Glacial geomorphology of the Ahuriri River valley, central Southern Alps, New Zealand

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ABSTRACT
Detailed geomorphological mapping of ice-related and post-glacial landforms is widely used to explain past glacial geomorphological description of the landform assemblages produced by the former Ahuriri Glacier, Southern Alps, New Zealand (44° 15′ S, 169° 36′ E). The Southern Alps of New Zealand experienced multiple episodes of glaciation during the Late Quaternary with large mountain glaciers in many valleys, but very little is known about the Ahuriri River valley, one of the main tributaries of the Waitaki River. We selected a region extending approximately 45 km downstream from the headwaters of the Ahuriri River covering an area of about 532 km². Our goal was to create a detailed 1:38,000 scale glacial geomorphological map of this area and provide a geomorphological context to support future geochronological work. Glacial geomorphological mapping was performed by combining several field investigations and remote sensing surveys. We provided high-resolution spatial information for all the glacial-related landforms shown on the map (see main Map). The distribution of post-glacial landforms in the middle and lower section of the main valley outline at least three advances or stillstand phases of past glaciers and suggesting the maximum length (∼41 km) of the former glacier during the Last Glacial Maximum. Most of the tributary valleys were also probably covered by ice at this time. Other prominent but smaller size moraine landforms, mostly in the tributary river valleys, also suggest relatively small, post-glacial advance phases of former glaciers.

1. Introduction
Geomorphological mapping is an established tool for reconstructing and documenting landscape development (Seijmonsbergen, 2013). There are two primary approaches in geomorphological mapping (Chandler et al., 2018): (i) Classical – with mapping all geomorphological features and different landforms. This approach of mapping also defines the formation of all landscape terrain located at any particular area. This approach is mainly used in Europe (e.g. Klimaszewski, 1990; Rączkowska & Zwoliński, 2015). (ii) Thematic – e.g. detailed geomorphological mapping in glacial environments which mainly emphasis glacial and periglacial landforms and processes (e.g. Bendle et al., 2017; Darvill et al., 2014; Izagirre et al., 2018). This type of mapping helps us in understanding past glacier behaviour and processes in any particular place.

A number of glacial-geomorphological studies have recently been published on both individual river basins in New Zealand (Borsellino et al., 2017; Evans, 2008; Wallace, 2001) and regionally in the central Southern Alps (Barrell et al., 2011). The Ahuriri River valley lies to the south and outside of the boundary of the existing central Southern Alps mapping. However, Late Quaternary glaciation has created well-preserved landforms in this valley that can be used to understand palaeo-glacier extent and behaviour. Thus, there is a need to provide a detailed geomorphological description and map for this area. The detailed geomorphological mapping will help to better understand past glacier-climate interactions in the Southern Alps and in the Southern Hemisphere in general.

2. Study location and previous work
2.1. Study location
The Southern Alps are located in the Southern Hemisphere in South Island, New Zealand, and span approximately 700 km from north-east (41° S 173° E) to south-west (45° S 167° E). Both western and eastern slopes of the mountain range are occupied by glacial valleys of various ages, many of which are infilled with glacial lakes, especially on the eastern side. There are seventeen mountain peaks in the Southern Alps that exceed 3000 m above sea level (a.s.l.) with
Aoraki/Mount Cook – the highest point of New Zealand (3724 m a.s.l.) (NZ Topo Map, 2016).

The Ahuriri River is one of the largest river systems in Waitaki (Mackenzie) River basin, flowing about 70 km southeastward from its headwater before reaching the Ahuriri Arm of artificial Lake Benmore – one of the lakes in the Waitaki hydroelectric project. The selected area of this study covers the upper portion of the Ahuriri River catchment, spanning 45 km from the headwater and approximately 532 km² in area (Figure 1). Landscapes of the Ahuriri River valley form as a function of climate, elevation and tectonics, and a diversity of erosional processes including glacial, periglacial, fluvial and gravitational.

2.2. Previous work

The glacial geomorphology of both the eastern and western side of the central Southern Alps was documented by Barrell et al. (2011) on a five sheet 1:100,000 scale geomorphological map and in an associated monograph. This work shows the distribution of a range of landforms, such as glaciers, moraines, and outwash plains. These landforms are placed in broad age groups, emphasising different climatic events. Particular attention is paid to glacial landforms of Late Quaternary age.

Further detailed glacial-geomorphological investigations have been carried out in individual river basins following Barrell et al. (2011). For example, Putnam et al. (2013) presented a record of glacier behaviour during the local Last Glacial Maximum from Lake Ohau, situated just east of the Ahuriri catchment. Based on detailed glacial geomorphological mapping and 10Be surface-exposure dating methods they produced a robust chronology of well-preserved terminal moraines. Overall, they distinguished six major moraine landforms across the study area. Borsellino et al. (2017) provided large scale 1:20,000 glacial geomorphological map of the Brabazon and Butler Downs, Rangitata River valley. They mapped and subdivided glacial landforms into three main zones, such as kame terraces, kettles and meltwater channels, and lateral moraines. Strand et al. (2019) used glacial geomorphological mapping along with 10Be surface-exposure dating in order to study the left-lateral moraine sequence of the palaeo Pukaki Glacier. They identified six different moraine landforms dating to the Last Glacial Maximum. Sutherland et al. (2019a) generated a 1 m digital elevation model (DEM) based on airborne LiDAR data along with high-resolution aerial imagery and field observations to analyse well-preserved glacial geomorphology surrounding Lake Tekapo. They distinguished a group of Last Glacial Maximum moraines and described in detail landform assemblages such as the glacio-lacustrine, glacio-fluvial, supra-glacial, sub-glacial, and recessional ice-marginal features.

Figure 1. a - Hillshaded 15 m Digital Elevation Model (Columbus et al., 2011) showing the area covered by the map presented with this paper. b - Locations and orientation of photographs presented in Figures 3–7 are shown by red dots and black boxes. Location of aerial imagery presented in Figure 8 is shown by black box.
3. Methods

3.1. The geomorphologic approach

In this study, we used the methodology of Barrell et al. (2011) as a baseline for our geomorphological approach. We used this thematic mapping approach, because this map is the first step towards a climate reconstruction from the glacial history — achieving this goal required consideration of all landscape elements as interaction of glacial and non-glacial landforms (e.g. cross-cutting relationships) can inform the glacial history. In total, four general land surface features were mapped as polygon, line, and point symbols based on their geomorphologic characteristics: hillslope landform features, moraine landform features, fluvial landform features, and other landform features (Table 1). In addition, we were guided by the glacial landform interpretations developed within recent studies listed in Table 1.

3.2. Mapping and compilation method

The glacial geomorphology of the area surrounding the Ahuriri River valley was mapped using a combination of remote sensing analysis and field work. The geomorphological mapping was conducted by visual interpretation of high-resolution (40 cm) individual co-registered aerial imagery (140 sheets) from the New Zealand (NZ) national dataset (2014). High-resolution Google Earth images were also used for the mapping in areas where cloud cover was present in photos, or where the three-dimensional (3D) landscape recognition was required. Basic topographic variables (e.g. contours, rivers) are derived from the NZ LINZ Topographic online collection (https://data.linz.govt.nz). The images and maps were overlain on a 15 m resolution digital elevation model (DEM) (Columbus et al., 2011) to provide topographic context, elevation range and to aid landform type (or shape) identification in areas of complex terrain.

Field campaigns in April 2019 and February 2020 allowed us to crosscheck features mapped from remote imagery and maps. We did not cover the entire ~532 km² study area on the ground due to the remote and challenging nature, however we accessed the major landform features by 4 × 4 vehicle and general hiking tracks in the main river valley.

Based on the field work and detailed visual analysis we mapped the shape, size, position and surface composition of glacier-related landform systems visible in the aerial imagery and topographical maps. All the landforms and objectives were mapped using ESRI ArcMap software (version 10.6.1). All files were projected in the New Zealand Transverse Mercator 2000 (NZTM2000) grid system. The map was exported into the Adobe Illustrator CS7 from ArcGIS for final editing (see Main Map). The full data sources used in this study are listed in Figure 2.

4. Results

4.1. Glacial geomorphology

The 1:38,000 scale glacial geomorphological map of the Ahuriri River valley (see Main Map) presents a variety of glacial-related landform assemblages that are summarised below and in Table 1. These include modern glaciers, rock glaciers, cirques, ice-scoured bedrocks, ice-contact slopes, moraines (moraine ridges and hummocky moraines), outwash plains, and alluvial fans. All landform types were classified and manually digitised as polyline and polygon shapefiles. The Main Map also includes other landform types (e.g. steep eroded slopes, active scree slopes, vegetated scree slopes, debris cones, river terraces, active river plains, alluvial plains, etc.) and topographic features (e.g. rivers, lakes, peaks, fault lines, etc.), which are useful for topographic and physiographic context.

4.1.1. Modern glaciers

There are very few modern glaciers in the Ahuriri River basin and they are mainly located in the headwater of the main river. The largest glacier of the entire catchment (Thurneysen Glacier ~ 0.9 km²) is located in the headwater of the Canyon Creek (44° 9' 56" S, 169° 35' 55" E) (Figure 3). Modern glaciers were identified using the most current version of the Global Land Ice Measurements from Space (GLIMS) glacier database. These outlines come to GLIMS via the Randolph Glacier Inventory (RGI. https://glims.org/RGI/). Original outlines are primarily from Chinn (2001), which were derived by manual delineation using oblique aerial photography collected in 1978. The GLIMS database has had several regional updates (e.g. Gjermundsen et al., 2011), with the first comprehensive revision published recently by Baumann et al. (2020). This recent update used semi-automatic classification, based on average resolution (~15 m) Landsat 8 and Sentinel 2 imagery from the year 2016. While this approach is well-suited for national-scale assessment, the resolution is less appropriate for a larger-scale mapping such as that presented here. We thus took an independent approach to glacier delineation, which involved manual modification of the previous GLIMS outlines. This manual classification high-resolution (40 cm) aerial imagery from Land Information New Zealand (https://data.linz.govt.nz). Overall, we identified 22 modern glaciers in the Ahuriri River basin with total area of about 2.2 km².
| Landform category          | Landform type             | Morphology/general description                                                                 | Possible identification errors                          | Interpretation                                                                 | Reference                      |
|---------------------------|---------------------------|-------------------------------------------------------------------------------------------------|----------------------------------------------------------|--------------------------------------------------------------------------------|--------------------------------|
| Hillslope landform features | General bedrock terrain    | Land surface developed on bedrock, beyond the limits of Late Quaternary glaciers. Commonly has irregularly dissected surface texture produced by fluvial gullying or gravitational erosion processes. | Possible underestimation where bedrock is obscured by vegetation. | Marks former areas of relatively thick, fast-flowing and warm-based ice causing efficient subglacial erosion. | Barrell et al. (2011)          |
|                           | Ice-sculpted bedrock      | Widespread exposures of bare or lightly vegetated bedrock, sometimes containing small lake basins. Evidence for extensive areas of former ice at pressure melting point. |                                                          |                                                                                 |                                |
|                           | Steep eroded slope        | Cliff face or steep slope formed on poorly consolidated deposits. Large-scale version of the terrace edge geomorphic feature. | Potential for confusion with active scree slopes.         |                                                                                 | Barrell et al. (2011)          |
|                           | Active scree slopes       | Accumulations of debris on steep valley slopes at the foot of rockwalls.                        | Possible, but unlikely, confusion with steep eroded slope. |                                                                                 |                                |
| Moraine landform features  | Moraine ridge             | Ridges of positive relief that display arcuate, crenulate or saw-tooth planform, and sharp crests. | Very low-relief ridges may be difficult to detect in imagery and possible confusion with trimlines. | Indicate former ice-front position. Characteristic landform features are ice-contact slopes. | Barrell et al. (2011), Bendle et al. (2017), Izagirre et al. (2018), Leger et al. (2020) |
|                           | Hummocky moraine terrain  | Hummocky or irregular surface texture of rises or troughs developed on ice-deposited (glaciogenic) sediments. Crests are less well defined than moraine ridges. Includes lateral and terminal moraine. | Boundaries of individual ridges are difficult to delimit. Linear patterns are difficult to map in the field. Will be missed in areas not covered by high-resolution aerial photography. | Marks former ice-marginal zone, or zone of stagnant ice. | Barrell et al. (2011), Darvill et al. (2014), Bendle et al. (2017) |
|                           | Outwash plain             | Large, open, approximately flat surfaces graded to former ice-limits (e.g. moraines). Often dissected by meltwater channels and relax stream networks. | Exact limits of outwash are often difficult to define. Surface grading is often only apparent in the field or over large distances on high-resolution aerial photos. Often form narrow corridors, so can be difficult to distinguish from channels. | Indicates former pathways of meltwater during glacier advance or still-stand. Characteristic landform features are terrace edges. | Barrell et al. (2011), Darvill et al. (2014), Bendle et al. (2017), Leger et al. (2020) |
|                           | Alluvial plain             | As for outwash, but where the water source was mainly from non-glaciated catchments.            |                                                          |                                                                                 | Barrell et al. (2011)          |
|                           | Alluvial fan               | Sub-horizontal fans on valley sides and on distal parts of the outwash plains, often fed by meltwater channels or streams. | Possible misinterpretation as ice contact deposit.        | Reworking of unconsolidated material by contemporary meltwater channels and streams. | Glasser and Janson (2008), Izagirre et al. (2018) |
|                           | Debris cone                | Cone- or fan-shaped accumulations of sediment at the base of a steep gully, chute or tributary valley. Typically, steeper than alluvial fans, which are similar morphologically. | Possible misinterpretation as rockfall.                  | Record the deposition of successive debris flows.                             | Chandler et al. (2019)         |
|                           | River terrace              | Raised, relatively flat areas located immediately adjacent to, or near, a stream or river. Characteristic landform features are terrace edges. | Potential for confusion with linear features such as palaeo shorelines. | The result of periods of aggradation and incision.                             | Chandler et al. (2019)         |
| Other landform features    | Peak                       | Mountain peaks, often pyramidal in shape due to glacial and periglacial erosion on two or more sides. | Possible misplacement due to snow or ice on the summit. A DEM helps to pinpoint the exact summit. | Divides one or more present or former ice masses.                            | Izagirre et al. (2018)         |
|                           | Cirque                     | Up-slope crest of a formerly glaciated, amphitheatre-shaped basin (corrie).                     | Possible, but unlikely, confusion with mass movement or landslip Scars. | Records local cirque glaciation during phases of glacier advance/recession.    | Glasser and Janson (2008), Barrell et al. (2011), Izagirre et al. (2018) |

(Continued)
| Landform category | Landform type | Morphology/general description | Possible identification errors | Interpretation | Reference |
|-------------------|---------------|-------------------------------|--------------------------------|----------------|-----------|
| Contemporary glacier | Bare ice, snow and debris. Surface structures such as crevasses and seracs are common. | Possible overestimation in glacier extent if confused with snow cover. Possible, but unlikely, misinterpretation as rockfall deposit. | Indicative of slope instability. | Barrell et al. (2011) |
| Rock glacier | Wrinkled or undulatory surface developed on an accumulation of angular rock debris, with ridges transverse to the down-slope direction. | | | Barrell et al. (2011) |
| Hanging Valley | Mouth of a formerly glaciated valley where it adjoins a larger, deeper, formerly glaciated valley. Line is oriented, so that it can be symbolised with teeth that point upstream into the hanging valley. | | | Barrell et al. (2011) |
| Landslide terrain | Prominent breaks on the slope originating a steeped topography with presence of linear features and small lacustrine basins or mass wasting deposits with signs of downslope flow associated to semi-circular scarp in the headwall. | No significant changes in colour in comparison with moraine ridges or moraine terrain. Flowslide deposits are similar to moraine terrain. Fieldwork and high-resolution DEM are needed for proper identification. | Indicative of slope instability. | Soteres et al. (2020) |
| Rock avalanche deposit | Broken bedrock deposit from a destabilised slope. | Potential for confusion with landslide deposit. | | |
| Active river plain | Bare river bed or the episodic floodplain of a water course. Boundaries between contiguous floodplains are drawn at confluences. | | | Barrell et al. (2011) |
| Lake | Bodies of water surrounded by land (with no link to the sea). Extent of many lakes is very seasonally variable – so their size can vary in different imagery and in the field. | Not always obvious in aerial photos (a counterpart photo is sometimes necessary). | Indicate impeded drainage and can result from rock basins formed by glacial over deepening. | Glasser and Jansson (2008), Darvill et al. (2014), Izagirre et al. (2018) |
| River and stream | Channels of water draining a valley. | | Indicate contemporary drainage routes and may be sourced from modern glaciers. | Izagirre et al. (2018) |
| Waterfall | Water flows over a vertical drop or a series of steep drops in the course of a stream or river. | | | |
| Swamp | Low-lying area with wetland vegetation. | | | Barrell et al. (2011) |
| Alluvial fan | Formline denoting the down-slope direction on alluvial fans. Drawn schematically to give a visual sense of fan geometry. | Potential for confusion with alluvial plain. | | Barrell et al. (2011) |
| Fault | Topographic step produced by late Quaternary tectonic fault displacement or buckling of the ground surface. | | | Turnbull (2000), Rattenbury et al. (2010), Barrell et al. (2011) |
| Cliff and terrace edge | Break of slope around flat-area edges. Line is oriented, so that it can be symbolised with ticks on the downslope side. | Potential for confusion with shorelines. | Individual terraces indicate down-cutting and aggradation events. | Glasser and Jansson (2008), Izagirre et al. (2018) |
| Ice contact slope | Steep escarpment of predominantly glaciofluvial sediment that was deposited against the wall of glacier ice, marking the position of relatively static ice margin; an irregular scarp against which glacier ice once rested. | Possible confusion with morainic complexes or outwash plains. | Sediments deposited by streams draining tributary valleys onto/against glacier ice. Indicate the thickness and extent of ice. | |
| Palaeo-shorelines | A linear, smooth-continuous sediment outline, characterised by a mono elevation-interaction with topography. Only visible in the field or from high-resolution imagery. | Potential for confusion with linear features such as terrace edge, low-relief moraine ridge or, kame terrace. | Indicates former lake surface levels. Some shorelines indicate the presence of former icedammed lakes. | Glasser and Jansson (2008), Leger et al. (2020) |
4.1.2. Rock glaciers

Surface morphology and size makes rock glaciers easily identifiable in high-resolution imagery. Based on permafrost presence and mobility of rock glacier, three activity states are distinguished: active (containing ice, moving), inactive (containing ice, not moving), and relict rock glaciers (not containing ice, not moving) (Martin & Whalley, 1987). Latest rock glacier inventory for the Southern Alps has been recently completed by Sattler et al. (2016) accounting majority of rock glaciers to the east of the Main Divide in high-altitude areas (Sattler et al., 2016). Based on this study almost 60% of the mapped rock glaciers were classified as relict features that no longer contain ice. Rock glaciers from the Ahuriri River valley were omitted in this study.

Morphological evidence for rock glacier identification includes ridges and furrows, lateral slopes and steep front, collapse structures, flow structures and distinct changes of the slope in the rooting zone (Schmid et al., 2015). For digitisation of the individual rock glacier boundaries we also followed the most recent polygon-based rock glacier inventory by Wagner et al. (2020). The distribution of rock glaciers...
4.1.3. Cirques
Cirques are amphitheatre-shaped hollows on the headwater slopes of the main river valley (e.g. 44° 4’ 29″ S, 169° 39’ 51″ E). They usually display sharp boundaries with the surrounding terrain. Cirques are concentrated in areas that have been deglaciated since the Last Glacial Maximum and the concave shapes of glacial cirques are open on the downhill side. The features are particularly well-developed in tributary valleys such as Ahuriri River East Branch (44° 17’ 57″ S, 169° 43’ 31″ E), Snowy Gorge Creek (44° 15’ 38″ S, 169° 39’ 22″ E), and Canyon Creek (44° 10’ 43″ S, 169° 34’ 38″ E). The floor of some cirques most often contain small lakes (tarns) behind the dam (moraine or bedrock), which mark the downstream limit of the glacial over deepening (Figure 3).

4.1.4. Ice-sculpted bedrock
Many examples of ice-sculpted bedrock landforms are found in our study area. They include broad benches and flattened spurs on former glacier valley sides as well as valley floors and cirque basins. A prominent example is found on the eastern slope of the main river valley at the conjunction of Watson Stream next to the largest landslide terrain (44° 12’ 22″ S, 169° 38’ 15″ E). Also notable is the Canyon Creek valley, where the full spectrum of ice sculpted bedrock is presented, ranging from cirque headwalls (44° 10’ 9″ S, 169° 35’ 11″ E) to the valley floor (44° 11’ 26″ S, 169° 35’ 23″ E) (Figure 3). Relatively small features of ice-sculpted bedrock are present at the head of the main river valley (44° 5’ 3″ S, 169° 40’ 57″ E), as well as Ahuriri River East Branch (44° 17’ 5″ S, 169° 45’ 5″ E) and Watson Stream (44° 8’ 42″ S, 169° 41’ 34″ E). The ice-sculpted bedrock terrain in the study area has been primarily identified using satellite and aerial imagery due to difficulty of access, although ice-sculpted bedrock in the middle and lower sections of the main river valley were confirmed in the field.

4.1.5. Ice-contact slopes
These accumulations represent ice-contact glaciofluvial deposits that have been mainly formed over the floor of the valley or low-lying bedrock outcrops. The topography marks former marginal or terminal positions of both Ahuriri and side valley glaciers. The best example of this feature is presented in the middle section of the main river valley (largest terminal-lateral moraine ridge), while relatively small features are present in the Ahuriri River East Branch basin. Even smaller and relatively young ice-contact slopes are also located in the headwater of the main river valley.

4.1.6. Moraine terrain
Moraines can form as a result of a different geomorphological processes, depending on ice dynamics,
sediment characteristics, and the location on the glacier at which the moraine forms (Benn & Evans, 1998). Processes of moraine formation can be conditionally divided into active and passive. Active processes form or rework moraine deposits directly through glaciotectonism. This includes moraine ridges of pushing and thrusting blocks, which often consist of tills and reworked proglacial deposits (Bennett, 2001). Passive processes include the placement of chaotic supra-glacial deposits around a former glacier margin with limited processing (reworking), usually with the formation of hummocky or hilly moraines. These moraines are composed of supraglacial deposits from the ice surface (Kjær & Krüger, 2001).

4.1.6.1. Moraine ridges. The mapped moraine ridges in the Ahuriri River valley are mainly single, linear or curvilinear, elongate features exhibiting ~5 to 40 m relief that demarcates the limits of former glacier margins. They are often discontinuous, and it is rare to find entire lateral-terminal moraine ridges. The prominent terminal-lateral moraine system (44° 15′ 44″ S, 169° 36′ 41″ E) runs for approximately four kilometres in the middle section of the main river valley between 760 and 800 m a.s.l. This feature comprises fragmentary crested ridges (divided by meltwater channels or river streams), usually up to a few hundred metres long and less than 40 metres high (Figure 5). Other lateral moraine ridges are present on the left bank of the Ahuriri River (44° 22′ 36″ S, 169° 40′ 6″ E; between Snowy Gorge Creek and Ahuriri River East Branch). Two more less-well defined ridges located at the lowest section of the main valley, between Ahuriri and Avon Burn rivers. The length of this first possible moraine ridge is ~2.1 km (44° 25′ 11″ S, 169° 39′ 51″ E) while the second one is ~1.7 km long (44° 25′

![Figure 5. Glacial geomorphological mapping comparison in 3D. a – Lateral-terminal moraine ridge in the middle section of the Ahuriri River valley with surrounding area (photo by L. Tielidze). b – Key landscape elements are shown in the accompanying sketch. Figure 1 shows exact location of this area.](image)

![Figure 6. Hummocky moraine surface in the lower section of the Ahuriri River valley (photo by L. Tielidze). Figure 1 shows exact location of this area.](image)
40° S, 169° 40′ 50″ E). A smaller ~1 km-long moraine ridges extends below a well-preserved cirque in the Ahuriri River East Branch basin at an elevation between 1440 and 1220 m a.s.l. (44° 19′ 4′′ S, 169° 42′ 38′′ E). Several well-preserved terminal and lateral moraine systems are discovered near the head of the valley (the unnamed third right tributary) of the Ahuriri River, at an elevation of 1280 and 1190 m a.s.l., ranging from 150 to 500 m long (44° 7′ 56″ S, 169° 38′ 39″ E). Groups of minor and relatively recent moraine ridges are frequent in the headwater of the main river valley, Canyon Creek, and Snowy Gorge Creek, where they exhibit sharp crest lines.

4.1.6.2. Hummocky moraines. One large hummocky moraine unit (~3.5 km length and 1.6 km width) was identified in the lower section of the main river valley, defining a former ice margin (~760 m a.s.l.). The surface of this landform is significantly broader than moraine ridges described above and are not sharp-crested, however, it is often scattered with large 1 to 2 m (diameter) sized greywacke boulders. Two small ponds occur on the surface of this terrain. The upper surfaces of the hummocky moraine in some places are occasionally lined by low hardly distinguishable relief ridges that range in height from 1 to 5 metres above the smoothed rounded surface (Figure 6). The middle part of the terrain is cut by meltwater channels dividing it into two parts, northern (44° 23′ 54″ S, 169° 39′ 48″ E) and southern (44° 24′ 36″ S, 169° 40′ 25″ E). Overall it was difficult to distinguish individual ridges/ice-contact slopes on the hummocky terrain even during the field investigation.

A smaller hummocky moraine system was identified near the confluence of Ahuriri River and Snowy Gorge Creek (44° 21′ 6″ S, 169° 39′ 16″ E). The surface of this terrain is strongly modified by meltwater channels and possible by Snowy Gorge Creek. Several small pond and swamps occur on the surface of this hummocky system.

4.1.7. Outwash plains

A large outwash plain is present in the lowest section of our study site. It is characterised by broad, gently sloping surfaces of glaciofluvial gravel and sand. The plain was identifiable on aerial imagery as a planar surface with clear meltwater channels with several terrace levels were identified within the outwash. These have been mapped separately along with main river stream and active river bed dividing the outwash surface into two sections (Figure 7).

4.1.8. Alluvial fans and debris cones

Alluvial fans are common throughout the Ahuriri study site, some of them associated with drainage originating in side valleys. Fans vary greatly in size depending on the amount of source material. Most of the fans on aerial imagery are characterised by conical or semi-conical shapes. The majority of the fans are observed on the right side (west relative to Ahuriri.
River) slopes across the main river stream, while the largest alluvial fan is located at the conjunction of the Ahuriri and Snowy Gorge Creek (44° 20′ 37″ S, 169° 38′ 35″ E) (Figure 8). The surface of this fan is strongly modified by fluvial processes. Most of the other fans are less eroded and often vegetated by shrubs and grasses.

Debris cones in the Ahuriri River valley are mostly attributed to smaller creeks that increase their flow seasonally during periods of increased snowmelt or rainfall.

4.1.9. Palaeo lake landforms

Proglacial lakes are a common feature of present-day glacier retreat in the Southern Alps (Kirkbride, 1993) and may have been pervasive after the Last Glacial Maximum (Thomas, 2018). Sutherland et al. (2019b) identifies several major landform features for identifying former proglacial lakes in the Southern Alps. These landforms are: sub-aqueous mass flow deposits, shorelines, grounding zone wedge, sub-lacustrine moraine, palaeo-delta, iceberg grounding structure, and below wave base lacustrine deposits. We identify the following evidence in the Ahuriri River valley:

1. multiple shorelines (44° 23′ 25″ S, 169° 39′ 31″ E) at different elevations (720–740 m a.s.l.) occur inner (upper) valley side of hummocky moraine system which likely represents initial impact of lake regression. These shorelines represent single platforms nested at single elevations and stretching from ~50 to ~300 of metres. Overall, there are three clearly visible (and a few more uncertain) shorelines running parallel to each other (Figure 9a);

2. a small/thin deposit of possible lacustrine sediments was found during the field investigation, approximately 2 km upstream from the hummocky terminal moraine system. The top 1 m of this sediment consisted of fine fraction clay–mixed sand or silt, while the lower unit (0.5–1.0 m) consisted of gravels (Figure 9b). However, since the river has a low inclination in this section and is characterised by meanders, an alternative explanation for sediment creation can be an oxbow lake;

3. the valley profile suggesting that this hummocky terminal moraine (44° 23′ 24″ S, 169° 39′ 52″ E) was likely merged with the lateral moraine at the other side of the river (44° 23′ 55″ S, 169° 40′ 1″ E), which may have created a dam (Figure 9c);

Figure 8. a – High-resolution (40 cm) aerial image showing the largest alluvial fan and surrounding area in the lower section of the Ahuriri River valley. b – Digitised example of geomorphological mapping conducted for the same place. Figure 1 shows exact location of this area.
(4) former ice-contact lakes associated with glacier retreat after the Last Glacial Maximum in the Southern Alps are often associated with gently sloping terrain due to sedimentary infilling (Sug-gate & Almond, 2005; Thomas, 2018). Today, the valley floor immediately inboard of the

Figure 9. a – Palaeo-shorelines on inner side of the hummocky moraine system. Figure 1 shows exact location of this area. b – Possible lacustrine sediments (gravels and sand) in 2 m-high sediment exposure at the left bench of the Ahuriri River. c – Terminal and lateral moraine systems and possible palaeo lake covered area.

Figure 10. A general overview of simulated palaeo Lake Ahuriri. Elevation profile of the possible glaciolacustrine basin is presented as an inserted diagram based on yellow dotted line (from A to B point) on main image. The lake depths are conditional for the modern day and are marked by circles (O) at the different distance on both images. Lake bathymetry was provided according to the palaeo lake shorelines based on DEM contours. Red star shows the location where lacustrine sediments were found (see also Figure 9b). The blue dotted line shows the maximum possible level of the lake, where the hypothesised lake level coincides with the maximum elevation of the moraines. This is a theoretical limit as we did not find any evidence confirming former lake existence at this level.
hummocky moraines is occupied by active river plains, wetlands, alluvial plains, and alluvial fan deposits. This low-inclination (∼3 m/1 km) surface may also be weak evidence of former lake presence.

In order to see the possible area that covered by a former lake we did a DEM-based simple computer calculation. Based on our hypothetical estimate, the post-glacial lake which might have occupied the Ahuriri River valley had a total area of about 14.4 km². It is possible that, after recession of the former Ahuriri Glacier, a lake became impounded behind the hummocky moraine system that blocked the gorge and extended for about 13 km up valley. The surface level of the lake could not have an elevation higher than the highest point of the impounding moraines (∼750 m a.s.l. Figure 10). We think that the subtle evidence for the lake in the Ahuriri River valley today likely represents shallow/short-lived nature, which has largely been overprinted by subsequent fluvial aggradation.

5. Discussion

The spatial distribution of the glacial landform assemblages in the Ahuriri River basin provides evidence for more extensive glaciation during the Late Quaternary, as well as glacier recession and post-glacial sedimentation. Clear evidence of former extensive glaciers includes the presence of well-preserved moraine ridges in the main and tributary river valleys. Large hummocky moraine system in the lower section of the main valley (44° 23′ 54″ S, 169° 39′ 48″ E and 44° 24′ 36″ S, 169° 40′ 25″ E) outlines the maximum length (∼41 km) of the former glacier. It is likely that small glaciers in tributary valleys (Canyon Creek, Watson Stream, Hodgkinson Creek, Snowy Gorge Creek, and Birch Creek) merged with main trunk of the former Ahuriri glacier at during the Glacial Maximum. The prominent terminal-lateral moraine ridge in the middle section of the main valley (44° 15′ 44″ S, 169° 36′ 41″ E) indicates a more limited advance or stillstand of the former valley glacier with a length of ∼23 km. Other prominent but smaller size moraine landforms mostly in the tributary river valleys (see Main Map) also suggesting relatively small advance phases of former glaciers.

Based on our investigation it is reasonable to assume that glaciation in the Ahuriri River valley was smaller in scale than those in other river valleys in the Waitaki River basin (e.g. Putnam et al., 2013; Strand et al., 2019; Sutherland et al., 2019a), which is broadly consistent with the lower-elevation headwaters of the Ahuriri River valley. Additionally, the distribution and number of post-glacial landforms such as multiple terminal-lateral moraines in the Ahuriri River valley is relatively smaller than in other well-mapped valleys in the central Southern Alps. For example we found only one well-preserved moraine ridge in the middle section of the main valley and two terminal hummocky moraine system at the lower section of the valley, while Putnam et al. (2013) and Strand et al. (2019) described at least six different moraine landforms that were formed by the Ohau and Pukaki glaciers during the Last Glacial Maximum.

Geomorphic evidence for a lake to have ever existed in the Ahuriri River valley is weak. If such a lake did exist during deglaciation then it was likely shallow, as it has since silted up entirely, unlike other larger lakes, Pukaki, Tekapo, etc., which receive much higher sediment inputs (Hicks et al., 2011). Weak evidence for former lake occupation suggests that the lake did not persist for very long and thus was likely shallow, exerting little influence on glacier length changes. A similar pattern of post-glacial lake evidence elsewhere in New Zealand was found by Barrell et al. (2019) in current lake-free the upper Rangitata River valley.

6. Conclusions

This paper presents the first comprehensive map of the glacial geomorphology of the Ahuriri River valley, in the central Southern Alps, New Zealand. Geomorphological mapping from high-resolution aerial imagery, large scale topographical maps, average resolution DEM (15 m), and several field investigations allowed us to produce this 1:38,000 scale map for the entire study site covering an area of about 532 km² (see Main Map). Mapped landforms consist of modern glaciers, rock glaciers, cirques, ice-scoured bedrocks, former ice-contact slopes, moraine terrain (moraine ridges and hummocky moraines), outwash plains, and alluvial fans, which have not been previously recorded. This map will provide the necessary context for robust dating of the former Ahuriri Glacier limits and will assist future investigations on the glacial history of this study site.

The main findings highlight several important characteristics of the glacial geomorphology:

(1) Even though the surface morphology of the Ahuriri River valley has been modified (eroded or buried) by post-glacial fluvial processes (e.g. alluvial fans, debris fans) there are still well-preserved glacial landforms allowing us to understand past glacier behaviour.

(2) Hummocky moraines at the base of the Ahuriri River valley suggest that the maximum length of the former glacier could have been ∼41 km. Furthermore, the ∼17 km distance between two prominent moraine landforms (well-preserved moraine ridge in the middle section and hummocky moraine
system at the lower section of the valley) suggests two major advances or stillstands of former glacier occurred during the Late Quaternary.

(3) Geometric and field investigation of the lower valley suggest the potential occurrence of a small, shallow proglacial lake shortly after the former glacier retreated from it’s maximum extent. The lake area could not have exceeded \( \sim 14.4 \text{ km}^2 \) with a length \( \sim 13 \text{ km} \). In comparison, the former Ahuriri Lake was about four times smaller than Lake Ohau today (\( \sim 54 \text{ km}^2 \)). Such a restricted lake is unlikely to have affected glacier response to climate change.

Software

The Geographic Information System ArcGis® 10.6.1 (ESRI) software was used to digitise, visualise, and map all the datasets. Google Earth Pro was used for three-dimensional (3D) landscape recognition and map all the datasets. Google Earth Pro was used for three-dimensional (3D) landscape recognition and improved interpretation. The final editing of the map and photos was made with Adobe Illustrator CS7 and was exported from to pdf format.

Acknowledgements

We are grateful to the landowners who permitted to work on their property. We thank Lisa Dowling and Emily Moore for help in the field. The authors also wish to thank the Google Earth software (https://www.google.it/intl/en/earth/) and Land Information New Zealand data service (https://data.linz.govt.nz/) for providing aerial photos and topographical maps used for investigations. We gratefully acknowledge the support of the associate editor, Dr. Jasper Knight, and three reviewers, Peter Almond, Jenna Sutherland, and Chandra Jayasuriya, for useful suggestions and detailed comments which clearly enhanced the quality of the paper.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by Victoria University of Wellington (Doctoral Scholarship) and Marsden Fund – Royal Society of New Zealand [grant number E3230].

Data availability

The new database created during the investigated period will be submitted to PANGAEA* Data Publisher (https://www.pangaea.de/) and can be used as a basis data set for future studies.

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