimate the recurrence interval of fault movement (Fig. 11; Table 1).

Samples Tr1/2 and Tr1/5 from the base of the peat are assumed to mark the minimum age of the event that formed the swamp and a minimum age of the abandonment of the Loburn 3 channel. Tr 1/2 and Tr 1/5 were dated giving conventional ages of 4280 ± 170 (4785 ± 255 CalBP) and 4160 ± 60 years BP (4675 ± 155 CalBP) respectively giving a combined calibrated age range of 4780 ± 260 CalBP (calendar age 3090 –2570 BC at 1σ)) and provide the best-constrained rupture event. Samples Tr1/3 and Tr1/9 are thought to represent the second-to-last and last more cryptic events respectively and are separated by a silty-peat layer. Tr1/3 is dated at 3530 ± 60 years BP (3765 ± 75 Cal years BP and Tr1/9 at 3240 ± 70 years BP (3420 ± 60Cal years BP) (1890 - 1740 BC and 1530 –1410 BC respectively).

6.2 Trench 2

Trench 2 was excavated across an abandoned part of the same swamp as Trench 1, but ~80 m to the west. Excavation of Trench 2 exposed an impermeable cemented layer in the fault scarp and released a perched groundwater system leading to high inflow into the trench. The trench contained no organic material and was quickly abandoned as the influx of water made it unworkable.

6.2.1 Stratigraphy and structure

The trench exposed an iron oxide cemented, fine sandy gravel at a depth of ~0.9 m on the northern side of the fault. Excavation to a depth of ~1.5 m on the southern, downthrown, side of the fault did not encounter this layer. The cemented layer has apparently been displaced by a single fault plane, exposed in the trench walls, presumably reflecting a comparatively cleaner break in the more indurated material.

It is possible that the iron oxide cemented layer is a correlative of the silt layer logged in Trench 1 (as this layer also confines ground water flow to its upper surface) and it may indicate the western continuation yellow-brown silt layer (of Trench 1). The origin of this layer may coincide with activity on the Ashley Fault with uplift and backtilting on the hanging wall resulting in a reduction in surface water flow leading to the deposition of finer sediments.

Unfortunately, this trench did little for the determination of the Ashley Fault's history, but, the presence of the iron oxide cemented aquaclude could provide a target for future shallow geophysical investigations such as GPR.

6.3 Trench 3

Trench 3 was excavated 360 m east of Trench 1, 6.6 m above the Loburn 3 channel surface on the southern side of the elevated area of the 'the Oaks' and immediately east of the homestead. Here the Ashley Fault offsets Burnham Formation deposits and forms one of the three fault depressions present in the field area (Fig. 11). As a result of the depression and a step-over structure, the height of the fault scarp varies both east and west of this location. The total displacement at this locality is probably the cumulation of events that both include and precede those identified in the Trench 1.

The trench was excavated across the steepest and one of the highest (5.5m) scarps along any section of the Ashley Fault; west of a point at which the scarp splays into a northern thrust strand and step-over transfer fault and coinciding with the western limit of the associated fault depression swamp. The site was not ideal because the age of the surface being displaced and the height of the scarp would imply a long history of scarp modification. However, given the lack of more promising sites this was chosen on the expectation that colluvial material generated from the fault scarp would build out into the swampy depression at the foot, and might be expected to bracket fault rupture events older than those exposed in Trench 1. In the event, lack of a constant flow of water into the fault depression (water only present during the winter months), organic deposits were much thinner than expected and no buried organic material was recovered.

6.3.1 Stratigraphy

As with the other trenches, Trench 3 can be subdivided into northern and southern sections separated by the dominant fault zone, (here at the 5.0 m station; Fig. 11).

South of the fault zone the stratigraphy generally consists of loess and loess colluvium deposits with no visible internal layering (Fig. 12). The lowest lithology exposed in the Trench 3 south of the fault was a mottled orange-brown silty-clay that graded up into a yellow-brown clayey-silty fine sand with occasional gravel clasts. Above this layer are two colluvial units apparently derived from the fault scarp. Between the 7.3 m and 9.5 m stations, is a mixed gravelly-clay colluvial deposit. Overlying this layer is the second a silty-gravel deposit, approximately 0.3 m thick, with a notable increase in the gravel component down-slope, the reason for which is unclear.

Deposits on the hanging wall, north of the fault, are dominated by gravels of differing textural compositions, ranging from silty-gravels to gravelly-clay to colluvial deposits (Fig. 12). The lower four units, up to 1.5 m total thickness from the base of the trench at the 3.5 m station are deposits of normal fluvial processes with incipient layering that has warped in response to faulting but not dipping significantly as a whole. Above these, incipient internal layering sub-parallel to the ground surface and oblique to the underlying layers indicates deposits of colluvial origin. The main fault zone is defined by highly disrupted gravel with no internal structure (Fig. 12), abutting into the lower colluvial wedge on an irregular, deformed contact.

Organic surface soil deposits of a more or less constant thickness overlie all the deposits in Trench 3, apart from in three places where the surface soil thins in response to irregularities in the surface generated by fault traces that reach the top face of the upper colluvium.

6.3.2 Structure

The internal structure within the trench is dominated by a principal shear zone between the southern loess and colluvial loess deposits and northern colluvial and alluvial deposits (Fig. 12). A faulted contact between sheared alluvium and the lower colluvial unit on the south side is strongly curved back into a "bull-nosed" re-entrant, which is bypassed by the main shear plane extending to the modern soil. This unusual fault geometry probably formed by deformation of an older or secondary splay by the effects of strike-slip accommodated by the Ashley Fault indicating the complexities associated with the oblique displacement. The anticlinal warping of alluvial deposits on the hanging wall of the fault zone is a feature typical of the reverse component of strain accommodated by the Ashley Fault.

Evidence of minor fault splays is shown in the trench associated with the folding of the gravel deposits away from the main fault zone. Two of these do not appear to affect the top colluvial wedge on the north side of the trench and may be related to an older rupture. Thinning of the soil horizon above other obvious underlying anomalies records the most recent activity of these minor fault splays, which, together with the main fault trace must be related to the most recent rupture event intersected by the trench.

6.3.3 Interpretation

No quantification of the total cumulative displacement could be made at this site (aside from saying that it must be greater than the 2-3 m depth of the trench) as no deposits could be directly correlated across the fault. The presence of the fine silts and sands on the footwall side is compatible with the prediction that a small depression was accumulating sediment on the footwall, but this unfortunately proved to be free of organic material and no other datable samples could be found.

The trench did provide a good section into the fault scarp showing the structural style associated with the Ashley Fault and the propagation of the oblique thrust displacement through near surface cover sediments. The fault stratigraphy in Trench 3 represents at least two events, based on both the two colluvial wedges overlying the silts and on the fault termination and contact relationships. Because no correlative deposits were exposed across the fault, it is neither possible to reconstruct the vertical component of displacement associated with each event, nor estimate the total number that have created the scarp. The similar (40-50 cm) thickness of the two colluvial wedges at the point where they terminate against the fault may be a general indication of the amount of scarp face exposed with each uplift, but strike-slip offsets cannot be determined from trench data.

6.4 Trench 4

Trench 4 (Fig. 13) was the only excavation across the Loburn Fault and was situated in the Loburn 2 channel where the last rupture event(s) on the fault is represented by a 0.5 m high scarp. Displacement during the last event on the Loburn Fault impeded drainage north of the trace leading to an extensive swampy area that has since modified by artificial drainage. It was hoped that organic material had accumulated in positions that would yield a date for the last rupture of the Loburn Fault, or at least an age for the abandonment of the Loburn 2 channel.

Located west of Round Hill and ~10 m east of Swamp Road, the site was selected because of its proximity to a locally active spring system which, prior to the farming modifications, probably fed a more extensive swamp than that now preserved 20 m to the east of the trench.

6.4.1 Stratigraphy

The deepest deposits exposed in the trench are alluvium and represent the last fluvial activity in the Loburn 2 channel. On the north side of the fault zone the alluvial deposits are overlain by a 0.2 m thick, light grey-green silty clay, representing deposits post-dating the fault rupture, this layer contains no sign of preserved organic material. The modern solid overlies both this layer, on the northern side of the fault, and alluvial deposits, on the southern side. The modern soil layer is approximately 0.4 m thick on the northern down thrown side of the fault, thinning across the fault to 0.15 m the southern side.

The fault zone is identifiable by the presence of a blue-grey gouge and an increase in water flow (Fig. 13).

6.4.2 Interpretation

From the presence of the silty-clay on the northern side of the fault one event can certainly be identified and from thickness variation seen in modern soil it possible that two events are preserved in the trench.

The first event is represented by the deposition of the grey-green silty-clay layer probably due to impedance and ponding stream flow caused by uplift on the fault. The >0.2m thickness of the layer is therefore a minimum estimate for the uplift of the impeding scarp barrier. The total offset of alluvial gravels across the fault is 1.0m.

A second event is suggested by the subsequent deformation of the grey-green silty-clay layer towards the fault and the increase in the thickness of the overlying soil layer, so the 0.5 m surface scarp height is a little less than the actual displacement of the base of the soil. Because of the intimate mixing of modern plant matter in the soil it was not possible to use this source of organic material to date either event.

6.5 Event displacement on the Ashley Fault

Constraining the vertical displacement on the Ashley Fault is difficult due to the lack of features which can be assumed to have been at precisely the same elevation prior to displacement. This is because of the uncertainty as to the component of strike slip movement, where it cannot be assumed that the scarp height necessarily measures the difference between matching surfaces. Scarp heights are also affected by and the presence of fault step-overs along the fault trace. Within the Loburn 3 channel there are four features from which vertical displacements can be measured and a case for offsets per event can be made. The first two features are preserved in the 'stepped' terraces on the western side and the fourth is an abandoned stream channel which is now ponded (Fig. 9). Two preserved terraces on the western side of the Loburn 3 channel are interpreted to represent the cumulative vertical offset of two events during the occupation of the channel by the river (Fig 13). Displacement of the terraces may have been affected by uplift resulting from the formation of the flower structure to the west, but this is unlikely as the terraces are situated at the eastern limit of this zone of increased uplift and scarp height is therefore probably representative of the actual vertical displacement. Scarp height relates to the terrace that is displaced, decreasing in elevation from west to east as a result of river slip-off following each event (i.e. older terraces are displaced by the greatest amount). Fault displacement of the western most terrace (T1) is by 2.5 m, the next terrace to the east (T2) by 1.7 m, and the remaining terrace, in the Loburn 3 channel, by 1.5 m. Assuming these terraces have resulted from individual events on the Ashley Fault, it can be inferred that the average vertical displacement per event is ~0.5 m.

Half a metre of vertical displacement per rupture is also suggested by an abandoned stream channel at the eastern edge of T2 on the Loburn 3 channel surface. The stream channel has been impeded by activity on the main fault and a minor backthrust (the backthrust is more prominent on the terraces to the west; Fig. 9). The stream bed has been displaced vertically by 0.5 m where it crosses the main fault trace. The presence of a ponded area behind the minor backthrust suggests that the elevation of the stream bed point has not been significantly modified by subsequent erosion.

This sequence of events is compatible with the data from Trench 1 where evidence for an event during river occupation and for one after abandonment was clear. Given the 1.5 m height of the scarp across the channel, it is plausible that this represents the cumulative throw of three events, which may be reflected in the two cycles of accumulation of the 0.5m thick silt and peat accumulations in the swamp trough observed in Trench 1. The lack of deformation in these units militates against total acceptance of this interpretation. The 0.5m average throw is also compatible with the colluvium thicknesses noted in Trench 3.

The amount of strike-slip motion accommodated on the Ashley Fault during any, or all, of the events is uncertain. It might have been expected that the terrace margins and the small stream on the western side of the Loburn channel would have shown up any significant strike-slip component. There is one possible exception where the highest terrace offset on the western side (Fig. 9) which is stepped over by approximately 40 m for a scarp height of 2.5m. Since the same scarp height is recorded for the next terrace below which shows no sign of an offset margin, this anomaly is likely to have been an artifact of selective erosion. The vertical displacements suggested here therefore represents minimum values for slip per event on the fault plane, and it may be that the last few events are atypical relative to longer term slip orientation. If the analogue with the Richards et al. 1995 model of 0.6 SS/DS oblique slip ratio fault pattern discussed earlier is accepted as an approximation, then 0.5m of throw translates to an increase in the net slip of 0.58m, an insignificant increase relative to the likely real variations between events.

7. DISCUSSION AND SUMMARY OF THE ASHLEY-LOBURN STRUCTURE

7.1 Fluvial development and fault activity

During the formation of the Woodlands Formation the Okuku, Karetu, Grey and Makerikeri Rivers flowed in a structurally controlled orientation as a result of NNW-trending folds. At this time the east branch of the Grey River drained into the channel of the Makerikeri River and the west branch drained through the Loburn 1 channel (Fig. 4a), perhaps continuing to Windwhistle time. At the same time the Karetu River still may have been independent of the Okuku, occupying the Loburn 2 channel, to the west of Round Hill. Round Hill and 'the Oaks' were preserved above the affects of fluvial activity due to activity on the Ashley Fault System.

During the period that the Karetu-Grey River occupied the Loburn 2 channel (late Burnham Formation-early Springston Formation), activity on the NW-trending folds continued, as represented in the Loburn 1 channel, coinciding with latest record of significant uplift rates and of activity on the Loburn Fault (Fig 4b). Minor fluvial activity occurred in the Loburn 1 channel, maintaining two small streams across the structure and leaving terraces and abandoned channels preserved there. The Karetu River was controlled on the eastern side by the presence of a remnant NW-trending fold, while the western side remained structurally uncontrolled and may have amalgamated with the Okuku River. During this period it appears that there was a rupture event on the Ashley Fault preserved on degraded Burnham surfaces at the southern end of 'the Oaks' and on the "flower" structure west of the eventual Loburn 3 channel. This event may have caused the apparent eastward change in the channel's orientation as it approaches the Ashley Fault.

The orientation of the Loburn 3 channel shows little in the way of structural control (Fig 4c). The scarps on the degradation terraces show that at least 2 events occurred on the Ashley Fault during the occupation of the Loburn 3 channel and are represented in the Loburn 2 channel, with flow in the Loburn 3 channel impeded and deflected eastward across the zone of faulting by the development of the flower structure to the west. During the period of Loburn 3 channel activity two probably events occurred on the Loburn Fault represented in Trench 4.

Since the abandonment of the Loburn 3 channel, at least one and up to 2 more events have occurred on the Ashley Fault possibly indicating an increase in the rate of activity, with a corresponding decrease in activity on the Loburn Fault. The small Loburn Fault scarp in the Loburn 2 channel suggests that the Loburn Fault has not been very active since formation of that channel and has not moved at all since the abandonment of Loburn 3 by 4780 ± 260 Cal BP at the latest.

7.2 Ashley and Loburn Faults

Seismic activity on the Ashley and Loburn faults is expressed at the surface by scarps of varying heights and by fault propagated folding.

The Ashley and Loburn faults appear to converge to the west, somewhere along the axis of the current Ashley River. The plane of Ashley Fault dips to the north, the Loburn Fault to the south. Both of these faults have demonstrably significant reverse slip displacements which have uplifted the intervening area. More indirect evidence suggests that these faults have a component of dextral oblique-slip transpression.

The Loburn Fault was most active during occupation of the Loburn 2 channel, based on the vertical displacements of up to 7.5 m preserved in the Loburn 1 channel. Degradation of the fault scarp and the lack of activity since abandonment of the Loburn 2 channel does not allow the interpretation of any component of strike-slip motion on the fault. Round Hill is may be an interference structure resulting from the oblique intersection of a NW-trending fold with the uplifted block, but it also coincides with the swing in strike of Loburn Fault, and this structure is closely analogous to similar curved anticlines developed on restraining bends elsewhere in Canterbury and reproduced on the AFS in the Cust Anticline. There is a general southeastward tilt on the upper surface of the block.

The Ashley Fault is the most recently active fault in the area and has accommodated multiple ruptures, displacing the northern side vertically by up to 6.8 m at the 'flower' structure. The heights of scarps vary along the fault's length closely related to relative surface age, strike-slip movement, and fault step-overs at two different scales. On a small scale, the formation of fault depressions at three areas along the fault indicate right step-overs, while at the 'flower' structure the fault steps left resulting an increased rate of uplift, both types of structure are associated with strike-slip movement. On a larger scale a similar process is also occurring, beginning just west of Swamp Road this zone extends west, at least to the eastern side of 'the Oaks', producing a ~1m increase in scarp height due to a broad change in the strike of the fault (Map 1). Uplift on the western end of the Ashley Fault is tending to reverse the former tilt direction. At the eastern end the fault scarp becomes progressively diminished to disappear as a surface trace 1km before reaching the Makerikeri River. This suggests that the fault may be propagating eastward.

7.3 Regional relationships of the Ashley-Loburn structure

7.3.1 Western extension of associated structures (Ashley Fault Zone and Springfield Fault)

The active scarp on the Ashley Fault has been recognised for a long time and appears on the 1:250,000 Geological Map of New Zealand Sheet 21, Christchurch Sheet (Suggate, 1973). Cowan (1992) proposed that the Ashley Fault connects to the structures controlling the growth of the Cust Anticline. The latter has been extensively investigated during recent petroleum exploration by Indo-Pacific Energy Ltd. and is intersected by several seismic lines. It was unsuccessfully drilled as a possible prospect in 1999. The structure was interpreted as a wedge shaped pop-up, and the seismic profiles clearly show an anticlinal structure complexly faulted internally. It is bound on the north by a fault following the projection of the Ashley Fault up the bed of the river and reappears as a recent trace on a low terrace at the junction of the Ashley and Okuku Rivers. The whole structure curves to the southwest, and both recent traces and seismic lines, show the presence of secondary faults with a reverse displacement, trending northeast into the south side of the structure (Fig. 3).

Reconnaissance mapping (Jongens et. al., 1999) has identified active scarps crossing late Pleistocene surfaces continuing around the foot of Starvation Hill to extending along its south flank, with a return to an east–west strike past Oxford township. These traces appear to connect with intermittent scarps which again swing to the southwest across the surface of the Plains towards the Waimakariri River striking towards Springfield. West of Springfield the hills rising from the Canterbury Plains are formed by a major anticline bringing basement to the surface and cored by a thrust fault, the Springfield Fault, which appears to lie on the same line. This fault has been shown to have ruptured several times during the late Pleistocene and Holocene (Evans, 2000), but the timing of these events is still under investigation (Fig. 3).

Active fold growth on the Hillside Anticline and a post-Burnham displacement on the Mt. Lowry Fault has been described upstream of the AFS across the Okuku River (Powell, 2000) relating to fault propagation along the range front below Mt Thomas and forming part of the activity associated with the PPTZ. Recently, evidence of multiple Holocene rupture events on the southwestern end of the Porters Pass Fault has been documented (Howard, 2001). The mechanism of interconnection between these range front structures and the AFS is not certain, but it is clear that the systems are not independent.

7.3.2. Eastern extension of associated structures (Springbank Fault).

During the same petroleum exploration programme, a seismic line across the Canterbury Plains south of Cust crossed a significant fault marked by a broad anticlinal fault-propagation fold in the hanging wall and subsequently named the Springbank Fault. This structure was found to mirror an uplifted surface of older Pleistocene gravels above the Burnham surface, and from the seismic stratigraphy, is interpreted to have 350m of reverse displacement on the fault since deposition of the Kowai

Formation. This is thought to be a very significant structure, although its full extent has yet to be mapped.

Southwestward, the surface expression of the fault is lost, but strikes towards the Hororata Fault which bounds the eastern margin of the Malvern Hills, suggestive of a regionally extensive system extending down the central Canterbury Plains. (Fig. 3)

The strike of the fault projecting northeast across the Cust River lies at the eastern limit of the Cust Anticline and virtually coincides with the easternmost limit of visible traces on the Ashley Fault. It may terminate here, or swing eastwards around the foothills. The AFS therefore appears to link the northeast striking, east facing thrust of the Springbank Fault, to the northeast striking, west facing Springfield Fault at an orientation that suggests that it functions as a transfer fault. Backthrusts off the Springbank Fault seen in seismic lines, form the faults that intersection the curved western end of the Cust Anticline, and may be genetically related to the location of the step-over and segmentation of the AFS at this point. By implication, similar relationships at depth may control the swing in strike of the Loburn Fault and its splay into the Ashley Fault. Logically, given the general evidence of relative age, it is likely that the south dipping Loburn Fault is the primary structure extending at depth to link with the plane of the listric Springbank Fault at it flattens in dip towards the west. The north dipping Ashley fault may therefore be a relatively shallow backthrust off the Loburn Fault. The seismic data does not extend to the Torlesse basement unconformity so that the projection of these structures into basement is speculative. There are two possible models whereby the AFS could be functioning in relation to the Springbank and Springfield Faults, each of which has different implications for the seismic potential of the system.

Model 1: The AFS may be a classic transfer structure in that it penetrates only as far as the detachment zone, allowing the upper plate to move along the detachment independently, relative to the sequence north of the transfer boundary. Such a model accounts well for the evidence of longer and greater deformation in the Cust and Starvation Hill sectors by comparison with the Ashley sector, the latter terminating at the eastward limit of the emerging thrust front and presumably propagating in response to forward motion. The predominance of vertical movement at the eastern end is also consistent with the fault propagation fold growth and uplift occurring along the leading edge of the Springbank structure, where horizontal displacement at depth is translated to vertical displacement at the emergent tipline. The implication of this model is that movement on the Ashley system is a secondary response to increments of relative motion on large detachment faults to the north or south. The inferred dextral component on the AFS implies the sense of long-term net relative motion.

Model 2: Alternatively the AFS may be a more fundamental strike-slip fault splaying off the southern side of the Porters Pass-Amberley Fault Zone and penetrating deep into upper crustal depths to the seismogenic zone, functioning independently of the thrust systems, which become truncated by it as it propagates across them. Favouring this interpretation is general evidence from structures to the north, that many similar east-west striking faults are reactivated late Cretaceous normal faults associated with the then prevalent crustal extension regime.

8. SEISMIC HAZARD ASSESSMENT

8.1 General considerations

The extent to which the data presented here can be interpreted in terms of a well constrained estimate of the seismic hazard presented by the Ashley-Loburn fault system is very limited for two reasons.

Firstly, sites from which extensive and well constrained records of seismic events can be extracted are serendipitous. In this case few sites appeared to offer much likelihood of preserving datable material and of those trenched, only one yielded useful dates. The possibility remains that a choice of a trench line a few metres away, or at an apparently less promising location could have yielded more data. Limitations on finding suitable materials to date various erosion and aggradation surfaces, meant that long term slip rates based on the height of scarps intersecting these surfaces depend on speculative correlation of these surfaces with Pleistocene events. The general evidence for a shift in activity, propagation of the system and variation in scarp heights due to local discontinuities mean that long term slip rate calculations based on scarp heights have little meaning, or reliability, because they are unlikely to be linear.

Secondly, even a better constrained data set leaves open the question of how the seismic history of this segment relates to activity on the larger fault array

8.2 Single event displacements and recurrence intervals for the Ashley and Loburn fault system

The best data for estimating the level of late Holocene activity on the Ashley Fault comes from the combination of scarp heights on the degradation terraces and Trench 1 in the Loburn 3 channel. However, the evidence is ambiguous.

The scarps on the undated terraces and the channel differ by increments of approximately 0.5 m, although the cumulative scarp height of the trace across the channel floor is 1.5 m (Fig. 8). It was suggested that the ~0.5 m increments represented the displacement per event, thereby implying that three events account for the scarp across the channel. This may be reconciled with the evidence in the trench, if the deformation of the lowest blue-grey silt and the two subsequent dated cycles of silt and peat relate to these ruptures (Fig. 10). The following discussion deals with the logical consequences of this interpretation with regard to single event displacements and recurrence intervals.

A total record of at least five ground rupture events has occurred since the river was well entrenched into the Loburn 3 channel. The oldest event initiated the scarps on T1 and also cut the higher, but degraded Burnham surface for the first time, while the river was at the level of T2. The next increment(s) of scarp growth took place while the river occupied the floor of the Loburn 3 channel, and is evident in the deformation of the yellow-brown silt on the north side of Trench 1, unconformably overlain by onlapping fluvial gravels. Three further events post-date the abandonment of the channel initiating peat accumulation in the trough at 4780 ± 260 CalBP and at close to 3765 ± 75 and 3420 ± 60 CalBP. These dates represent intervals between events of 1015 ± 336 and 3450± 135 years respectively, and it is of interest to compare these to the elapsed time of 3420 yrs since the last of these events. Also to be considered is the lack of any significant increase in the scarp height of the degraded, but highest surface to the west of the channel and the total height of 5.5 m on the better preserved late Burnham surface east of the Loburn 3 channel at Trench 3. While the age of these surfaces is not known, general field relationships suggest a post- Last Glacial Maximum age of less than 18 ka and possibly significantly younger for the latter, but it must have been formed prior to the occupation of both the Loburn 2 and 3 channels incised into it.

The implication of this interpretation of the data is that if the characteristic displacement per event averages 0.5 m, then the recurrence interval is very irregular. For a maximum time of 18 ka for the accumulation of 5.5 m scarp height over approximately 11 events, then the average recurrence interval would be of the order of 1600 years, approximately half the elapsed time since the last event and significantly longer than the interval between dated events in Trench 1. Any younger age assigned to the highest scarp clearly reduces this calculated recurrence time and in this context it should be noted that the Ashley Fault scarp across the Loburn 2 channel is very close to the same height as on the higher surface, although complicated by the accentuation of the stepover effect. This observation suggests that either the time between the occupation of the Burnham surface at "the Oaks" and the cutting of the Loburn 2 channel was no more than a few thousand years, or that the activity on the Ashley Fault only broke through to these surfaces at about the time of the cutting of the Loburn 2 channel, in the latest Pleistocene to early Holocene.

An alternative interpretation of the trench data, suggests that the two youngest cycles of silt and peat accumulation, which are apparently little disturbed, may not represent rupture events. This implies the possibility of a single displacement of 1.5 m. immediately prior to the 4780 BP peat. The scarps on the terraces still require some smaller incremental events prior to this, so that a characteristic displacement cannot be assumed in estimating the number of events needed to create the 5.5 m scarp. It does allow for the possibility of a fewer number of events, some of which may be significantly greater in magnitude.

What can be concluded, is that the Ashley Fault clearly has a history of multiple, significant ground rupture events in the Holocene. General evidence suggests that it may have become active in the late Pleistocene to early Holocene and is propagating eastward. Felt intensity of shaking is therefore likely to be concentrated here and to the east, in the vicinity of Ashley and Rangiora and in the high density rural development and subdivision currently taking place around the eastern end of the Ashley-Loburn structure.

While the Loburn Fault now appears to be the less active of the two, there is still potential for activity to occur.

It should be noted that regardless of either interpretation of the data outlined above, that it is possible that more recent ruptures may have taken place which were unrecorded, or unrecognised in the trench stratigraphy.

8.3 Magnitude of earthquakes

Calculating the maximum credible earthquake (MCE) for an individual fault is only as accurate as the parameters that define the fault in question. Regression analyses involving fault rupture length and event displacements can only be used if uncertainty as to the rupture length is not greater than 20% and there is one estimate of surface displacement at what is assumed to be the location of maximum offset (e.g. Wells and Coppersmith, 1994; Bonilla et al, 1984).

8.3.1 Surface rupture length and single event displacement

The observed continuity of scarps for the Ashley Fault as strictly defined, is only 4.5 km before ceasing to form a visible scarp on the Springston surface to the east and disappearing into the active bed of the Ashley River to the west. There it is probably joined by the curving projection of the Loburn Fault. This junction has the potential to act a segment boundary, dissipating displacement propagating along the system. The strike of the Ashley Fault projects past the north side of the Cust Anticline and is likely to be essentially continuous to the western end. The restraining bend stepover to the continuation past Starvation Hill presents a much more significant segment boundary, but too little is known of this system to be able to demonstrate whether or not the entire length of the AFS ruptures, a distance of approximately 35–40 km.

The two models for the possible deep structure and linkages of the AFS have an important bearing on the implications for the seismic characteristics.

In Model 1, the fault functions as a transfer fault delineating the northern boundary of a system of thrust faults propagating to the surface at the eastern end as the Springbank Fault. From our little knowledge, of this structure it is clearly propagating to the surface as a still blind, or just emergent tipline. Substantial increments of displacement at the root of the structure are disseminated into an actively growing, fault- propagation fold at the leading edge. An analogy can be drawn with the structure associated with the Northridge earthquake. At times, some or all of this displacement on deep seated detachments will be transferred into the backthrusts on the hanging wall such as the Springfield and Cust structures, telescoping the upper plate. Such variations in deformation of the upper plate can be expected to affect the displacements along the bounding transfer system i.e. the AFS. The effect of both processes will be to step down the displacement towards the east, particularly across the segment boundaries. This means that the figures for individual event displacements on the Ashley Fault may be conservative.

The predictable consequences with regard to this model of the system as a seismic source can be summarised.

- The rupture may initiate on the detachment system well to the west along the range front, but will propagate eastward. It can be expected to produce strong shaking in a northeast to southwest zone along and to the east of the outcrop of the Springbank Fault-fold structure, extending from Rangiora to Christchurch. A comparison can be drawn with the effects of the 1999 Taiwan Chi Chi earthquake. Other sites of high energy concentrations may be predicted at the restraining bend stepovers along the AFS.

- Obvious surface rupture may not occur along the Springbank Fault although geodetic measurements may be expected to show significant uplift and shortening. It is likely that more obvious scarp formation will take place on elements of the AFS and the other northeast trending thrusts such as the Springfield Fault.

- The traditional interpretation of rupture length as a measure of the diameter of the rupture area of a simple planar ellipsoidal fault is inapplicable where the fault being used is the subvertical boundary of a much larger, low angle detachment.

- Given these considerations quantifying an estimate of the MCE is not possible using standard methods and the available data.

In Model 2, the AFS is regarded as a more simple, steeply dipping, oblique strike-slip fault penetrating deep into the upper crust and splaying off the Porters Pass Amberley Fault Zone. While the importance of segmentation in arresting or stepping down rupture propagation remains, a surface rupture length of approximately 40 km may be a reasonable measure of the maximum credible earthquake, provided that other elements of the Porters Pass system are not involved synchronously. This second model carries with it then the following implications:

- From the model for faulting proposed by Wells and Coppersmith (1994), it is possible that the Ashley Fault is capable of producing an event of M 6.9 (Fig. 14), a value which is little affected in this range, if treated as either strike-slip or reverse.

- Using similar regression relationships of moment magnitude against slip displacement (Fig. 15) and taking the 0.5 m average displacement value for the Ashley Fault scarps produces a lower figure of M 6.6. For a displacement of 1.5 m, the height of the scarp in the Loburn 3 channel if formed in a single event, increases only slightly for a pure thrust motion but approaches a similar value of M 6.9–7.0 depending on the contribution of strike-slip to the net-slip.

- The zone of maximum felt intensity would be concentrated along the northern margin of the Canterbury Plains, most strongly affecting the townships of Oxford and Rangiora and other smaller settlements in an elongate zone centred on the AFS with a strong west – east directivity.

This latter view of the seismic potential of the AFS is probably the more conservative of the two. If the much more extensive thrust system is the primary seismic source as discussed for the first option, then it is probable that the moment magnitude generated by a rupture resulting in an equivalent length of surface break and displacement along the length of the AFS, will involve a substantially larger rupture surface area. The area affected by the maximum felt intensity will extend further south into the central Canterbury Plains and be more strongly felt in metropolitan Christchurch and the central plains townships as well as being severe through the Oxford to Rangiora zone.

8.4 Seismic hazard assessment

From the preceding discussion, taking this analysis further to attempt a probabilistic statistical treatment of seismic hazard assessment would not be appropriate, both because of the limited data and its ambiguities and because of the uncertainty of the geometric and mechanical links of the Ashley Fault to the regional fault pattern.

Taking just the Ashley-Loburn system in isolation, the data show that this is a Class 1 Fault with a history of three or more ground displacement events in the Holocene, with the potential for credible magnitudes frequently up to M 6.6 and perhaps some events close to M 7.0, particularly if the fault is part of a larger rupture along the full length of the AFS. Unless younger events have been missed, the elapsed time since the last event is between 3,400 to 5,000 years depending upon the interpretation of Trench 1 data. Recurrence intervals may be irregular, but given that three to five events in the Holocene have been identified, it is likely that this elapsed time must be close to the upper limit of reasonable values for average return periods.

Regardless of the alternative cases discussed, it is evident that Rangiora, the small townships and intensive rural development along the northern margin of the Canterbury Plains will be strongly affected by events in this magnitude range. The likely west-east directivity and 40 km separating Christchurch from this area mean that for the city the effect will be less severe, but obviously can be very variable in relation to the modulating effects of ground conditions.

If the Springbank Fault system is involved, the projections are significantly affected. This is particularly so with respect to the impact on metropolitan Christchurch, both in terms of the possible upgrading of the magnitude of event the system could generate and the zone within which the maximum felt intensity would be concentrated.

9. FURTHER WORK

9.1 Ashley-Loburn Fault system

Further work within the Ashley-Loburn system could yield some useful data. Extensive trenching of more fault scarps may yield datable material, but with the exception of the untrenched swamp just west of the Loburn 3 channel, for which access was declined, there are few further sites offering much promise.

The prospect of getting subsurface information on details of structures in the top kilometre is now much better since the purchase of multi-channel seismic equipment, which is in the process of being used successfully on similar structures. This may help to improve estimates of fault dip, total displacement of key reflectors and the folding and dip of underlying strata, but probably adds little to problems of isolating individual rupture events.

The most fundamental problem remains the reliable dating of the age of displaced surfaces, exacerbated by the lack of radiocarbon datable organic material. Other methods such as OSL and cosmogenic dating are now becoming more reliable and readily accessible, although costly. These methods still require that appropriate material in correctly stratigraphically-controlled sites can be found.

Possibly other geophysical techniques such as geodetic monitoring of ground deformation, and studies of microseismic activity could provide some indication of whether or not active deformation is currently taking place, but such data are ambiguous with respect to their implications for precursor indicators of major seismic events.

9.2 The Springbank–AFS system

It is clear that since the initiation and bulk of the work done on this project, that it has been overtaken by events that have highlighted the presence of a much more extensive network of faults underlying the Canterbury Plains. At this time, further work would be more profitably directed towards these structures, and in practice some student projects have been undertaken and further work is in progress. The size of the area, and the scope of the problems, make the capture of the kind of data needed for a definitive assessment of the seismic hazard posed by these sources a long term project.

10. REFERENCES

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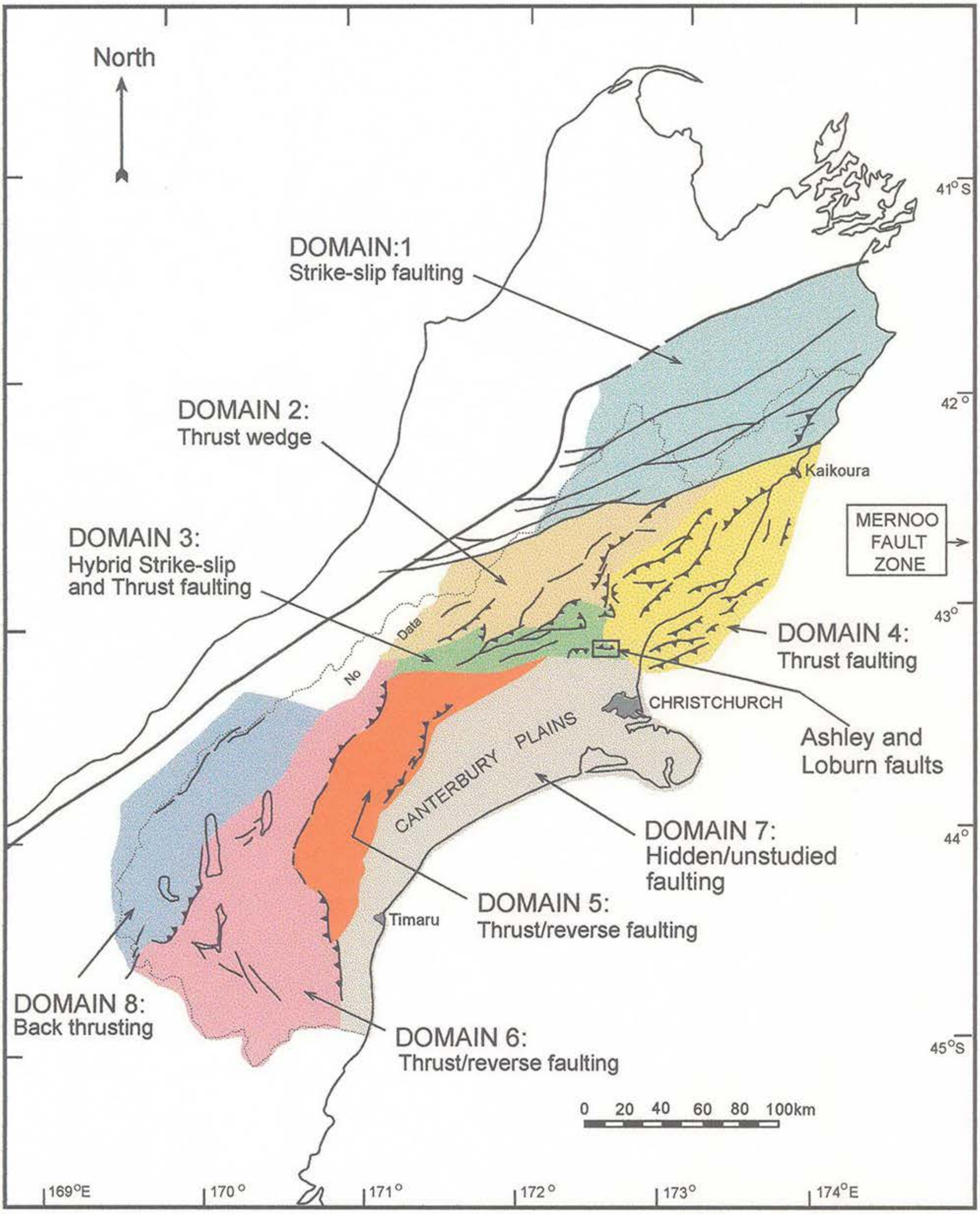


Fig. 1. Summary map of the structural domains 1 - 8 for the Canterbury region (Pettinga et al, 1998).

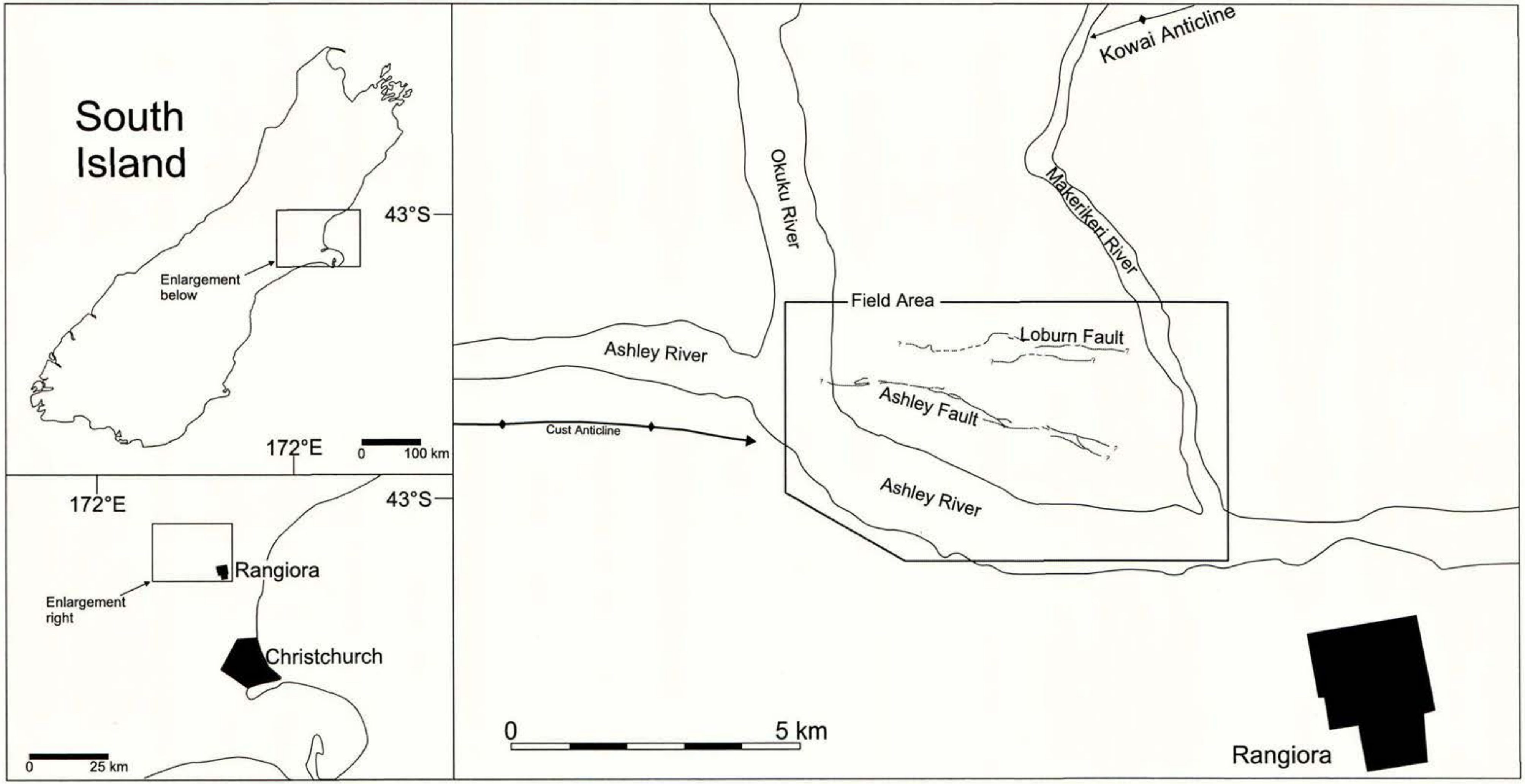


Fig. 2. Location map of the field area. The Ashley and Loburn faults are located 4.5 km northwest of Rangiora. 30 km from metropolitan Christchurch. The geology of the field area is shown on Map 1.

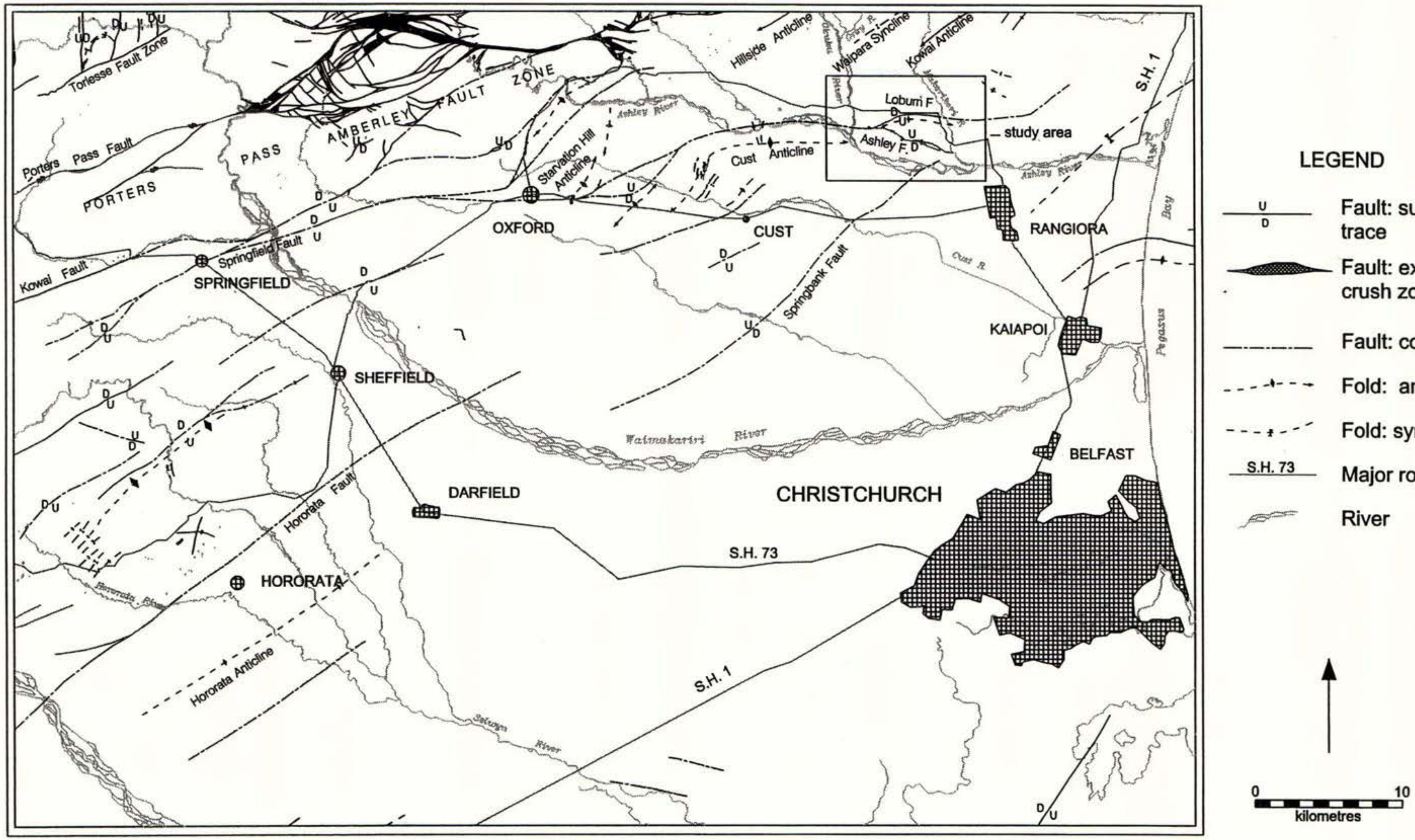


Fig 3. The Canterbury Plains showing the location of major faults and folds defined by both surface mapping of displaced surfaces, surface exposure and subsurface geophysical data. The Ashley-Loburn structure discussed in this report is located in the marked area in the northeastern sector of this map. All the structures shown displace Quaternary sediments or surfaces and are potentially active.

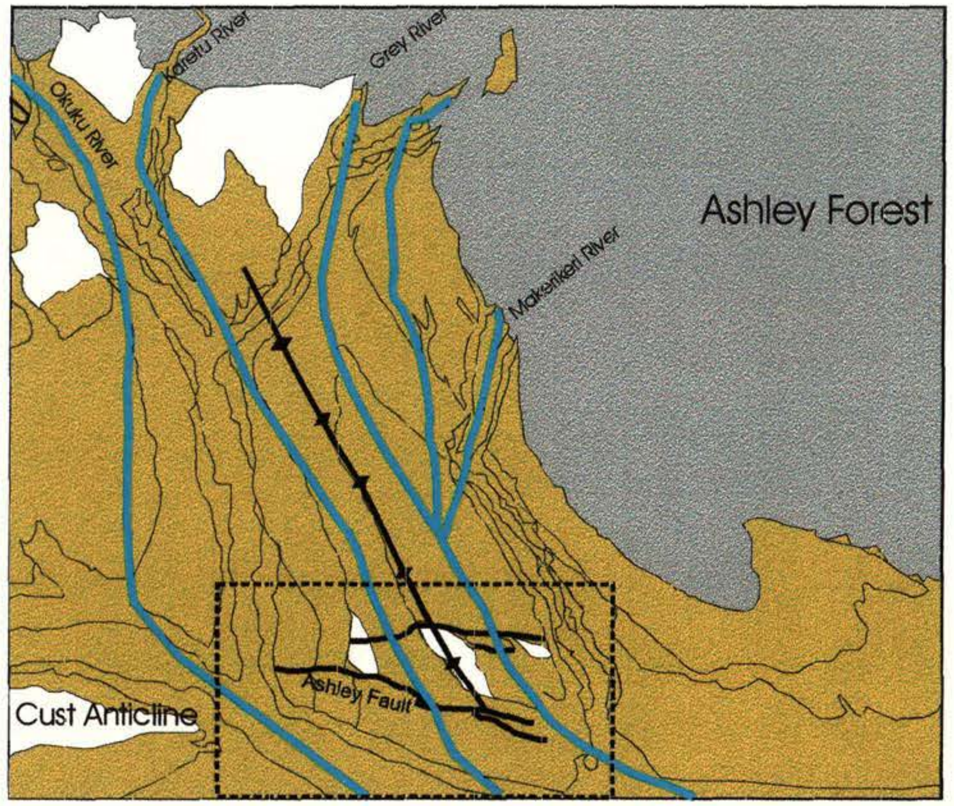


Fig. 4a Fluvial activity during the formation of the Woodlands Formation

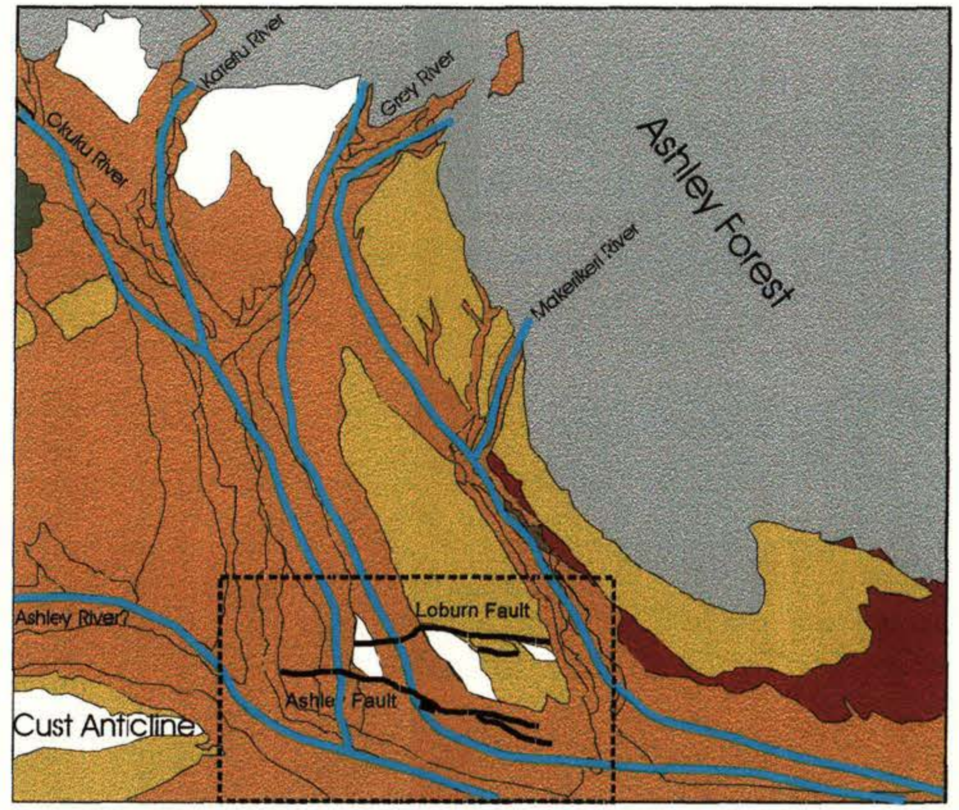


Fig. 4b Fluvial activity during the deposition of the Burnham Formation

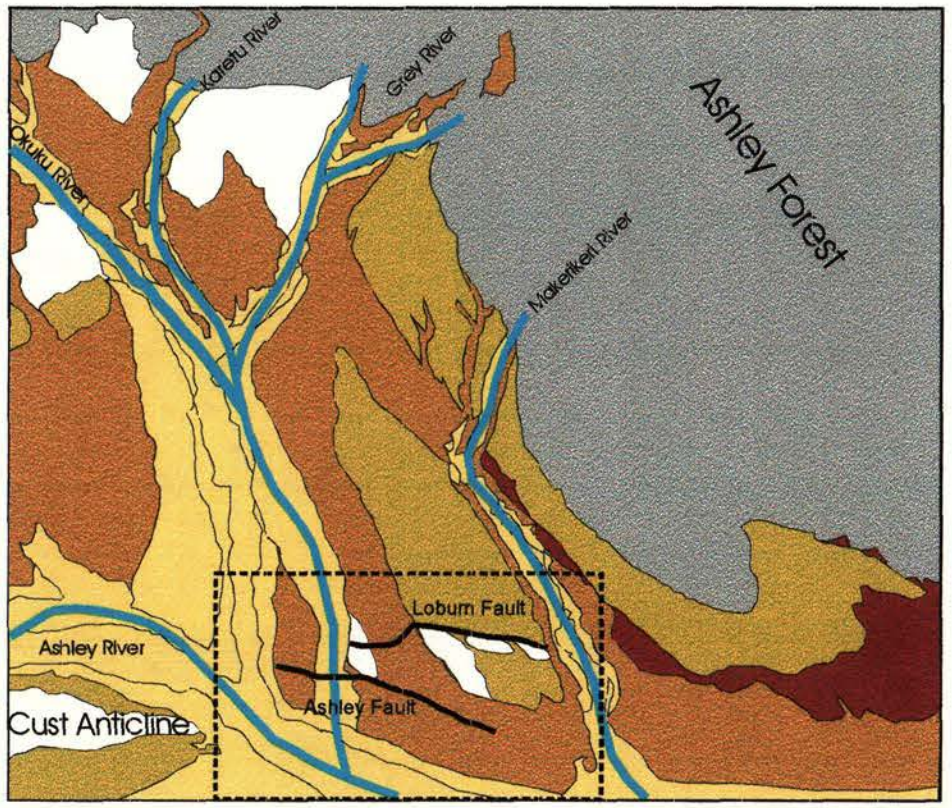


Fig. 4c Fluvial activity during the deposition of the Springston Formation

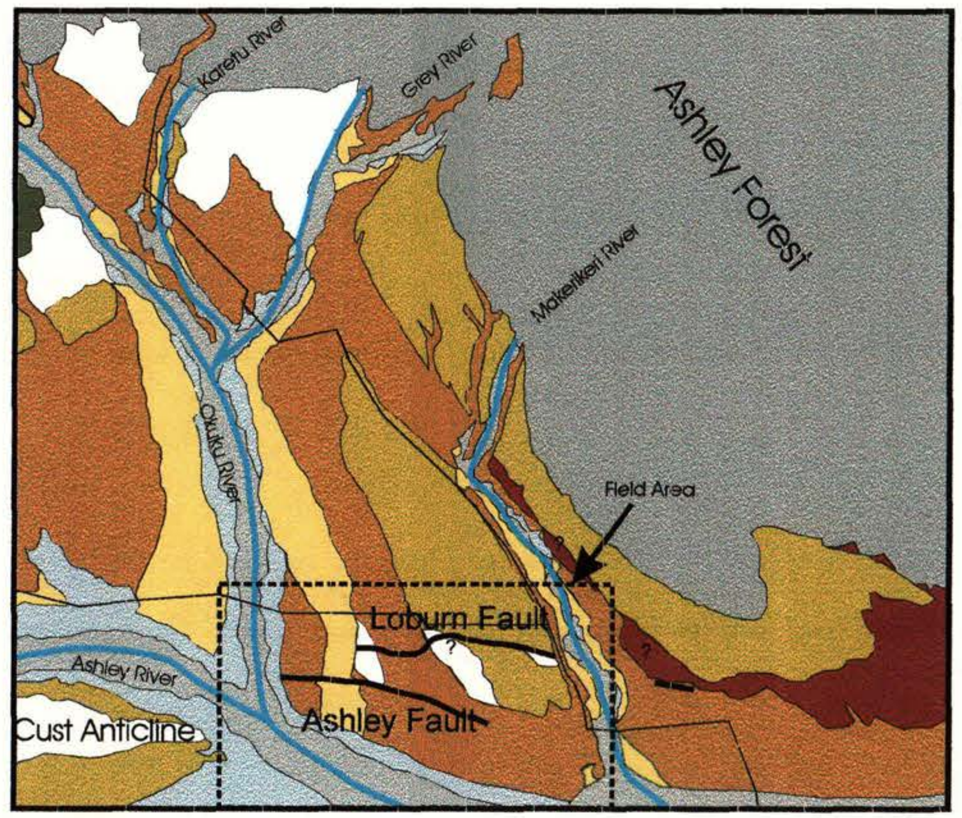


Fig. 4d Present day fluvial activity.

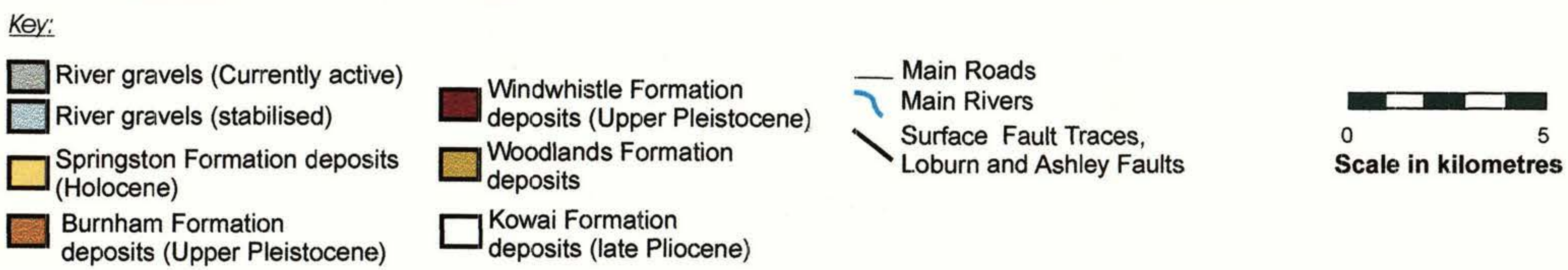


Fig. 4. The development of the Okuku River system.

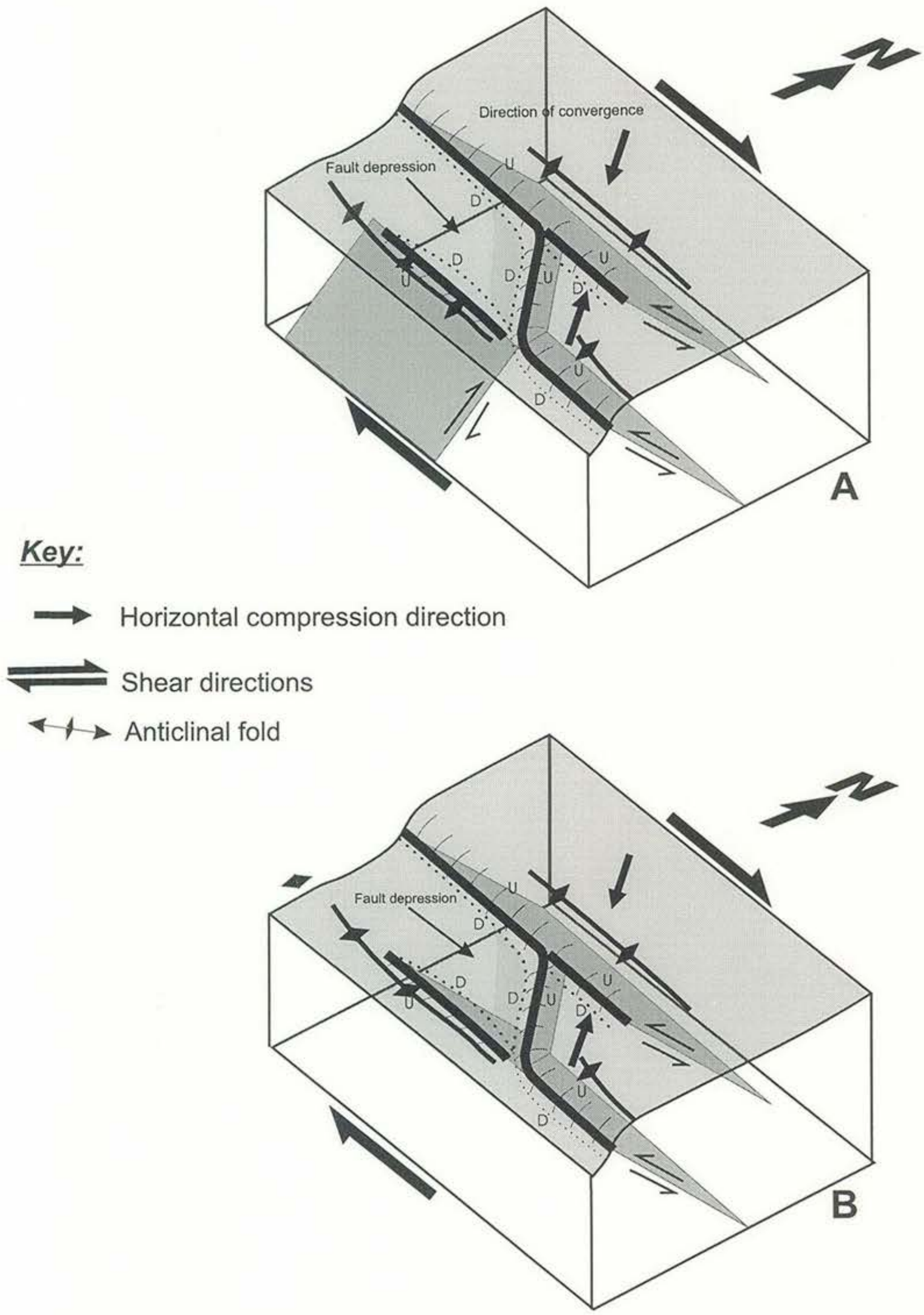


Fig. 5. A) Model of the fault depression formed by a southward dipping fault plane on the southern side of the depression. **B)** Model of the fault depression formed normal fault on a north dipping fault plane on the southern side of the depression. Normal faulting occurring as a result of post-event settlement.

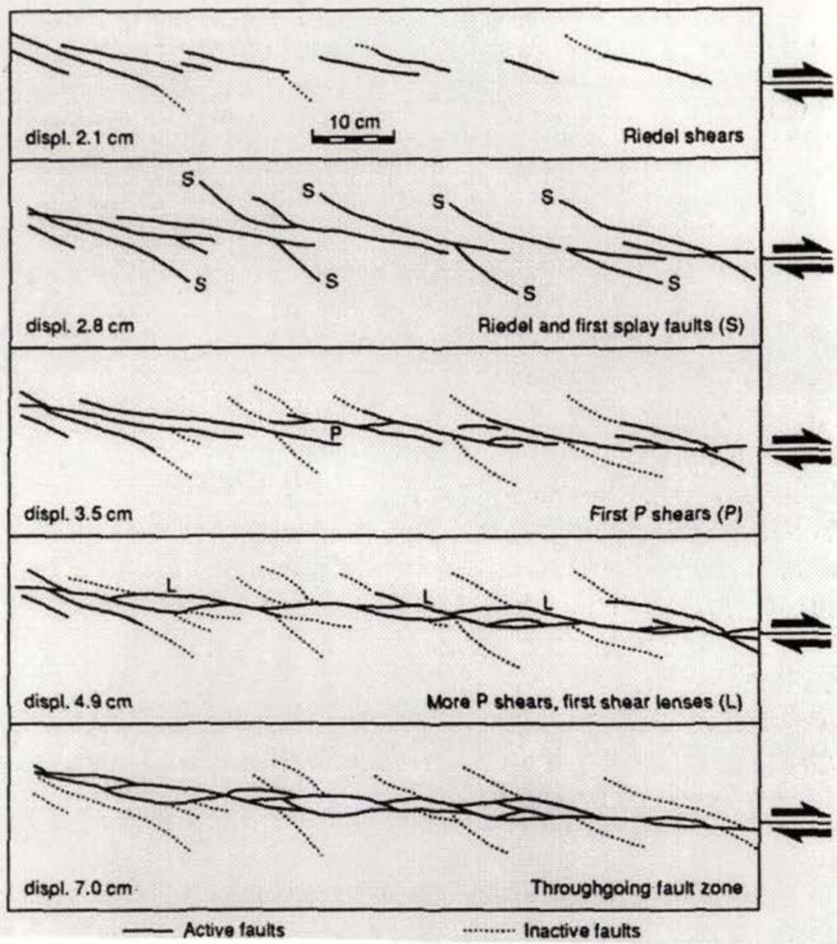


Fig. 6. Sequential development of a dextral thoroughgoing strike-slip fault zone (from Naylor et al, 1986).

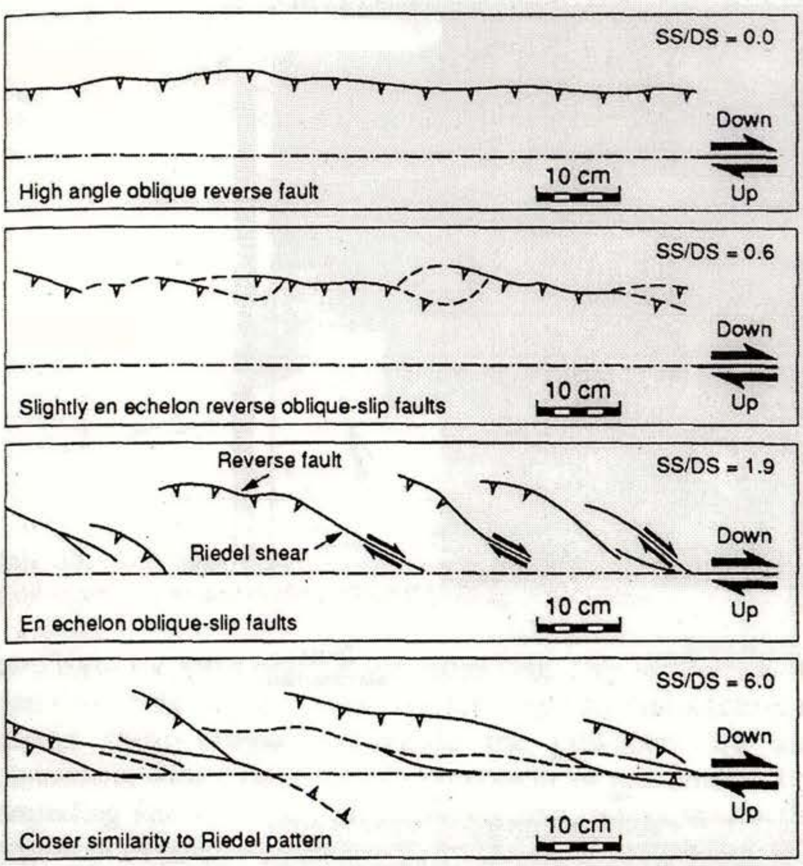


Fig. 7. Reverse oblique-slip faulting: fault patterns formed above a reverse basement fault (Richard et al, 1995)

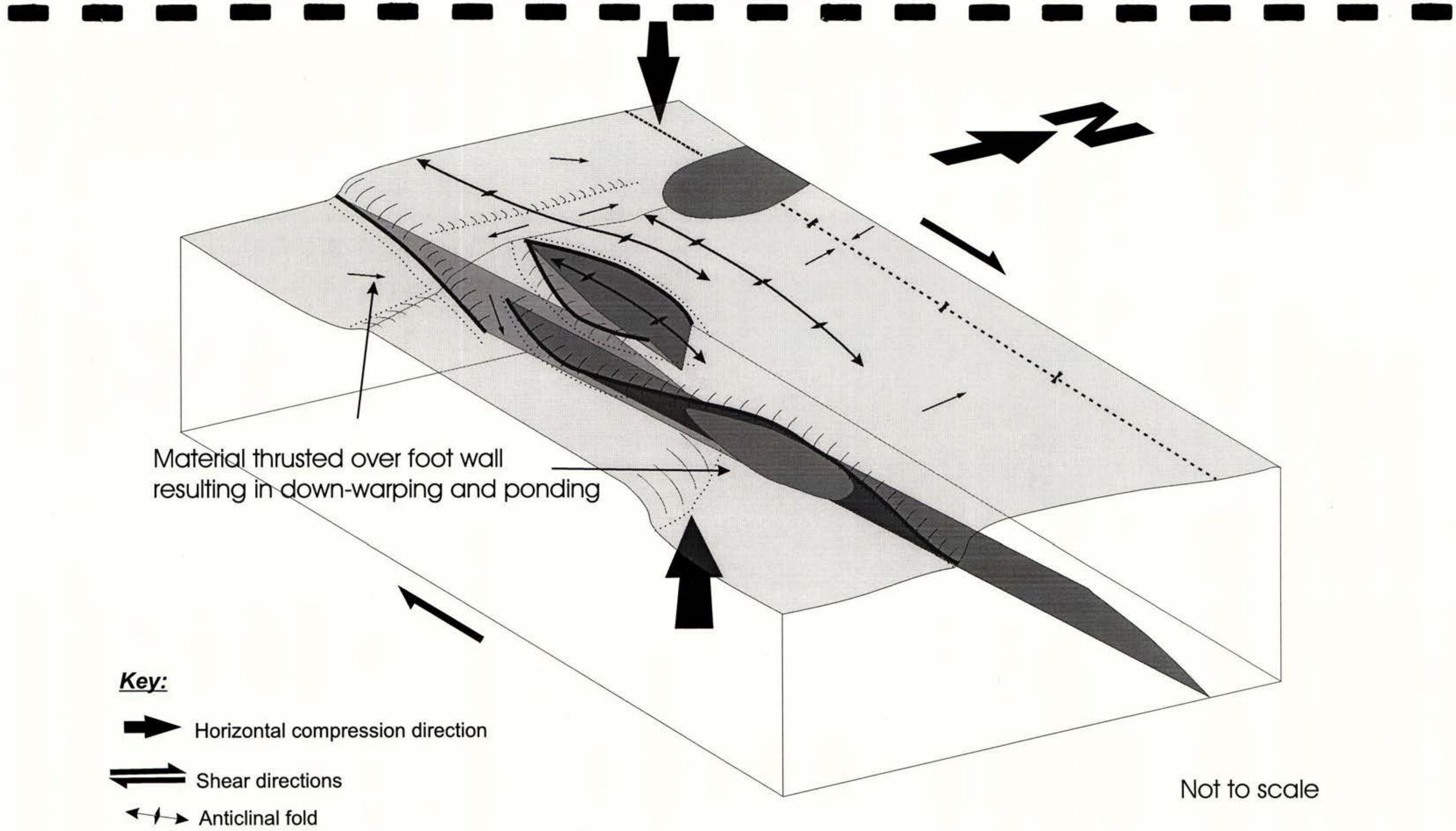


Fig. 8. 3D block diagram of Flower Structure, western end of Ashley Fault.

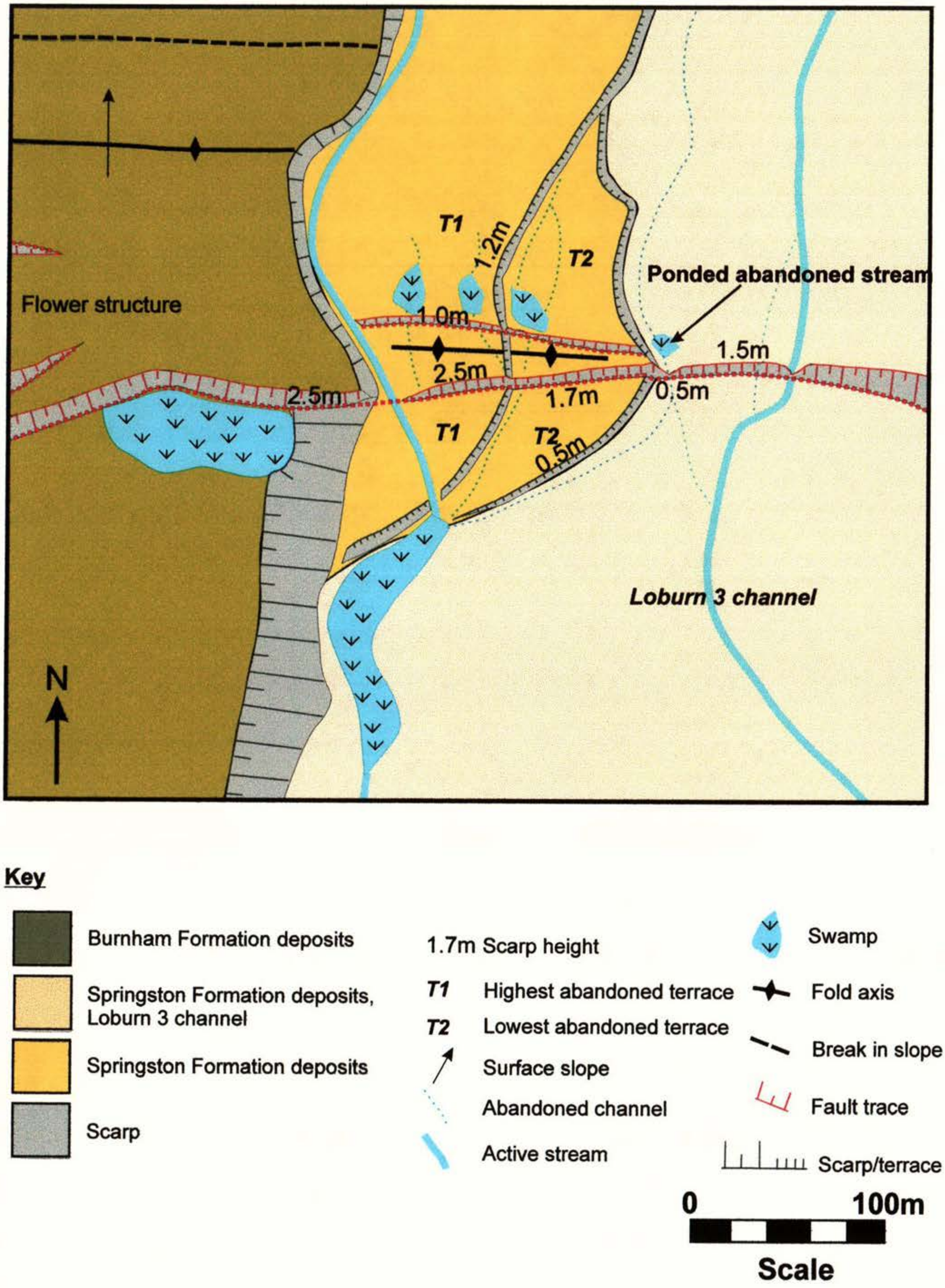


Fig. 9. Fault offsets, abandoned terrace and stream channel, western side of the Loburn 3 channel.

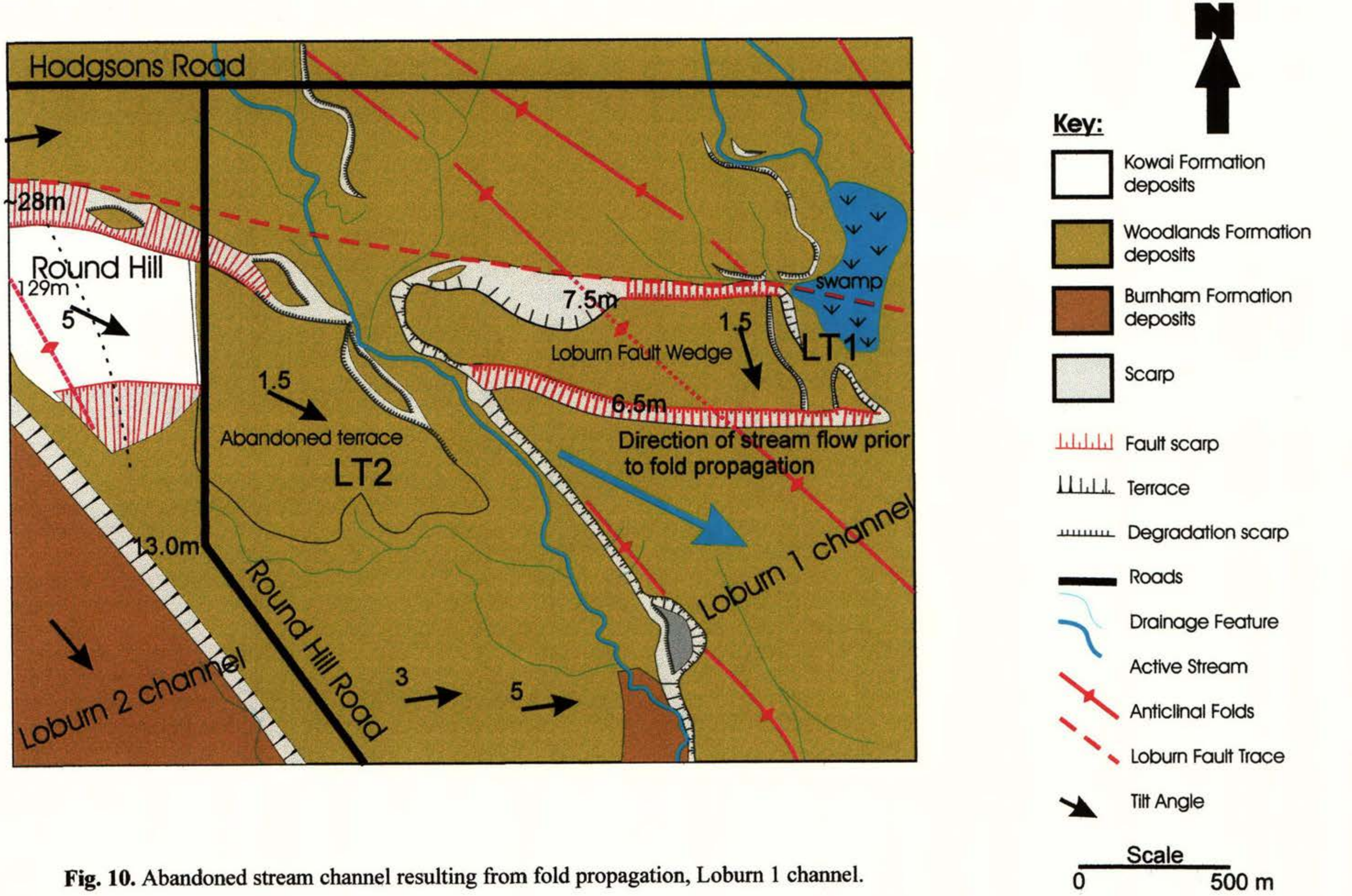


Fig. 10. Abandoned stream channel resulting from fold propagation, Loburn 1 channel.

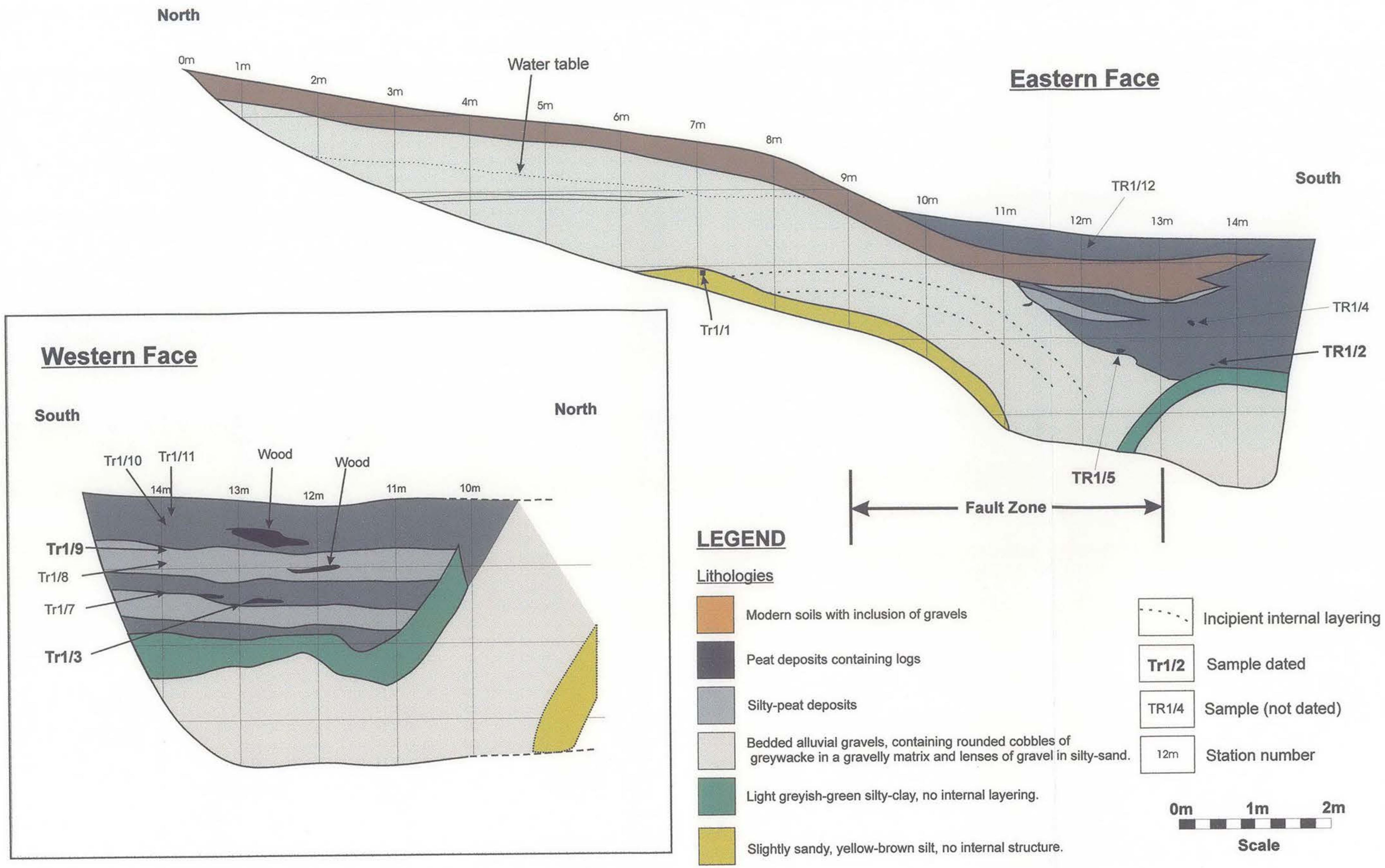


Fig. 11. Trench 1, Ashley Fault, Loburn 3 channel. NZMS260, M34/687719.

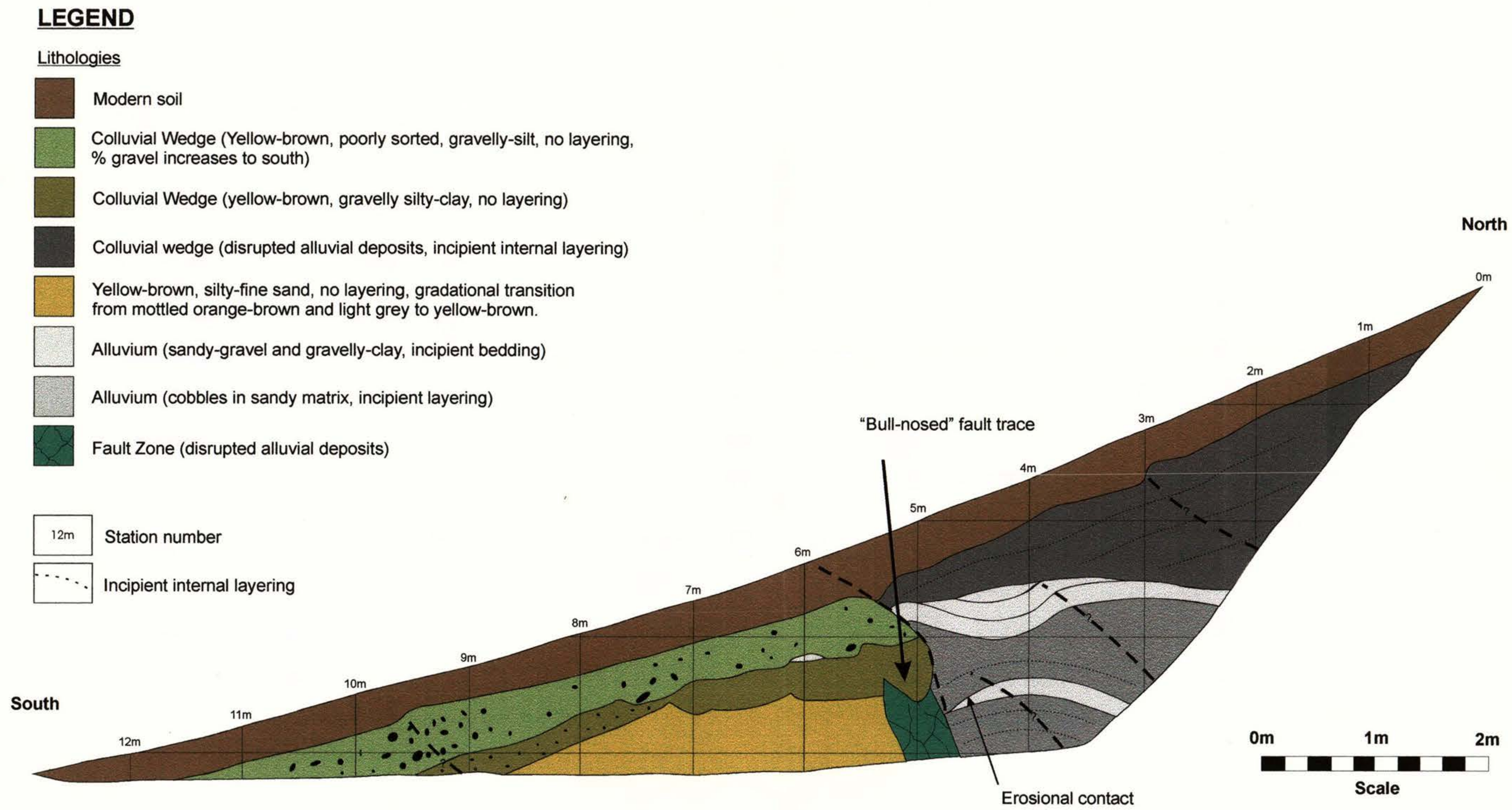


Fig. 12. Trench 3, Ashley Fault, 'the Oaks', western face. NZMS260 M34/691718

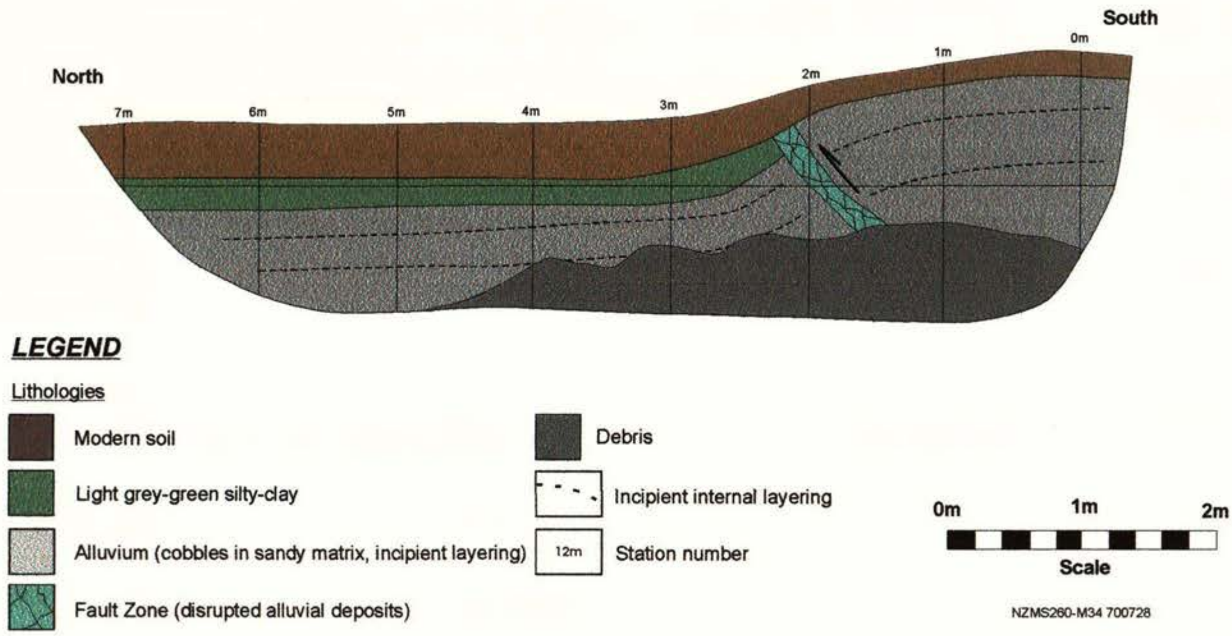


Fig. 13. Trench 4, Loburn Fault, Loburn 2 channel, west of Round Hill, eastern face.

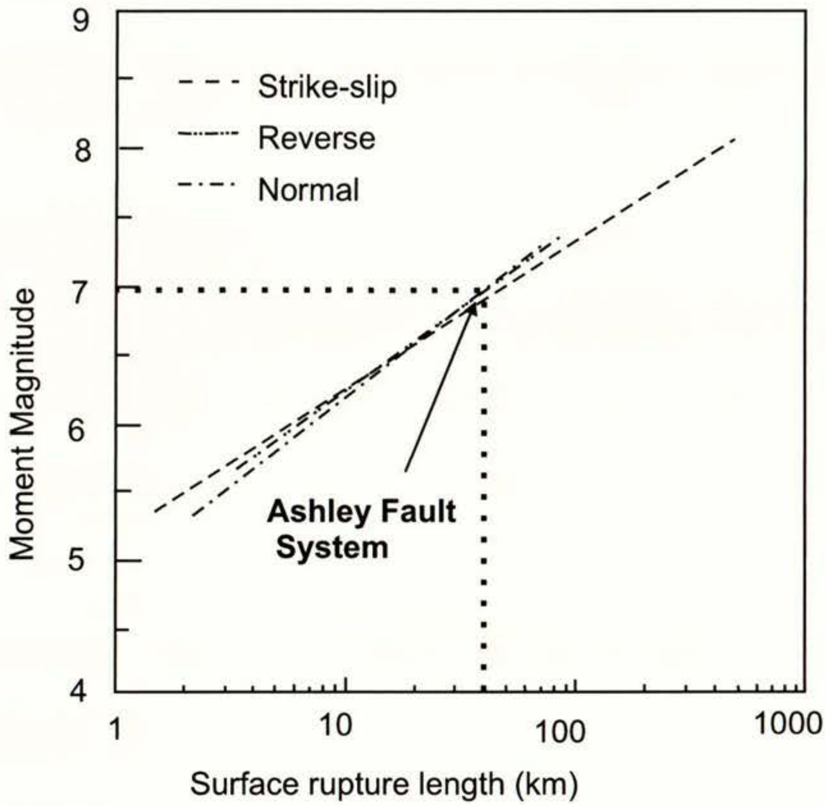


Fig. 14. Regression lines for strike-slip, reverse and normal slip relationships. Relationships of the Ashley Fault System indicate a maximum possible Moment Magnitude of 6.9 for the Ashley Fault.

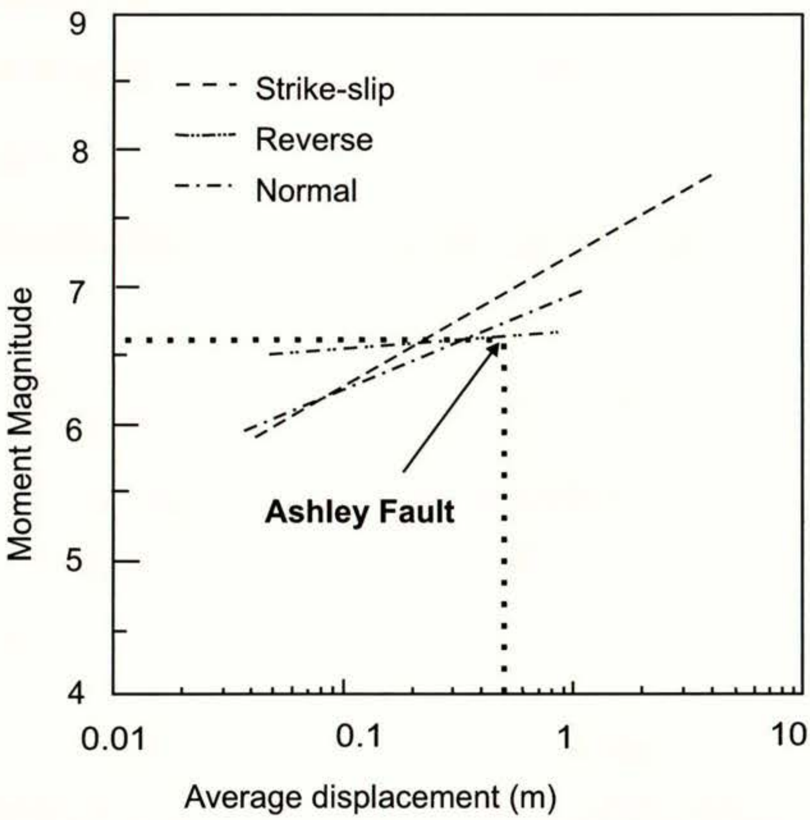
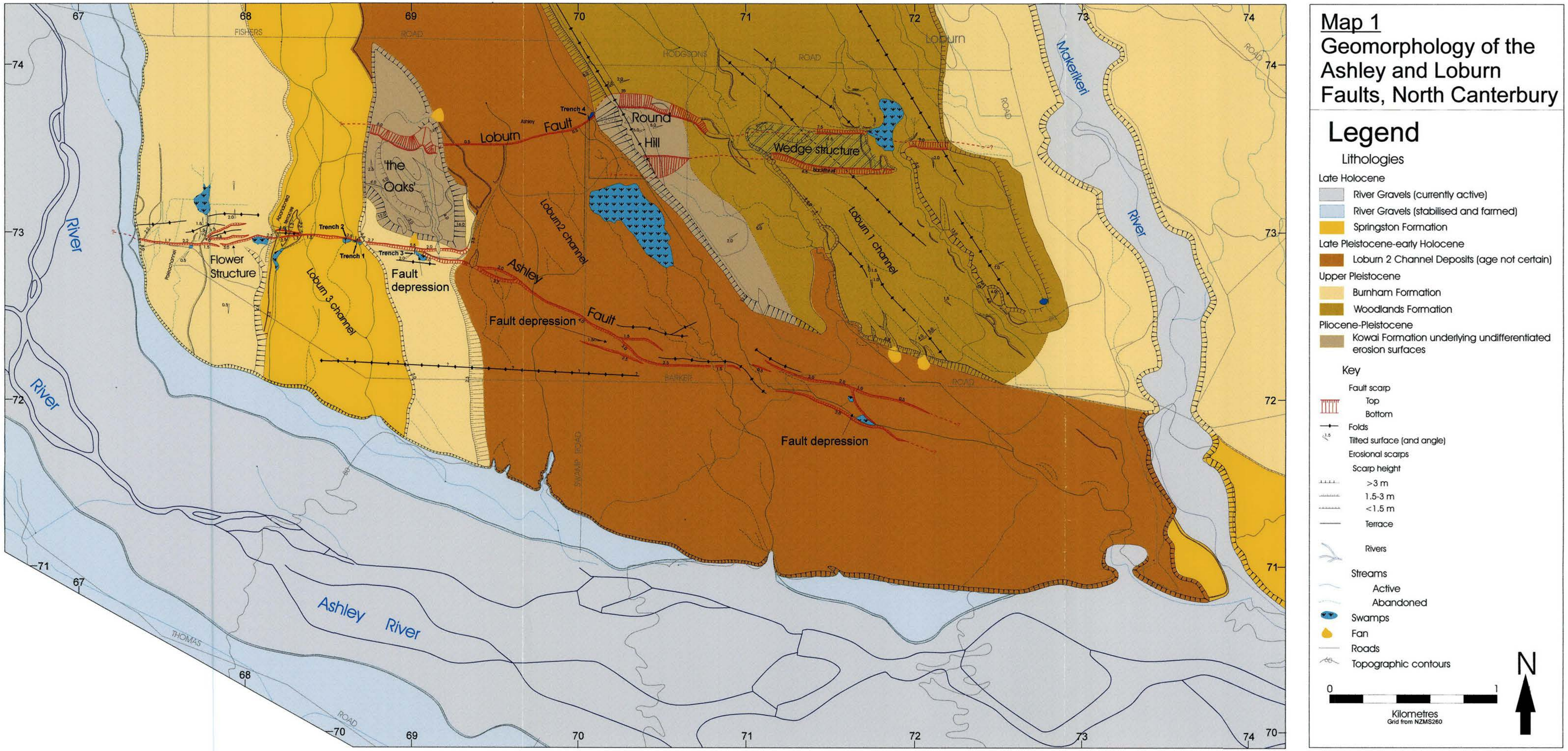


Fig. 15. Regression lines for strike-slip, reverse and normal slip relationships. Displacement of 0.5 m per event on the Ashley Fault resulting in a minimum Moment Magnitude of 6.6.

Trench Code	dC13	% Modern	Depth (m)	Radiocarbon dates	Calibrated C_{14} results	Stratigraphic location	Comments
Tr1/2	-26.6±0.2	58.7±1.2	1.55	4280±170 years BP	**4785±255 years BP**	Above silty-clay in lowest peat, eastern face.	Probably represents the minimum age of Loburn 3 channel surface and the oldest datable rupture event.
Tr1/3	-24.0±0.2	64.4±0.5	1.30	3530±60 years BP	**3765±75 years BP**	Bottom of second peat above the first silty-peat layer, western face.	Probably represents the second youngest event on the Ashley Fault.
Tr1/5	-25.5±0.2	59.6±0.5	1.40	4160±60 years BP	**4675±155 years BP**	Interface between alluvium and peat, eastern face.	As for Tr1/2 above.
Tr1/9	-25.0±0.2	66.9±0.6	0.65	3240±70 years BP	**3420±60 years BP**	Interface between the most recent peat deposit and the uppermost silty-peat.	Probably represents the youngest event preserved before the formation of the recent peat deposits.

Table 1. Results from four samples extracted from Trench 1.


Map 1
Geomorphology of the Ashley and Loburn Faults, North Canterbury
Legend
Lithologies
Late Holocene
River Gravels (currently active)
River Gravels (stabilised and farmed)
Springston Formation
Late Pleistocene-early Holocene
Loburn 2 Channel Deposits (age not certain)
Upper Pleistocene
Burnham Formation
Woodlands Formation
Pliocene-Pleistocene
Kowai Formation underlying undifferentiated erosion surfaces
Key
Fault scarp
Top
Bottom
Folds
Tilted surface (and angle)
Erosional scarps
Scarp height
>3 m
1.5-3 m
<1.5 m
Terrace
Rivers
Streams
Active
Abandoned
Swamps
Fan
Roads
Topographic contours
0
1
Kilometres
Grid from NZMS260
N
Loburn Fault
Ashley Fault
Round Hill
Wedge structure
'the Oaks'
Flower Structure
Fault depression
Fault depression
Fault depression
Loburn 1 channel
Loburn2 channel
Loburn 3 channel
Trench 1
Trench 2
Trench 3
Trench 4
Loburn
Makerikeri River
Ashley River
River
River
FISHERS ROAD
HODGSONS ROAD
BARKER ROAD
SWAMP ROAD
THOMAS ROAD
67
68
69
70
71
72
73
74