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Loess Studies in Aotearoa New Zealand

Brent V. Alloway[1] | David J. Lowe[2] | Bradley J. Pillans[3] | Peter C. Almond[4] | Alan S. Palmer[5]

[1]Instituto de Geografía, Pontificia Universidad Católica de Chile, Santiago, Chile | [2]Te Aka Mātuatua–School of Science, The University of Waikato, Hamilton, Aotearoa New Zealand | [3]Research School of Earth Sciences, The Australian National University, Canberra, Australia | [4]Soil and Physical Sciences, Lincoln University, Christchurch, Aotearoa New Zealand | [5]School of Agriculture and Environment, Massey University, Palmerston North, Aotearoa New Zealand

Correspondence: Brent V. Alloway (brent.alloway@gmail.com) | David J. Lowe (david.lowe@waikato.ac.nz)

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ABSTRACT

Loess in Aotearoa New Zealand (ANZ) has been studied since its first documented recognition (on Banks Peninsula) in 1878 by Julius von Haast. A decade later, John Hardcastle revealed that southern ANZ loess was both glacial in origin and contained signals of past climates. As a fine-grained aeolian deposit dominated by quartz and feldspar (± mica), it is derived mainly from greywacke and schist rocks shattered by frost cracking at high elevations, fluvially comminuted then deflated from aggrading floodplains, and from exposed continental shelves during cold periods. Such quartzo-feldspathic loess predominates in eastern and southern parts of both South and North islands and in Westland and Tasman. In addition, subsurface tephric loess prevails in central-western North Island. Unlike many deposits overseas, ANZ loess generally lacks secondary calcium carbonate, is denser (with lower macro- and mesoporosity, higher clay content) and, although less prone to collapse, is susceptible to accelerated erosion including tunnel gullying and landsliding. Mean rates of accumulation in the Last Glacial Maximum were ~3–25 mm/century; mass accumulation rates were generally 70–150 g cm^{-2} yr^{-1} but locally could be as low as 20 g cm^{-2} yr^{-1} and as high as 360 g cm^{-2} yr^{-1}. Studies mapping and characterizing loess have been driven in part by cognizance of its importance as a widespread parent material (~60%–70% of ANZ's soils contain loess) for arable/pastoral soils underpinning ANZ's predominantly agronomy-based economy. A key feature of ANZ loess studies has been the recognition of developmental upbuilding pedogenesis involving syn-depositional alteration of loess as it accumulates in cold and/or cool (stadial) periods, and stronger alteration (forming more-developed soils, which subsequently become recognizable as buried soil stratigraphic units or paleosols) during minimal accumulation in interglacial and/or warm (interstadial) periods. Multisequal loess-paleosol successions are the result. ANZ loess-paleosol successions have been dated and correlated via a range of dating and age-equivalent techniques including tephrochronology and paleomagnetism. Most loess is ≤500 kyrs old, but occurrences as old as Pliocene (Otago) and c. 1.7–1.0 Ma (Waikato, Wairarapa) are recognized. Loess chronostratigraphy has enabled loess and associated buried soils/paleosols to be correlated to the Quaternary marine oxygen isotope records, which, alongside mapping efforts, have revealed landscape responses to climate and tectonic controls particularly along the eastern regions of ANZ bordering the Hikurangi Subduction Margin.

1 | Introduction

Loess is a fine-grained aeolian sediment dominated by silt-sized particles that have been entrained, transported, and deposited by the wind, and which can be identified in the field as a distinct sedimentary body (Crouvi et al. 2025). As a weakly consolidated cover-bed deposit, most loess is finer than aeolian sand but

Brent V. Alloway and David J. Lowe contributed equally in this study.

coarser than aeolian dust (<~10 μm), and hence it may also be described as "coarse dust" or "paleodust" (Rousseau et al. 2021; Crouvi et al. 2025). In this review article, the term "cover-bed" includes unconsolidated or weakly consolidated deposits such as alluvium, landslide debris and colluvium, tephra, peat, till, etc., as well as loess (Laffan and Mew 1988). Sometimes the term "regolith" (from Greek *rhēgos* for "blanket[-ing] rock") is used as an equivalent general term for unconsolidated deposits of fragmental and earth material overlying bedrock and forming land surfaces (Reed 1962; New Zealand Soil Bureau 1973). The word "loess" itself is of German origin (*löss*), indicative of a deposit of "loose" or loamy appearance (Selby 1976). Many deposits globally contain secondary calcium carbonate, the presence of which at one time was considered an essential diagnostic criterion to define loess (discussed later).

Covering around 7% of the Earth's land area (based on data in Li et al. 2020), loess is one of the most important terrestrial archives for paleoclimate studies, i.e., reconstructing environmental changes, including climates, of the past (e.g., Muhs 2013; Rousseau et al. 2020, 2021). In many parts of the world, loess-derived paleosols, typically buried, mark warm (interglacial) periods, and loess-paleosol successions are well recognized and studied (Lehmkuhl et al. 2021; Rousseau et al. 2021; Muhs 2025). A paleosol is a soil, or soil horizon, formed on a landscape of the past (non-buried paleosols are formed in an environment of the past) (Palmer et al. 2025). But in some regions including Aotearoa New Zealand (ANZ hereafter), the accumulation of loess (a geological process) and the formation of soil horizons (referred to also as "pedogenesis", a term used hereafter) occur as "competing" processes, collectively called upbuilding pedogenesis. Together, they mark the syn-depositional alteration of loess mainly during cold or cool periods (Kemp 2001; Muhs 2025). Hence, much of the loess in ANZ ought to be considered sediment-soil rather than simply as sediment (Lowe et al. 2015). Pedogenesis is related to the discipline "pedology" (from German *pedologie* after Greek *pedon* "ground, earth"), which is defined as a branch of geosciences that addresses soils as naturally occurring phenomena including their stratigraphy, properties, genesis (origins), and distribution in the landscape; their classification; and their evolution through time (Schaetzl and Thompson 2015).

Loess comprises a significant deposit in much of ANZ, with a loessial component estimated to contribute as much as ~60%–70 % of the country's soils, and many of the studies on loess have arisen through recognition of its importance as a soil-forming parent material underpinning high agronomic productivity (e.g., Smalley and Davin 1980; Hewitt et al. 2021a; see also Catt 2001). In addition, loess research undertaken using stratigraphic and chronological approaches in ANZ has helped to decipher climatic change, including correlation of loess records with the marine oxygen isotope record, and to evaluate landscape development through the Quaternary (Alloway et al. 2007).

In this article, we review the development of loess studies in ANZ, which began ~150 years ago. Key issues and controversies are included, and we describe how and why loess in ANZ is different from that in many other parts of the world. We discuss the multigenerational efforts made using a range of tools to characterize, map, and correlate loess, and we present genetic models of how loess in different parts of ANZ is formed, typically as multisequal loess-paleosol successions involving upbuilding pedogenesis. We refer to such successions as "multisequal" in the sense of multiple occurrences of couplets or triplets of soil horizons (sequums), each characteristic of a soil formed in a period of slow loess accumulation with environmental conditions conducive to pedogenesis. The soil units separate weakly pedogenically altered loess (Lowe 2000). These components, respectively, represent interglacial or interstadial (i.e., warm or mild, usually wetter) climates and glacial or stadial (i.e., cold or cool, usually drier) periods (e.g., see Lowe and Walker 2014, for a review of concepts and terms used in paleoclimate studies). The term "soil welding," the merging of one sequum (soil profile) with another over time (Ruhe and Olson 1980; Schaetzl and Sorenson 1987; Schaetzl and Thompson 2015), is applicable to multisequal successions where individual loess sheets are thin (Lowe 2019).

We also examine the many dating methods, including the valuable method of tephrochronology, that have been routinely applied to loess in ANZ. Finally, we emphasize that our review is not just about loess per se—we also outline the substantial efforts of many past and present researchers who worked to better understand loess and associated soils and paleosols and their links to climate change and the evolution of the ANZ landscape through the Quaternary.

2 | Development of Loess Studies in ANZ

2.1 | Historical Recognition and Advances

Loess was first recognized and documented in ANZ by Haast (1878, 1879) who described (to the Philosophical Institute of Canterbury on 7 March 1878) the loess on Banks Peninsula via excavations associated with the Lyttelton and Christchurch railway tunnel (Haast 1878, 508):

> *"Beginning at the southern or Lyttelton side of the tunnel, we observe that a large bed of loam has been deposited upon the volcanic rocks, being thickest on the lowest third of the caldera wall. This peculiar rock, which, when in small pieces, is easily pulverized between the fingers, has a remarkable consistency and solidity when in large masses, and is of sub-aerial origin. It may be designated as loess, an expression now extensively used in Europe for similar deposits."*

Haast's view that these deposits were of aeolian origin was later shared by several other contemporary scientists (including R.S. Speight, P. Marshall, and A. Heim: see Raeside 1964), but it was a citizen scientist and journalist/editor, John Hardcastle (Figure 1A,B), who described, in general terms, their soil stratigraphic context (Hardcastle 1889, 1890a) using descriptive criteria essentially unmodified and mostly still used today for multisequal loess-paleosol successions at Timaru, South Island. Hardcastle (1890b) additionally proposed the hypothesis that these loess successions also contained a comprehensive register of past climates, a recognition well ahead of its time (Smalley 1983; Smalley and Fagg 2015). As stated by Smalley (1983, 480), Hardcastle's papers (especially that of 1890b) comprise a "most perceptive and clearly expressed conception of loess as a recorder of glacial climates, and possibly the earliest recognition of the importance of palaeosols in loess stratigraphy; in fact a truly amazing insight."

FIGURE 1 | (A) John Hardcastle (1847–1927) immigrated to New Zealand in 1848 from the UK when aged 10. After training as a teacher, and then briefly teaching, he became, in 1879, a junior reporter and proof-reader for *Timaru Herald* followed by nearly 40 years as a journalist and occasionally editor for *South Canterbury Times* (Fagg 2001; Smalley and Fagg 2014). Regarded as the pioneer of loess stratigraphy in ANZ, Hardcastle studied loess in the vicinity of Timaru and made several important loess-related observations in 1889 and 1890. He is best known for his recognition of loess as a "climate register," which at the time was among the very first relatively sophisticated paleoclimatological inferences made globally (Smalley and Fagg 2015; Fagg and Smalley 2024) (photo courtesy of Roger Fagg). (B) Dashing Rocks coastal section at Timaru (photo courtesy of Ian Smalley) where some of Hardcastle's observations were made, with a schematic showing the general profile of the section, location of defining profile features (e.g., fragipans), and interpreted loess units (after Tonkin et al. 1974).

However, Hardcastle's climate-related assertions were not without detractors at the time, including no less a figure than Professor Frederick W. Hutton, prominent within the uppermost echelon of ANZ academia (and still commemorated today via the Hutton Medal by the Royal Society of New Zealand), whose dismissive comments were recorded not only in the minutes of the Philosophical Institute of Canterbury but also in the local newspaper *The Star* (Christchurch), 3 October 1890 (Smalley and Fagg 2015, 53). Hutton was a convinced supporter of the theory that loess was a marine deposit (e.g., Hutton 1882)—even in 1904 he continued to regard the "wind hypothesis" as "inadequate" (Hutton 1904, 471). In addressing earlier criticism, Hardcastle, in contrast, noted that "Every detail of the loess at Timaru emphatically denies it is of marine origin" (Hardcastle 1890b, 325). Hardcastle has subsequently been recognized globally for his significant contribution to identifying loess in ANZ and ascribing the intimate association of loess (-soil) sequences with climate change (Smalley 1983; Smalley et al. 2001; Lowe et al. 2015; Smalley and Fagg 2015; Fagg and Smalley 2019), with his work being routinely cited subsequently (e.g., Raeside 1964). A commemorative symposium to honour Hardcastle was organized at the 13th International Union for Quaternary Research (INQUA) Congress in Beijing in 1991 (Fagg and Smalley 2024)—just over 100 years since the publication of his pathfinding papers of 1889 and 1890.

In the decades following World War II, a slew of Department of Scientific and Industrial Research (DSIR) Soil Bureau surveyors (followed much later by university post-graduate students) emerged who were responsible for mapping and characterizing the physical, mineralogical, and chemical properties of surface loessial soils and underlying multisequal loess-paleosol successions in Manawatū, Taranaki, and Wairarapa in the North Island, and Marlborough, Canterbury, Southland, Otago, and Westland in the South Island (e.g., Raeside 1964; Young 1964, 1967; Rhea 1968; Ives 1973; Bruce 1973a, 1973b, 1983; Neall 1972, 1975; Palmer 1982; Eden 1987; McIntosh and Eden 1989; McIntosh 1984; Palmer and Vucetich 1989; Vella et al. 1988; McIntosh et al. 1990; Warnes 1992; Vucetich et al. 1996).

Within the Rangitīkei Valley, where one of the most complete river terrace sequences in the lower North Island can be recognized, Te Punga (1952) identified seven episodes of terrace formation, matched heights of terrace treads on either side of the present-day river channel, and linked these episodes to changes in relative base level (the lowest level or surface toward which erosion constantly progresses, such as lakes or waterfalls in long profiles of rivers, the ultimate base level being the sea: see also discussion in Bull 1990). A decade later in southern Wairarapa, Vella (1963) mapped three fluvial aggradation terraces and correlated them from highest to lowest with the first, second, and third stadials of the Last Glacial period, respectively. Palmer and Vucetich (1989) subsequently described the cover-bed sequences on these terraces comprising Porewa loess (first stadial), Rata loess (second stadial), and Ohakea loess (third stadial) overlying Last Interglacial deposits (following the terrace and loess nomenclature of Milne 1973b). Each loess layer was presumed to be derived from dust that was blown mainly by the prevalent northwesterly wind from an actively aggrading floodplain at lower elevation. Around the same time that Vella was mapping fluvial aggradation terraces in southern Wairarapa, Cowie (1964a, 1964b) in the Rangitīkei–Manawatū region was able to show the systematic distribution and thickness of loess downwind of major river channels (Figure 2A) and illustrate their direct bearing upon adjacent soils and terraces, their drainage and/or fertility, and, hence, their agronomic productive potential (Figure 2B). Cowie's initial priority in this research was to demonstrate that the silty cover beds overlying the Tokomaru Marine Terrace in the area (see Ryan et al. 2021) were, following a suggestion first made by Fleming (1953), in fact loess, and not marine or alluvial silts. His rationale is summarized below (Cowie 1964a, 389–390):

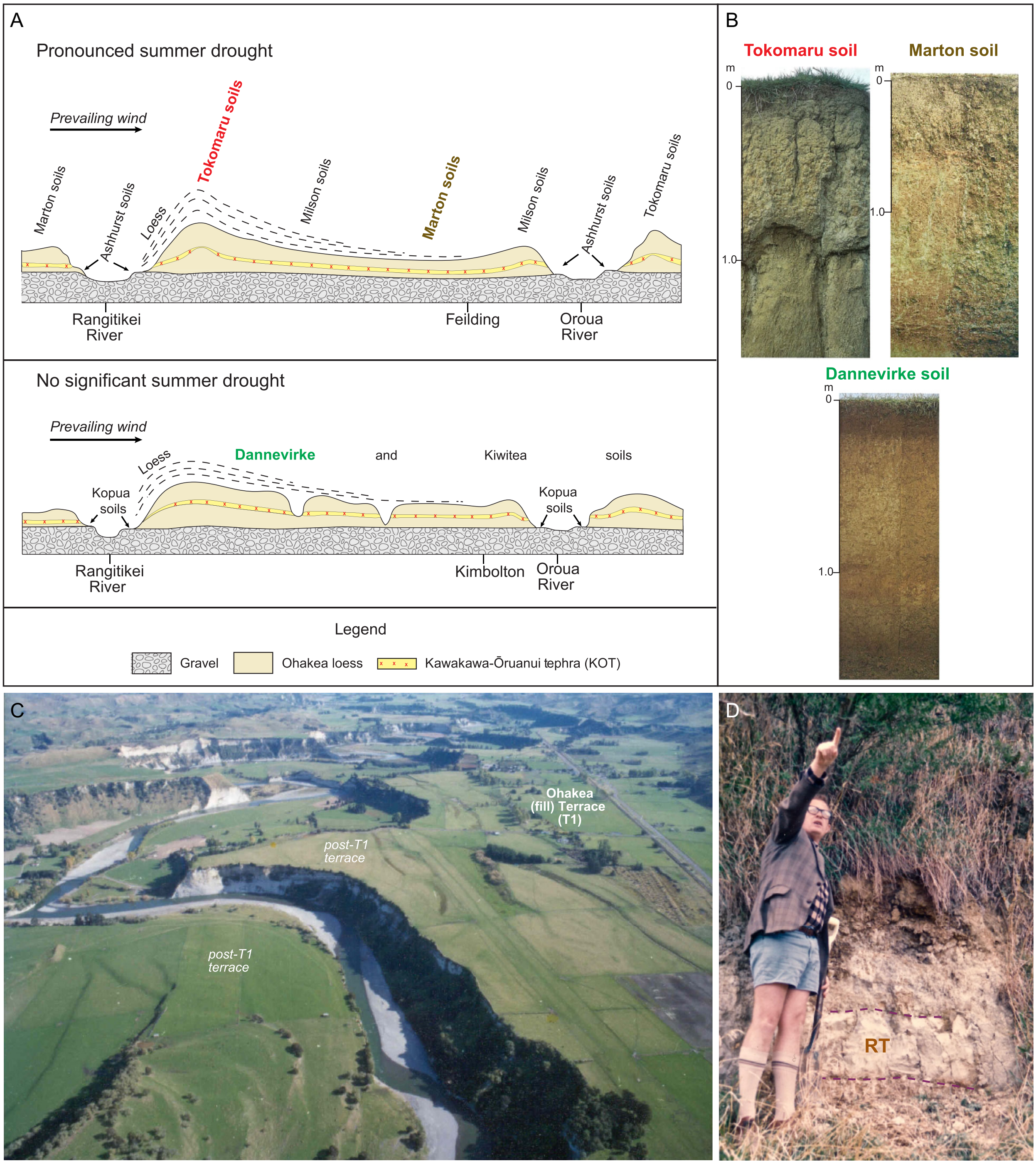

FIGURE 2 | (A) The distribution and thickness of loess downwind of the Rangitīkei and Oroua river channels and (B) their direct bearing upon soils formed on adjacent terraces, influencing soil drainage/fertility capabilities and, hence, their arable and/or pastoral potential (modified from Cowie 1964a, 1964b; Molloy 1998). For instance, Tokomaru soils are formed on high terraces on the leeward margins of the Rangitīkei and Oroua rivers where the loess is thicker and coarser. These soils have a dense grey morphology with a mottled veined and clay-rich Btg horizon above large fragipan columns (Cxg) developed in only weakly altered loess parent material (Molloy 1998). The compact, mottled nature of the Btg horizon indicates seasonal moisture changes (e.g., pronounced summer drought conditions). Under these same moisture conditions, Marton soils have formed in the finer-textured and thinner loess away from the margins of the major rivers and are more strongly gleyed than the Tokomaru soils. In other areas of the region where no significant summer drought is experienced, the Dannevirke soils are found on the moister loess-covered terraces and gently rolling landscapes of Manawatū and southern Hawke's Bay. Their properties contrast sharply with those of the dense grey Tokomaru soils because they are not gleyed and the top ~40 cm of their profiles are typically friable with low bulk density. They are also fairly uniformly dark yellowish brown in colour throughout the profile (Molloy 1998) (soil profile photos courtesy of Les Molloy and Quentin Christie/New Zealand Society of Soil Science). Note the scale for the Marton soil is from 0-50 cm depth, not 1 m as indicated. (C) View looking southward down the Rangitīkei River valley, southwest North Island. Here, in 1973, Derek Milne was the first to recognize that major aggradational terraces within this catchment had a direct age correlation with the number of loess cover-beds, such that the riverbed during the formation of each aggradation terrace was the source of loess found on adjacent higher terraces. This research provided a significant template for further soil and landscape studies in southern North Island. In this image, the Ohakea (T1) aggradation (fill)

"The ash extends as a sheet over surfaces of different ages and heights and therefore both it and the overlying surface material must have been deposited subaerially. The ash is well bedded and was deposited fairly rapidly, but the overlying loess is unbedded, with numerous old root channels and worm casts indicating that it accumulated more slowly than the ash."

Collectively, the pioneering studies of Te Punga, Vella and Cowie, conducted in the lower North Island through the 1950s–60s, were highly influential on subsequent researchers including Derek Milne in his seminal study of loess beds and their relationship to an uplifted sequence of nine major aggradational terraces in the Rangitīkei catchment (Milne 1973a) (Figure 2C,D). This work was published as a series of four maps (scale 1: 50,000) but without accompanying text (Milne 1973b). Milne's findings in turn fostered subsequent pioneering research on the South Taranaki–Whanganui uplifted marine terraces by Brad Pillans—who, being an Australian National University (ANU, Canberra) post-graduate student, stood outside the DSIR Soil Bureau institutional sphere. Pillans was supervised and heavily influenced by Professor John Chappell, who cut his post-graduate teeth completing an M.Sc. thesis in 1964 (at Auckland University) on Quaternary sequences of the west coast of the North Island, including the North Taranaki uplifted marine terraces and their cover-beds (Chappell 1964, 1970). Chappell was later instrumental in elucidating Pleistocene sea-level change from uplifted coral reef terraces located in Huon Peninsula, Papua New Guinea (Chappell 1974), which became a template for further coastal work in the North Island of ANZ (Chappell 1975) including Pillans' own Ph.D. thesis (Pillans 1981).

Around the same time (from the late 1970s–early 1980s), David Lowe was being guided in his post-graduate studies at Waikato University by Harry Gibbs, John McCraw, and Michael Selby. Gibbs and McCraw had presented Lowe with a challenge, namely to determine the origin of the silt-rich cover-beds that overlie an extensive paleosol on strongly weathered Hamilton Ash beds (Lowe 2019) in the northern Hamilton Basin, the silt being ascribed a loessic (rather than pyroclastic) origin at that time (McCraw 1967a; Pullar 1967). Like many fledgling researchers of his day operating in North Island, Lowe was influenced by the work of pioneering tephrostratigraphers, Alan Pullar and Colin Vucetich. He was able to demonstrate through hand-over-hand mapping in conjunction with mineralogical and grain-size analyses that the post-45,000-year-old silt coverbeds in the central Waikato region were incrementally deposited and pedogenically altered tephra-fall deposits and not loess (Lowe 1981). The deposits conformed with size-distance and size-sorting relationships characteristic of primary tephra-fall beds demonstrable using the median diameter and sorting coefficient ratio model of Fisher (1966). The firm, loess-like character of these tephra deposits was attributable to the formation of halloysite (rather than allophane) during developmental upbuilding pedogenesis of the thin tephra cover-beds, its genesis being favored by the colder and drier climate of the Last Glacial and by the moderate drainage imposed on the cover-beds by perching on the shallow underlying (impermeable) paleosol (Lowe 1981, 1986, 2002, 2019; see also Churchman and Lowe 2012). Later, in the Rotorua area, Benny et al. (1988) utilised grain-size and mineralogical parameters to distinguish between tephra-fall and tephric loess (e.g., Figure 3A).

One person in particular, who made an outstanding but perhaps under-appreciated contribution to loess studies in ANZ, was Colin Vucetich (DSIR Soil Bureau, 1946–1965) (see Lowe, Tonkin Neall et al. 2008) (Figure 4). As well as his own research, Vucetich's input as an academic supervisor was exceptional. At Victoria University of Wellington (1965–1982), he was responsible for the supervision of many loess-related thesis projects including those undertaken by post-graduates Derek Milne, Philip Tonkin, Vince Neall, Kelvin Berryman, Peter McIntosh, Hugh Wilde, Dennis Eden, and Alan Palmer. Later in retirement, and as an honorary staff member at Massey University, Vucetich co-supervised (with Vince Neall) his last Ph.D. student, Brent Alloway. Meanwhile, at Lincoln University, Peter Almond (a former student of Vince Neall) became the last Ph.D. student associated with Philip Tonkin (Figure 4).

The agricultural and horticultural industries, and ANZ's national identity in part, continue to be heavily reliant on the productivity of its soils which, to a large degree, are formed in cover-beds including loess (e.g., Hewitt et al. 2021a). Arguably, loess studies in ANZ have been an essential (although largely invisible) element in shaping the nation's ongoing strategic agro-development and export of pastoral (dairy, meat and wool), horticultural (fruit and vegetables), viticultural, and forestry products. From the earliest inception of farming in ANZ, studies of soils formed in loess were an integral part of governmental efforts to better understand the distribution, benefits, and limitations of arable and pastoral soils, and, later, their spatial and stratigraphic association with underlying cover-beds in which they are developed and the landforms they mantle. It is noteworthy that the development of widespread farming, involving clearance of native vegetation and the introduction of large numbers of grazing animals to ANZ, has also increased potential for accelerated erosion, especially in areas where soils are dominated by loess (e.g., Watt 1972; Basher and Painter 1997; Basher 2013). In more recent years, loess and tephra chronostratigraphy, together with mapping, have allowed the periodicity of landscape change to be linked to master climate records (e.g., the marine oxygen isotope record) to reveal relationships between climate and landscape response (e.g., Pillans 1991, 1994, 2017; Naish et al. 1996, 1998; Newnham et al. 1999; Alloway et al. 2007, 2018; Barrell et al. 2005, 2013; Bostock et al. 2012). Researchers now recognize the utility of loess-paleosol stratigraphy in dating and correlating uplifted marine- and fluvial-terrace successions and, consequently, assessing tectonic, base level, and sediment supply

terrace (Milne and Smalley 1979) is indicated along with a succession of post-Ohakea degradation (cut) terraces. (D) Derek Milne (February, 1987) pointing out the Rangitīkei valley terraces at a roadside locality close to the Stormy Point Lookout along the Cheltenham–Hunterville Road (SHW 54). To the right of Milne is an exposure of Rangitawa Tephra (formerly known as Mt. Curl Tephra) (photo: B.V. Alloway). Figure 2A modified from Molloy, L. (1998). Soils in the New Zealand Landscape – the Living Mantle, Fig. 6.2 (p. 102), with permission from Mallinson Rendel in association with the New Zealand Society of Soil Science.

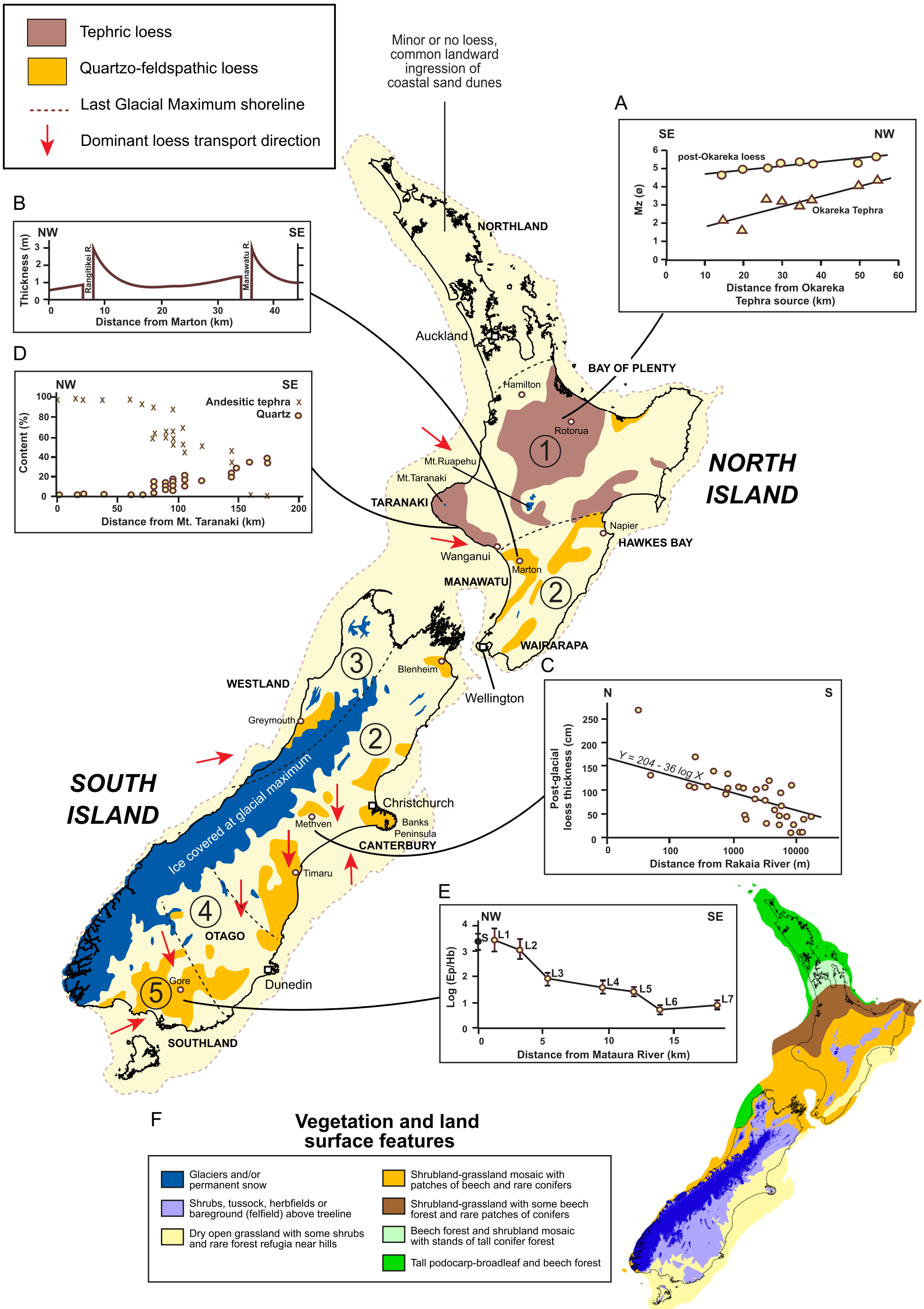

FIGURE 3 | Map of Aotearoa New Zealand (ANZ) showing distribution of major loess deposits and loess regions (modified from McCraw 1975; Eden and Hammond 2003). *Region 1:* Tephric loess. The southern limit could be extended southward to encompass southern Hawke's Bay at least because the quartzo-feldspathic loess still has considerable tephra content (A. S. Palmer, unpublished data). *Region 2:* Quartzo-feldspathic loess from greywacke. *Region 3:* Quartzose, strongly weathered loess. *Region 4:* Quartzose-loess with mica from schist. *Region 5:* Feldspathic loess from tuffaceous greywacke (see text). Place names mentioned in text and selected defining characteristics of loess (as insets A–E) from the various loessial regions are also shown. (A) Grain-size variations in Okareka Tephra (c. 23.5 cal ka BP) and loess derived from Okareka Tephra (after Benny et al. 1988). (B) Post Kawakawa-Ōruanui tephra (KOT, c. 25.6 cal ka BP) loess thickness in Manawatū area showing thinning away from major river sources (after Cowie 1964b). (C) Thicknesses of post-glacial loess in relation to distance from source, near Methven, Canterbury (after Ives 1973). (D) Mineralogical changes in loessic soil A-horizons with increasing distance from Mt. Taranaki (after Symes and Wells 1973). (E) Epidote/hornblende ratio in relation to distance from the Mataura River near Gore, Southland (after Eden et al. 1987). (F) Vegetation and land surface features of ANZ during the extended Last Glacial Maximum (eLGM) ~30–18 cal ka BP (Alloway et al. 2007) to show correspondence with loess distribution.

FIGURE 4 | Some notable contemporary loess events and contributors in ANZ. (A) Photograph of participants at the first triple-discipline INQUA-led meeting held in February 1994 at Waikato University, in which the integration of studies of loess, paleosols, and tephras was the primary theme. Individuals are named in Lowe et al. (2022) (photo: Ross Clayton, Waikato University). (B) Some participants on coastal slopes of Mt Karioi during the first intra-conference field-trip of the 1994 meeting: (L-R) Brent Alloway (then Auckland University), Philip Tonkin (Lincoln University), John Bruce (ex-Soil Bureau), Brad Pillans (Victoria University of Wellington), David Lowe (Waikato University), Alan Palmer (Massey University), and (kneeling) Peter Almond (Lincoln University). (C) Colin Vucetich in the late 1980s indicating the interglacial-aged L4 loess at Kohi Road, Whanganui area. (D) Philip Tonkin (Lincoln University) in the early 1990s describing a recent soil formed in a piedmont alluvial fan deposit, eastern Southern Alps. (E) Kelvin Berryman (L) and Pilar Villamor (R) (GNS Science) pausing for a moment as they describe the cover-bed stratigraphy of trench walls straddling a fault scarp located in the central North Island. In many paleoseismic investigations conducted throughout ANZ, tephra-loess-paleosol chronostratigraphy has proven to be essential in recognizing fault displacements and evaluating fault rupture histories (e.g., Berryman et al. 2022). A similar chronostratigraphic approach has been instrumental in ascertaining rates of tectonic uplift upon, and geomorphic response to, flights of fluvial and marine terraces located in eastern North Island and immediately adjacent to the obliquely convergent plate margin (e.g., Berryman 1993; Litchfield and Berryman 2005; Wilson et al. 2007). (F) Philip Tonkin, Bill (William) Bull (University of Arizona) and (unnamed) student support an extended soil auger designed to retrieve (deep) soil samples from the cover-beds of a fill terrace at Charwell, inland Kaikoura (photos C-F: B.V. Alloway).

and their control on these landforms within the actively uplifting inner forearc (and partially uplifted outer forearc) of the Hikurangi Subduction Margin (e.g., Bull 1990, 1991; Berryman 1993; Berryman et al. 2000; Litchfield and Berryman 2005; Wilson et al. 2007). Loess-paleosol successions, in combination with intercalated tephras, have also provided sound chronostratigraphic units essential for paleoseismic/fault rupture investigations in the central and eastern North Island (e.g., Berryman et al. 2022) and for deciphering the chronology of glacial advances in Westland (Almond 1996; Almond et al. 2001; Suggate and Almond 2005).

Through the years, loess studies have involved numerous researchers whose observations and surveys still prominently stand either as institutional maps and bulletins or journal articles, or both. Many of the early researchers were government employees within the DSIR, formed in 1926. They worked either within the Soil Survey Section of the Geological Survey (formed 1933), the Soil Survey Division (formed 1936), and its successors—the Soil Bureau (1946–1988), DSIR Land Resources for several years, and then Manaaki Whenua Landcare Research (1992–2025)—or within the Geological Survey (1865–1990) and its successors (DSIR Geology and Geophysics (1990–1992) and Geological and Nuclear Sciences/GNS Science (1992–2025)) (Tonkin 2007a, 2007b). Another organization of importance was the National Soil and Water Conservation Organisation (NWASCO) of the Ministry of Works (which itself was disestablished in 1988). Land and soils were mapped at 1: 63,360 scale as part of the New Zealand Land Resources Inventory (NZLRI) project. This project provided considerable new information about the extent and depth of loess cover in ANZ (as utilized by Schmidt et al. 2005) as well as documenting its value for food production through Land Use Capability (LUC) classes 1–3, and its propensity for accelerated erosion (tunnel gully, rill, soil slip, sheet, and wind) through LUC classes 6 and 7.

Through the 1970s to the early 1990s, academic staff (including some recruited from DSIR), together with their students from Massey, Lincoln, Victoria (Wellington), and Waikato universities, also made very significant contributions in characterizing loess, often in collaborative partnership with staff of DSIR.

At times through these institutions' histories, restrictive boundaries between the "right" to study soils and what lies beneath were imposed. Research was also hindered by territoriality and head-regional office disputes (involving strong personalities) that impeded interdisciplinary cross-over and extension (see Lowe 2002; Tonkin 2007a, 2007b). Fortunately, dogged researchers (mostly based in the regional offices), sometimes clandestinely, advanced earlier pioneering work (e.g., Grange and Taylor 1931; Baumgart 1954). This covert innovative research, sometimes occurring outside normal working hours as "secret correlation missions" (Vucetich 1977), especially that involving pioneering work on tephras and associated subsurface tephric loess in central North Island (Lowe 1990), resulted in the eventual release of a series of seminal bulletins and publications (e.g., Vucetich and Pullar 1964, 1969, 1973; Pullar and Birrell 1973). These publications have proven foundational not only to modern understanding of soil genesis and the variable environmental factors involved but also they were far-sighted enough to be intimately applied in Quaternary landscape evolution and palaeoclimate change.

Based on decades of collective research effort it was finally becoming obvious that soils throughout ANZ could not be simply characterized and understood in isolation: the immediately underlying cover-beds into which they were developed, and the landforms they mantled, were key. Loess is an integral part of that colourful story of science progression.

2.2 | Loess in the ANZ Context

Loess in ANZ is a significant and widespread cover-bed deposit, whose thickness >1 m covers at least 10% of the land area (McCraw 1975; Eden and Hammond 2003) (Figure 3). These deposits are somewhat unusual in comparison with major loess occurrences described elsewhere in the world (McCraw 1975; Smalley 1978, 1982; Pye 1995; Muhs 2013; Crouvi et al. 2025). First, the ANZ archipelago represents a relatively small southern mid-latitude land area surrounded by a vast expanse of ocean in the southwest Pacific, whereas loess in many other parts of the world is typically associated with continental settings and peripheral to extensive continental and piedmont ice sheets or deserts (e.g., Selby 1976; Pye 1995; Rousseau et al. 2018, 2021; Li et al. 2020; Schaetzl et al. 2018; Crouvi et al. 2025). Second, most (but not all) ANZ loess is non-calcareous (see next section below). Third, in parts of ANZ there is an intimate association between loess and tephra since much of the loess in the central and western North Island (but not the eastern or southern parts, especially south of Taihape, where quartz and feldspar dominate) is predominantly composed of rhyolitic and andesitic glass and mineral constituents and derived mainly from aeolian reworking of freshly deposited unconsolidated and/or weathered tephra (e.g., Milne and Smalley 1979; Vucetich 1982; Palmer and Pillans 1996; Lowe et al. 2015). Furthermore, a number of dated tephra horizons encapsulated within loess sheets provide invaluable isochrons (as documented later), enabling loess to be correlated across terrestrial and marine realms (e.g., Pillans 1988; Alloway et al. 2007; Barrell et al. 2013).

2.2.1 | Defining Loess in ANZ

A definition of loess better suited for ANZ's southern mid-latitude maritime context was introduced by Raeside (1964, 811) who applied the term to "any fine-textured deposit of aeolian origin other than sand dunes (where particles are transported chiefly by saltation)." This new definition embraced all aeolian deposits where "transport has been primarily by suspension, irrespective of organic matter content, mineralogical composition, calcium carbonate content, degree of compaction, or texture." Raeside's (1964) definition of loess was supported by Young's (1964, 1967) pioneering sedimentological and mineralogical studies (themselves inspired by Dr Bill Sevon, University of Canterbury: Simon Nathan, *personal communication*, 2024) and also by the work of Stevens (1968). This definition, widely used in ANZ including to the present day, was somewhat broader than that of the United States or European usage at that time (McCraw 1975), which typically included considerable amounts of secondary calcium carbonate. Until relatively recently, the presence of $CaCO_3$ was one of several prerequisites for a sediment to be considered true loess through its weak cementation, thereby excluding most of the ANZ deposits from being classified as loess (e.g., see Smalley 1971, 1978, 1982; Pécsi, 1990; Pye 1995; Sprafke and Obreht 2016). However, as Muhs (2013) and others have pointed out, this restrictive definition, if applied worldwide, would eliminate many silt-dominated but non-calcareous aeolian sediments as loess bodies in South America, Siberia, and Alaska as well as ANZ. Moreover, by 1982, the "world" definition of loess was evolving more towards that used in ANZ anyway (Smalley 1982, 101) (e.g., see Muhs 2013; Crouvi et al. 2025).

Even though ANZ loess in the South Island conformed with the grain-size criteria (of the time) of overseas loess (e.g., at least 50% of particles must lie between 10 and 50 μm diameter, e.g., Russell 1944; Swineford and Frye 1945; Smalley 1975 and papers therein), some ANZ deposits were considered "loess-like" in this regard because of their higher densities and higher clay contents, and lower porosities, lower compressibility, and lesser proneness to collapse (e.g., Birrell and Packard 1953; Young 1964; Smalley 1978, 1982; see also Yates et al. 2018). Smalley (2008, 133) reported that I.P. Gerasimov (Director of the Geographical Institute in Moscow) famously visited the widespread loess in the South Island of ANZ on a field trip during the 1973 INQUA Congress in Christchurch and denied that there was any loess present. In addition, a conceptual problem regarding the origin of loess in southern North Island emerged because of its lack of glacierisation (apart from minor glaciers on the highest points in the landscape, e.g., see Barrell 2011; Brook and Kirkbride 2018). Note that we use the term "glacierisation" or "glacierised" (cf. glaciation, glaciated) to refer to the direct erosive action of ice on the land over which it flows. A long-running debate in the literature about the ultimate origins of loess (e.g., see Smalley 1975, 1978, 2008; Pullar and Kennedy 1978) saw the concept of "mountain" loess arise, and this origin, rather than "glacial" or "desert" origins, was assigned to southern North Island loess. It was thought to form via a process of enhanced physical weathering of relatively weak greywacke during cold conditions (e.g., Smalley 1978, 1982; Milne and Smalley 1979). Greywacke is usually described as a resistant sandstone in a muddy matrix (e.g., Mortimer et al. 2015), but it is also described on maps as both sandstone and mudstone (argillite) beds (e.g., Edbrooke 2017). Consequently, there was major discussion and initial resistance to this redefinition (involving mountain loess) principally from European researchers within INQUA and its multidisciplinary working groups. However, by the time the 1973 INQUA Congress was held in Christchurch, a decade on, loess was being recognized much more widely in New Zealand (e.g., Bruce 1973a; Ives 1973; Griffiths 1973; McCraw 1975), and, although its legitimacy as "true" loess was still challenged by some researchers, maps showing its distribution had been prepared for both North and South islands at 1: 1,000,000 scale (Bruce et al. 1973; Cowie and Milne 1973).

Another problem at this time (late 1960s–early 1970s) was the recognition in central North Island of tephric loess (also known as volcanic loess) interbedded with subsurface tephra deposits. Described initially as "almost homogenous unbedded deposits… composed of subangular pumice and glass particles" and "invariably local in distribution", it was denoted "loess" (Vucetich and Pullar 1969, 809), this word being written deliberately within inverted commas because of its disputed origin at the time. The tephric loess was distinguishable from tephras because it was usually finer in texture (mainly fine sand to silt to clay), it lacked graded bedding and pumice lapilli, and it typically thickened away from the tephra source volcanoes (Pullar and Pollok 1973; Birrell 1974; Kennedy 1980a, 1982, 1988; Vucetich 1982; Barratt 1988; Nairn 1992). However, its aeolian origin and designation as loess remained opposed by some geoscientists (noted by Simon Nathan, *personal communication*, 2024). Nevertheless, maps showing the occurrence of subsurface tephric loess in the Rotorua and Taupō regions (at scale 1: 250,000) were published by Pullar and Birrell (1973) with accompanying texts by Pullar et al. (1973a, 1973b).

In 1977 the INQUA Loess Commission expanded from its central European base to include the Western Pacific Working Group (WPWG), which was formed to establish new cooperative loess research linkages involving China, Australia, and New Zealand (Smalley and O'Hara-Dhand 2010). ANZ delegates to WPWG were Ian Smalley, Derek Milne, Neil Kennedy, and Colin Vucetich, all well-known ANZ loess practitioners. To kick things off in ANZ, a 1-day "Loess Workshop," organized by Colin Vucetich, was held at Victoria University of Wellington on 23 May, 1979 (Smalley 1979). Subsequently, WPWG field meetings were held in Australia (in 1980), China (in 1985), and ANZ (in 1987), with Dennis Eden and Derek Milne of DSIR Soil Bureau organizing and leading the ANZ meeting (February 14–21, 1987) that resulted in the publication of a book of conference proceedings (Eden and Furkert 1988). From the inception of WPWG, the initial furore concerning ANZ loess definition "blew over" and gained widespread acceptance. Similarly, the ongoing disputes about tephric loess, which arose to a degree during the 1980 "Tephra Workshop" meeting held in Wellington (Kennedy 1980b; Lowe 1980), have also been laid to rest, especially since publication of the detailed mineralogical and textural study by Benny et al. (1988) on tephric loess near Rotorua (see Figure 3A). Furthermore, comprehensive field studies undertaken in central North Island and Taranaki regions also demonstrated its legitimacy (e.g., Alloway et al. 1988; Froggatt 1988; Kennedy 1988, 1994).

3 | Multisequal Loess-Soil and Paleosol Successions and the Importance of Upbuilding Pedogenesis

3.1 | Upbuilding Pedogenesis Explained

The formation of soil, as recognized classically, proceeds where a pre-exisiting parent material is modified by soil-forming processes that have varying impacts according to the well-known soil-forming factors (Jenny 1940; Simonson 1959). In this case, the soil profile originates via a two-step process: step 1, accumulation (or exhumation) of a fresh parent material at the land surface, followed by step 2, the modification of the parent material by soil-forming processes and weathering to form soil horizons, generating a gradually deepening soil profile. This classical model of "topdown" (surface-process driven) pedogenesis, however, is modified when geological deposits, such as loess, tephra, colluvium, or alluvium, are simultaneously added to the land surface as occurs commonly in various ANZ landscapes dominated by cover-beds (Almond and Tonkin 1999; Kemp 2001; Lowe and Tonkin 2010; Hewitt et al. 2021a; Alloway et al. 2018; Palmer et al. 2025). In this scenario, step 1 and step 2 occur together, not sequentially, so that the soil profile deepens as the land surface rises concomitantly over time, an integrative process called upbuilding pedogenesis as noted earlier (Johnson and Watson-Stegner 1987; Johnson et al. 1990)—in effect, a "competition" between geological and pedological processes (Muhs et al. 2004; Lowe et al. 2012; Muhs 2025). The deposition of geological material (typically sediment or tephra) may be incremental, such as occurs with the deposition of loess (giving rise to "developmental" upbuilding pedogenesis); or it may be the sudden or rapid deposition of a relatively thick deposit that buries and isolates the antecedent soil (giving rise to "retardant" upbuilding pedogenesis) as occurs, for example, with exceptionally fast loess accumulation very close to source or the sudden deposition of a thick tephra or alluvial deposit (>~50 cm) (Hartemink et al. 2020; Palmer et al. 2025).

In summary, developmental upbuilding pedogenesis in loess involves the relatively slow addition of loess incrementally in glacials or stadials to the land surface whilst surface-driven (topdown) soil processes concomitantly modify it (syn-depositional alteration of Kemp 2001) to form a weakly altered sediment-soil. These 'slightly pedogenic horizons' have been correlated to formally-defined interstadials in European loess sequences (Rousseau et al. 2017, 2021). During minimal or zero loess accumulation in interglacials or interstadials, topdown soil processes are able to more effectively modify the antecedent weakly altered loess-soil profile to form more strongly developed soil horizons, which become buried paleosols when the next cycle of loess deposition begins. This form of sequence is commonly referred to as loess-paleosol succession, but in much of ANZ, it would be more accurate to call it a (multisequal) loess-soil/paleosol succession. This succession represents an integration of the "changing balances between pedogenesis and loess accumulation" over geological time (Kemp 2001). In effect, this multisequal status can be viewed as a resolution of what Sprafke and Obreht (2016) referred to as the major conflict regarding the definition of loess that has bedeviled studies for many decades involving competing perspectives from two disciplines: sedimentologists have stressed the processes involving material production, transport, and accumulation by wind; pedologists have focussed on post-depositional pedogenic processes that modify the loess but are not unique to it (see also Smalley 1971).

3.2 | Application of Models of Loessic Upbuilding Pedogenesis to ANZ Landscapes

The recognition of multisequal loess-soil/paleosol successions that reflect predominantly developmental upbuilding pedogenesis has been a very significant advance in loess studies of ANZ (Alloway, Stewart, et al. 1992; Almond and Tonkin 1999; Lowe 2000; Lowe and Tonkin 2010; Lowe et al. 2015; Palmer et al. 2025). In 1994, New Zealand hosted (at the University of Waikato, Hamilton) the first triple-discipline meeting to be held under the aegis of INQUA. As noted earlier, the integration of studies of loess, paleosols, and tephras was the primary theme (Lowe 1996) (Figure 4A). The linkage of loess and other terrestrial deposits, correlated in part using tephrochronology, to the marine oxygen isotope record (MIS hereafter), which featured also during the 1987 WPWG meeting (e.g., Alloway et al. 1988; Pillans 1988), was another major focus of the conference, especially during associated field trips (e.g., see Pillans and Palmer 1994). Since then, these same themes and concepts have extended to other Southern Hemisphere mid-latitude loess-forming settings (Alloway et al. 2018; Flores-Aqueveque et al. 2024; Crouvi et al. 2025). In deciphering the age of successively older landforms, such models of upbuilding pedogenesis have been formulated, and we document three examples below.

3.2.1 | West Coast, South Island

An excellent example has been described for the temperate rainforest of south Westland (West Coast, South Island) where six distinct moraines and associated outwash terraces were recognized (Almond 1996; Almond et al. 2001). Here, loess cover-beds thickened and the number of buried soils/paleosols increased systematically with the age of the landforms they mantled. Up to five loess sheets and morphologically identified soil features were recognized (Figure 5).

On the western side of the South Island, very high rainfall rates (>3 m annually) promote rapid pedogenesis including strong leaching and acidification (Tonkin and Basher 2001; Eden and Hammond 2003; Marx and McGowan 2005; Eger et al. 2012) and, consequently, the relatively thin loess sheets characteristic of the region (first identified by Young 1967) are strongly altered from the overprint of topdown and developmental upbuilding pedogenesis (Almond 1996; Almond and Tonkin 1999). In these circumstances there is no obvious distinction between loess and soil: all the loess is altered by pedogenesis to a greater or lesser extent (i.e., the loess displays a soil fabric of root traces and worm burrows inherited when the loess was part of the surface A-horizon) between loess sheets, and, as emphasized earlier, the loess is clearly a sediment-soil (Scott and Lewis 1979; Lowe et al. 2015). In well-drained environments on West Coast sites, buried soils/paleosols are identified by the occurrence of repeating E-Bs horizon pairs characteristic of Orthic Podzol Soils of the *New Zealand Soil Classification* (NZSC: Hewitt 2010) (Almond et al. 2001; Eger et al. 2012) (Figure 6A(i)). At these sites, mineralization of organic matter from the A horizon as it becomes buried reveals a bleached horizon subsequently identified as a buried E horizon, e.g., bE in Clayden and Hewitt (1989) as applied in the NZSC (Hewitt 2010), or an Eb horizon as applied in *Soil Taxonomy* (Soil Survey Staff 1999, 2022). As loess accumulation continues, podzolising pedogenic processes release Fe, Al, and Si (Childs et al. 1983; Sauer et al. 2007) and translocate it into the subsoil, forming a Bs horizon that builds upwardly behind the rising (near-surface) A and E horizons (Almond and Tonkin 1999). A characteristic feature of these soils is the deep soil acidification when compared with that of topdown soils due to weathering and loss of acid-neutralizing capacity when subsoil increments were in the aggressive weathering environment at the land surface.

On poorly drained fluvio-glacial outwash terraces, soils are characteristically organic-rich with the form O/A/Er/Bh (Perch-gley Podzols). When they are buried by accumulating loess, the anaerobic environment preserves the organic matter so that the tops of buried soils may be readily identified by buried organic (bO or bA) horizons. However, complications for identifying buried O/A horizons can occur as a result of subsequent developmental upbuilding and topdown phases. First, Al solubilized in the low pH environment may be translocated downward

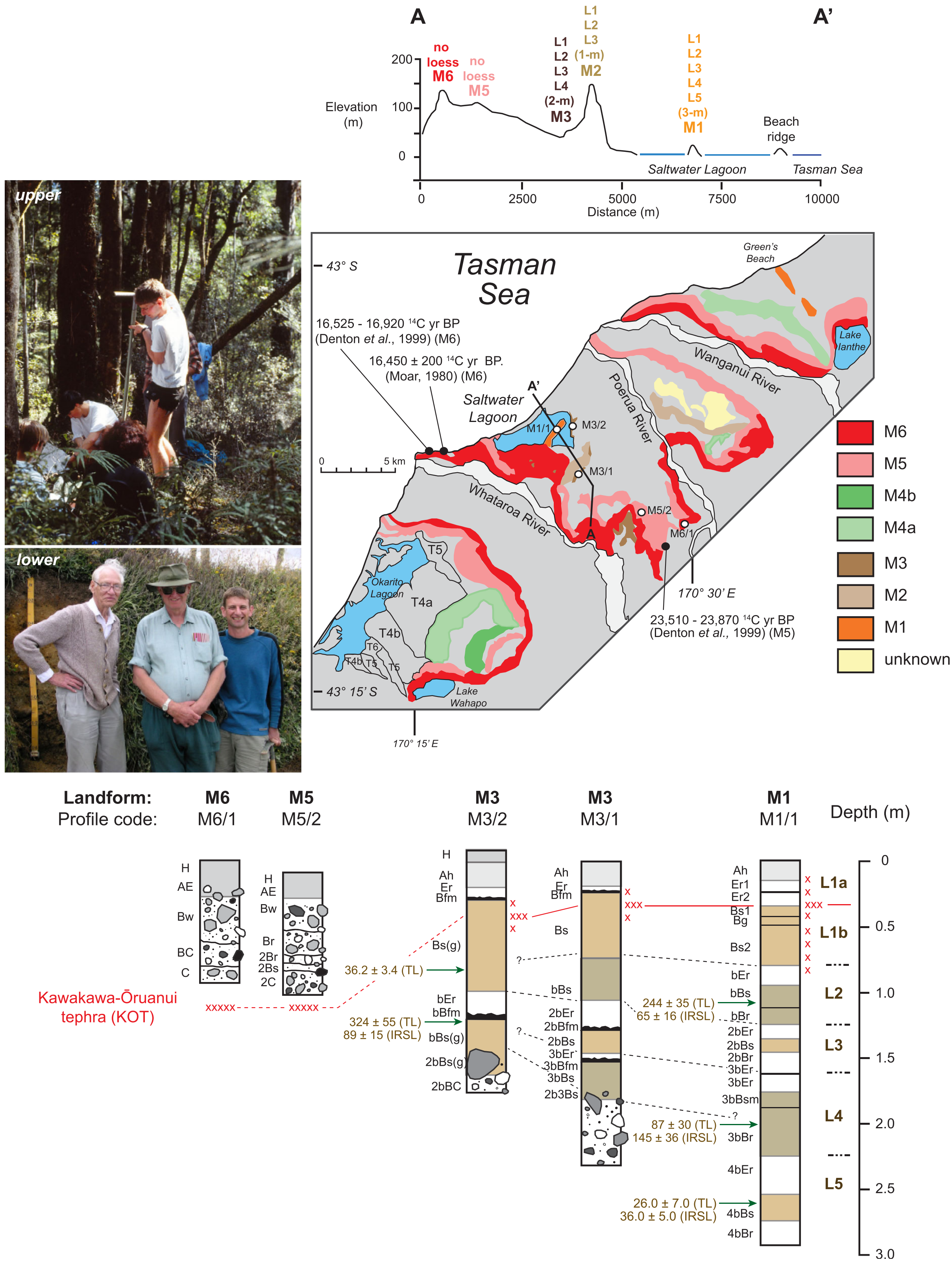

FIGURE 5 | Soils and loess stratigraphy of moraines (M6 to M1) occurring within Saltwater Forest, south Westland (modified from Almond 1996; Almond et al. 2001). Saltwater Forest is located between the Whataroa and Poerua rivers on the map. Moraines are designated M6, M5, etc., in order of increasing age and their associated outwash terraces are correspondingly designated T6, T5, etc. The three oldest moraines (M1, M2, and M3) lie within Saltwater Forest and are subparallel to the coastline. The locations of key radiocarbon (^{14}C) sample sites in this area are indicated (Moar 1980; Denton et al. 1999). In the moraine profiles note the persistent occurrence of the 25.6 cal ka BP KOT (indicated in red) occurring in the upper part of the profiles of pre-LGM moraines (M3, M1) and at the contact between L1a and L1b. TL and IRSL ages are also indicated and were deemed of limited value since they show unacceptable and low-precision ages that were anomalously old, and in stratigraphically reversed sequence (Almond et al. 2001). An elevational transect (A–A') across these moraines extending from the foothills of the Southern Alps to the coastline is indicated, as well as the

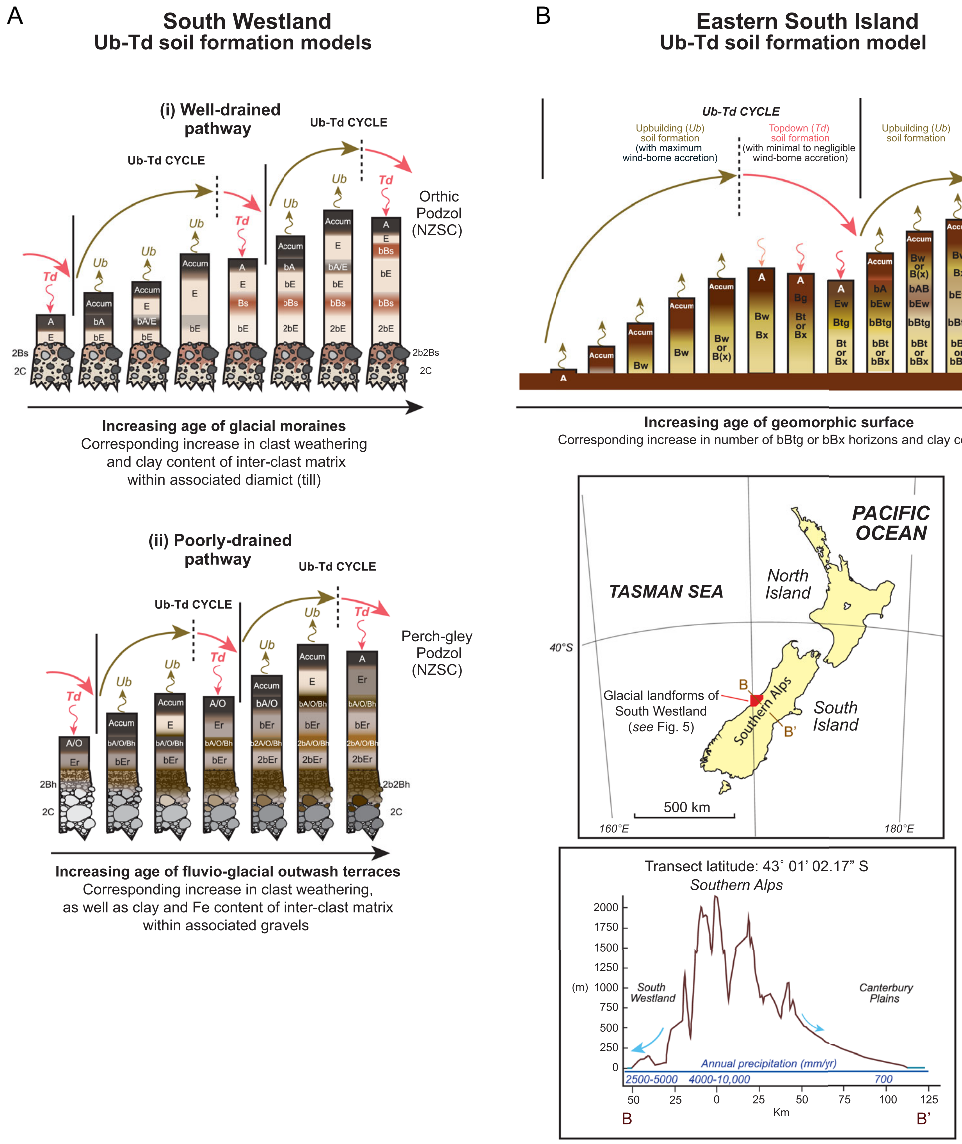

FIGURE 6 | Conceptual models of upbuilding (*Ub*)-dominated and topdown (*Td*)-dominated soil formation for multisequal soils formed from loess in a transect (~41° 37'S) extending across South Island, New Zealand. (A) In south Westland, which receives from 2500 to 5000 mm mean annual precipitation, *Ub-Td* soil formation on well-drained sites (glacial till) typically form Orthods (Soil Survey Staff 2022), equivalent to Orthic Podzol Soils in NZSC (Hewitt 2010; Hewitt et al. 2021f) (i) (top left panel), whereas poorly-drained sites (glacio-fluvial outwash) form Aquods or Perch-gley Podzol Soils (ii) lower left panel (Almond and Tonkin 1999; Almond et al. 2001; Hewitt 2010; Hewitt et al. 2021f; Soil Survey Staff 2022). (B) In eastern South Island, with < 700 mm mean annual precipitation, *Ub-Td* soil formation typically forms Fragiustalfs or Fragiustepts or Fragic Pallic Soils, top right panel (Hewitt 2010; Lowe and Tonkin 2010; Hewitt et al. 2021b; Soil Survey Staff 2022). Note that the horizon notations are after Clayden and Hewit (1989). The prefix 'b' denotes an identifiable soil horizon with pedogenic features developed (at/near the land surface) before its burial. The numeral prefixes identify changes in parent materials (lithologies) and burial events (although the numeral "1" is omitted in the case of the uppermost soil profile). This scheme differs slightly from that of *Soil Taxonomy* (Soil Survey Staff 2022) where "b" for buried is a suffix rather than prefix. See also soil horizonations in Figure 5. Figure modified from Alloway, B.V., Almond, P.C., Moreno, P.I., Sagredo, E., Kaplan, M.R., Kubik, P.W. and Tonkin, P.J. (2018). Mid-latitude trans-Pacific reconstructions and comparisons of coupled glacial/interglacial climate cycles based on soil stratigraphy of cover-beds. Quaternary Science Reviews 189, Fig. 1 (p. 59), with permission from Elsevier.

and form a complex with the organic matter of the buried O/A, giving them the chemical character of podzolic Bh horizons. Second, if the loess accumulation rate is slow, and environmental conditions favour ongoing input of organic matter to the soil, the buried O/A horizons may grade into an upbuilding A horizon, blurring loess sheet boundaries. Detailed analyses of fossil pollen

number of loess horizons mantling each moraine. The upper inset photo shows Peter Almond augering one of the oldest moraines within Saltwater Forest—often one of the most challenging field environments in ANZ to characterize loess on account of the poorly accessible dense forest with high rainfall (cf. the drivable terrace treads of Charwell, see Figures 4F and 20). The lower inset photo shows a collegial 'chronosequence' of South Island Quaternary science expertise (L-R): Pat Suggate, Philip Tonkin, and Peter Almond. Inset photos: B.V. Alloway. Figure modified from Alloway B.V., Almond, P.C., Moreno, P.I., Sagredo, E., Kaplan, M.R., Kubik, P.W. and Tonkin, P.J. (2018). Quaternary Science Reviews 189, Fig. 2 (p. 60), with permission from Elsevier.

and cryptotephra have been used to overcome these problems (Almond et al. 2001).

3.2.2 | Eastern Areas, South and North Islands

In drier eastern parts of both main islands of ANZ where loess accumulation rates tend to be higher (Eden and Hammond 2003) and sufficiently distant to avoid significant tephra inputs, loess sequences take on a character more similar to the classically described loess-paleosol sequences described for the Northern Hemisphere as well as for the drier, eastern side of the Andes in South America. Pedogenesis is less intense than that of the wet West Coast of the South Island and soils evolve to Fragiustalf or Fragiustept great groups of *Soil Taxonomy* (Soil Survey Staff 2022) (equivalent to Pallic Soils in NZSC: Hewitt 2010; Hewitt et al. 2021b). These soils comprise dense, often prismatic-structured, fragipans (designated as Bx horizons) usually overlain by horizons with conspicuous redoximorphic features (Bg or Btg horizons) (as defined in Clayden and Hewitt 1989; Soil Survey Staff 2022) (see Figure 6B). Often, loess sheets are in the order of metres in thickness (Tonkin et al. 1974), and within a loess sheet, there is a clear distinction between basal loess of weak or minimal pedogenic alteration and the overlying Fragiustalf or Fragiustept formed in the upper part of the loess sheet. This stratigraphy may represent an episode of retardant upbuilding if the accumulation rate of loess is extremely high, such as may occur proximal to source, so that topdown pedogensis is ineffectual. More likely, it represents very weak developmental upbuilding pedogenesis during relatively rapid loess accumulation followed by much more effective developmental upbuilding pedogenesis (dominated by more effective topdown pedogenesis) in the intervening warm phases when loess accumulation is much slower or negligible (Lowe et al. 2015). There is evidence to support this interpretation in that the fragipan is at least partly a consequence of pedogenesis during the loess accumulation phase (Raeside 1964; Kemp et al. 1998), and the accompanying topdown pedogenesis results in a range of features including formation of redoximorphic horizons, clay illuvial (Bt) horizons, gley veins between prisms in the fragipan, and general degradation of the fragipan (Bruce 1973b, 1996; Hewitt et al. 2021b).

3.2.3 | Western and Central North Island

In the western and central North Island, multiple incremental contributions of andesitic or rhyolitic tephra, dominated by easily weatherable glass shards, have enhanced (stronger) pedogenesis (e.g., Churchman and Lowe 2012). For instance, in Taranaki during cold and/or cool climate phases (stadials), developmental upbuilding pedogenesis occurred during the incremental accumulation of mixed, thin andesitic tephra and quartzo-feldspathic loess (Sy- beds of Alloway, Stewart, et al. 1992; Alloway, McGlone, et al. 1992), now manifested as weak- to moderately-structured, yellowish-brown moderately allophanic Bw horizons. Topdown pedogenesis occurred during such accumulation, but, as the land surface slowly built up, it was only weakly effective in modifying the deposits. During intervening warm and relatively wet climate phases (interstadials), developmental upbuilding pedogenesis continued (including with the incremental deposition of thin tephra deposits, which accumulated irrespective of climate conditions), but the intensity and thus impact of topdown pedogenesis increased because the rate of loess deposition was much slower or close to negligible. This scenario resulted in the accumulation of strongly weathered, pedogenically modified andesitic tephra-derived material manifested as well-structured, reddish-brown highly allophanic Bw horizons (Sr- beds of Alloway, Stewart, et al. 1992; Alloway, McGlone, et al. 1992).

A conceptual model of developmental upbuilding pedogenesis (*Ub*) and topdown-dominated (*Td*) soil formation in North Taranaki is presented in Figure 7A (Alloway et al. 2018). The Sy- and Sr- successions (e.g., Figure 7B) described in Taranaki are "andic" in character meaning that they typically have properties dominated by nanocrystalline clays allophane and/or ferrihydrite (and/or Al-humus complexes if present) derived from the synthesis of the weathering (dissolution) products of tephra-derived glass and associated felsic or mafic minerals (e.g., Neall 1977; Hodder et al. 1990; Alloway, Stewart, et al. 1992; Alloway, Neall, et al. 1992; Alloway, McGlone, et al. 1992; Churchman and Lowe 2012; Hewitt et al. 2021c). "Andic soil properties," as defined by Soil Survey Staff (2022), include low bulk density ($\leq$0.9 g/cm^3) and high P retention ($\geq$85%), essentially equivalent to "allophanic soil material" as defined for NZSC by Hewitt (2010). Such andic Sy- and Sr- successions (matching stadial versus interstadial conditions, respectively) are conspicuous on uplifted marine terrace and laharic planeze surfaces throughout Taranaki. Such surfaces are planar, gently inclined fan-like features formed from the repeated deposition of non-cohesive and/or cohesive volcaniclastic mass flows (including debris avalanche deposits) onto the lower flanks surrounding a stratovolcano. The term "lahar" is a general term to encapsulate all types of volcanic mass flows that comprise hot or cold mixtures of water, pyroclastic material, and rocky debris (e.g., see Alloway et al. 2005). Similar multisequal soil successions are also observed on the South Taranaki–Whanganui uplifted marine terraces (Pillans 1983, 1988, 2017; Palmer and Pillans 1996) (Figure 7A,B), and at similar southern latitudes in northern Patagonia (Alloway et al. 2018) (Figure 7C).

3.3 | Supporting Evidence for past Climates in ANZ

The inferred climate control on loess accumulation and associated syn-depositional alteration to some degree, and cessation of the loess flux and the consequent greater imprint of pedogenesis on soil horizon properties, is supported by a range of paleoenvironmental studies (including palynological, paleobotanical, paleolimnological, and paleopedological research) and chronological studies (including development and application of new techniques such as Bayesian age modeling and U-series zircon double dating in tephra studies, as described below). These studies encompass a vast New Zealand Quaternary-focussed "paleoenvironmental" literature (some of which is cited in this article) including reviews by Newnham et al. (1999, 2013), Bostock et al. (2012), Alloway et al. (2025), Green and Lowe (2025), and Palmer et al. (2025). Outputs of the NZ-INTIMATE (New Zealand INTegration of Ice core, MArine, and TErrestrial records) project provide recent summaries of the latest findings pertaining to the past 30,000 years and include Barrell et al. (2005, 2013); Alloway et al. (2007), Newnham, Lowe, et al. (2007), Lowe et al. (2013), and Vandergoes et al. (2013).

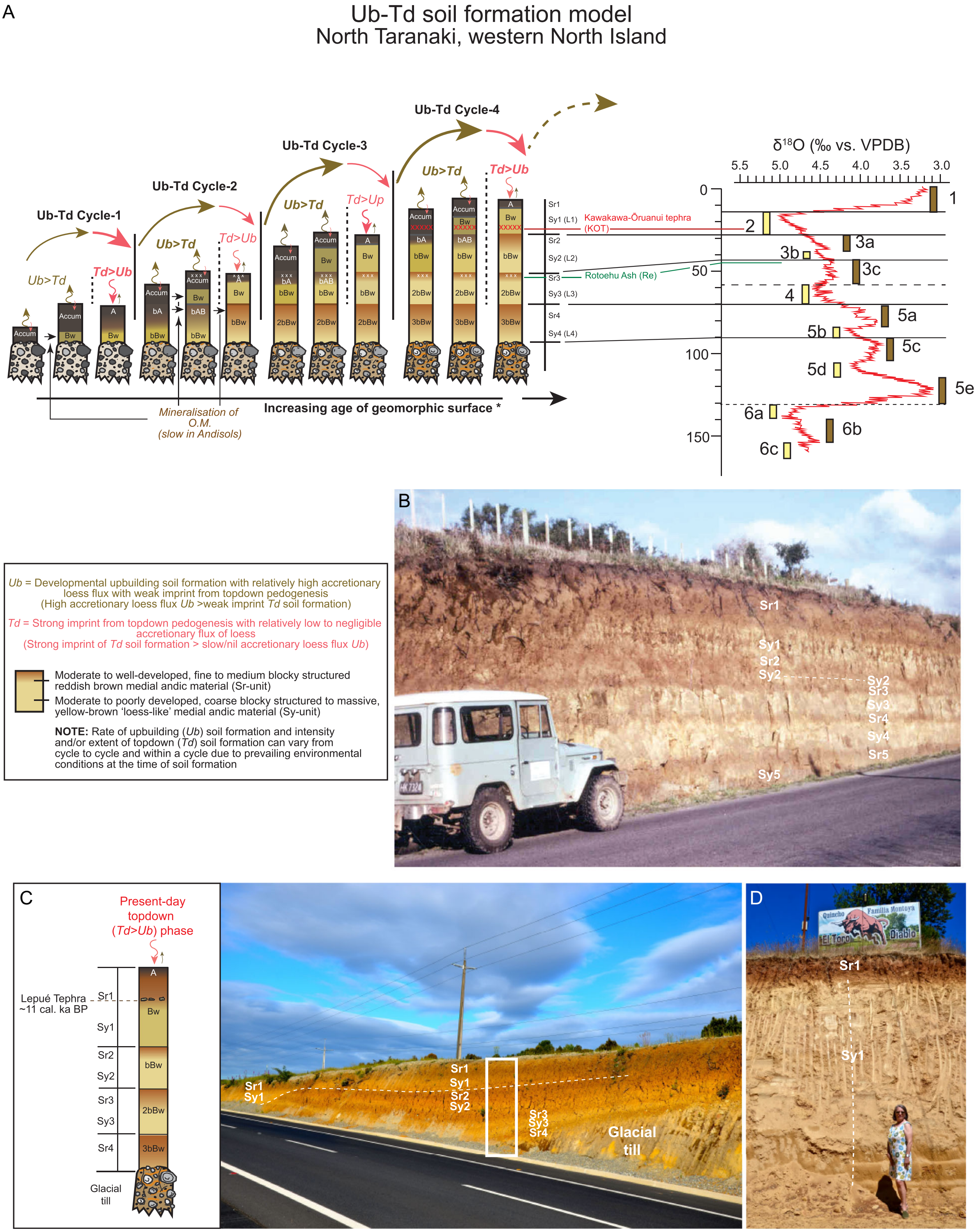

FIGURE 7 | (A) Conceptual model of developmental upbuilding (*Ub*)- and topdown (*Td*)-dominated soil formation in cover-bed deposits on uplifted marine terrace and laharic planeze surfaces (defined in text) in Taranaki-Whanganui. It is important to recognize that developmental upbuilding reflects the interplay of geological accumulation and concomitant (but only weakly effective) topdown pedogenesis. Topdown pedogenesis becomes dominant when it occurs with nil or negligible geological accumulation, and hence it is thus much more effective and intense with marked impact on soil properties. With increasing numbers of coupled *Ub-Td* cycles there is a corresponding increase in reddish-brown (Sr-) and yellowish brown (Sy-) soil horizon couplets. Coupled *Ub-Td* cycles are associated with fluctuations in cool/cold–warm paleoclimate during the Quaternary, respectively. The occurrence of rhyolitic tephra horizons (e.g., KOT and c. 45 cal ka BP Rotoehu Ash) sourced from the central North Island within these andic successions provide chrononological tie-points that facilitate direct correlation to the MIS records. (Andic properties are defined in the text.) (B) A typical multisequal soil succession of dominantly andic provenance is exposed on NT3 (Ngarino) Terrace (Q7b of Neall and Alloway 2004) at Egmont Road, North Taranaki.

The NZ-INTIMATE project (one arm of the Australasian INTIMATE project) included an attempt to match all the available environmental archival records to a common timescale (Alloway et al. 2007; Barrell et al. 2013).

4 | Distribution, Thickness, and Character

4.1 | Distribution and Thickness

Loess is a significant surficial deposit throughout most of ANZ. Soils with a loessial component cover up to 60 or 70 % of the country (Bruce et al. 1973; Eden and Hammond 2003; Schmidt et al. 2005) (see Figure 3). Schmidt et al. (2005) evaluated loess distribution and thickness in the South Island using expert knowledge at the land system scale, and generated new maps showing significant increases in the spatial resolution and mapping detail of loess distribution in comparison to those of previous studies (such as Bruce et al. 1973; Bruce 1978). They provide a more detailed description of extent, depth, and pattern of loess distribution, the occurrences being quantitatively assessed as well (Schmidt et al. 2005). Hughes, Schmidt et al. (2009) applied two quantitative modeling techniques (automated landform stratification, environmental correlation) to test and refine loess-landscape models for a higher-resolution study window in North Otago, South Island, but with varying degrees of success. They suggested that quantitative loess-landscape models need to be further refined using higher-resolution terrain data derived from LiDAR and photogrammetric surveys.

Loess is typically distributed in lowland flat to rolling areas of ANZ (Figure 3), but it is known at higher elevations, as described below. The major areas of loess occur in eastern drier parts of South Island and North Island (typically in areas with mean annual rainfall today of <1200 mm), including Southland, Canterbury, Marlborough, Wairarapa, and Hawke's Bay. Loess is also present in areas of higher rainfall (of today) including Westland, Tasman, and Taranaki. Occurrences in the Tasman area (Schmidt et al. 2005; see also the online digital soil mapping project, Smap: https://smap.landcareresearch.co.nz/) are limited in extent and localized probably because few outwash surfaces provide source areas (narrow valleys prevail instead) (Iain Campbell, *personal communication*, 2025). However, near Waingaro River for example, loess up to ~0.6 m thick has been identified on the aggrading Hamama Terrace (Campbell 2010), and in the Aorere River catchment near Collingwood, a silt-rich mantle ~1 m thick (in which bisequal Podzol Soils are formed) is likely to be aeolian in origin and derived from local sources (Andre Eger, *personal communication*, 2025).

Loess occurs as subsurface Last Glacial tephric loess, as reported earlier, or as older (pre-45,000 years) deposits in central North Island including Bay of Plenty and parts of the Waikato and King Country regions (Birrell et al. 1981; Stevens and Vucetich 1984, 1985; Kimber et al. 1994; Hill 1999; Horrocks 2000; Lowe, Tippett et al. 2001; Lowe et al. 2015; https://smap.landcareresearch.co.nz/).

Loess is uncommon north of Auckland although some has been recognized as "exotic components," especially fine quartz particles in basalt-derived soils, which originated from aeolian deposits derived from local sedimentary rocks or reworked derivatives or as global aerosolic dust (e.g., Stewart et al. 1984, 1986). We acknowledge that such components, not being evident in the field or visible to the naked eye, fail the full definition for loess (presented at the start of Section 1, "Introduction") in that loess should be "identifiable in the field as a distinct sedimentary body" (based on Crouvi et al. 2025). Nevertheless, these aerosolic quartz components are present and therefore might usefully be described as "cryptoloess," equivalent conceptually to cryptotephra deposits (defined below in Section 6.7.1). Aerosolic cryptoloess contributions are also manifest via an increase in continental-shelf-derived loess in lake sediments that are indicated by increasing Sr/Ca and decreasing Ti/K ratios in Lake Kai Iwi (a dune lake on the west coast about 20 km northwest of Dargaville) during MIS 4 and 2 (Evans et al. 2020). As well, Orbell (1974, 1977) reported the "fairly common" presence of silt-rich "wind-blown volcanic ash" (i.e., tephric loess) in the Pukekohe area in greater Auckland. The deposits are associated with small dune-like mounds on old land surfaces underlain by weathered (>45 cal ka BP) Hamilton Ash beds in turn overlying buried paleosols on weathered basalt lavas. In this instance, these dune-like deposits do meet all the criteria for loess. On the other hand, although not strictly loess per se, but supporting its likely hidden presence, we note that dune sands of Pleistocene and Holocene age are common along western coastal regions of Auckland and Northland (e.g., Schofield 1970; Richardson 1985; Bland et al. 2023). Similarly, fine-grained sand layers relating to periods of deposition in MIS 4 and 2 have been recognized at inland locations (Newnham et al. 2017; Evans et al. 2020; D.J. Lowe, *unpublished data* 2025). These may correlate with Last Glacial dune sands (Mokai Sands: Vucetich and Pullar 1969) identified alongside tephric loess on the Mamaku Plateau (Kennedy 1994) and in central North Island. (See also comparable studies of aeolian deposits in Tasmania, e.g., McIntosh et al. 2021.)

Here, at least four Sr-Sy couplets can be clearly observed (Alloway, Stewart, et al. 1992) (photo: B.V. Alloway). (C, D) Multisequal soil successions in western North Island have strong morphological resemblance with andic soil successions occurring at a similar southern latitude in continental Chile (Alloway et al. 2018; Flores-Aqueveque et al. 2024). (C) A road section on the Pan-American Highway near the city of Puerto Montt (Ruta 5, road-marker km-1054.2, 41°37'S) exposes an andic multisequal soil succession with four Sr-Sy couplets overlying a highly weathered glacial diamict (till). At this locality a well-dated tephra marker bed (c. 11 cal ka BP Lepué Tephra; Alloway et al. 2017) occurs near the base of Sr1 and occupies a similar stratigraphic role to that of the c. 17.6 cal ka BP Rerewhakaaitu Tephra in most parts of the central North Island of ANZ (Newnham et al. 2003), by delimiting the cessation of most regional loess accumulation. (D) A road section on V-206 near the southern Chilean city of Valdivia (39°58'S) showing a localized, thick wedge of yellow–brown sandy loess (Sy1) of LGM-age beneath a thinner veneer of uniformly-thick reddish–brown andic material (Sr1) of post-glacial age occurring at ground surface. Walescka Pino–Ojeda provides the scale. Such exposures in this temperate rainforest environment (comparable to the West Coast, South Island of ANZ) are rare. Photos C, D: B.V. Alloway. Figures 7A, -B and -C modified from Alloway, B.V., Almond, P.C., Moreno, P.I., Sagredo, E., Kaplan, M.R., Kubik, P.W., and Tonkin, P.J. (2018). Mid-latitude trans-Pacific reconstructions and comparisons of coupled glacial/interglacial climate cycles based on soil stratigraphy of cover-beds. Quaternary Science Reviews 189, Figs. 5 and 6 (pp. 65 and 66), with permission from Elsevier.

Loess is largely but not entirely absent from most elevated steepland and montane areas. For example, it occurs on Banks Peninsula at elevations up to ~600 m above sea level (asl), including in higher parts of the Eastern Bays area where it is up to 5 m thick (Yates et al. 2025), and in the Canterbury foothills (Schmidt et al. 2005). Within montane/alpine valleys, soils mapped in the Mesopotamia soil set, comprising up to 1 m of Holocene loess, occur on steep (~30°) lower slopes adjacent to the braided beds of the large rivers. In Southland, loess is most common below 300 m asl, but some is recognized up to 400 m altitude (Raeside et al. 1968; Eden et al. 1987; McIntosh 1992). In nearby east Otago, loess occurs between 60 and 480 m altitude (McIntosh 1984). In the North Island, loess is most common below 500 m elevation. The patchiness or rarity of loess occurring at higher elevations means either that it was never deposited there or, more likely, that it has largely been eroded (see also Schmidt et al. 2005; Yates et al. 2025).

On the flanks of Banks Peninsula, loess (Birdlings Flat Formation) is ~16 m thick; at Barrys Bay in the Akaroa caldera, it is at least 16 m in thickness, but above 270 m elevation, it thins to <2 m (Bell and Trangmar 1987; Yates et al. 2018). In the Timaru area of South Canterbury, deposits up to 20 m thick are quite common (Tonkin et al. 1974). In the Awatere valley south of Blenheim, loess up to 24 m thick is exposed in coastal cliffs (Eden 1987; Campbell and Oliver 2020).

In many areas, loess thickness is greatest immediately downwind of major river flood plains and rapidly thins away from the river (e.g., downwind of the Rangitīkei, Manawatū, and Rakaia rivers) (see Figures 2A and 3B,C). Large rivers and their floodplains are clearly the major sources of loess throughout ANZ (Smalley et al. 2009; Eden and Hammond 2003; Eger et al. 2012; Lowe et al. 2015). Fluvially modified continental shelf areas exposed during glacial low sea-level stands (such as during the Last Glacial Maximum, LGM: Figure 3F) were also an important but subordinate source, along with glacial grinding (see Section 5 on "Sources of loess" below).

4.2 | Mineralogical and Physical Characteristics Including Geotechnical Properties

McCraw (1975) recognized five major mineralogical categories of ANZ loess, each of which is predominant in a particular region (Figure 3).

- *Region 1*: Volcanic or tephric loess in Bay of Plenty, central North Island, northern Hawke's Bay, and Taranaki areas with a high content of volcanic glass, interbedded with, and derived from rhyolitic and andesitic tephra deposits, volcanogenic mass-flow deposits, fluvio-volcanogenic aggradational surfaces, and pre-existing loess (Kennedy 1988, 1994; Alloway et al. 1988).
- *Region 2*: Quartzo-feldspathic loess derived from greywacke (comprising massive sandstone and alternating beds of sandstone and mudstone, e.g., see Edbrooke et al. 2015) in southern Hawke's Bay, Manawatū, Wairarapa, Marlborough, and Canterbury regions.
- *Region 3:* Quartzose, strongly weathered loess in areas with >2000 mm rainfall/year (e.g., Westland, Tasman).
- *Region 4:* Quartzo-feldspathic loess containing mica and chlorite derived from schist in Otago.
- *Region 5:* Feldspathic loess derived from "basic tuffaceous greywacke" in Southland. Note that a number of sandstone- and mudstone-dominated geological map units in Southland of Mesozoic or Paleozoic age (as depicted by Edbrooke et al. 2015) may correspond to this broad "tuffaceous greywacke" descriptor, some of which are described as "with tuff" or "commonly tuffaceous" or "with altered mafic, felsic, and ultramafic igneous rocks."

Mineralogical variations occur with distance from major source areas. For example, quartz content increases with distance away from andesitic tephra sources centered in Taranaki region, western North Island (Figure 3D) (e.g., Symes and Wells 1973). Similarly, decreasing epidote/hornblende ratios with increasing distance from the Mataura River in Southland reflect a decreasing (regional) schist source and an increasing (local) tuffaceous greywacke source (Eden et al. 1987; McIntosh 1992) (Figure 3E).

As mentioned earlier, most New Zealand loess is non-calcareous, although there are local exceptions. Secondary calcium carbonate in small amounts has been recorded in some locations including Marlborough, Waitaki valley, Timaru, Banks Peninsula, North Canterbury, and Central Otago (Raeside 1964; Leamy and Rafter 1972; Trangmar and Cutler 1983; Bell and Trangmar 1987; Almond et al. 2007, 2020; Campbell 2011; Tonkin et al. 2015; Campbell and Oliver 2020; Hewitt et al. 2021d; Craw et al. 2022; Yates and Russell 2023.) In these drier parts of South Island, remnant root traces in soil fabrics are sometimes filled by secondary $CaCO_3$ (Lowe et al. 2015). Around 7%–8% calcium carbonate content was reported for loess in the Akaroa Harbour area of Banks Peninsula (Yates and Russell 2023). In North Canterbury, carbonates are derived from associated calcareous rocks, and in places subfossil avian bird bone, egg-shell, and terrestrial gastropod remains are preserved (Almond et al. 2020). These latter authors reported that in ANZ conditions, mean annual rainfalls <500 mm are generally necessary for pedogenic carbonate to accumulate (Hewitt 2010; see also Hewitt et al. 2021d), and, consequently, higher rainfalls must generate too much leaching for secondary carbonates to persist. A radiocarbon date on the youngest carbonate of c. 16 cal ka BP in loess of North Canterbury is indicative of an increase of rainfall above the ~500 mm threshold after this time and also that annual precipitation in the LGM and late glacial must have been at least 20% lower than that of today (Almond et al. 2020).

The cyclic accretion of salts and subsequent sodification may be creating conditions favouring precipitation of secondary (pedogenic) carbonate in the coastal loess on Banks Peninsula (Griffiths 1973, 1974; Almond et al. 2007). In the Crownthorpe district of central Hawke's Bay, calcareous loess occurs in a rainfall regime of 800–1000 mm/yr with a pronounced summer deficit. Here, the underlying rocks, and partial source of the loess, are Pliocene limestones and siliciclastic sandstones.

The five general (primary) mineralogical categories of loess outlined above have distinctive physical properties and constituent secondary minerals, mainly clays. The quartzo-feldpathic loess of *Region 2* generally contains minor amounts of accessory minerals and generally illite, vermiculite, interstratified illite-vermiculite, and occasionally kaolinite clays (e.g., Griffiths 1973; Raeside 1964; Jowett 1995; Yates et al. 2018; Yates and Russell 2023).

For example, at Timaru (Figure 1), clay minerals are 84% illite and 16% interstratified vermiculite-illite, whereas at Ahuriri Quarry on Banks Peninsula, the clay minerals comprise 54% illite, 27% interstratified vermiculite-illite, 11% kaolinite, and 8% vermiculite (Yates et al. 2018). Such loess commonly reaches a dry bulk density of 1.6–1.8 t m^{-3} in subsoil horizons and up to 2.2 t m^{-3} have been measured in fragipans/Bx horizons (including in Marlborough) (Palmer and Barker 1984; Pillans and Palmer 1994; Jowett 1995; Yates et al. 2018; Palmer 2026). Paleosols in the loess have lower bulk densities (0.7–0.8 t m^{-3}) and higher loss-on-ignition values (Palmer and Pillans 1996; Graham et al. 2001). Clay contents can be up to 45% in loess on Banks Peninsula (Yates et al. 2018) but typically range from 17 to 32% (Jowett 1995; Yates and Russell 2023). In eastern Southland and east Otago, clay contents in loessic soils range from 17 to 39% (McIntosh 1992) and 19 to 33% (McIntosh 1984), respectively.

In an overview of the geotechnical properties of Canterbury loess and loessic colluvium, Yates et al. (2018) and Yates and Russell (2023) reported that these deposits generally are denser and more compact (dry bulk densities average 1.7 t m^{-3}, ranging from 1.6–1.8 t m^{-3}) than loess in China (where dry bulk densities average 1.2–1.6 t m^{-3}). This is the probable reason that collapse failure, common in Chinese loess, has not been observed in Canterbury. Yates et al. (2018) also noted that Canterbury loess when dry typically has high dry strength and forms vertical exposures with fissuring within the soil mass controlling the strength and stability. However, a reduction in shear strength (a weakened soil matrix), and hence decrease in factor of safety, is accompanied by just small increases in soil moisture of a few percent (e.g., Trangmar and Cutler 1983; Hughes 2002), and that periodic wetting (such as the high intensity rainfall event in Eastern Bays in December 2021) can lead to a variety of slope failures related to internal erosion (tunnel gullying) and rapid loss of shear strength (debris flows, soil slides, and rotational failure) (Yates et al. 2018, 2025).

Tunnel-gully erosion is a common feature in loess in eastern North Island (Gibbs 1945) and in South Island loess including in Canterbury and North Otago, with perhaps the most extreme occurrences documented in the loess cover-beds of the Wither Hills area near Blenheim in Marlborough (near their likely source, the aggrading glacial outwash sediments on the Wairau plains) (Laffan 1973; Laffan and Cutler 1977; Lynn and Eyles 1984; Jowett 1995; Campbell 2011). Gibbs (1945) attributed the tunnel-gully erosion to the collapse of surface soil into tunnels scoured in the deep subsoil by accelerated run-off into fissures and rabbit-holes. He suggested that although water was the agent of erosion, the cause was the denuding of the soil brought about by burning, together with excessive grazing by sheep and rabbits. The subsurface cracks and fissures were considered to have formed through shrinkage from excessive wetting and drying resulting from a depleted vegetation cover. Once formed, the collapsed tunnels widened with the concentrated waters allowing the formation of open gullies. However, Campbell (2011) suggested, following Knodel (1991), that a more fundamental cause is that the loessic soil material itself is readily dispersible. Laffan (1973) showed that horizons with high dispersion and slaking indexes were mostly the B or Cx (fragipan) horizons, which also had higher clay percentages and higher exchangeable sodium percentages, whereas horizons with greater organic carbon percentages had lower dispersion indexes. The highest dispersion and slaking indexes, however, were evident in deeper horizons below 1 m. Consequently, Laffan (1973) and Laffan and Cutler (1977) considered that tunnels were initiated mainly in the dispersible lower B horizon with tunnel deepening and collapse of surrounding material ultimately leading to the formation of the extensive gully system. Campbell (2011) recorded evidence for both mechanisms and suggested the most common cause of collapse to be from large, deep pipes rather than piping at shallow depths in the B horizons of the soils.

The tephric loess of *Region 1*, in contrast, usually has dry bulk densities ranging from 0.8 to 1.1 t m^{-3} (Kennedy 1982, 1988), but they may be as low as 0.3–0.4 t m^{-3} (Birrell et al. 1981; Stevens and Vucetich 1984). Density changes are accompanied by significant changes in macroporosity, and hence both internal drainage and water availability to plants are affected (Barratt 1988). Although subsoil macroporosity of the quartzo-feldspathic loess of *Region 2* is commonly less than 5% (e.g., Scotter et al. 1979; Bruce 1984), in the tephric loess of *Region 1*, it is usually >15% (commonly 50%–65%: Kennedy 1982). These physical differences are superimposed upon, and accentuated by, climatic conditions during developmental upbuilding. Throughout their accumulation, the tephric loesses experienced relatively uniform rainfall through the year (referred to as an udic soil moisture regime by Soil Survey Staff 1999). On the other hand, much of the quartzo-feldpathic loess in *Region 2* was deposited where current rainfall is between 750 and 1100 mm/year, commonly with a marked dry season (referred to as an ustic soil moisture regime by Soil Survey Staff 1999), but the pore size distribution is another important factor in restricting the permeability of the loess (Birrell and Packard 1953). As a result, in winter when evapotranspiration is low, the soils become saturated, whereas in summer they bake hard and dry out when evapotranspiration exceeds rainfall.

The mineralogy and moisture regime have also led to fundamental differences in weathering products. As noted, quartzo-feldspathic loess typically weathers to form mainly illite and vermiculite or intergrades, and sometimes kaolinite. In contrast, tephric loess in central North Island of Last Glacial or older age is typically dominated by halloysite, being formed when climates were colder and drier, thus favoring the formation of halloysite, which is Si-rich, rather than Al-rich allophane (Parfitt et al. 1984; Parfitt and Wilson 1985; Churchman and Lowe 2012). In long (old) sequences of tephras and loess beds, with paleosols, such as on the Mamaku Plateau in North Island and in the Rotorua region and King Country, halloysite tends to increase with depth while allophane content diminishes (e.g., Kirkman 1980; Stevens and Vucetich 1985; Lowe 1986; D.N. Eden *cited in* Lowe and Percival 1993), consistent with the Si-leaching model (Parfitt et al. 1983, 1984; Singleton et al. 1989; Pillans et al. 1993; Churchman and Lowe 2012; Palmer et al. 2025). In southern North Island quartzo-feldspathic loess, the clays include illite, vermiculite, kaolinite, or halloysite (formed during the glacial periods), with Pillans and Palmer (1994) showing a marked decrease in allophane with depth (but with fluctuations) at the Rangitatau East section. Analyses of meteoric $^{10}Be/^{9}Be$ in samples taken from a drill core through the Rangitatau East sequence by Graham et al. (2001) showed that ^{10}Be values were lower during glacials, supporting the hypothesis that these were "relatively arid", i.e., in agreement with the predominance of halloysite in loess and allophane in paleosols, the carbonate and the low annual rainfall-related data of Almond et al. (2020), and with decreased ^{10}Be fluxes in Antarctic ice cores during glacial periods (Graham et al. 2001). In Southland (*Region 5*), McIntosh and Whitton (1988) showed that loess-derived soils at lower altitudes (<300 m altitude) have clay fractions dominated by chlorite, mica-vermiculite, and kaolinite, whereas at sites >300 m in altitude, under higher rainfall, greater leaching, and more acid conditions, mica and chlorite have been transformed to interlayered mica-chlorite and chlorite-vermiculite along with the formation of imogolite-like allophane (see also Churchman et al. 1991).

Allophane (occasionally with gibbsite) may also be recorded at depth in weathered loessic and associated tephric paleosols (in *Region 1*), in this instance coincident with warmer and wetter interglacial or interstadial conditions when stronger leaching regimes prevailed that favoured strong desilication (e.g., Stevens and Vucetich 1985; Lowe 1986; Lowe and Briggs 1994; Bakker et al. 1996). In contrast, nanocrystalline clays allophane and ferrihydrite, which were previously referred to as short-range order clay (SROC) or, if with organic materials, as SROCO (Alloway, Neall, et al. 1992), are more common in loessic deposits in Taranaki. Here, the higher abundance of Al in the mainly andesitic parent tephras (cf. more silicic rhyolitic tephras in the Rotorua-Taupō area) may be responsible for the formation of allophane, which is Al-rich, despite a drier and colder climate (Parfitt and Wilson 1985; Churchman and Lowe 2012).

Loess in ANZ is typically more clay-rich than in overseas counterparts (especially in old, pre-Rotoehu Ash loesses), as noted above, although estimating the grain size of tephric loess can be problematic if allophane and ferrihydrite are dominant because they are strong flocculants, making size analysis by settling techniques inaccurate in many cases (e.g., Hewitt et al. 2021c). Tephric loess of LGM-age in Taranaki was found to be between 50% and 60% dissolvable in acid oxalate, implying that this amount was nanocrystalline material (see Parfitt and Henmi 1982; Parfitt and Wilson 1985; Parfitt and Childs 1988) generated as a weathering product of andesitic volcanic glass, plagioclase, and ferromagnesian minerals (Alloway, Neall, et al. 1992). Quartzo-feldspathic loess of equivalent age contains less clay (15%–25%), but higher clay contents are evident in paleosols on Ratan and Porewan loess in southern North Island (Palmer 2026). Various authors (e.g., Claridge 1978; Stewart et al. 1984; Churchman and Tate 1987; Palmer 2026) have reported that by pretreating samples with citrate bicarbonate dithionite (CBD) (Mehra and Jackson 1960), which removes iron oxide coatings or cementation, thus breaking down aggregates, typically leads to higher clay yields. Other pretreatments, including sonication and shaking with H_2O_2, have similar effects (e.g., see Tanino et al. 2024). Older loesses have weathered more completely and commonly contain 50%–60% clay, sometimes higher, including over 90%, for very old, extremely weathered loess in Waikato and King Country (Salter 1979; Stevens and Vucetich 1985; Horrocks 2000). Even loess that is currently accumulating alongside South Island rivers (e.g., Eden and Hammond 2003) can contain up to 20% clay, much of which may have been transported as silt-sized aggregates. In common with loess elsewhere in the world, the quartzo-feldspathic loess in ANZ has a marked size mode in the 30–60 μm silt fraction, and varying amounts of fine sand depending on proximity to source.

5 | Sources of Loess

Primary sources are areas in which silt-sized particles are deposited by sedimentary (e.g., fluvial) processes and which are available for transport or, less commonly, where silt-sized material generated by in situ weathering can be mobilized. In ANZ there are five major primary sources.

1. Volcanic, pyroclastic-draped areas in the North Island (Figure 3) where unconsolidated rhyolitic and andesitic tephra-fall deposits as well as gas- (nonwelded) and water-supported mass-flow deposits, and debris avalanche deposits, were readily eroded by wind and water during cold periods to generate tephric loess. During cool and/or cold climate intervals, including MIS 4 and 2 in the central North Island, the pervasive lack of tree cover within the landscape enhanced aeolian erosion of unconsolidated tephra deposits (Kennedy 1982, 1988, 1994; Palmer and Vucetich 1989; Newnham et al. 2013).

2. Aggrading floodplains and fans in mountains and adjacent outwash plains (Figure 8A,B). Here, most of the fine material is derived by abrasion and breakdown of rocks as they are transported in rivers, especially during glaciations. During glacial periods over long periods of time (tens of thousands of years), large amounts of sediment are supplied to rivers by erosion. Rivers aggrade and widen, and take on a braided channel pattern, whereby bars separating channels are mantled by fine sediment during floods, and re-exposed leaving the sediment to dry and deflate during lower flow. The fine sediment provides the main source of loess, with the riverbeds thus being the major ‘dust engines’ from which the bulk of the loess in New Zealand is derived (Lowe et al. 2015). Moreover, climate at the time—cold, dry, and windy with the core of the southwesterly winds over ANZ—was conducive to entrainment and transport of the fine sediment.

3. In mountainous catchments, smaller amounts of fine sediments are derived from glacial grinding and frost cracking processes, generating deposits including rockfall debris and scree (or talus). Frost-cracking probably generated large quantities of sediment that made its way to rivers, caused their aggradation, and was then comminuted fluvially to silt size to provide a loess source. The process likely produced sediment in nonglacierised regions of the North Island (rather than enhanced surface erosion arising from the lowering of treeline as invoked in the past, because the frost-cracking is effective even under forest: Marshall et al. 2015, 2021).
   Coarse-grained scree debris is fed into stream and river tributaries and initially primarily transported as bed load (to be dealt with by fluvial abrasion as noted in source no. 2 above), with relatively small amounts of finer-grained debris carried as suspension load. The production of silt-sized particles by glacial grinding and frost-cracking activity appears to have been enhanced during intervals of cool and/or cold climate such as during the LGM or MIS 2. Marx et al. (2026) show that dust/loess production is strongly linked to the timing of enhanced cold climate processes, including glacial advances and associated periglacial activity, driving fine-grained sediment production.

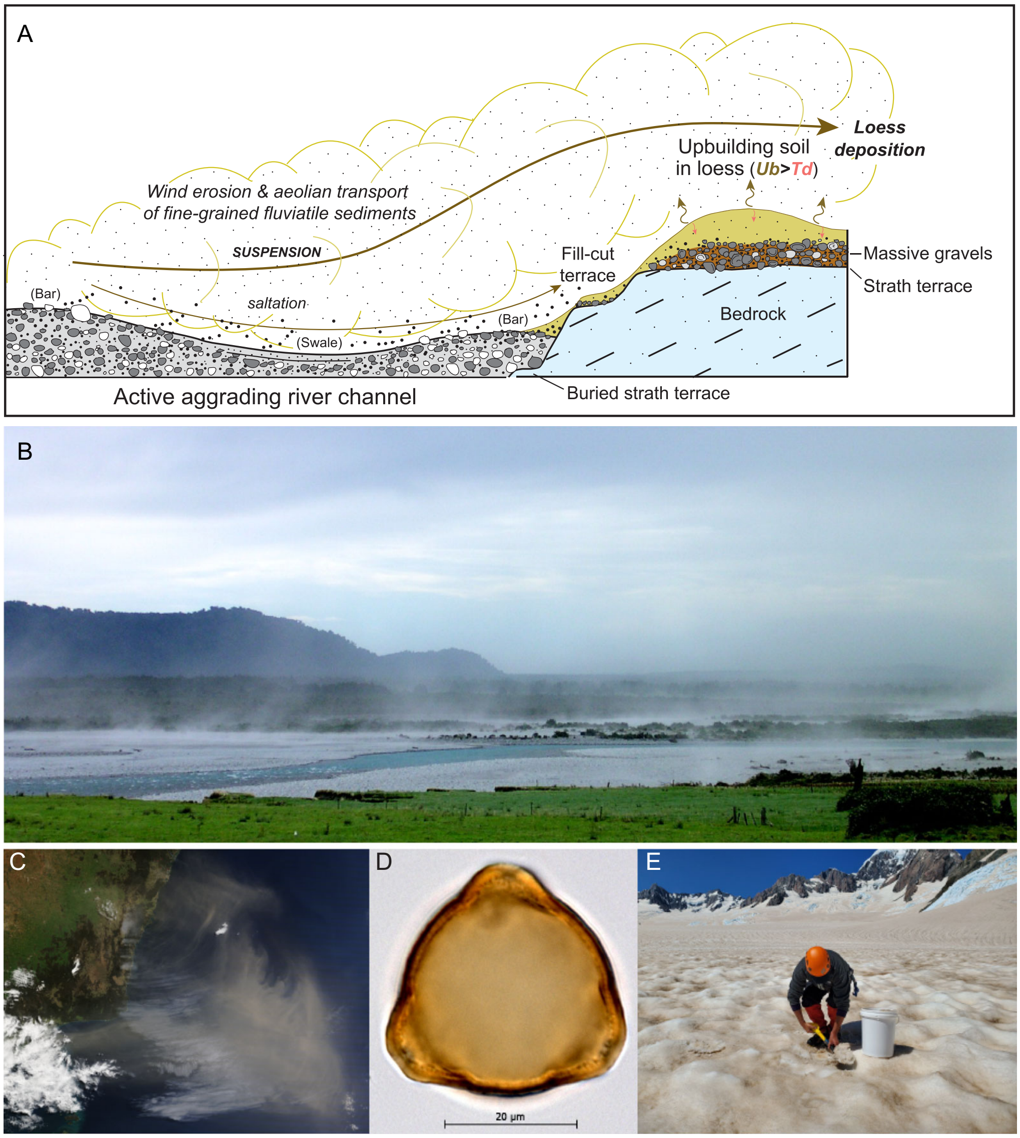

FIGURE 8 | (A) Schematic model showing wind erosion and aeolian transport of fine-grained fluviatile sediments from an active aggrading river channel with loess deposition and soil upbuilding on older adjacent river terraces. The predominant mechanism of transport is suspension. Such a model provided a template for Derek Milne (Milne 1973a, 1973b) to construct his seminal Rangitīkei terrace and loess stratigraphy. (B) This modern-day analog shows loess being winnowed from the braided Waiho River bed in south Westland by a strong southwesterly wind and blown onto adjacent older and densely forested terraces (photo: B.V. Alloway). (C) A Terra satellite image of dust extending across southeast Australia into the Tasman Sea on September 12, 2009. The dust (visible by its tan hue and wispy form) probably originated from the dry Lake Eyre basin of interior Australia and was transported by strong northwesterly winds (e.g., see Petherick et al. 2009) (photo courtesy of Jeff Schmaltz, NASA). (D) Some exotic pollens of Australian provenance have been identified in South Island bogs and lake sediments of pre-European colonization age (e.g., Moar 1969; Macphail 1979; Mildenhall et al. 2006). This image shows the distinctive triporate pollen of *Casuarina equisetifolia* (also known as coastal she-oak), which typically grows on rocky headlands and near estuaries in eastern New South Wales and Queensland (photo courtesy of the Australasian Pollen and Spores Altas, Australian National University, Canberra). The genus *Casuarina* is frequently identified in ANZ along with other common genera (e.g., *Eucalyptus*) but other minor components of the Australian flora (e.g., Amperea and Gyrostemonaceae species) have also been identified. (E) Sampling snow in the Fox glacier accumulation area, southwestern Southern Alps, following deposition of red dust from the late-2019 and January-2020 Australian bushfire and desert dust event (see Winton et al. 2024) (photo courtesy of Phil Novis, Manaaki Whenua-Landcare Research New Zealand).

Loess production in these environments continues today although the flux is significantly reduced from that produced during cooler and/or cold climate episodes.

From studies on loess in the Wither Hills area of Marlborough, Iain Campbell (2011), an Antarctic veteran (e.g., see Campbell and Claridge 1987, and Section 5.1 below on loess in Antarctica), suggested that the regional environment at the time of loess deposition was likely very cold and arid and extremely windy with an inland continental climate (as a consequence of lowered sea level). He noted that some boulders on ridge tops had distinct ventiforms (wind-faceted shapes derived from abrasion by strong winds) and that relatively large stones within the loess were probably deposited by gelifluction, a process whereby thawing material slides down-slope on a firm or frozen surface. Moreover, he suggested that the fragic (Bx) horizon probably represents an interval of severe cold with soil freezing, as is suggested by the vesicular structure that is present, the small voids being left after ice crystals in the soil have thawed. Another possibility is that the microfabric is induced by wetting and drying cycles where evapotranspiration gradually closes the pores. These interpretations complement (or contrast with) that of Hewitt et al. (2021b) who explained the vesicular fabric of loessic Pallic Soils in Canterbury as being vermiform in origin (i.e., back-filled worm burrows) or marking voids once filled with now-dissolved calcium carbonate. In the Manawatū, the vermiform fabric in Ohakean loess is clearest beneath the Kawakawa–Ōruanui tephra (this tephra bed is defined below). Somewhat speculatively, Iain Campbell (*personal communication*, 2025) considers that the prismatic subsoil structure common in loessial soils may relate to freezing conditions at the time of loess deposition (Campbell 2011). He also noted the possibility that during this period of extreme cold and loess deposition, soluble salts accumulated in the soils (some remain evident today), perhaps even forming a salt pan. This interpretation is supported by the occurrence of stones within the loess that often show in situ fracturing that is attributable to higher soil salt concentrations during the colder and drier glacial periods (Campbell 2011). Such fracturing may alternatively be the result of frost action or tectonism.

4. Exposed continental shelves and the fluvial channels that extended across the then exposed shelves during periods of low sea level in glacials provide another source of loess (Figure 3F)—the loess being mixed, derived from both fluvial and marine shelf sources. Raeside (1964) observed the presence of opal phytoliths and marine sponge spicules in South Island loess and noted that the latter were more common and larger near the east coast. He concluded that there were significant loess source areas on the continental shelf, associated with lower sea levels during glacial periods. Increased loess thicknesses toward the coast in Canterbury are also consistent with derivation from these offshore sources. Similarly, on the west coast of the North Island, concentrations of aerosolic quartz grains, deposited during MIS 4 and 2, in the andesitic-dominated aeolian cover-bed deposits of Taranaki (Alloway, Stewart, et al. 1992), and in a 117-ka-old lake sediment record in Northland (Evans et al. 2020), both support an offshore, continental-shelf source.

5. Aeolian material of Australian provenance is also likely to be represented, albeit in a relatively minor way, within ANZ loess sequences with aeolian dust deposits being recognized in sediment cores from the Tasman Sea and southwest Pacific Ocean (Figure 8C), and in montane peat bogs and lakes, and glaciers, on land (Theide 1979; Stewart and Neall 1984; Hesse 1994; Hesse and McTainsh 1999; Marx and McGowan 2005; Marx et al. 2005, 2009; De Deckker 2020). As well as geochemical provenance studies, such as ^{210}Pb analyses of chemically characterized contemporary Australian-derived dust samples (Marx et al. 2005), and trace-element analyses of Holocene dust preserved in a South Island peat bog (Marx et al. 2009, 2026), the legitimacy of such a distant source is further supported by the occurrence of pollen of Australian provenance (e.g., *Casuarina*, Figure 8D), which has also been identified within pre-European lake and bog sediments in the South Island (Moar 1969; Macphail 1979; Graham et al. 2005; Mildenhall et al. 2006). In addition, historic dust-storm events have been documented depositing particles of clay and quartz from Australia over large areas of New Zealand, including ready recognition on icefields and glaciers (Marshall 1903; Marshall and Kidson 1929; Healy 1970; Mokma et al. 1972; Stewart and Neall 1984; Winton et al. 2024; Figure 8E). De Deckker (2020) studied "airborne dust traffic from Australia" for the late Quaternary (as well as in modern times), and observed a shift in the direction of dust plumes exiting Australia during the LGM including a substantial northerly shift of the trans-Tasman dust plume, coinciding with stronger westerlies and an equatorward shift of oceanic fronts.

5.1 | Loess Occurrence in Ross Dependency, Antarctica

The Ross Dependency, administered by ANZ, contains the largest ice-free areas in Antarctica (about 6700 km^2) and many soils generally comprise a stony desert pavement from which fine material has been removed, predominantly by wind erosion (Hewitt et al. 2021e). ANZ researchers have had an active role in the characterization and mapping of loess-like material in the Ross Dependency, particularly within, and adjacent to, the Dry Valleys of Southern Victoria Land (Hewitt et al. 2021e). The first descriptions of loessic material were by McCraw (1967b) and Campbell and Claridge (1968) where loess-like material was observed in the lee of upstanding ground-surface boulders and as small (~1 m^2) patches of yellowish silty material that collects in, and on, small snow drifts which accumulate behind boulders (originally described as "snow loess," Stepanov 1962). Although very localized patches of gravel- and sand-dunes have been described in the lower Victoria Valley by Selby et al. (1974), finer-grained loess is neither conspicuous nor widespread on continental Antarctica and there are many factors that have contributed to its paucity. Such factors include the pervasive ground surface armouring by lag gravels (forming stony desert pavements, see Figure 9A) where there is little to no ablation of underlying fine sand- and silt-sized particles by wind unless the surface is physically disturbed in some way; and an almost complete absence of running water because associated outwash surfaces and stream deposits are typically rare. In contrast to mid-latitude deserts where the desert pavement and underlying vesicular horizon are important for trapping aeolian sediment (Wells et al. 1985), vesicular horizons in Antarctic apparently do not serve the same function (Bockheim 2010).

Since there is a limited supply of fine-grain-sized material with no obvious accumulation of such materials, the small amounts available for aeolian transport must have been blown out from the valleys dissecting the Trans-Antarctic Mountains and onto adjacent ice-fields, seasonal sea-ice, and/or the open sea (Campbell and Claridge 1968, 1987, 1988; Barrett et al. 1983) (see Figure 9B,C). In a much later study, Chewings et al. (2014) reported aeolian sediment dispersal patterns over 3000 km^2 of sea-ice in McMurdo Sound and adjacent to the

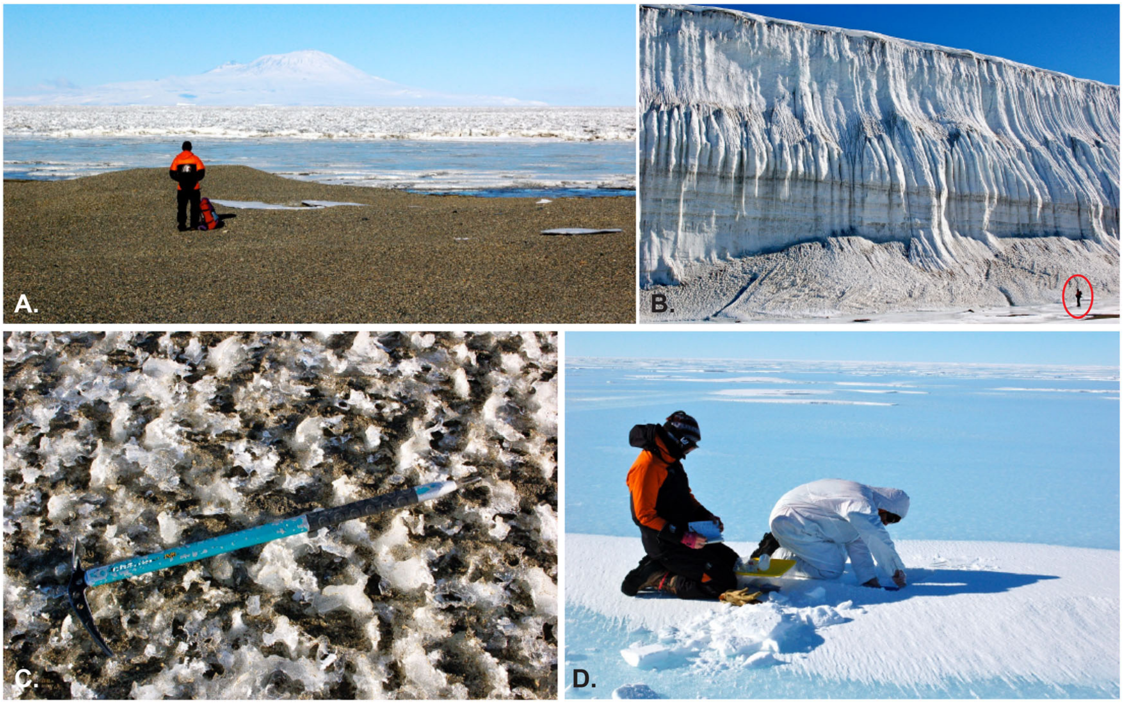

FIGURE 9 | (A) View southeast from Explorer's Cove at the entrance of the Taylor Valley across the sea-ice of McMurdo Sound towards Ross Island and Mt Erebus in the distance. Here on the coastal fringe of continental Antarctica, the ice-free ground-surface is entirely a pebbly desert pavement or pediment (a thinly veneed rock plain or rock-carved plain) from which surficial fine material has been entirely removed by wind erosion. (B) Prominent dust and sand layers exposed within the Commonwealth Glacier, Taylor Valley (see person for scale on lower right-hand side). Melting of the glacier front releases this material enabling down-valley aeolian remobilization during katabatic wind events. (C) A veneer of sand and dust distributed over the seasonal sea-ice surface in McMurdo Sound. (D) Sampling snowdrifts on the McMurdo Sound sea-ice for aeolian material (see Chewings et al. 2014) (photos A-D: B.V. Alloway).

largest ice-free areas in Antarctica (Figure 9D). Here, mass accumulation rates (see Section 6.8 below on "Loess accumulation rates") on the sea-ice were reported as varying between 0.2 and 55 g m^{-2} yr^{-1} and confirmed the transportation of dust and sand onto the sea-ice, which was then released into the ocean during summer melt. However, the abundance of McMurdo Sound Volcanic Group-derived glass in these deposits showed that most sediment originated from the McMurdo Ice Shelf and nearby coastal outcrops, with surprisingly negligible sediment input derived from the extensive ice free-areas of the McMurdo Dry Valleys. De Deckker (2020) concluded that Australian dust was blown as far as Antarctica more frequently during the Holocene than in earlier times, with isotopic fingerprints in Antarctic ice cores pointing to South America as being the main source of dust during the LGM and previous glacial periods, with intermittent occurrences likely to have come from Australia and New Zealand as well.

6 | Developing a Loess Chronology in ANZ and Its Application

Loess sheets and the landforms on which they sit have been dated by a range of techniques including numerical dating techniques, such as luminescence dating of the sediment itself, radiocarbon and amino acid racemization dating of included organics, and fission-track dating of incorporated tephric (volcanic) materials. Correlative (age-equivalent) dating techniques include magnetostratigraphy and tephrochronology (e.g., see geochronology reviews by Walker 2005; Lowe and Walker 2015; Banerji et al. 2022; Jull 2025). Radiocarbon, zircon-based fission-track dating, glass-based isothermal plateau fission-track dating (ITPFT), $^{40}Ar/^{39}Ar$, and U-decay series (e.g., (U-Th)/He double dating using zircon) techniques have been applied to tephra deposits including ocurrences within multisequal loess-paleosol successions (e.g., Hopkins, Lowe, et al. 2021; see below). These dating techniques and their efficacy are briefly described in the subsections below.

The Kawakawa–Ōruanui tephra (KOT), aged c. 25.6 cal ka BP, has become a key isochronous marker bed (Pillans et al. 1993) because it was deposited in the extended LGM (eLGM, Newnham, Lowe, et al. 2007; Newnham et al. 2013) when loess accession rates were generally fast, hence allowing loess accumulation rates for this period to be estimated (see section below on this topic).

An important milestone in the application of ANZ loess studies was the recognition that loess cover-bed stratigraphy, in conjunction with the occurrence of dated tephra marker beds, could be effectively used to differentiate and correlate uplifted fluvial terraces—and, later, uplifted marine terraces. In turn, the independently dated marine terraces provided an additional age constraint in the Whanganui region and elsewhere (e.g., Pillans 2017; Ryan et al. 2021). As introduced earlier in the historical section, Milne (1973a), following Rhea (1968), was one of the first to recognize that major aggradational terraces within the Rangitīkei catchment in southwest North Island showed a systematic increase in the number of loess sheets with increasing age. From this pattern, it was inferred that the river-bed during the accumulation of each valley fill, which subsequently became an aggradation (fill) terrace after river downcutting, provided the source of loess found on adjacent higher terraces. Thus, each loess unit was named after the correlative fluvial aggradation terrace. Milne and Smalley (1979) published the following loess names and ages: Ohakea (Ok), 12–25.5 radiocarbon ka BP; Rata (Rt), 32–40 calendar/calibrated (cal) ka BP; Porewa (Po), 70–80 ka BP; Marton (Ma), 125–135 ka BP; and Burnand (Bu) Loess, 170–180 ka BP. Ages for the various loess layers were initially estimated from the presence of radiocarbon and radiometrically dated tephra marker beds including KOT (c. 25.6 cal ka BP) and Rangitawa Tephra (c. 345 ka BP) (see below) and by essentially counting back loess episodes with coincident cold and/or cool climate interval recognized within the then fledgling marine $\delta^{18}O$ (MIS) record (e.g., Pisias and Shackleton 1984).

These Rangitīkei loess layers and associated aggradational terraces were not stratigraphically formalized with designated type and reference sections, and their status as chronostratigraphic units, diachronic or otherwise, has only recently been resolved by Rees et al. (2026). Although Leamy et al. (1973) formalized the soil stratigraphic units within the sequences, the Rangitīkei loess nomenclature of Milne and Smalley (1979) has been adopted and more widely used for equivalent-aged loess units on both marine and fluvial terraces preserved throughout eastern and lower North Island (e.g., Palmer 1982; Pillans 1983, 1988; Alloway et al. 1988; Wilde and Vucetich 1988; Palmer et al. 1989; Berryman 1992; Palmer and Pillans 1996; Pillans 2017; see also Rees et al. 2026). Aggradation (fill) terraces T1, T2, and T3 recognized in eastern North Island catchments were correlated with Milne's Ohakea (Ok), Rata (Rt), and Porewa (Po) terraces of the Rangitīkei, respectively, based on loess and tephra marker bed occurrence in conjunction with radiocarbon and optically stimulated luminescence age data (Litchfield and Reiser 2005; Litchfield and Berryman 2005) (Figure 10).

6.1 | Radiocarbon Dating

The first radiocarbon (^{14}C) date (NZ-1) in ANZ was derived from charcoal collected by Ian Baumgart from the c. 232 CE Taupō eruption deposits (Fergusson and Rafter 1953; Lowe 1990). Until 1973, ^{14}C ages provided the only chronological underpinning for ANZ loess. The ages were derived from either organic material interbedded with, or encapsulating, the loess. Alternatively, they were inferred from interbedded silicic tephras which were dated elsewhere, the ages being transferred tephrochronologically using stratigraphy together with the characterization or "fingerprinting" of tephras using their physical, mineralogical, and geochemical properties (e.g., see Froggatt and Lowe 1990; Hopkins, Lowe, et al. 2021). Many of the early ^{14}C ages on interbedded organic materials were later shown to be unreliable (e.g., Goh et al. 1978; Hammond et al. 1991), ambiguous, or "out of range" (Newnham et al. 1999), but a number of later dates were considered reliable (e.g., Denton et al. 1999). Ages inferred from dated tephra inter-beds, many now derived using Bayesian-based flexible age-depth modeling and ^{14}C wiggle-matching methods (see below), have proven to be more reliable in most cases (e.g., Buck et al. 2003; Hopkins, Lowe, et al. 2021). However, some tephras remain poorly dated because of limited sample material or because of a sparsity of dates in sequences in which they occur that have been subject to Bayesian statistical analysis (Lowe et al. 2013).

6.2 | Amino Acid Racemization

Amino acid racemization (AAR) dating relies on the degree of racemization (equilibration) that has occurred since the death of an organism, or suite of organisms, a process that sees the naturally occurring L-amino acids in protein convert to the D-form (Kimber et al. 1994). The proportion converted, D/L, is used to estimate the time elapsed since death. Kimber et al. (1994) applied AAR data to a drill core section of loess and interbedded, mainly rhyolitic, tephra deposits, and associated buried paleosols, at Tapapa on the western margin of Mamaku Plateau, near Rotorua (see Froggatt 1988; Kennedy 1988; Shane et al. 1994; Lowe et al. 2012). Twenty samples including loess were analyzed and the ages obtained were calibrated against available radiocarbon (utilized as conventional ^{14}C ages) and fission-track data for the same core samples. Many AAR-derived ages in the upper 5.5 m of the core were consistent with previous results obtained by tephrochronology and correlation with the MIS record. However, as well as using uncalibrated ^{14}C ages, it is now known that some other ages used in the calibration were inaccurate (e.g., Mamaku Ignimbrite has been re-dated to c. 230 ka BP rather than 140 ka BP as used by Kimber et al. 1994). Nevertheless, Kimber et al. (1994) suggested that the AAR method could be useful as a basis for dating loess sequences using degree of racemization of amino acid released from the more tightly bound (protected) peptides within the deposits and paleosols.

In the South Taranaki–Whanganui region, Pillans (1983, 1990a) applied AAR dating to fossil wood preserved in loessic cover beds (up to 500,000 years old) overlying the well-known sequences of uplifted late Quaternary marine terraces in the region (see Pillans 2017, for a review). Using the c. 345 ka BP Rangitawa Tephra as a calibration, wood-derived AAR ages for Ngarino and Rapanui Terraces (and associated loessic cover beds) indicated minimum ages of 190 and 110 ka BP, respectively. On this basis, the Rapanui strandline was correlated with the Last Interglacial high sea-level (Stage 5e) at around 120 ka BP (Pillans 1983, 1990a, 1990, 2017).

6.3 | Luminescence Dating

Thermoluminescence (TL), infrared stimulated luminescence (IRSL), and optically stimulated luminescence (OSL) dating have become widely used in Quaternary studies. These techniques measure the time elapsed since the last light exposure of a deposit (assumed to have been at time of burial after deposition). They are being increasingly used where traditional techniques, such as ^{14}C dating, are not possible. Quartz or feldspar grains within sediment that has been adequately exposed to sunlight, such as loess, dune sand, beach sand, and fluvial sediments, are usually targeted. Many luminescence applications are still experimental and specialists disagree to this day as to the reliability (accuracy) of these methods with certain materials and over certain time ranges. Reviews of numerous luminescence-dating studies highlight the method's potential and its challenges (see Wintle 1990; Bösken and Schmidt 2020, and references therein).

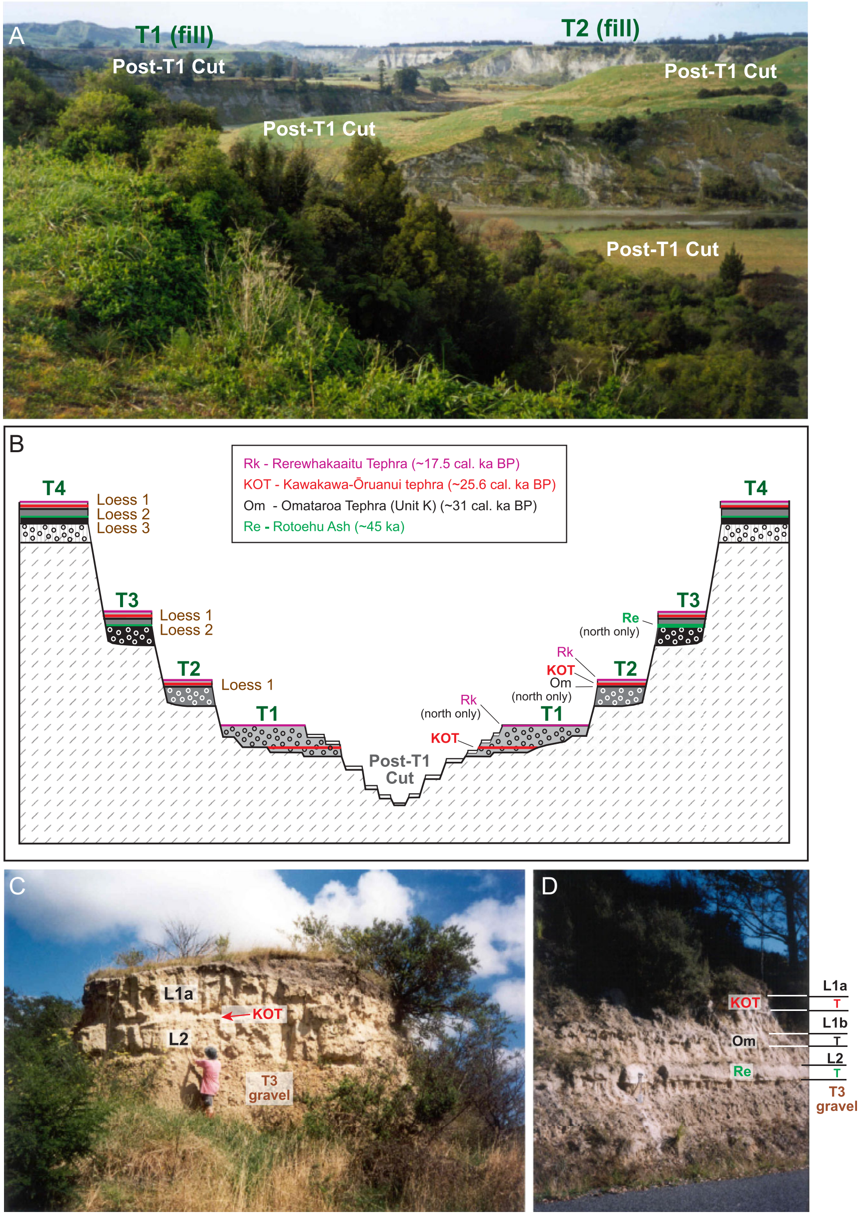

FIGURE 10 | (A) A suite of cut'n'fill terraces within the Waipawa–Tukituki catchment, eastern North Island (T1 and T2 are aggradation (fill) terraces) that correspond in age with Ohakea (Ok) and Rata (Rt) aggradation terraces of the Rangitīkei River valley (Milne and Smalley 1979), respectively. The gravel of T2 is visible resting on a strath cut into early Pleistocene siltstone bedrock (white cliffs in the distance). (B) Schematic cross-section from Litchfield and Berryman (2005) summarizing the relationship between terraces and their associated loess and tephra cover-beds. (C, D) Exposures of fluvial deposits and cover-bed deposits of T3 in the Ngaruroro and Waiau-Wairoa River catchments, respectively (Litchfield and Rieser 2005; Litchfield and Berryman 2005) (photos A, C, and D courtesy of Nicola Litchfield, GNS Science). Abbreviations Rk, KOT, Om, and Re are defined in panel B. Note that in (C), loess L1a overlies KOT, and in (D) loess L1b underlies KOT.

From the 1980s onwards there have been considerable efforts utilizing luminescence in ANZ to establish or try to improve the age of loess and enable correlation between sites and to the MIS timescale. The first application in ANZ of TL dating was that of Berger et al. (1992), who used fine-grained (4–11 μm) polymineral loess samples spanning 20–800 ka, the latter age being well beyond the (disputed) upper age limit of 100–150 ka BP at the time. The TL age results were somewhat constrained by independent ages of associated tephra beds. This initial work was followed by further TL-dating studies of post-glacial loess adjacent the Rakaia River in Canterbury (Berger et al. 1996). Later studies from western (Almond et al. 2001; Berger, Almond, et al. 2001; Pruesser et al. 2005), eastern (Berger, Pillans, et al. 2001), and southern (Berger et al. 2002) South Island utilized both TL and IRSL techniques where ages of loess back to at least ~350 ka BP were inferred (Figure 11A,B)—the oldest being the near-coastal Romahapa site located in northern Southland. Among the plausible results are those from the youngest Canterbury site (Cust), for which three samples were dated (Figure 11A). On the northeastern coast of South Island, Ota et al. (1996) and Oakley et al. (2017) applied TL and IRSL ages, respectively, to loess coverbeds (together with AAR ages on marine shells) to help date marine terraces and their uplift and deformation. The most rigorous application of luminescence dating was from

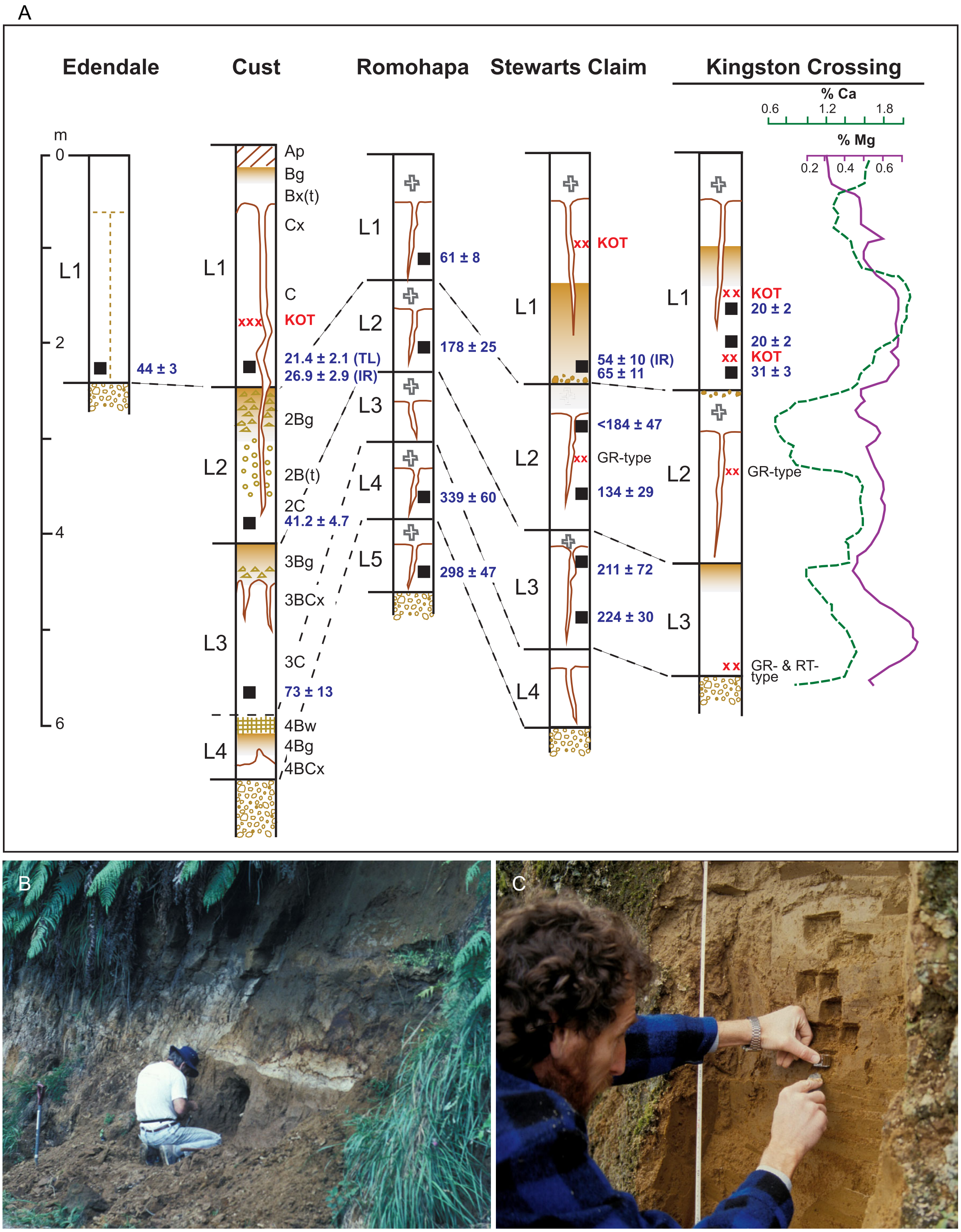

FIGURE 11 | (A) Summary of luminescence (TL and IRSL) chronology of loess-paleosol sequences from eastern South Island (from Berger, Pillans, et al. 2001; Berger et al. 2002). Also shown are the positions of trace concentrations of glass shards (cryptotephras) and speculative correlations based on TL/IRSL results. At far right is a profile of total element Mg and Ca percentages derived from unpublished XRF analyses through the Kingston Crossing (Southland) loess core mentioned by Eden et al. (1992). These data were subsequently used by Berger et al. (2002). Ages of loess back to at least ~350 ka BP were determined, the oldest being the near-coastal Romahapa site located in northern Southland. The most satisfactory results are those from the youngest Canterbury site (Cust), for which three samples were dated. However, at other South Island sites and in some units, poor precision and stratigraphic reversals were recorded which precluded unambiguous correlation between sites. (B) Glenn Berger retrieving TL samples from beneath Fordell Ash near Whanganui (photo: B.J. Pillans). (C) Brad Pillans retrieving samples for magnetic susceptibility and magnetic excursion measurements through a 230 ka-long tephra-loess-paleosol sequence at Tapapa on the western edge of the Mamaku Plateau, central North Island (photo: D.J. Lowe).

Sohbati et al. (2016) who applied paired quartz OSL and feldspar IRSL dating to loess and loessic colluvium on Banks Peninsula. Generally, very good agreement between the two techniques was reached. This study was not aimed at loess chronology—instead it focussed on timing of rockfalls—but it gives some encouragement for future reliable luminescence dating of loess. Discouragingly at other sites in the South Island, IRSL has produced ages of loess in conflict with well constrained ages and sometimes out of stratigraphic sequence, frustrating attempts of regional correlation (Almond et al. 2001, 2007, 2020). Attempts to explain the inconsistencies invoked "unknown and malign traits" of the samples, as colourfully described by Berger, Pillans, et al. (2001, 514): such traits included possible salt spray effects, induration, unrecognized postdepositional faunal burrowing/mixing, and unrecognized feldspar-mixture inhomogeneity (see also Almond et al. 2007 and discussions in Preusser et al. 2005; Shulmeister et al. 2019). However, more recent studies have shown some promising results using both post-infrared–infrared (pIRIR) signals derived from fine-grained polymineral fractions (Brezeanu et al. 2021) and OSL on fine-grained quartz samples (Avram et al. 2022). Marx et al. (2026) obtained satisfactory Holocene ages using pIRIR on silt-sized (11–63 μm) polymineral fractions and sand-sized (90–150 μm) K-feldspar samples. Thus, hope remains that luminescence will contribute to a better understanding of South Island loess chronology, which, excepting KOT (and possibly Rangitawa Tephra: Eden et al. 1992), currently lacks the tephrochronostratigraphic control of most North Island loess.

In the North Island, the earliest OSL-dating was applied to loess cover-beds in the Wairarapa area (Wang 2001; Formento-Trigilio et al. 2003). However, subsequent OSL studies (Litchfield 2003; Litchfield and Reiser 2005) targeted both loess cover-beds and silt/sand beds within and immediately underlying gravel-dominated deposits. The original intention of this work was to test and validate earlier age estimates and correlation of loess and aggradation terraces, particularly the most widespread aggradation terrace (T1), the putative correlative of the Ohakea Terrace, as well as older terraces (e.g., T3, Porewa Terrace correlative, MIS 4) within the Rangitīkei catchment. Similar work was applied to catchments of the East Coast of North Island where tephra inter-beds were able to validate OSL-age results of four fill terraces (T1–T4) and their loessial cover-beds dating back to ~110 ka BP (MIS 5d) (Litchfield and Berryman 2005; see also Wilson et al. 2007) (Figure 10B).

On an elevated alluvial terrace adjacent to the Rangitīkei River in southern North Island, Grapes et al. (2010) reported eight new IRSL ages from a loess-dominated section containing the KOT. The ages were calculated from IRSL signals obtained from polymineral 4–11-μm fractions obtained from bulk samples of loess together with one bulk sample of the KOT. The IRSL signals in the loess samples were dominantly derived from feldspar grains and possibly from glass shards in the tephra sample. However, the bulk polymineral IRSL age data on the tephra and encapsulating loess were significantly younger than multiple radiocarbon ages on tephra sequences bracketing the KOT and with paleoenvironmental evidence elsewhere for the time period concerned (Lowe et al. 2010). In a later study in the Rangitīkei River catchment, Guyez et al. (2022) showed that single-grain IRSL dating on fluvial sediments was well suited to date terraces and provide proxies to reconstruct sediment sources and pathways. In another example, Lian and Shane (2000) used OSL to estimate the age of loess bracketing the Rotoehu Ash at two sites in central North Island. Their OSL age of c. 45 ka BP for the Rotoehu Ash closely matches the age for this tephra derived using several other radiometric methods (as reported below).

With a very sound tephrochronological framework, loess in the North Island offers a golden opportunity to resolve the problems of luminescence systematics. If luminescence dating could be reliably applied in the South Island it would allow loess to be used to link regional landscape dynamics from strongly glacierized (South Island) to mostly nonglacierized (North Island) tectonically active settings. One promising new approach could be to investigate using Bayesian hierarchical age modeling for single-grain optical dating of either quartz or feldspar, as reported by Li et al. (2023, 2024) (see also Bayesian age modelling approaches used by Zhang et al. 2022 and Vercelot et al. 2025).

6.4 | Paleomagnetism

In many studies, numerical ages derived from glass-ITPFT, $^{40}Ar/^{39}Ar$, U-decay series, fission tracks in zircons, and luminescence methods are used in conjunction with magnetostratigraphy. This combination is helpful because the age of geomagnetic polarity transition (reversal) zones is well known for late Cenozoic time and provides an independent check on the reliability of numerical ages or age-equivalent methods including tephrochronology. However, in ANZ most (but not all) loess sequences are younger than the Matuyama–Brunhes polarity transition (~0.773 Ma: Haneda et al. 2020) (e.g., Berger, Pillans, et al. 2001; Pillans 2003). Hence, in the following section, we report mainly magnetic susceptibility applications in loess stratigraphy and paleoclimatic inferences; then, we note several studies involving the use of magnetostratigraphy.

6.4.1 | Magnetic Susceptibility

Magnetic susceptibility variations in North Island loess were seen to be largely controlled by volcanism, rather than climate (Pillans and Wright 1990), consistent with the "Alaskan" rather than "Chinese" loess model (see Begét et al. 1990; Begét 1996; Liu et al. 1987, 2001; Maher 1998; Vlag et al. 1999), and therefore generally precluding use of these variations for correlation to the MIS chronology. Unlike Chinese loess, magnetic susceptibility (χ) in Alaskan (and Siberian) loess is lower in paleosols and higher in inorganic loess, reflecting the size and concentration of magnetic grains present in the loess which, in turn, are controlled by changes in wind intensity (Chlachula et al. 1998; Jensen et al. 2016). Thus, high magnetic susceptibility values occur during cold stages with extensive glaciation, whereas low values are associated with intervals of decreased glacier coverage and wind intensity during interglacials or interstadials (Begét et al. 1990; Jensen et al. 2016). However, at Rangitatau East, Palmer and Pillans (1996) found the sequence essentially complied with the Chinese loess model. The lowest magnetic susceptibility values corresponded with the most quartzo-feldspathic-rich (QFR) loess of glacial maxima: rapid QFR loess deposition diluted sporadic andesitic ash-fall. In contrast, high magnetic susceptibility values were recorded in the paleosols because of the much reduced (or negligible) QFR loess deposition, additions of andesitic ash, and likely pedogenic enhancement.

Pillans (1991, 1994) suggested that the susceptibility signatures in New Zealand loess sequences were effectively masked by iron remobilization in soils, particularly in areas having <1200 mm mean annual rainfall (such as much of eastern and northeastern South Island). In the quartzo-feldspathic loess sequences of South Island, Froggatt (1988) obtained susceptibility variations within one section (near the mouth of the Awatere River, north-east South Island) and was optimistic that paleosols could be identified for correlative purposes. However, there was no follow-up study to validate this approach. At the Dashing Rocks loess section exposed in coastal Timaru, Liu (2000) reported very low variations in magnetic susceptibility, with peaks and troughs of the susceptibility records not matching well the variations in the equivalent MIS record. In a subsequent study at the same section Ma et al. (2013) revealed highly complex relationships between magnetic properties and pedogenic development within the loess succession that likely related to differing degrees of magnetic mineral transformation at variable depths and at different times during its formational history. Thus, they concluded that the use of magnetic susceptibility and secular variation for high-resolution correlation and dating of many South Island loess-paleosol sequences was problematic.

More recently, however, three studies on the magnetic susceptibility of North Island loess have revealed, somewhat cautiously, a relationship with climate change, and so the application of magnetic susceptibility—together with other proxies of past climate including phytolith analysis—does warrant further consideration. First, at Tapapa on the western edge of the Mamaku Plateau, closely spaced measurements of magnetic susceptibility (by Begét, Lowe, Pillans, and Horrocks) through a 230 ka-long tephra-loess-paleosol sequence (Figure 11C) allowed identification of numerous well developed paleosols (including MIS 5e, MIS 5c, MIS 5a in clay-rich loess), which were correlated with two sequences—Rangitatatu East (Whanganui) and Airedale Reef (Taranaki)—using tephra marker beds in common (Newnham et al. 1999; Lowe et al. 2012).

Secondly, in the Rotorua Basin, Lanigan (2012) examined tephric loess (Figure 12), up to 4.3 m in total thickness, at 13 sites dating from c. 30,600 cal yr BP through to c. 15,600 cal yr BP (Rotorua Tephra) and measured magnetic susceptibility (and other proxies noted below) at two sections (Dansey Road, Maniatutu Road). She identified three broad climate periods:

(i) A warm interstadial period (c. 30.6–25.6 cal ka BP).

(ii) A cold stadial period in the LGM (c. 25.6–18.4 cal ka BP) with interstadials.

(iii) A warming/transitional period leading to an interglacial (c. 18.4–9.4 cal ka BP) but including a late-glacial reversal (c. 13.8–12.8 cal ka BP).

The Rotorua basin magnetic susceptibility record together with loess accumulation rates, grain-size data, and K_2O contents allowed

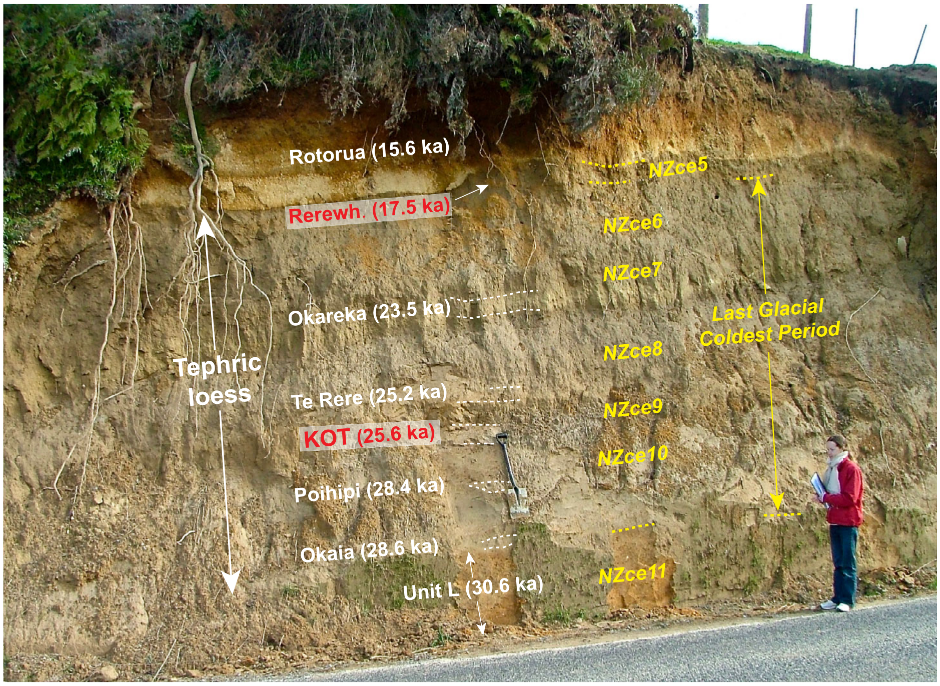

FIGURE 12 | Sequence of greyish brown, ~4 m thick, tephric loess, and eight interbedded tephra layers, exposed at Oturoa Road near Ngongataha in the Rotorua Basin at ~340 m elevation. The loess was deposited during the eLGM (referred to here as the Last Glacial Coldest Period) between c. 30,600 cal yr BP (marked by the reddish-yellow basal tephra/paleosol, Unit L, of the Mangaone Subgroup) and c. 15,600 cal yr BP (marked by the yellowish brown to orange Rotorua Tephra near the surface). Such loess with intercalated tephra beds is common in the basin (Lanigan 2012). Tephra ages are from Lowe et al. (2013), Danišík et al. (2020), and Peti et al. (2021). Relevant New Zealand climate events (NZce) of Barrell et al. (2013) are also included, the cold periods (stadials) being NZce-10, −8, and −6. The dull greyish brown colour of the loess here probably reflects in part its reducing character, as shown by a positive test for ferrous iron (Childs 1981) applied to loess between Rerewhakaaitu and Okareka tephras, and also its mainly halloysitic mineralogy (e.g., as evident in equivalent deposits at several other sites in the Rotorua area and Tapapa: Birrell and Pullar 1973; Green 1987; Lowe and Percival 1993). The greyish brown halloysitic loess contrasts markedly with the brighter yellowish to orange colour of the allophane- and ferrihydrite-bearing paleosol developed on Rotorua Tephra. Kerri Lanigan (right) provides the scale. Image modified after Lowe et al. (2015). Photo: D.J. Lowe.

nine shorter climate phases (within the three broad periods) to be detected. We note that in loess soils (where each part of the soil profile has at one point been an A horizon and hence highly susceptible to weathering and leaching of K_2O: Lanigan 2012), the degree to which K_2O losses have occurred is related to the intensity and duration of weathering (Palmer and Pillans 1996). In turn, these losses generally increase under warmer and wetter climatic conditions, and Hay et al. (1976) showed (for loess-derived soils in Canterbury) that the K_2O content decreased as the rate of loess accumulation decreased and rainfall increased.

With respect to the New Zealand Climate Event (NZce) Stratigraphy of Barrell et al. (2013), the peaks in magnetic susceptibility corresponded to interstadials F (NZce-11), D (NZce-9), and B (NZce-7), and lows corresponded approximately to stadials E (NZce-10), C (NZce-8), and A (NZce-6) (Figure 12). To test her climate interpretation further, Lanigan (2012) also examined phytoliths, total carbon, and $\delta^{13}C$. Previous studies on phytoliths by Sase et al. (1988) and Kondo et al. (1994) had demonstrated that they were particularly well preserved in tephric loess of the North Island, probably as a result of high Si saturation of soil pore water. Therefore, they provided a potential means for reconstructing vegetation of equivalent age to loess deposition, and Lanigan (2012) indeed showed her phytolith record to generally agree with the nine identified climate phases. However, the total carbon and $\delta^{13}C$ analyses supported only the broad three-period record (Lanigan 2012; Lowe et al. 2012). In general, although the magnetic susceptibility record corresponded reasonably well with the New Zealand Climate Event Stratigraphy and other records of climate change through the LGM and subsequent climatic transition in northern New Zealand (e.g., Newnham et al. 2003, 2013; Alloway et al. 2007; Barrell et al. 2013), there were discrepancies between sites, and the timings of correlations were not always well synchronized despite the multiple rhyolitic tephrostratigraphic framework that enabled all sites to be linked and synchronized to a common timescale (Lanigan 2012). Analyses using magnetic susceptibility (along with K_2O content, grain size, and phytolith analyses) at a higher resolution and at more sites may help improve the climate record obtained from the late-glacial and post-glacial tephric loess in the Rotorua Basin.

Thirdly, in western Waikato, Horrocks (2000) examined the extremely weathered, composite, Kauroa Ash sequence comprising multiple (altered) tephra deposits and interbedded loess and paleosols (Salter 1979; Briggs et al. 1989, 1994; Lowe Tippett et al. 2001; Lowe 2019; McLeod et al. 2024). Up to ~12 m in thickness, and very rich in clay (most beds contain ~70%–90 % <2 μm clay), the sequence ranges in age from c. 2.25 Ma to c. 0.8 Ma (the uppermost bed being >0.77 Ma, see magnetostratigraphy below). Seven separate loess beds dating from c. 1.7 to c. 1.1 Ma, and another four "tephric loess" beds represent some intermediate stage between "mostly tephra" and "mostly loess" (Figure 13).

The Kauroa sequence includes the oldest loess identified thus far in the North Island (Horrocks 2000; Lowe et al. 2015), but Pliocene loess at least 3 Ma in age, the oldest known in ANZ, has been identified (using isotopes and clay mineralogy) in Central Otago in the South Island (Scott et al. 2025). Previously, the oldest known loess in ANZ was identified in the Wairarapa, aged between 1.00 and 0.87 Ma (Shane et al. 1995), and in the Whanganui Basin (Rangitatau), aged up to c. 0.5 Ma (Pillans and Wright 1990; Palmer and Pillans 1996). The Kauroa sequence loess was distinguished from the encapsulating, much-altered tephra beds and paleosols on the basis of physical properties, magnetic susceptibility, and grain-size analysis: typically yellowish brown, friable, apedal fine-earthy to structureless (i.e., lacking prismatic or blocky structures, root traces), siltier (silty clays texturally), and lacking the visible silt- and sand-sized crystals and pumice clasts associated with the (weathered) tephra deposits (Horrocks 2000).

Horrocks (2000) showed that mass-specific susceptibility (χ) (the proportionality between magnetization and magnetic field strength) did not always conform to the established model of susceptibility enhancement in paleosols. However, the frequency dependent susceptibility (χ_{fd}) (the percentage difference between measurements made at two frequencies), and the CBD-modified susceptibility measurements (χ^{CBD}) (the difference in mass-specific magnetic susceptibility before and after dissolution by CBD) (Mehra and Jackson 1960), were found to be reliable diagnostic features to identify paleosols (intitially defined by their physical properties) by means of their enhanced ultrafine iron oxide content. This content is a pedogenic rather than lithogenic feature (e.g., Hunt et al. 1995; Singer et al. 1996; Vidic et al. 2000). Moreover, Horrocks (2000) recorded that the model of magnetic susceptibility for Chinese loess (e.g., Kukla 1987; Liu et al. 1987, 2007), representing a glacial (low susceptibility) to interglacial (high susceptibility) paleoclimate signal, was able to be matched, largely, to the pattern of mass-specific and frequency-dependent magnetic susceptibility for the Kauroa loess and paleosols. The seven main loess beds identified in the Kauroa sequence were correlated with MIS units by Horrocks (2000), including the oldest, MIS 60 (c. 1.70 Ma), together with MIS 58-56 (c. 1.64–1.60 Ma), 54 (c. 1.57 Ma), 48 (c. 1.44 Ma), 46 (c. 1.40 Ma), 42 (c. 1.32 Ma), and the youngest, MIS 30 (c. 1.06 Ma) (Figure 13).

6.4.2 | Magnetostratigraphy

Froggatt (1988) identified a possible excursion, namely the Blake event (c. 120 ka BP) in a loessic paleosol (MIS 5d) in clayey loess at the 230-kyr BP-long Tapapa section, western Mamaku Plateau. However, this excursion was not identified in a later study in the late 1990s by Pillans and Lowe (reported in Lowe et al. 2012, 24).

Horrocks (2000) was able to develop a chronology for the long Kauroa Ash sequence in western Waikato, with ages between c. 2.25 and c. 0.77 Ma as described above, using measurements of paleomagnetic polarity changes supported by zircon fission-track dating and tephrochronology (involving analyses of melt inclusions, viz., glass, in quartz grains). She measured changes in magnetic polarity and identified three chrons (Gauss, Matuyama, Brunhes) and two subchrons (Jaramillo, Olduvai) (Figure 13). The uppermost paleosol/bed of the Kauroa sequence, having reversed polarity (Matuyama chron) is therefore dated at >0.77 Ma (the age on the Matuyama–Brunhes boundary: Haneda et al. 2020), and overlain unconformably by c. 0.345 Ma Rangitawa Tephra and the younger series of Hamilton Ash beds, all with normal polarity (Brunhes chron). That the clay-rich, very strongly altered Kauroa sequence has preserved reversed magnetic polarities dating back to 2.58 Ma (the age on basalt of Okete Volcanics that underlies the Kauroa beds) means that the remanence carrier has been unchanged by chemical weathering, consistent with the findings of Pillans (1997) who measured paleomagnetism on weathered basaltic lava flows in semi-arid tropical northern Queensland as old as 5.6 Ma.

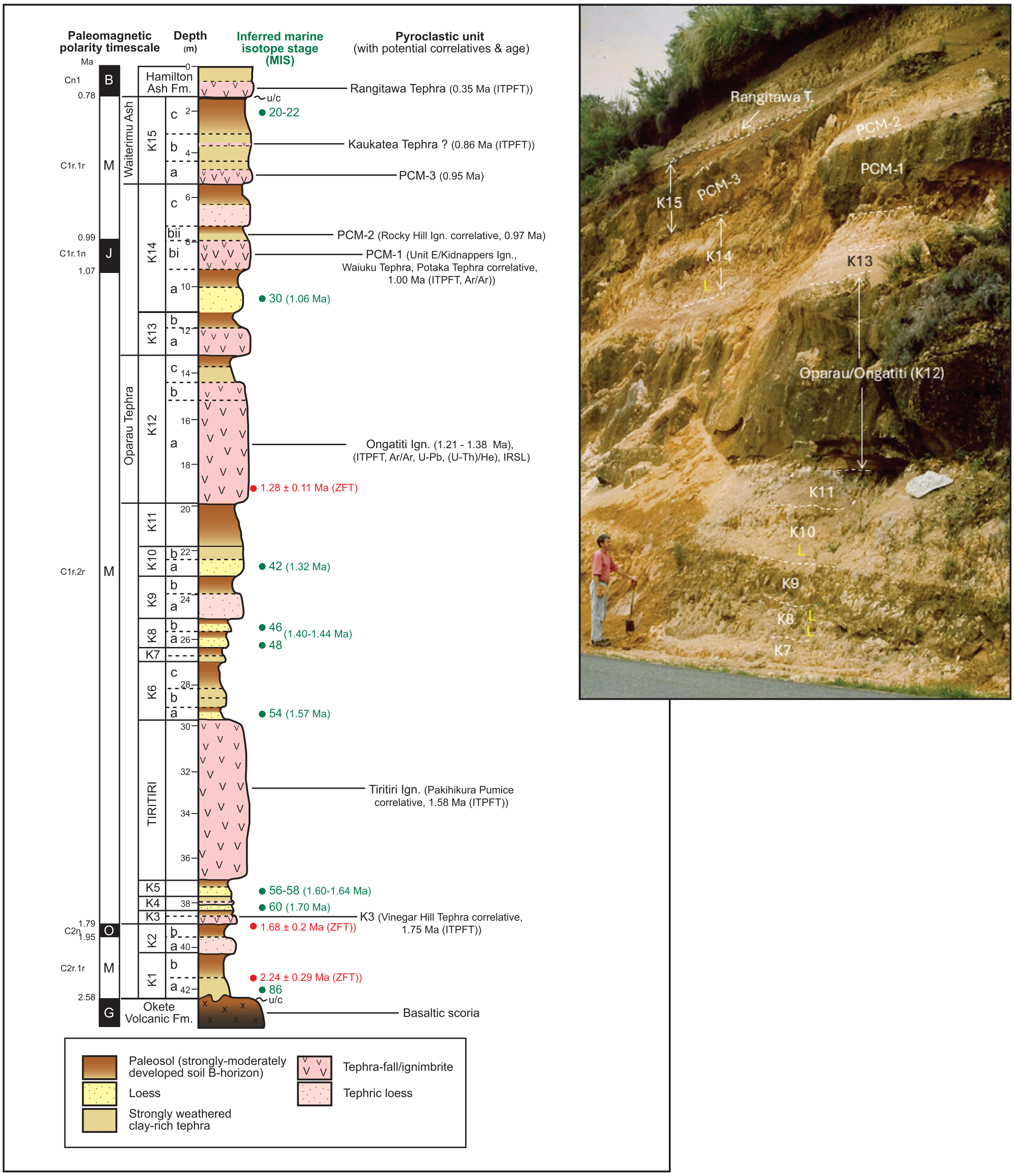

FIGURE 13 | Summary stratigraphy and chronology of the composite, strongly weathered Kauroa tephra- and loess-bearing sequence in western Waikato (modified from Hopkins, Lowe, et al. 2021). The depicted sequence, initially defined by Ward (1967) and divided into beds K1–15 (shown at left) by Salter (1979), is based on Horrocks (2000). She subdivided the 'K-beds' using lower-case letters (a–c), and lower-case roman numerals (bi, bii), and dated the sequence using palaeomagnetic polarity measurements (B = Brunhes Chron, M = Matuyama Chron, J = Jaramillo Subchron, O = Olduvai Subchron, G = Gauss Chron), zircon fission-track (ZFT) dating (indicated by red text) by Lowe, Tippett, et al. (2001), and tephrochronology (based on melt-inclusion glass compositions in quartz grains: data shown in Hopkins, Lowe, et al. 2021). The loess beds identified were correlated with marine oxygen isotope stages (MIS) by Horrocks (2000) and are marked by green dots and ages. Inset photograph at right shows the type section for the Oparau Tephra (defined by Pain 1975, and now correlated with the Ongatiti Ignimbrite and unit K12), and other members of the clay-dominated Kauroa sequence at the Papakura Creek section (on Kawhia Road) between Oparau and Kawhia. Distal ignimbrite units denoted PCM1–3 are informal Papakura Creek members (Horrocks 2000). L = loess bed (see text). Roger Briggs (bottom left) provides the scale. Photo: D.J. Lowe.

6.5 | Fission-Track Dating

In 1973, fission track (FT) dating of tephra using both glass and zircon was used for the first time to extend ANZ's loess chronology well beyond the ~40 ka BP limit of ^{14}C dating of those times. The fledgling FT techniques used for dating glass and zircon constituents of Quaternary silicic tephra resulted in a suite of ages that seemed to be consistent with the interpreted loess stratigraphy. However, as further FT ages were acquired, inconsistencies emerged that resulted in robust discussion regarding the chronology of the loess succession and its FT-dated tephra inter-beds (e.g., Kohn et al. 1996; Vella and Vucetich 1996; Vella 1997; Pillans and Kohn 1998).

Milne (1973c) reported the first glass FT age of 230 ± 0.30 ka BP for Mt Curl Tephra occurring near the base of the loess sequence located at its type section in Rangitīkei Valley, eastern Whanganui Basin. Mt. Curl Tephra was subsequently recognized and correlated more widely in southern North Island and South Island loess (Milne and Smalley 1979; Eden 1987; Eden et al. 1992), and this led to an assortment of glass- and zircon-FT ages being acquired that ranged from 230 to 290 ka BP (Seward 1979; Pillans and Kohn 1981; Froggatt et al. 1986). For the first time, a reliable loess stratigraphy spanning the last 250 ka seemed to be emerging. However, a problem arose when another prominent tephra marker bed—Rangitawa Tephra—was recognized in western and central portions of Whanganui Basin, with field properties, mineralogy, and glass-shard compositions indistinguishable from those of Mt. Curl Tephra as well as occupying a similar stratigraphic juxtaposition relative to enveloping loess-paleosol beds. Despite these similarities, Rangitawa Tephra (at first) had an entirely older associated zircon- and glass-FT age of between 370 and 390 ka BP (Seward 1976; Boellstorff and Te Punga 1977; Pillans and Kohn 1981). It was also incongruous that these two prominent tephra markers were never recognized together within the same section (Pillans et al. 1992). Subsequent dating of early-middle Quaternary-aged distal silicic tephra, including Rangitawa Tephra utilizing both zircon-FT (Kohn et al. 1992; Lowe, Tippett, et al. 2001; Holt et al. 2010) and hydrated glass-shard ITPFT techniques (Alloway et al. 1993), in conjunction with magnetostratigraphy and spectral analysis of marine sediments (Black et al. 1988; Nelson 1988), were able to show that many of the earlier acquired FT ages in ANZ (Seward 1974, 1976, 1979) were significant under-estimates resulting from unrecognized glass annealing, inaccurate thermal neutron dose determinations, and under-etching. Nowadays, Mt Curl Tephra is a known correlative of the c. 345 ka BP Rangitawa Tephra (Alloway et al. 1993; Pillans et al. 1996).

6.6 | Bayesian Age Modelling and ^{14}C Wiggle-Match Dating in ANZ

A major advance in the past two decades for dating late Quaternary lacustrine and peat sequences, and tephra deposits, has been the development of both Bayesian-based flexible age-depth modelling and wiggle-match dating involving dendrochronology and ^{14}C dating (Hopkins, Lowe, et al. 2021). A Bayesian approach has also been applied to AAR dating (Allen et al. 2013; Oakley et al. 2017). In ANZ, Bayesian age modelling was used at Kaipo bog (in eastern North Island) to derive more accurate and precise ages on ≤17.5 cal ka BP tephras than had been attained previously (Hajdas et al. 2006; Lowe, Shane, et al. 2008; Lowe et al. 2013). Peti et al. (2020, 2021) and Läuchli et al. (2021) applied Bayesian age modelling to lake sediments containing multiple tephras aged ≤130 ka BP in two maars in Auckland, where they integrated ^{14}C-dates, luminescence dates, magnetic palaeointensities, and tephrochronology, to derive or improve tephra ages. In the Taupō region, a Bayesian-modelled age for Kawakawa–Ōruanui tephra of 25,360 ± 160 cal yr BP (± 2 standard deviations, SD) was derived by Vandergoes et al. (2013). This age was supported by an identical age of 25,580 ± 258 cal yr BP (± 2 SD) determined from KOT glass shards preserved within the WDCO6A ice core, West Antarctica (Dunbar et al. 2017). The most recent modelled age derived for the KOT eruption is 25,568 ± 232 cal yr BP (± 2 SD) (Muscheler et al. 2020), which is based on a revision of the age of Vandergoes et al. (2013) using the SHCal20 calibrations of Hogg et al. (2020).

Danišík et al. (2020) used Bayesian age modeling based on a target-event date model incorporating (U-Th)/He zircon double-dates and ^{14}C dates, as well as stratigraphic superpositioning, to develop new ages for a sequence of multiple tephras of the Mangaone Subgroup erupted from Ōkataina Volcanic Centre, the sequence being sandwiched by c. 45 cal ka BP Rotoehu Ash (below) and c. 25.6 cal ka BP KOT (above).

Calendar dates on two late Holocene tephras in ANZ, Kaharoa (1314 ± 12 CE) and Taupō (232 ± 10 CE), have been obtained by wiggle-match dating log-derived tree-ring sequences dated by ^{14}C and dendrochronology (Hogg et al. 2003, 2012, 2019; Lowe and Pittari 2021).

Barrell et al. (2013) used records with ages established by Bayesian sequence modeling or applied them to existing records to determine the timing of events in the New Zealand Climate Event Stratigraphy of the NZ-INTIMATE project (noted earlier).

6.7 | Tephrochronology

Tephras have two key features: (i) they are erupted and deposited over very short time periods, geologically speaking, usually a matter of only hours or days to perhaps weeks or months, and (ii) they can be dispersed widely over land and sea to form a thin blanket that (unless reworked) has the same age wherever it occurs, forming an isochron (Lowe 2011). Therefore, once it is identified by its physical, mineralogical, and geochemical properties, a tephra layer provides an isochron for an "instant" in time, that instant being the date of the explosive volcanic eruption that produced the layer (Alloway et al. 2025). Tephrochronology is thus an age-equivalent dating technique that uses tephra deposits as isochrons to stratigraphically correlate sequences or events in different settings and to establish and transfer relative or numerical ages from one site to another. Various methods have been used to date tephras numerically, including those discussed above (see Lowe and Alloway 2015; Hopkins, Lowe, et al. 2021; Alloway et al. 2025).

6.7.1 | Key Tephra Marker Beds for Loess Chronology

Numerous rhyolitic and andesitic tephras are interbedded with tephric loess of Bay of Plenty (as noted earlier), central North Island, and Taranaki-Whanganui areas (*Region 1* of McCraw 1975). These include upper beds of the Mangaone Subgroup (referred to as units K and L) and the Okaia, Poihipi, Te Rere, Okareka, and Rotorua tephras, which provide important, and now mostly well-dated, marker beds locally (e.g., Figure 12; Vucetich 1982; Kennedy 1988, 1994; Lanigan 2012; Lowe et al. 2013; Danišík et al. 2017, 2020). However, the most valuable tephras relating to ANZ loess more broadly comprise four key marker beds, the widespread Rerewhakaaitu Tephra, Kawakawa–Ōruanui tephra, Rotoehu Ash, and Rangitawa Tephra, which are each described in turn below. Notable but much older rhyolitic tephras associated with loess on fluvial and marine terraces of South Taranaki–Whanganui include Ararata Road, Fordell Ash, and Griffin Road tephras (Pillans 1988; Bussell and Pillans 1992; Pillans et al. 2005).

Several rhyolitic tephras have also been detected as glass shard concentrations (i.e., as cryptotephras, defined below) in quartzo-feldspathic loess of the South Island (Eden 1987; Eden et al. 1992), but, other than Kawakawa-Ōruanui tephra, they have yet to be reliably matched with near-source correlatives in the North Island. Cryptotephras are the explosively erupted ash-sized tephra deposits, preserved as glass shard and/or crystal concentrations in sediments (including ice), or soils or paleosols, that are insufficiently numerous, or too small, to be visible as a layer to the naked eye (Lowe and Hunt 2001; Lowe 2011).

6.7.2 | Rerewhakaaitu Tephra

The uppermost (youngest) silicic tephra associated with the uppermost Pleistocene loess sheet in central and north-eastern North Island, is Rerewhakaaitu Tephra, erupted from Ōkataina Volcanic Centre at c. 17,496 ± 462 cal yrs BP (± 2 SD) (Lowe, Shane, et al. 2008; Lowe et al. 2013). This widespread land-sea marker is now known to have erupted just after onset of the amelioration (climatic warming) following Termination I at c. 18 cal ka BP (Newnham et al. 2003; Barrell et al. 2013), as follows. In parts of the Rotorua–Bay of Plenty and Gisborne regions, especially in the lowlands, changes in the development of buried soils (paleosols) interfingered with successions of tephra beds including KOT (c. 25.6 cal ka BP), Te Rere (c. 25.2 cal ka BP), Okareka (c. 23.5 cal ka BP, Rerewhakaaitu (c. 17.5 cal ka BP), Rotorua (c. 15.6 cal ka BP), and Waiohau (c. 14.0 cal ka BP) tephras (ages from Lowe et al. 2013; Peti et al. 2021) were recognized by various authors (Vucetich and Pullar 1964, 1969; Vucetich 1968; Birrell and Pullar 1973). They noticed that the degree of development of these paleosols (based on both field and laboratory assessment) tended to be greater, and colours changed from dull brown/pale yellowish brown to brighter yellowish brown/reddish yellow, after the deposition of Rerewhakaaitu Tephra (RKT). The pre- and post-RKT colour change, and bulk densities, reflected the clay minerals changing from an assemblage dominated by halloysite (with Si-rich allophane) before deposition of the RKT to one dominated by Al-rich allophane (usually with minor ferrihydrite) at around or a few thousand years after deposition (Birrell and Pullar 1973; Green 1987; Hodder et al. 1990; Lowe and Percival 1993; Churchman and Lowe 2012). As well, phytolith analyses (at the Te Ngae section near the eastern shoreline of Lake Rotorua) showed that grass-derived phytoliths predominated in the deposits/paleosols stratigraphically up to the c. 15.6 cal ka BP Rotorua Tephra, whereas forest-derived phytoliths predominated in the c. 14.0 cal ka BP Waiohau Tephra and younger tephra beds/paleosols prior to Polynesian arrival c. 1300 CE (Sase et al. 1988; Kondo et al. 1994; see summary diagram in Palmer et al. 2025, 763). Thin deposits of loess (5–30 cm in thickness) were subsequently identified overlying RKT, and underlying Rotorua Tephra, at a number of sites in the Rotorua-Bay of Plenty region (Newnham et al. 2003; Lanigan 2012), with just a handful of sites showing some even younger loess dating to c. 14.0 (Waiohau Tephra) and one site to c. 9.4 cal ka BP (Rotoma Tephra) (Lanigan 2012). Thus, for many areas of central and north-eastern North Island, the c. 17.5 cal ka BP RKT forms a convenient marker generally approximating, or preceding by up to a few millennia, the termination of continuous LGM-loess deposition. Further study is needed to explain the occurrence of some of the younger loess in the area (Lanigan 2012; Lowe et al. 2012).

6.7.3 | Kawakawa–Ōruanui Tephra

Kawakawa–Ōruanui tephra (KOT) is the set of widespread fall deposits generated by the Ōruanui super-eruption of the Taupō Volcanic Centre c. 25.6 cal ka BP (Wilson 2001; Wilson et al. 2009; Barker et al. 2021). KOT has been known by various other names including Scinde Island ash, Aokautere ash, and Kawakawa Tephra (Berry 1928; Vucetich and Pullar 1969; Vucetich and Howorth 1976; Froggatt and Lowe 1990).

In the southern and western North Island, KOT occurs within the lower half of the youngest Pleistocene loess layer named Ohakea Loess (Cowie 1964a, 1964b; Rhea 1968; Milne and Smalley 1979; Palmer 1982) and its andic loessial correlative (Sy1) in Taranaki (Alloway, Stewart, et al. 1992; Alloway et al. 1995). Indeed, this widespread tephra-fall bed is found as a visible layer in the uppermost Pleistocene loess sheet throughout the central to lower regions of the North Island through to Nelson and Christchurch on the South Island (Campbell 1979, 1986; Kohn 1979; Eden and Froggatt 1988; Nicol et al. 1994), and as disseminated glass shards (i.e., as a cryptotephra) in loess in Westland (Robertson and Mew 1982; Mew et al. 1986, 1988a, 1988b; Almond 1996; Neall et al. 2001; Suggate and Almond 2005; Cole-Baker 2006) and Southland (Eden et al. 1992) (see Figure 14A–H). KOT also occurs as a visible layer in marine cores southeast of ANZ (Carter et al. 2004; Alloway et al. 2005; Ronge et al. 2016) and on the Chatham Islands (Holt et al. 2010; Miller et al. 2026), and as a cryptotephra in Antarctica (Dunbar et al. 2017). The KOT marker bed therefore facilitates widespread linkage to other types of equivalent-aged sediments and associated climate proxies across a significant portion of terrestrial and offshore ANZ (Figure 14I) and Antarctica (Pillans et al. 1993; Vandergoes et al. 2005, 2013; Alloway et al. 2007; Dunbar et al. 2017).

The common occurrence of KOT in the lower one-half to one-third of the upper loess sheet on the North and South islands (Eden et al. 1992) indicates that loess accumulation was underway in many areas by around 30,000 cal yr BP, consistent with the concept of the eLGM, essentially equivalent to the Last Glacial Cold Period (LGCP, Alloway et al. 2007; Newnham et al. 2007) beginning at around that time. This inference is supported by occurrences of the c. 30,600 cal yr BP Unit L (uppermost unit of the Mangaone Subgroup) underlying loess in the Rotorua Basin (see Figure 12) and the c. 30,800 cal yr BP Omataroa Tephra (equivalent to Unit K of the Mangaone Subgroup, dated at 30,800 + 8000, −1000 cal yr BP (± 2 SD) by Danišík et al. 2020) near the base of the upper loess sheet in the East Cape region (Litchfield 2003). Differences in the relative stratigraphic position of KOT, however, suggest some significant spatial variations in loess accumulation rates. As an extreme example, KOT occurs at 2.8–4 m depth below the top of the 10+ m-thick upper loess sheet at Mt Cass on South Island. In loess of South Westland, it is commonly found only ~35 cm below the top of the upper loess sheet (which is ~80–100 cm thick) within a buried soil A, O, or E horizon (Almond 1996; Suggate and Almond 2005). The decrease in loess accumulation c. 25.6 cal ka BP indicated by this buried soil can be

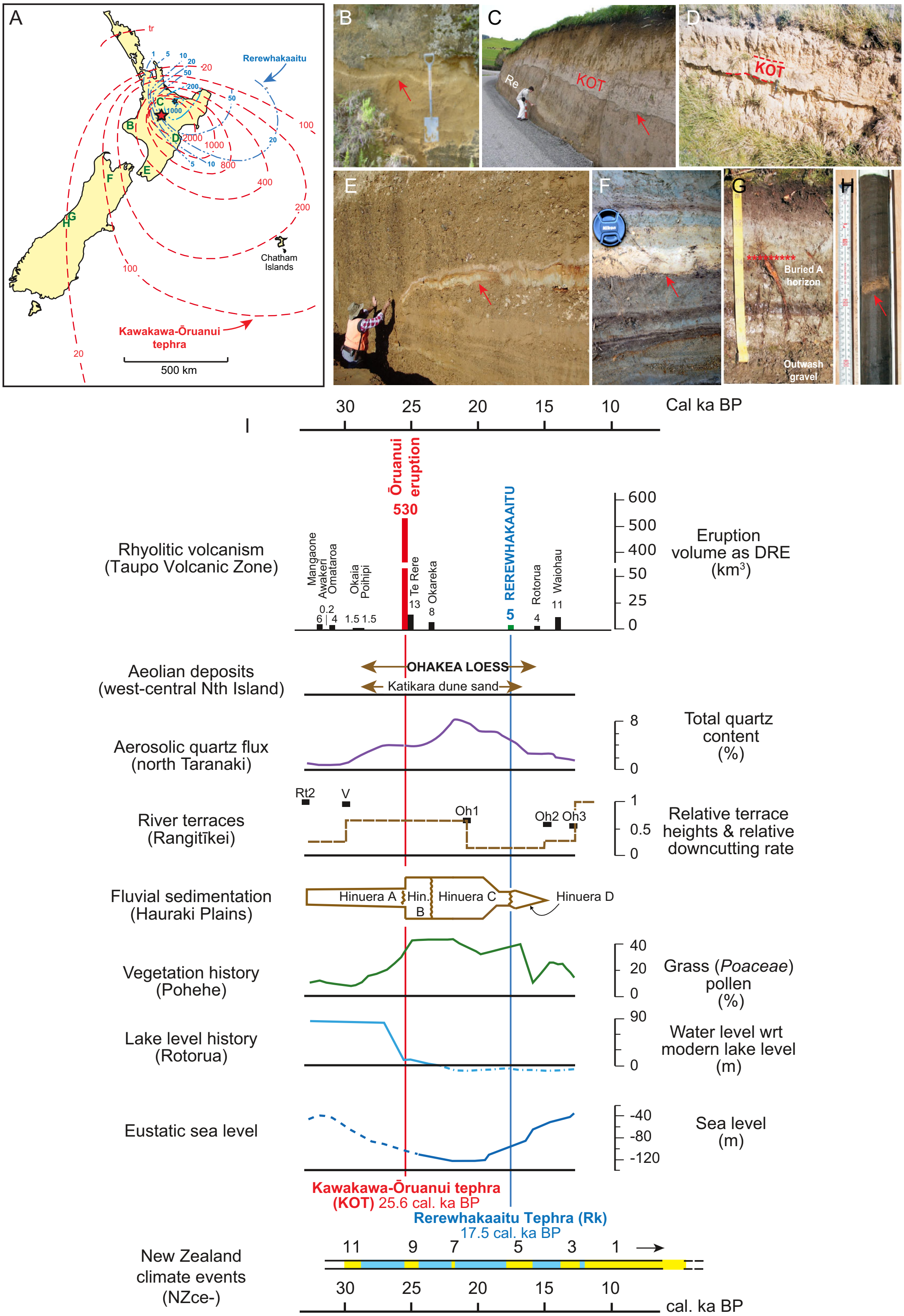

FIGURE 14 | Distribution and geomorphic association of the widespread 25.6 cal ka BP Kawakawa-Ōruanui tephra (KOT) emphasizing its importance as a widespread chronostratigraphic marker in paleoenvironmental reconstruction. (A) Distribution of the KOT (red dashed line, isopachs in millimetres) and locations (B–H) of medial-to-distal terrestrial ANZ sections where KOT, in different landscape settings and cover-bed stratigraphies, has been described. Eruptive source area is indicated as a red star. Distribution of the Rerewhakaaitu Tephra (blue dashed line, isopachs in millimetres) and eruptive source area are also shown (modified from Newnham et al. 2003). Examples of KOT in medial-to-distal terrestrial ANZ sections are as follows. (B) In North Taranaki, western North Island, showing KOT interbedded with andesitic aeolian dune sands (Katikara Formation of Neall 1975). (C) Near Putaruru, North Island, showing KOT as a prominent (~0.5 m thick) pinkish-grey marker bed overlying a succession of tephric loess and paleosols. Pale tephra bed near base (by person) is c. 45 cal ka BP old Rotoehu Ash (Re); it is underlain by a paleosol on pre-Re loess. (D) KOT within loess mantling

linked via KOT to glacier recession (Suggate and Almond 2005) and climatic amelioration (Vandergoes et al. 2005). Together, these records provide compelling evidence for significant climatic variation in ANZ during the eLGM/LGCP commencing at c. 30 cal ka BP (marked by NZce-10) through to the onset of Last Glacial-Interglacial Transition (LGIT) at c. 18 cal ka BP (NZce-5 and younger) (Alloway et al. 2007; Barrell et al. 2013) (see also Putnam et al. 2013; Rother et al. 2014; Lorrey and Bostock 2017). The LGIT is the interval of deglaciation between Termination I c. 18 cal ka BP to the onset of the warm Holocene c. 11.7 cal ka BP (e.g., Lowe, Hoek, et al. 2001; Alloway et al. 2007; Barrell et al. 2013). The break in loess accumulation is not evident in deposits derived from river systems draining the east side of the Southern Alps, which poses an interesting question. The difference may relate to problems in resolving soil stratigraphy in the drier east coast environment, or to something more fundamental about glacier and loess source area behavior on either side of the Southern Alps.

6.7.4 | Rotoehu Ash

Rotoehu Ash forms a regionally important stratigraphic marker through central and northern New Zealand (Pullar and Birrell 1973), and in sediments in the adjacent Pacific Ocean (Pillans and Wright 1992; Allan et al. 2008). It is notably useful therefore for onshore-offshore MIS 3 paleoclimatic reconstructions (e.g., Shane and Sandiford 2003; Lorrey and Bostock 2017; Newnham et al. 2017). Rotoehu Ash is derived from the caldera-forming Rotoiti eruption from the Ōkataina Volcanic Centre (Nairn 1972, 2002; Wilson et al. 2009). For many years, the age of Rotoehu Ash (and of coeval Rotoiti Ignimbrite) has been vigorously debated. Many ages have been acquired via a wide range of dating techniques (summarized in Hopkins, Lowe, et al. 2021), but now it is generally accepted to be c. 45 ka BP based on $^{238}U/^{230}Th$ disequilibrium and (U–Th)/He dating of zircon, various ^{14}C ages, and $^{40}Ar/^{39}Ar$ ages (on K-feldspar and biotite crystals) that places the eruption squarely within the MIS 3 interstadial (i.e., ~59.1–29 ka BP) (Danišík et al. 2012; Flude and Storey 2016). This age is in good agreement with some previously published estimates based on paleoclimate (palynology), luminescence dating of enclosing sediments (Lian and Shane 2000), ^{14}C ages (Santos et al. 2001), and sedimentation rates in both terrestrial and marine settings (see Molloy et al. 2009; Danišík et al. 2012, and references therein).

In soil cover-beds of Bay of Plenty, Waikato, and Coromandel areas, which may include tephric loess, Rotoehu Ash is identified as a decimetre-thick "grey-banded bed" at the base of a prominent reddish-colored paleosol informally referred by Vucetich and Pullar as "Hematite Harry." This paleosol (developed completely through thin L2) intervenes between more prominent tephric loess units L1 and L3 with L1 representing tephric loess of the LGM (encapsulating KOT) and L3 being correlated with Porewa loess of the Rangitekei Valley (and correlated with stadial (cold) conditions of MIS 4) (Kennedy 1988, 1994).

In Northland, as well as being preserved as a layer in lacustrine and other settings (e.g., Newnham et al. 2004, 2017), Rotoehu Ash occurs as isolated or semi-continuous cream-colored sandy clasts, termed "cream cakes" by ANZ pedologists, in a fine aeolian sand matrix or overlying aeolian fine sands and silts. The term "cream cakes," first used by Healy (1964) and Neall (1972), represents partly weathered yet coherent remnant "clasts" of ash (sand)-sized material of the c. 45 cal ka Rotoehu Ash, this correlation confirmed by its cummingtonite-rich mafic mineralogy (e.g., Pain 1975; Hogg and McCraw 1983; Froggatt and Lowe 1990; Hopkins, Lowe, et al. 2021).

In Taranaki, millimetre-thick Rotoehu Ash occupies an identical stratigraphic position within a reddish-brown unit 3 (Sr3) developed into a loess-like yellowish brown soil unit (Sy3) that contains a prominent peak of aerosolic (loessic) quartz that was derived from the adjacent North Taranaki continental shelf then exposed by lowered sea level (Alloway, Stewart, et al. 1992).

6.7.5 | Rangitawa Tephra

Introduced earlier, Rangitawa Tephra has an FT-weighted mean age of 345 ± 0.12 ka BP ($n = 9$) (Kohn et al. 1992; Alloway et al. 1993; Pillans et al. 1996), and its age is further confirmed by two orbitally tuned calibrated age estimates of 340 ± 0.07 ka BP from deep-sea cores (DSDP Site 594, Nelson 1988; SO-36-61, Hesse 1994) (see Figure 15A) . Orbital (or astronomical) tuning involves correlating cyclical variations in multiple or "stacked" marine oxygen isotope records with known changes in the Earth's orbital parameters, known as Milankovitch cycles (the timings of which have been tested and confirmed by independent radiometric or age-equivalent dating) (e.g., see Martinson et al. 1987; Pillans 1994; Lisiecki and Raymo 2005; Lowe and Walker 2014). Within these marine cores, Rangitawa Tephra is stratigraphically constrained by several well-established biostratigraphic datums (Black et al. 1988) that place tephra deposition close to the MIS 9/10 boundary. At terrestrial sites located in Whanganui-South Taranaki and Waikato, Rangitawa Tephra occurs within a loess layer with a well developed paleosol (the latter representing alteration during MIS 9) immediately above it

fluvial gravel, Hawke's Bay, eastern North Island. (E) KOT preserved within bedded colluvial fan deposits, McKay's Crossing, Wellington, southern North Island (photo courtesy of Russ van Dissen, GNS Science). (F) KOT within well-bedded glacio-fluvial silts and sands, Howard Valley, northern South Island (Callard et al. 2013). (G) KOT preserved as glass shard concentrations (indicated by asterisks), i.e., as a cryptotephra, associated with the upper part of a buried soil, Saltwater Forest, south Westland. (H) Pale yellowish-brown layer of KOT preserved within organic-rich lacustrine muds from a sediment core retrieved at Galway Tarn, south Westland, South Island, c. 650 km from its eruptive source (photos B, E, F: B.V. Alloway; photo C: D.J. Lowe; photos D, G, H along with associated credits can be found in Alloway et al. 2007). (I) Summary diagram for the period c. 30 to 10 cal ka BP in central and southern North Island, showing the relationship of KOT and Rerewhakaaiti Tephra marker beds with respect to an array of age-equivalent geomorphic elements and proxy records. Eruption volumes are expressed as dense-rock equivalent (DRE), or magma, rather than as loose pyroclastic (tephra) material. Shown at the base of (I) is the NZ-INTIMATE Climate Event (NZce) Stratigraphy spanning c. 30 to 8 cal ka BP, which is based on boundaries derived from the composite stratotype (Barrell et al. 2013) but with the age on Okareka Tephra modified following Peti et al. (2021). Figure modified from Pillans et al. (1993), Manville and Wilson (2004), and Alloway et al. (2025), that in the lattermost reference with permission from Elsevier.

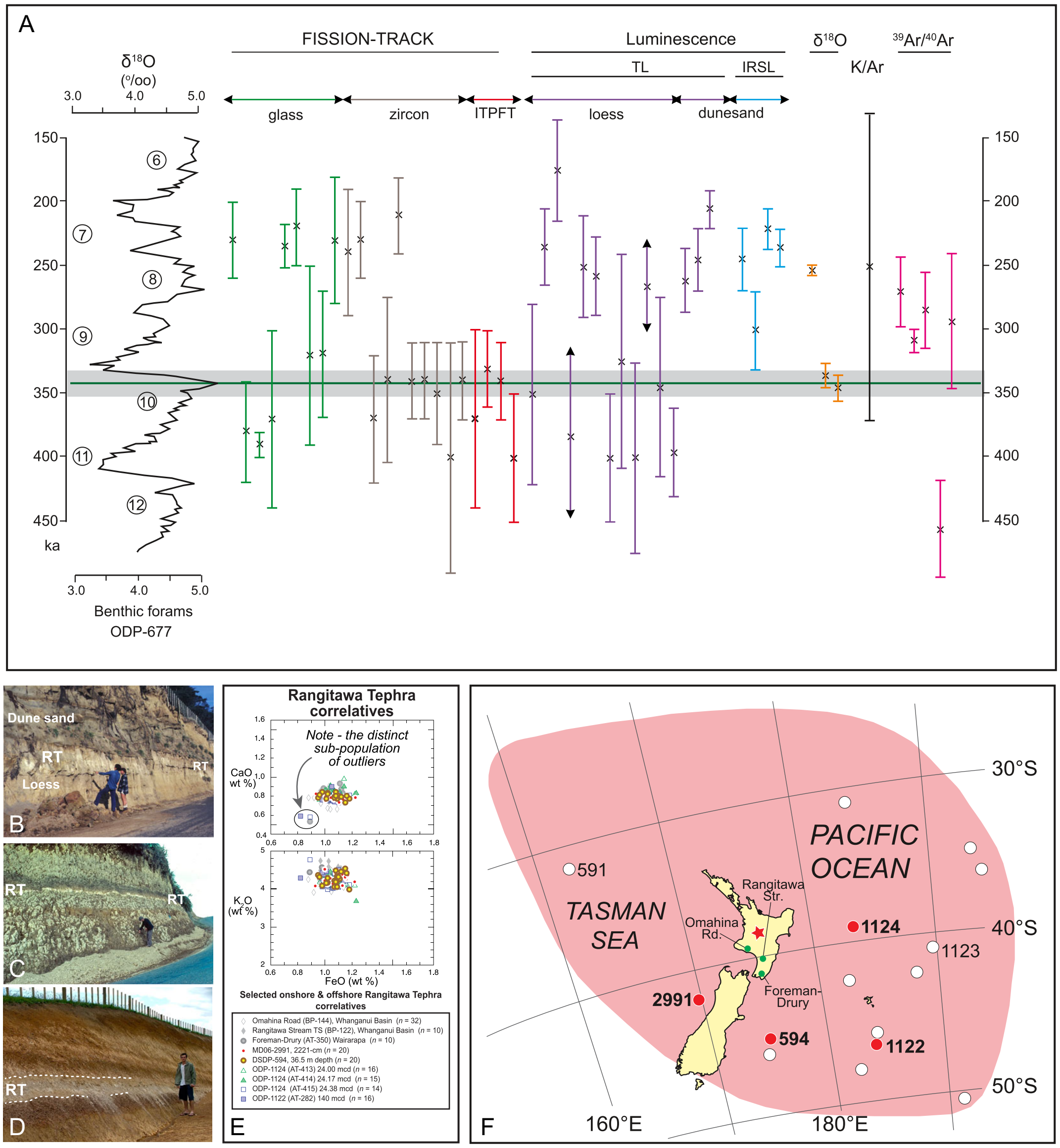

FIGURE 15 | (A) Summary of numerical age determinations on Rangitawa Tephra (RT; 0.345 Ma), with 1 SD error bars plotted. This panel illustrates the substantial effort over the years using many different techniques to resolve the age of the Mt Curl/Rangitawa Tephra—a widespread stratigraphic marker bed occurring within mid-Pleistocene loess successions throughout ANZ and beyond. Figure modified from Pillans et al. (1996) and Alloway et al. (2025). (B) RT (formerly known as Mt Curl Tephra) exposed at the Mt Curl type section bordering the Rangitīkei River valley. Here, the RT occurs between Brunswick Dunesand (above) and Aldworth loess (below) (Milne 1973c). (C) RT showing up as the prominent white layer in a section of weathered tephra and paleosols (darker horizons) at Ball Road, inland South Taranaki (photo: B.V. Alloway) and (D) Gordonton Road near Hamilton, northern North Island (photo: D.J. Lowe). Note the strongly developed paleosol directly overlying RT at both localities, representing pedogenesis during MIS 9 (see also Figure 16B). At (D) Rangitawa Tephra unconformably overlies a prominent and very strongly weathered buried paleosol older than 0.77 Ma on the uppermost Kauroa Ash beds (Lowe, Tippett, et al. 2001; Lowe 2019). (E) Selective major element analysis (e.g., FeO vs. CaO, FeO vs. K_2O, in wt%, normalized to an anhydrous basis) of glass shards acquired through electron microprobe analyses reveal two compositional domains within the elemental field (a dominant tightly clustered population with a sub-population of clustered outliers) facilitating tephra identification and correlation. Note the elemental correspondence between samples acquired from both terrestrial and marine sites (see F for locations). (F) Minimum known extent of Rangitawa Tephra (from Alloway et al. 2025; see also Matthews et al. 2012). Figures A, C, D and F modified from Alloway, B.V., Lowe, D.J., Jensen, B.L.J. and Plunkett, G. (2025). Tephrochronology. In Elias S.A. (editor), Encyclopaedia of Quaternary Science, 3rd edition, Vol. 5, Fig. 18 (p. 797), with permission from Elsevier.

(Pillans 1988; Palmer and Pillans 1996; Pillans et al. 1996; Lowe, Tippett, et al. 2001) (see Figures 15B–D and 16A,B).

Rangitawa Tephra, like KOT and Rotoehu Ash, is a geochemically distinctive unit that enables its identification and correlation in both terrestrial and marine realms (such correlations normally including stratigraphic/chronological as well as geochemical information). Selective major element (e.g., FeO versus CaO) compositions of glass shards acquired through electron microprobe analyses reveal two compositional domains within the elemental field (a dominant tightly clustered population with a subpopulation of clustered outliers) (Figure 15E). Although the genetic significance of these domains is currently

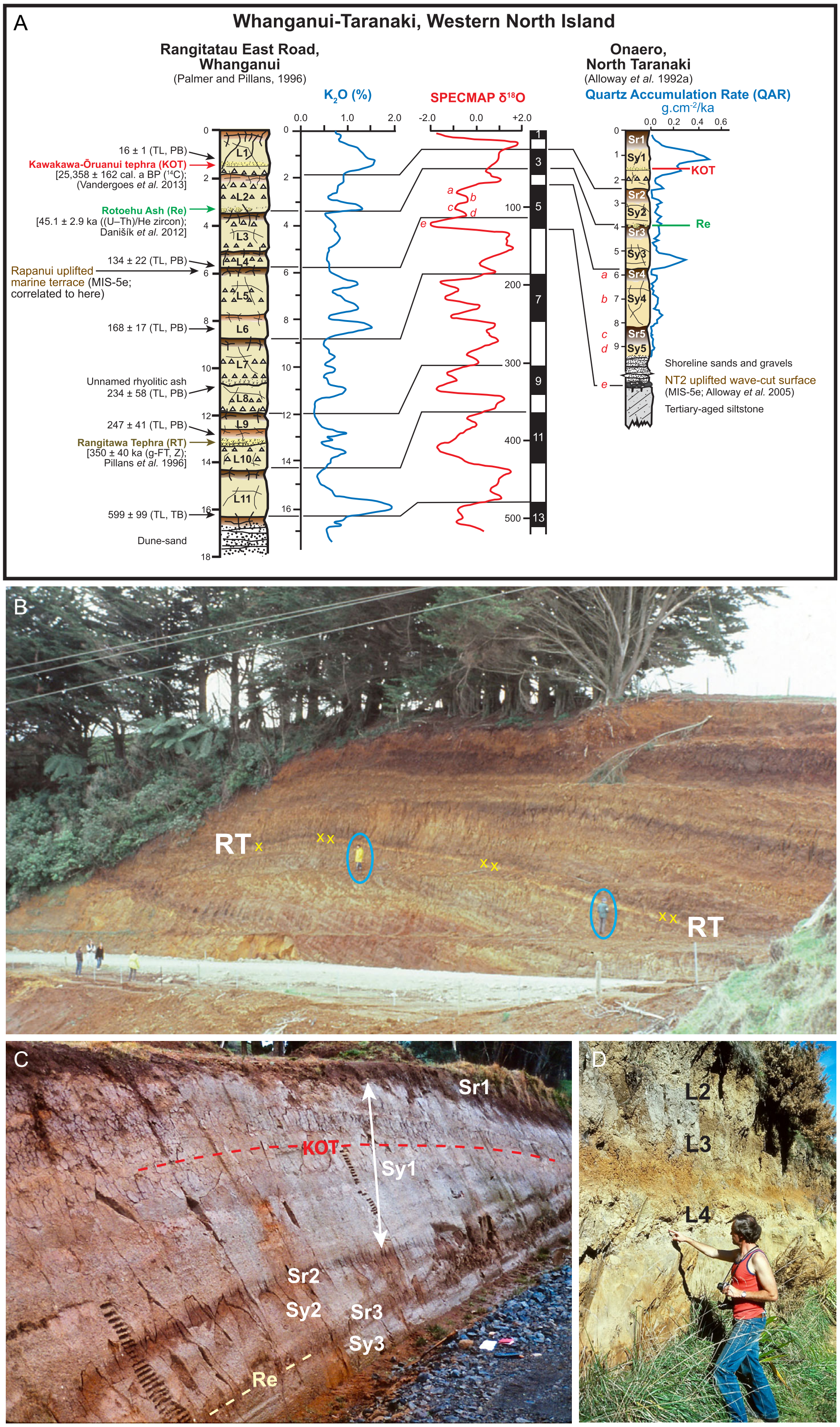

FIGURE 16 | (A) Stratigraphic loess-dominated profile at Rangitatau East Road, Whanganui (Palmer and Pillans 1996), and profile of andic beds at Onaero, North Taranaki (Alloway, Stewart, et al. 1992) that shows multiple couplets of reddish-brown (Sr-) and yellowish brown (Sy-) soil horizons indicating repeated *Ub-Td* soil formation phases relating to variable climate through the Quaternary (see text). Accompanying the Rangitatau East section and core are potassium variations with depth expressed as K_2O (± 0.1 wt%) and SPECMAP $\delta^{18}O$ curve and isotope stages (Imbrie et al. 1984). K_2O content provides a good proxy of environmental change, especially weathering and leaching: maximum K_2O values correspond with major cold periods of the $\delta^{18}O$ curve, while minimum values correspond to loss by leaching during the warmest (and wetter) periods of greatest duration (Palmer and Pillans 1996). Both successions are punctuated by the occurrence of rhyolitic tephra horizons sourced from the central North Island that have provided independent chronological control. Such successions with chrononological tie-points facilitate direct correlation to the marine isotope

uncertain (they may represent different magma types: see Harmon et al. 2024), the glass analyses still provide a useful means by which to identify and correlate the tephra. (Note that various aspects of tephra composition and correlation for ANZ are described in detail by Hopkins, Lowe, et al. 2021 and Hopkins, Bidmead, et al. 2021.)

Rangitawa Tephra has been mineralogically, chemically, and chronologically linked to the Whakamaru Group ignimbrites (Froggatt et al. 1986; Wilson et al. 1986; Kohn et al. 1992; Harmon et al. 2024), and the eruptions of these are associated with the collapse of the Whakamaru Caldera (Wilson et al. 1986, 2009; Downs et al. 2014). The Whakamaru super-eruption, with an $^{40}Ar/^{39}Ar$ age of 349 ± 4 ka BP (± 2 SD), is volumetrically the largest eruption known to have occurred in the ~2 to 3 Myr history of the Taupō Volcanic Zone (Brown et al. 1998; Prentice et al. 2025). Ash-fall was dispersed across the Pacific Ocean southeast of eruptive source (Froggatt et al. 1986) including on Chatham Islands (Holt et al. 2010; Matthews et al. 2012; Miller et al. 2026). Significant deposits have also been recorded in multiple dispersal directions away from eruptive source with occurrences reported in Taranaki (Alloway 1989; Naish et al. 1996); Waikato (Lowe, Tipppett, et al. 2001); in the Tasman Sea (Nelson et al. 1985); in Bay of Plenty (Manning 1996; Harmon et al. 2024); and in Hawke's Bay, Wairarapa, and Manawatū/Wellington (Figure 15F).

6.8 | Loess Accumulation Rates During the eLGM in ANZ

The widespread distribution of KOT across much of ANZ provided an opportunity for Eden and Hammond (2003) to estimate loess accumulation rates, expressed as mass accumulation (flux) rates (MAR), during the eLGM. Loess MAR (in g cm^{-2} yr^{-1}) was calculated as follows:

$$\mathrm{MAR} = [D/T]\rho$$

where D is the depth of loess increment in cm, T is the time for accumulation of loess increments in years, and ρ is the measured or estimated bulk density of the loess increments in t m^{-3} (Almond and Tonkin 1999).

During the eLGM, MARs were generally within the range 70–150 g cm^{-2} yr^{-1}, but locally could be as high as 360 g cm^{-2} yr^{-1} (Eden and Hammond 2003). In southern Westland, where dissolution, leaching, and weathering have affected preservation, MARs were slower, from 25 to 76 g cm^{-2} yr^{-1} (Almond and Tonkin 1999). In the eastern Waikato, Lowe (2000) estimated MARs for loess-dominated accessions (including some distal tephra) essentially for the LGM period to range from approximately 20–78 g cm^{-2} yr^{-1}. Contemporary (modern) MARs of 40–100 g cm^{-2} yr^{-1} were determined for distances of 1.75–0.4 km downwind of the Rakaia River in eastern South Island (Eden and Hammond 2003). These MARs for ANZ are somewhat comparable with those in China, although the highest rates in China are around double those in ANZ. In much of Europe, however, MARs are greater by an order of magnitude: the highest European MARs range from 1710–3803 g cm^{-2} yr^{-1} and the lowest from 325–945 g cm^{-2} yr^{-1} (Rousseau et al. 2021).

Expressed in depth units, Eden and Hammond (2023) estimated rates of ~3–10 mm/century based on 18 sites, with faster rates ~15–25 mm/century where deposition was enhanced by turbulence (Lowe et al. 2015). In southern Westland, rates were slow, only ~4–12 mm/century (Almond and Tonkin 1999), similar to those for tephric loess in eastern Waikato of ~3–8 mm/century. These figures can be compared with Holocene loess accumulation rates, which vary with proximity to sources, and they range from ~60 mm/century within 5 m of a flood plain to ~3 mm/century at a distance of 2 km away from it (Lowe et al. 2015). In comparison, the highest accumulation rates in Europe range from 104–231 mm/century whereas the lowest rates are 14–57 mm/century; rates for China broadly are <100 mm/century (Rousseau et al. 2021).

7 | Stratigraphy and Correlation: An ANZ Overview

Many loess sequences in ANZ consist of successions of loess, commonly altered to some degree by pedogenesis during developmental upbuilding, alternating with intervening and more pedogenically developed paleosols marking a cessation or minimal rate of loess accession (forming multisequal loess-soil/paleosol successions as described earlier). In many areas of ANZ, little or no loess is accumulating today—although contemporary loess is generated from wide braided river-beds such as Rakaia River (east coast South Island: see above) and Haast River (west coast South Island: Eger et al. 2012). However, as described in the section above, loess accumulation was widespread and relatively rapid during the eLGM/LGCP (c. 30–18 ka BP) as a result of the intensification of the south westerly wind (SWW) system, colder drier climate, and expanded loess sources (Alloway et al. 2007; Newnham, Vandergoes, et al. 2007; Newnham et al. 2013; Ryan et al. 2012; Barrell et al. 2013; Shulmeister et al. 2019).

The last major phase of regional loess accumulation in the North Island ceased in places around or soon after c. 17.5 cal ka BP

records (e.g., Alloway et al. 1988; Alloway, Stewart, et al. 1992; Pillans 1988, 2017) that would otherwise be based on relative age constraints and counting loess-paleosol couplets back from present day. (B) Rangitawa Tephra (RT) preserved within a multisequal loess-paleosol succession exposed at Rangitatau East Road, Wanganui (Palmer and Pillans 1996) (photo: A.S. Palmer). Elliptical circles indicate persons standing immediately adjacent to the Rangitawa Tephra exposed in the section (for scale purposes and additionally indicated by yellow x symbols). Such successions form the dominant cover-beds on uplifted marine terraces in western North Island. (C) The sequence of Sr- and Sy- andic beds exposed at Waitui drilling platform, near Inglewood, Taranaki (Alloway, Stewart, et al. 1992). Here, the morphological expression distinguishing the two types of andic units (Sr- and Sy-units) could not be any clearer. The positions of KOT and Rotoehu Ash (Re) within the sequence are indicated. (D) Hugh Wilde (Soil Bureau and Manaaki Whenua Landcare Research) at Kohi Road, western Whanganui, indicating the boundary between L4 (a Last Interglacial loess deposit) and underlying weathered dune sands and pebbly sands overlying the Rapanui wave-cut platform—the oldest and most widespread Last Interglacial terrace (MIS 5e) of South Taranaki–Whanganui. So far, Last Interglacial-aged loesses have only been recognized in Taranaki–Whanganui and at Tapapa, western Mamaku Plateau. The occurrence of equivalent-aged loess elsewhere in ANZ has yet to be substantiated. Similarly, Last Interglacial loesses have not been so far described in overseas loess successions. Photos C, D: B.V. Alloway.

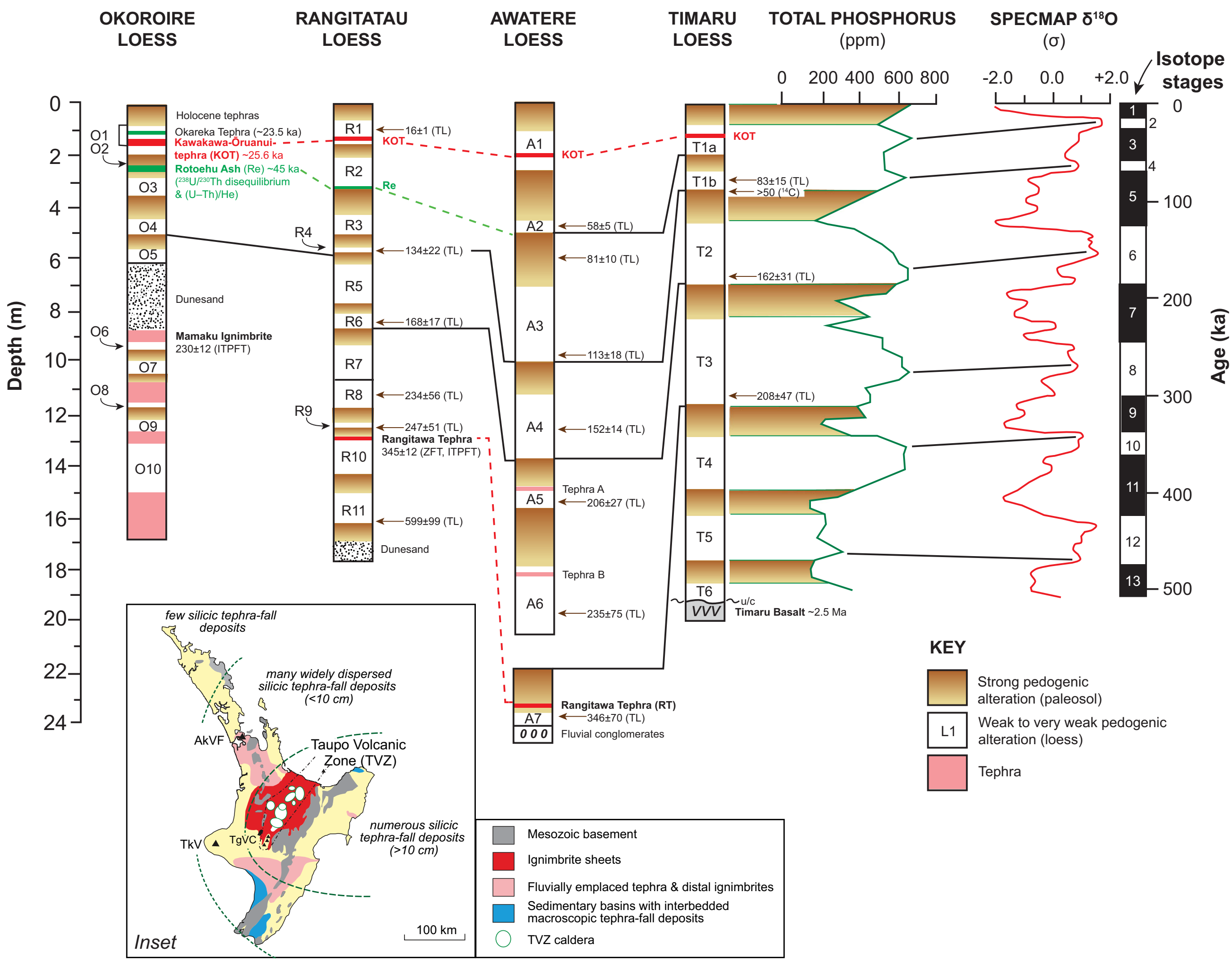

FIGURE 17 | Stratigraphic columns and correlations between four major loess sections in ANZ and possible correlations with the global isotope stratigraphy of deep-sea cores. Stratigraphy from Kennedy (1988), Pillans and Wright (1990), Eden (1987), Eden and Froggatt (1988), and Tonkin et al. (1974). TL ages from Berger et al. (1992, 1994) and unpublished data. Other ages from Shane et al. (1994) [Mamaku Ignimbrite], Vandergoes et al. (2013) [Kawakawa-Ōruanui tephra, KOT], Danišík et al. (2012) [Rotoehu Ash, Re], Pillans et al. (1996) [Rangitawa Tephra, RT], Goh et al. (1978) [Timaru ^{14}C age]. Total P for Timaru section from Runge et al. (1974). Oxygen isotope stratigraphy from Imbrie et al. (1984). Inset: Distribution of Quaternary silicic pyroclastic and associated reworked deposits in North Island to highlight overall tephra occurrence within loess sequences through ANZ. AkVF, Auckland Volcanic Field; TkV, Taranaki Volcano; TgVC, Tongariro Volcanic Centre (modified after Westgate et al. 2013).

(coincident approximately with deposition of Rerewhakaaitu Tephra of the same age) through to about 14 cal ka BP in other locations, the time of deposition of the 14.0 cal ka BP Waiohau Tephra (Pillans et al. 1993; Lanigan 2012; Lowe et al. 2013).

The stratigraphies of four regionally significant loess sections, with TL and other ages, are shown in Figure 17. Loess layers are numbered from youngest to oldest in each section using a letter prefix appropriate to the section. Correlations between the sections are indicated, as well as correlations with the MIS stratigraphy of deep-sea cores. The numbers and thicknesses of tephras decrease rapidly southwards in the loess sections with increasing distance from sources. At Okoroire, in the eastern Waikato area, primary tephra-fall deposits comprise some 30% of the total sequence thickness, including KOT, which is a key tephra marker-bed and isochron in all four sections. A tephra at ~9-m depth in the Okoroire section is likely the tephra-fall equivalent of the Mamaku Ignimbrite dated at 230 ± 12 ka (Shane et al. 1994) or 220 ± 10 ka (Houghton et al. 1995). The c. 45 cal ka BP Rotoehu Ash is identified in both the Okoroire and Rangitatau East sections. The c. 345 ka BP Rangitawa Tephra is identified in both the Rangitatau East and Awatere sections. Tephras A and B in the Awatere section remain uncorrelated.

At Timaru, KOT is present as a cryptotephra comprising glass shards in the 20–200 μm size fraction of the loess (Eden and Froggatt 1988). Glass shards are distributed in small amounts in the loess down to 1.3 m in depth, with a maximum glass concentration near 1.1 m. At a depth of 2.06 m, Eden and Froggatt (1988) recognized a paleosol within loess T1 associated with a zone of low total phosphorus values attributed by Runge et al. (1974) to a decrease in the rate of loess accumulation. Runge et al. (1974), supporting earlier findings of Childs and Searle (1975) that P, K, Ca, and Mn are most useful in identifying paleosols (on the basis of XRF-derived elemental studies on three South Island loess columns), showed that the distribution of total

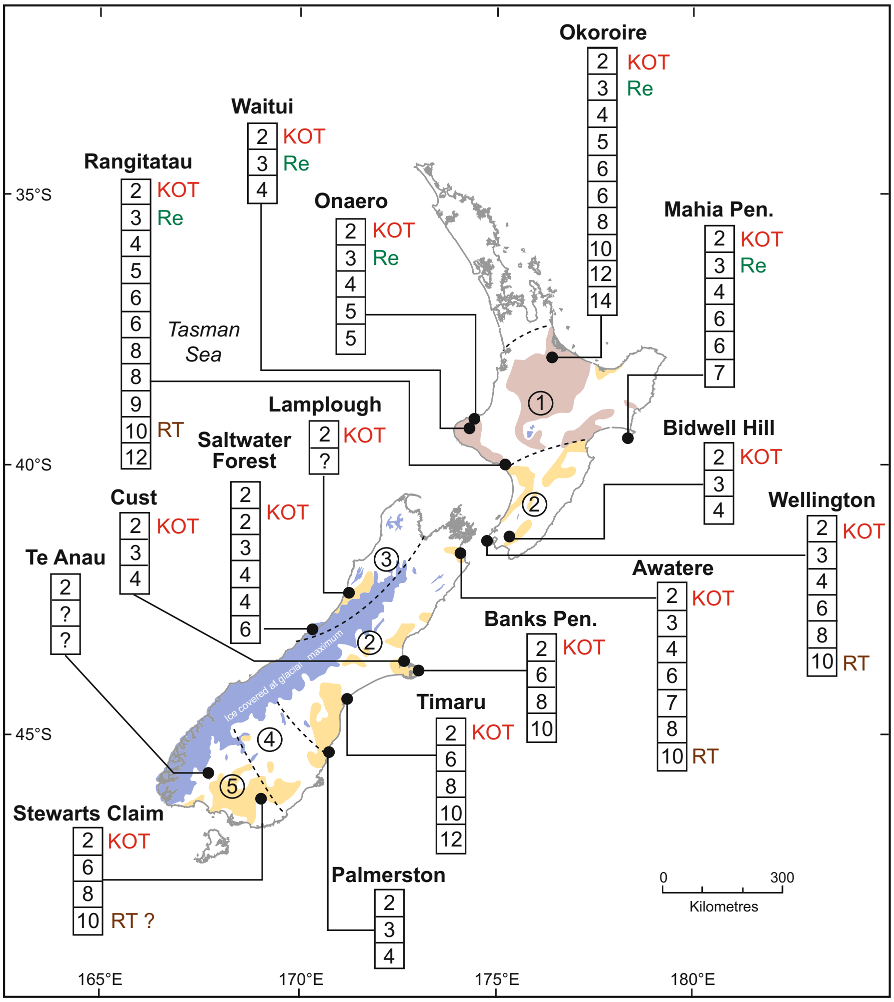

FIGURE 18 | Summary loess stratigraphy for representative regional sections showing marine isotope stage correlations (numbers) for individual loess layers. Loess regions 1–5 (after McCraw 1975) are also indicated (see also Figure 3). Loess stratigraphy after Kennedy (1988) [Okoroire], Berryman (1993) [Mahia Peninsula], Palmer and Vucetich (1989) [Bidwell Hill], Milne and Smalley (1979) [Wellington], Pillans and Wright (1990) [Rangitatau East], Alloway, Stewart, et al. (1992) [Onaero, Waitui], Eden (1987) [Awatere], Milne (1987) [Cust], Griffiths (1973) [Banks Peninsula], Eden and Froggatt (1988) and Tonkin et al. (1974) [Timaru], B.J. Pillans, *unpublished data* [Palmerston, Te Anau], Bruce (1973) and Eden et al. (1992) [Stewarts Claim], Almond et al. (2001) [Saltwater Forest], and Mew et al. (1988a) [Lamplough]. KOT = Kawakawa-Ōruanui tephra; Re = Rotoehu Ash; RT = Rangitawa Tephra.

phosphorus (P) in Timaru loess is a good indicator of paleosols, and hence loess accumulation rate: total P is presumed to be little affected during phases of upbuilding pedogenesis, but experience major redistribution occurring by plant uptake and downward leaching during topdown-pedogenesis-dominated phases to produce P minima in soil B-horizons (see also Muhs 2025, and references therein). A secondary minimum and underlying maximum in the lower part of L1 may represent a slowing of loess accumulation and increased importance of P redistribution characteristic of enhanced topdown pedogenesis in a more clement climate. A TL age of 83 ± 15 ka BP in the lower part of the L1 loess suggests the slowing may correspond with MIS 3. Revised ^{14}C ages of c. 10 ^{14}C ka and >50 ^{14}C ka BP (Goh et al. 1978) bracket the age of loess L1. Earlier ^{14}C ages from the base of loess L1 were in the range of 12–31 ^{14}C ka BP (Tonkin et al. 1974), but these ages were considered unreliable because of contamination. Pollen analyses of peat at the base of L1 (Moar 1973) indicate vegetation consistent with interglacial conditions, presumably MIS 5. Loess L2 must therefore predate the Last Interglacial and is inferred to correlate with MIS 6. A TL age of 162 ± 31 ka BP for loess L2 is consistent with this interpretation.

Paleomagnetic samples from loess layers L4, L5, and L6 are all of normal polarity (B.J. Pillans, *unpublished data*), consistent with an age of less than 770 ka (the age of the Matuyama-Brunhes polarity transition: Haneda et al. 2020). Since the underlying Timaru Basalt is K/Ar dated at c. 2.5 Ma (Mathews and Curtis 1966), there are some 2 million years of time not represented by sediment deposition. Whether loess was deposited in the interval 2.5–0.5 Ma and then subsequently eroded, or there was no loess deposition, is currently unknown.

Representative loess columns showing possible correlations of loess layers at 16 sites throughout ANZ to the MIS record are shown in Figure 18. Clearly, there is no reliable basis here for correlating between sections on a "count-down-from-the-top" basis. Rather, the loess chronology suggests that either there are missing (eroded) layers in some sections (as inferred in Southland by Eden et al. 1992), or there was regionally variable climate coupling, or both.

7.1 | Correlation of Fragmentary Loess Records With Marine Proxy Records

The best opportunity to correlate or reconcile the fragmentary loessial record with higher resolution marine proxy records is attained from cover-beds upon the uplifted marine and fluvial terraces of western and southern North Island, which are conveniently located adjacent to the active Taupō Volcanic Zone. As reported above, various tephras including three key marker beds (KOT, Rotoehu Ash, and Rangitawa Tephra) associated with multisequal loess-paleosol successions have played a fundamental role in establishing chronological time lines that can be fixed to the MIS record. For instance, KOT occurs within the New Zealand LGCP/eLGM (equivalent to NZce-10 of Barrell et al. 2013) of MIS 2, Rotoehu Ash within the MIS 3 interstadial, and Rangitawa Tephra close to the MIS 9/10 boundary (i.e., in late MIS 10). With these three tephra isochrons or tie-lines, other intervening loess-paleosol couplets were then correlated to stadial-interstadial intervals of the MIS based on relative age constraints and counting paleosol-loess couplets back from present day. Wherever possible, these correlations were affirmed by palynological investigations (e.g., McGlone 1985; Newnham and Alloway 2001, 2004); those younger than c. 30 cal ka BP can be related directly to the pollen- and tephra-isochron-based New Zealand Climate Event Stratigraphy of Barrell et al. (2013). The loess-paleosol correlation schemes seemed to be effective for some southern North Island areas (Rangitīkei–Manawatū–Wairarapa), but it quickly became apparent from the cover-bed stratigraphy of Last Interglacial-aged uplifted marine terraces of North Taranaki (NT1 and NT2; Alloway et al. 1988, Alloway, Stewart, et al. 1992, 2005) and South Taranaki–Whanganui (Hauriri, Inaha, and Rapanui; McGlone et al. 1984; Pillans 1988, 1990, 2017) that more than the usual three Last Glacial-aged loess sheets (MIS 2, Ohakea loess; mid-MIS 3, Rata loess; and MIS 4, Porewa loess), pervasively identified throughout southern North Island, were present and that two newly identified andic loess sheets represented aeolian deposition during stadials of the Last Interglacial (MIS 5b and 5d, respectively). Five loess-like andic deposits (Sy-1 to -5) were identified in North Taranaki post-dating the highest sea-level transgression at c. 127 ka BP (MIS 5e), whereas four loess deposits (L1–L4) were recognized on the oldest and most widespread interglacial (Rapanui) terrace of South Taranaki-Whanganui (Wilde and Vucetich 1988; Pillans 1988; Palmer and Pillans 1996) (see Figure 16D). No equivalent-aged loess deposits have so far been identified elsewhere in ANZ apart from those at Tapapa, western Mamaku Plateau (Kennedy 1988; Kimber et al. 1994; Newnham et al. 1999; Lowe et al. 2012). Similarly, Last Interglacial (MIS 5b and 5d) loess has not been described in overseas successions in continental and/or desert settings, although they are probably likely to occur in other southern mid-latitude areas with high andesitic tephra accretionary flux (e.g., in north-western Patagonia).

A correlation summary of loessial cover-bed deposits and associated landforms from western and central regions of ANZ, including Westland, South Island, Whanganui-Taranaki, and Taupō Volcanic Zone (TVZ) extending over the last 0.5 million years is presented in Figure 19.

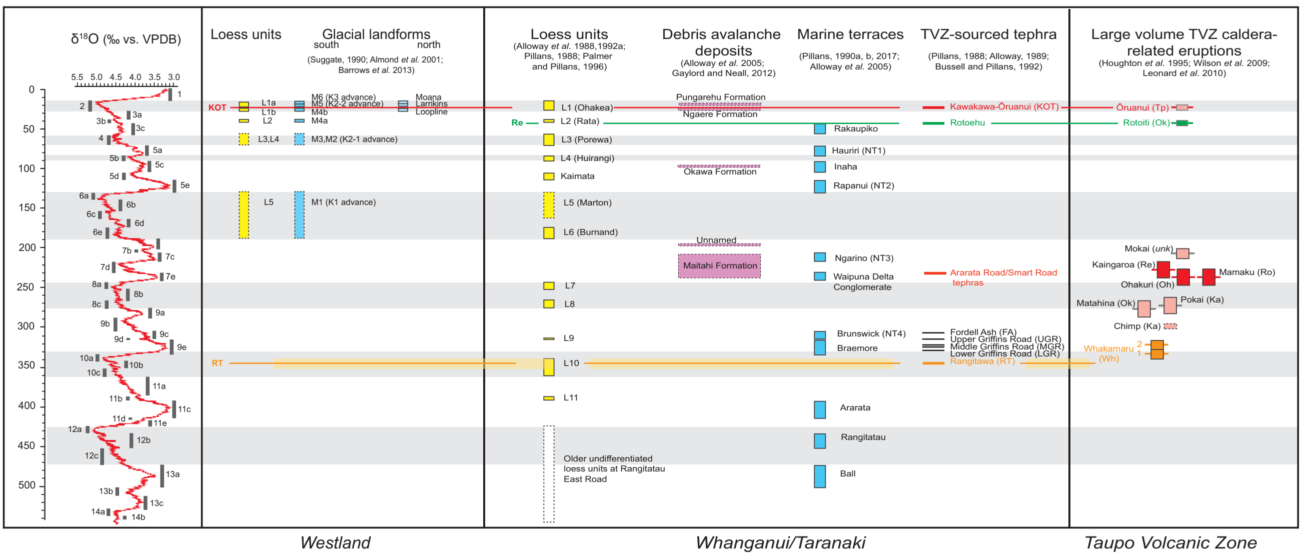

FIGURE 19 | Correlation summary of loessial cover-bed deposits and associated landforms from western and central regions of New Zealand, including Westland, South Island (Suggate 1990; Almond 1996; Almond and Tonkin 1999; Almond et al. 2001, Barrows et al. 2013), Whanganui-Taranaki (Alloway et al. 1988; Alloway, Stewart, et al. 1992; Alloway et al. 2005; Palmer and Pillans 1996; Pillans 1983, 1988, 1990a, 1990b, 2017; Pillans et al. 1993, 1996), and Taupō Volcanic Zone (TVZ) extending over the last 0.5 Myrs (Houghton et al. 1995; Wilson et al. 2009; Leonard et al. 2010). Dated tephra marker beds sourced from the TVZ occurring within these regions are indicated as coloured horizontal lines with 1-SD age ranges indicated. In panel at far left, the $\delta^{18}O$ record is from the LR04 stack of Lisiecki and Raymo (2005), while the scheme of lettered marine isotope substages is from Railsback et al. (2015); horizontal zones mark glacials (grey) and interglacials (white). In panel at far right, colours used for each group of eruptives are simply for clarity. Figure modified from Alloway, B.V., Almond, P.C., Moreno, P.I., Sagredo, E., Kaplan, M.R., Kubik, P.W., and Tonkin, P.J. (2018). Mid-latitude trans-Pacific reconstructions and comparisons of coupled glacial/interglacial climate cycles based on soil stratigraphy of cover-beds. Quaternary Science Reviews 189, Fig. 12A (p. 72), with permission from Elsevier.

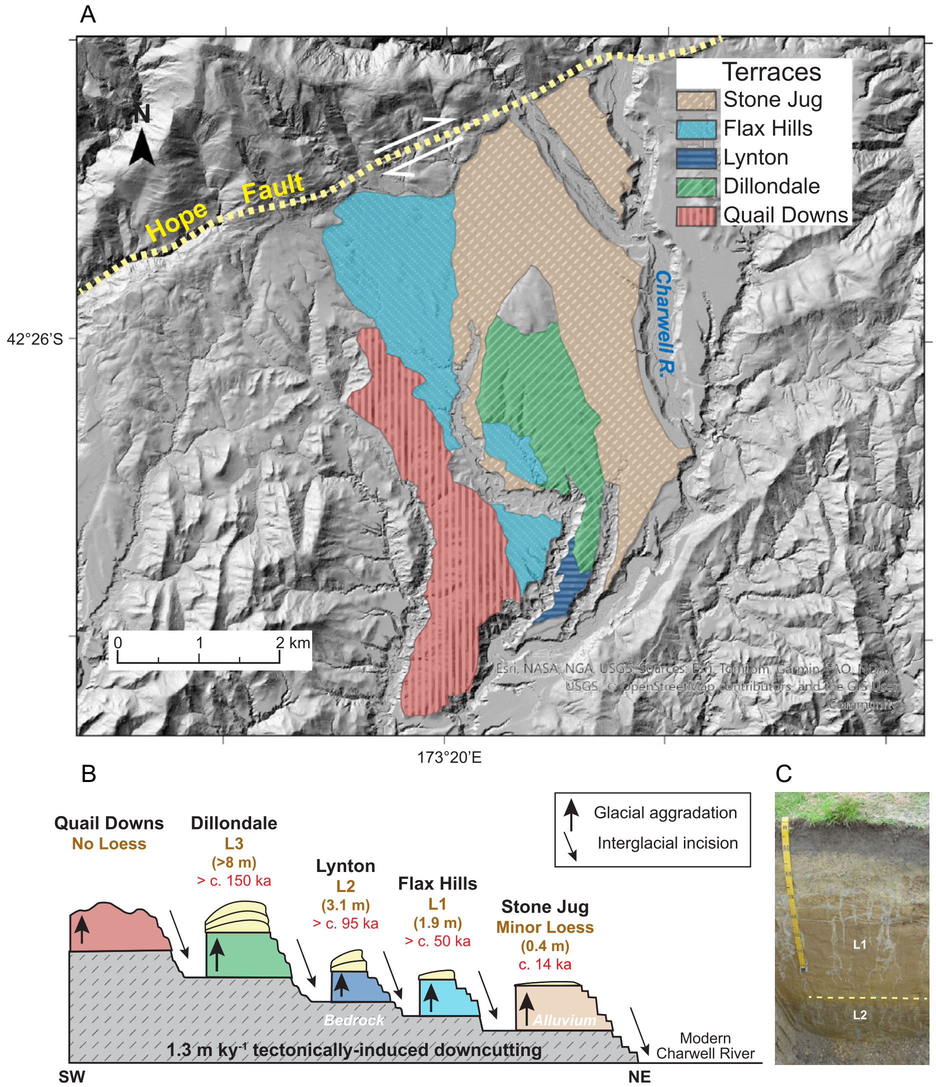

FIGURE 20 | (A) Late Quaternary aggradation (fill) surfaces underlain by a shaded relief model of the Charwell Basin, a 6 km-wide structural depression to the immediate south of the Seaward Kaikoura Range in north-eastern South Island. The terrace treads (sequentially coloured), assumed to have been originally planar, are increasingly dissected and have greater relative relief with increasing age. The location of Hope Fault and its sense of motion are indicated (from Rattenbury et al. 2006). Hillshade model sourced from New Zealand LiDAR 1 m DEM, Land Information New Zealand, downloaded 14/9/2025. (B) Model of terrace formation within Charwell Basin based on Bull (1991), Tonkin and Almond (1998), and Hughes (2008) showing the number and thickness of loess sheets systematically increasing with increasing terrace age, but with loess absent on the oldest erosionally modified valley fill (Quail Downs). A high rate of right-lateral slip along the Hope Fault is responsible for preserving cold-climate valley fills and associated fill terraces in the basin by translocating them away from the locus of erosion and deposition associated with the river channel so that terraces become progressively older to the southwest. Figure modified from Hughes et al. (2010). (C) A Fragic Perch-gley Pallic (NZSC) soil profile (equivalent to Aquic Fragiudalf in *Soil Taxonomy*) situated on a Dillondale terrace interfluve showing two of the three loess units recognized upon this aggradational terrace (photo: P.C. Almond). Figures 20A,B, modified from Hughes, M.W, Almond, P.C., Roering, J.J., and Tonkin, P.J. (2010). Late Quaternary loess landscape evolution on an active tectonic margin, Charwell Basin, South Island, New Zealand. Geomorphology 122, Fig. 2 (p. 297), with permission from Elsevier.

8 | Loess Occurrence Associated With Landscape Response to Climate-Tectonic Controls

The chronological relationships of loess with the surfaces it mantles are important for determining rates of uplift and deformation (Berryman 1993; Berryman et al. 2000; Ryan et al. 2021) as well as a variety of landscape responses to Quaternary climate and sea-level change, or even "extreme" geological events. An example of the latter uses OSL-dated loess to help determine that large imbricated boulders underlying it on a MIS 5 marine terrace on the Otago coast were emplaced by a tsunami (Kennedy et al. 2007). Similarly, occurrences of loess, in association with tephra beds straddling fault scarps, have been useful to determine the timing and size of surface fault ruptures (e.g., Berryman et al. 2022; see Figure 4E).

Studies of fluvial terraces and their cover-beds have traditionally been viewed from a climate-controlled, geomorphological perspective (e.g., Pillans 1991, and references therein), but over the last two decades, the role of other controls such as tectonics and sea level (or some other local base level) has started to be better understood (e.g., Litchfield and Lian 2004; Litchfield and Berryman 2005). Two areas of ANZ in particular where loess has been used to great effect in deciphering geomorphic responses to both climate and tectonics are, first, at Charwell, inland Kaikoura, north-east South Island (Bull 1990, 1991; see Figure 4F), and, second, within catchments of eastern North Island (Litchfield and Reiser 2005; Litchfield and Berryman 2005) (Figure 10).

The stream terraces of the 40 km^2 Charwell Basin provide an exemplar of fluvial system response to climatically forced changes in sediment supply and tectonic effects on local base level. The Charwell catchment straddles the Hope Fault, which is an active dextral fault within the Marlborough Fault System (Rattenbury et al. 2006). Right lateral displacement of c. 20 mm yr^{-1} on the fault (Khajavi et al. 2016) progressively dislocates older valley fills in the basin from the mountainous catchment outlet, and c. 1.3 mm yr^{-1} uplift in the basin (Bull 1991) serves to raise the terraces formed on them above subsequent valley fills. Accordingly, older fill (aggradation) terraces are progressively displaced to the north, uplifted, and dissected (Figure 20). The number of loess sheets mantling fill terraces increases with age (maximum loess depth in parentheses): Stone Jug 0 (0.4 m), Flax Hills 1 (1.9 m), Lynton 2 (3.1 m), and Dillondale 3 (>8 m). However, the rolling to hilly surface of the oldest valley fill—Quail Downs—has no loess (Figure 20). The chronology of these loess sheets is poorly constrained, with only the occurrence of KOT in the top one third of L1 (at about 0.8 m depth as a cryptotephra, i.e., glass-shard maximum concentration) providing a definitive isochron (25.6 cal ka BP). As fill terraces become older, more dissected, and with more integrated drainage systems, the spatial complexity of loess-sheet preservation and thickness increases to reach a maximum on the Dillondale surface but then declines to the Quail Downs surface where all loess appears to have been eroded.

The preservation of loess in relation to the evolving topography on the Dillondale terrace provided an opportunity for a research group including Matthew Hughes, Josh Roering, Peter Almond, and Philip Tonkin, to explore mechanistically the co-evolution of loess and topography in a setting of tectonically driven base-level fall. They calibrated a linear slope-dependent model of soil transport on hillslopes using three approaches: (1) the change in thickness of loess above KOT in relation to hillslope curvature (Roering et al. 2002); (2) transient numerical modelling of the dilution of glass shards of the KOT cryptotephra (Roering et al. 2004); and (3) infilling rates of a gully using KOT and the Pleistocene–Holocene boundary (based on phytoliths) as isochrons (Hughes, Almond, et al. 2009). Together, these studies not only determined values of the hillslope diffusivity, but importantly also showed that the diffusivity, which quantifies the efficiency of diffusive soil transport per hillslope gradient, increased from the Pleistocene to the Holocene by a factor of nearly 2. This finding runs counter to many assumptions about the effect of climate and vegetation on hillslope erosion. Hughes, Almond, et al. (2009) attributed this increase in soil transport during the Holocene to the increase in vigour of soil bioturbation including tree throw beneath forest versus Pleistocene grassland. Hughes et al. (2010) then tested the calibrated soil transport model's ability to predict loess preservation on the Dillondale and Quail Downs terraces. They derived a critical hillslope curvature, factoring in the time/climate-dependence of the hillslope diffusivity, above which the full thickness of L1 should be absent (erosion rate >time averaged loess accumulation rate). The model satisfactorily predicted loess presence/absence on the Dillondale surface. However, it failed to predict the complete absence of loess on the older Quail Downs surface, thus suggesting processes other than post or syn-depositional soil creep are at play in determining loess preservation.

In eastern North Island, four fill terraces (T1–T4, see also Figure 10) can be correlated between catchments, based on loess and tephrostratigraphy as well as numerical age control via ^{14}C and OSL dating (Litchfield and Berryman 2005). This terrace-catchment correlation suggests that the terraces have formed in response to the same external (climate) control (e.g., Eden et al. 2001). However, the preservation of a flight of terraces (e.g., older terraces not buried by successive aggradation events), and the spacing differences between equivalent-aged terraces within different catchments along the North Island's East Coast, is clearly a function of variable tectonic controls. Litchfield and Berryman (2005) also found that rates of uplift determined the upstream position of the intersection point between steeply graded LGM aggradation terraces and more gently sloping post-glacial river terraces. Thus, tectonics also determines the legacy of climatic versus eustatic sea (base level) control along the forearc of the Hikurangi Subduction Margin.

9 | Concluding Remarks: Prospects

Loess studies in ANZ have always had a degree of ascribed national importance in terms of the mapping and characterization of loess, especially for understanding the distribution and productivity of extensive areas of soils used for farming, horticulture, and viticulture, and, equally, in recognizing the intimate stratigraphic and spatial connection of loess (and associated tephra isochrons) and the evolution and shaping of the landscape of ANZ during global climatic change, and active tectonism, of the Quaternary.

As with other disciplines in the geosciences, much remains to be done in both field and laboratory. Unfortunately, numbers of geoscientists including pedologists with a good understanding of loess and soil stratigraphy in ANZ have been dwindling over the years through retirements, redundancies, or relocations—perhaps a less-than-optimal outcome all round considering the longevity of loess studies (~150 years) and the substantial contribution that such geoscientists have made to ANZ's scientific understanding and economic prosperity. Despite shifts in research priorities resulting in employment changes affecting the scientific community, initiatives, including the development of Smap (https://smap.landcareresearch.co.nz/), clearly indicate that the show goes on. The Smap digital soil-mapping platform is based on an arsenal of technological innovations including remote sensing, LiDAR-based digital elevation models, and digital soil mapping together with pedotransfer functions residing within a complex inference engine to derive important soil accessory properties such as soil water holding capacity, field capacity, and hydraulic conductivity amongst many. Smap incorporates decades of hard-won legacy soil mapping data and is intended to support current and future sustainable development objectives.

Laboratory avenues for improving our understanding of loess include refining mineral magnetic and luminescence techniques (including potentially targeting fine-grained fractions in luminescence dating) that could resolve some of the difficulties and ambiguities of the loess-soil/paleosol succession (e.g., Berger et al. 2002; Marx et al. 2026) that currently make many successions problematic to interpret and date (particularly in the South Island). Bayesian hierarchical age modeling for single-grain optical dating is one potential new avenue. High-resolution phytolith, grain size, and elemental analyses (e.g., P and K_2O) might allow spatial inconsistencies to be resolved as well as better delineate down-profile paleosols within multisequal successions. Similarly, attempting to detect, characterize, and correlate (identify) more distal cryptotephras within South Island loess would enable the more precise chronostratigraphic correlation of such loess to deposits of the North Island. An improved chronology would potentially enable millennial-scale climate variations to be identified and correlated, such as those derived from detailed, high-resolution multidisciplinary studies of European loess sequences in which paleosols and weakly pedogenically altered horizons have been correlated with Greenland interstadials (Dansgaard-Oeschger events) (Rousseau et al. 2017, 2021).

It is our opinion that loess studies in ANZ provide an exemplar of the continuum of inter- and multidisciplinary learning, knowledge extension and progression involving distinctive but modest personalities, intergenerational connections, and the associated transfer of knowledge. Past and present loess research achievements and practitioners are acknowledged and applauded, and, in championing those tasked with taking the discipline forward, we trust in the spirit of "continuous fellowship in science that goes back to its origins. Such fellowship derives largely from the passing on of philosophical attitudes and absolute standards of truth from great scientists to those who learn from them." (Lee 1976).

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