50th Kaikoura05

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

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

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Kaikoura

Field Trip Guides

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Field Trip Guides – Contents

Field Trip 4

FAULTS OF EASTERN MARLBOROUGH: PICTON, AWATERE AND KEKERENGU

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INTRODUCTION

In this excursion we will examine evidence for faulting, folding and uplift at four sites on our way from Picton to Kaikoura. The purpose of the field trip is to provide a brief overview of some of the main structures which are both well exposed and easily accessible to State Highway 1 in eastern Marlborough. Of principal interest will be the Picton Fault System (and associated Oligocene strata), and the active Awatere and Kekerengu faults. In particular, we will examine alluvial terrace and soil stratigraphy in the Kekerengu area, and evidence for the late Quaternary slip rate of the Kekerengu Fault.

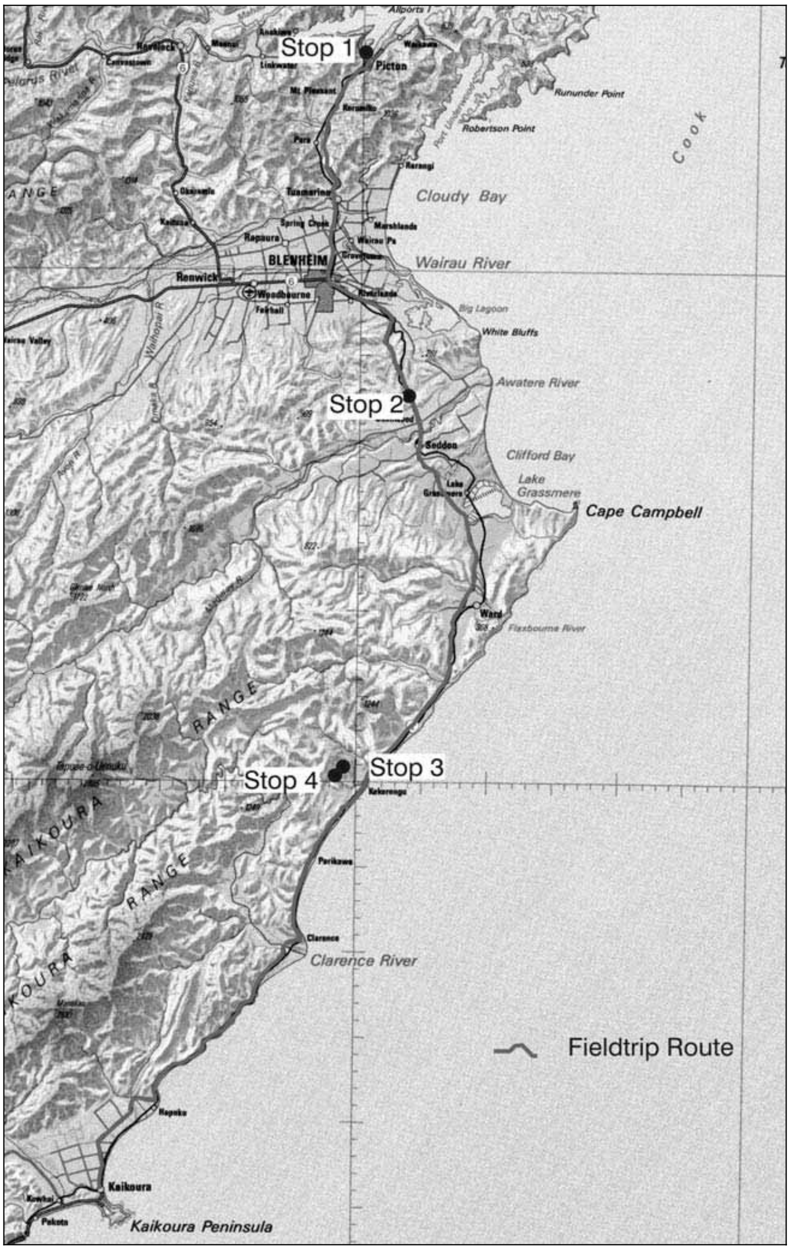

Figure 1. Field trip route map.

This field trip departs from the Interislander Ferry Passenger Terminal in Picton at about 1.00pm. Our first stop will be Shakspeare Bay, near Picton, where we will take in an overview of Oligocene sedimentary rocks which have been overthrust by Marlborough Schist and Pelorus Group rocks. From Picton we travel to the Awatere Valley to view and discuss the active trace of the Awatere Fault. Our last two stops are at Kekerengu and will involve a short walk along Glencoe Stream to examine the Kekerengu Fault, and displaced alluvial terraces. The route and stop locations are shown on Figure 1. The fieldtrip is expected to take approximately 4-5 hours.

STOP 1: PICTON FAULT SYSTEM – SHAKESPEARE BAY, QUEEN CHARLOTTE DRIVE

By Andy Nicol
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Background Information

In the Marlborough Sounds, near Picton, Permian-Jurassic Marlborough Schist and Pelorus Group rocks are juxtaposed in fault contact (Fig. 2). Locally these basement rocks overthrust Oligocene sedimentary rocks which form two tectonic inliers (Nicol & Campbell, 1990). These Tertiary rocks were first described by MacKay (1877) and have been revisited by geologists numerous times in the past 40 years, primarily to assess the economic potential of coal seams (e.g., Hector, 1894; Morgan, 1920).

The Tertiary strata are most probably Whaingaroan in age (~27.3-33.7 Ma) and comprise basal conglomerate, medium to coarse sandstone and massive blue-grey mudstone. These strata rest unconformably on Pelorus Group and were deposited in terrestrial (fluvial) to inner shelf marine environments. The presence of high volatile bituminous C rank coals with vitrinite reflectance of up to 0.58, probably indicate that the Tertiary sequence was several kilometres thick prior to faulting.

Oligocene rocks are folded and faulted on both meso and macro scales with bed dips in the range of 25° to 90° (Fig. 2). The principal faults that bound Tertiary rocks strike mainly NNE and dip at between c. 25° and 65° both to the west and east. These faults juxtapose Oligocene rocks against textural zone III and IV Marlborough schist (with a common quartz, albite, muscovite and chlorite mineral assemblage) and Pelorus Group (which have been subject to prehnite-pumpellyite low-grade metamorphism). Faulting within the schist may also locally juxtapose textural zone III and IV schist.

Analysis of fault displacement directions using fibre striations on small-scale faults close to thrusts and calcite twin lamellae (from a Tertiary limestone bed) together with fold orientations suggest that deformation resulted in approximate east-west shortening (Nicol & Campbell, 1990). Reverse faulting, thrusting and folding resulted in significant local shortening (≥40-50%) along the Schist-Pelorus Group contact.

The faults clearly post date deposition of the Oligocene sedimentary rocks and are no longer active today; however, the precise timing of faulting is poorly constrained. Reverse faults appear to have deformed coal seams after they reached their present rank. This suggests that the strata presently exposed in Shakespeare Bay were probably buried by several kilometres of strata before the onset of faulting. Therefore, Nicol & Campbell (1990) speculated that thrusting and shortening was mainly Early Miocene in age, consistent with the widespread occurrence of Early Miocene thrusting and faulting elsewhere in Marlborough and the eastern North Island (e.g., Rait et al., 1991).

At Stop 1

At Stop 1 we gain an overview of the locations of faults, Marlborough Schist, Pelorus Group and Oligocene strata in Shakespeare Bay. The reason for stopping at this location is that it is one of the few places in the Marlborough Sounds where we can unequivocally demonstrate Tertiary faulting and folding.

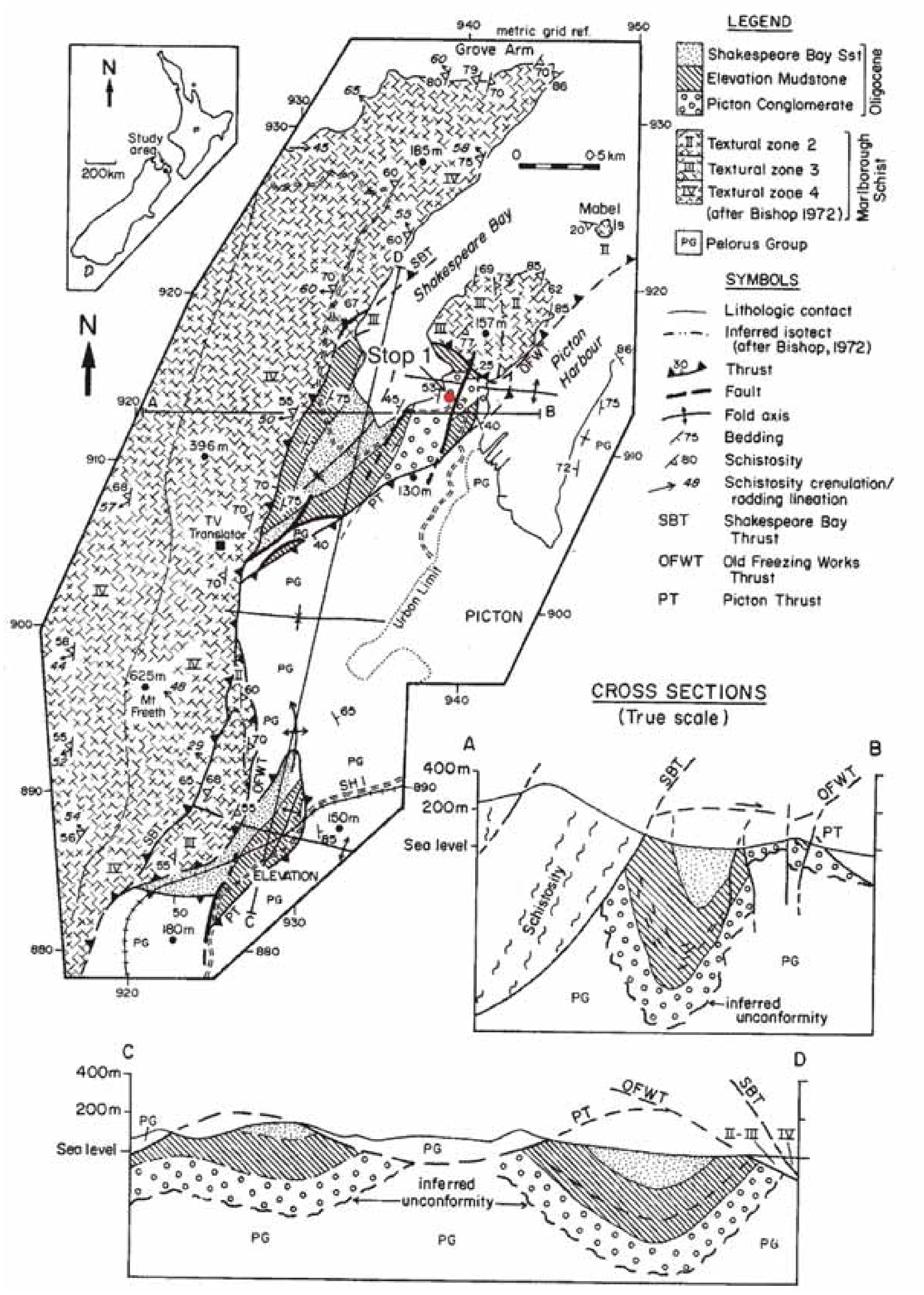

Figure 2: Geological map and cross sections of the Marlborough Schist – Pelorus Group faulted contact, immediately west of Picton, Marlborough Sounds (Nicol & Campbell, 1990).

Stop 1 is located on the eastern side of Shakespeare Bay (see Fig. 2). From here we can see the Marlborough schist rising steeply on the western side of the bay. Schist is separated from Tertiary strata along a fault that dips at about 65° westwards beneath the range and runs across the lower slopes. To the north on the far side of the port facility and about 10 m up from the base of slope a shallow (c. 25°) northward dipping thrust separates schist from underlying Tertiary coal measures and conglomerate. South of our present position, Pelorus Group rocks rest structurally upon Tertiary strata across a 40° southeastward dipping thrust. Between the faults, Oligocene rocks have been preferentially eroded and now occupy much of the low ground in the valley. A second outcrop of Tertiary rocks is exposed on State Highway 1 about 2 km to the south. These Tertiary rocks are again structurally overlain by schist and Pelorus Group along fault contacts. Both areas of Tertiary rocks separate Pelorus Group to the east from schist to the west.

All of the main faults which bound Tertiary rocks appear to be reverse and suggest a period of shortening post deposition of Oligocene strata. Shortening was predominately east-west and, in addition to the faults bounding Tertiary rocks, produced reverse faulting within the schists and tight folding of Tertiary beds. Mesoscale folding together with the geometries of the main faults and folds indicate late-stage folding about east-west hinges (the present Tertiary outcrops occur in the cores of these east-west folds). As indicated in the Background Information section, the timing of shortening is poorly constrained. Vitrinite reflectance from coal seams within Tertiary strata indicate that these rocks were probably buried by several kilometres of sedimentary strata before the onset of shortening. Based on these data, Nicol & Campbell (1990) speculate that faults near Picton formed mainly in the Early Miocene during a period of regional contraction.

Given the tectonic complexities observed in the Tertiary rocks it is perhaps no great surprise that coal mining never really took off in Shakespeare Bay. The coal is of high enough rank to warrant extraction and seams reach thicknesses of up to 5 m; however, it was found to be discontinuous in the seam strike and dip directions. These continuity problems were often exacerbated by steep bed dips and slope stability problems along the base of the Mt Freeth range. Despite these problems, locals continued to produce very small quantities of coal (perhaps 10's of bags in a good year) for domestic use into the 1980's.

En Route to Stop 2: Drive From Picton to Awatere Valley

From Picton, south along State Highway 1, the road climbs and briefly crosses Tertiary strata before dropping into the Tuamarina River Valley. This valley becomes progressively more swamp filled approaching the Wairau River, which runs along the northern margin of the Wairau Plains. Reduction in grade of the Tuamarina River (and related swamp production) is presumably related, in part, to aggradation of the Wairau River and infill of Cloudy Bay during the Holocene (Pickrill, 1976), and to tectonic subsidence of the Marlborough Sounds causing back-tilting of the drainage. The resultant Wairau Plains appear not to be displaced by the Wairau Fault along State Highway 1; the fault and related surface deformation is observed no further east than Renwick some 10 km west of State Highway 1.

Our route takes us through Blenheim and around the eastern end of the Wither Hills. These hills are given their distinctive morphology by extensive gully erosion of loess covered slopes. As we leave the Wairau Plains we head towards the Awatere Valley (across the Weld and Dashwood passes) and our next stop.

STOP 2: AWATERE FAULT – SOUTH OF DASHWOOD PASS AT CALROSSIE STATION

By Tim Little
Victoria University of Wellington

Background Information

To the north of the Awatere Fault, the Wither and Vernon Hills consist of Late Miocene to early Pliocene mass-flow marine conglomerates that occur interbedded with slope mudstones (Fig. 3a). On the basis of their distinctive lithology, late Tongaporutuan (~8-6 Ma) age, NE-paleocurrent directions, and bathyl foraminiferal assemblages, Little & Jones (1998), correlated this deep-marine conglomeratic unit with a western lithofacies of the Upton Formation in the lower Awatere Valley on the southern side of the Awatere Fault (Roberts & Wilson, 1992; Roberts et al., 1994). This correlation of similarly bedded late Miocene conglomeratic units across the Awatere Fault was originally suggested by King (1934). On both sides of the Awatere Fault, the western (more proximal) marine conglomerate lithofacies of the Upton Formation rests unconformably on Torlesse Terrane bedrock.

On our drive southward, note that the blue-weathering, moderately dipping conglomerate strata (well exposed in the Pukapuka Stream quarry, on your left) are underlain by brown-weathering exposures of Torlesse greywacke basement (exposed in the road and railway cuttings near Weld Pass). Farther south, on the southern side of the Awatere Fault, in the Awatere Valley, the conglomeratic lithofacies of the Upton Formation occurs much farther inland to the west, where it intertongues northeastward into monotonously fine-grained basinal strata that is also of late Tongaporutuan age. In the Awatere Valley, this west-to-east facies boundary (marine conglomerate to marine mudstone) is mappable, and strikes NW at a high angle to mean bedding, which dips gently NE. On the northern side of the Awatere Fault, the occurrence of the western conglomerate lithofacies as far east as White Bluffs at the coast suggests a dextral strike separation of this conglomerate body. Little & Jones (1998) used a piercing point approach, employing the linear intersection of the bedding-discordant facies boundary with the Torlesse unconformity surface, to argue that the Awatere Fault system has slipped dextrally by >34 km since the late Miocene. The occurrence of a locally derived alluvial fan deposit of late Miocene on the SE side of the fault (called “Wairau conglomerate” in Fig. 3a) indicates that this structure had become active by ~7 Ma. Near the coast, the ancestral Awatere Fault on which most of this slip accumulated is inferred to have been abandoned in the Quaternary in favour of a younger strand that cut northward into the marine conglomerates (Fig. 3b). The ancestral strand is well exposed in the central Awatere Valley, where it is called the Fuchia Fault. The younger currently active strand has managed to displace the Miocene-Pliocene unconformity surface near White Bluffs by at most 4 km of dextral-slip (Little & Jones, 1998).

As supported by detailed surveys of displaced landforms, and C-14, TL and OSL dating of river terraces, rates of late Quaternary strike-slip on the inland Awatere Fault since ~15 ka are 5-6 mm/yr both at Lake Jasper on the central part of the fault (Benson et al., 2001a; Little et al., 1998), and at Saxton River on the western, inland section (Mason et al. 2004, and manuscript in review). By contrast, a site at Boundary Stream near the coast yielded a slip-estimate of <1.3 mm/yr, implying that strike-slip on the fault decelerates eastward in proximity to the coast (Little et al., 1998). Little & Roberts (1997) inferred that this slip-gradient reflects the eastward splaying (e.g., Vernon Fault) and dying out of the Awatere Fault towards Cook Strait, a transition along which fault-slip is converted into clockwise vertical-axis rotation of a crustal block (the Awatere block) on the Marlborough east coast (see also, Roberts, 1992, 1995).

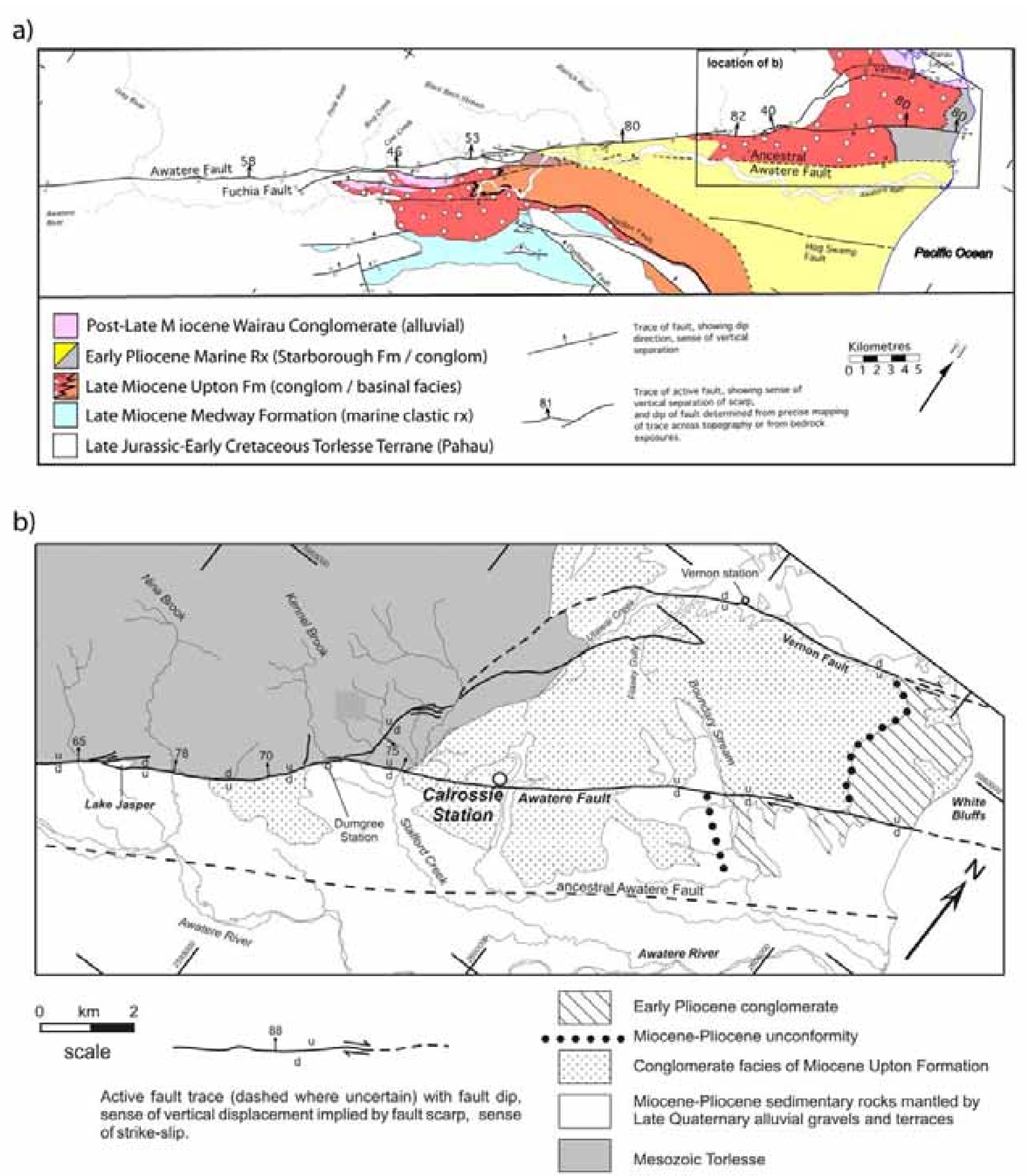

Figure 3: a) Map of an eastern part of the Awatere Fault, showing simplified bedrock geology and active and inactive coastal strands of the fault (after Little & Jones, 1998). b) More detailed view of eastern part of the fault showing location of Calrossie Station, and other selected features (geology from Benson, 2000; Little & Jones, 1998; Little et al., 1998).

Recent paleoseismological trenching studies on the Awatere Fault at Lake Jasper (2 trenches) and Upcot Saddle (2 trenches) reveal that the eastern section of the Awatere Fault has ruptured 8-10 times since 8610 cal yrs B.P. at a mean recurrence of 860-1080 yrs, and with the most recent earthquake being the M_W~7.5 Marlborough earthquake of 1848 (Benson et al., 2001a, 2001b). Another trench at Saxton River near Molesworth Station reveals that the inland section of the fault has ruptured 8 times since 6.3 ka, yielding an average recurrence interval of c. 800 years (Mason et al., 2004). The C-14 bracketed timing of five of these earthquakes on the inland section statistically overlaps with other earthquakes on the eastern strand, suggesting the possibility of simultaneous or triggered rupture of the two fault sections along a cumulative fault length of >150 km.

At Stop 2

The current topographic slope-break along the northern margin of the Awatere Valley approximately coincides with the ancestral strand of the Awatere Fault in bedrock (Fuchia Fault, Fig. 3a). Near the vineyard-mantled banks of the Awatere River, this abandoned strand of the Awatere Fault juxtaposes Late Miocene Upton conglomerate against Early Pliocene mudstone of the Starborough Formation. To the north, about 2.3 km north of the Awatere River, the currently active strand of the fault is located near Calrossie Station, and is, by contrast, remarkably inconspicuous in both the landscape and the bedrock – threading through the gentle swales of the Vernon Hills without much topographic expression or throw, and cutting similar marine conglomerate of the Upton Formation on both sides.

Figure 4: Photograph, looking west, of exhumed surface of the Awatere Fault at Calrossie Station on State Highway 1 to the south of Dashwood Pass. Note the triangular facet caused by truncation of a ridge spur (topped by lone pine tree) against the near-vertical scarp of the fault. The scarp is held up by a cemented Late Miocene conglomerate.

Although the active trace of the Awatere Fault near Dashwood Pass is geomorphically indistinct near Highway 1, with vigilance it can be spotted on the west side of the road near Calrossie Station (on your right). There, a ~20 m high fault surface has been exhumed along the canyon wall of a small stream (Fig. 4). Held up by well-cemented Upton conglomerate, the near-vertical fault surface defines a conspicuous triangular facet on the southern side of the fault. This bedrock facet is the truncated end of a ridge spur (topped by a lone pine tree) that is cut and displaced by the fault. The spur and an abandoned stream channel flanking it to the west are dextrally offset by ~190 m and vertically displaced (up to the NW) by ~10 m (Fig. 5). The same abandoned channel occurs as a wind gap at the stockyards on the north side of the fault. After looking at this faceted scarp and considering this offset, we will walk up-stream and westward onto a nearby hill slope. There we will see remnants of the 1848 earthquake fissure traversing a series of grassy hill-slopes.

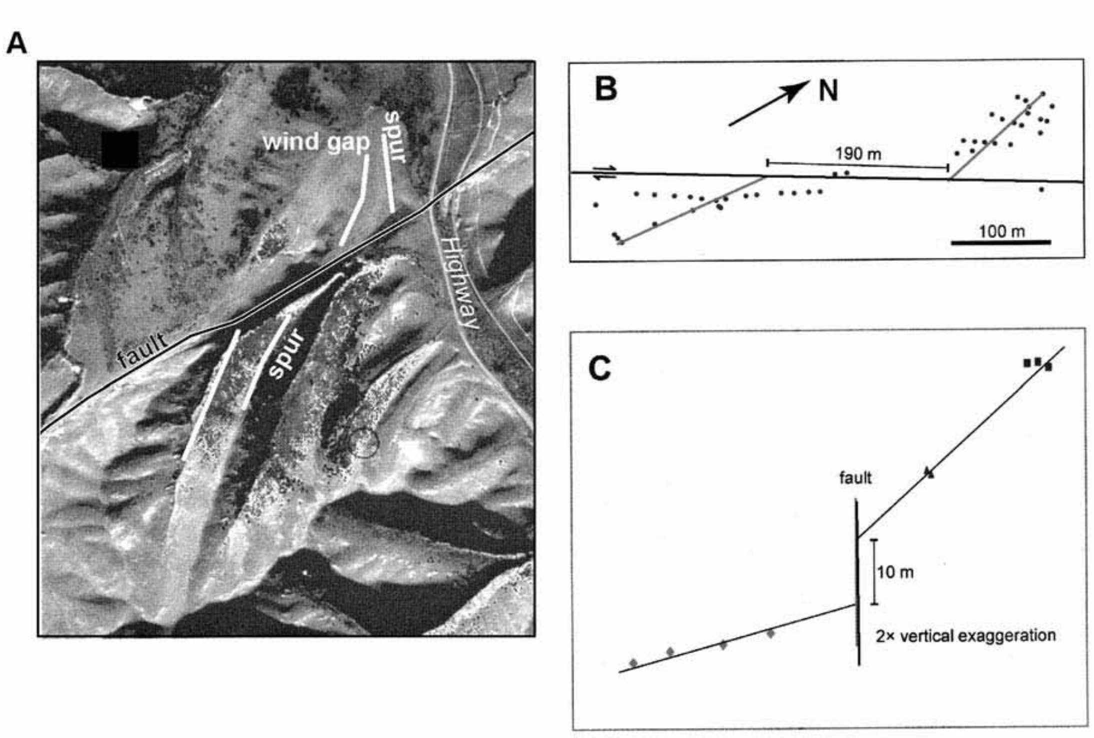

Figure 5: a) Aerial photograph of the Awatere Fault at Calrossie Station showing offset spur and small valley to the west of that ridge. On the uplifted, northern side of the fault, the drainage has been diverted parallel to the fault, and this valley has been abandoned to form a wind gap. b) EDM theodolite survey points constraining location of the ridge crest on both sides of the fault. These data were used to project the linear spur crest to the fault on both sides, and to measure its dextral displacement (~190 m). c) Vertical profile of the offset ridge-crest segments, suggesting ~10 m of throw (up to the NW) of that linear feature across the fault.

En Route to Stops 3 & 4: Drive South to Kekerengu

The rest of the field-trip will chiefly be concerned with the late Quaternary tectonics of the Kekerengu Fault (near the southern margin of the Marlborough Fault system), and the alluvial terrace and soil stratigraphy in the Kekerengu area, but we will also try to point out some highlights to be seen from the vehicles on our drive south to Kekerengu.

After passing the enigmatic Hog Swamp Fault, which may have moved during the Seddon earthquake of 1966, disrupting the Main Trunk railway near State Highway 1 (Adams & Lensen, 1970), the next major dextral-strike-slip fault of the Marlborough Fault System is the Clarence Fault. Remarkably, the active trace of this structure does not extend as far east as State Highway 1, or the Marlborough coast, and does not significantly offset the Late

Miocene-Pliocene marine rocks of the Awatere Basin. From the vehicles, we will see many gently tilted outcrops (mainly of grey mudstone) of the late Pliocene Starborough Formation, for example on the banks of the Awatere River at Seddon, and, farther south, in road cuts on the approach to Lake Grassmere. This Pliocene bedrock is overlain by an extensive flight of late Quaternary alluvial terraces cut and filled by the Awatere River (Eden, 1989), including the Starborough 1 Terrace, an especially extensive aggradational terrace that was abandoned at ~15 ka (Little et al., 1998).

Lake Grassmere is a depression that has subsided relative to sea-level in the Holocene (Ota et al., 1995), and which is structurally controlled by the active Ward Syncline, an asymmetric fold with a gentle east-dipping limb and a steeper west-dipping limb. Its hinge plunges ~ 4° to the NNE. As we drive by, we will see the old seacliff marking the previous maximum extent of transgression of the sea into this embayment during the Holocene. The outlet of the estuary was artificially closed off during construction of the saltworks. The ridge to the east of the lake consists chiefly of Paleogene Amuri Limestone that has been uplifted due to reverse-slip on the ~60° east-dipping London Hills Fault on the eastern flank of Lake Grassmere. This reverse fault outcrops in bedrock at Mussel Point near Marfell's Beach, where it is marked by a ~50 m thick zone of cataclasite and gouge and by an overlying zone of ductile shearing in limestone of the hanging wall (Townsend & Little, 1998). The London Hill Fault had begun moving by the late Miocene and continued to slip in the Quaternary. It is probably still active, as evidenced by its scarp, and by active flexural-slip along bedding planes in the Pliocene bedrock in its footwall to the west (Townsend, 1996). Growth of the Ward syncline, especially tilting of its steeper eastern limb, was probably accompanied by slip on the London Hills Fault. The main fault scarp is now partially buried by a >50 m thick unit of scarp-derived gravel of mixed alluvial fan /colluvial origin that is overlain by loess and is probably no younger than the Last Glacial Maximum (Townsend, 1996). The London Hill Fault has undergone a post-Early Pliocene (Opoitian) dip-slip of ~1.8 - 2.2 km (Townsend & Little, 1998).

Approaching Ward, note Lake Elterwater on the left. This natural lake has been trapped in a depression between the rising London Hills to the east and a tectonic dam (active anticline) to the north that prevents streams from draining north into Lake Grassmere. Townsend (2001) noted that this anticline is on trend with the EW-striking Haldon Hills Fault to the west, and may be related to slip on an active (if blind) segment of this fault at depth. He related this deformation and tilting and bulging of late Quaternary alluvial terraces in the upper Flaxbourne Valley to distributed deformation near the eastern tip or fault-termination of the active Clarence Fault. The lower part of Flaxbourne River follows an antecedent river course through a limestone gorge in the uplifted hanging wall of the London Hills Fault before reaching the east coast.

South of Ward, the highway joins the Kaikoura coast. We may pause briefly by the road at Willowa Point (Fig. 6) to note an outcrop of folded and cleaved Amuri Limestone. To the south, the limestone is unconformably overlain, along a poorly exposed buttress unconformity by the Early Miocene Great Marlborough Conglomerate, which contains recycled boulders of the cleaved limestone. Mapping by Townsend (2001) indicates that the conglomerate in this area infills submarine canyons incised into the limestone. Now tilted to the south, this unconformity is the stratigraphic expression of the so-called "Kaikoura Orogeny".

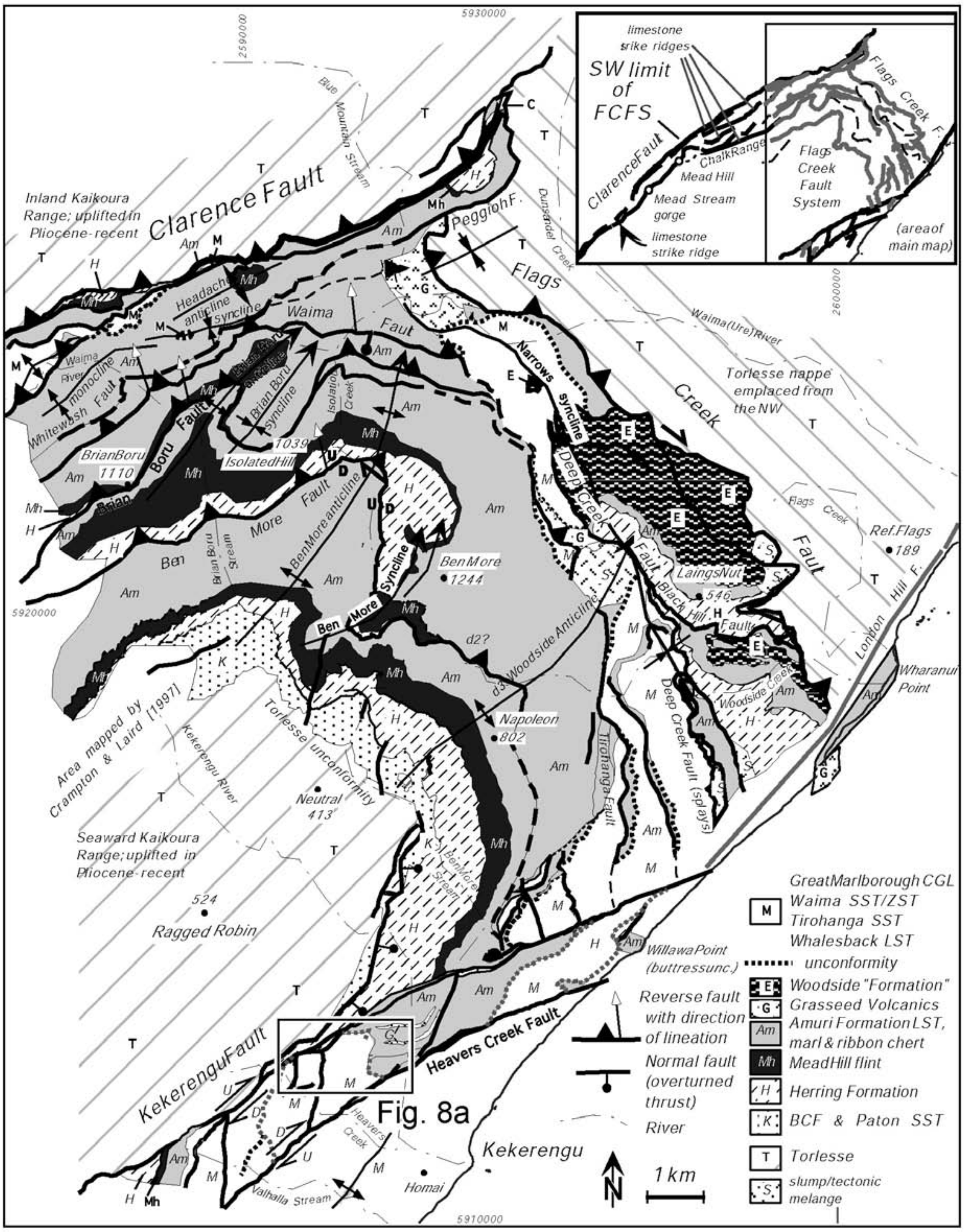

Figure. 6: Bedrock tectonic map (from Townsend, 2001) of NE Marlborough showing Early Miocene thrusts of the Flags Creek Fault System (FCFS); and younger dextral strike-slip faults of the (still active) Marlborough Fault System (MFS). The Great Marlborough Conglomerate, Waima Siltstone, and related early Miocene clastic units (labelled "M" on the map) are marine foredeep deposits that were deposited syntectonically during the onset of the Pacific-Australia plate boundary in this part of New Zealand. Inset in lower right shows location of more detailed map of Figure 8a.

STOP 3: KEKERENGU FAULT – GLENCOE STREAM, KEKERENGU

By Tim Little
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Background Information

The Early Miocene Flags Creek Fault System

Plate reconstructions for the Early Miocene suggest that the Pacific-Australia plate boundary trended NW-SE and consisted of an array of thrust faults striking parallel to the paleo-Hikurangi margin and the Chatham Rise (Fig. 7a). Located near the transition between the Hikurangi subduction margin (to the north), and the Alpine Fault system (to the south), the plate boundary zone in Marlborough has experienced a complex structural history as it has adjusted to the southward migration of this subduction-transform junction (relative to the Australia Plate), and also to local changes in the azimuth of plate motion. Deformation since the early Miocene has included thrust faulting and vertical-axis rotations, and was followed in the late Neogene by development of the NE-striking, dextral strike-slip Marlborough Faults, in part from reactivation of older structures. Much of the structural complexity of the Marlborough region is related to Miocene shortening across the Flags Creek Fault System (FCFS), an originally seaward-verging stack of thrust sheets. Folding, uplift, erosion, and clockwise vertical-axis rotation has deformed this stack of thrust sheets which today are exposed in a NE-plunging, oblique cross-sectional view (Fig. 6).

The imbricate Flags Creek Fault System (FCFS) initiated coevally with deposition of the Great Marlborough Conglomerate (Otaian-Altonian), a deep-water trench or foredeep deposit that was fed by uplift and erosion of the thrust sheets (Fig. 7b). Recent structural mapping and analysis of folded thrust sheets in the FCFS by Townsend (2001) indicates predominant *in-situ* vergence to the SE. This present-day transport direction is strongly discordant to the inferred NW-SE strike and NE vergence of the Early Miocene subduction complex. By 15 Ma, an extensive nappe of Torlesse basement floored by the Flags Creek Fault (FCF), an eastern part of the Proto-Clarence Fault, had been overthrust >10 km across underlying thrust sheets of the FCFS to form a duplex thrust system (Fig. 7c). The hanging wall ramp of the nappe became a culmination, the Ben More anticline (Figs 6 and 7d). Paleomagnetic data from coastal Marlborough suggest that the entire area has undergone clockwise vertical-axis rotation of at least 100º during the Middle and early Late Miocene (Vickery & Lamb, 1995; Townsend, 2001; Hall & Lamb, 2002) (Fig. 7e). This deformation is responsible for the current SE-vergence of the FCFS. By ~8 Ma, a younger system of SE-vergent thrusts had begun to form in the area of the current Awatere Valley. In the Pliocene (Fig. 7f), the FCF was reactivated as a SW-vergent structure and the London Hills Fault (LHF) and Ward Syncline (WS) accommodated shortening near the eastern end of the Awatere block. Since ~4 Ma, the Awatere block has experienced an additional 20-44° of clockwise vertical-axis rotation about the hinge zone labelled "RB2" as the transcurrent Marlborough Fault System tried to propagate northeastward into Cook Strait (Little & Roberts, 1997). Late Pliocene to Quaternary dextral shear strain within ~5 km of the active Kekerengu Fault has locally produced additional clockwise vertical-axis rotation (up to 45º) near Woodside Creek (Townsend, 2001).

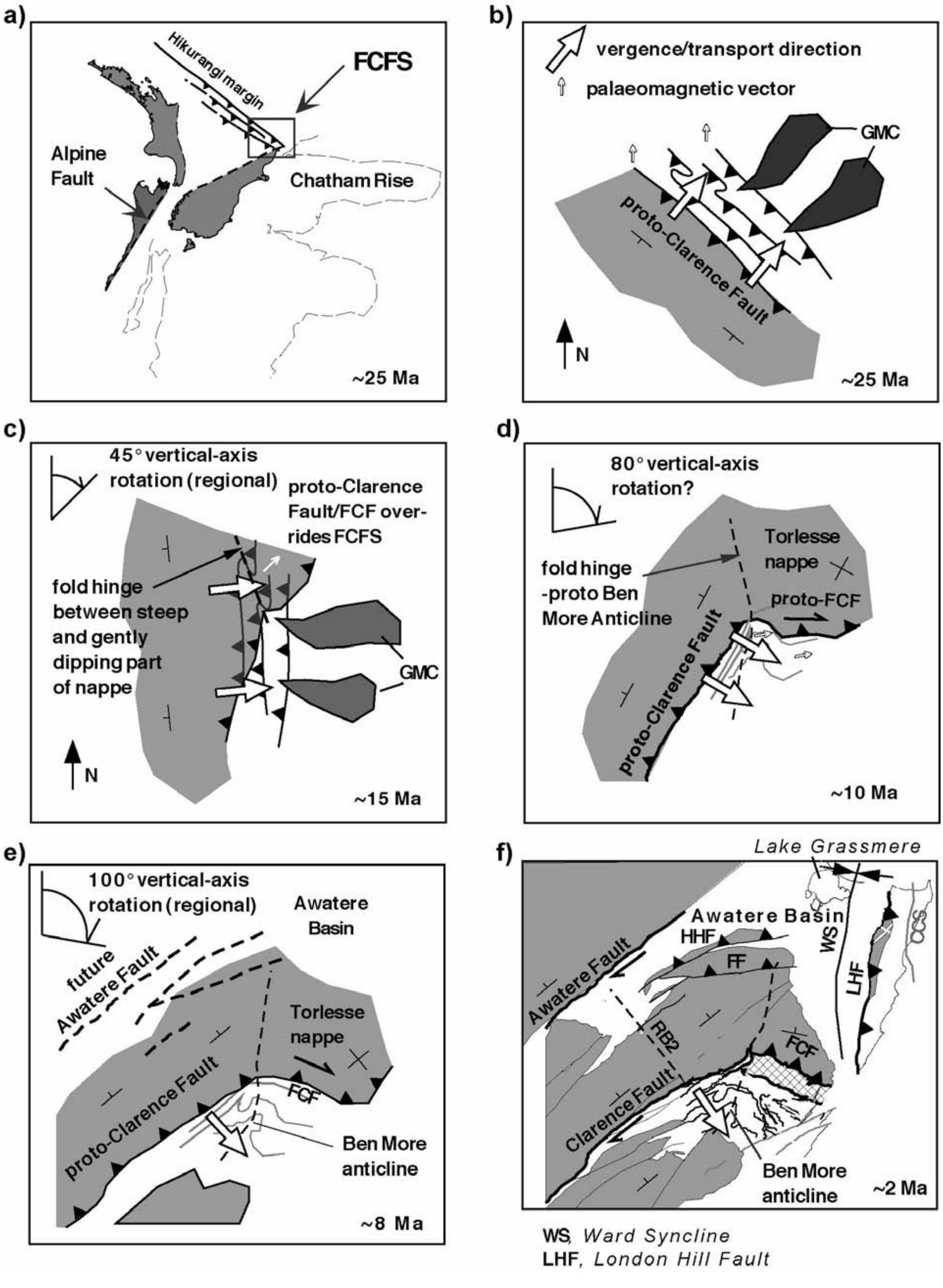

Figure 7: Schematic structural reconstructions of NE Marlborough and the Flags Creek Fault System from Early Miocene to Present-Day (from Townsend, 2001). See text for explanation.

Restoration of strike-slip on the MFS and of the above-described rotations realigns the Early Miocene FCFS back to its original NW-SE strike and NE- (seaward-) vergent configuration. The proto-Clarence Fault is inferred to have initiated as a NW-SE striking thrust within the Early Miocene subduction complex. Balanced geological cross-sections by Townsend (2001) reveal that the FCFS accommodated >26 km of shortening before being folded, and strongly clockwise-rotated. In the late Neogene, oblique plate motion has allowed the long-lived Clarence Fault and other faults in the MFS to remain active while transitioning from dip-slip to oblique- or strike-slip styles of deformation.

Stratigraphy

In capsule, the stratigraphy of the Kekerengu Region records mid-Late Cretaceous rifting and extension, followed by early Cenozoic foundering of a passive continental margin and submergence. The Burnt Creek Formation is a Late Cretaceous unit of diverse clastic marine rocks including conglomerates, mass-flow deposits and shale. The Late Cretaceous Paton Formation consists chiefly of bedded greensand and siltstone. The Herring Formation of Late Cretaceous age, and an equivalent of the Whangai Shale on the North Island, consists of sandstone, siltstone, and organic (or fetid) shale. The Mead Hill Flint contains the Cretaceous-Tertiary boundary. It is conformably overlain by the well-bedded and chaulky Amuri Limestone, a Paleocene-Eocene component of the regionally widespread Muzzle Group. The Amuri Limestone includes at least one smectitic Marl Member near its top. Near Kekerengu, this mechanically weak interval commonly functions as a thrust and/or fold-decollement, is commonly emplaced as a diapiric “goo” along faults, and is quite prone to slumping in the landscape. Near Kekerengu, the white-weathering Marl may be interbedded with greensands or with basaltic marine volcanic rocks of the Grasseed Volcanics. The Marl is locally overlain conformably by sandy limestone of the late Oligocene Whalesback Formation, and is elsewhere unconformably overlain (with angular discordance) by either the turbiditic Early Miocene Waima siltstone, or by the spectacularly coarse-grained Great Marlborough Conglomerate (an in-part time-equivalent facies to the Waima). This unconformity represents the Early Miocene inception of Pacific-Australia plate motion (“Kaikoura Orogeny”) in this part of New Zealand (e.g., Rait et al., 1991).

At Stop 3

At this stop we will park near the active Heaver’s Creek dextral strike-slip fault at the junction of Glencoe Stream with the Kekerengu River, and walk up Glencoe Stream as far as the Kekerengu Fault. Cross-Section X-X’ is located close to our route in Glencoe Stream (Fig. 8). Near the road are outcrops of Grasseed Volcanics interbedded with the Upper Marl unit of the Amuri Limestone. These rocks are part of an allochthonous thrust sheet that sits structurally on top of younger, Miocene rocks of the Waima Formation (Fig. 8). As we walk upstream, note the very thick sequence of terrace gravels in Glencoe Stream. Farther up the stream, a vertical to overturned sequence of thin-bedded turbidites of the Waima Siltstone that young downstream is exposed on the true left bank of the stream. As these were deposited unconformably above the Upper Marl of the Amuri Limestone (or the Whalesback Formation), these Early Miocene beds appear to be preserved in the down-folded “keel” of a syncline. Closer to the Kekerengu Fault, an overturned depositional contact between the Whalesback Formation and the Waima turbidites is exposed on the true right bank of the stream. Behind this is the fault zone: a 10’s m wide zone of smectitic pug derived from the Upper Marl of the Amuri Limestone. On the true left bank is an exposure of the Kekerengu Fault, here consisting of two strands (Fig. 9). The SE-strand emplaces a fault slice of thick terrace gravels over the white smectite and its thinner gravel cover. The NW strand places the thick gravel slice against Herring Formation bedrock.

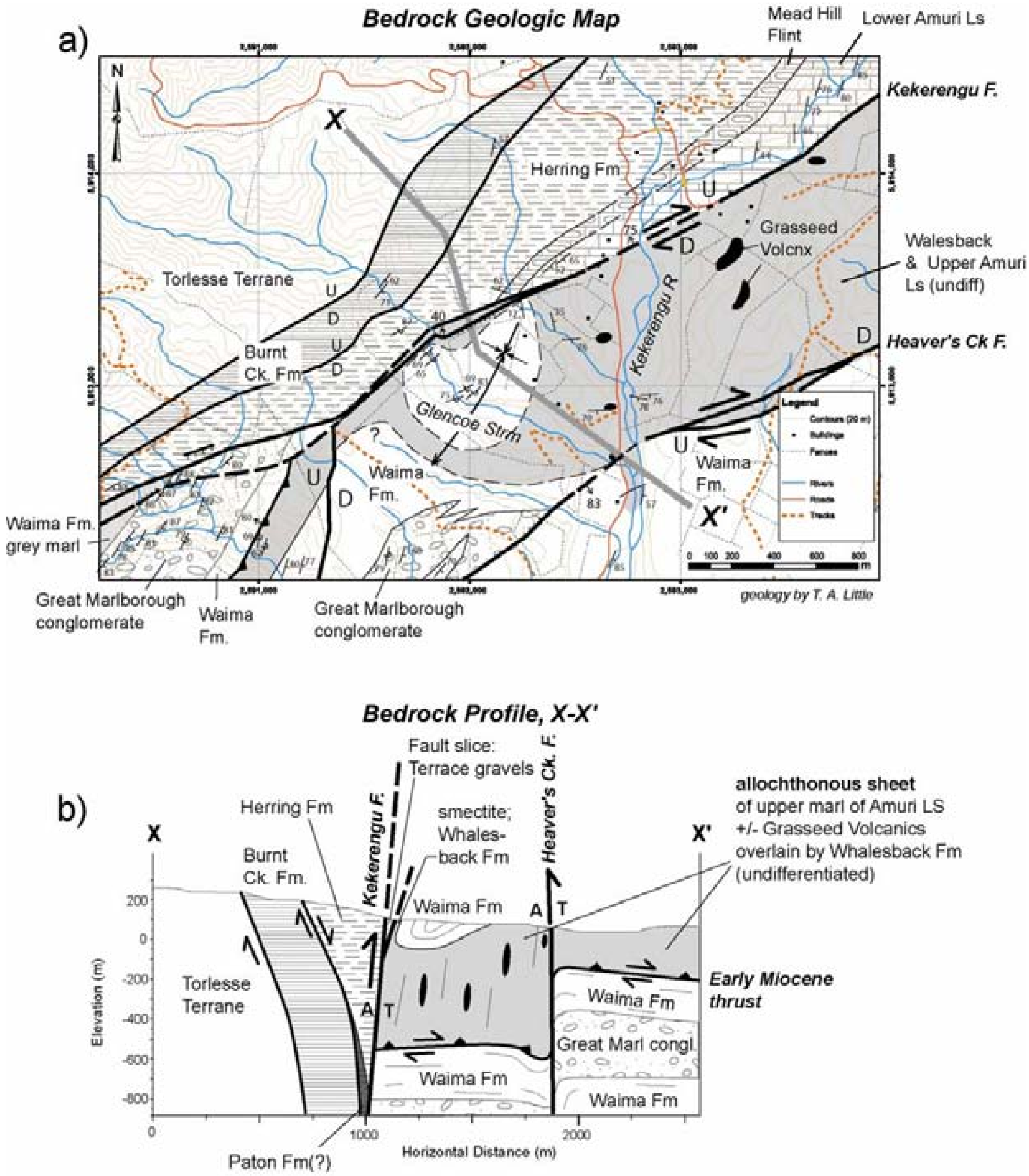

Figure 8: Geologic map and cross-sections X-X' across Kekerengu and Heaver's Creek faults near Glencoe Stream. a) Bedrock geological map showing location of Glencoe Stream and profile X-X'. For location of map see Fig. 6. b) Interpretive bedrock structural cross-section along X-X'.

Figure 9: Photograph of true left bank of Glencoe Stream showing fault slice of Late Quaternary alluvial gravels bounded by double strands of the Kekerengu Fault. Of these, the SE strands appears to be the most active, as there is evidence of a recent surface rupture cutting the terrace tread at the top of this outcrop.

We will then climb to the top of the alluvial terrace above this outcrop. There we will examine the fault scarp, including evidence for its rejuvenation by 0.5-1.0 m during a recent surface rupturing event along this part of the Kekerengu Fault.

STOP 4: KEKERENGU FAULT – ASSESSMENT OF LATE QUATERNARY SLIP RATE USING ALLUVIAL TERRACE AND SOIL STRATIGRAPHY

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Background Information

As judged by slip rate, the right lateral strike slip Hope Fault is the major element of the Pacific-Australian plate boundary through the northern South Island. In fact, of the onshore faults in New Zealand, the late Quaternary slip rate of the Hope Fault (c. 20-25 mm/yr; see Van Dissen & Yeats, 1991; Bourne et al., 1999; Langridge et al., 2003) is second only to that of the Alpine Fault. However, Freund (1971) noted that towards Kaikoura the expression of the Hope Fault becomes less and less distinct and he had difficulty tracing the fault to the coast. Twenty years later, Van Dissen & Yeats (1991) proposed that most (60-90%) of the slip on the central portion of the Hope Fault is transferred northeastward, near Kaikoura, onto the northwest dipping Jordan Thrust. They proposed this model primarily to explain 1) the significant decrease in the late Quaternary lateral slip rate on the Hope Fault east of its junction with the Jordan Thrust, 2) abundant evidence for late Quaternary displacement on the thrust, and 3) the stunning physiography of the Kaikoura region with high, steep mountains west of the Jordan Thrust, and relatively subdued topography along the coastal section of the Hope Fault east of the thrust.

Approximately 25 km northeast from its junction with the Hope Fault, the Jordan Thrust is joined by the Fidget Fault, changes name, and continues northeastward as the Kekerengu Fault (Fig. 10, see also Fig. 6) which extends offshore c. 5 km north of Kekerengu. The slip-transfer model of Van Dissen & Yeats (1991), if correct, implies that a large amount of slip on the Hope Fault is eventually transferred onto the Kekerengu Fault, via the Jordan Thrust. Constrained estimates of slip rate for the Jordan Thrust and/or Kekerengu Fault would provide a direct test of this model. For example, if the slip rate on the Jordan Thrust / Kekerengu Fault is small, compared to that of the Hope Fault, then the model is in big trouble. Conversely, if the Jordan Thrust / Kekerengu Fault's slip rate is a significant percentage of the Hope Fault's, then the model is strongly supported.

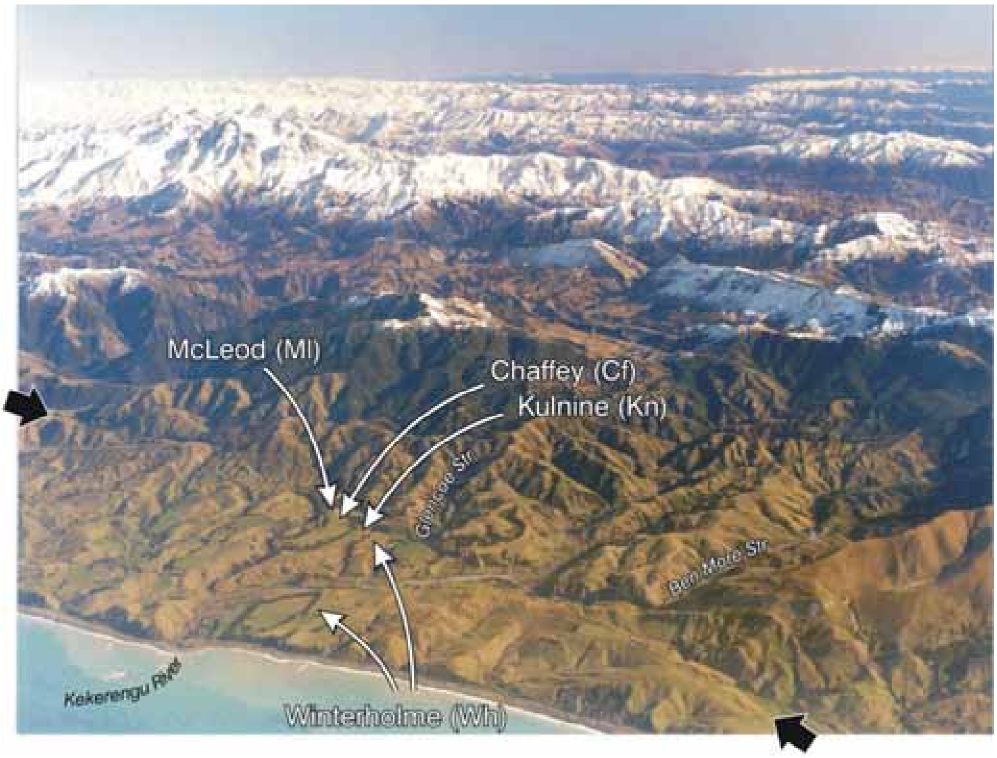

Figure 10: Oblique areal photograph of the Kekerengu area. View looking WNW across the Kekerengu Fault (location denoted by bold black arrows) towards the Inland Kaikoura Range and beyond. Representative distribution of alluvial terrace map units in the vicinity of the Kekerengu River and Glencoe Stream is shown, and, from youngest to oldest, these are Winterholme (Wh), Kulnine (Kn), Chaffey (Cf), and McLeod (Ml). See Figures 11-15 for greater detail regarding the distribution and characteristics of these units. (photo by Lloyd Homer. CN 20112-16).

The largest expanse of late Quaternary age alluvial terraces found along the Jordan Thrust / Kekerengu Fault is at Kekerengu (Figs. 10-13). Over January 1997, and December1999-January 2000 we mapped these terraces in detail, and investigated the lateral displacement of a beheaded channel and terrace riser near Glencoe Steam in an attempt to establish the late Quaternary lateral slip rate of the Kekerengu Fault. The results of this work are briefly outlined below.

At Stop 4 – Glencoe Stream, Kekerengu

Soil Stratigraphy and Alluvial Terrace Correlations

The soil stratigraphy (including soil profile development, number of loesses, and degree of gravel weathering and clay plugging) associated with the various alluvial terraces in the Kekerengu area was described at c. 70 localities from a combination of natural exposures, hand-dug soil pits, and auger holes. Based on differences (and similarities) in soil stratigraphy, and relative elevational position in the landscape the alluvial terraces of the Kekerengu area are grouped into five distinct map units. From youngest to oldest, we gave these units the following names – Winterholme, Kulnine, Chaffey, McLeod, and Older (undifferentiated). Figures 10-13 show the geographic distribution of these units in the Kekerengu area, and their relation to the Kekerengu Fault. Figure 14 shows the relative elevational position of these units southwest of Glencoe Stream, and Table 1 and Figure 15, together, depict some of the characteristic features of these units.

Ages (i.e. Oxygen Isotope Stages) for the Kekerengu alluvial terraces are tentatively inferred (Table 1) based on comparisons with well-studies terrace sequences along the Charwell and Awatere Rivers (Table 2), the presence of disseminated Kawakawa tephra (c. 26 ka) in the lower half of the youngest loess (loess 1 of Figure 15), and a few C-14 dates from the Kekerengu area (Table 3).

Table 1: Kekerengu alluvial terrace map units, some characteristic features, and their inferred correlations with Oxygen Isotope Stages.

Kekerengu alluvial terraces	Characteristic features	Oxygen Isotope Stage
Winterholme	Thin cover (typically <0.5 m) of overbank silt on top of unweathered to slightly weathered gravel. Terrace surfaces are relatively undissected.	2
Kulnine	One loess (typically 1-1.5 m thick, with disseminated Kawakawa tephra in lower half) on top of slightly to moderately weathered gravel. Terrace surfaces are moderately dissected with large portions of original terrace landform still preserved.	3
Chaffey	Two loesses (typically with a total thickness of 2.5-3 m) on top of moderately weathered gravel. In field area, this terrace is of limited extent, it is poorly preserved, and almost completely dissected.	3/4
McLeod	Up to three loesses (total thickness of c. 4 m) on top of reddish-coloured, clay plugged, moderately weathered gravel. Terrace surfaces are almost completely to totally dissected with little, if any, preservation of original terrace landform.	5 or 6
Older (undifferentiated)	Variable to no loess cover on top of clay plugged, moderately weathered gravel. No preservation of original terrace landform.	>6

Notes: Inferred Oxygen Isotope Stage correlations apply only to the respective aggradational gravel fill package and overlying aggradation terrace surface, not to the age of subsequent incision and younger degradational terraces.

Characterization of the degree of weathering of the older gravels (e.g. Chaffey and McLeod) is based on limited outcrop exposure, and auger hole cuttings, and, as such, should be regarding as indicative only.

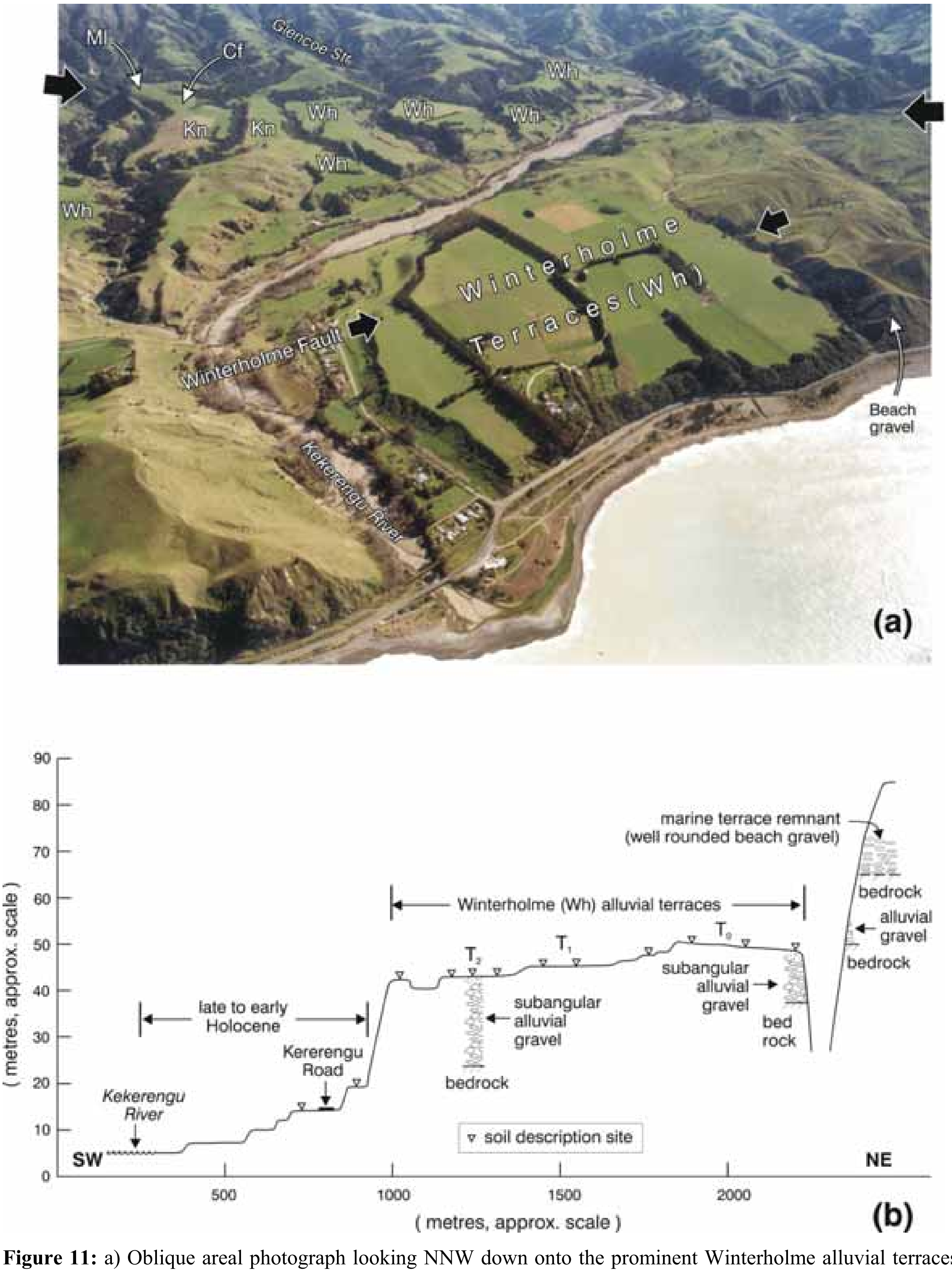

Figure 11: a) Oblique areal photograph looking NNW down onto the prominent Winterholme alluvial terraces (Wh). The general distribution of older alluvial terraces – e.g. Kulnine (Kn), Chaffey (Cf), and McLeod (Ml) – in the vicinity of Glencoe Stream and the Kekerengu River is also depicted. Bold arrows denote the location of the Kekerengu Fault and the Winterholme Fault. (photo by Lloyd Homer. CN 46342a). b) Schematic topographic profile extending NE from the Kekerengu River across the Winterholme alluvial terraces, including the late to early Holocene alluvial terraces between the river and Kekerengu Road. T_0 is probably the Winterholme aggradation surface, and its NE component of slope is no doubt a consequence, in part, of the original fan-shaped nature of the aggradation surface.

Figure 12: Oblique areal photograph looking NW across the Kekerengu River and the Kekerengu Fault (location denoted by bold black arrows) into the headwaters of Glencoe Stream and beyond. Distributions of alluvial terrace map units – Winterholme (Wh), Kulnine (Kn), Chaffey (Cf), and McLeod (Ml) – are show. The lateral displacements of the riser between the Kulnine and Winterholme surfaces (denoted as "Riser Gully" on photo), and the beheaded channel of Kulnine-age (location marked by the bold white dashed line) are used to establish the late Quaternary right lateral slip rate of the Kekerengu Fault (see text for discussion). (photo by Lloyd Homer. CN 46368a).

Table 2: Kekerengu alluvial terrace map units, and their inferred correlations with alluvial terrace sequences along the Charwell and Awatere rivers.

Kekerengu alluvial terraces	*Inferred correlations with other Marlborough alluvial terrace sequences*		
	Charwell River	Awatere River	
	Bull 1990, 1991	Eden 1989 (based on his Table 1)	Townsend 2001 (based on his Table 4.3)
Winterholme	Stone Jug	Starborough	Starborough
Kulnine	Flax Hills 1	Downs	Downs-2?
Chaffey	Flax Hills 2	Upton	Downs-1
McLeod	Dillondale	Clifford	Upton-1
Older (undifferentiated)	Quail Downes		Clifford & Muritai

Figure 13: Oblique areal photograph showing distribution of alluvial terrace units in the vicinity of Glencoe Stream and Heaver's Creek. From youngest to oldest these units are Winterholme (Wh), Kulnine (Kn), Chaffey (Cf), and McLeod (Ml). View looking NW across the Kekerengu Fault (location denoted by bold black arrows). In the centre of the photo, "Riser Gully" marks the location of the terrace riser between the Kulnine surface and the lower Winterholme surface. Also in the centre of the photo, the location of the Kulnine-age beheaded channel that, like the Kulnine-Winterholme riser, is also truncated and laterally displaced by the Kekerengu Fault is marked by the bold white dashed line. See text for further discussion on how the offset of these two features is used to establish the late Quaternary right lateral slip rate of the Kekerengu Fault. (photo by Lloyd Homer. CN 46704b).

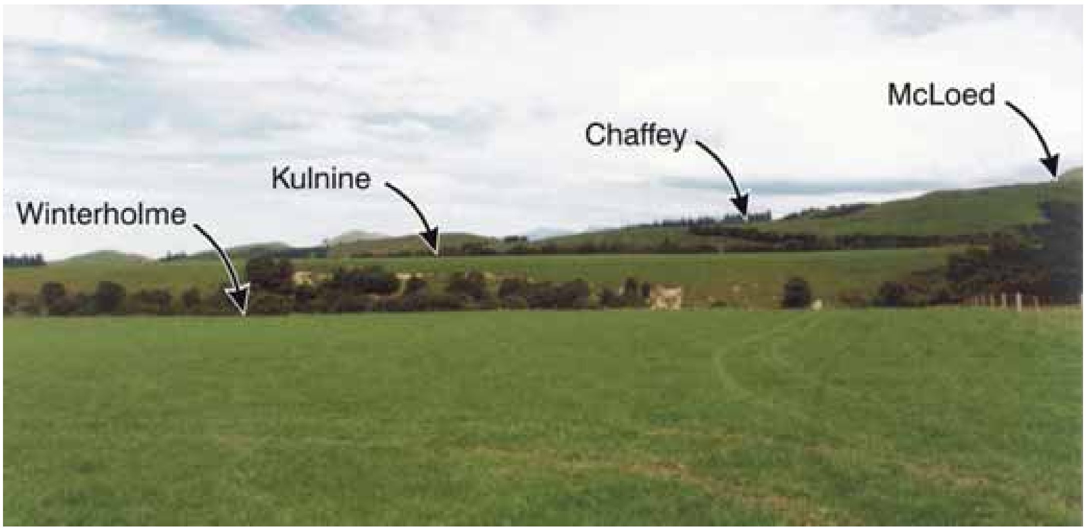

Figure 14: Photograph looking SW from near Glencoe Stream showing the relative elevational position of the Winterholme, Kulnine, Chaffey, and McLeod alluvial surfaces/units. At this locality there is about 13 m elevation difference between the Winterholme and Kulnine surfaces, c. 20 m between the Kulnine and Chaffey, and c. 45 m between the Chaffey and McLeod. (photo by Russ Van Dissen).

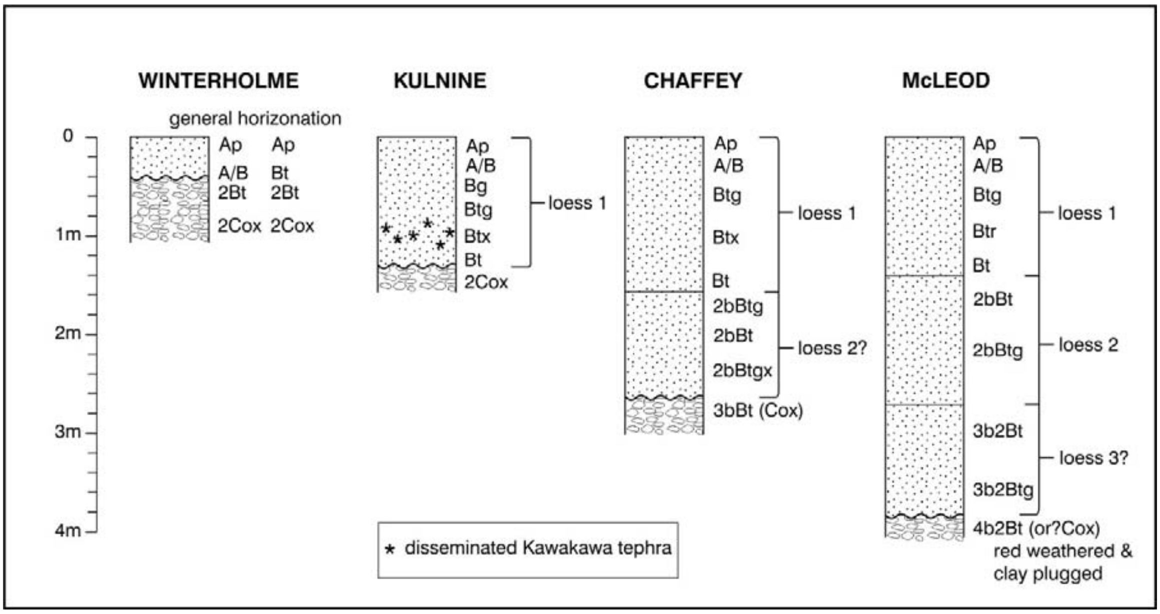

Figure 15: Characteristic soil stratigraphic features of key alluvial terrace units in the Kekerengu area. From youngest to oldest, these units are Winterholme, Kulnine, Chaffey, and McLeod. Loesses 1, 2, and 3 typically have clay loam to silty clay loam textures, though it is not uncommon for loess 1 to have a slightly more sandy texture (e.g. sandy clay loam), and the older loess to be more clay-rich. As used in our study, the horizon suffix "g" indicates at least 2% reddish mottles and between 50-85% of grey matrix colours. For more detail and explanation regarding soil profile description and horizon notation, the reader is directed to the geomorphology-oriented soils texts of Birkeland (1999) and Molloy (1998).

Table 3: Kekerengu area radiocarbon results.

Sample number	Lab number	Radiocarbon age (yr BP)	Grid reference, material dated & brief site description
Kekerengu #00-01-06-C14-1	Wk-8152	modern	P30/924100. Wood collected from the south bank of Valhalla Stream about 0.5 km from coast. Sample taken from 2.5 m below ground surface from within a 14 m thick alluvial gravel deposit interbedded with silt and fine sand beds up to 2 m thick. Alluvial deposit rests on a bedrock strath about 15 m above modern level of Valhalla Stream. Modern age of sample strongly suggests that sample is from a plant that established itself on the outcrop face long after deposition of the alluvial unit (i.e. sample is most probably much younger than alluvial deposit at this locality). Sample collected from gravels overlain by a Winterholme degradation terrace.
Ben More C14-1	Wk-8150	9000±80	P30/941151. Wood collected from west bank of Ben More Stream. Sample taken from an organic-rich layer interbedded with silt, sand and fine gravel (alluvium?) which overlies a course subangular alluvial gravel layer resting on a bedrock strath about 9 m above level of modern stream bed. The position of this sample projects to an elevation well below Winterholme aggradation terrace.
Ben More C14-3	Wk-8151	9080±70	P30/941151. Wood collected from same locality as Ben More C14-1. Sample taken from an angular gravel-rich deposit (possibly landslide debris) that overlies a course subangular alluvial gravel layer resting on a bedrock strath about 9 m above level of modern stream bed.
KEK-2	Wk-5321	>45,000	P30/917123. Wood collected from very small south flowing tributary of Heaver's Creek. Sample taken from a 1-2 m thick organic-rich unit that contains in-growth-position tree stumps and large detrital wood pieces. Sampled organic-rich unit rests directly on a bedrock strath, and is, in turn, overlain by c. 10 m of weathered alluvial gravel. Sample collected from deposits overlain by Kulnine terrace.

Lab number: Wk, University of Waikato, New Zealand

Radiocarbon age: Conventional radiocarbon age before present (AD 1950) calculated using Libby half-life of 5568 yr, and corrected to $\delta^{13}C$ of –25 ‰. Quoted error is ± 1σ.

Grid reference: Given on NZMS 1:50,000-scale topomap sheet P30 as easting (first three digits) and northing (last three digits)

Assessment of Kekerengu Fault Slip Rate

Southwest of Glencoe Stream, the prominent riser between the Winterholme terrace and the higher Kulnine terrace (Fig. 14) is sharply truncated by the Kekerengu Fault, and has a trend that is roughly perpendicular to the strike of the fault (Figs. 12 & 13). Near the fault, the riser has been the locus of subsequent gully erosion draining into the Kekerengu River, and is denoted as "Riser Gully" on Figures 12 & 13. The distance measured along the Kekerengu Fault between the riser where it is truncated by the fault, and Glencoe Stream upstream of the fault, the source of the riser, is approximately 500-550 m. The age of the riser is constrained by the ages of the Kulnine and Winterholme surfaces and deposits (Table 1). We consider that the bulk of the riser was cut during the peak of Kulnine degradation, sometime after Kulnine aggradation (i.e. sometime after c. 30 ka ago), and before the onset of extensive Winterholme aggradation (i.e. sometime before c. 25 ka ago). However, continued Winterholme aggradation through to c. 14 ka ago could have eroded back the riser somewhat, and thus the 500-550 m distance between the riser and Glencoe Stream should be regarded as a maximum displacement since the time of peak Kulnine degradation. A maximum lateral offset of c. 500-550 m within the last c. 25-30 ka implies a maximum right-lateral slip rate for the Kekerengu Fault of c. 17-22 mm/yr.

Further southwest from Glencoe Stream, there is an abandoned, beheaded channel on a Kulnine surface that is truncated by the Kekerengu Fault (Figs. 12 & 13). Like “Riser Gully” this Kulnine-age channel has subsequently become the focus of gully erosion. It now forms part of a very, very small tributary of Heaver’s Creek, but its original source was undoubtedly Glencoe Stream some 700 m to the northeast. In Table 1 we infer that the age of the Kulnine surface correlates with Oxygen Isotope Stage 3. If this is the case, then c. 700 m of right lateral displacement has accumulated on the Kekerengu Fault within the last c. 30-40 ka, indicating a lateral slip rate of c. 18-23 mm/yr.

Taken collectively, the above two rates suggest that the Kekerengu Fault has a right lateral slip rate of c. 18-22 mm/yr. Better age control for the alluvial terraces in the Kekerengu area is needed to further substantiate this high slip rate, but, in the meantime, it certainly supports the Van Dissen & Yeats (1991) slip-transfer model, and suggests that a high proportion of slip on the Hope Fault is, in fact, transferred northeastward onto the Kekerengu Fault via the Jordan Thrust.

En Route to Kaikoura

South from Kekerengu, State Highway 1 follows the narrow coastal plain to the Clarence River. Along this stretch of road are spectacular sets of small inset Holocene-age alluvial fans. The hills to the west (right) are very prone to landsliding, and the marine and alluvial terraces capping and inset into these hills were the subject of investigations by Ota et al. (1995). Between the Clarence River and Kekerengu, they document uplift of these hills at c. 1 mm/yr and northward tilting. At the Clarence River bridge, looking up the Clarence River, there is a good view of the Seaward and Inland Kaikoura ranges, if the weather is fine. About 8 km upstream of the bridge, in Miller Stream (a small tributary of the Clarence River that drains a portion of the steep southeast flank of the Seaward Kaikoura Range) a large rock avalanche at c. 1700 years ago inundated the catchment and resulted in c. 20 m of aggradation (Van Dissen et al., in press).

South of the Clarence River the road becomes more windy as it follows the rocky, and at times precipitous coastline to the Hapuku River. Lots of seals hang out at Ohau Point, no doubt because they like the nice view of a well-exposed, uplifted, wave-cut platform, and the proximity to the Hope Fault which extends offshore at Half Moon Bay.

From the Hapuku River it is a short drive to Kaikoura Memorial Hall where the conference is set to kick-off with an informal “ice-breaker” between 5-7:00 pm Monday night. On the drive to Kaikoura there are spectacular views of the Seaward Kaikoura Range, Kaikoura Plain, and Kaikoura Peninsula. For addition geological information regarding these features please refer to Field Trip Guides 5 & 6 of this conference.

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