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The Forces that Shape the Upper Waimakariri Catchment

RESEARCH PROJECT

BY JACKSON BABE, HANNAH THOMPSON, WITCH-HAZEL MCALISTER AND PHOEBE MCINTOSH

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Abstract

The New Zealand mountainous environment carries the unmistakable legacy of the ice age. Glaciers have been one of the most powerful forces which shape the land and are imperative to the story of the South Island. In this report, the role of glaciers in the Upper Waimakariri was explored. Geographic Information Systems (GIS) were employed to create visualisations of the land-forming processes and geomorphological aspects of glaciers. Visualisations of glacial extents in the late Otiran and early Holocene glaciation periods were created to show the ebb and flow of glaciers across time, as they respond to climate fluctuations. This movement across the landscape is responsible for the distinct features which help define this landscape. Alongside corresponding information, these visualisations were presented on a storyboard to tell the story of the Upper Waimakariri. An essential component of this was ensuring effective visual communication, in order to produce a widely applicable and comprehensible resource. The nature of this project meant that the synthesis of prior, relevant literature was the primary source of information. Analysing glaciation within the Upper Waimakariri has helped to contextualise and understand the role of glaciers in sculpting the New Zealand landscape.

Tangata Whenua

This report acknowledges Māori as tangata whenua and Te Tiriti o Waitangi (Treaty partners) in Aotearoa. We acknoledge Ngāi Tahu, namely Ngāi Tūāhuriri Rūnanga, as mana whenua of the Upper Waimakariri whenua (land). We open this report with a Ngāi Tahu Whakataukī (proverb) to recognize the importance of preserving Mātauranga and whenua for future generations;

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"Mō tātou, ā, mō kā uri ā muri ake nei"

"For us and our children after us"

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Introduction

A landscape tells the story of its past through its features and forms. The earth's surface is dynamic and ever-changing. On shorter timescales, this is driven by violent actions of natural events (water, wind) and volcanic activity which can cause dramatic changes, some acting with such strength that prior landscape features cease to exist (Bruce at al., 1999). Fluctuations of climate can drive glacial advance and retreat, bringing about erosional forces that shape and carve the landscape around these large masses (Bruce at al., 1999; De Pascale et al., 2016). On longer timescales, the movement of tectonic plates reconstruct entire oceans and continents (Bruce at al., 1999). Each of these forces act to change the face of the earth. Evidence of these are preserved within the landforms of an area, which come together to tell the story of the landscape.

New Zealand is a geologically active area, situated on the boundary between the Indo-Australian and Pacific plates (De Pascale et al., 2016). Much of the New Zealand landscape has the distinct mark of tectonic activity, including the distinct, rugged coastlines, the flow of waterways, volcanic activity, hot springs which have been formed over long timescales (De Pascale et al., 2016). Often characteristic for New Zealand is the uplift of mountains. The subduction of the Pacific plate under the Australian plate defines the Alpine Fault, which lies under the South Island (Adams, 1980; Heads, 1998). This uplift of bedrock forms the Southern Alps - the large mountain range which extends the length of the South Island. The continued tectonic movement means this mountain range continues to rise, regenerated from the earth's deep crust, as fast as it deforms through erosional processes like rivers and glaciers which transport material (Adams, 1980; Heads, 1998). Thus, uplift and denudation have modified the geomorphological expression of the New Zealand landscape (James et al., 2019).

The legacy of the ice age is evident within the New Zealand mountainous landscape. Glaciers have been one of the most powerful forces in shaping the land and have been imperative to the story of landscapes (McSaveney, 2009). New Zealand acts as host to numerous land-terminating, alpine mountain glaciers, totally to 2900 glaciers (Baumann et al., 2021). Most of which are located within the Southern Alps, along the Main Divide (Baumann et al., 2021). A glacier both moulds itself to the surrounding shape of the landscape and shapes the land as it creeps back and forth in ne valley (Hambrey, 1994; Oerlemans, 2001).

Considering this, the project aims to answer the question:

"What do geomorphological features reveal about the roles of glaciers in shaping the Waimakariri basin, and how can the significance of these features and landscapes be communicated to the general public?"

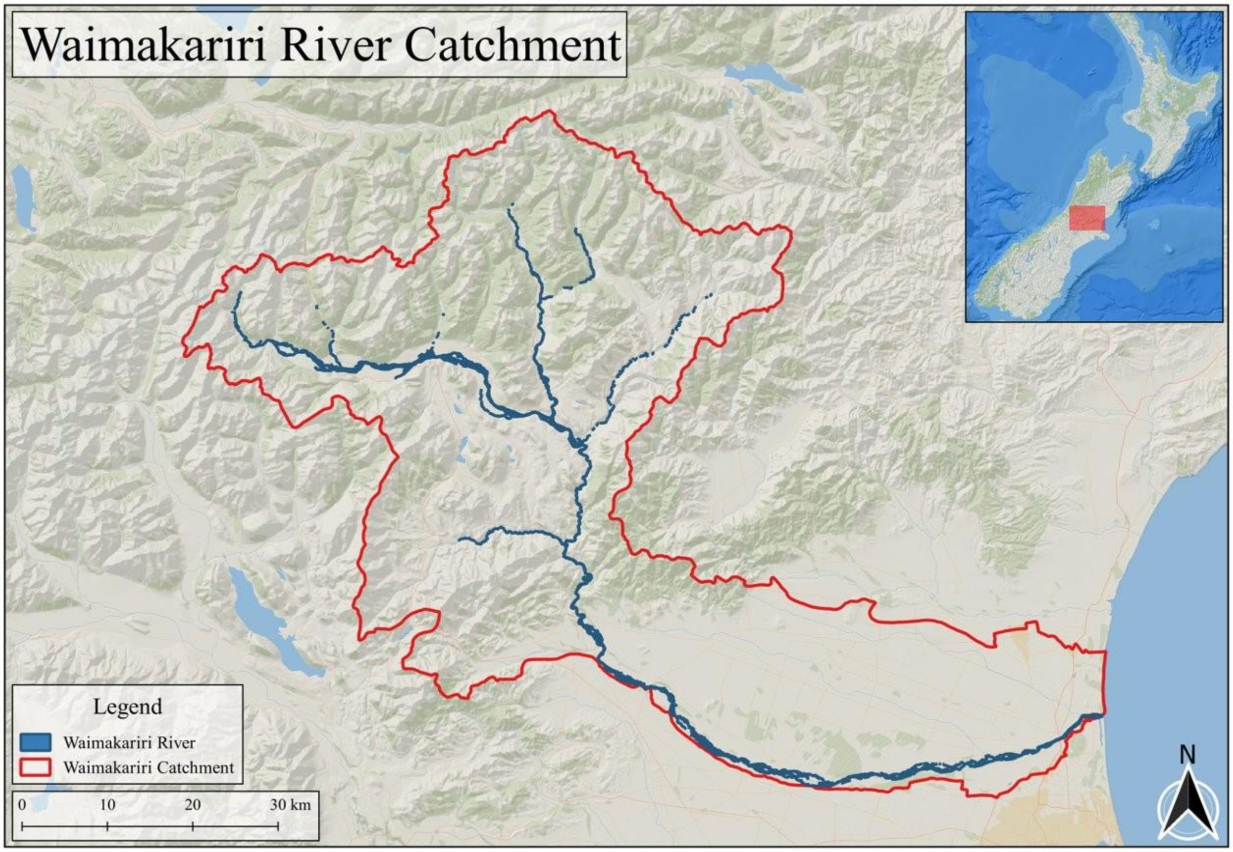
This report will present the findings in an engaging manner to provide an accessible resource on the glacial history of the Upper Waimakariri. Visualisations are an important component to this project and will be presented in a storyboard to depict the narrative of glaciation and relevant processes that helped shape the Waimakariri. The process for creating this report included literature review and synthesis, geospatial analysis, expert consultation and in-class workshops. The Programs used in geospatial analysis included: ArcPro, ArcScene, Cesium, MOVE Suite (PETEX) & Qgis. These programs analysed data sourced from GNS science / Te pū ao database in accordance with pre-existing literature. The resources will be publicly available online through the University of Canterbury and Lucas Associates.

Location

The Upper Waimakariri catchment encompasses the head of the Waimakariri river as well as the Poulter River, situated between Arthurs Pass National Park and the Waimakariri River to the north, Torlesse Range and the Torlesse Tussock lands Park to the east and south, and the Craigieburn Range and Conservation Park to the west, of the Southern Alps, in Northern Canterbury, New Zealand (Figure 1) (Snoyink, 2015). The catchment passes through Craigieburn, towards Otarama to the East. The Upper Waimakariri is a highly dynamic intermontane environment situated within significant mountain ranges, which encompasses a prominent glacial-formed basin, scree slopes, gorges, alluvial fans, tarns, kettles, lakes, and whose vegetation and watersheds have been defined by historic processes (Gage, 1958).

Figure 1.

The Waimakariri Catchment Shown with the Waimakariri River Highlighting the Projects Area of Interest.



Note. Adapted from *LINZ Data Service,* by Land Information New Zealand | Toitū Te Wenua, n.d. (https://data.linz.govt.nz/).

Current Land Use

The Waimakariri basin has economic, environmental, and social importance. Its boundary encompasses the highly productive agricultural patchwork in the Canterbury Plains and extends up to the alpine highlands (Environment Canterbury, 2022). These intensive farmlands are scattered along the banks of the Waimakariri River (Environment Canterbury, 2022). A dominant feature of this landscape, the river holds an alpine braided river ecosystem whose headwaters begin to the west of Arthur's pass, and travels across the Canterbury plains to the Pacific Ocean and is primarily fed by glacier runoff and snow melt (Snoyink, 2015). Braided rivers are a globally rare feature within an ecosystem and houses a plethora of endangered and rare species, and act as a host of biodiversity hotspots (Gray et al., 2006). This area is encompassed by the Cass Ecological District, which recognises that there are at least sixteen vegetation groups within this area including: tussocklands, shrubland (subalpine and upper montane), matagouri, cushion bogs, manuka forest and mountain beech forests, as well as wetland and lake communities (McEwen, 1987). For this reason, this area encompasses many conservations areas (Table 1).

Table 1

DOC Public Conservation Areas land classification

	Status
Arthurs Pass National Park	National Park
Craigieburn Forest Park	Conservation Area
Bealey/Waimakariri Riverbed	Conservation Area
Bealey Spur	Conservation Area
Mt Horrible	Conservation Area
Waimakariri Riverbed Paddys Bend	Conservation area
Cora Lynn Gravel Reserve	Reserve
Hawdon Flats Reserve	Reserve, proposed addition to Arthurs Pass National Park
Corner Knob & Goldney Hill reserve	Reserve, Government Purpose
Castle Hill / Kura Tawhiti	Reserve and Conservation area

Note: Obtained from Koordinates. (2017). *DOC Public Conservation Areas* https://koordinates.com/layer/754-doc-public-conservation-areas/)

The unique biodiversity and natural landscapes within this area has meant it is of significant important to a variety of conservation and recreational groups. Within the catchment, Department of Conservation (DOC) maintains six active huts and two historic huts, the Canterbury Mountaineering Club maintains the Barker hut as well as the Wilderness lodge in Arthur's pass (Department of Conservation, n.d.-a; Harriss, n.d.). In the catchment area above the Bealey bridge, DOC is undertaking pest management or elimination of apple, gorse, scotch broom, sweet briar and Russell lupin. Notable pest management below the Bealey bridge includes Gorse containment, willow control and Russel lupin containment (Boffa Miskell Limited, 2022).

The basin provides access to the heights of the Kā Tiritiri o te Moana (Southern Alps) and consequently acts as an important travel route for people. This includes traffic highways such as State Highway 73, which is considered a key transport route of major importance by providing inter-regional access to the west coast. (Environment Canterbury, 2016).

Importance to Tangata Whenua

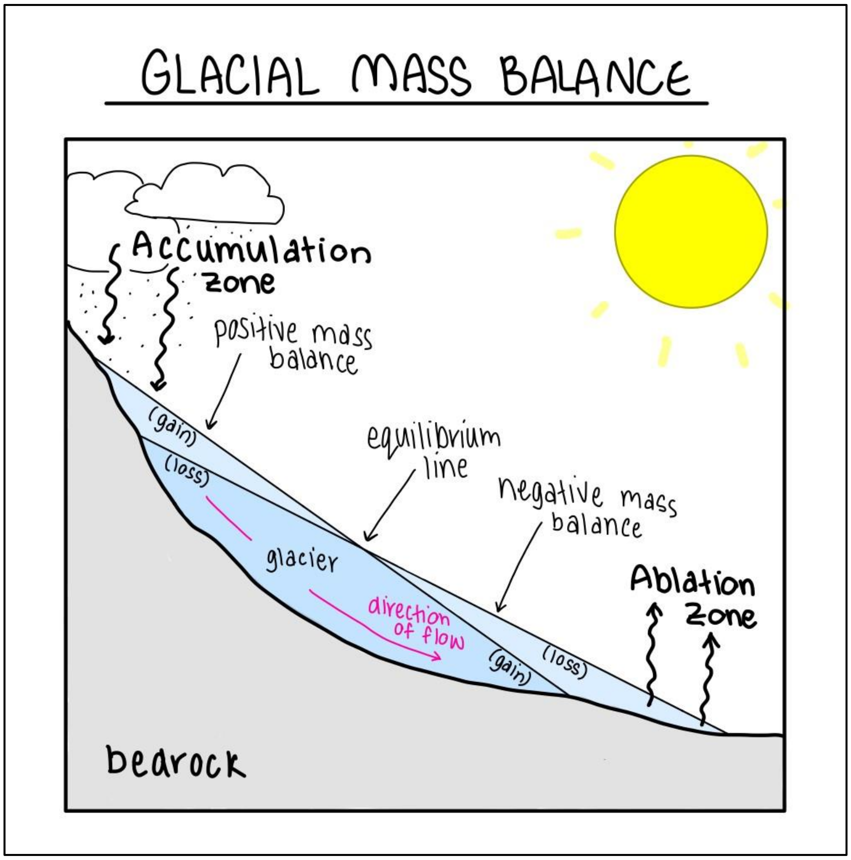
Tangata Whenua, meaning the people of the land, is a foundational in te ao Māori and recognises how all things living and non-living are interrelated (Ministry for the Environment — Manatū Mō Te Taiao, 2021). In this way, Whenua intrinsically links people to place as seen in the whakataukī: "Ko au te whenua, ko te whenua, ko au" ("I am the land, and the land is me"). Whenua guides important facets of te ao Māori, including Hauora (holistic wellbeing) and Whakapapa (lineage or identity) (Ministry for the Environment — Manatū Mō Te Taiao, 2021). The Waimakariri, meaning 'cold rushing water' is a culturally significant region for Ngāi Tahu iwi, namely Ngāi Tūāhuriri hapū. The Upper Waimakariri whenua contains publicly acknowledged areas of significance to mana whenua sites in Te Rūnanga o Ngāi Tahu (Ngāi Tahu Atlas) include Ōpōrea (Lake Pearson), Ōpōreaiti (Lake Grasmere), and Kura Tawhiti (Castle hill). The Waimakariri valley also provided access between Te Tai Poutini (West coast) and Waitaha (Canterbury). Ngāi Tahu used this to obtain pounamu and source mahinga kai (food resources) (Goodall et al., 1990; Kapelle, 2001). The Waimakariri was used as an access way to mahinga kai which is still relevant as Ngāi Tahu Farming (n.d.) note significant agricultural investment in Waimakariri, managing thirteen farms with a collective area of 6,757 hectares (Te Rūnanga o Ngāi Tahu, n.d.).

Glacial Fluctuations

Glaciers are large, thick masses of accumulated, perennial ice which are constantly deforming, and moving across the landscape under the influence of their own weight (Fitzharris et al., 1999; Oerlemans, 2001). The gradual accumulation and compression of snow begins the processes of metamorphism, whereby the snow transitions to glacial ice (Fitzharris et al., 1999; Hambrey, 1994). A glacier flows down the slope as it accumulates ice in its upper portion and ablates in its lower portions (Fitzharris et al., 1999). The input into a glacier system is precipitation (snow, ice, freezing rain), and wind-blown snow (Anderson & Mackintosh, 2012). The output of a glacier consists of melting, sublimation, and iceberg calving at the ablation zone, at the terminus of the glacier (Anderson & Mackintosh, 2012). When the rate of accumulation is equal to the rate of ablation, it has entered a 'steady-state' known as equilibrium and will not change in shape or size (Anderson & Mackintosh, 2012). The altitude at which this occurs is known as the 'equilibrium line altitude (or ELA) (Chinn, 1995; Porter, 1975). Changes in the accumulation and ablation rates of a glacier change the position of the ELA and drives advance and retreat (Chinn, 1995). The difference between accumulation and ablation is known as the mass balance of glacier (Figure 2) (Fitzharris et al., 1999; Porter, 1975). If the accumulation (ablation) is greater than ablation (accumulation), the glacier has a positive (negative) mass balance, the ELA will decrease (increase) in elevation, and the glacier will advance (retreat (Porter, 1975). The rate at which these changes occur, the flow, motion and velocity of a glacier, is primarily controlled by the glacier mass balance and the geometry of the glacier (as well as ice properties, valley geometry, bedrock conditions, sub-glacier hydrology, terminal environment) (Anderson & Mackintosh, 2006; Purdie at al., 2011).

Figure 2

Glacial Mass Balance

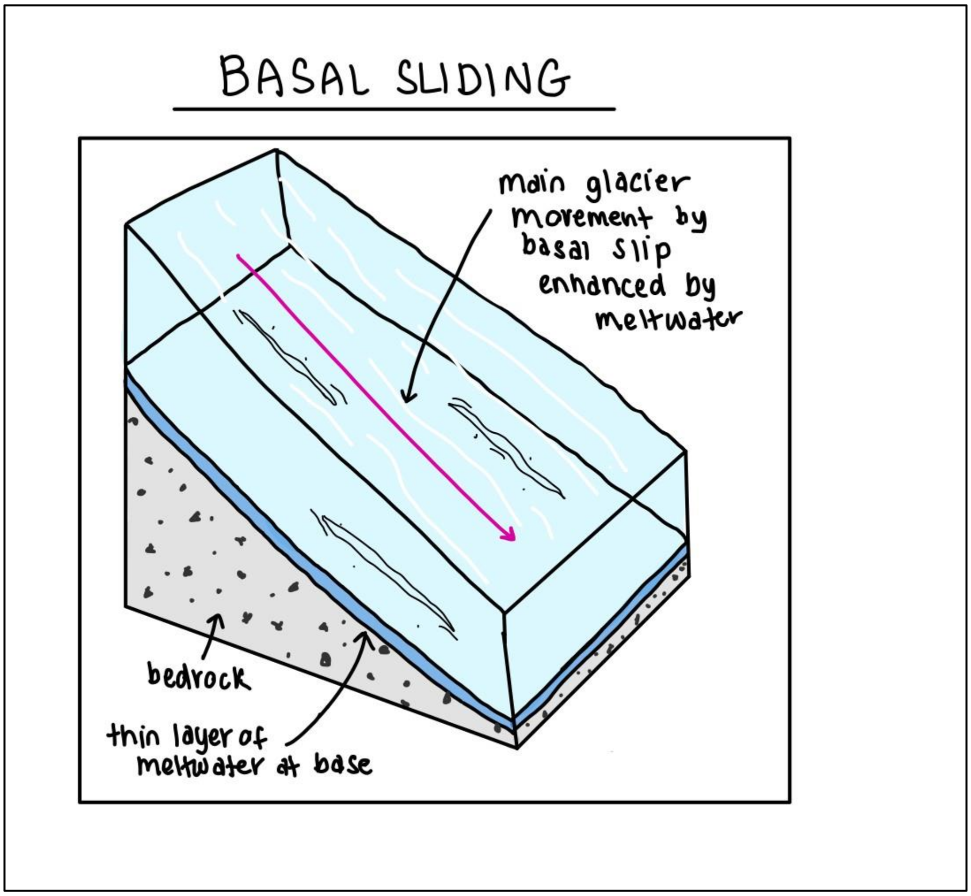


Note. The accumulation zone is at the top of the glacier and is where precipitation occurs. In this area, there are more gains than losses which creates a positive mass balance. The ablation zone is where melting occurs and has greater losses than gain. This area has a negative mass balance. The equilibrium line is where the gains equal the losses.

When glaciers move downslope, there are resistive forces which mean the glacier will undergo internal deformation and basal sliding (Alexander et al., 2011). Internal ice deformation is when the internal ice crystals align themselves with the direction of movement and can slide past one another (Cuffey & Paterson, 2010). The fastest movement from this occurs at the surface of the glacier, where the resistive stresses are the lowest (Cuffey & Paterson, 2010). The ice will deform due to being plastic but can become brittle if thresholds are exceeded to create features such as crevasses (Cuffey & Paterson, 2010). Of importance to the movement of New Zealand temperature glaciers is basal sliding (Alexander et al., 2011; Purdie et al., 2008) (Figure 3). Basal sliding is the movement of ice as it slides over the bedrock (Alexander et al., 2011). This is enabled through the presence of meltwater, which acts as a lubricant to the ice (Alexander et al., 2011). Ice can melt under pressure which creates this film of water at the basal ice-bed interface. Basal sliding, especially with a rough bed that reduces basal friction, can enhance fast ice flow (Alexander et al., 2011).

Figure 3

Diagrammatic representation of basal sliding.



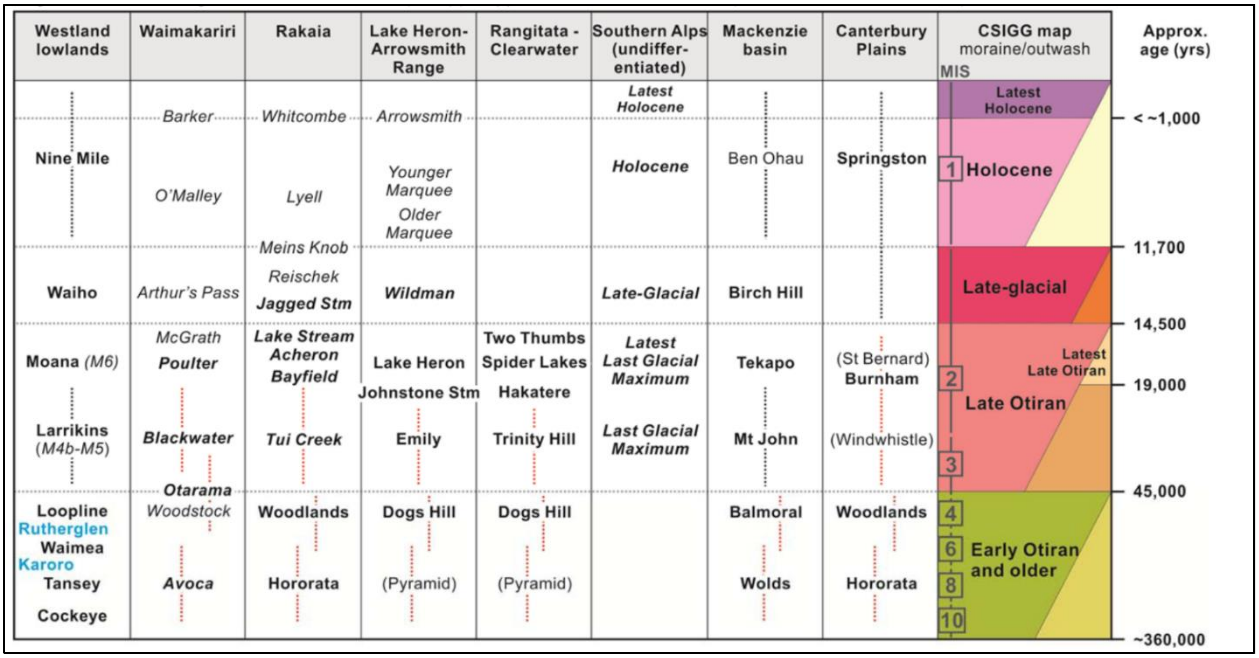
Note. Basal sliding is the movement of a glacier due to the presence of a thin layer of meltwater at the bottom of the glacier.

Climatic changes are the dominant drivers behind glacial mass balance changes, with temperature being the dominant driver behind the advance and retreat of glaciers in the Southern Alps (Fitzharris et al., 1999; Salinger et al., 2019). Earth's climate cycles between glacial and interglacial periods due to periodic cycles in the Earth's rotation, axial tilt, and shape of its orbit, which occur over the thousands of years (Bennett, 1990). Of consequence to this, is the 30 major oscillations in climate which have occurred over the last two million years (Figure 4 is a timeline of the last 360,000 years) (Bennett, 1990). Glacial periods, or an ice age, are where global temperature decreases.

Lower temperatures increase snow accumulation and contribute to positive glacial mass balances and advancement (Purdie et al., 2011). Interglacial periods are situated between glacial periods and are defined by warmer temperatures which cause glaciers to retreat (Bennett, 1990). This drives greater ablation rates and creates negative mass balances (Purdie et al., 2011). The coupling of glaciers with climate has seen these glaciers expand to cover large areas during periods of cooling and retract into the high mountains during periods of warming, over hundreds of thousands of years (Fitzharris et al., 1999). As earth has undergone these glacial and interglacial periods, it is the interaction of climate and topography of the glacier which has caused changes in mass balance which have controlled their ebb and flow across the landscape (Purdie et al., 2011; Fitzharris et al., 1999).

Figure 4

Paleoclimate timeline for New Zealand.



Westland lowlands	Waimakariri	Rakaia	Lake Heron-Arrowsmith Range	Rangitata - Clearwater	Southern Alps (undifferentiated)	Mackenzie basin	Canterbury Plains	CSIGG map moraine/outwash MIS	Approx. age (yrs)
	Barker	Whitcombe	Arrowsmith		Latest Holocene			Latest Holocene	< ~1,000
Nine Mile	O'Malley	Lyell	Younger Marquee Older Marquee		Holocene	Ben Ohau	Springston	1 Holocene	11,700
Waiho	Arthur's Pass	Meins Knob Reischek Jagged Stm	Wildman		Late-Glacial	Birch Hill		Late-glacial	14,500
Moana (M6)	McGrath Poulter	Lake Stream Acheron Bayfield	Lake Heron Johnstone Stm	Two Thumbs Spider Lakes Hakatere	Latest Last Glacial Maximum	Tekapo	(St Bernard) Burnham	2 Latest Late Otiran Late Otiran	19,000
Larrikins (M4b-M5)	Blackwater	Tui Creek	Emily	Trinity Hill	Last Glacial Maximum	Mt John	(Windwhistle)	3	45,000
Loopline Rutherglen Waimea Karoro Tansey Cockeye	Otarama Woodstock Avoca	Woodlands Hororata	Dogs Hill (Pyramid)	Dogs Hill (Pyramid)		Balmoral Wolds	Woodlands Hororata	4 6 Early Otiran and older 8 10	~360,000

Note. Adapted from Barrell, D.J.A.; Andersen, B.G.; Denton, G.H.; Smith Lyttle, B. (2013). Glacial geomorphology of the central South Island, New Zealand – digital data. GNS Science monograph 27a. Geographic Information System digital data files + explanatory notes (17 p). Lower Hutt, New Zealand. GNS Science.

The Last Glacial Maximum (Last Glacial Coldest Period) which peaked around 20,000 years ago, is when New Zealand's glaciers were at their greatest, with some extending beyond the West Coast coastline (McSaveney, 2009). At this time, temperatures were 6C colder, and the sea level was 120-130m lower than current. Around 18,000 years, the climate shows progressive warming which forced the melt and retreat of much of New Zealand's glaciers (McSaveney, 2009). Consequently, sea level was raised. New Zealand glaciers were their smallest between 9,500 and 5,000 years ago, where temperatures were 1-1.5C higher than today (McSaveney, 2009). Since this time, there have been prolonged cold temperatures which has driven glacial advance. Around 500BCE, the current climate was established. Of importance to glacial extents in New Zealand are the westerly winds whereby local and short-term glacier advancements correspond to greater snowfall, lower temperatures brought by stronger westerly flows, and greater cloud cover (McSaveney, 2009; Schulmeister ....). Glacier retreat in New Zealand corresponds to less snowfall, higher temperatures through weakened westerly winds and lower cloud coverage (Shulmeister et al., 2018).

New Zealand glacial advance and retreat is tightly correlated with temperature (Anderson et al., 2010; Mackintosh et al., 2017; Purdie et al., 2011), more-so-than than precipitation, with the central Southern Alps, needing an 82% increase in precipitation to offset a 1K of warming (Salinger et al., 2019). As temperatures continue to reach new highs, New Zealand glaciers continue to experience significant mass loss (Anderson et al., 2010; Chinn, 1996; Kidston et al., 2009). Important to the glacial mass balance is the temperatures experienced during the summer/ablation period (Purdie et al., 2011). The increasing frequency and intensity of extreme heat events is driving increased melt, enhancing positive feedbacks, raising the freezing level and reducing precipitation (Purdie et al., 2011). This is causing glacial retreat, evidence of which can be seen across the country (Figure 5) (Purdie, 2013).

Figure 5.

Example of a retreating glacier in New Zealand.

Note. Looking Towards Frind, Tuckett, Huddleston, Tewaewae, and Eugenie Glacier. Taken from Kea Point in the Aoraki/Mount Cook National Park.

New Zealand Glaciers

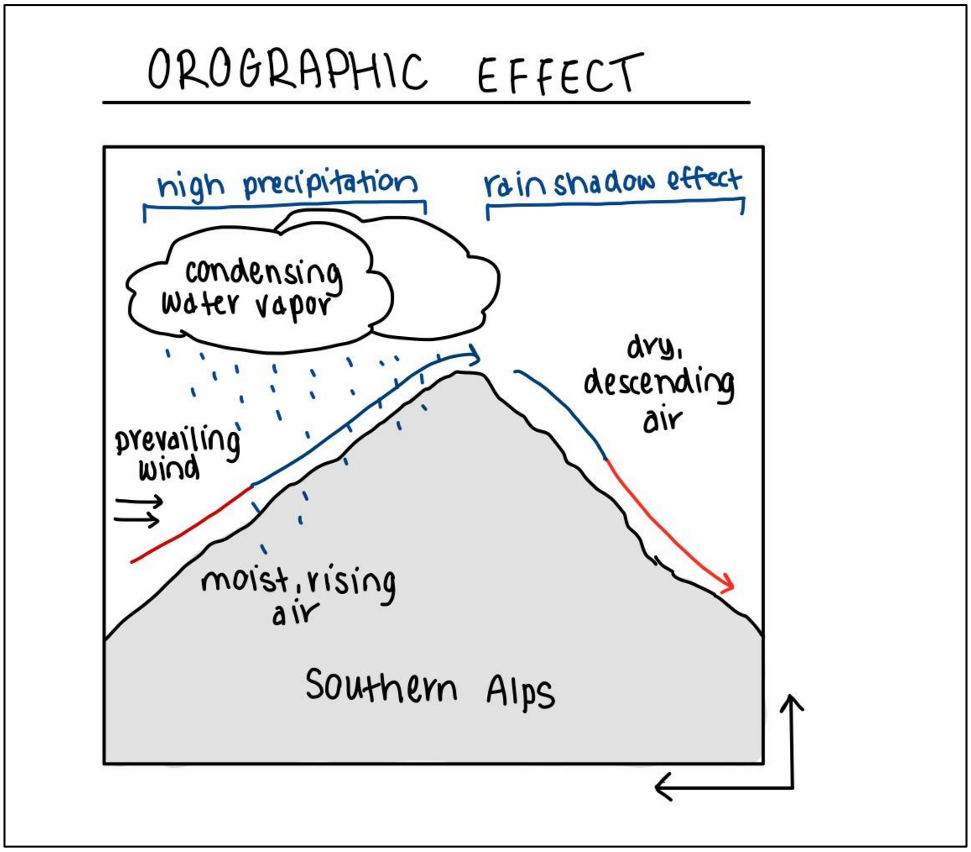
Glaciation in New Zealand can be characterised by high sedimentation, temperature, maritime climate, and presence of water within the proglacial areas. This has produced unique glacier systems with extensive outwash fans and small terminal moraines (Shulmeister et al., 2018).

New Zealand straddles the boundary between the active junction of the Australian and Pacific tectonic plates (Anderson & Mackintosh, 2006; Shulmeister, 2017). This positionality and high activity of these plates has meant the Southern Alps are one of the most rapidly rising mountain ranges in the world. The high surface uplift rates create high erosion rates, as seen through landslides and rockfall (Shulmeister et al., 2018). Erosion is enhanced through the presence of greywackes, schists and lower-grade metamorphic rocks dominant, such as in the central South Island (Shulmeister et al., 2018). The high supply rates in combination with strong glacifluvial activity (flowing meltwater which causes erosion and deposition) in the terminus of the glacier means that glacial deposits (i.e., moraines) are significantly smaller than glaci- fluvial or lacustrine deposits and landforms (Shulmeister, 2017).

Being situated in the mid-latitudes of the Southern Hemisphere, the New Zealand climate is wet, relatively warm, and heavily influenced by the presence of the Southern Alps and their interaction with the prevailing westerly winds (Anderson & Mackintosh, 2006). The uplift of this mountain chain acts as an obstruction to the westerly-dominated atmospheric flow, which travels across 42° and 45°S (Shulmeister et al., 2018). This creates an orographic weather pattern, with high precipitation on the western side of the mountains, between 2500-3000mm at sea-level on the West Coast which can rise to extreme values of 13,000 mm per year (Figure 6) (Anderson & Mackintosh, 2006; Shulmeister, 2017). These values decrease rapidly to the east, as the rain-shadow effect becomes apparent, which can cause value of 500-700mm only 30km from the Main Divide (Shulmeister, 2017). With many of the glaciated headwaters within the highest zones of precipitation, the annual snowfall is large and can occur in all seasons (Shulmeister, 2017). This is assisted by cold conditions brought upon by the westerly weather systems (Shulmeister et al., 2018). Whilst the snowpack is maintained by high snowfall, ablation rates are high due to the above zero degrees temperature conditions (Shulmeister et al., 2018). This means that even during the winter/accumulation period, melt events can occur. Consequently, these glaciers have high input-output systems (Fitzharris, 1999). Comparing the freezing seasons of maritime, temperature glaciers to continental to high latitude, continental regions, the season is much shorter, more interrupted. This means that there is year-round water flow at the terminus of regional glaciers.

Figure 6

Orographic rainfall effect of the Southern Alps



Note. Orographic rainfall is caused by the uplift of mountains which obstruct airflow, causing warm, moist air to rise, condense and fall as precipitation.

Importance of Glaciers

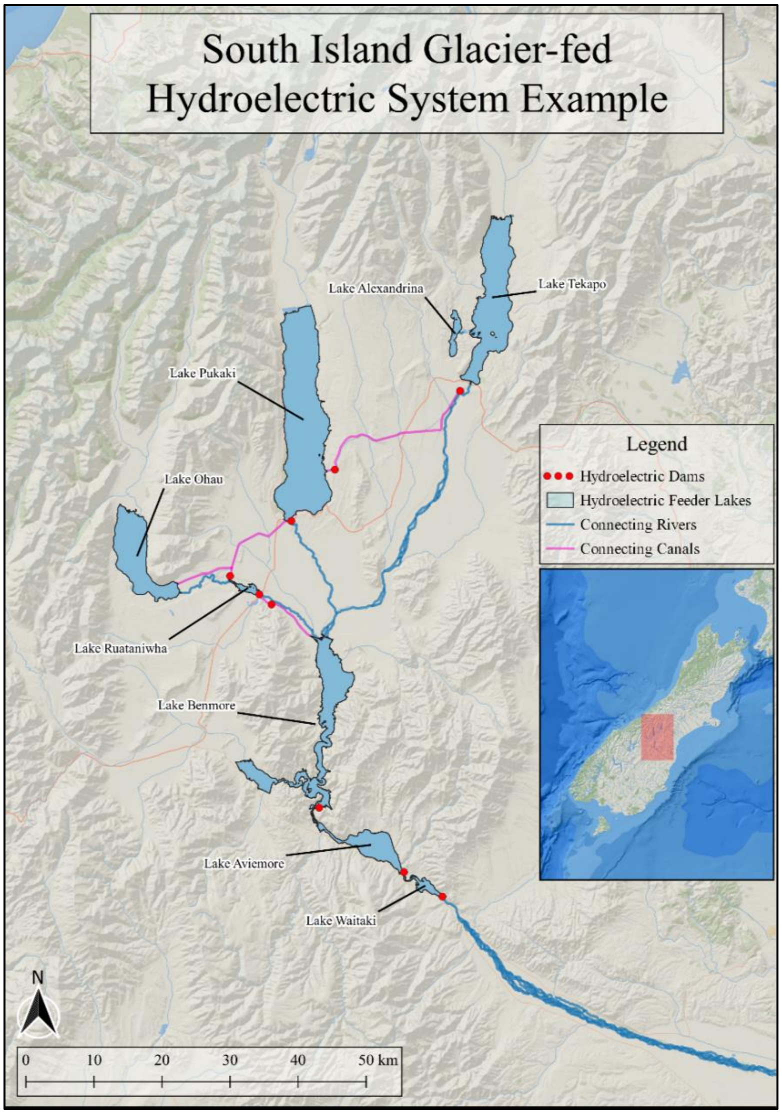
The significance of a glacier depends on whether it is alpine, continental, or marine terminating as this determines what their ‘use’ in a modern context. This report focuses on alpine glaciers, given that they are the only type seen in New Zealand. Historically, New Zealand has had marine-terminating glaciers; however, these no longer exist.

National Snow and Ice Data Center (n.d.) state that glaciers provide communities with many valuable resources, for example, glacial till provides fertile soil for crop growing, deposits of sand and gravel are utilised for asphalt and concrete, and the melting of glaciers feeds many large rivers. This melt ultimately feeds hydroelectric systems and agricultural areas. Arguably the most crucial glacial remanent is fresh water. While some of these advantages are lesser seen in New Zealand, globally, the dependence on glaciers is of great significance. Specific to the Waimakariri catchment, while no hydroelectric systems depend on the Waimakariri river, it is a source for local agriculture and culturally significant land, supplying the water needed to sustain large scale farming and the freshwater aquifers (Environment Canterbury, 2017).

Glaciers in New Zealand feed the waterways used to power some of the largest hydro dams in the South Island, modifying stream flow down into the hydro dams' reservoirs, and moderating the levels of the feeder lakes. An example of such is the Waitaki Hydropower system, operating across eight hydro stations, encompassing Lakes Tekapo, Pukaki, Ohau, Benmore, Aviemore, and Waitaki (Figure 7) (Martin, 2010). The accumulation of glacial melt is transported to the Lake Ohau watershed and put through the hydroelectric turbines to generate power. This is one example of how New Zealand utilises glacial melt to generate clean energy. Hydroelectricity accounted for 82% of New Zealand's generation of renewable energy sources in 2019 (Ministry of Business, Innovation & Employment, 2020).

Figure 7

Waitaki Glacier-fed Hydroelectric System in the Southern Alps of New Zealand.



1. *Note.* Adapted from *LINZ Data Service*, by
2. | Toitū Te Wenua, n.d. (https://data.linz.govt.nz/)

Methodology

The project objective was to create a storyboard on the land-forming processes within the Waimakariri basin that were highly accessible, using research methods that best suited the project. This was approached through secondary literature synthesis of mixed-form research and data. This approach was a result of limited resource parameters and the available literature. Secondary data allowed for otherwise impractical large-scale, high-quality analysis; however, consequential interpretation must account for the variability of methodology and results (St Martin & Pavlovskaya, 2010).

Preliminary research analysed 25 articles to assess the state of the literature in the area. Detailed subtopic reviews, as found in the ‘Literature Review’ section, focusing on

1. New Zealand paleoclimate and interactions with glacial periods;
2. Applications of machine learning and artificial intelligence techniques for paleoclimate analysis;
3. Geomorphological features and processes attributed to New Zealand glaciers;
4. the role of glacial sensitivity and effective communication of Earth Science to the public through geospatial visualisation; and
5. Vegetation within the Waimakariri basin and how vegetation can aid in identifying geomorphology, dating and glaciation within the valley.

Compiling available data through secondary literature synthesis with photogrammetry techniques allowed for verification concerning land-forming processes, historical glacial extents, and present-day extents. Combining multiple data sources and research into one repository increased confidence in the visualisations and final findings. Photogrammetry, secondary remote sensing, and computer-aided design (CAD) cartography were the primary geospatial methods utilised.

Due to project limitations, methods were narrowed to existing data and research, restricting the overall capabilities of the analysis. In addition, interpretations of the historical glacial activities and the land-forming processes were challenged continually through ongoing literature synthesis and informal glaciologist expert consultations. This process was used to advise contemporary geospatial interpretation of glacial extents specific to the Otiran period, Holocene, and Last-glacial Maximum (LGM). The geospatial data stems from research conducted by Rother et al. (2015), Schulmeister (2018), and GNS Science (n.d.), cleaned, interpreted, and finalised using GIS programs.

Manual data cleaning was selected as the appropriate method given the subjectivity of the required parameters needed to complete the visualisation interpretations; automating scrubbing was not feasible given time constraints and highly variable data. The data required thorough assessment, appropriately classifying and understanding of what visualisations can/could not be effectively communicated, completed using a combination of ArcGIS Pro and QGIS due to user preferences. As stated, this process was labour-intensive, ensuring an accurate representation of historical glacial movement and the processes involved in sculpting the landscape.

Interpretation and finalisation of the data following cleaning is arguably the most critical stage of the analysis and project, including manipulation and visualisation. To properly visualise glacial extents and the attributed land-forming processes, the drawing of each extent was manually completed through Google Earth and MOVE, utilising basin modelling as the primary technique. This, however, raised the issue of elevation inaccuracy, with the 3D extents misrepresenting the actual height of the glacier at specific points throughout the Waimakariri catchment. An example of this was in the Cass Basin, where the model showed extents exceeding their actual limits, disregarding how glaciers deform given changes in the surrounding environment. Hence, post-modelling, manual corrections were completed to align with varying research. Upon completion, the finalised extents were imported into ArcScene, QGIS, and ArcGIS Storyboard to create maps, 3D models, and an interactive continuous scrolling webpage to best communicate the findings.

Literature Review

To gain a comprehensive understanding of glaciology in New Zealand, an assessment of five sub-themes was undertaken. This included applications of machine learning and/or AI techniques for paleoclimate analysis; geomorphological features and processes attributed to New Zealand glaciers; effective communication of Earth Science to the public-through geospatial visualisation' and vegetation within the Waimakariri Basin and how vegetation can aid in geomorphology-dating and glaciation. Summaries of these assessments are below.

Geomorphology Characteristics and Processes Attributed to New Zealand Glaciers

This subtheme discusses how the Upper Waimakariri Basin was sculpted with relevance to glacial and geomorphological characteristics. It primarily focused on Glacial Mass Balance (GMB), paleoclimatic factors, methodologies and the implications therein. Synthesis found that GMB is prominently affected by paleoclimate, therefore historic climactic factors such as atmospheric circulation are integral to estimating past glacial maximums (Anderson & Mackintosh, 2012; Anderson et al., 2010; Dowling et al., 2021; Vincent, 2002). Regarding methodology, the review found that the older the period, the more erroneous the data. Overall, the review expressed there was limited available data, and indicated that recent radiocarbon methods were found to be the most dependable for Neoglacial and older dating. Results were recommended as best regarded as an estimate to account for errors typically associated with proxy data (Chinn, 1975; Dowling et al., 2021; Gellatly, 1988).

Vegetation within the Waimakariri Basin and Usage in Identifying Geomorphology, Dating and Glaciation within the Valley

Throughout the literature, four scientific methodologies were generally employed to identify historic vegetation, landscape dating, and geomorphology: research synthesis (Soons, 1994), dendroclimatology (Norton & Ogden, 1987), lichenometry (Birkeland, 1982; Gellatly, 1982), and palynology (Burrows & Lintott, 1973). Each approach has advantages and disadvantages, with lichenometry seen as a supplemental method and research synthesis offering limited detail. On the other hand, dendroclimatology and palynology provide more exact measurements and estimates of paleoclimate and vegetation in a specific time. Dendroclimatology research has offered a general estimate of the previous paleoclimate dated 300 years by dating native flora; nevertheless, vegetation-specific research is significantly impeded by plant loss events such as glacial advance and its subsequent regeneration. Furthermore, given the diversity in results, the limited research on the Waimakariri limits each dating method's reliability. Finally, it is crucial to note that radiocarbon dating techniques are now considered the most accurate for paleoclimate modelling and assessment; nonetheless, vegetation-based research methodologies are still feasible as supplementary resources.

Effective Communication of Earth Science to the Public through Geospatial Visualisation

In the last few decades there has been a focus on researching the inclusions of interactivity. This has shown there is a retention of information and engagement seeing a shift from static to dynamic. But there is little research into why this works, this could be because interactivity is not well defined it ranges from a fully dynamic storyboard to a map with pop-ups. Looking at story-maps teachers and students have found them to be the preferred form for information retention and engagement. Because we want our research to be used as an educational tool then according to research story-mapping is our best option for us.

New Zealand Paleoclimate and Interactions with Glaciers

The aim of this essay was to obtain an understanding of New Zealand paleoclimate and its reconstruction through proxy data. This was with the intention of helping to contextualise glacier-climate relationships that are ultimately responsible for glaciated features within an environment. Barrell et al. (2013) created an inter-regional climatic event timeline for the past 30,000 years through pollen-based proxies. This research is recognised as being foundational and a point of comparison for other paleoclimate reconstructions. Fitzsimons (1997) used glaciated-created landforms within Westland of Canterbury to create a stratigraphic review glacier event. This was focused on the Late Quaternary period. One contended issue within broader literature is whether the Younger Dryas event of the North Atlantic had a strong on New Zealand. This was addressed by Williams et al. (2005) using stalagmites from caves in the South Island. Burrows (1983) used radiocarbon samples from Cass Basin to provide insight into the Otira period and intended on resolving uncertainties around Late Quaternary. Rother et al. (2015) analysed glaciation sequences of the Waimakariri Valley by re-assessing ice extent during MIS-2 using moraines. The findings of Barrell et al. (2013), Fitzsimons (1997), and Williams et al., (2005) are imperative pieces of research that assist with identifying and ordering significant climatic events, the timing of glacial advances and retreats, and hemispheric variations more generally. The findings of Burrows (1983), Rother et al. (2015) and Fitzsimons (1997) are foundational in revealing glaciation within the Waimakariri and explain how hemispheric paleoclimatic events are expressed within this specific area. The collation of information, when drawing from all five pieces of literature, aids in reconstructing the highly complex paleoclimate.

Applications of Machine Learning and/or AI techniques for Paleoclimate Analysis

There have been several different approaches to methods in recent years all indicating that there are strengths and weaknesses to each approach due to this being relatively new there is not much information out there yet, but all show promising results with Machine Learning and Artificial Intelligence improving constantly. There are several problems though 2 that seem the most common is not knowing what is happening so very little human input and/or change, and computing power.

Glacier Extents of the Upper Waimakariri

The extent of a glacier and the landforms that it creates are inherently linked – whereby the landforms come as consequence to the glacier, and it is these remnants of glaciers which are used to reconstruct extinct glacier extents. This dependency highlights the need to understand the glacier extents in order to fully comprehend the landforms, the processes which created them, and which litter the upper Waimakariri. Visualising the glacier extents is imperative to this understanding. Figures 7- 10 are the visualisations of glacier extents from the Otiran period. The dating of each extent is as follows; Blackwater 1 was found to be 25,000 to 24,000 years ago, Blackwater 2 at 21,000 to 20,000 years ago, Blackwater 3 at 17,000 years ago, Poulter advance 21,000 to 20,000 years ago, and the McGrath advance unfortunately still slightly less accurate ranging 19,000 to 14,500 years ago (Figure 8). Table 2 provides the dates of the advances which are visualised. These were based on The Otiran glacial extents observed in the Upper Waimakariri, which were derived from GNS Science (n.d.), are shown on Figure 4.

Table 2

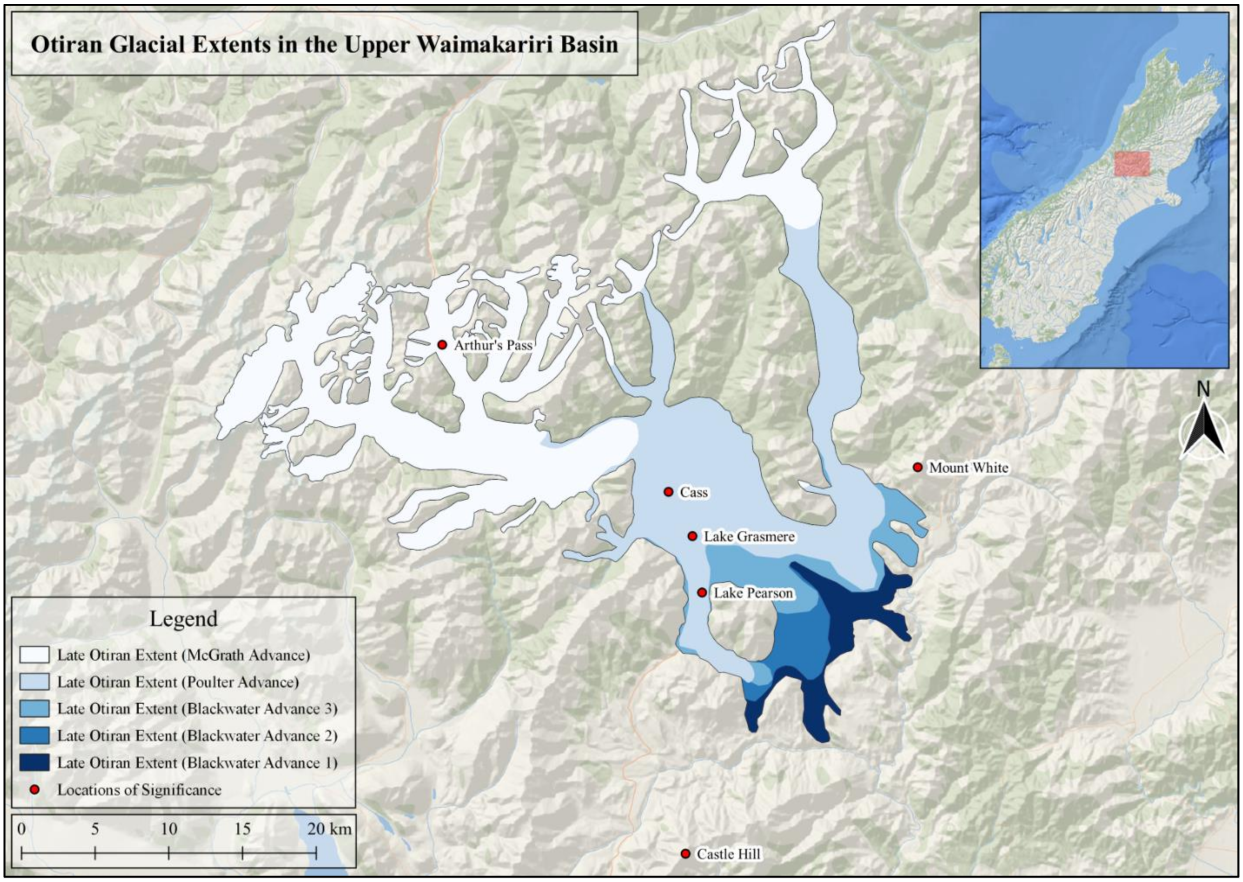
Timeline of the Otiran Glacial Extents.

Name	Date	Period
Late Otiran Blackwater 1	24.8 ± 0.71 ka	MIS-2 (main LGM)
Late Otiran Blackwater 2	20.7 ± 0.5 ka	MIS-2 (main LGM)
Late Otiran Blackwater 3	17.1 ± 0.5 ka	MIS-2 (main LGM)
Late Otiran Poulter	17.6 ± 0.4 ka	Otiran
Late Otiran McGrath	19 to 14.5 ka	Otiran

Note. Adapted from *Surface exposure chronology of the Waimakariri glacial sequence in the Southern Alps of New Zealand; implications for MIS-2 ice extent and LGM glacial mass balance.* Rother et al., 2015. (https://doi.org/10.1016/j.epsl.2015.07.033).

Figure 8

Otiran Glacial Extents Seen in the Upper Waimakariri Basin Using GNS Science Data, Covering the McGrath, Poulter, and Blackwater Advances.

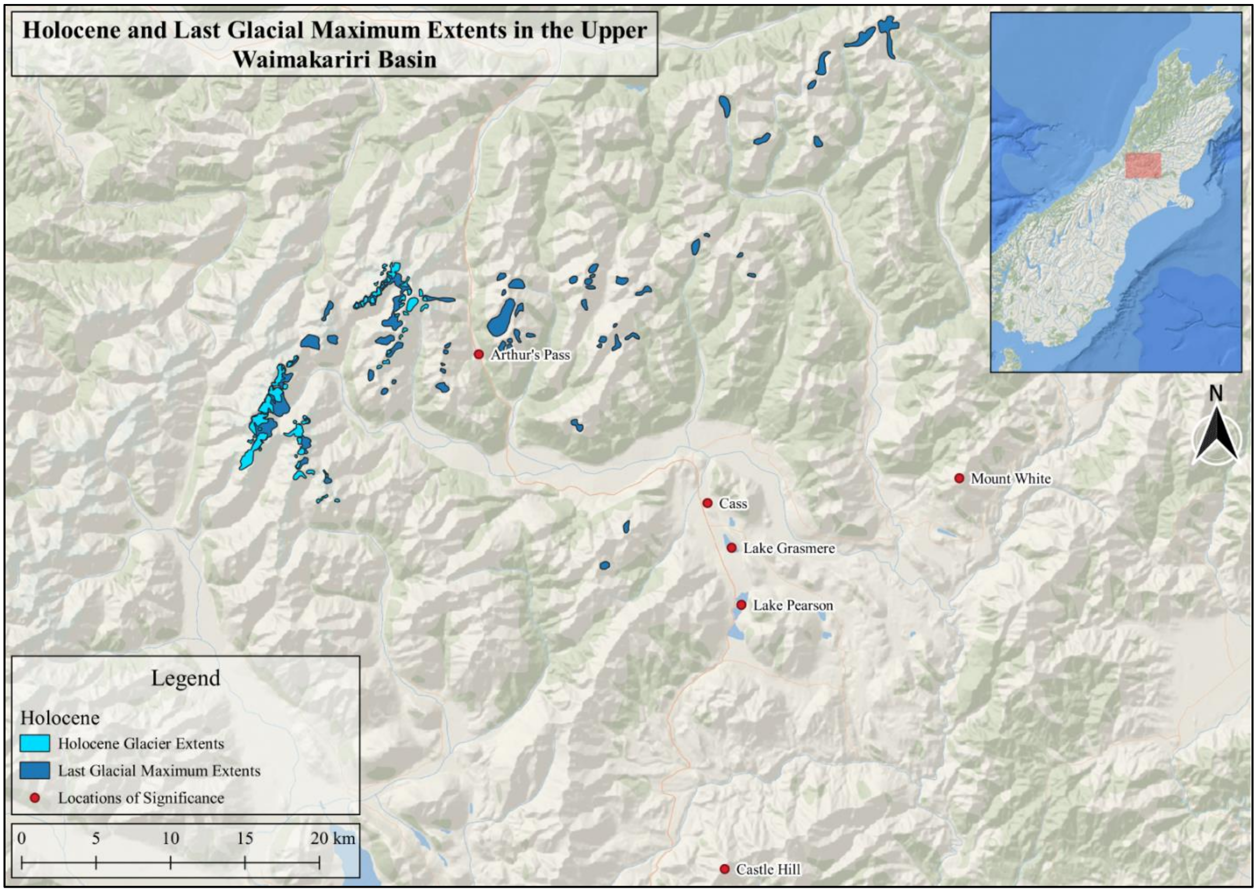


Note. Adapted from *Central South Island Glacial Geomorphology*, by GNS Science, n.d. (https://data.gns.cri.nz/csigg/map.html.

The extents seen in Figure 9 indicate a rapid retreat during the latest glacial maximum and the Holocene, ranging from 14,500 to 11,700 years ago and 11,700 to 1,000 years ago respectively, with the extents seen to barely exceed the mountain tops.

Figure 9

Holocene and Last Glacial Maximum Extents Seen in the Upper Waimakariri Basin Using GNS Science Data.

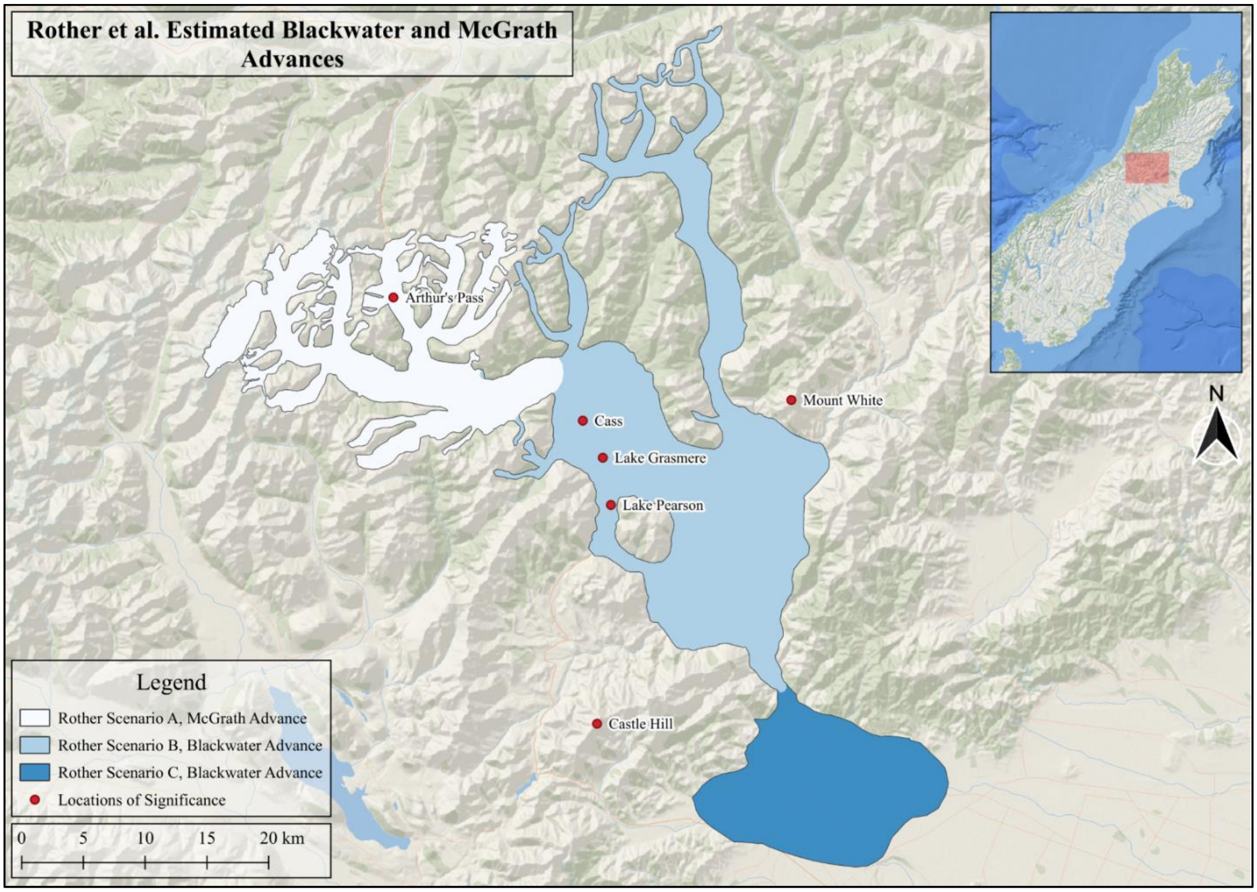


Note. Adapted from *Central South Island Glacial Geomorphology*, by GNS Science, n.d. (https://data.gns.cri.nz/csigg/map.html).

Rother et al. (2015) has estimated the maximum blackwater advance to extend beyond the Otarama gorge, flowing out onto the Canterbury plains, then receding back to the extent seen ending within the Otarama gorge as seen in Figure 10. These are currently under contention, with other sources suggesting the Blackwater extents never flowed onto the plains. Rother et al. (2015) found the McGrath advance to flow to the bottom of Mount Horrible before the Cass Basin, this has been verified against other research showing similar extents. Blackwater advances date between 29,000 and 19,000 years ago. The McGrath advance only dates between 19,000 and 14,500 years ago.

Figure 10

Blackwater and McGrath Advance Extents Seen in the Upper Waimakariri Basin Using Rother et al. (2015) Data, Visualised Through Georeferencing.

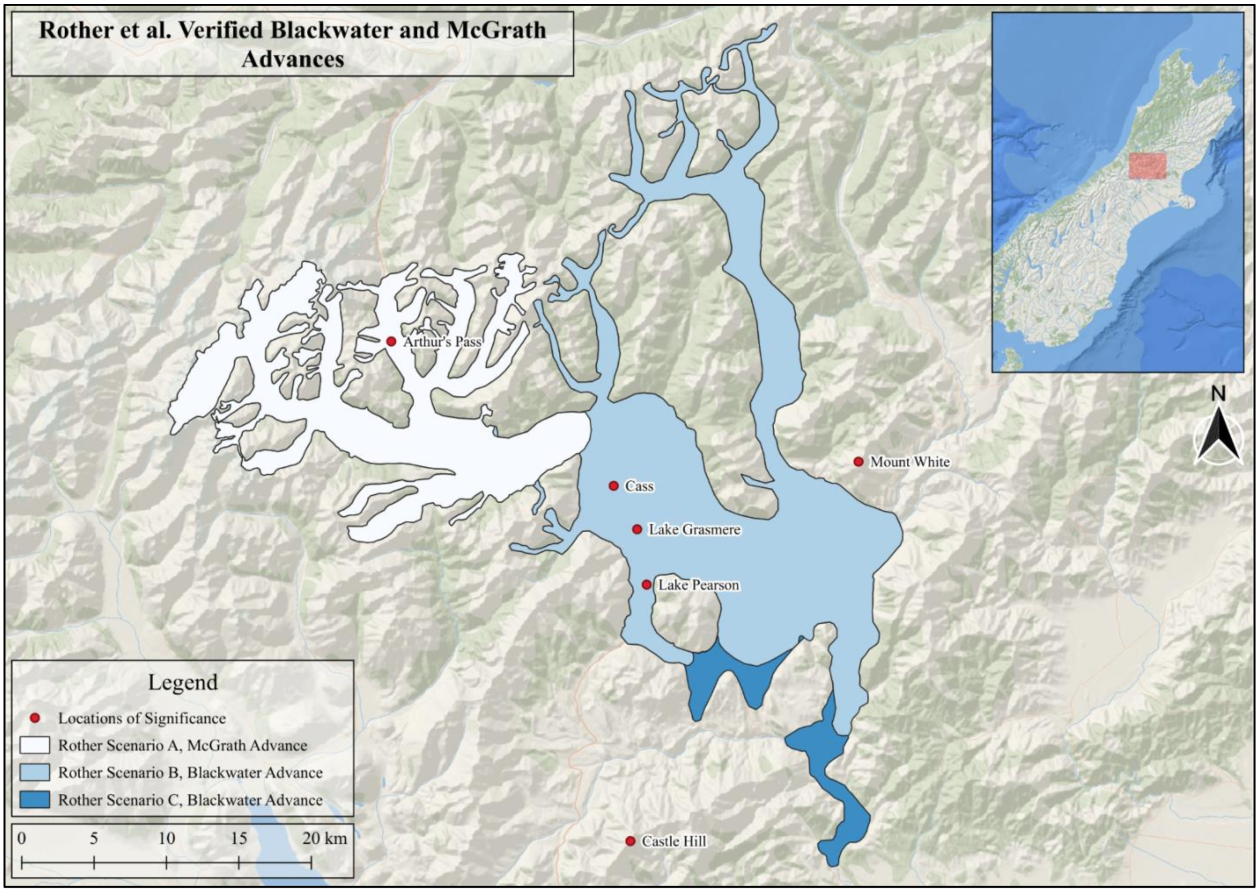


Note. Adapted from *Surface exposure chronology of the Waimakariri glacial sequence in the Southern Alps of New Zealand: Implication for MIS-2 ice extent and LGM glacial mass balance,* by Rother et al., 2015. (https://doi.org/10.1016/j.epsl.2015.07.033).

Figure 11 highlights the changes made post-informal meeting with Shulmeister (2022). Jamie provided new literature (Shulmeister et al., 2018) that contented Rother et al. (2015), suggesting the Blackwater extents never flowed onto the Canterbury Plains, instead ending in the Otarama Gorge, with three primary lobes over Lake Pearson, through Craigieburn, and the Waimakariri River. These extents are regarded as accurate for its methods and results; however, this is subject to change with new research.

Figure 11

Blackwater and McGrath Advance Extents Seen in the Upper Waimakariri Basin Using Rother et al. (2015) Data, Altered and Guided by Expert Consultation.



Note. Adapted from *The timing and nature of the last glacial cycles in New Zealand*, by Shulmeister et al., 2018. (https://doi.org/10.1016/j.quascirev.2018.12.020).

Land-Forming Processes

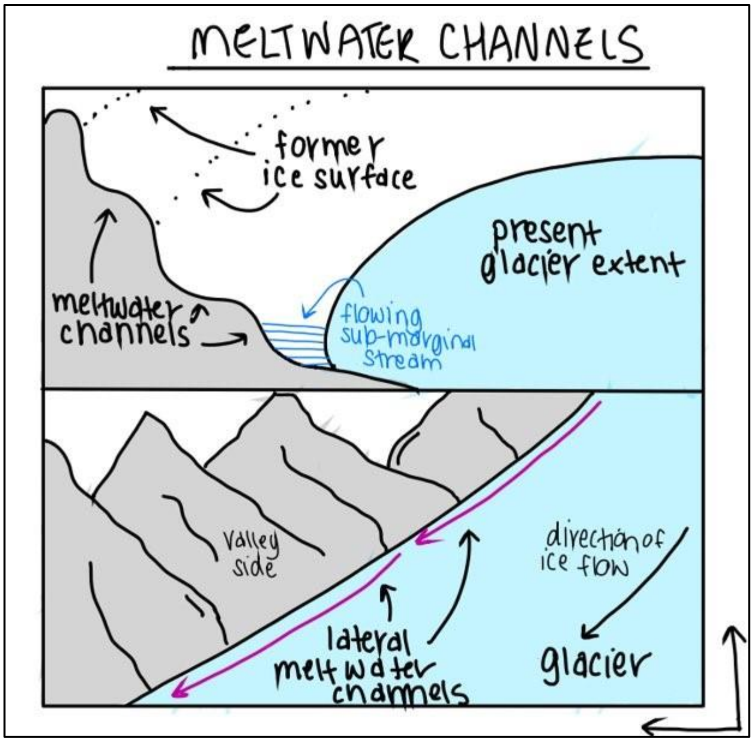
As temperatures warmed and the ice began to retreat thousands of years ago, the glacier-formed valley of the Waimakariri was carved out. Armed with rock debris, the moving ice of glaciers scoured the bedrock which they sat upon. As the glacier retreated, moraines and alluvial fans were formed from the deposition of sediment. Melt-water channels, kettle holes, and truncated spurs were formed due to glacier-hydrology interactions and valleys with steep sides. These features are characteristic of a glaciated environment and provide stark evidence of the presence of glaciers (Glasser & Bennett, 2004).

Melt Water Channels

The New Zealand glacier landscape continues to be dominated by water processes. The high volume of available water that flows beneath or beside ice sheet margins can erode the surrounding rock and sediment and create erosional features known as ‘melt water channels’ (Glasser & Bennett, 2004) (Figure 12). Water which is released from glacial melt can run along channels formed from pre-existing rivers (Atkins, 2011). This meltwater has high energy and high sedimentary load (composed of rock fragments) which can induce rapid erosion through processes like abrasion (Atkins, 2011). Abrasion is the frictional wear of a surface, where the material being transported can rub, scour, and scrap surfaces through stress and motion and is able to deepen the channels it runs through (Rea, 2013). Although these are most commonly amongst cold-based and polythermal glaciers, they can form along the margins of temperature glaciers (Atkins, 2011). Evidence of these “micro-valleys” can be seen in most east and south flowing valleys in the Southern Alps. The Upper Waimakariri basin has lateral meltwater channels – ice-carved rock gorges which run parallel with contemporary contours (parallel to the extinct glacier in the main valley floor) (Gage, 1958). These channels are present on valley sides, formed in the marginal position between the glacier (or ice-cored lateral moraine) and the valley side (Atkins, 2011). These channels are quite short (tens to hundreds of meters) and shallow (typically less than 20m). These provide good indications of the previous glacial extent (Shulmeister et al., 2018; Rea, 2013).

Figure 12

Meltwater channels.



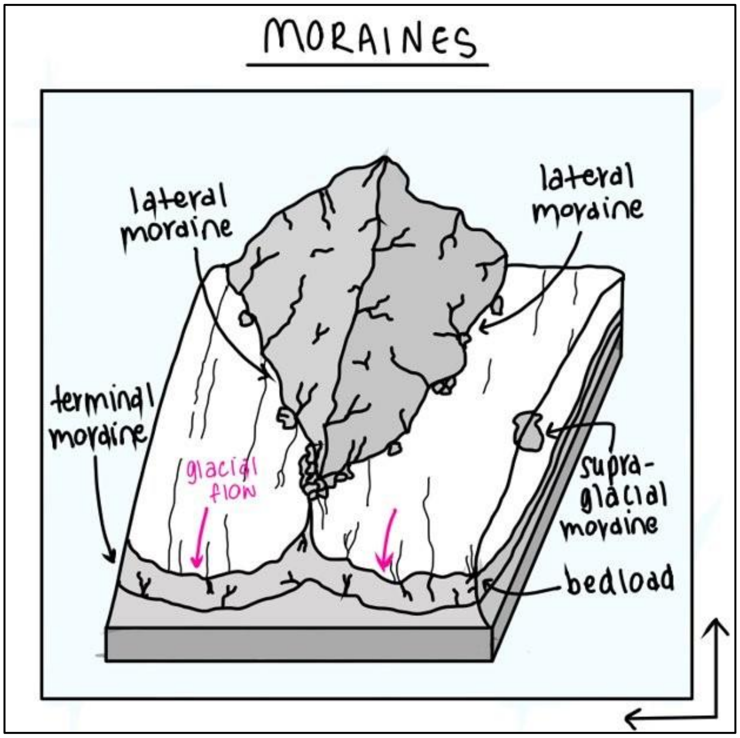
Note. Meltwater channels are formed through glacial meltwater which has high energy and sedimentary load, which induces rapid erosion.

Moraines

Moraines are formed from the material that is deposited by a glacier, including rocks and boulders that come down from the glacier as it melts. Longitudinal or terminal moraines are those which mark the limit of the glacier (Figure 13) (Shulmeister, 2017). These are often formed from material that has been pushed in front of a glacier that is advancing or one that is stationary (Shulmeister, 2017). These are commonly large, impressive features which tend to dominate the landscape. In New Zealand however, as discussed previously, terminal moraines are often small and of the subdued nature (Shulmeister, 2017). Remnants of terminal moraines, as the glacier retreats into the valley, are pictured in Figure 14. Lateral moraines form along the side of a glacier (Figure 13). It is formed from mass wasting of deposited debris in the accumulation area, as the glacier tears off rock and debris from the sides of its path. This is then transported to sit between the glacier and the valley (the flank of the glacier) (Shulmeister, 2017). These are often tens of meters high, steep-sided, and is well-preserved as it will remain as high rims of valleys as the glaciers melt (Shulmeister, 2017).

Figure 13

Moraines



Note. Moraines are formed from glacier debris, and can be defined as terminal, lateral. Supraglacial moraines are presented in this diagram but not known to have been present in the Upper Waimakariri.

Figure 14

Terminal Moraine

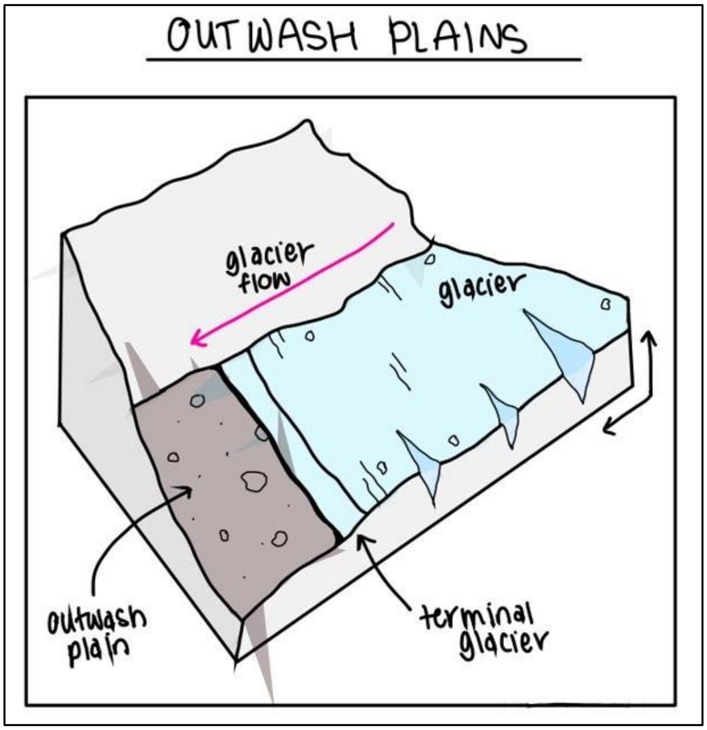
Note. Obtained from Google Earth (n.d.). This image clearly shows the retreat of an extinct glacier back into the valley, as the remnants of terminal moraines are prominent within the shape of the land. Retrieved 10/10/22.

Outwash Plains

Arguably the most distinctive features of the New Zealand glaciation are outwash fans (Figure 15) (Shulmeister, 2017). An outwash fan is a fan-shaped body of sediments that is deposited from a melting glacier, through braided river systems (Shulmeister, 2017). As the glacier melts and begins to retreat, meltwater deposits debris which was previously locked in the ice of the glacier, at the terminus on the outwash plain (Shulmeister, 2017). This can get transported by braided rivers (formed from glacial melt). This process of transportation is responsible for the fan-like shape, as seen in Figure 16 which is located adjacent to the Waimakariri River.

Figure 15

Outwash Plains



Note. Outwash plains are built from the deposition of previously trapped material, to beyond the terminal of the glacier driven by a melting glacier and transported by braided river systems.

Figure 16

Outwash plain emerging from the Waimakariri River.

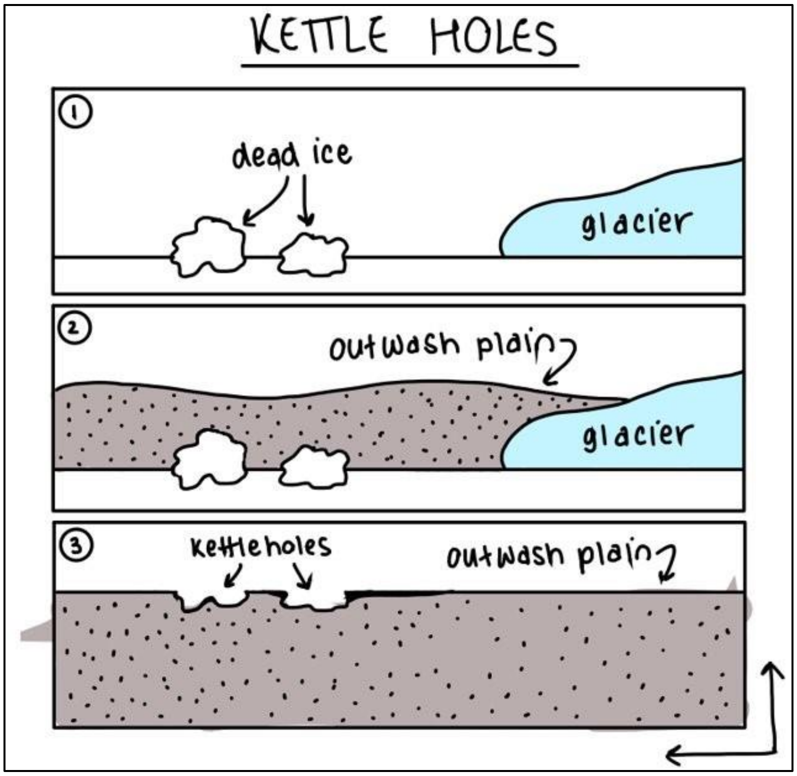
Note. Obtained from Google Earth (n.d.). This image shows the fan-shaped outwash plains, transported through sedimentary deposition as a result of glacial activity. Retrieved 10/10/22.

Kettle Holes

Kettle holes are fluvioglacial landforms formed by blocks of ice separating from the main glacier, after they detach, they become partially or fully buried in the soil/sediment. The blocks of ice proceed to melt, leaving a depression which often fills with water to become kettle hole lakes, as seen in Figure 17 (Department of Conservation, n.d.-b). The Upper Waimakariri catchment has evidence of kettle holes, primarily in the Cass Basin, as shown in Figure 18. The kettles separating from the terminus of the glacier tend to be at their largest and most prevalent near the glacial margin. This ice melts, leaving the characteristic circular patterned deformation in the soil/sediment that can be seen in the Upper Waimakariri today (Carrivick & Russell, 2013).

Figure 17

Kettle Holes



Note. Kettle holes are formed from dead ice leaving a depression within sediment. These can then become partially filled with water to create a kettle hole lake.

Figure 18

Kettle Hole within the Waimakariri

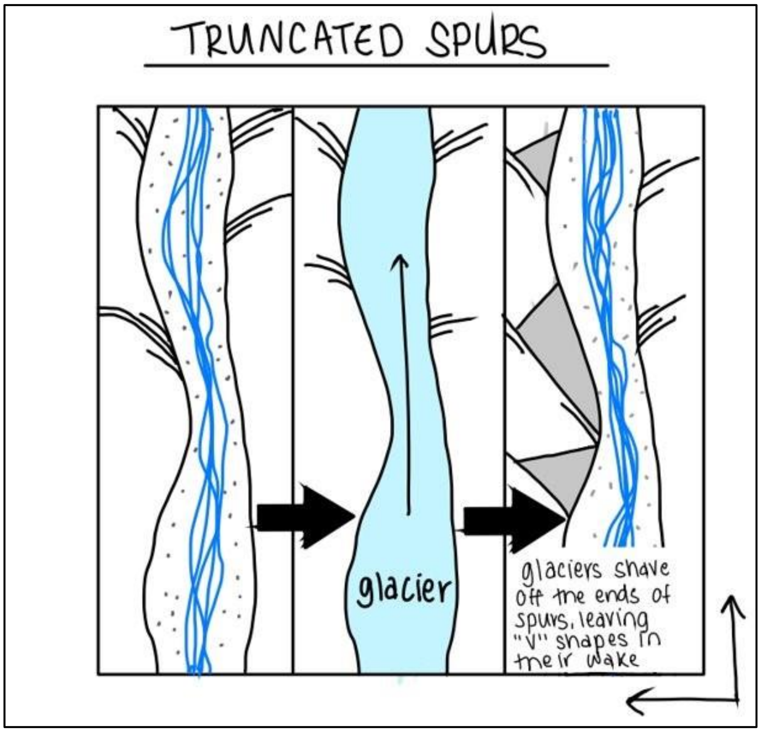
Note. Obtained from Google Earth (n.d.). This image is taken in the Craigieburn Valley in the Upper Waimakariri Basin. This is an example of a kettle hole that filled with water, now forming a small lake. Retrieved 10/10/22.

Truncated Spurs

A common glaciated landform found within the Waimakariri are known as truncated spurs (Figure 19, Figure 20). A spur is a ridge that descends towards the valley floor and in this case, are caused by glaciation shaving the sides or "roundedness" of a spur, as it moves through the landscape. Visually the truncated spur looks like a ridgeline descending towards the lower valley that ends in an inverted V shape, which is where the glacier has cut off the spur, as can be seen in fig x below (Mayhew, 2015).

Figure 19

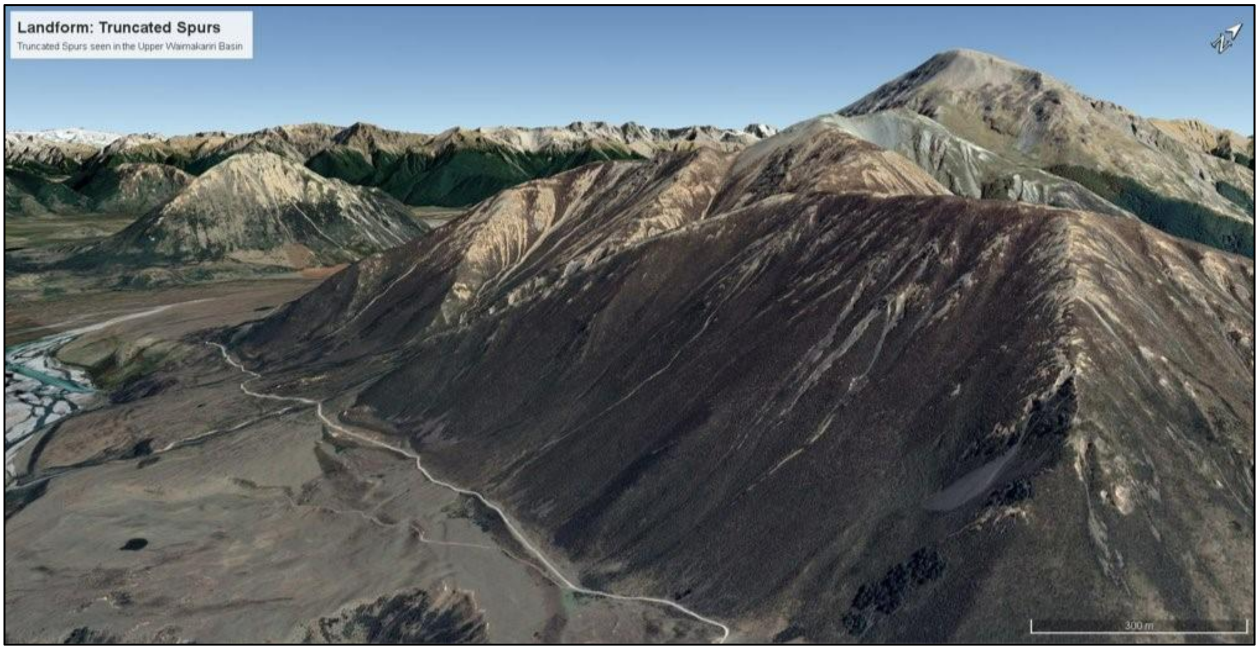
Truncated Spurs



Note. Truncated spurs formed by glacier movement.

Figure 20

Truncated spurs in the Waimakariri.



Note. Obtained from Google Earth (n.d.). This is an example of a truncated spur within the Upper Waimakariri Basin below Mount Binser. Retrieved 10/10/22.

Effective Presentation

Story Maps are an effective presentation method with manifold benefits. The most obvious advantage is the fact that they are interactive which has been proven as being a highly effective type of communication, especially within science (Egiebor & Foster, 2019). A storyboard is designed like a 'roadmap', one that is user-centric and emphasises interactivity (Egiebor & Foster, 2019). There is a consensus that best communication includes a user-centric, interactive or visually pleasing design. (Roth, 2013; Roth et al., 2017). This is significant for use in educational settings such as schools, as the dynamic and interactive medium can engage students in a more meaningful manner. Additionally, the 'roadmap' design can guide the user through the information, which is essential in telling a story based around visualisations and scientific literature. It is this which allows for the pubic to obtain a greater understanding of an often highly complex topic. It is for these reasons that this medium was used, as it can seamlessly bring together a combination of information and visualisations and is an excellent vessel to communicate scientific research.

Data Analysis

This project uses secondary research, primarily proxy data, to reconstruct glacial extents and to understand land-forming processes. One of the foundational pieces of research used in this project was Rother et al. (2015). This uses Beryllium-10 isotopic dating to date glacial moraines. The GNS Science (n.d.) used a range of methods including proxy data, field inspection, the interpretation of topographic maps and stereoscopic aerial photographs. The use of this secondary data means that any collection bias (e.g., Rother et al. (2015) used 33 samples for the area, which means that not every area is able to be truly represented) or model bias (e.g., human error, and assumptions of the model), have been transferred to this project. These are limitations which are difficult to counter. Another point of consideration is the differences between these research papers, and others in terms of defining the glaciation events within this area. To create a project that was as accurate as possible within these limitations, we have made informed rounding to our dates on our maximum extents, altering them based on expert consultation and newer dating from Rother et al. (2015). With consultation with various experts, the glacier extents from Rother et al. (2015) were altered. This was specifically in regard to the lobes which flow down the Waimakariri Basin and into the Poulter.

For the reconstruction of paleoclimate in the future, there is research being conducted overseas, as well as within New Zealand (specifically NIWA), that are looking into the use of machine learning and artificial intelligence. This is with the aim of reducing uncertainties and limitations within paleoclimate research.

Limitations

The nature of this research means that there are some limitations within the research undertaken and visualisations produced. As mentioned previously in ‘Data Analysis’, the use of secondary research has natural restrictions including data variations, modelling, and sampling bias’. In regard to the completion of this project specifically, there has been limited time and resources available within this specific area. In combination with the inability to conduct field-research, this has created entire dependency on secondary data, which was limited and sometimes outdated within this specific area. Additionally, when creating the visualisations, there were consistent problems in regard to the amount of computational power which was needed to run large scale spatial analysis. To account for this, the dates of glaciation were rounded (as mentioned in ‘Data Analysis’) and sources were appropriately referenced, ensuring that the validity of the data at the time can be assured.

A foundational component to the completion of this project was the work of the group members involved. However, this project was designed for a five-person, third-year undergraduate, research team. Due to unfortunate and unforeseen circumstances, one member had to leave halfway through the project. These new circumstances were accounted for as best as possible, however it reduced the time availability and delayed access to some of the datasets.

Approaches Taken Towards Understanding

Glaciology in and of itself, and more specifically within the Waimakariri, is constantly evolving, as is the nature of science. 'Good' science perpetually improves upon itself, disregarding and strengthening old findings and hypotheses as it goes (Armstrong & Green, 2022). Because of this inherent uncertainty, research, methods and areas of importance vary considerably amongst paleoclimatic and glaciological researchers. This leads to different schools of thought, which acts to create both synergistic and contended perspectives within literature. The complexity of glaciation in combination with various methodologies and perspectives of importance, means that there are many different narratives for the story of this landscape. To provide consistency, this report focuses on key research from (Gage, 1958; GNS science, n.d.; Rother et al., 2015 & Shulmeister et al., 2018). The findings of this research are currently regarded as accurate for its methods and results, although this might be subject to change in the future and contended amongst researchers who favour other narratives.

Locale specific information is limited, and many of the most detailed research is older or uses bygone glacial dating methods (Chinn, 1975; Gage, 1958). Early work by Gage (1958) proposed five glacial periods within Waimakariri using climate proxy data, which was later superseded by Rother et al. (2015). Our visualisations are based primarily off the work of Rother et al. (2015) and Schulmeister et al. (2019), which superseded earlier science.

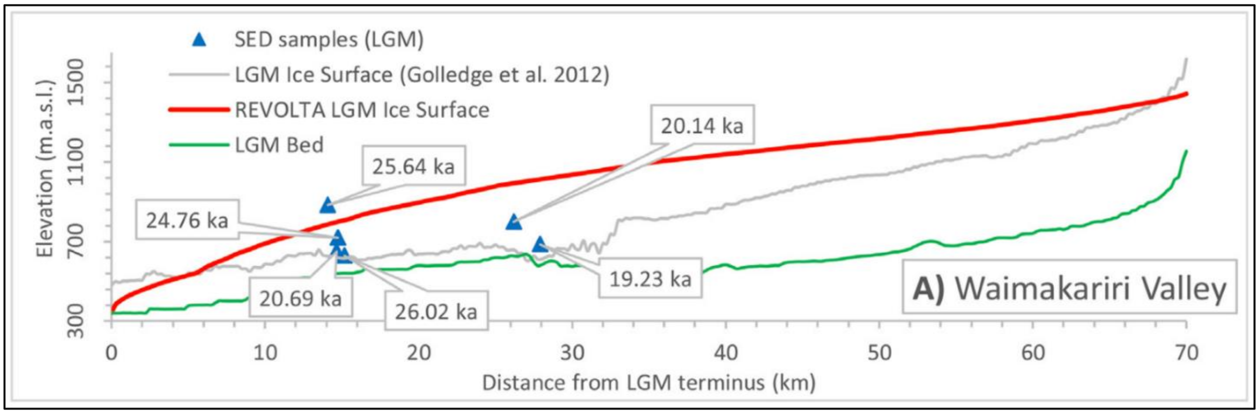
Work by Rother et al. (2015) used ^{10}Be dating on moraines to discover that previously dated mid-Pleistocene glacial surfaces (Chinn, 1975; Gage, 1958) were significantly younger at around MIS-2 in age, having occurred within the LGM. Schulmeister et al. (2019) synthesizes emerging evidence on paleoclimate using modern techniques that include CRN and luminescence dating, concluding eight regionally significant advances.

Paleoclimate modelling in the region has been relatively sparse. The first reconstruction was undertaken by Golledge et al. (2012), using climate proxy data and a Parallel Ice Sheet Model to reconstruct the Southern Alps during the LGM, which included data on the Waimakariri. Their findings concluded that there was approximately a cooling of 6-6.5 degrees Celsius and a 25% reduction in precipitation during the LGM compared to present day, to reach the newly found extents.

This was since succeeded by James et al. (2019), which used geomorphological evidence as a basis for a perfect plasticity model on ice thickness distribution in the southern alps named 'REVOLTA'. James et al. (2019) notably adjusted their extents at the catchment level to account for recent discoveries. This included a 20km downstream adjustment to the Otarama advance within the model output, based on the Surface Exposure Dating and mapping by Rother et al. (2015). Due to constraints, the LGM ice thickness modelling results from REVOLTA was unable to be included in this project. However, the study also provided extent mapping based on Rother et al. (2015) that was used as a cross reference in the final analysis. James et al. (2019) noted limitations of Golledge et al. (2012), including the underestimation of ice extents in Waimakariri, and the lack of recognition for spatially variable climatic differentials. Despite this, both models produced similar results for total ice volume km3 which shows consistency across methods.

Figure 21

Surface Exposure Dating

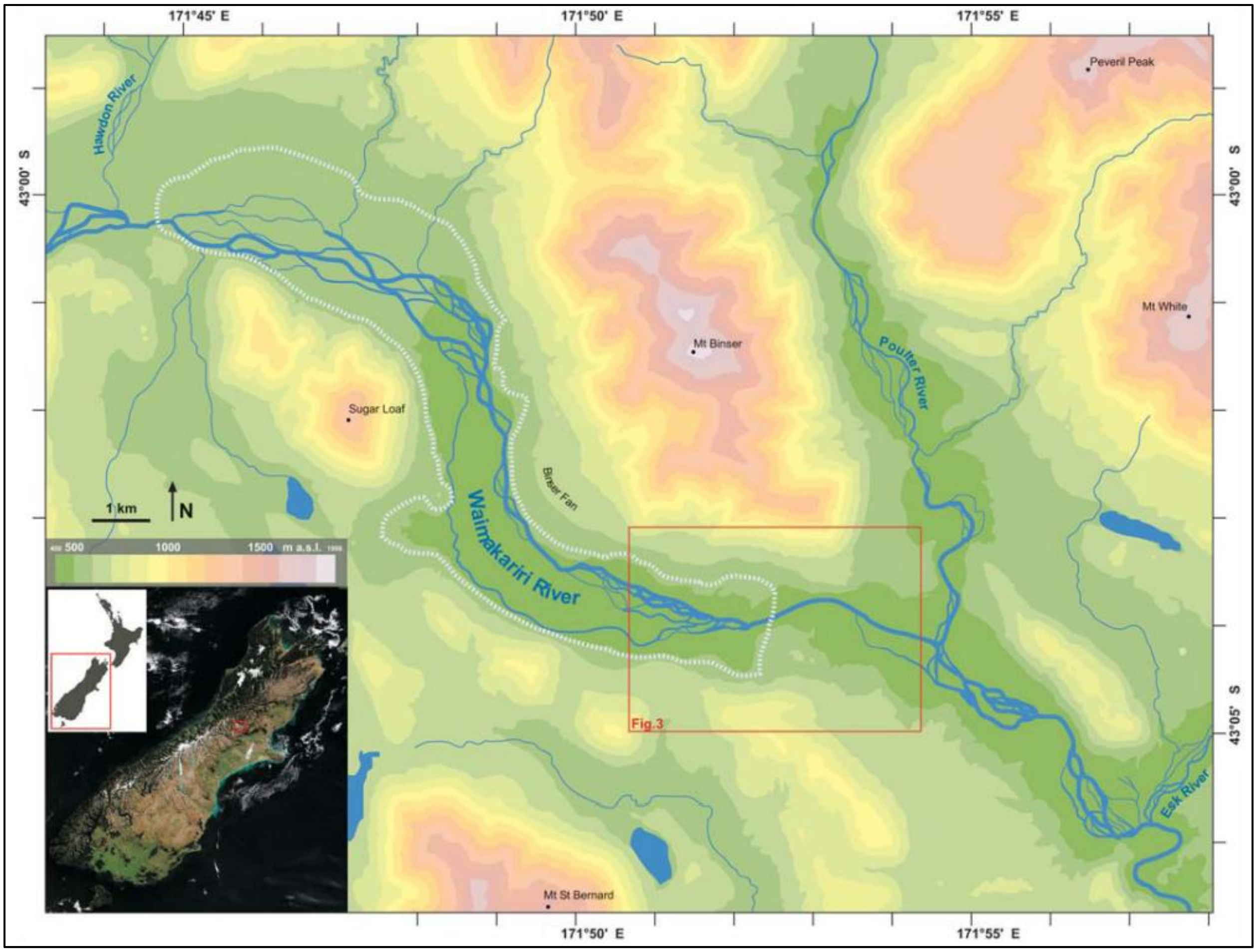


Note. Optimal surface elevation profile for LGM derived from REVOLTA. Blue triangles represent Surface Exposure Dated (SED) 'targets' for ice thickness distribution. Obtained from "A geomorphology based reconstruction of ice volume distribution at the Last Glacial Maximum across the Southern Alps of New Zealand," by W. James, J. Carrivick, D Quincey and N. Glasser, 2019, *Quaternary Science Reviews, 219*, pp. 20-35 (https://doi.org/10.1016/j.quascirev.2019.06.035).

Regionally, there has been ongoing scientific discoveries. Winkler et al. (2018) disestablishes the proposal of "Glacial Lake Speight" (figure 22) made by Gage (1958), citing Geomorphological mapping and analysis. Wrinkler et al. (2018) further noted the limitations of paleo glaciological modelling, noting how recent scientific progress are not always reflective in the larger scale data (which can be slow to update). This concept was carried through this project, where glacial extents were manually adjusted to fit the science provided by the explored literature.

Figure 22

Elevation Map of the Waimakariri



Note. Elevation map of the Upper Waimakariri showing the approximate outlines of the disestablished "Glacial Lake Speight" in red. Obtained from "A Disestablishing "Glacial Lake Speight", New Zealand? An example for the validity of detailed geomorphological assessment with the study of mountain glaciations," by S. Winkler, D. Bell, M. Hemmingsen, K. Pedley and A. Schoch, 2018, *Quaternary Science Reviews*, *67*, pp. 25-31 (https://doi.org/10.5194/egqsj67-25-2018).

Denton et al (2021) acts as one of the most current papers on New Zealand glaciation. The paper focuses on understanding two climactic knowledge gaps: (1) the cause of millennial-scale climate oscillations, and (2) why major climactic shifts like the LGM occurred synonymously in both hemispheres, despite contradictory summer solar radiation factors, named Mercers paradox. Their proposed hypothesis was an underlying climactic factor called the 'Zealandia switch', wherein orbital forcing on the southern hemisphere impacts global climate oscillations. The Zealandia switch creates important considerations and implications, which are felt throughout research, and which may transform scientific understanding of present and paleoclimate. Though Waimakariri is not specifically mentioned, Denton et al (2021) infer that chronology of major LGM mountain valley moraines like the neighbouring Rakaia chronology can be interpreted as a primary climatic record. Given the paradigm of paleoclimatology as an evolving science, the evidence is under constant reflection, analysis, and development. Considering this, it is reasonable to expect that the extents within this report will be gradually overturned by more accurate representations of the glacial climate at the time, as science and technology continues to grow and improve.

Interests to the Community Partner

This project was suggested by Di Lucas, and more broadly Lucas Associates. As a landscape architect, Di designs and advises on current landscape projects. However, she also stated her interests in landscapes which extend well beyond the scope of the city, and the present day. Di's aspirations were to convey glacial land-forming processes of the Upper Waimakariri to the public, in an easy-to-access and understandable manner. This project was tailored to encapsulate this vision – to convey the landscape as a dynamic system heavily influenced by the ice-driven erosional and depositional geomorphic process of previous glacial eras. In terms of being available to the public, the work produced was uploaded to a website Di is strongly affiliated with – Landtyping.co.nz. This is where the maps, storyboard, and shapefiles will be available for public use. It can be expected that future research lies in extending the scope of this project to encompass areas beyond the Upper Waimakariri, within other catchments of the Southern Alps.

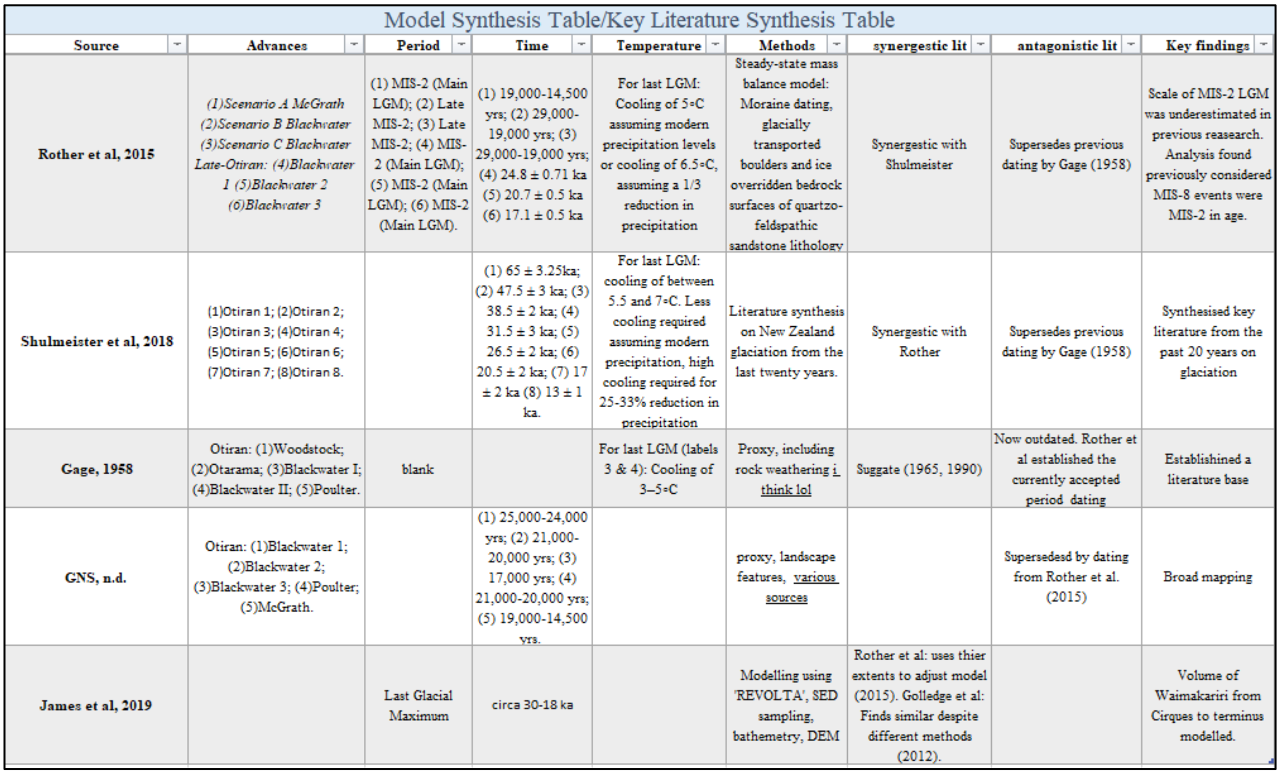
Conclusion

The history of New Zealand is held within its complex, dynamic landscape. Preserved remnants, like that from glaciers, are foundational pieces of evidence which shed light on an extinct environment and climate, that of which is different from today. The upper Waimakariri is a heavily glaciated environment, nestled within the mountainous range of the Southern Alps. The geomorphological history of this area is almost synonymous with the glaciation history, indicating the significance of ice as a powerful driver behind environmental change considering this, the story of this area has two main narratives – one of which is focused on the fluctuations of glaciers across time, and the other, focused on capturing the land-forming processes that come in turn. This project was able to encapsulate these narratives and contextualise broader glacier-climate relationships through exploring glaciation in the Upper Waimakariri. The findings of which were then presented on storyboard, a medium which allows the story of the landscape to be effectively visualised and understood by the public. Future research lies in undertaking field-research within the Waimakariri to incorporate site-specific information, extending the scope of the project to other catchments as well as undertaking a broad literature analysis, one that analyses the different perspectives of glaciation within the area. In this way, the story of the New Zealand landscape can continue to be written.

Acknowledgements

This project was completed with the help from Di Lucus, our community partner who provided such great enthusiasm and joy for this project that it was hard not to do the same. This project also acknowledges the help of our tutor, Peyman Zawar-Reza, who provided essential guidance and help, and for Simon Kingham who organised this paper and gave us this opportunity. We would also like to take this time to thank Emma Coumbe, one of our group members, who helped to create the foundation of this project.

Appendix 1



Model Synthesis Table/Key Literature Synthesis Table

Source	Advances	Period	Time	Temperature	Methods	synergestic lit	antagonistic lit	Key findings
Rother et al, 2015	*(1)Scenario A McGrath (2)Scenario B Blackwater (3)Scenario C Blackwater Late-Otiran: (4)Blackwater 1 (5)Blackwater 2 (6)Blackwater 3*	(1) MIS-2 (Main LGM); (2) Late MIS-2; (3) Late MIS-2; (4) MIS-2 (Main LGM); (5) MIS-2 (Main LGM); (6) MIS-2 (Main LGM).	(1) 19,000-14,500 yrs; (2) 29,000-19,000 yrs; (3) 29,000-19,000 yrs; (4) 24.8 ± 0.71 ka (5) 20.7 ± 0.5 ka (6) 17.1 ± 0.5 ka	For last LGM: Cooling of 5°C assuming modern precipitation levels or cooling of 6.5°C, assuming a 1/3 reduction in precipitation	Steady-state mass balance model: Moraine dating, glacially transported boulders and ice overridden bedrock surfaces of quartzo-feldspathic sandstone lithology	Synergestic with Shulmeister	Supersedes previous dating by Gage (1958)	Scale of MIS-2 LGM was underestimated in previous reasearch. Analysis found previously considered MIS-8 events were MIS-2 in age.
Shulmeister et al, 2018	(1)Otiran 1; (2)Otiran 2; (3)Otiran 3; (4)Otiran 4; (5)Otiran 5; (6)Otiran 6; (7)Otiran 7; (8)Otiran 8.		(1) 65 ± 3.25ka; (2) 47.5 ± 3 ka; (3) 38.5 ± 2 ka; (4) 31.5 ± 3 ka; (5) 26.5 ± 2 ka; (6) 20.5 ± 2 ka; (7) 17 ± 2 ka (8) 13 ± 1 ka.	For last LGM: cooling of between 5.5 and 7°C. Less cooling required assuming modern precipitation, high cooling required for 25-33% reduction in precipitation	Literature synthesis on New Zealand glaciation from the last twenty years.	Synergestic with Rother	Supersedes previous dating by Gage (1958)	Synthesised key literature from the past 20 years on glaciation
Gage, 1958	Otiran: (1)Woodstock; (2)Otarama; (3)Blackwater I; (4)Blackwater II; (5)Poulter.	blank		For last LGM (labels 3 & 4): Cooling of 3–5°C	Proxy, including rock weathering i think lol	Suggate (1965, 1990)	Now outdated. Rother et al established the currently accepted period dating	Establishined a literature base
GNS, n.d.	Otiran: (1)Blackwater 1; (2)Blackwater 2; (3)Blackwater 3; (4)Poulter; (5)McGrath.		(1) 25,000-24,000 yrs; (2) 21,000-20,000 yrs; (3) 17,000 yrs; (4) 21,000-20,000 yrs; (5) 19,000-14,500 yrs.		proxy, landscape features, various sources		Supersedesd by dating from Rother et al. (2015)	Broad mapping
James et al, 2019		Last Glacial Maximum	circa 30-18 ka		Modelling using 'REVOLTA', SED sampling, bathemetry, DEM	Rother et al: uses thier extents to adjust model (2015). Golledge et al: Finds similar despite different methods (2012).		Volume of Waimakariri from Cirques to terminus modelled.

Appendix 2

Description

The areas outlined below are of importance due to their cultural, societal, and recreational significance to the broader Canterbury district. In addition, each area has rich glaciological history, providing an insight into the formation of the Upper Waimakariri Catchment.

Arthurs Pass

The Bealey Valley region where Arthur's Pass Village is located has a particular geomorphological feature. The Bealey River runs through a somewhat large riverbed and floodplain to form the valley's base, and the hills are typically reasonably steep. The river follows the path cut by glacial advances in the upper sections of the Bealey Valley (Paterson, 1996).

Several glacial moraines in the Bealey Valley have been recognised as recording small Holocene advances throughout the Holocene epoch (Paterson, 1996). However, only the glacial features, such as the steep, U-shaped valleys, have been retained as evidence of the deposits generated during the great Pleistocene glaciations (Paterson, 1996).

Arthur's Pass present day is a mix of extensive shingle riverbeds, beech forest, deeply gorged rivers, and dense rainforest, depending on the side of the main divide you stand.

Cass Station

Glacial geology is particularly well displayed in the Cass Basin, with valleys well filled with the Waimakariri Glacier ice flow during the earlier advances during the Otira glaciation period (Burrows et al., 1977). Today the Cass Basin is filled with montane grasslands, scrub, riverbed, scree, beech forest, swamp, bog, lake, stream and alpine habitats.

Lake Grasmere

Lobes of the Waimakariri Glacier advanced and then retreated from this area several times during the Pleistocene. Since the ice ablation, more alluvial fans have been built out into the valleys; as such, high-country alluvial fans can be seen between Lake Pearson and Lake Grasmere (Department of Conservation, n.d.). Today, this lake is a popular trout fishing destination and home to a wide array of native avian wildlife.

Lake Pearson

Similar to Lake Grasmere, lobes of the Waimakariri Glacier advanced and then retreated from this area several times during the Pleistocene. Since the ablation of the ice, more alluvial fans have been built out into the valleys. The large alluvial fans from Mount Manson and Purple Hill almost divide the lake in two (Department of Conservation, n.d.).

Mount White

Overlooking the stunning braided Waimakariri River and the Craigieburn Valley, Mount white sits East of the Cass Basin. At 1,741m tall, it is a clear result of the tectonic uplift known to form the Southern Alps. Mount White Station is at the mountain's base, a high-country farm utilising the post-glacial rich environment.

Castle Hill

Lying between the Torlesse and Craigieburn Mountain ranges, Castle Hill is characterised by its distinctive rock formations. These formations are the water-eroded remnants of limestone formed during the Oligocene age 30-40 million years ago, with New Zealand dominantly covered in water (CastleHill.NZ, n.d.).

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