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Interactions between Slope and Lake Sedimentary Processes:

Study from Aerial Imagery and Ground Penetrating Radar Survey

In the Alps of New Zealand

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Abstract

Lake Pearson is an alpine lake located amid a paraglacial landscape subject to accelerated rates of erosion, in the Upper Waimakariri Basin, South Island, New Zealand. Preliminary research into the shallow subsurface has been conducted with the use of ground-penetrating radar, supplemented with observation of surface sedimentology and landscape features. Distinct subsurface structures have been found beneath sections of Craigieburn Fan and the southern bed of Lake Pearson and the geomorphic processes responsible for the formation of each of these structures have been interpreted. Radargrams display evidence of avulsion of Craigieburn Stream, with the identification of several palaeochannels beneath the western side of Craigieburn Fan. Buried slope deposits at the base of Purple Hill show historic hill slope erosion and suggest hill slope stability is strongly linked to surface vegetation. Foreset bedding and onlap sedimentary sequences provide depositional evidence of lake level rise and lake currents have been identified as having a role in redistribution of fine sediment. Craigieburn Stream is the largest source of sediment to the area, though avulsion of the stream and progradation of Craigieburn Fan occurs on an episodical basis, in accordance with sediment availability and high stream flows capable of shifting large volumes of sediment.

Introduction

1.1 Overview

The Southern Alps of the South Island, New Zealand, are a region of tremendous geological and geomorphological activity. The Alpine Fault marks the transform boundary between the Pacific and Australian Plates. Over the last 20 million years immense tectonic forces associated with the collision of these plates have formed the Southern Alps, a mountain chain extending almost the entire length of the South Island. In this time, enough rock has been uplifted to form a mountain range 20 km high (Coates, 2002), yet today the highest peaks reach less than a fifth of that height. The mountains are being eroded almost as quickly as they are rising, literally being broken down by weathering processes and seismicity. The 'missing' material has been redistributed amongst the surrounding high country by glacial, fluvial, and mass wasting processes (Coates, 2002). Throughout the Late Pleistocene period the peaks and valleys of the Southern Alps were heavily moulded by glacial action. Ice sheets, thousands of metres thick in places, once extended eastwards from the Main Divide, literally carving through solid rock to form broad glacial valleys (Gage, 1958; Fitzsimons, 1997). Glaciers went through cycles of advance and retreat in accordance with global and local climatic conditions. Following the retreat of ice at the start of the Holocene period, the high country entered a phase of instability known as 'paraglacial conditions'.

The term 'paraglacial' is described as non-glacial geomorphological processes, sediment accumulations and landforms which operate and exist in landscapes that have in the past been shaped by glaciation (Church & Ryder, 1972; Ballantyne, 2002). Paraglacial landscapes are highly dynamic due to their exposed condition and instability and geomorphic processes are accelerated. They often exist in regions of extreme topography and climate, i.e. alpine environments, which are already susceptible to accelerated erosion. Most models of post-glacial sediment flux have an initial period increased landslide frequency and sediment production immediately following glacial retreat, which diminish as deglaciation progresses (McColl, 2011). Paraglacial sedimentation peaks in the period during the glacial recession due to the abundance of melt water and loose sediment available for reworking. The 'paraglacial period' is not restricted to the closing phases of glaciation, but may extend well into the ensuing non-glacial interval (Church & Ryder, 1972). The relaxation of a landscape shifting from glacial to non-glacial can occur over a period of tens of thousands of years and many areas that went through deglaciation in the Late Pleistocene have still not adjusted to non-glacial conditions (Ballantyne, 2002). Paraglacial landscapes are characterised by their 'temporary' appearance, where sediment is often in state of transition between source and sink.

Every year an estimated 4,500 tonnes of material per square kilometre is eroded from the Southern Alps (Adams, 1980). The eroded sediments have been redistributed and deposited by various geomorphic agents, forming the sedimentary landforms that exist today (Gage, 1958; Hales & Roering, 2005). Ground penetrating radar (GPR) analysis has been applied in a wide range of sedimentary environments, including fluvial systems (Roberts *et al*, 1997; Smith & Jol, 1997; Abbott *et al*, 2000; Ekes & Hickin, 2001), debris flow deposits (Starheim *et al*, 2013) and lahar deposits (Gomez & Lavigne, 2010). It has proved to be an effective tool for shallow subsurface investigations (Gomez & Lavigne, 2010). GPR provides two-dimensional imaging (radargrams) of the shallow subsurface to produce a stratigraphy of sediment beds laid down by depositional processes. Each of these processes produces a specific bedding formation or facies, which has a distinctive reflection signature in the radargrams (Ekes & Hickin, 2001; Neal, 2004). These allow interpretation of the different geomorphic processes that have operated in the past and the piecing together of the recent depositional history to see how each of these processes has interacted with each other to produce the present landforms. Understanding the various processes responsible for the formation of the present landscape is important for anticipating how the landscape will change in the future. This is especially important for geomorphologically active landscapes like the Canterbury high country, where paraglacial conditions have accelerated the rate at which these processes occur. There are a very few studies in New Zealand that have utilised GPR to interpret the formation of sedimentary landforms and certainly none in the immediate vicinity of the Craigieburn Fan or Southern Lake Pearson.

1.2 Glacial and Geomorphic History

The glacial history of the Southern Alps in Canterbury has been pieced together by various researchers, initially through examination of landscape features (Gage, 1958) followed with more sophisticated dating techniques and correlation with climatic history (Chinn, 1981; Burrows, 1983; Ricker, 1992). Despite this, glacial deposits are thought to have been poorly dated (Fitzsimmons, 1997; Pugh, 2008) and though advances are considered to have occurred simultaneously throughout different parts of New Zealand, precise timing of regional ice advances is largely determined by local environmental conditions (Fitzsimmons, 1997). The Otira Glacial Stage extended from 75-14 ka BP (Burrows, 1983) and the last glacial maximum (LGM) occurred between 22-18 ka BP (Fitzsimmons, 1997). Three major advances occurred in the Waimakariri catchment during that stage; the Otarama in the early Otira and the Blackwater and Poulter advances in the late Otira. The Blackwater advance occurred in three stages and was the farthest reaching of the LGM in the Waimakariri area. Deposits from the youngest of these, Blackwater 3, have been given a maximum age of 18.4 ± 1.8 ka BP based on weathering rind ages (Ricker *et al*, 1992). The Waimakariri River represents the former course taken by the main lobe of ice during these advances as they flowed eastwards from the Main Divide. A separate lobe diverged from the main lobe and crossed over Goldney Saddle and into the Cass Basin, making marginal contact with the trunk glacier east of Lake Sarah. The main stream of this distributary during the Blackwater 3 advance remained separate from the trunk glacier and continued beyond the Cass Basin as the Lake Pearson-Winding Creek lobe, leading to the excavation of bedrock and eventual formation of glacial lakes in the area; Sarah and Grasmere. The ice was so thick at the present location of Lake Pearson that the Winding Creek lobe deposited moraine on the Craigieburn Saddle and a melt water stream drained into Castle Hill Basin (Gage, 1958). Retreat of Blackwater 3 began before 17 ka BP (McGlone *et al*, 2004). The Poulter advance was the final major advance in the Waimakariri catchment, but it only extended just past Lake Grasmere (Gage, 1958; Suggate, 1990). Dating of moraine ridges and deposits from the terminus has produced different ages; Burrows (1983) suggests a minimum age of 13.7 ± 0.2 ka BP, while more recent work by Ricker *et al* (1992) puts the minimum age between 12 ± 0.1 and 9.7 ± 0.9 ka BP.

Following the Poulter advance the climate entered a warming phase and the subsequent glacial retreat marked the beginning of the Aranui Interglacial, where with the exception of a few minor advances during brief cold periods (the two McGrath advances suggested by Chinn, (1981)) ice masses have reduced significantly in volume. Glaciers and areas of permanent ice are still in this part of the Southern Alps, but they are restricted to only the highest altitude basins along the Main Divide. Monitoring of ice volume change reveals they have been in an overall state of retreat over the last few decades (Chinn *et al*, 2012).

Upon the retreat of the ice during the Aranui Interglacial, paraglacial processes replaced glacial processes as the dominant geomorphic activity in the high country landscape. In the absence of ice, widespread erosion occurred on the slopes of the steep glacier-carved valleys and newly-exposed landscape (Ballantyne, 2002). Gage (1958) suggests that alluvial fan development around Lake Pearson and Cass may have begun during the Poulter advance rather than during the interglacial, but regardless of when it started it has certainly continued throughout the Holocene period. The formation and progradation of two of these fans, Ribbonwood Stream fan and Craigieburn Stream fan, ultimately led to the development of Lake Pearson over the last 10,000 years through blocking of drainage as the valley filled with fluvial outwash sediments, surface runoff and groundwater discharge. Because of this, Lake Pearson is regarded as a 'non-glacial' lake as it was not formed directly by glacial action (Gage, 1959). Ribbonwood Stream has incised a deep gully in the Craigieburn Range and as it emerges into the valley a fan has formed and prograded eastwards across the valley to Long Hill, which forms a barrier between Lake Pearson and Lake Grasmere (Fig. 1.3.1). The gravel-bed Craigieburn Stream has created an extensive fan with a very gently sloping, almost sub-horizontal gradient. The stream has built the fan out in a north-east direction from the narrow valley between Mt Manson and Broken Hill and occupies the whole width of the Lake Pearson valley floor, to the base of Purple Hill. The maximum extent of progradation marks the southern shoreline of Lake Pearson.

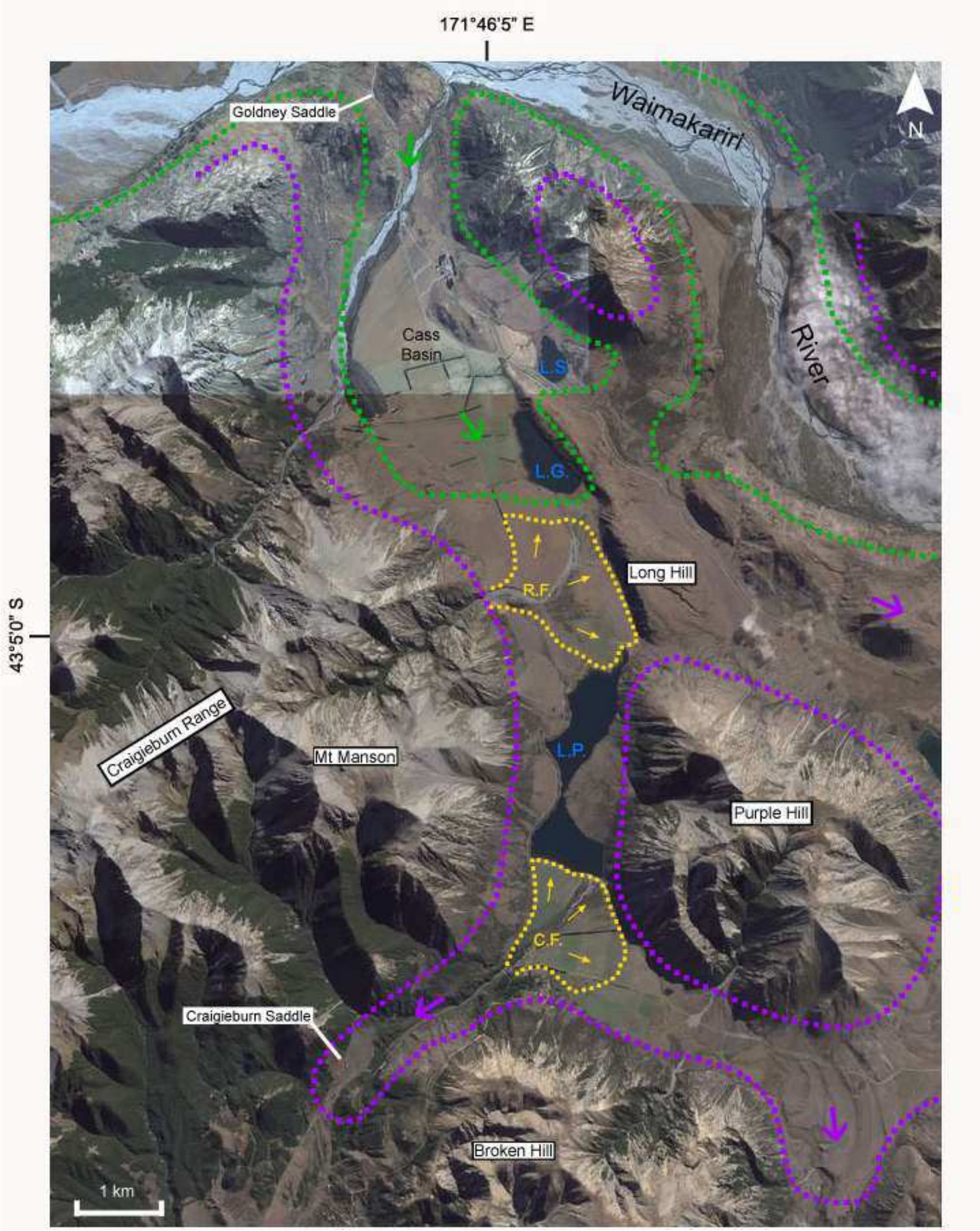


Figure 1.2.1 The maximum extent of different glacial advances. Blackwater 3 (purple) and Poulter (green). Arrows show the direction of ice flow. Ribbonwood Fan and Craigieburn Fan (both in yellow) developed after the retreat of ice.

1.3 Lake Pearson and Surrounds

Lake Pearson is located in the Upper Waimakariri Basin in the Canterbury high country, 80 km northwest of Christchurch. The lake has a north-south orientation and lies at an altitude of 600 m between two mountain ranges; Purple Hill (1,680 m) to the east and Mt Manson (1,860 m) to the west (Fig. 3.1). It has an area of 2 km² and has a maximum depth of 17 m in its southern half (Irwin, 1970). The lake has a distinctive 'hourglass' shape due to the two intrusive debris fans that have developed from the opposing eastern and western shorelines, narrowing it to a mere 50 m wide near its midpoint. The steep slopes of Purple Hill start rising immediately from the eastern lake edge. The lower slopes of Mt Manson don't rise as steeply on the western side; the base of the range is mantled with thick colluvium, across which State Highway 73 traverses.

Figure 1.3.1 View north toward Cass Basin from Purple Hill. The northern end of Lake Pearson is the foreground; Ribbonwood Stream can be seen the mid-ground and Lake Grasmere is to the right in the background (photo Richard Allen).

Lake Pearson has only ephemeral surface inflows. The largest of these is Craigieburn Stream, which enters the lake at the eastern end of the southern shoreline.

The stream carries only a small volume of water; it was gauged by the author with a flow of 0.6 m^3/s at SH73 Bridge in May 2013. For much of the year the stream permeates to groundwater a few hundred metres upstream of the lake as it flows across the fan past Flock Hill, leaving only a dry channel at the surface (Fig. 1.3.2). Observation of the stream mouth suggests that continuous surface flow right to the lake only occurs during winter and spring when the water table is high enough and during maximum flows in summer. The steep slopes either side of the lake exhibit evidence of ephemeral channels whose flow is dependent on rainfall and snowmelt. Much of the surface runoff permeates to groundwater as it flows onto the deep colluvial deposits at the base of the slope. In many places the topography is too steep for a coherent stream channel to form. Groundwater is presumably an important component of both inflow and outflow to the lake. Springs were observed on the shoreline at the northern end of the lake and seepage beneath the Craigieburn fan at the southern end causes springs to appear in Winding Creek downstream from where it exits the lake (Gage, 1958). Winding Creek is the only surface outflow from Lake Pearson and like Craigieburn Stream its channel remains dry for a large portion year; only when the lake level is high enough can water drain out. Winding Creek flows to the southeast along the base of Purple Hill.

Figure 1.3.2 View upstream of the Craigieburn Stream from the lakeshore. For much of the year it runs dry.

The Southern Alps are a highly active tectonic zone. Their uplift rate decreases from 11 mm/yr at the Alpine fault to 1 mm/yr at the eastern range front (Coates, 2002; Hales & Roering, 2005). Brittle greywacke of the Torlesse super-group dominates the geological composition of the eastern Southern Alps. Colluvial sediments mantle the valley slopes, increasing in thickness towards the base of the slopes (McArthur, 1987). Scree is a collection of loose rock fragments on hill slopes and is a common feature in the landscape, especially on the bare slopes above the tree line where bedrock is exposed. Scree deposits are produced by rockfalls and rock avalanches which are a common on the steep slopes. Whitehouse and Griffiths (1983) found about 50 deposits larger than 10^6 m^3 in volume within a 10,000 km^2 area of the eastern Southern Alps. Debris flows are present on some of the slopes surrounding Lake Pearson, for example on the northwest slope of Purple Hill (Starheim *et al*, 2013). The two fans that intrude into Lake Pearson also appear to be formed by successive debris flows though their vegetation cover suggests they are rarely active. Through a combination of these processes slope erosion was calculated to occur at a rate 0.6 mm/yr which is approximately enough to balance tectonic uplift (Hales & Roering, 2005).

Slope erosion has no doubt been exacerbated by the lack of vegetation cover on the slower slopes which would naturally lie below the tree line, which sits at around 1,250 m (McGlone *et al*, 2004). Research by McGlone *et al* (2004) into Holocene vegetation in the Cass Basin through dating organic matter in kettle bog sediments, suggests that tall Podocarp forests existed during a period of climate warming between the Blackwater and Poulter advances. During these advances tundra-like grassland and shrubland dominated the landscape. By 7,500 BP following the Poulter advance montane beech forest clothed the landscape. Present-day vegetation cover is far sparser than it once was. Evidence of widespread occurrence of forest fires in the eastern Southern Alps has been used as a reason for this. Burrows (1996) conducted radiocarbon dating of charcoal in palaeosols at several high country locations, including Ribbonwood Stream. At the Ribbonwood Stream site, thin layers of soil containing charcoal were identified at varying depths. The oldest of these had a radiocarbon date of 2547 ± 66 BP and indicates the time of a fire which destroyed the vegetation at the site and led to a period of slope instability. A series of fires occurred episodically between then and present day, each time destroying vegetation and creating unstable slope conditions. In modern times, vegetation typical of intermontane South Island basins, like matagouri, Coprosma, native tussocks and sedges is abundant (Burrows, 1960) although much of the lakeside vegetation is introduced willow trees and Briar rose. Low vegetation covers the slopes surrounding the lake, reaching no more than a few metres in height with the exception of a few patches of stunted Mountain Beech, which remain on the lower slopes and in some gullies. Sections of Craigieburn Fan are part of the working Flock Hill Station and is grazed by sheep and cattle. It is almost entirely covered by grazed pasture except for a fenced corridor of matagouri, Coprosma and broom on either side of Craigieburn Stream. The valley slopes are designated 'outstanding natural landscape' Department of Conservation land and are no longer grazed.

The Southern Alps create an orographic effect on the prevailing mid-latitude westerly airflow that flows over the South Island, moist from its journey across the Tasman Sea. Rainfall west of the Main Divide can be as high as 12,000 mm/yr (Griffiths & McSaveney, 1983) as the moist air is forced to rise 3,000-4,000 metres over the mountains. Being in the lee of these high ranges, the floor of the Cass Basin receives a mean annual precipitation of 1,300 mm, but this increases with altitude (McGlone *et al*, 2004). Cass has a mean annual temperature of 9°C, with warm summers and quite mild winters. Snow usually lasts on the tops for the duration of winter and into spring and snowfall on the basin floor is a yearly occurrence.

Figure 1.3.3 Panoramic view of Lake Pearson and Cass Basin from Purple Hill (photo Richard Allen).

2 Geomorphic Processes

Erosion ultimately stems from the combination of gravity and hydraulic action on exposed surfaces (Ballantyne, 2002; Davies & McSaveney, 2008). Precipitation and subsequent surface runoff mobilises loose sediments made available by weathering processes and seismicity. Mass wasting is a common feature of paraglacial landscapes (Fig. 2.1) and plays an important role in redistributing sediments. Landslides, rockfalls and debris flows are initiated by gravity and provide an abundance of loose sediment available to be transported further afield by fluvial processes and deposited in terrestrial and lacustrine sediment sinks. Erosion is enhanced in alpine areas by the steep topography, climatic extremes in precipitation, temperature variation and lack of vegetation (due to anthropogenic or natural cause). A variety of transportation mechanisms can co-exist and interact with each other, resulting in complex sediment landforms that can be difficult to interpret (Pharo & Carmack, 1979; McColl, 2011).

2.1 Mass Wasting

Mass wasting is the downslope movement of soil and rock through the force of gravity and without direct involvement of water (Selby, 1985). There are different types of mass wasting, each with its own conditioning process, triggering mechanism and type of downslope movement. Low precipitation east of the Main Divide means mechanical weathering from runoff is less influential in the eastern mountains of the Southern Alps than what is found on other high mountain slopes. However, mechanical weathering is much more important than chemical weathering here. This is because the climate is cool and the Torlesse rocks are relatively inert in regard to chemical alteration (Coates, 2002). Wide temperature variation through diurnal heating followed by cooling at night causes expansion and contraction of rocks. Over time this opens small cracks, in which water can penetrate. As water freezes it expands, further opening cracks and eventually breaks rocks apart.

Rockfalls are features of steep rock slopes and are one of the most important processes in rock slope erosion (Selby, 1985). Rockfalls are characterized by the dislodging of one or more rock fragments from exposed bedrock, which descend downslope by rolling, bounding and sliding. They are conditioned by mechanical weathering which can act on pre-existing joints and bedding in the rock mass (McColl, 2011). They occur when the force of gravity exceeds the shear stress between the rock and the slope. Bedrock detachment is usually triggered by debuttressing and seismic events (Korup *et al*, 2004). Rock avalanching is a type of landslide where rock material moves downslope en masse (Whitehouse & Griffiths, 1983). Rock avalanches are mainly composed of bedrock but when they also consist of coarse soils they can be termed debris slides (Selby, 1985). While over-steepening of valley sides following glacial retreat was a cause of some of the rock avalanches in the Southern Alps, most rock avalanche deposits postdate the likely instability period and were most likely triggered by the other known mechanisms, such as earthquakes, heavy rainfall and removal of slope support (Whitehouse & Griffiths, 1983). High intensity rainfall is usually responsible for the triggering of shallow landslides and debris-type movement, which result in slopes being stripped of colluvium (Selby, 1985).

Scree is the commonly used term for the slope deposits produced through rock avalanches and rockfalls. Hales & Roering (2005) describe the correlation between different environmental variables and prevalence of scree slopes within the central section of the Southern Alps. They identified that the zone of maximum scree extent within the Southern Alps is 40-60 km east of the Main Divide, which includes the area Lake Pearson lies in. The majority of scree lies within a distinct altitudinal range (1,200-1,600 m), suggesting that its production is most closely associated with freeze-thaw weathering induced by extreme temperature variation and mobilisation by precipitation. Accumulations of scree on steep gullies can often provide good conditions for the formation of another type of mass movement, debris flows. Debris flows are moving masses of unconsolidated mud, soil, rock, water and air and are triggered by intense rainfall (Selby, 1985). They can travel at very fast speeds and pose a significant risk in mountain environments worldwide due to their highly destructive nature and unpredictability. Debris flows operate in a way that fine sediments allow buoyancy of large heavy material which is able to flow on top. They can often be recognised in the landscape by their reverse graded deposits. Debris flows do form fans and cones, though the formation process is completely different to that of fluvial fans. While many alluvial fans are initially attributed to be of fluvial origin, mass movements are quite often involved in their development (McArthur, 1989; Ballantyne, 2002; Davies & McSaveney, 2008).

Figure 2.1 Erosion is characterizing feature of the landscape surrounding Lake Pearson. The base of the Craigeburn Range is mantled with a thick layer of colluvium.

2.2 Fans

Alluvial fans are among the most common features of paraglacial reworking (Ballantyne, 2002). Fans are prominent features of landscape surrounding Lake Pearson and are generally quite easy to identify due to their distinctive morphology. Fluvial fans are low-gradient, cone-shaped sediment deposits that have accumulated where the transporting power of a river or stream becomes inadequate to carry its entire sediment load any farther downstream, so that the coarser fraction of the sediment is deposited on the streambed (Bagnold, 1977; Davies & McSaveney 2008; Roberts *et al*, 1997). This includes the bed load, which is defined as the solid material that is not constantly suspended in the water column by upward currents or turbulence and instead bounces (saltates) along the stream bed. Saltation applies to coarse sediment and is distinguished from very fine material which becomes suspended within the flow (Church, 2002). Deposition generally occurs where a river or stream that has been confined to a narrow valley transitions abruptly onto an area of flat land such as a valley floor and is able to spread and wander freely. Fluvial sediment transport is a function of stream power and is inversely related to the size of the sediment (Bagnold, 1977; Church, 2002). The flow depth, and velocity determine the capacity of the stream to move particular sediment sizes but the availability of material able to be transported by the stream is also important. Glacial moraines also provide large reservoirs of relatively loose sediment available to be gradually reworked by fluvial processes. The grain size of bed material is usually directly correlated to the channel gradient, as this is reflective of the stream power (Church, 2002). In fan development the combination of greater width (which causes a reduction in depth) and lower slope (which reduces water velocity) reduces the ability of the stream to transport the same capacity of sediment that it carried when confined in the narrower, steeper valley upstream. Sediment drops out of suspension and is deposited locally, causing an increase in the streambed elevation (aggradation). As the fan immediate to the active channel builds up, an area of higher elevation relative to the rest of the fan is created. Avulsion occurs when the channel is overtopped during high flows and the stream cuts a new path to the lower elevation parts of the fan. Over time this new flow path is built up too, causing the process to repeat and the stream to wander back and forth across the fan (Davies & McSaveney, 2008). When the stream changes course, the former channel becomes inactive and over time gets filled in. Buried stream channels are known as palaeochannels and are channels that were once active but have since become inactive and been buried as the stream that used to occupy them changes course and abandons them (Toonen *et al*, 2012). Fan development normally requires a significant supply of coarse sediment available for mobilization. Shallow-gradient alluvial fans require large amounts of sediment to be repositioned to alter their morphology, as their bed load sediment concentration is usually quite low.

2.3 Lacustrine Processes

Displacement of beach sediments by longshore currents is a significant component of sediment movement in New Zealand lakes (Allan, 1996). Longshore currents are induced when the incident wave angle approach occurs at an oblique angle to the shoreline. Sediments are gradually transported along the shoreline in the direction of the current. Natural beach armouring occurs in response to the sorting actions of waves and currents which remove gravels and fine sediments from the beach and leave behind larger cobbles and boulders. The result of this process is increased protection of the beach foreshore and near-shore beneath the water line (Allan, 1998). Berms are raised, linear mounds that lie parallel to the shoreline on gravel beaches. Berm size and shape are functions of wave energy and the nature of the sediment present (Allan, 1998). Re-suspension of fine bed sediments occurs when waves, generated by strong winds, interact with the lake bed.

Fluvial deposition in a lacustrine environment often leads to the formation of a submerged delta platform extending out from the river mouth. Deltas are distinct shoreline protrusions that form where an alluvial system (river) enters a lake. Sediment carried by the incoming river is rapidly deposited when the river water experiences quick deceleration upon meeting the lake water. The sediment is also supplied at a rate more rapid than the speed at which lacustrine redistribution processes operate (Phillips & Nelson, 1981). Foreset bedding is beds of sediment that dip in the direction of stream flow. It occurs where moving water meets still water and is common in underwater deltas (Abbott *et al*, 2000; Ekes & Hickin, 2001). The way river water travels through the lake upon arrival also depends on the difference in density between the two water bodies (Orton & Reading, 1993). Density is influenced by the water temperature and the sediment concentration of the incoming flow. Density currents will often form during flood flows, when both discharge and the suspended sediment concentration are high. Density currents flow as underflow and penetrate further into the lake, with some forming sub-lacustrine channels, often following the thalweg of the lake. These channels are also likely to form under the lake surface beneath well-developed debris flow paths. When river water is of higher temperature or of similar or lower sediment concentration, sediment will usually disperse in a plume-shape formation over a wide area, either along the lake surface or as interflow (Phillips & Nelson, 1981).

3 Study Area

Field investigation was focused on the southern lakebed and shoreline of Lake Pearson and also on the Craigieburn Fan (Fig. 3.1). The area can be further separated into three distinct areas, A, B and C, based on the landforms present and dominant geomorphic processes operating (Fig. 3.2).

3.1 Area A

This area includes the shallow south-eastern corner of the lake and the base and lower slopes of Purple Hill. During extended dry periods the lake level drops at least 1 m, revealing tens of metres of lakebed and in this south-eastern corner a flat with fine gravels and occasional patches of fine silts and muds is exposed. For ease of explanation this area will be referred to as the ‘mudflat’ from now on.

3.2 Area B

This area includes the mouth of Craigieburn Stream as it enters Lake Pearson. Here there is a 150 m wide ‘v’ of gravel mouth bars and cobbles, through which the active channel of Craigieburn Stream flows. Surface gravels and cobbles are well-rounded but are poorly sorted and crudely bedded. Area B also includes the western edge of the mudflat.

3.3 Area C

This area includes the western half of Craigieburn Fan close to the shoreline. The southern shoreline of Lake Pearson marks the northern extent of Craigieburn Fan and is composed of fine to coarse gravels and cobbles. A small (20 cm) wave-cut step along parts of the shoreline marks the high water level (fig._). The near-shore lakebed is composed of gravels, ranging from fine gravels (<1 cm) to cobbles (<6 cm). Pasture continues right to the shoreline along this section of the fan. The lakebed slope at the southern end is very shallow and Irwin's 1970 bathymetry of Lake Pearson shows that this slope continues for several hundred metres offshore, although it likely that the lakebed has changed in the time since this survey was conducted.

3.4 Research Aim

The aim of this research is to examine the sedimentary depositional structures present beneath the subsurface of Craigieburn Fan and the Lake Pearson lakebed and interpret the geomorphic processes responsible for their formation. This involves identifying the roles played by paraglacial fluvial, hill slope and lacustrine geomorphic processes and interpreting how they have operated in the landscape and interacted with each other to produce the landforms present. GPR imagery was used to image the subsurface and was supplemented with field observation of surface sediments and landforms. Research was focused here because the location lends itself to being suitable for examination of multiple geomorphic agents operating within close proximity to each other. This research may provide useful information to promote the effective management of high country land and allow consideration of potential future hazards.

Figure 3.1 Map of Lake Pearson and surrouds.

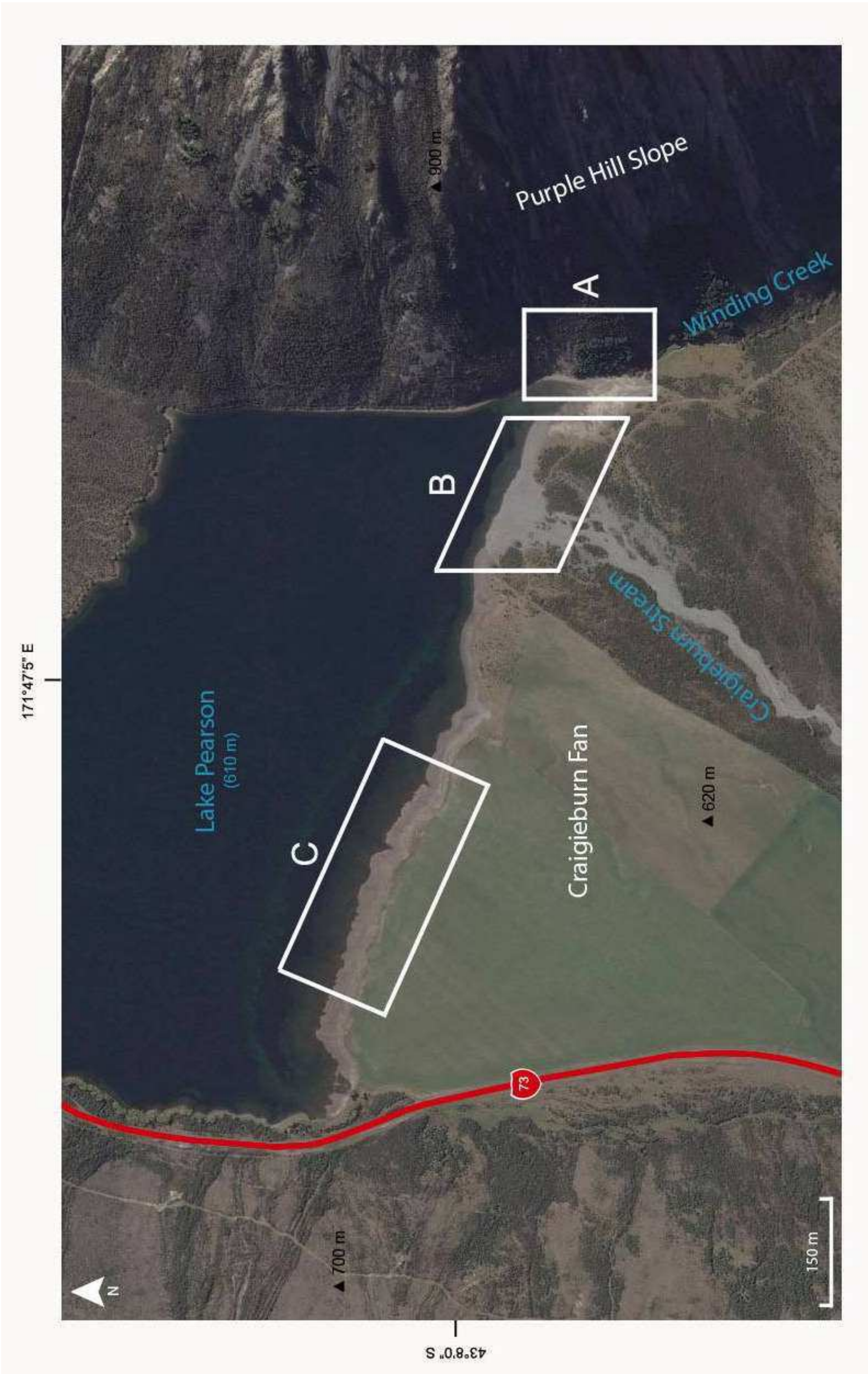


Figure 3.2 Map of study area including three sub-areas, A, B and C.

4 Methods

The method relied mainly on subsurface radar imagery as well as geospatial data and field observations. It also took advantage of the seasonally low lake level during late autumn, which saw tens of metres of extra lakebed exposed. A PulseEKKO PRO GPR system, equipped with 500 MHz antennae, was used to image the subsurface (Fig. 4.1.1). The GPR emits electromagnetic radar pulses into the ground and relies on the dielectric properties of the subsurface mediums. As radar waves transition through one material and into another, i.e. through overlying depositional layers with slightly differing sediment composition, some of the wave energy is reflected. This reflected energy is received by the GPR and a two-way travel time and wave amplitude is recorded. The amplitude is the strength of the signal coming back to the receiver– a stronger difference in composition between two layers will result in more reflection and stronger amplitude. The 500 MHz frequency means that everything 5 cm or larger is registered as an individual object. Subsurface structures are presented as 2D radargrams. With increasing frequency the penetrating depth of the electrical pulse is generally greater; however there is also a loss in resolution. The frequency at which radar pulses were emitted was set to occur every 1 cm horizontal distance travelled. This was controlled by an odometer attached to the GPR.

Figure 4.1.1 A 500 MHz PulseEKKO GPR system was used in this project

4.1 GPR Processing

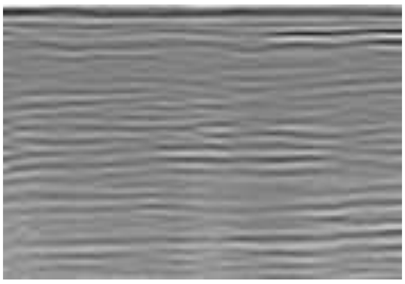
Once GPR field data had been collected it required processing so that the radargrams could be properly interpreted. This involved several steps using Reflexw software (Sandmeier, 2011). The first step was adjusting the automatic gain control (AGC). This is similar to enhancing the colour contrast of an image. AGC can be adjusted so that larger changes in velocity are amplified to produce a more distinctive layer boundary. The key is to maintain some 'amplitude fidelity' and not allow enhancement of all signals captured, or else insignificant features will be made unnecessarily prominent. The vertical axis is initially recorded as a measure of time rather than distance, i.e. the time it takes for the electromagnetic waves to travel through the earth. This needs to be adjusted to provide a spatial component, rather than temporal. In some cases the energy decay filter was also used to compensate for the loss of energy as the waves travelled. This filter enhances the signal at deeper layers so they appear stronger. The air signal was also removed as the pulse travels unimpeded through the air. Topographic correction is the process of linking the surface topography to the GPR data. If GPR transects are conducted on uneven or undulating terrain, the depth value recorded will not be a true representation of the vertical distance beneath the surface. When this happens one subsurface object can be recorded twice and identified as two separate objects. Topographic correction was not necessary in this project because the surface was near enough to flat. A Trimble R8 differential global navigation satellite system (dGNSS) was used for accurate spatial positioning of GPR transects. This involved use of a base station, which was set up on a local known point. The base station allows errors from atmospheric conditions to be corrected. A rover was used to map out the transect lines. Arcmap 10.1 was used to display spatial data.

Unfortunately on the first day of GPR surveying technical difficulties resulted in us being unable to use the GNSS gear, meaning exact positioning of GPR transects could not be obtained but the problem was corrected for the second day of surveying. Aerial and field observation of surface landforms and sedimentology was used to supplement GPR and GNSS data. The size, shape, organisation and orientation of surface sediments provide information about the nature of their deposition and the possible mechanism behind their deposition. Interpretation of the radargrams requires an understanding of the spatial context; consideration of their locations in relation to potential processes that may be operating around them. The shape, slope and orientation of some structures give insight into the possible mechanism behind their deposition.

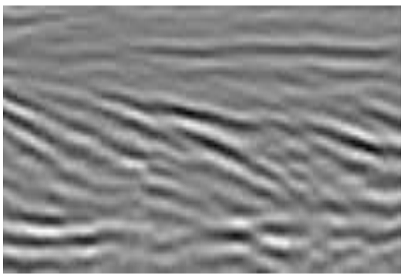
Transect recording was focused on the western side of Craigieburn Fan and on the mudflat in the south-eastern corner, with a few in between (Fig. 4.1.2). Transects were conducted in a grid pattern, perpendicular and parallel to the shoreline. Most transects were kept under 100 m in length to help with ease of processing.

4.2 GPR Facies

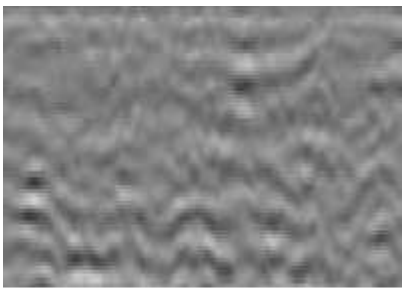
Different radargram reflection signatures are associated with different depositional environments. Various research from other studies involving GPR such as Neal (2004) and Ekes & Hickin (2001), describe the range of reflection geometries and the terminology used to describe them. The following three are common facies:



Horizontal, smooth, parallel beds. This indicates well bedded fined silts and sands.



Smooth dipping, beds. This is known as foreset Bedding, and is associated with deltaic environments.



Discontinuous, hummocky, chaotic beds. This usually indicates poorly bedded gravels and sands.

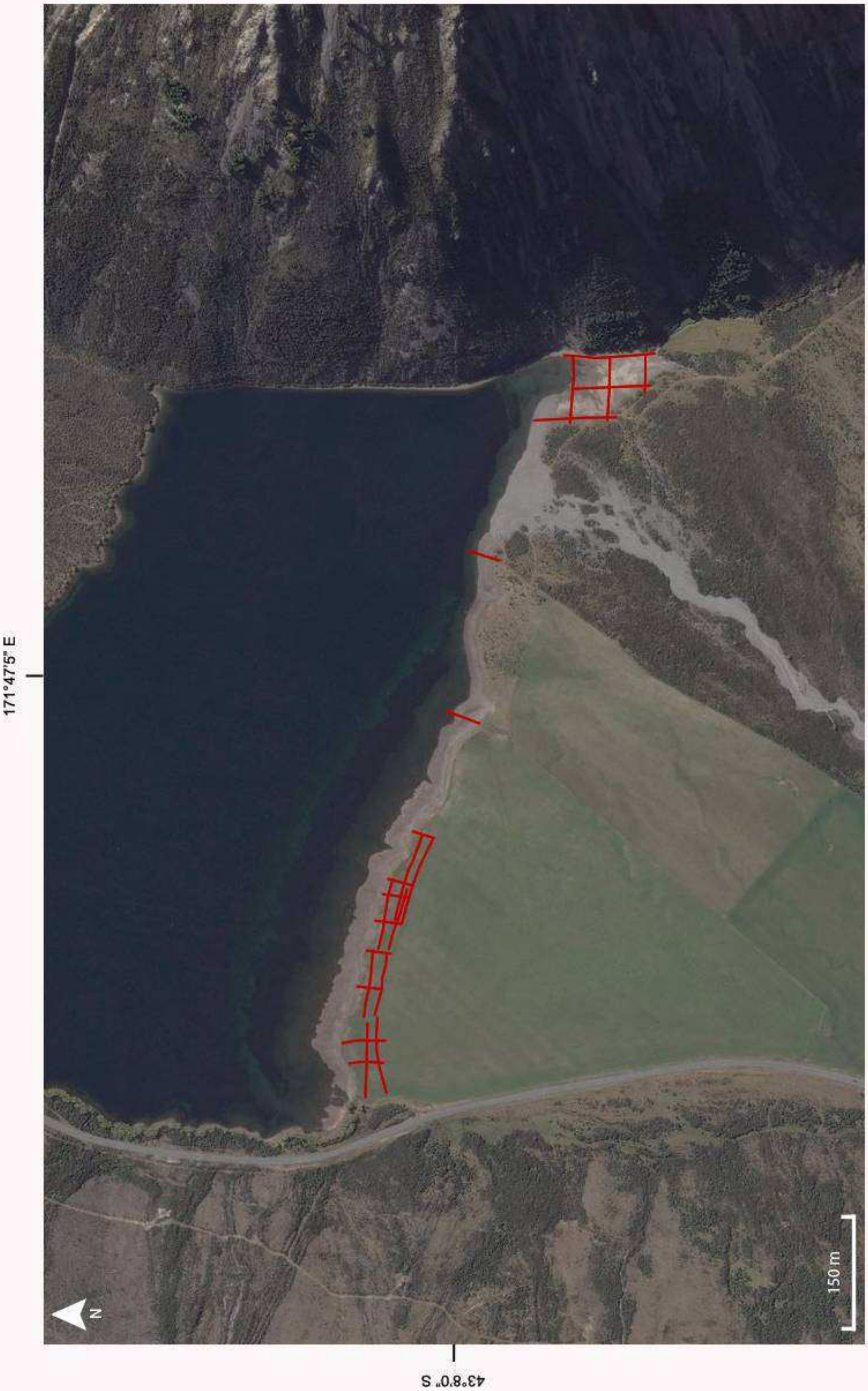


Figure 4.1.2 Map showing locations of GPR transects in the study area

5 Results

In total 24 GPR transects (T1-T24) were recorded on Craigieburn Fan and the Lake Pearson lakebed over two different days; once in May (late autumn) and once in July (winter). On the first day of recording a depth of just over 2 m was achieved and the radargrams were able to display clear sediment bedding. On the second day of recording a depth of only 0.8 m was achieved and the radargrams were not as sharp as on the first day. Two weeks prior to the second collection a southerly storm brought heavy snow to much of the South Island, particularly inland Canterbury. While most of it had melted by the time we collected data there were still large patches remaining which were approximately 10 cm thick. It is likely that the snow melt saturated the soil and raised the water table, which would have affected the ability of the radar waves to penetrate the earth. Groundwater presents a highly conductive medium which reduces penetration depth. The lake level was at least 50 cm higher too, and approximately 20-30 m of the lakebed that was previously dry, was inundated. This meant that additional radargrams of the lakebed were unable to be obtained and accessibility along the shoreline was reduced as previously we had been able to walk along the lakebed to get to the eastern side of the lake. It seems that the lake level is this high for the majority of the year, therefore there is no 'shore' as such, so the correct term 'lakebed' will be used instead of 'lakeshore'.

Several of the radargrams from the three areas A, B and C, reveal the presence of distinct subsurface structures beneath the lakebed and Craigieburn Fan, including slope deposits, deltaic deposition, palaeochannels and berms. The geomorphological mechanisms behind the formation of these structures are able to be interpreted with knowledge of how they operate in the landscape and their spatial relation to surface features. All radargrams have to been adjusted to be to-scale, unless stated otherwise. East-west radargrams are displayed from a southern perspective, i.e. with east on the right. North-south radargrams are displayed from an eastern perspective, i.e. with north to the right.

5.1 Slope Deposits

There is an unconformity been two distinct areas of sediment bedding beneath the mudflat, against the base of Purple Hill. T20 reveals a series of westward-dipping hummocky beds overlain with onlapping beds of fine sediment (Fig.5.1.1). The beds are part of a structure, 6 m wide and at least 2 m tall, possibly larger if it extends beyond the range of the GPR. Based on its parallel orientation the structure could initially be assumed to be a subsurface continuation of the beds that make up the slope of Purple Hill, but this seems unlikely considering there is almost 1 m of horizontal bedding on top of it. The structure dips at an angle of approximately 30° and appears to be composed of large clasts that are arranged chaotically rather than in uniform layers. Its appearance suggests that the structure is, or part of, a colluvial deposit originating from the hill slope directly above (Fig. 5.1.2). Given its location at the very base of the steep hill slope, it is probably too coincidental to assume otherwise. The smooth beds on top of it appear to be of lacustrine origin and must be younger to be positioned earlier in the vertical sequence; this is emphasised by the lacustrine beds conforming to the shape of the underlying deposit (onlap deposition). The lacustrine sediment appears to be fine-grained, suggesting it is similar to the mud that is present on the surface (Fig. 6.1.2). The surface sediment at the base of the hill slope is composed of a range of chaotically-arranged, angular hill slope deposits that range in size from cobbles to boulders (>40 cm) and there are some rocks strewn tens of metres further out onto the mudflat.

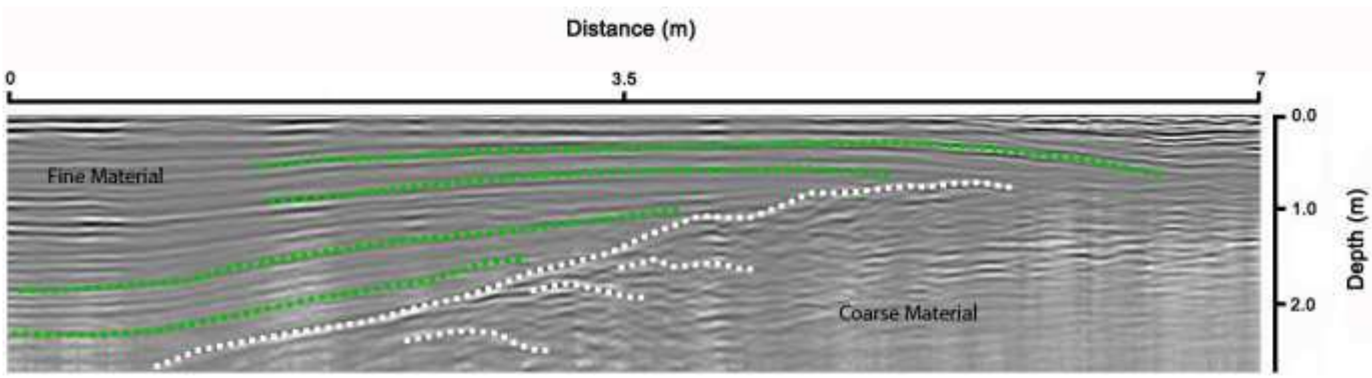


Figure 5.1.1 Transect 20 from the base of the Purple Hill slope (on the right). The uniform, fine-grained lacustrine layers (green) can be easily distinguished from the coarse hills slope deposits (white).

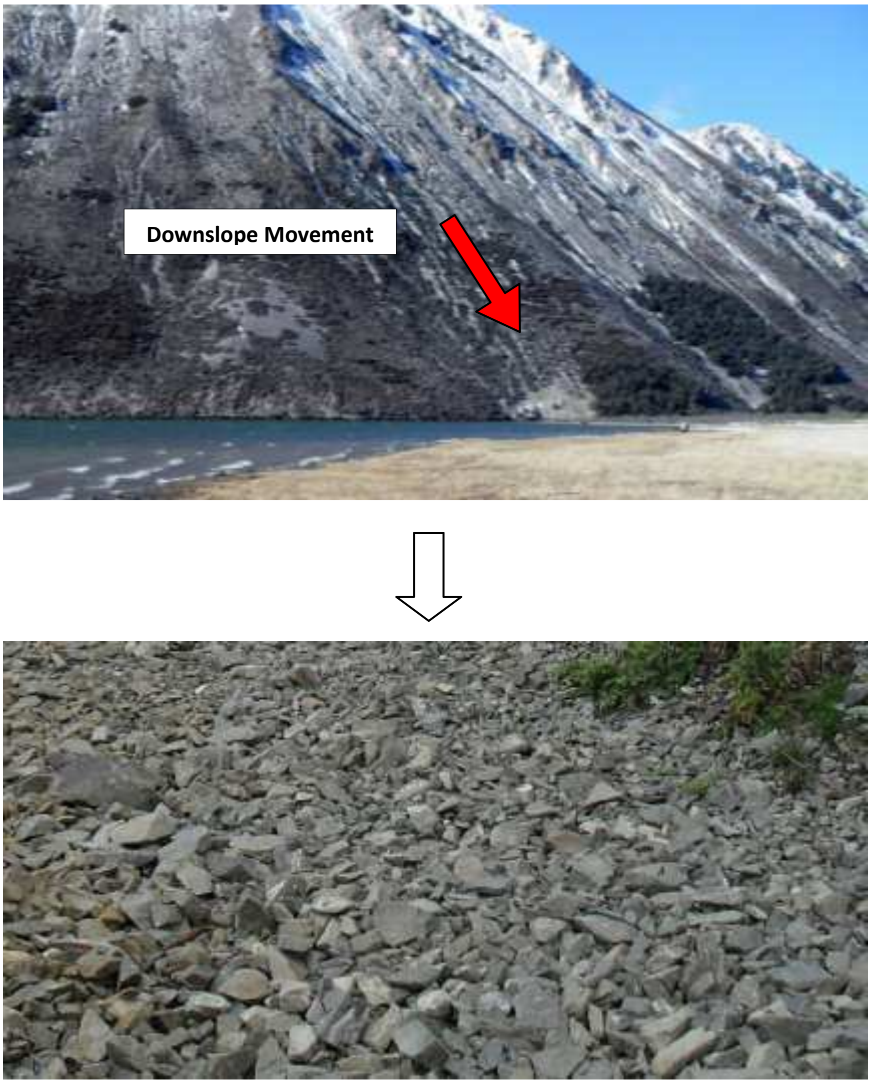


Figure 5.1.2 The buried hill slope deposit appears to be similar to the material on the surface at the base of Purple hill slope, which is coarse and angular.

5.2 Deltaic Deposition

T21 beneath the mudflat reveals cross bedding and a distinct dipping sequence signalling a period of deltaic progradation (Fig. 5.2.1). The sequence extends across a horizontal distance of about 10 m and is perpendicular to the current direction of Craigieburn stream flow. Strong foreset bedding occurs through a specific depth range of around 0.7-1.5 m. The bedding planes with the strongest signal dip to the west at around 20° although they are not uniform at all and vary between the latter angle and horizontal. Cross-bedding is evident as dipping beds are overlain with about 0.5 m of subaerial topset beds composed of fine-grained lacustrine material. Topset beds are horizontal, parallel and uniform, from the surface to 0.5 m depth. Bottomset beds are not easy to recognise due to the weak reflective signal however they appear to revert back to horizontal beyond 1.7 m depth. All beds through the sequence are also composed of fine material.

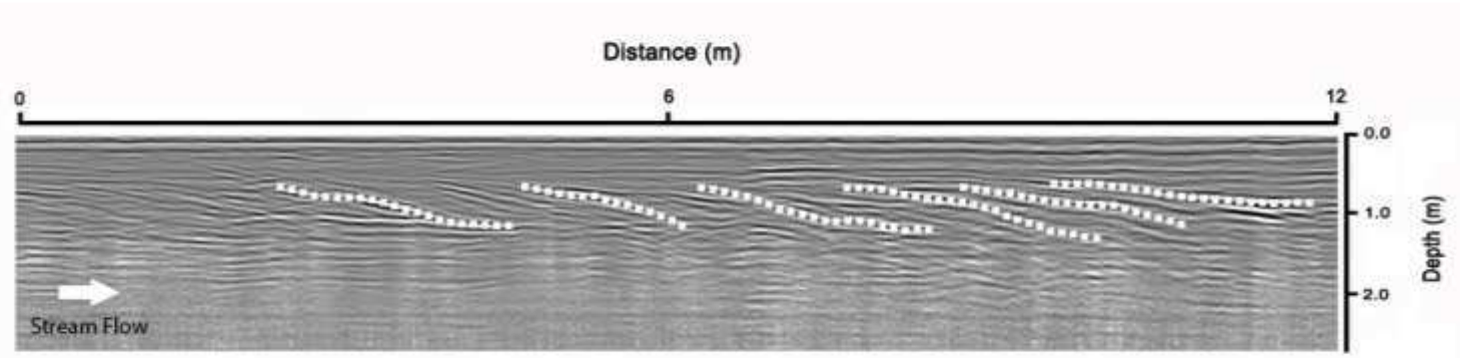


Figure 5.2.1 Foreset bedding beneath the mudflat provides evidence that Craigieburn Stream has avulsed in the past.

Foreset bedding is also evident beneath the lakebed just west of Craigieburn Stream mouth (T18) with bedding planes dipping toward the lake at angles varying from 10° to 30° (Fig. 5.2.2). The depth at which these planes lie is wider than Fig. 5.2.1, ranging from 0.2-2 m. Beds with strong reflective signal appear further apart here, with the bedding in between each being relatively quiet. There is almost an absence of topset beds, with only 0.2 m of horizontal beds below the surface, but these are sub-parallel. Below 2 m depth the bedding planes revert back to horizontal. Sediment here appears to be coarser in places, with large clasts visible between 1.5 and 2 m depth, specifically between 4 and 6 m along the horizontal axis.

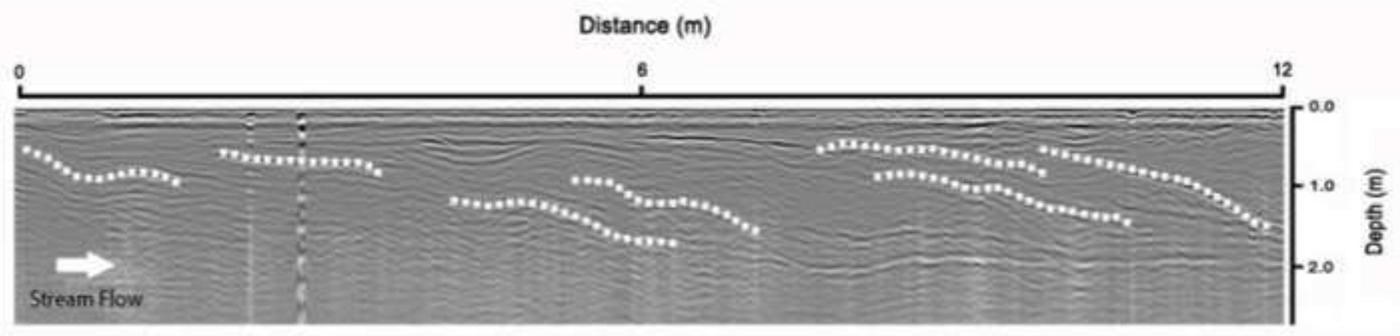


Figure 5.2.2 Radargram from transect 18 just west of the active stream channel.

5.3 Palaeochannels

Beneath Craigieburn Fan are several longitudinal structures which appear to resemble former stream channels (palaeochannels). They have been interpreted as continuous channels rather than stand-alone features because of their continuation through parallel points in two respective radargrams and their perpendicular position to the lakeshore. The largest palaeochannel is located approximately midway across Craigieburn Fan. T14 and T15 which are approximately 20 m apart (Fig. 5.3.2.), both reveal a channel just over 10 m wide and 0.5 m deep at its deepest point. It is approximately 0.6 m beneath the surface and has an irregular bed shape, with a series of humps and hollows. A 0.4 m high and 1 m wide point bar is present part way across channel A (Fig. 5.3.1.). The bed of the channel has been preserved and is composed of horizontal beds of coarse gravel. It has been filled in with sediment which has faint horizontal beds with a very weak reflection signal, meaning it is very fine. It is not an erosional truncation as the beds are mostly continuous across the channel width, conforming to the shape of the channel bed. The beds immediately below the surface and either side of the channel are horizontal and parallel. The channel corresponds to a distinct surface feature; it is in line with a shallow, longitudinal depression in the lakebed, perpendicular to the waterline, where the surface gravels are of smaller size than those of the lakebed surrounding it (Fig. 5.3.3). This may represent a continuation of the palaeochannel as it intersects with the surface topography. The geometry of this palaeochannel is similar to the present surface channel at Craigieburn Stream.

One other palaeochannel was identified on the western half of the fan (see Fig. 5.4.1 in appendix). This is far smaller than the first palaeochannel, being only 5 m wide, less than 0.4 m deep and it lies approximately 0.6 m beneath the surface.

It has a coarse sediment bed, characterized by the ‘hummocky’ shape of radargram surface lines, with an infilling of very fine-grained sediments.

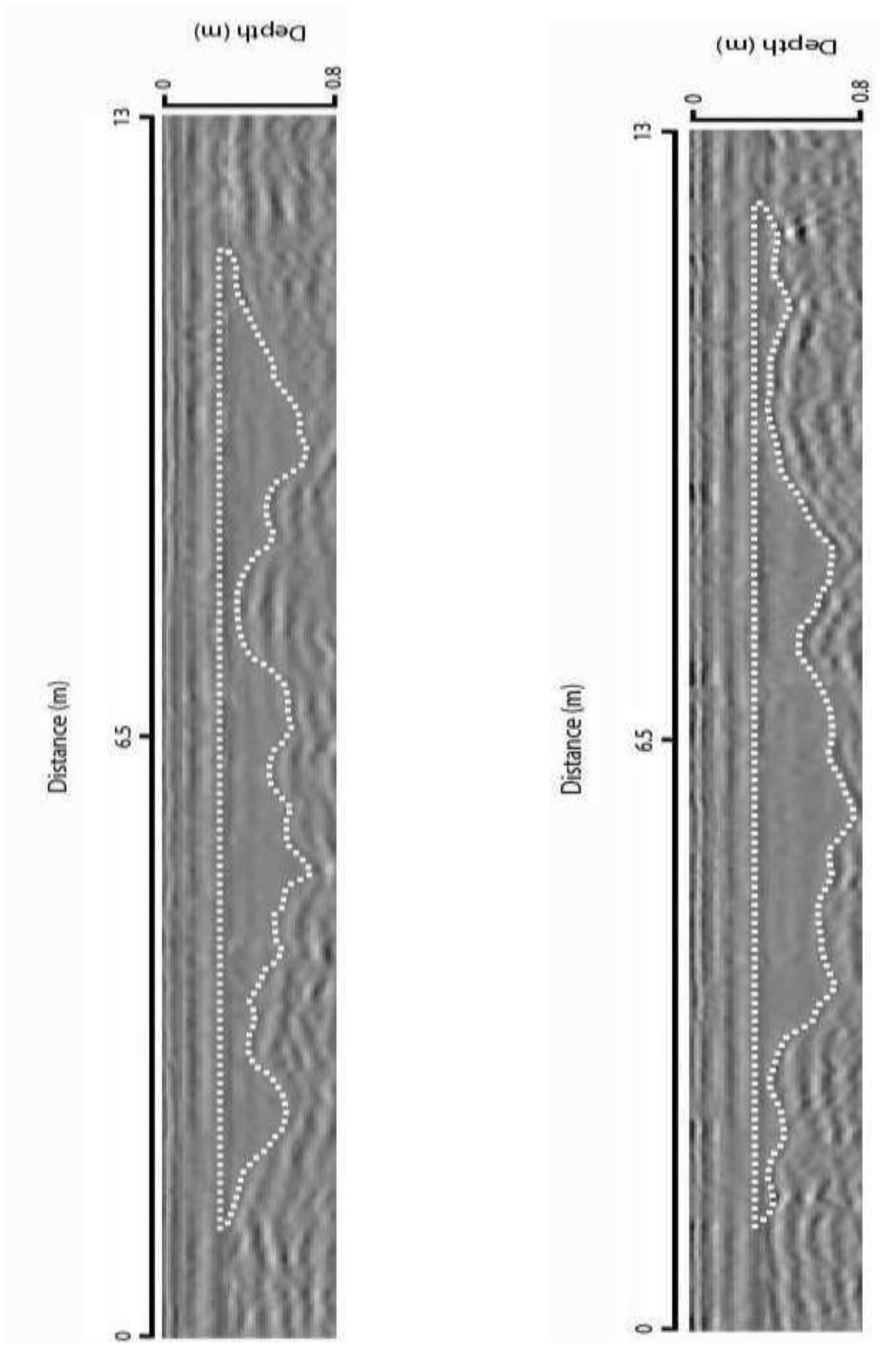


Figure 5.3.2 A palaeochannel was found beneath Craigieburn Fan which appears to extend to the lake.

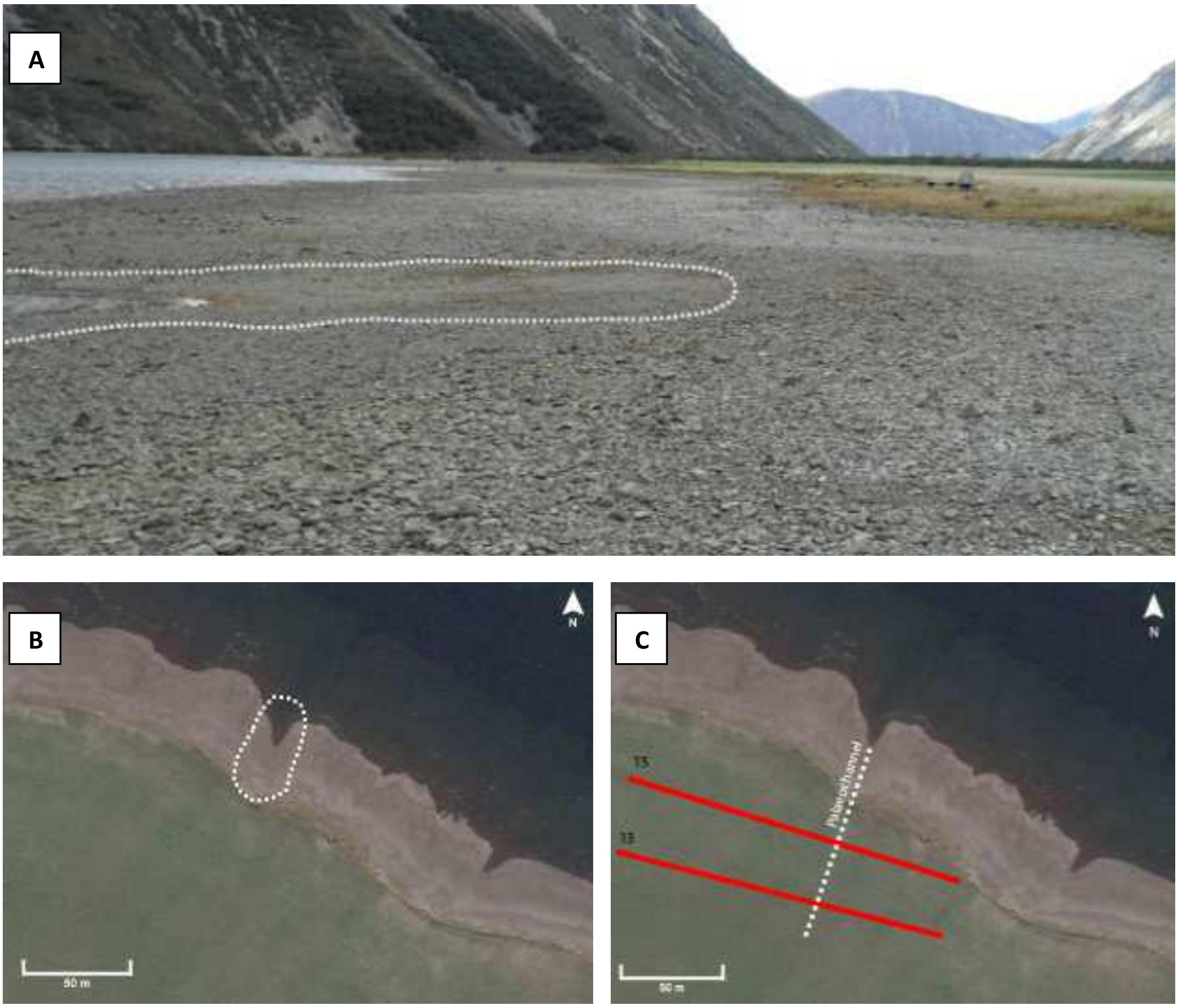


Figure 5.3.3 The surface of the shallow depression in the middle distance is comprised of much smaller sediments than that in the foreground (A). The location of the depression can be seen in (B) and the location of the palaeochannel relative to it in (C).

5.4 Lake-bed sediment and Lacustrine Currents

Observation of surface sediment shows there is a gradual change in sediment composition with distance along the southern lakeshore. At the western end the lakebed is composed mainly of small gravels (0.5-2 cm) (Fig. 5.4.1 A) Further east closer to the stream mouth the lakebed is mainly composed of cobbles (5-8 cm) which are quite angular (Fig. 5.4.1 B). Material from the stream mouth itself is large and is also, in general, more angular than rounded. This suggests there is less influence of fluvial working further away from the current stream mouth. The near-shore lakebed profile differs too; to the west is has a rather horizontal profile

(Fig. 5.4.1 C) whereas at the Craigieburn Stream mouth it is convex (Fig. 5.4.1 D). East of the stream mouth lies the mudflat, which has a surface composed of fine sandy material (Fig. 6.1.1).

Figure 5.4.1 Lakebed grain size gradually increases from west (A) to east (B). Boot for scale.

Small gravel berms were observed on the surface at several locations above the high water mark along the southern shoreline. The largest of these were bare gravel, roughly 0.5 m in width and 0.3 m in height. As well as surface berms, radargrams revealed the presence of what appear to be small berms buried beneath the surface. The closest of these to the lake is approximately 1 m in width 0.5 m in height and the other is the same height but approximately 5 m in width. The beds on the tops of the berms exhibit strong radar reflection. Re-suspension of fine lakebed sediments was evident; these can be seen in Fig. 5.4.2.

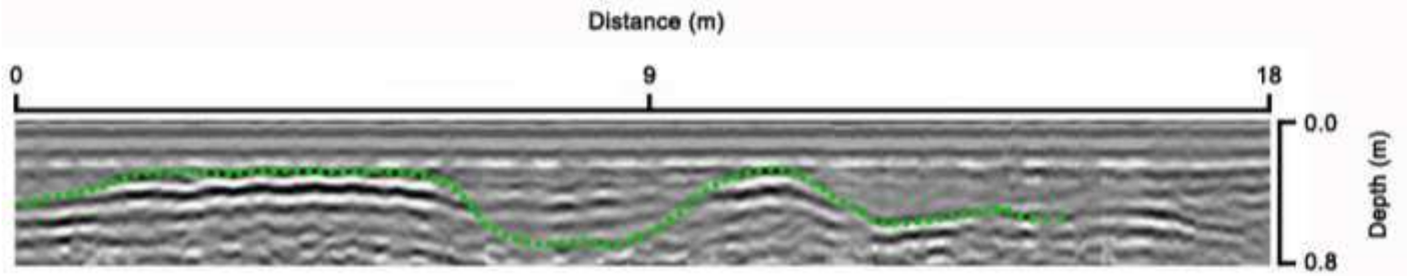


Figure 5.4.2 These structures could be interpreted as berms given their size and proximity to the shoreline (NB not to scale).

There is a noticeable difference between the stirred-up water in the near-shore where sediment has been entrained and the bluer, deeper water further out. Waves were observed during data collection, when a strong breeze was blowing. Small waves were breaking on the southern shore and the near-shore water was discoloured by the re-suspension of bed sediments (Fig. 5.4.3 A). There is also a line of debris that marked the maximum recent extent of the lake level (Fig. 5.4.3 B).

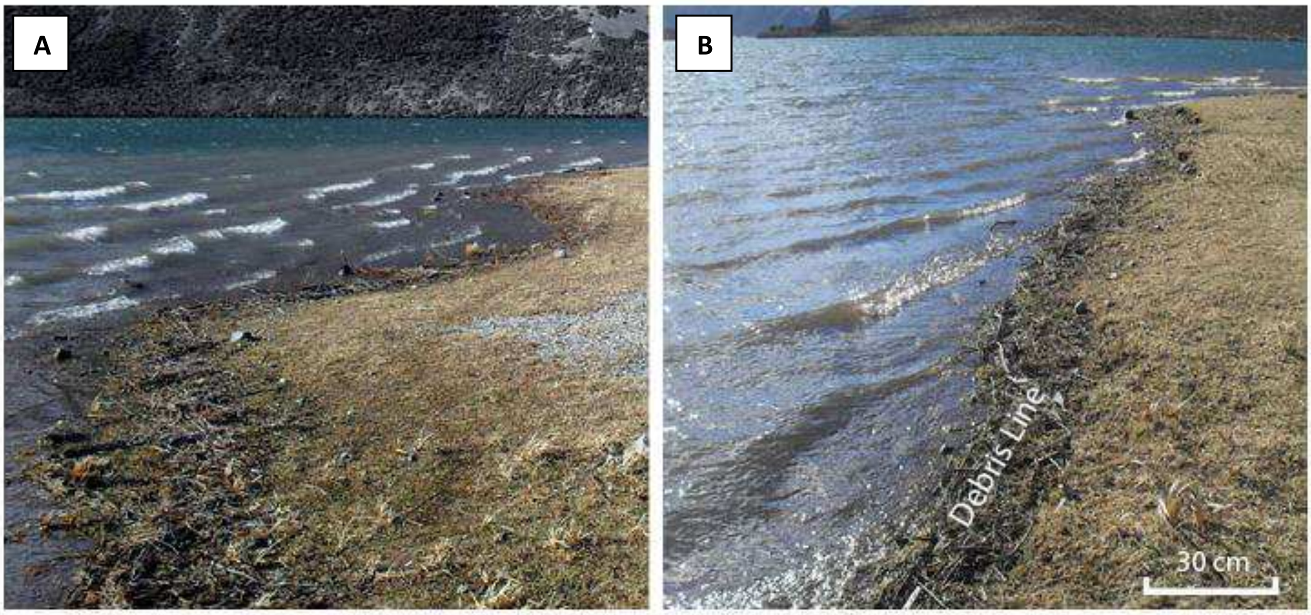


Figure 5.4.3 The water discoloured by sediment re-suspension is evident in A. The debris line indicates the height that the lake level can get to in B.

6 Discussion

Ground-penetrating radar has proved to be an effective tool for imaging the subsurface of the Pearson Lakebed and Craigieburn Fan. GPR facies and subsurface structures typical of fluvial and deltaic systems in paraglacial environments that have been found in similar studies around the world have proved helpful in the interpretation of the features found in this study. Each of the individual features identified has been associated with one or more wider-arching geomorphic processes operating in the landscape. Most of these structures can be assumed to be relatively recent (in a geomorphological sense) as they are all less than 2 m below the surface.

6.1 Area A

The geomorphic formation of Area A has been dominated by lacustrine deposition of fine sediment; although subsurface features provide evidence that hill slope and fluvial processes have also played a role in the evolution of this area. The presence of a fine-grained sedimentary bed in this south-east corner of Lake Pearson suggests that the area has developed in a low energy depositional environment. The surface sediment here is much finer than anywhere else along the southern lakeshore or lakebed, so the process of sedimentation must differ from the rest of the shoreline. The mudflat surface (Fig. 6.1.1) is characterized by patches of mud and gravels with a scattering of seemingly randomly placed cobbles and boulders. This part of the lake can be considered as a backwater, where the lack of currents and turbulence allows fine sediment suspended in the lake water to settle. This tends to indicate that there is little fluvial influence, or else it would be likely that the bed would be influenced, if not dominated by gravel; as one can observe at the Craigieburn Stream mouth. Lake Pearson's north-south orientation in between two mountain ranges means that it is subjected to wind funnelling, particularly from north-west winds. The waves that were observed breaking did so at a slight angle to the lakeshore, which has a northwest-southeast alignment.

Figure 6.1.1 The surface of the mudflat is composed of saturated silt and sand and occasional patches of coarse gravel.

Aerial imagery shows waves being directed into the south east corner. This suggests longshore currents may play a role in redistributing sediment eastwards into the mudflat along the lakeshore. This would help to explain the presence of the fine-grained bed. Fine sediments stirred up by wave action and those delivered to the lake suspended in the Craigieburn Stream during high flows may drift into the mudflat during periods of the year when it is inundated. When lake water slows and becomes less turbulent, sediment falls out of suspension and settles on the bed (Phillips & Nelson, 1981). The radargram from T21 beneath the mudflat shows that this process has been in operation for a while as the subsurface stratigraphy is composed entirely of horizontal bedding planes of fine-grained lacustrine sediment, unbroken for the entire 2 m depth (Fig. 6.1.2).

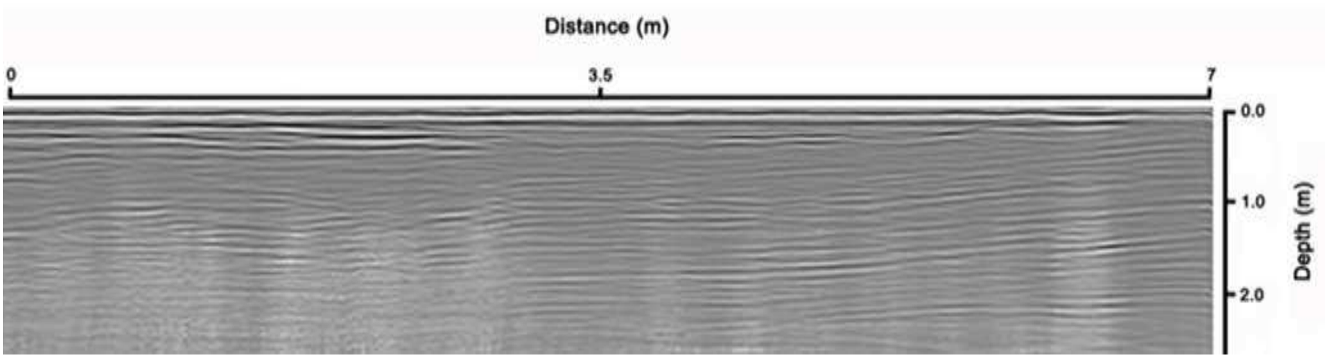


Figure 6.1.2 The subsurface of the mudflat is composed of fine-grained lacustrine sediments.

Figure 6.1.3 Longshore currents transport fine-grained sediment onto the mudflat.

6.2. Area B

There is evidence in Area B that Craigieburn Stream took a different course to what it does today. Deltaic depositional features at a specific depth range beneath the mudflat (Fig. 5.2.1) suggest that Craigieburn Stream deposited sediment here. Foreset bedding occurred when the bed load of Craigieburn Stream met the resistance of stationary Lake Pearson water, lost momentum and was deposited on a submerged delta platform. This delta progressively built outwards as more sediment was deposited, each new sediment rolling over the edge of the deltaic bedform. The presence of foreset bedding and a delta platform means that at some point in the past Craigieburn Stream flowed eastwards towards the base of Purple Hill (Fig. 6.2.1). The limited depth range of foreset beds means that this direction of flow only occurred through a specific period of time. At the time this happened the lake water was at a level higher than at least 0.7 m below the surface. Onlap deposition of fine lacustrine sediment occurred against the delta platform after the stream avulsed to a flow in a northward direction and the lake level rose. This means that the mudflat has been gradually being encroached upon with fluvial gravels as the fan progrades eastwards and that this process will continue until eventually the mudflat is filled in with fluvial gravels and represents something similar to what the rest of the southern shoreline looks like. How this process affects the lake's only outlet, Winding Creek, is yet to be seen. Seasonal fluctuation in the lake level will influence the area at which fluvial deposition occurs. When the lake level is low, surface flows will travel further onto the lakebed before they reach the lake water, meaning fluvial sediments will be deposited on the lakebed.

Figure 6.2.1 Craigieburn Stream may have taken a different path (white) to what it does at present (blue).

Foreset bedding is also present near the Craigieburn Stream mouth beneath T18 (Fig. 5.3.2). These beds dip northward towards the lake, the same direction as Craigieburn Stream flows in present day. Deltaic progradation appears to be more episodical here than beneath the mudflat, as the dipping beds are comprised of coarser sediment too. This means that progradation is probably associated with high energy flood events where large volumes of sediment are brought down the stream. This transect lies only 40 m from the mouth of the current active channel, so coarser subsurface material here reflects the surface sediment and suggests that the current northward direction of stream flow is probably the dominant long-term direction and the current stream mouth probably existed in a similar position at a time in the past when the lake level was 2 m lower than it is today.

6.3 Area C

Craigieburn Fan is composed of coarse gravels characterized by the hummocky facies and sometimes poorly bedded sediment displayed in the radargrams. An intriguing feature of the larger palaeochannel beneath T14 and T15 (Fig. 5.3.2) is the sequence through which the different beds formed. The bedding sequences either side of the channel appear to be part of the same depositional process through the entire depth of the radargram; the beds lie horizontal and parallel to each other and appear to be very similar, if not identical, above and below the channel immediately beside them. This initially suggests the depositional process continued throughout the entire history of the 0.8 m stratigraphy that is visible in the radargram. However, a divergence occurs at the channel lip at 0.3 m depth; below this depth the beds conform to the channel shape and dip down, while those above 0.3 m depth continue above the channel horizontally. This contradicts the idea that these beds were deposited the same way – how does the stream responsible for the formation of the channel fit into this? For the 'same process' theory to be true, the beds below the channel edge would not conform to the channel shape, rather they would have been cut off by the stream flow as it eroded them. Likewise the beds above the channel depth would not continue horizontally above the fine channel infill, as they do. The only explanation is that the same process that went into forming these beds continued in the same fashion before and after the channel formed. The very fine infill of this palaeochannel would have occurred over a long period, being gradually filled with sediment deposited by the margins of successive flood flows. It may also be partly composed of organic material (Selby, 1985).

6.4 Stream Avulsion

Craigieburn Fan is composed of fluvial sediments originating from higher elevations further up the Craigieburn catchment. Paraglacial fan progradation northwards is responsible for the formation of Lake Pearson (Gage, 1959) and this process is still in operation as Craigieburn Stream continues to transport sediment onto and across the fan. Alluvial river channels unrestrained by their surrounding topography are highly mobile and avulsion across a fan is primarily controlled by sediment supply and stream power (Davies & McSaveney, 2008; Wickert *et al* 2013). Both Gage's 1959 and Irwin's 1970 maps show Craigieburn Stream to follow roughly the same course as it does today, although this has little significance as a stream flowing across a fan, particularly a large fan, may remain stationary for decades at a time (Church, 2002; Davies & McSaveney, 2008).

Deltaic depositional bedding beneath the mudflat in Area B (Fig. 5.3.1) provides physical evidence that Craigieburn Stream has avulsed in the past. The palaeochannels in Area C (Figs. 5.3.1 and 5.3.2) also provide possible physical evidence that avulsed to the western side of Craigieburn Fan, but evidence of whether or not these are former paths of Craigieburn Stream would require more transect lines further up the fan to map their full extent. There is some evidence for avulsion on the surface of the fan with the identification of at least one inactive channel, albeit significantly modified, through examination of aerial imagery. This may be a former path of Craigieburn Stream, considering it seems to continue along the same line the Craigieburn takes before it turns suddenly to the east near the head of the fan. It is also possible that this channel is that of a separate ephemeral stream that flowed on the fan from the western slopes. Craigieburn Fan is now completely pastured and its surface has probably been significantly modified since settlers arrived in the area in the late 19th century. While the geomorphic origin of many of the subsurface features can be speculated upon, it would be wise not to discount the influence anthropogenic activity may have had on the landscape over this time. Construction of State Highway 73 in the 1930s probably involved the rerouting or filling in of ephemeral stream channels that ran down the slopes and onto the western side of the fan. Ephemeral streams are now no longer able to continue their natural path downslope across the fan and instead surface runoff is directed conveniently into a road-side ditch that flows through a pipe beneath the road. It is also possible that the palaeochannels identified do not continue along the entire length of the fan, but instead represent the drainage channels of former springs that used to emerge at points across the fan where the water table met the land surface. This may help to explain why both the palaeochannels discovered lie at the same depth below the surface.

Anthropogenic change in land use through activities like farming generally only alters soil erosion rather than bedrock erosion, and thus does not have much of an effect on long-term, i.e. geological, erosion and sediment delivery (Davies & McSaveney, 2008). Soil erosion usually only delivers fine material to streams, too fine to cause significant alteration to stream morphology or trigger stream avulsion. On a large fan a considerable increase in the volume of coarse sediment is required to cause major changes in stream morphology. Alteration of vegetation is likely to be more influential on sediment delivery rates in large, low-gradient catchments than in small, steep ones, but on the contrary, the former are associated with correspondingly large, low gradient fans, which respond slowly to even large changes in the sediment input rate. Therefore changes in land use are likely to be less significant than tectonic or climatic changes in altering large fan morphology. This leads to the idea that large sediment pulses from events such as heavy rain and seismic events triggering mass wasting are largely responsible for sediment delivery, avulsion and ultimately the progradation of Craigieburn Fan. This may not have always been the case in the past, when the fan did not extend as far north as it does today and the gradient was steeper, increasing stream power and allowing more sediment to be shifted. The highly active tectonic setting Lake Pearson resides in means it is susceptible to frequent earthquakes of high shaking intensity. It lies a mere 50 km east of the Alpine Fault, which is capable of generating earthquakes greater than M_W 8 and has experienced major ruptures four times at regular intervals over the past thousand years, the last time in 1717 (Wells & Goff, 2006). Porters Pass Fault is another fault lying only 20 km further east. Earthquakes are powerful triggers for mass wasting in steep topography. Co-seismic mass wasting increases the sediment flux in drainage catchments (Davies & McSaveney, 2008). On the West Coast, formation of some coastal landforms has been attributed to sediment delivery from co-seismic mass wasting triggered by Alpine Fault ruptures. The dates of past ruptures have been closely associated with the formation of beach ridges at Haast. It takes many years for these sediments to be transported out of the catchment. Following the M_W 7.8 Murchison earthquake in 1929, the majority of sediment had moved to the coast within a decade (Wells & Goff, 2006). Goff and McFadgen (2005) proposed in the same event on the eastern South Island sediment would take as long as 4,000 years to make its way from the Southern Alps to the coast, due to the longer distance to the coast, gentler gradient and lower precipitation available to shift sediment. Localised redistribution of sediment from source to sink in a small catchment like Craigieburn Stream has a much smaller distance to occur over, however, its delivery onto the fan and subsequent progradation is still limited by the transporting power of streams.

Craigieburn Stream has a catchment area of approximately 24 km^2 and drains steep forested valleys. This is not large in comparison with those of nearby alpine stream and river catchments and the Craigieburn is sub-horizontal. This means a prolonged period of steady rain (to saturate the ground) or a localized high intensity downpour is likely to be required for generation of high flows or flood flows capable of shifting large volumes of material onto and along the fan. If aggradation occurs at any section along stream length, the resulting base level change will alter the stream gradient and increase its velocity and therefore its sediment transporting capacity. This may result in the incision of previously aggraded sections. Downstream movement of sediment occurs in phases as a stream alternates between aggradation and incision, gradually shifting sediment downstream (Selby, 1985). Fan progradation occurs episodically when sediment reaches the base of the fan, in accordance with the occurrence of heavy rain and periods of high sedimentation that follow seismic events. The poor bedding at the Craigieburn Stream mouth suggests that flood events are responsible for the majority of sorting. Though the stream remains dry for most of the year, high flows must occur relatively frequently as the channel has remained clear of encroachment from vegetation.

The riparian vegetation on either side of the active Craigieburn channel may restrict its mobility. Experiments have shown that vegetation in channel bar systems leads to huge reductions in channel bar migration rates. This is attributed to the strengthening effect vegetation has on banks, which reduces eroding sediment from vegetated banks and the funnelling effect vegetation has, which reduces channel width (Wickert *et al*, 2013). Establishment of plants on channel edges and point bar systems acts to stabilize flood plain sediments and generate a positive feedback cycle where further deposition of fine-grained sediment suspended in flood water is promoted due to the slowing effect they have on the flow (Mouw *et al*, 2008). Without historic aerial imagery to see the former path of Craigieburn Stream, it is hard to say whether anthropogenic vegetation has reduced the rate of avulsion, although, it is likely that the vegetation that exists on the slopes probably also grew on Craigieburn Fan prior to European settlement and conversion of the fan to pasture.

6.5 Slope Stability

It is widely accepted that vegetation stabilizes steep hill slopes and strengthens them from erosion by mass movements (Selby, 1985; Greenwood *et al*, 2004). The eastern mountains of the Southern Alps are characterized by tussocklands and scrublands and mass wasting and slope deposits are characterizing features of the landscape. Through a combination of anthropogenic and natural causes, much of the beech forest that would have naturally clothed the land is no longer in place. Vegetation plays a significant role in maintaining soil cohesion and hill slope stability through root arming and it also influences hill slope hydrology (Greenwood *et al*, 2004). Trees help to intercept precipitation and reduce surface splash erosion. Leaf litter and plants on the ground slow the velocity of surface runoff and reduce its ability to entrain sediment and cause erosion. Root growth between potential failure surfaces helps to bind them together and remove soil moisture, reducing the volume of water held in pores, as well as pore pressure (Selby, 1985). Above the tree line on the mountains surrounding Lake Pearson, thousands of years of physical, chemical and freeze-thaw weathering on the exposed bedrock peaks has resulted in the upper slopes being mantled in a thick layer of shattered rock. Over time this has its way down to the valley floor through further rockfalls, landslides and debris flows to form thick colluvium deposits. Removal of vegetation through anthropogenic or natural causes can lead to extensive erosion below the tree line and can create a positive feedback cycle; as vegetation is removed from the slope, the slope is eroded more easily. Topsoil is stripped, reducing its ability to support vegetation growth, making re-vegetation of the slope very difficult (Cochrane & Acharya, 2011). The steeper upper slopes of Purple Hill are heavily eroded however the lower slopes are quite well vegetated with scrub and do not bear much evidence of slope failure, although radargrams from the mudflat reveal some of the erosional history of the hill slope. There is a significant difference in the subsurface bedding between the two transects on the mudflat and this corresponds directly to the vegetation cover present on the respective areas of Purple Hill slope each transect. The contrasting subsurface structures can be used to show the important role vegetation plays in stabilizing hill slopes.

Figure 6.5.1 Very little beech forest remains on the high slopes of Mt Manson, resulting in accelerated erosion (photo Richard Allen).

T20 reveals a cross section of a slope deposit approximately 1 m below the surface of the mudflat, right against the base of Purple Hill (Fig. 5.1.2). The structure is composed of large, poorly-bedded material, suggesting it is similar to the material lying loose on the Purple Hill slope immediately above. The latter slope is a 30 m by 30 m area devoid of vegetation that resembles a rockslide deposit and is composed of loose cobbles, gravels and boulders. The entire Purple Hill slope is very steep, rising 750 m vertically in only 1000 m horizontal distance (an angle of approximately 37°). It has a concave shape, with steepness increasing with altitude. Scrubby vegetation grows for a few hundred metres directly above the bare slope, but above this lies the lobe of a rock avalanche deposit, emanating from a chute of loose scree between crumbling bedrock outcrops 1000 m above the valley floor. The lack of vegetation on this part of the slope above the lakebed here has resulted in the rocky debris identified in the radargram, being deposited on the lakebed. Whether this deposit occurred in one event or over successive events is uncertain.

T21 is on the mudflat, 80 m south of T20 but the subsurface sediment composition is completely different. Beneath T21 the subsurface is composed entirely of horizontal uniform beds of fine-grained lacustrine sediment, with no influence of hill slope sediment deposits (Fig. 6.5.2). The role vegetation plays in hill slope stability becomes apparent when the vegetation cover on the hill slope immediately above this transect is considered. A stand of beech trees grows on the slope here, presumably a remnant of the vegetation that used to cover the entire hill slope. The trees have protected the slope from being eroded by sheet wash and surface runoff and also acting as a buffer to rocks and cobbles from further upslope rolling onto the mudflat. As a result there has been no input of sediment from the hill slope above.

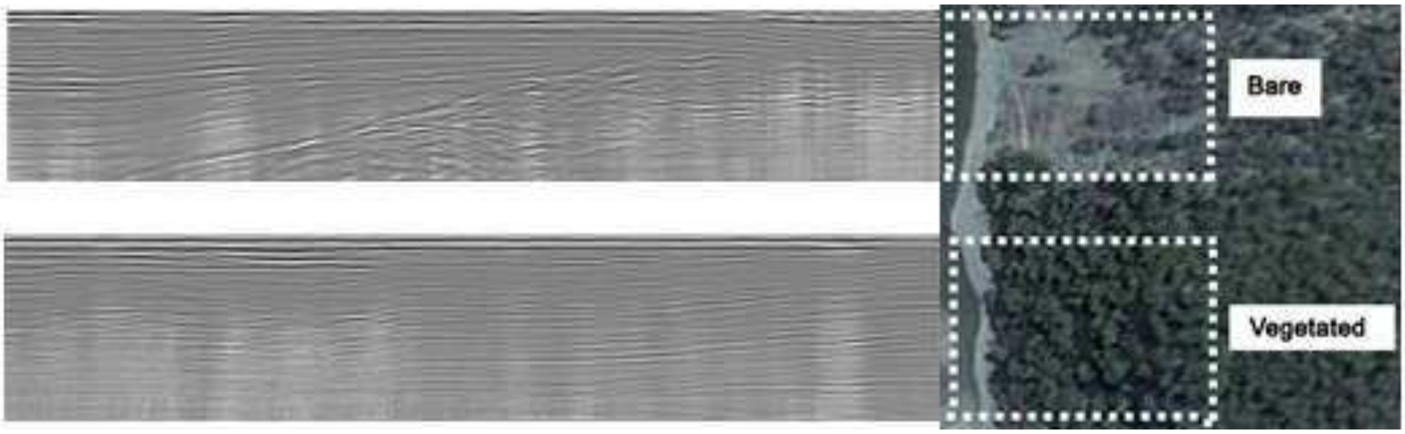


Figure 6.5.2 Vegetation appears to play a significant role in stabilizing hill slopes.

The sequence of sediment deposition can be surmised through the nature of the cross bedding present. Younger sediment appears at a shallower depth in the sequence. Onlap deposition of fine lacustrine sediment on top of the hill slope deposit indicates that it was laid down earlier. For fine sediment to be deposited in this fashion, it is likely that it occurred in a low-energy aqueous environment. Onlap deposition is typical of a lake basin filling with water over time (Abbott *et al*, 2000). This would imply that the slope deposit was in position at a time when the lake was at least 2 m below what it is now. Lacustrine sediment beds were progressively deposited over time as the lake level rose.

6.6 Anthropogenic Implications

In an anthropogenic context, some of these findings may have implications for further development in the area. Many high country areas that were previously thought to be too inhospitable and inaccessible for agriculture and viticulture are now being considered for new development - one of these areas is the Cass Basin. In 2012 Environment Canterbury recently received a proposal to abstract water from the Cass River to irrigate 554 ha of land on Grasmere Station for intensified farm production. This has implications for the quality local lakes and streams.

Groundwater pollution is one of the key environmental issues New Zealand is facing at the moment. The underlying sediment composition of high country areas can make them vulnerable to the effects of activities on the land surface, due to the ease at which pollutants can leach to groundwater. Coarse alluvial gravels are highly permeable and allow high rates of throughflow (Selby, 1985). Groundwater flow was observed to be an integral component of inflow to Lake Pearson. Increasing the amount of irrigation for farming also increases the risk of pollution from surface runoff. The Craigieburn Fan has been shown to be composed of coarse gravels and contain more than one palaeochannel not far below the surface. Palaeochannels are of particular significance for groundwater pollution, as they can act as conduits for faster rates of through-low (Revil *et al*, 2005; Mastrocicco *et al*, 2011). This means they can act preferential pathways to the lake for groundwater pollutants.

Increased farming activity is likely to have two major effects; firstly, it will result in a greater presence of nutrients and bacteria from livestock effluent, which is likely to make its way to the lake through groundwater leaching or surface runoff. Over-enrichment of nitrogen and phosphorus is the fundamental cause of eutrophication. Lake Pearson is currently in a mesotrophic state, changing from an oligotrophic state 10 years ago. Nitrogen and phosphorus levels have been increasing in the lake over recent years and this is thought to be caused intensified farm production on its fringes (Environment Canterbury, 2007).

Secondly, inflow to the lake will be reduced if water is abstracted from Craigieburn Stream, or groundwater at either the northern or southern end of the lake. Increased demand for water around the lake may reduce groundwater recharge which Lake Pearson is clearly dependent on. Sustained periods of low rainfall have caused the lake's water level to drop by a metre or more in the past (Environment Canterbury, 2007) and this was also observed during field collection.

The Maori name for Lake Pearson is Moana Rua, which translates to 'two lakes'. This suggests that a low lake level is nothing new; when Maori discovered Lake Pearson centuries ago the water must have been so low that the bed was exposed at the narrow midpoint, dividing the lake into separate northern and southern lakes. A reduction in lake capacity will affect the lake's ability to deal with extra pollutants. It could make the shallow sections more susceptible to heating during summer, which will help to facilitate algal growth. Lake Pearson is a wildlife refuge and a popular location for camping and recreational pursuits. Any degradation in local surface water quality will significantly reduce the aesthetic appeal of the lake and surrounds and may also threaten its ability to provide for these uses.

7 Conclusion

This research aimed to examine the sedimentary depositional structures present beneath southern Lake Pearson and Craigieburn Fan and interpret the geomorphic processes responsible for their formation. GPR imagery proved to be a very useful tool for this. Radargrams have allowed identification of depositional structures of fluvial, lacustrine and hill slope origin. The one or more geomorphic processes and the interaction between each of these processes in the formation these structures, have been described. Evidence of Craigieburn Stream's avulsion was found through identification of palaeochannels and deltaic depositional bedding. There are apparent links between surface features and underlying structures, with a strong linkage found beneath subsurface hill slope deposits and the cover of surface vegetation on the hill slope directly above. This suggests vegetation is a strong determinant of hill slope stability in the area. Onlapping sediment sequences reflect the depositional structures associated with lake level rise. As paraglacial landscapes are so dynamic, observation of present landforms offers only a tiny snapshot in time amid a landscape which, in a geomorphological sense, is constantly changing. This research certainly forms the basis for further, more in depth investigation in the area, possibly with the use of historic aerial imagery or absolute dating techniques to assess the rate at which these processes are operating. It also advocates the use of GPR imagery for analysis of similar landscapes. This may be for the benefit of further anthropogenic development of high country areas, through managing the landscape in a way that takes into consideration the way natural processes have operated in the past and will continue to operate in the future.

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