New Zealand Journal of Geology and Geophysics

ROYAL SOCIETY TE APĀRANGI

RESEARCH ARTICLE OPEN ACCESS

Rangitīkei River Terraces Formed During the Otira Glaciation: Lithostratigraphic Type Sections, Review and Conceptual Model

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Received: 30 April 2025 | **Revised:** 5 January 2026 | **Accepted:** 27 January 2026

Keywords: loess | Otira Glaciation | Quaternary | Rangitīkei River | river terraces | tephra | Whanganui Basin

ABSTRACT

The Rangitīkei Valley in the lower North Island of New Zealand contains flights of river terraces that are influenced by changes in sediment supply, stream power and base level associated with Quaternary climate events over the last ~350 thousand years. Despite providing a valuable record of past environmental change, most work on the Rangitīkei terraces remains unpublished, and a majority of the stratigraphic units lack formal definition. Our study presents a review of the Rangitīkei River terraces and new reference and type sections for the lithostratigraphic units formed during the Otira Glaciation, building on the seminal work of Derek Milne. Site selection is based on outcrop quality, ease of access and health and safety considerations whilst aiming to preserve historic precedence and geographic proximity to associated place names. A conceptual model of Rangitīkei terrace formation is presented, highlighting the transition out of full glacial conditions where reduced sediment supply and increased stream power result in incision, upstream knickpoint migration, reworking of alluvium and terrace formation. This model provides an update on earlier work by incorporating concepts around knickpoint retreat and the complex response of the fluvial system to produce multiple terrace levels within a single terrace set.

1 | Introduction

Many of New Zealand's young, active landscapes have been shaped by rivers, glaciers and coastlines in response to Quaternary climate events and related changes in vegetation, sediment supply, temperature, precipitation and sea level (Newnham et al. 1999). The Rangitīkei Valley in the lower North Island of New Zealand (Figure 1) is particularly young, having only largely emerged from the sea during the Quaternary (Beu et al. 1981; Naish and Kamp 1995). Ongoing Late Quaternary uplift has preserved a suite of river terraces that records the strath or former bed level of the river and the switch from aggradation to degradation in response to one or more controls such as climate, uplift, sediment supply and base level (Milne 1973; Litchfield and Berryman 2005). Overlying loess-paleosol cover beds provide complementary sedimentological and pedological evidence that refine our understanding of climate controls on the fluvial system.

The Rangitīkei River terraces were first described by Te Punga (1952) and later surveyed in detail by Milne (1973) who separated them into eight 'cold climate' terrace sets spanning 350 thousand years. Milne (1973) undertook detailed soil stratigraphic analysis, presenting a series of depositional and soil weathering facies and introducing many of the stratigraphic names that continue to form the basis of work in the Rangitīkei today. Furthermore, this framework has now been utilised in many areas around New Zealand, including Gisborne (Berryman et al. 2000), Wairarapa (Vella et al. 1988; Palmer et al. 1989; Vucetich et al. 1996), Wellington (Melhuish et al. 1997; Litchfield et al. 2004), Southland and

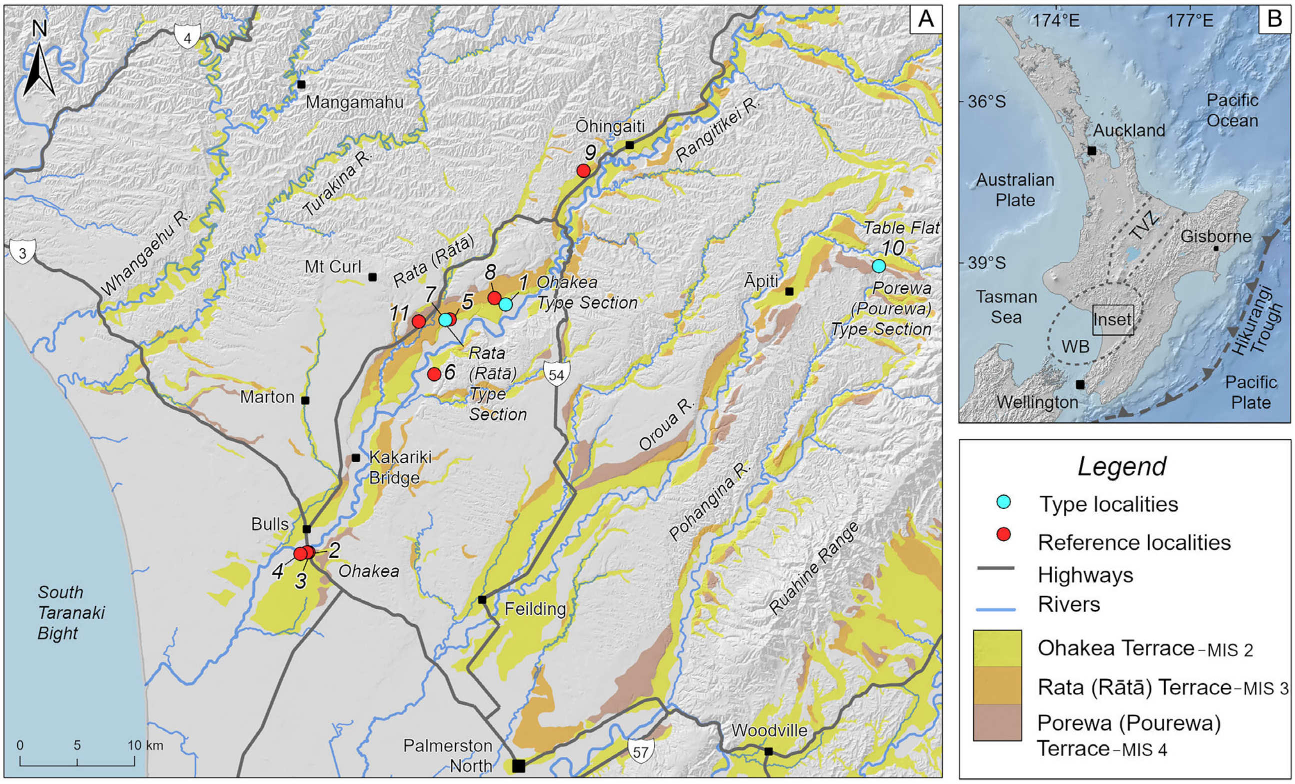

FIGURE 1 | (A) Distribution of MIS 2-4 river terraces, type and reference localities (numbered sites) along the Rangitīkei and adjacent rivers. Geological data from the GNS QMAP 1:250 000 project. (B) Location of the study area relative to the Taupō Volcanic Zone (TVZ), Whanganui Basin (WB) and Hikurangi Trough (Townsend et al. 2008).

Otago (Berger et al. 2002). Each river terrace has a unique loess-paleosol cover bed succession, and recognition of key rhyolitic marker horizons has allowed for correlation to the high-resolution astronomically tuned Marine Isotope Stages (MIS) (Pillans and Kohn 1981; Pillans et al. 1993; Naish et al. 1998) and magnetostratigraphic record (Pillans 1994).

Leamy et al. (1973) set out seven type localities and associated type (stratotype) and reference sections for paleosols within the Rangitīkei terrace record, focusing on terrace exposures between the Porewa (Pourewa) river terrace (MIS 4, ~70–80 ka) and the Ararata marine terrace (MIS 11, ~400 ka). This was done to take advantage of areas with thick and complete cover bed successions, good access and exposure quality. No formal type localities or sections have been designated for the terrace alluvium. The names introduced by Te Punga (1952) and Milne (1973) are now in common usage as New Zealand Quaternary chronostratigraphic units (Vucetich et al. 1996; Berryman et al. 2000; Formento-Trigilio et al. 2003; Litchfield and Rieser 2005; Hewitt et al. 2021). However, the units lack type sections and therefore remain informal.

Here, we aim to support the seminal work of Te Punga (1952), Milne (1968), Milne (1973) and Leamy et al. (1973) by providing a review of the Rangitīkei River terraces and formally introducing type and reference sections for lithostratigraphic units formed during the Otira Glaciation, spanning MIS 2–4. Our selection criteria are outcrop quality, ease of access, landowner relationships, health and safety considerations, preserving historic precedence and achieving geographic proximity to associated place names where practical. We present photographs and stratigraphic logs of type and reference sections to support geotourism, education and ongoing research in the Rangitīkei. The development of Rangitīkei River terraces is illustrated by presenting a terrace model and describing the valley morphology with examples, including concepts around knickpoint retreat and the complex response of the Rangitīkei River to changes in internal system dynamics.

2 | Approach to Use of Māori Names

This article uses the spelling 'Whanganui' rather than 'Wanganui' as recommended by the New Zealand Geographic Board (Ngā Pou Taunaha o Aotearoa). The use of 'Whanganui Basin' as opposed to 'Wanganui Basin' was first introduced into published literature by Lowe (2015) and Pillans (2017). We also use the spelling 'Rangitīkei' rather than 'Rangitikei' when referring to the Rangitīkei River or Rangitīkei River Valley, noting that currently, the official name for the district remains the 'Rangitikei District' according to the New Zealand Geographic Board (Ngā Pou Taunaha o Aotearoa) and New Zealand Gazetteer.

New Zealand is a relatively young country. Our society and two official languages, Māori and English, continue to change, evolve and expand over time. According to Pou Kōrero (tribal historians), some of the geographic names in the Manawatū-Whanganui Region are misspelt and are inconsistent with correct pronunciation. There is a history in the Manawatū-Whanganui Region of compiling spelling errors and submitting them to the New Zealand Geographic Board (Ngā Pou Taunaha o Aotearoa) to seek an official name change. This often proceeds through territorial authorities in consultation with iwi and can be controversial, as the current names have often been in use for over 100 years and have taken on new meaning to the people accustomed to their use. To complicate matters further, geographic names are often used to name geological units in scientific literature. Many of these names have been introduced over the last 100 years with minimal iwi consultation and are well-established in the literature, again taking on new meaning to the people accustomed to their use.

For example, 'Porewa' is the current official name for a stream and geographic locality in our study area. It's correct Māori spelling according to Pou Kōrero and in keeping with the correct pronunciation is 'Pourewa'. This name has also been given to one of the Rangitīkei River terraces, Porewa (Pourewa) Terrace introduced by Milne (1973) during his seminal work in the Rangitīkei. Since 1973, this name has been cemented in the geological literature, both in terms of the terrace but also the associated loess deposit and interval of geological time (Milne and Smalley 1979; Palmer et al. 1989; Grapes 1991; Vucetich et al. 1996; Berryman et al. 2000; Formento-Trigilio et al. 2003; Litchfield and Rieser 2005; Hewitt et al. 2021). This name originating from the Rangitīkei has now been associated with many other areas and geological exposures throughout New Zealand (Berryman 1990; Grapes 1991, 1993; Vucetich et al. 1996; Berryman et al. 2000; Litchfield and Rieser 2005; Wilson et al. 2007).

To change a scientific name solely on the basis of a related official place name change or to accommodate a spelling correction is not advised in either the North American Stratigraphic Code (Easton et al. 2005) or the International Stratigraphic Guide (Salvador 1994). The status quo retains historic precedence and avoids unnecessary complications surrounding the history or use of a name, particularly when many complications arise purely from scientific developments.

To address this issue in our article, we retain the original stratigraphic names of Milne (1973) to maintain historic precedence and avoid any potential unnecessary confusion but also include in parentheses the correct Māori spelling. This makes for a somewhat more cumbersome manuscript, but it does effectively highlight where these differences occur. All Māori names have been checked for accuracy by Utiku Potaka (Strategic Advisor and Pou Kōrero for Te Rūnanga o Ngāti Hauiti). They are included in the article to ensure our research partners are able to relate to and understand this research and foster uptake. We also include these Māori names to acknowledge the work iwi are undertaking to highlight what are often spelling errors resulting from historic accidents or errors in translation during early European settlement in New Zealand.

3 | Stratigraphic Terminology

In this article, we use the stratigraphic terminology of Te Punga (1952) and Milne (1973) for the Rangitīkei River terraces formed during the Otiran Glaciation: Ohakea, Rata (Rātā) and Porewa (Pourewa) in order of increasing age. When referring to the related interval of geological time, we add an 'n': Ohakean, Ratan (Rātān) and Porewan (Pourewan).

Milne (1973) subdivided the Otiran Glaciation and Aranuian Interglacial Stages of Gage and Suggate (1958) and Suggate (1961) into the Ohakean, Apitian, Ratan (Rātān), Orouan and Porewan (Pourewan) substages. Milne (1973) defined the Ohakean, Ratan (Rātān) and Porewan (Pourewan) substages by gravel, loess and fan alluvium deposits laid down during stadials when the climate was cold enough to cause substantial devegetation of the main axial ranges. Interstadials (Apitian and Orouan) were defined by paleosols (Whanahuia and Kimbolton, see Site 10 in Supporting Information File A) developed in the top of loess beds and gravels deposited during the preceding cold climate substage, representing weathering during a phase of climate warm enough to allow substantial revegetation of the main axial range.

These climate-based time-stratigraphic substages proposed by Milne (1973) for the North Island of New Zealand have been used throughout the literature (Leamy et al. 1973; Palmer et al. 1989; Marden and Neall 1990), yet have never been correlated to or fully constrained by high-resolution climate proxy records. The Ohakean substage (~10–30 ka) includes multiple New Zealand Climate Events that are resolvable in the high-resolution climate proxy records of Alloway et al. (2007) and Barrell et al. (2013). Therefore, the Ohakean, and presumably the other substages, correspond to periods of geological time defined principally by river behaviour and should not be equated to climate events.

Fluvial systems have built-in lags related to response and relaxation times and are influenced by internal feedbacks and thresholds (Schumm 1973; Bull 1991). These act to reduce the sensitivity of the fluvial system to climate change on short timescales, leading to a degree of decoupling between shifts in climate and fluvial response. Furthermore, correlation of river terraces between valleys is problematic given changes in stream gradient, power, sediment supply and tectonic history.

Additional chronostratigraphic work is required to constrain the timing of fluvial response in the Rangitīkei Valley to allow composite type sections to be defined for the Ohakean, Ratan (Rātān) and Porewan (Pourewan) substages, according to the North American Stratigraphic Code (Easton et al. 2005). Given the complex response of fluvial systems as they adjust to internal system dynamics independent of external drivers such as climate, it could be useful to consider the definition of diachronic units for the substages that account for unequal spans of time represented by specific lithostratigraphic (alluvium and loess sheets) and pedostratigraphic units (paleosols).

In this article, we present new lithostratigraphic type and reference localities and sections for the Ohakea, Rata (Rātā) and Porewa (Pourewa) terraces to support geotourism, education and ongoing research in the Rangitīkei. The lithostratigraphic units presented include the strath, alluvium and overlying cover bed deposits associated with each terrace, delimited on the basis of lithic characteristics and stratigraphic position and conforming to the Law of Superposition. We give the terraces and associated lithostratigraphic units capital letters to formalise the names.

Herein, the Otira Glaciation refers to MIS 2, 3 and 4, and Ohakean time refers to ~10–30,000 years ago, including the Last Glacial Maximum (LGM) *sensu stricto* defined by Alloway et al. (2007) as the interval centred on 21,000 ± 3000 cal. year BP. Terminology such as the Last Glacial Coldest Period (LGCP) introduced by Alloway et al. (2007) for MIS 2 between ~28,000 and 18,000 cal. year BP is not adopted here as the Rangitīkei River terrace record currently lacks the detailed dating required to firmly establish correlations to the high-resolution records from Auckland maars, Kaipo, Otamangakau and Okarito wetlands, marine cores and speolothems presented in Alloway et al. (2007). We do not present new data in this article to refine the Rangitīkei terrace chronostratigraphic units but rather compile, retain and summarise existing ages based on previous work (Milne 1973; Pillans et al. 1993; Pillans 1994; Litchfield and Berryman 2005).

Conventional ^{14}C ages cited in this article have been calibrated to the calendrical timescale using OxCal version 4.4 (Bronk Ramsey 2021) and the SHCal20 atmospheric curve (Hogg et al. 2020). Calendar/calibrated ages from ^{14}C dating are reported in cal. year BP, 'present' being taken as AD 1950 (Stuiver and Polach 1977). Calibrated ages are included alongside conventional ^{14}C ages in brackets as 2-sigma ranges, representing a 95% probability. Optically and post-infrared infrared stimulated luminescence dating cited in this article are assumed to represent calendar years before the time of sample collection.

4 | Geological Setting

The islands of New Zealand are the surface expression of a large, mostly submerged subcontinent named 'Zealandia' that sits astride a convergent margin between the Pacific and Australian plates (Figure 1) (Townsend et al. 2008; Mortimer 2025). Subduction of the Pacific Plate and deformation of the overriding Australian Plate along the Hikurangi Subduction Margin generates~ uplift, earthquakes and volcanic activity in the North Island (Eberhart-Phillips et al. 2008; Henrys et al. 2025).

The Rangitīkei Valley occurs in a proto-back-arc position behind the subduction interface in the partly inverted Late Miocene-Quaternary Whanganui marine basin (WB, Figure 1). This basin contains ~4.5 km of dominantly marine sedimentary fill unconformably overlying Mesozoic greywacke–argillite. The basin depocentre migrated southeast through the Quaternary, whilst simultaneous uplift and offlap occurred along the northern and eastern margins (Fleming 1953; Anderton 1981). Uplift and erosion along the North Island Dextral Fault Belt has resulted in piercement through the basin fill and formation of the main axial range (Kingma 1959; Rees et al. 2019). The current topographic expression of the main axial range is thought to have largely formed through the Quaternary (Beu et al. 1981; MacDonald-Creevey 2011). Remnant marine and river terrace deposits now found capping structural highs between Palmerston North and Whanganui suggest a majority of the terrace and hill country landscapes have formed in the last ~300–400 ka. Older marine terraces (~400–680 ka) occur west of Whanganui, where uplift has been concentrated along the western basin margin (Pillans 1990).

The WB is bordered to the north by the Taupō Volcanic Zone (TVZ), the youngest volcanic zone in the central North Island's volcanic region. Voluminous, widespread welded and nonwelded ignimbrites and airfall deposits originating from the TVZ have provided an important source of sediment to the WB over the last ~2 Ma (Carter 1972; Pillans 1991; Shane 1993; Shane et al. 1996; Rees et al. 2018). The present area of active volcanism extends from White Island in the northeast to the Tongariro Volcanic Centre (TgVC) in the southwest, a zone that includes all activity over the past ~350 ka (Houghton et al. 1995; Gamble et al. 2003; Tost and Cronin 2015).

The Ruapehu and Tongariro ring plains within the TgVC are dissected by several southward flowing rivers that have transported Late Quaternary volcaniclastics into the WB and played an important role in Late Quaternary landscape development (Te Punga 1952; Campbell 1973; Milne 1973; Tost et al. 2015; Tost and Cronin 2016). The Hautapu River, a tributary of the Rangitīkei River, once provided a more direct connection to the TgVC up until ~15 ka when subsidence of the Ruapehu Graben and piracy by the Whangehu River is thought to have isolated the Rangitīkei River from Mt Ruapehu and its active source of volcaniclastic sediment (Kósik et al. 2022). TgVC andesite pebbles to boulders are common within Rangitīkei River terrace alluvium and on the Holocene floodplain (Te Punga 1952; Milne 1973). Large boulders of andesite relating to partial collapse of Mt Ruapehu at ~125–150 ka and subsequent reworking of volcaniclastic debris down the Rangitīkei Valley can be found as remnant deposits of Mataroa Formation on the Greatford River Terrace (MIS 5d, ~110–120 ka) and as sporadic reworked boulders on Ohakea through to Porewa (Pourewa) aged river terraces (MIS 2–4) as far south as Rata (Rātā).

5 | Physiography and Climate

The Rangitīkei River rises in the highly fractured Mesozoic greywacke–argillite of the Ruahine and Kaimanawa ranges and transports gravel bedload southwestward towards the Tasman Sea (Richardson and Fuller 2010). Its modern-day planform is best described as wandering, representing a transitional pattern between a multithreaded braided and single thread meandering channel (Ferguson and Werritty 1983; Fuller 2007; Fuller 2008). West of the Rangitīkei, rivers lack a modern-day source of greywacke–argillite, their headwaters instead located in the Cenozoic volcanics of the central volcanic plateau and soft sedimentary rock of the WB.

Moving from the headwaters, the Rangitīkei River becomes deeply entrenched within a broad belt of hill country underlain by soft WB sediments that extends from the foot of the Ruahine Range west, towards Taranaki. The hill country comprises subdued to steep (20°–40°) slopes, with a dominant south–southwest aspect. Erosion combined with the east–west strike of sedimentary units has formed a degree of uniformity in the landforms, characterised by similar slope angles and summit height accordance (Molloy 1998). Denudation of the soft, actively uplifting WB fill has formed a fine dendritic drainage pattern (Neall 1982).

The study area is characterised by dominant westerly winds and moderate temperatures without great extremes, including warm summers (15°C–22°C) and mild winters (1°C–10°C) (Radcliffe 1976; Cowie and Rijkse 1977; Chappell 2015). On average, rainfall does not show a strong seasonal trend. Rata (Rātā) receives on average between 1000 and 1100 mm/year, increasing towards the main axial range to >2000 mm/year (Fuller et al. 2016). Evapotranspiration follows a seasonal pattern, leading to potential soil moisture deficits in summer, depending on soil water holding capacity (Cowie and Rijkse 1977). Soil moisture deficits occur on average 10–15 days in both January and February (Burgess 1988; Hedley and Yule 2009).

6 | Methods

In this study, we scoped roadside, track, cliff and quarry exposures through the Manawatū-Whanganui hill country, specifically targeting terraces formed during the Otira Glaciation, MIS 2–4. Efforts were made to revisit any exposures described in the literature, particularly those described by Milne (1968), Milne (1973) and Leamy et al. (1973). We often found that old roadside exposures have become heavily vegetated. Rules for working along highways have also changed, with additional health and safety considerations and limitations around cleaning down sections. In response, we have excluded any potential sites on state highways and tried to seek sites that are dry and near vertical to encourage the persistence of a fresh outcrop face. Final type and reference site selection is based on outcrop quality, ease of access, landowner relationships, health and safety considerations, preserving historic precedence and achieving geographic proximity to associated place names where practical.

Sections were photographed and described using the guidelines of Palmer (n.d.) and Milne et al. (1995). Our method for determining soil drainage class varies from Milne et al. (1995) in that we only consider low chroma (grey) mottles as described in Palmer and Wilde (1990). Grey mottles indicate the water table or capillary fringe devoid of oxygen (reducing) for some period of the year. Hand texture follows the guidelines of Palmer (n.d.) based on the texture triangle from the US Department of Agriculture. The 25,360 ± 160 cal year BP Kawakawa Tephra (Vandergoes et al. 2013), a widespread product of the Oruanui supereruption from the Taupō volcano, is recognised in outcrop based on its stratigraphic position within the lower third of the Ohakea Loess. Soils are classified according to Hewitt (2010) and Clayden and Hewitt (2015). A Global Positioning System (GPS) was used to survey the type and reference localities. Local residents were sought whenever possible to obtain historical information on the local geology, soils and history of human modification.

Horizons Regional Council (HRC) provided access to 0.3 m ortho-rectified aerial photographs (2021–2022) with a final spatial accuracy of ±0.5 at 95% confidence level in clear flat areas, a 1 m Lidar-derived Digital Elevation Model (DEM) (2015–2016) with a nominal vertical accuracy of ±0.15 m and a 1 m photogrammetry-derived Digital Surface Model (DSM) (2015–2016) with a final spatial accuracy of ±0.6 m at 95% confidence level in clear open areas. Historic aerial photography was also sourced from the Crown aerial imagery archive. All coordinates and maps in this article use the New Zealand Transverse Mercator 2000 projection (NZTM2000) based on the NZGD2000 datum using the GRS80 reference ellipsoid.

7 | Type Sections

7.1 | MIS 2—Ohakea Type Section

A number of Ohakea Terrace sections outcropping between Bulls and Hunterville are documented in this study and presented in Supporting Information File A and B. An Ohakea Terrace type section was chosen along Putorino (Pūtōrino) Road near Rata (Rātā) (E 1820537, N 5569931) (Figures 2 and 3). Part of this section has been described and assessed for air permeability by Rees et al. (2020) and has been sampled for luminescence dating by Guyez et al. (2022) (sample RO_57 dated at 17.4 ±1.9 ka). Although the road cut is partially overgrown, it still provides near continuous exposure through a moderately well-drained Brown soil, Ohakea 1 Terrace gravel alluvium, a strath and approximately 10 m of underlying Pleistocene Rewa Formation (~1.2 Ma) (Rees et al. 2019). This type section is chosen in preference to sections around the Ohakea Aerodrome (namesake of the Ohakea Terrace set by Te Punga 1952) due to better exposure of the strath, its convenient and safe location along a quiet country road and its proximity to one of the most outstanding flights of river terraces preserved in the Rangitīkei Valley occurring between Rata (Rātā) and Mt Curl (Figure 1).

At the Ohakea type section, ~1 m of soil cover is present over ~5 m of Ohakea 1 gravel alluvium (Figures 2 and 3). Few rounded greywacke pebbles within the otherwise silt loam soil horizons suggest the soil has developed directly in Ohakea alluvium, which has weathered over the past ~15 ka under podocarp-hardwood forest (Cowie 1978).

Several reference sections (2–4) around the Ohakea Aerodrome are provided in Supporting Information File A. These sections provide continuous exposure through the soil and underlying Ohakea 1 Terrace gravels along Tangimoana Road. It is possible to observe the underlying strath in the eastern roadside drain at E 1802222, N 5547878 (Supporting Information File A); however, it is poorly exposed and the Ohakea Terrace dips below the Holocene fill approximately 8 km south of this locality.

A series of undulating (3°–7°) Late Ohakean dune deposits and sand ridges are recognised and described around the Ohakea Aerodrome (Supporting Information File A). The dunes overlie Ohakea 1 gravel alluvium and trend approximately west north–west, east south–east in the same orientation as the more prominent, undulating to steep (3°–35°) Foxton dunes (~6.5 ka) (Clement et al. 2010) to the south of Bulls. The Ohakean age dunes are up to 2 m high and extend over hundreds of metres, creating a subtle undulating pattern over the otherwise smooth surface of the Ohakea 1 Terrace tread. In contrast, the more prominent Foxton Dunes display up to 30 m of elevation change and have a greater influence on depth to the groundwater table, surface water pathways and the distribution of soil types.

7.2 | MIS 3—Rata (Rātā) Type Section

We designate a Rata (Rātā) Terrace type section off Te Hou Hou Road in Rata (Rātā) where a farm track exposes ~14 m of continuous outcrop (E 1815253, N 5568554) (Figures 2 and 4). The section contains a Pallic soil formed in Ohakea Loess. Kawakawa Tephra at ~1.6 m depth is enclosed by loess and dune sands. Dunes are prominent in the Rata (Rātā) area, forming undulating to rolling (4°–15°) topography up to 5 m high. The dunes occur along the confluence of the Porewa (Pourewa) Stream and Rangitīkei River, where thick Rata (Rātā) gravels (~10 m) and overlying dune sands suggest a concentration of fluvial aggradation and loess production. Reworking of associated finer sediment by the Porewa (Pourewa) Stream and subsequent gentle incision into the Rata (Rātā) 1 Terrace along the Rata (Rātā) flats has likely accentuated the dune topography.

Below the coverbeds, there is ~8.5 m of Rata (Rātā) gravel over an undulating strath (Figures 2 and 4A). Rip up clasts of underlying Kaimatira Pumice Sand Formation (~1 Ma) (Fleming 1953)

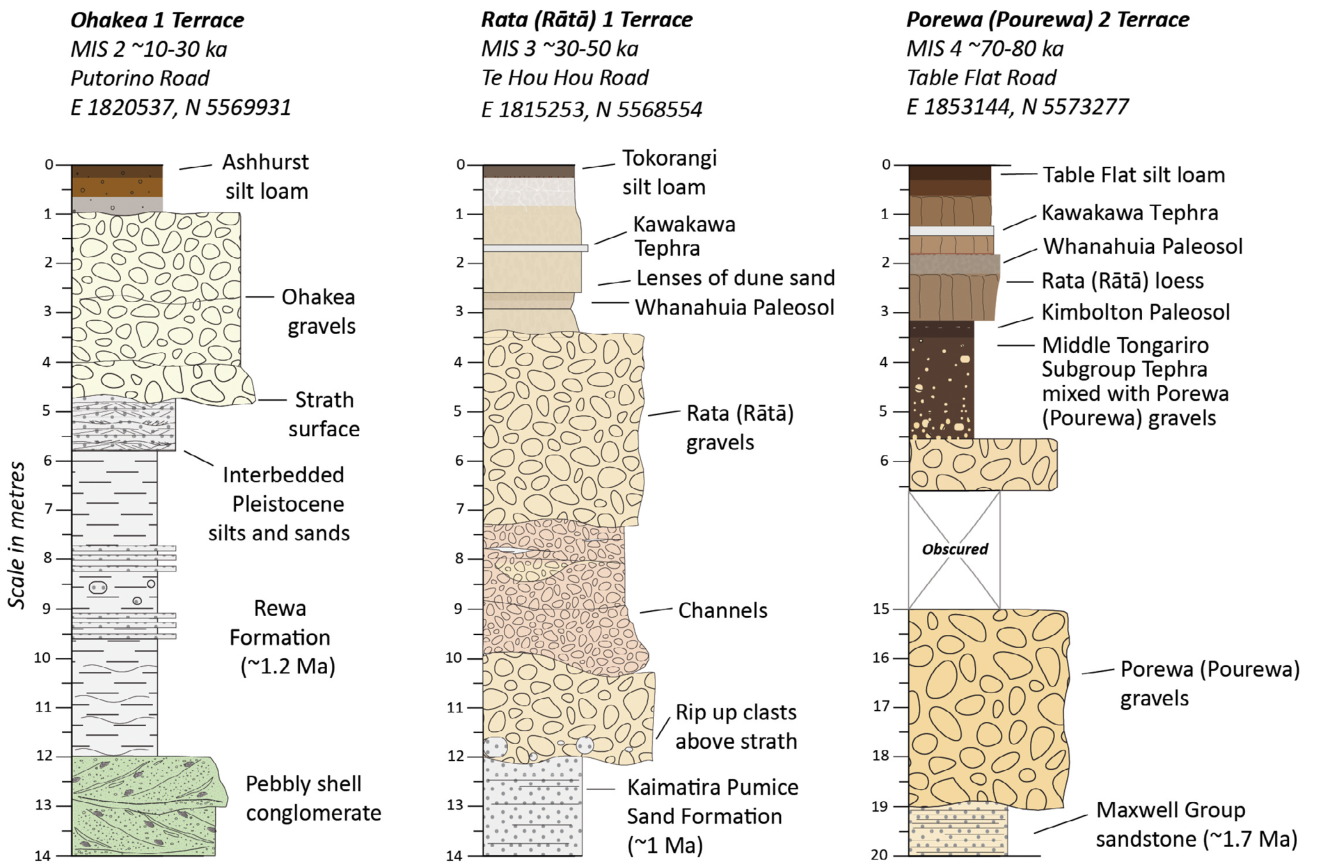

FIGURE 2 | Stratigraphic logs for river terrace sections in the Rangitīkei and Oroua valleys.

have been entrained into the gravel along the basal contact. Exposure of underlying Kaimatira Pumice Sand Formation is limited at the Rata (Rātā) type section, but further outcrop can be visited in the un-named stream valley below, including 2–3-m-thick wavy beds of coarse (2–100 mm long axis) sub-rounded Potaka pumice clasts containing charcoal fragments ~(Figure 4C). Reference sections for Rata (Rātā) 2 and Vinegar Hill (Rata (Rātā) 3) terraces are provided in Supporting Information File A.

7.3 | MIS 4—Porewa (Pourewa) Type Section

We could not find a suitable Porewa (Pourewa) section in the Rangitīkei Valley. Sites around Rata (Rātā) have been locally stripped of cover beds, contain fan alluvium or are overgrown. Excellent exposure of the Porewa (Pourewa) strath can be seen at the Kakariki Road cut (E 1807086, N 5556657); however, the overlying cover beds are difficult to access and the section is unsafe due to busy road conditions.

Leamy et al. (1973) designated a type section for the Whanahuia Paleosol (developed in Rata (Rātā) Loess) on Table Flat Road in the Oroua Catchment. This site has become overgrown since the 1970's but still contains good exposure of the cover bed stratigraphy, including Kawakawa Tephra and paleosols between loess sheets. Here, we propose that the type section of Leamy et al. (1973) is also used as the type section for the Porewa (Pourewa) Terrace alluvium and cover beds (E 1853144, N 5573277). This selection is based on the section containing the full cover bed succession with good contrast between beds, exposure of the Porewa (Pourewa) alluvium and strath and its location on a quiet country road where you can stop safely beside the outcrop. Furthermore, this section has already been used as a type section for the Whanahuia Paleosol by Leamy et al. (1973) helping to consolidate sections and avoid unnecessary complication.

Milne (1973) describes at least two distinct terrace levels within the Porewa (Pourewa) Terrace set but does not subdivide them. In this article, we separate the Porewa (Pourewa) Terrace 1 and 2 surfaces and correlate them to the two high terraces (H1 and H2) mapped by Milne (1968) along Table Flat Road. Our proposed Porewa (Pourewa) type section occurs on the H2 terrace of Milne (1968) which broadly correlates to the Porewa (Pourewa) 2 Terrace.

The Porewa (Pourewa) type section at Table Flat Road has become somewhat overgrown but the southern side of the roadside cut still displays one of the best examples of the Porewa (Pourewa) cover bed succession in the region (Figures 2 and 5). Rata (Rātā) and Ohakea Loess are discrete and separated by the Whanahuia Paleosol (Leamy et al. 1973). Kawakawa Tephra is prominent at ~1.2–1.4 m depth. The basal Kimbolton Paleosol (Leamy et al. 1973) developed in Middle Tongaririo Subgroup Tephra (Topping 1973) and mixed with Porewa (Pourewa) gravels is less well exposed and requires a spade or auger to access. The Porewa (Pourewa) gravels are more resistant to erosion than the overlying cover beds and form a ledge that supports vegetation growth, limiting their visibility. The strath is obscured by vegetation; however, it can be seen along the old roadside cut approximately 50 m

FIGURE 3 | Ohakea Terrace type section. (A) Ashhurst silt loam (moderately well-drained Typic Orthic Brown Soil). (B) Strath surface with Ohakea gravels over Pleistocene silty fine sands. (C) Cross-bedded pebbly shell conglomerate (Rewa Formation ~1.2 Ma).

to the south with permission from the landowner (E 1853097, N 5573191).

Milne (1968) visited th∼e table flat section when it was still fresh, describing up to ∼19 m of Porewa (Pourewa) gravel alluvium. We visited nearby gravel quarries excavated below the same terrace and were able to measure Porewa (Pourewa) gravel alluvium at least ∼15.7 m thick (Figure 5C). This suggests the terrace is likely aggradational (fill terrace), sitting atop a deep valley fill.

8 | Summary of the Rangitīkei River Terraces

This section summarises existing knowledge and information on the Rangitīkei River Terraces formed during the Otira Glaciation and integrates new data from the lithostratigraphic type and reference sections presented in Figures 2 and 6. Ohakea, Rata (Rātā) and Porewa (Pourewa) terraces are discussed in order of increasing age, with a summary of available dating information for each terrace provided to outline the current state of knowledge.

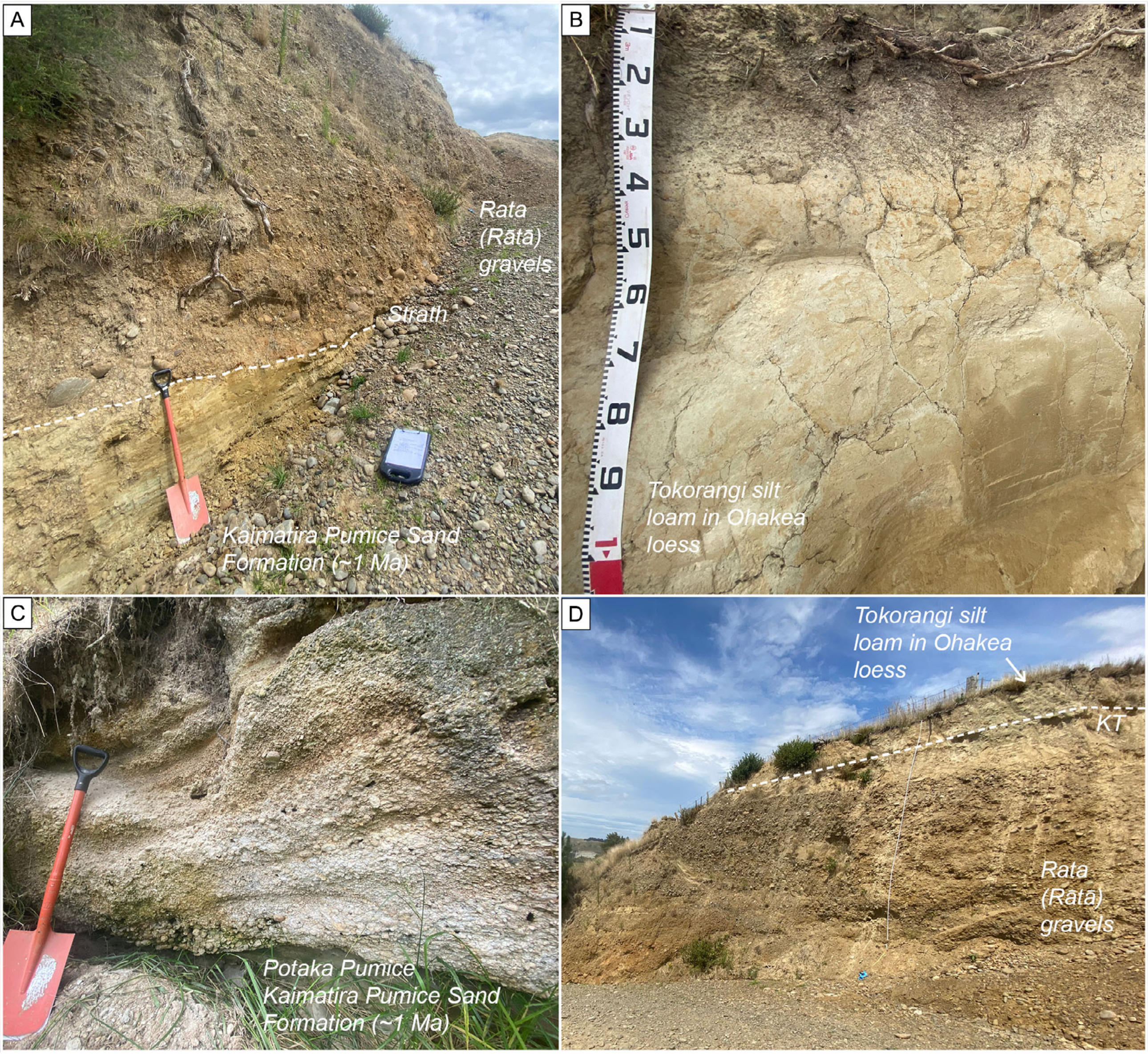

FIGURE 4 | Rata (Rātā) Terrace type section. (A) Undulating strath surface separating Kaimatira Pumice Sand Formation (~1 Ma) from Rata (Rātā) gravels. (B) Tokorangi silt loam with distinctive dark greyish brown Bgc horizon containing iron oxide nodules and coarse blocky grey Bg subsoil typical of Pallic soil. (C) Potaka Pumice (~1 Ma) within the Kaimatira Pumice Sand Formation. (D) Rata (Rātā) gravels with overlying cover bed succession including the Kawakawa Tephra (KT; ~25.4 ka) within the lower third of the Ohakea Loess.

Summarising and building on our understanding of the Rangitīkei River Terraces is intended to support geotourism, education and ongoing research in the Rangitīkei.

The terrace sequence (Figure 6) and type sections (Figure 2) outlined in this article reflect parts of the landscape where ideal preservation has taken place. However, most exposures are incomplete. This becomes even more pronounced when moving to older terraces that have been subject to longer periods of erosion and, therefore, have lower preservation potential. Digging or drilling pits or boreholes in the centre of the terrace on broad interfluves where loess cover is likely thickest is recommended, where possible. The type sections chosen in this work account for this by ensuring a suitable paddock is located nearby.

The cross-section illustrated in Figure 6 represents the central part of the valley where the aggradation gravels are the thickest (fill terraces) and the degradational terraces (fill-cut terraces) in each terrace set are cut into and are reworking aggradation gravel rather than cutting a new strath into the underlying Plio-Pleistocene marine sedimentary rock. However, along valley margins, it is possible for all terraces (aggradational/fill and degradational/fill-cut) within a terrace set to be cut into the underlying Plio-Pleistocene marine sedimentary rock. It is unlikely that the timing of abandonment on the degradational terraces will be the same down the Rangitīkei Valley due to the nature of avulsion and channel switching in the Rangitīkei River as it responds to floods and changes in sediment supply and base level.

FIGURE 5 | Porewa (Pourewa) type section on Table Flat Road. (A) Kawakawa Tephra (KT) at ~1.2–1.4m depth enclosed in Ohakea Loess. (B) Middle Tongariro Subgroup tephra mixed with Porewa (Pourewa) alluvium. (C) ~15.7 m of Porewa (Pourewa) alluvium exposed in nearby quarry. (D) Strath exposed in original road cut which can be accessed via private land. (E) Lateral soil variation and depth to gravel across the Porewa (Pourewa) 2 Terrace surface.

8.1 | MIS 2—Ohakea ∼10–30 ka

The Ohakea Terraces are the best preserved and the most extensive Otira Glaciation terraces within the Rangitīkei Valley. The Ohakea Terrace set includes three main terraces: Ohakea 1, Ohakea 2 and Ohakea 3, in order of decreasing age, soil cover and elevation. Milne (1973) considered Ohakea 2 and 3 to be degradational (fill-cut terraces) based on their gravel alluvium being generally less than 3 m thick. The critical thickness of 3 m is guided by the maximum thickness of alluvium on clearly degradational Holocene terraces and is adopted in this study.

The Ohakea Terrace set was named by Te Punga (1952) after the Ohakea airfield near Bulls (E 1804191, N 5546377), where one of the most extensive Ohakea Terrace remnants is preserved in the lower reaches of the Rangitīkei River valley. The Ohakea Terrace represents the first big step in the landscape moving up from the lower Holocene valley floor. It frequently occurs along both sides of major river and stream valleys from the main axial range south to Parewanui where it dips down beneath the Holocene valley fill and transgressive dune field.

Ohakea Terraces in the Rangitīkei Valley display evidence of wide, active multithread floodplains where the preserved microtopography (channels, bars, chutes and pools) of a braided type floodplain are clearly displayed (Milne 1973) (Figure 7). In places, the Ohakea Terraces are mantled by large stones and boulders. Towards the Rata (Rātā) riser, loess cover increases, masking the microtopography (Figure 7). All terrace sets older than Ohakea are blanketed by increasingly thick cover beds (up to ∼10 m) that obscure any microtopography. The degree of weathering increases with age, such that terrace alluvium older than Rata (Rātā) (∼30–50 ka) is often stained a dark red/brown from a mixture of iron and manganese oxides.

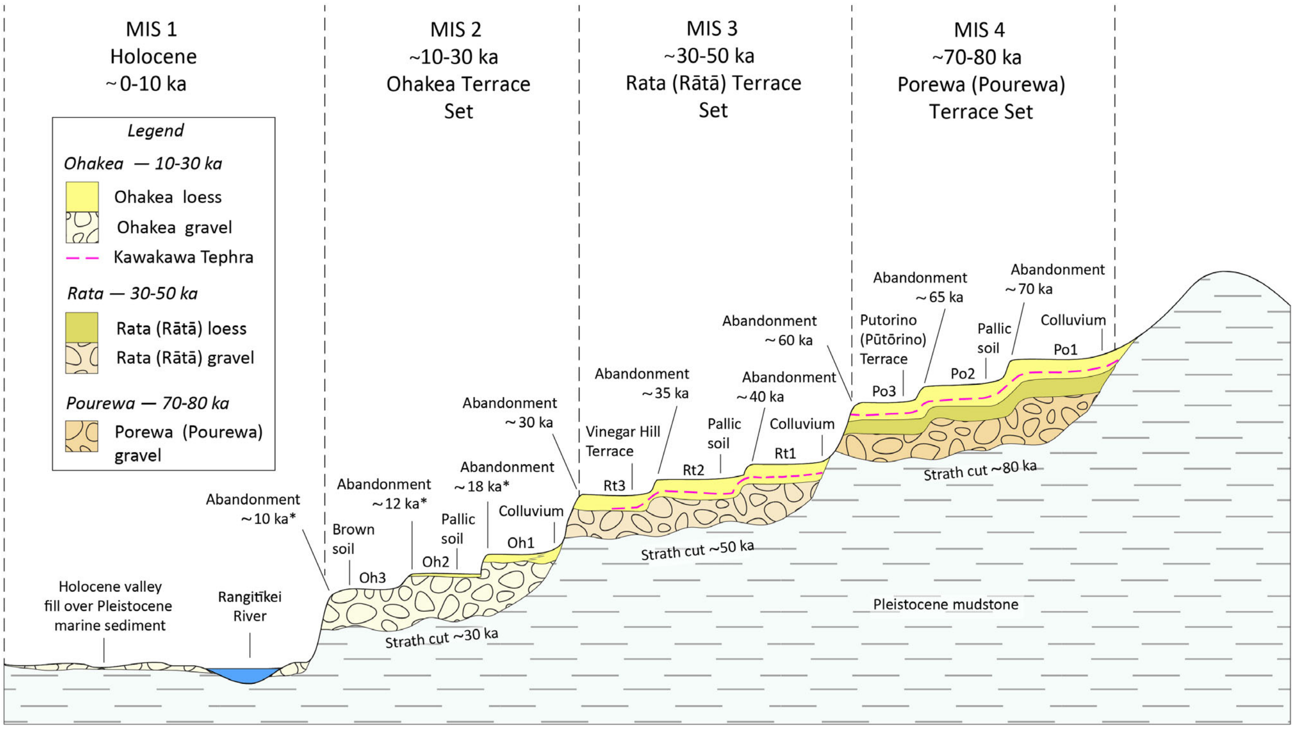

FIGURE 6 | Rangitīkei River terraces formed during the Otira Glaciation. *Ages from Milne (1973), Pillans et al. (1993), Pillans (1994) and Litchfield and Berryman (2005).

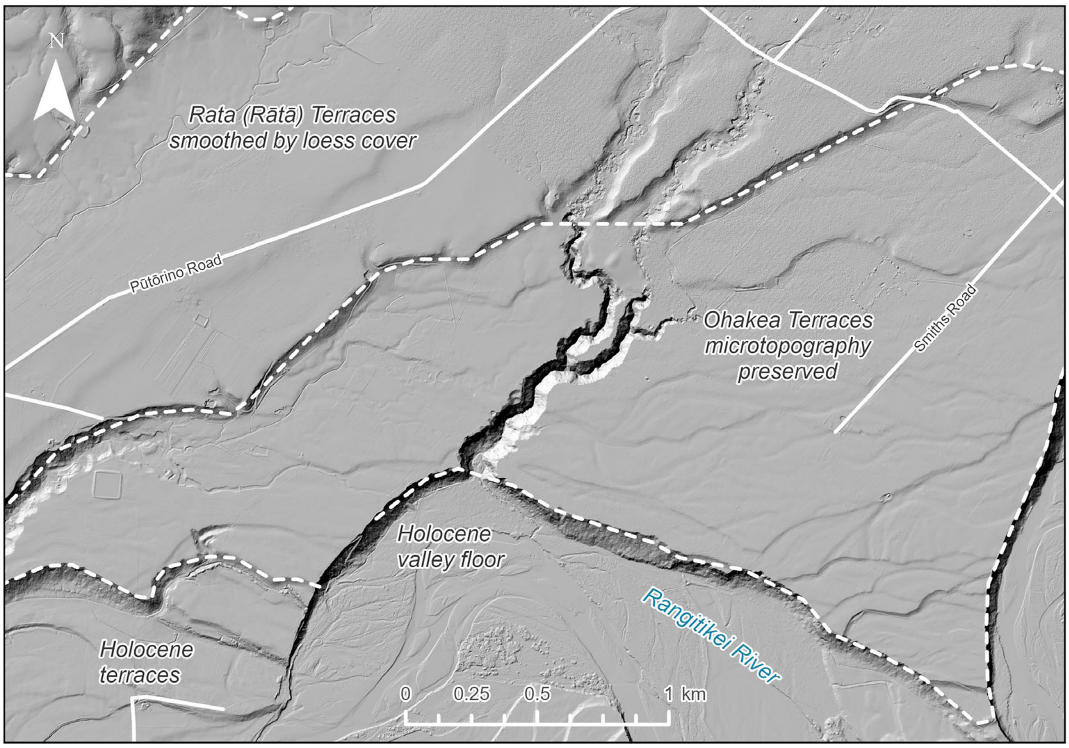

FIGURE 7 | Microtopography preserved on Ohakea Terraces along Putorino (Pūtōrino) Road near Hunterville (E 1818551, N 5570023). Note the braided channel morphology preserved on the Ohakea Terraces. Rata (Rātā) Terrace treads have been smoothed by the accumulation and preservation of Ohakea Loess. Hillshade derived from a mosaic of 1 m Digital Elevation Model (DEM) and Digital Surface Model (DSM) data from Horizons Regional Council captured between 2015 and 2024.

Soils on Ohakea Terraces frequently display rapid lateral variation in texture, depth to gravels and drainage class. Typically, this involves a transition from well to imperfectly drained Brown soils into poorly drained Pallic soils over a distance of 5 m or more, reflecting the nature of the high-energy fluvial depositional environment that formed the parent material. This same relationship is observed on all Otira Glaciation terraces, particularly along terrace edges or swales where the cover beds are draped by fan alluvium or have been reworked by streams locally stripping the cover down to the underlying terrace alluvium.

Milne and Smalley (1979) report ^{14}C dates for the Ohakea Loess in the Rangitīkei Valley. The base of Ohakea loess is radiocarbon dated at 25,500 ± 800 year BP (NZ3188A) (28,043–31,200 cal year BP), and the top is considered older than 9,480 ± 100 year BP (NZ3165A) (10,411–11,121 cal year BP) based on wood sampled from an Ohakea Terrace near Ohakea (Milne and Smalley 1979; Pillans et al. 1993).

8.2 | Oh1 ∼18–30 ka

The Oh1 terrace commonly displays at least 3 m of gravel over a strath and is considered aggradational (fill terrace), representing glacial conditions between ∼18 and 30 ka (Pillans et al. 1993; Pillans 1994; Litchfield and Berryman 2005), including the LGM sensu stricto defined by Alloway et al. (2007) as the interval centred on 21,000 ± 3000 cal. year BP.

Local evidence for the timing of Ohakean aggradation includes the widespread ∼25.4 ka cal. year BP Kawakawa Tephra (Vandergoes et al. 2013), which occurs in the lower Ohakea Loess, commonly preserved on older, higher surfaces in the landscape. Note the aggradation of gravel forming the Ohakea Terrace is considered contemporaneous with the accumulation of Ohakea Loess on older, higher surfaces in the landscape, allowing the Kawakawa Tephra to be used as a marker for timing of aggradation within the Rangitīkei Valley. Unlike the Waipaoa catchment in Gisborne (Marden et al. 2008), no Kawakawa Tephra has been found in the Ohakea aged gravel alluvium of the Rangitīkei Valley. The older Ohakea Terraces (Oh1 and Oh2 in Figure 6) can contain some loess cover, typically less than 1 m deep, often reworked by colluvial and alluvial processes and containing no Kawakawa Tephra.

Limited local evidence is available for the exact timing of the onset and end of aggradation in the Rangitīkei Valley. However, detailed chronostratigraphy in the Waipaoa catchment, Gisborne, suggests LGM aggradation began between the Omataroa Tephra (∼33 ka cal. year BP) and the Kawakawa Tephra (∼25.4 ka cal. year BP) and that the switch to degradation occurred around the deposition of the ∼17.5 ka cal. year BP Rerewhakaitu Tephra (Lowe et al. 2013; Marden et al. 2014). Here, we adopt the age range of ∼18–30 ka for the Ohakea 1 terrace, to be consistent with past literature (Milne 1973; Pillans et al. 1993; Pillans 1994; Litchfield and Berryman 2005). Currently, we lack sufficient tie points to accurately correlate the Rangitīkei River terrace record to the chronostratigraphic framework of Alloway et al. (2007). Ongoing work is being undertaken to better constrain the age of the Rangitīkei River terraces and improve the climate-based time stratigraphic substages for the North Island of New Zealand proposed by Milne (1973).

A ^{14}C date of 3,050 ± 200 years BP (2,751–3, ∼689 cal year BP) was obtained by Te Punga (1953) from logs within gravel deposits at Rangitawa Stream, originally thought to be of Ohakean age. This has since been shown to be from Holocene deposits (Cowie and Wellman 1962).

A luminescence study undertaken by Guyez et al. (2022) in the Rangitīkei Valley provides an age of 17.4 ± 1.9 ka for Ohakea 1 Terrace alluvium (RO_57), providing a maximum age of abandonment for the Oh1 terrace. This is broadly consistent with previous ages presented by Pillains (1994) and adopted here. However, a sample taken from a Ohakea 1 Terrace in the Kawhatau Valley (RO_39) appears to be unusually young at 14.7 ± 1.0 ka. Underestimation of ages can result from anomalous fading (Riedesel et al. 2021).

8.3 | Oh2 ∼12–18 ka

The Oh2 terrace has up to approximately 1 m of soil cover, commonly developed in fine alluvium with few subrounded greywacke pebbles through to fine loess material that likely represents the upper part of the Ohakea Loess. Milne (1973) suggests the pebbles that occur within the dominantly fine grained subsoils on the Oh2 terrace may represent root overturn from trees subject to windthrow bringing Ohakea gravels to the surface. Reasonable soil depth allows Oh2 terraces in general to be cultivated and provide good water-holding capacity.

Marden and Neall (1990) report two radiocarbon ages of 12,900 ± 200 year BP (NZ4651A) (14,519–16,018 cal year BP) and 12,650 ± 150 year BP (NZ5591A) (14,249–15,465 cal year BP) for wood collected from within Oh2 alluvium. These ages were used by Pillans et al. (1993) and Pillans (1994) to estimate the approximate abandonment of the Oh2 terrace in the Rangitīkei at ∼12 ka and are adopted in this article. This abandonment occurred as the river continued to adjust and degrade coming out of the LGM into the Holocene, with increased precipitation and stream power facilitating transport of the LGM gravel still in the system. A luminescence study undertaken by Guyez et al. (2022) in the Rangitīkei Valley provides an age of 13.4 ± 1.1 ka for Ohakea 2 Terrace alluvium (RO_32). This is broadly consistent with previous ages presented by Milne (1973), Pillans et al. (1993) and Pillans (1994) and adopted here.

8.4 | Oh3 ∼10–12 ka

Oh3 terrace has a clearly preserved microtopography consisting of channels, levees and bars that create undulating ground with a vertical elevation change of approximately ±1 m (Figure 7). A pronounced braided river planform can be seen in aerial photographs, contrasting with the wandering planform typical of the modern-day Rangitīkei River (Richardson and Fuller 2010). Soils are typically stony to the top, with quite variable cover of finer-grained alluvium up to 1 m thick. Large cobbles and boulders can sometimes be found on the terrace where they have not been cleared for farming. The stony soils dry out in summer, highlighting the channels across the terrace surface.

Marden and Neall (1990) report a radiocarbon age of 10,350 ± 100 year BP (NZ5320A) (11,765–12,590 cal year BP) for a wood sample in Oh3 alluvium at Woodville. This age has been used to establish a maximum age for abandonment of the Oh3 terrace in the Rangitīkei as rapid incision ensued during the transition into the Holocene. A luminescence study undertaken by Guyez et al. (2022) in the Rangitīkei Valley provides an age of 11.6 ± 1.5 ka for Ohakea 3 Terrace alluvium

(RO_04). This is broadly consistent with previous ages presented by Milne (1973), Pillans et al. (1993) and Pillans (1994) and adopted here.

8.5 | MIS 3—Rata (Rātā) ~30–50 ka

Rata (Rātā) Terraces are best preserved between Porewa (Pourewa) and Putorino (Pūtōrino) in the lower Rangitīkei Valley. Elsewhere, the treads become more localised and discontinuous. The Rata (Rātā) terrace set includes three main terraces: Rata (Rātā) 1, Rata (Rātā) 2 and Vinegar Hill (Rata (Rātā) 3) (Figure 6). Milne (1973) considered Rata (Rātā) 2 and 3 to be degradational (fill-cut terraces) and Rata (Rātā) 1 to reflect peak aggradation (fill terrace) during MIS 3. A luminescence study undertaken by Guyez et al. (2022) in the Rangitīkei includes a single sample from Rata (Rātā) 1 Terrace alluvium 32.1 ± 3.9 ka (RO_67) which is broadly consistent with the ages of Milne, (1973), Pillans et al. (1993) and Pillans (1994) adopted herein.

The name Rata (Rātā) was originally given by Te Punga (1952), taken from the small settlement of Rata (Rātā) near Hunterville. All the Rata (Rātā) Terraces are mantled by Ohakea Loess and Kawakawa Tephra. However, local stripping and reworking of cover bed deposits by streams and deposition of fan alluvium creates rapid lateral soil variation from full loess cover to gravel alluvium to the surface. Generally, the presence of cover beds obscures any channel patterns or microtopography (Figure 7). Instead, the topography on the terrace tread reflects shaping of the cover beds by erosion and also localised occurrence of sand dunes.

Milne (1973) proposed the name Vinegar Hill Terrace for the Rata (Rātā) 3 Terrace, using the geographic name of where the most extensive treads of the lowermost terrace of the Rata (Rātā) terrace set occur within the Rangitīkei River Valley. The Vinegar Hill Terrace is also mantled by Ohakea Loess incorporating Kawakawa Tephra where the full cover bed succession has been preserved (Supporting Information File A).

8.6 | MIS 4—Porewa (Pourewa) ~70–80 ka

The Porewa (Pourewa) Terrace is the least well preserved of the Otira Glaciation river terraces in the Rangitīkei Valley. Remnants are mainly located on the western side of the valley between Kakariki Bridge and Rata (Rātā). At least three terrace levels are preserved, the first two grouped into Porewa (Pourewa) and the lowermost terrace named Putorino (Pūtōrino) by Milne (1973) (Figure 6). The Porewa (Pourewa) 2 and Putorino (Pūtōrino) terraces are considered to be degradational (fill-cut terraces) by Milne (1973).

The name Porewa (Pourewa) was given by Te Punga (1952) during his work in the Rangitīkei, taken from the small settlement of Porewa (Pourewa) near Rata (Rātā). The terrace chronology of Milne (1973) depended on a fission track age for the Rangitawa Tephra of 230 ± 30 ka, which provides a key marker horizon at the base of the Aldworth and Waituna terrace cover bed deposits, allowing relative dating of loess layers and associated terraces between the Kawakawa and Rangitawa tephras. This age has since been found to be incorrect and is now considered to be ~350 ka (Kohn et al. 1992; Pillans et al. 1996; Downs et al. 2014). Pillans (1994) revised the terrace ages of Milne (1973), taking into account an older age for the Rangitawa Tephra, and we adopt these ages in this work. The ~70–80 ka age of the Porewa (Pourewa) Terrace first proposed by Milne (1973) is based on cover bed stratigraphy and correlation to climatic cooling and glacial advance in New Zealand during MIS 4 (Shulmeister et al. 2019).

Cover beds on the Porewa (Pourewa) Terrace include Ohakea Loess, Kawakawa Tephra and Rata (Rātā) loess. MIS 4 terraces have gently undulating to rolling topography resulting from stream incision and hillslope development in response to local base level fall. Fan alluvium complicates the terrace edges and sand dunes are interbedded within the overlying cover beds. Milne (1973) suggests there was a long interval between the abandonment of the Porewa (Pourewa) and Rata (Rātā) terraces, evidenced by the moderate to strong soil development of the Kimbolton Paleosol (Section 10, Supporting Information File A) and the degree of weathering of the Porewa (Pourewa) alluvium (Figure 5).

8.7 | Rangitīkei Terrace Model

The following section presents a summary and discussion of how the Rangitīkei river terraces formed during the Otira Glaciation (Figure 8). Stadial phases in the Rangitīkei Valley were characterised by an almost complete switch from full forest cover to shrub and grassland with only isolated beech and podocarp refugia able to survive (Milne 1973; Newnham et al. 2013). Cool temperatures caused a lowering of the treeline, created more bare ground and enhanced frost-cracking, which drove enhanced physical weathering, production of regolith and increased sediment supply to rivers and streams (Milne 1973). Frost cracking, in particular, has been shown to be a pervasive phenomenon during cold climate phases and provides a plausible mechanism for generating deep regolith and high hillslope sediment fluxes (Hales and Roering 2005; Marshall et al. 2015). A majority of the soils in the Rangitīkei hill country are younger than MIS 2, suggesting soil was effectively stripped from steep hill slopes during this heightened phase of erosion.

During stadials, lower precipitation and stream power combined with higher sediment supply caused aggradation within the Rangitīkei Valley, forming wide multithreaded floodplains reminiscent of the Waimakariri and Rakaia rivers on the Canterbury Plains today. Evidence of these former multithreaded floodplains is preserved as remnant terraces in the landscape (Figure 7). During these aggradation phases, the fluvial system was limited by its ability to transport the imposed sediment load.

Loess is blown from these floodplains during stadials, blanketing the surrounding landscape and is preserved on older, higher and more stable landscape surfaces (Vella 1963; Palmer and Pillans 1996). Loess sheets are thick and coarse immediately east or downwind of the Rangitīkei River, driven by the predominant westerly winds, before gradually thinning and becoming finer grained (Cowie 1964) (Figure 8A). The loess is dominantly quartzofeldspathic, derived from Mesozoic greywacke–argillite and Plio-Pleistocene sandstone and mudstones. There is also significant tephra input from the TVZ and Mount Taranaki/Egmont Volcano, although this tends to become diluted during cold glacial and stadial conditions when erosion is at its maximum (Palmer and Pillans 1996). Tephra content in the loess also

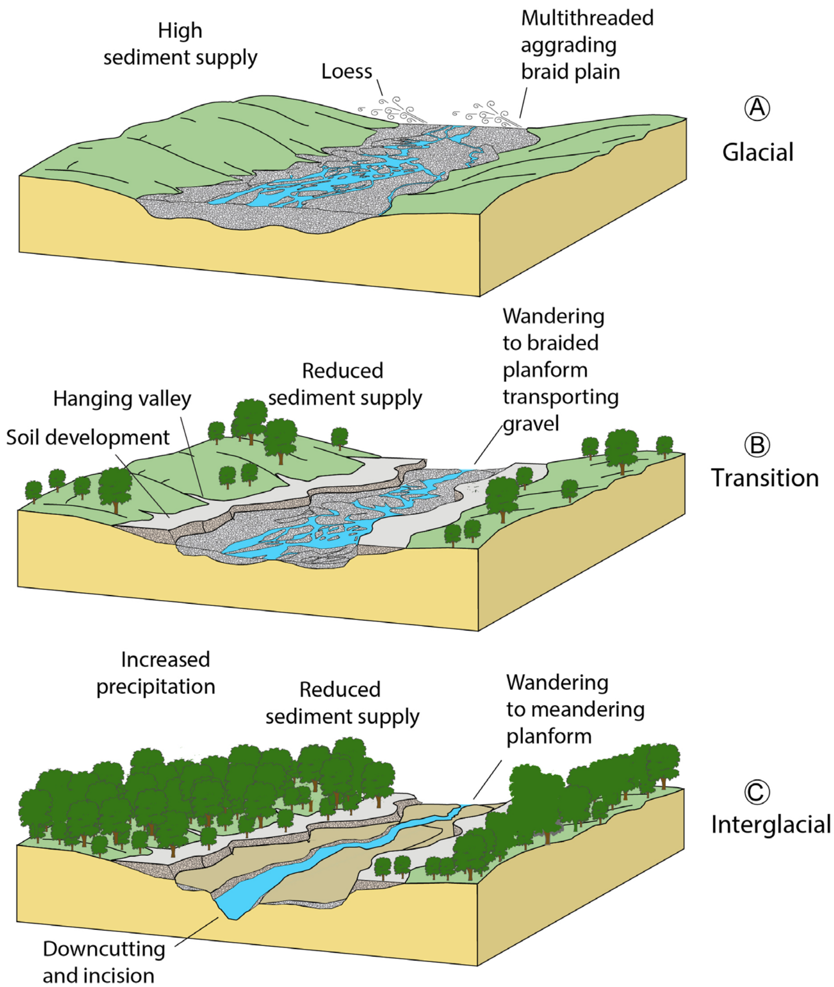

FIGURE 8 | Schematic diagram displaying the conceptual model for river terrace formation in the Rangitikei Valley.

increases north up the Rangitīkei Valley, reflecting closer proximity to the TVZ. Upbuilding pedogenesis continues as the loess accumulates. Top-down soil-forming processes are less effective due to high loess accumulation rates, allowing for only weak soil horizon development (Palmer et al. 2025).

The correlation between glacial/stadial periods and river aggradation is based on dating of Ohakea Terrace alluvium (Milne 1973; Marden and Neall 1990; Pillans et al. 1993; Pillans et al. 1996; Vandergoes et al. 2013; Lowe et al. 2015) and the occurrence of subalpine pollen assemblages in Marton terrace (MIS 6) alluvium (Barnett 1984; Palmer et al. 1988). The 'Ohakean' straddles multiple New Zealand Climate Events (NZCE) of the LGCP, including NZCE 7 and 9 (Otira Glaciation Interstadial B and D) of Barrell et al. (2013). This suggests either climate variation in the Rangitīkei Valley was different to the West Coast of the South Island, where the type record site for NZCE 6-11 is located, or aggradation in the Rangitīkei Valley was insensitive to climate warming of the magnitude of NZCE 7 and 9. In the South Island, piedmont plains have strong glacial sediment supply controls. The unglaciated mountains of the North Island may have a different sensitivity to climate fluctuations.

Interglacial and interstadial phases are characterised by increased vegetation cover, landscape stabilisation and reduced sediment supply, allowing the Rangitīkei River to begin transporting its imposed sediment load and have excess power to cut down into the landscape (Figure 8B,C). There is a lag time during the transition out of a glacial or stadial phase where the river is adjusting and continuing to transport vast quantities of greywacke–argillite gravel. Evidence of these transitional phases is recorded as degradational terraces (fill-cut terraces) in each terrace set (e.g., Oh2 and Oh3 surfaces in the Ohakea Terrace set), produced as the river responds and transitions out of aggradation towards a phase of downcutting. Enhanced precipitation and stream power allows the rivers to eventually flush excess gravel and begin to rapidly cut down through the soft rock of the WB. Downcutting creates a series of steep steps in the river channel, such as waterfalls or rapids. These sudden changes in gradient are called knickpoints and mark points where erosion is concentrated in the channel. As erosion takes place at a knickpoint, it gradually starts to migrate upstream, allowing the river to incise down into the underlying geology and promoting lateral widening of the channel.

Knickpoint migration and reworking of gravel alluvium mean that any two degradational terraces (fill-cut terraces) associated with the same terrace set in different reaches of the river are not necessarily coeval. This reflects the complex response of the fluvial system, which has built-in lags related to response and relaxation times and is influenced by internal feedbacks and thresholds (Bull 1991). Aggradation and downcutting are spatially and temporally variable, related to internal fluvial

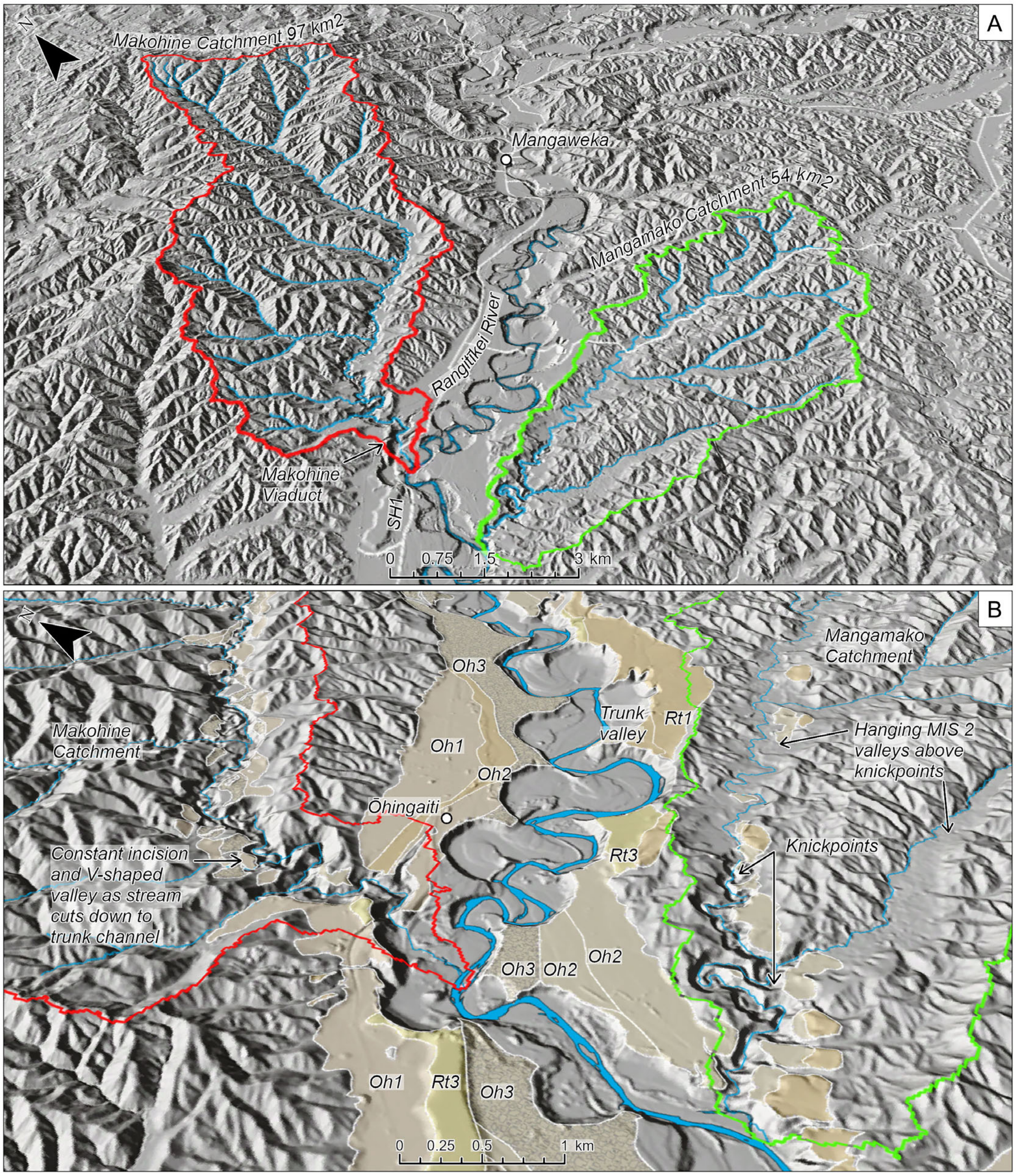

FIGURE 9 | (A) The Makohine (97 km^2) and Mangamako (54 km^2) stream catchments, two tributaries of the Rangitīkei River with different geomorphology associated with changes in stream power and post-LGM incision. (B) Close-up view of the lower Makohine and Mangamako stream valleys. Note the Makohine has a larger catchment area and stream power and has been able to keep pace with post-LGM downcutting in the main trunk channel of the Rangitīkei River, forming an incised V-shaped valley. In contrast, the smaller Mangamako stream valley is unable to match the downcutting in the trunk channel of the Rangitīkei River, reflected in hanging LGM valleys and prominent knickpoints. Maps produced using 1 m 2015–2016 DSM from Horizons Regional Council, the River Environment Classification (REC2) from Earth Sciences New Zealand and geological data from Rees et al. (2020). Oh, Ohakea Terrace; Rt, Rata (Rātā) Terrace.

system dynamics independent of external drivers such as climate (Schumm 1973; Bull 1991).

Uplift continues slowly through geological time, and eventually, the remnants of an abandoned aggradation plain are preserved within the wider valley, as the river becomes entrenched in a new degradational floodplain (Figure 8C). The terraces also become gently tilted as they are uplifted, resulting in the treads of older terraces occurring at progressively higher elevation and steeper dip (0.3°–1°) within the landscape (Milne 1973). The extent of fluvial dissection intensifies with increasing terrace age, such that the oldest terraces occur as highly dissected remnants between deeply incised valleys with high drainage density. The most widespread and best preserved terraces in the Rangitīkei Valley are the Ohakea Terraces associated with the LGM. Not only was this a pronounced phase of aggradation, but it has also been subject to the least amount of subsequent fluvial dissection and lateral corrasion.

8.8 | Rangitīkei Valley Morphology

The Rangitīkei River and its tributaries cut over a stratified marine basin succession, dipping 2°–10° SE to SW, that alternates between units of contrasting hydraulic and physical properties, typically in couplets, for instance, a noncohesive, unconsolidated sandstone overlying a relatively cohesive siltstone. Stream and river channels preferentially erode into the noncohesive sediment, covering the underlying Plio-Pleistocene bedrock with gravel alluvium, forming a low-relief reach that is characterised by loss of water during aquifer recharge. Downstream of this erosive reach, the stream then flows over the next underlying cohesive layer that provides more resistance to erosion. This high relief, gaining, reach is characterised by a high flow rate, generally more confined morphology and bedload bypass as the bedrock is swept clear of gravel alluvium by the higher discharge. Eventually, a tipping point is reached where the stream finally overcomes shear resistance of the cohesive layer incising through at a knickpoint, expressed as a steep rapid, waterfall or bedding plane exposure.

Particularly prominent knickpoints are associated with units of greatly contrasting hydraulic and physical properties. Multiple mechanisms have been proposed for knickpoint retreat. In areas where the substrate is horizontally stratified or a resistant cap layer prevents erosion of the knickpoint lip, circulation of water and sediment in the plunge pool at the base of the knickpoint undercuts the lip, facilitating upstream retreat (Gilbert 1896; Crosby and Whipple 2006). Others suggest that the impact of water and sediment against the bedrock base and steep face of the knickpoint drive retreat (Hayakawa and Matsukura 2003; Cook et al. 2013). In certain situations, ground water seepage along a permeability contrast is suggested to accelerate weathering and facilitate erosion by undercutting the knickpoint lip (Laity and Malin 1985; Pillans 1985; Paull et al. 1990).

Smaller tributary streams, such as the Mangamako (Figure 9), often discharge into the Rangitīkei River Valley by waterfalls and/or steep gorges along the LGM cliff front of the main trunk valley. An upstream hanging valley reach is present above a well-defined knickpoint, representative of the precliff formation LGM terrace surface (Figure 9). This landform demonstrates the difference in stream power between the trunk channel and side tributary, the latter lacking the competence to adjust its channel to the lowered local base level. The knickpoint will continue migrating up the length of the tributary valley, eventually transforming the upper valley to a deep V-shaped system (Hesp 1975). Larger tributary streams, such as the Makohine (Figure 9), lack these hanging valley features, suggesting their rate of downcutting is able to keep pace with the main trunk channel (Figure 9).

Knickpoint retreat propagating upstream in tributary channels is considered a result of postglacial acceleration of incision in the trunk river valley. Litchfield and Berryman (2005) showed that the effect of base level changes is restricted to the downstream parts of the Ruamahanga, Manawatū, Waipawa, Tukituki, Ngaruroro, Wairoa and Waipaoa rivers on the east coast of the lower North Island (first ~50 km from the coast) and that tectonic uplift only enhances the rate of incision, rather than triggering it. The southern half of the present study area is within 50 km of the modern-day shoreline. However, during the LGM, the shoreline is envisaged to have been located ~100–120 m below present-day sea level and thus ~30 km SWW of the present shoreline (Carter et al. 1986; Fairbanks 1989; Norris and Grant-Taylor 1989; Pillans et al. 1993; Clark and Mix 2002; Newnham et al. 2013). Lower sediment supply and ongoing regional uplift during interglacial and interstadial conditions are suggested to have induced deep incision, with the rate proportional to the size of the tributary catchment and corresponding stream power.

9 | Summary and Conclusions

The Rangitīkei River Valley contains a suite of river terraces that records the interplay between sediment supply, uplift, stream power, eustatic sea level and local base level control associated with Quaternary climate cycles over the last ~350 ka. We present a review of the Rangitīkei River terraces and new type and reference sections for lithostratigraphic units formed during the Otira Glaciation, spanning MIS 2–4. Selection is based on outcrop quality, ease of access and health and safety considerations whilst aiming to preserve historic precedence and geographic proximity to associated place names. New type sections target areas with easy access and avoid complications associated with erosion of aeolian cover beds or deposition of fan alluvium. Documenting new type and reference sections is intended to assist geotourism, education and ongoing research, including ongoing chronostratigraphic work to better define the Ohakean, Ratan (Rātān) and Porewan (Pourewan) substages.

A conceptual model of Rangitīkei terrace formation is presented, highlighting increased sediment supply during stadials when the fluvial system is limited by its ability to transport the imposed sediment load. The transition out of stadial conditions is characterised by reduced sediment supply and increased stream power, resulting in incision, upstream knickpoint migration and formation of multiple terrace levels within each terrace set. This gradual adjustment of the river system towards incision means that degradational terraces are likely not coeval between different reaches in the valley, reflecting the complex response of the fluvial system where aggradation and downcutting are spatially and temporally variable, related to internal fluvial system dynamics independent of external drives such as climate.

Acknowledgments

This article was inspired by the seminal work of Martin Te Punga and Derek Milne in the Rangitīkei. We thank residents in the Rangitīkei for land access. This work is part of the Te Horo i Whakakotahi a Pūtōrino e Rua: Discovering the past, present and future impact on land, water and people caused by the Pūtōrino landslide supported by the Ministry of Business Innovation and Employment Te Pūnaha Hihiko: Vision Mātauranga Capability Fund (grant number MAUX2309). We thank project partners from Whakauae Research Services (Te Rūnanga o Ngāti Hauiti) and He Waka Uru Ora (Te Rūnanga o Ngā Wairiki Ngāti Apa) for helping us develop an approach to the use of Māori names in western science publications and ensuring consistency and accuracy of the names used throughout this manuscript. Project partners InSite Archaeology and Horizons Regional Council have provided support with geospatial data.

Open access publishing facilitated by Massey University, as part of the Wiley - Massey University agreement via the Council of Australasian University Librarians.

Funding

The research was supported by the Ministry of Business Innovation and Employment Te Pūnaha Hihiko: Vision Mātauranga Capability Fund (grant number MAUX2309).

Conflicts of Interest

No potential conflict of interest was reported by the authors.

Data Availability Statement

The authors confirm that the data supporting the findings of this study are available within the article and its Supporting Information.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Figure S1**: Ohakea 1 Type Section (1). Ashhurst silt loam, moderately well drained Mottled Orthic Brown Soil (E 1820537, N 5569931). **Figure S2**: Ohakea 1 Type Section (1). Ohakea gravel over Pleistocene light grey silty fine sand exposed along Putorino Road (E 1820553, N 5569972). **Figure S3**: Ohakea 1 Type Section (1). Rewa Formation (1.2 Ma) cross-bedded pebbly shell conglomerate exposed along Putorino Road (E 1820673, N 5570108). **Figure S4**: Ohakea 1 Reference Section – Dune (2). Tokorangi silt loam over dune sand exposed near the Ohakea Aerodrome (E 1803271, N 5548250). **Figure S5**: Ohakea 1 Reference Section – Dune (2). Tokorangi silt loam over dune sand over Ohakea gravels exposed near the Ohakea Aerodrome. Tape is 6 m long (E 1803271, N 5548250). **Figure S6**: Ohakea 1 Reference Section – Ashhurst (3). Ashhurst stony fine sandy loam over Ohakea 1 gravels exposed along Tangimoana Road (E 1803135, N 5548274). **Figure S7**: Ohakea 1 Reference Section – Ohakea (4). Ohakea silt loam over Ohakea 1 gravels exposed near junction between Pukenui and Tangimoana Road (E 1802605, N 5548112). **Figure S8**: Ohakea 1 Reference Section – Ohakea (4). Ohakea 1 Terrace strath over Pleistocene sandy mudstone exposed along drain near junction between between Pukenui and Tangimoana Road at ∼40 m above sea level (E 1802222, N 5547878). **Figure S9**: Ohakea 2 Terrace Reference Section (5). Ashhurst silt loam over Ohakea 2 Terrace gravels, Rata (Rātā) (E 1815614, N 5568606). **Figure S10**: Ohakea 2 Terrace Reference Section (5). Ohakea 2 degradational gravels and strath (∼15-30 ka) over Kaimatira Pumice Sand Formation (∼1 Ma) exposed in farm track close to Te Hou Hou Road, Rata (Rātā) (E 1815614, N 5568606). **Figure S11**: Ohakea 3 Terrace Reference Section (6). Ashhurst fine sandy loam over Ohakea Terrace 3 degradational gravels at an exposure off Reu Reu Road, Halcombe (E 1814285, N 5563836). **Figure S12**: Ohakea 3 Terrace Reference Section (6). Ohakea Terrace 3 strath surface exposed at outcrop along Reu Reu Road, Halcombe (E 1814285, N 5563789). **Figure S13**: Rata (Rātā) 1 Terrace Type Section (7). Tokorangi silt loam exposed in an outcrop off Te Hou Hou Road, Rata (Rātā) (E 1815253, N 5568554). **Figure S14**: Rata (Rātā) 1 Terrace Type Section (7). Lower part of the Tokorangi silt loam profile, transitioning from Ohakea loess into Ohakea alluvial dune sand at ∼1 m depth, Kawakawa Tephra is preserved within the dune sands at ∼1.6 m depth, tape is 3.3 m long (E 1815253, N 5568554). **Figure S15**: Rata (Rātā) 1 Terrace Type Section (7). Undulating strath surface beneath the Rata (Rātā) 1 Terrace aggradational gravels exposed near Te Hou Hou Road, Rata (Rātā). Underlying interbedded Pliestocene silts and sands can be seen by the spade (E 1815253, N 5568554). **Figure S16**: Rata (Rātā) 2 Terrace Reference Section (8). Ohakea silt on the Rata (Rātā) 2 Terrace exposed along Putorino (Pūtōrino) Road (E 1819552, N 5570477). **Figure S17**: Rata (Rātā) 2 Terrace Reference Section (8). Ashhurst silt loam on the Rata (Rātā) 2 Terrace Tread off Putorino (Pūtōrino) Road. **Figure S18**: Rata (Rātā) 3 - Vinegar Hill Terrace Reference Section (9). Outcrop through Vinegar Hill Terrace cover beds on driveway to 92 Kie Kie Road, Hunterville (E 1827328, N 5581596). KT – Kawakawa Tephra. **Figure S19**: Rata (Rātā) 3 - Vinegar Hill Terrace Reference Section (9). Vinegar Hill Terrace strath surface cut into Pliestocene mudstone (E 1827288, N 5581580). **Figure S20**: Porewa (Pourewa) Terrace Type Section (10) exposed along Table Flat Road (E 1853144, N 5573277). Section and locality first designated by Leamy et al. (1973). KT – Kawakawa Tephra. **Figure S21**: Porewa (Pourewa) Terrace Type Section (10). Rata (Rātā) loess and overlying Whanahuia Paleosol (Leamy et al. 1973) exposed along Table Flat Road (E 1853144, N 5573277). **Figure S22**: Porewa (Pourewa) Terrace Type Section (10). Kimbolton paleosol (Leamy et al. 1973) developed in Middle Tongariro Subgroup tephra mixed with Porewa (Pourewa) alluvium along Table Flat Road (E 1853144, N 5573277). **Figure S23**: Porewa (Pourewa) alluvium exposed along the northern side of Table Flat Road (E 1851305, N 5573163). 15.7 m of gravel, spade is 1 m long. **Figure S24**: Porewa (Pourewa) alluvium and strath surface over Pliestocene sandstone and mudstone (Maxwell Group ∼1.7 Ma) exposed in the original road cutting approximately 50 m south of the type section (E 1853097, N 5573191). Note landowner permission is required to see the strath. Milne (1968) described the Table Flat Road section while it was still fresh, recording ∼18.9 m of gravel over the strath surface. The Kakariki Road section (E 1807076, N 5556594) (Potter, 1984) provides a better exposure through (Pourewa) alluvium and the strath surface over late Pleistocene deposits; however, the coverbed deposits are much harder to access and it is a dangerous road to stop and work on. **Figure S25**: Outcrop off 360 Table Flat Road showing the amount of lateral variation across the H2 (Porewa (Pourewa) 2) Terrace of Milne (1968) (E 1851138, N 5573216). Spade is 1 m long for scale. Over ∼5m, the soil changes from gravel to the top to 2m+ of fine grained allophanic cover with no obvious signs on the terrace surface above. This area is used for pastoral farming (sheep and beef + dairy) and market gardening. It has a shorter growing season due to cool temperatures but does not dry out in summer and has excellent soil physical properties. The soils have high P retention and require additional superphosphate to bring Olsen P into an optimal range. Springs are common above the strath where it is intercepted topographically, producing spring lines that are tapped by locals for drinking and stock water. **Figure S26**: Porewa (Pourewa) 2 - Putorino (Pūtōrino) Terrace Reference Section (11). Putorino (Pūtōrino) Terrace alluvium and overlying coverbeds exposed on farm track near Manaaki Urupa (E 1812920, N 5568444).