Quaternary Science Reviews 189 (2018) 57–75

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

# Mid-latitude trans-Pacific reconstructions and comparisons of coupled glacial/interglacial climate cycles based on soil stratigraphy of cover-beds

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ARTICLE INFO

*Article history:*
Received 19 December 2017
Received in revised form
6 April 2018
Accepted 6 April 2018

*Keywords:*
Tephra
Andic
Loess
Quaternary
Multisequal soils
Developmental upbuilding
Topdown weathering
Southern Chile
Northwest Patagonia
South Westland

ABSTRACT

South Westland, New Zealand, and southern Chile, are two narrow continental corridors effectively confined between the Pacific Ocean in the west and high mountain ranges in the east which impart significant influence over regional climate, vegetation and soils. In both these southern mid-latitude regions, evidence for extensive and repeated glaciations during cold phases of the Quaternary is manifested by arrays of successively older glacial drift deposits with corresponding outwash plain remnants. In South Westland, these variably aged glacial landforms are mantled by layered (multisequal) soils characterised by slow loess accretion and pedogenesis in an extreme leaching and weathering environment. These cover-bed successions have undergone repeated coupled phases of topdown and upbuilding soil formation that have been related to fluctuating cycles of interglacial/warm and glacial/cold climate during the Quaternary. In this study, we recognise multisequal soils overlying glacial landforms in southern continental Chile but, unlike the spodic (podzolic) soil sequences of South Westland, these are of dominantly volcanigenic (andic) provenance and are very similar to multisequal soils of andic provenance that predominate in, and adjacent to, areas of rhyolitic to andesitic volcanism in North Island, New Zealand. Here we develop a soil-stratigraphic model to explain the observed occurrence of multisequal soils mantling dominantly glacial landforms of southern continental Chile. Based on proxy data from southern Chile, we propose that persistent vegetation cover and high precipitation on the western side of the Andes, during colder-than-present episodes tended to suppress the widespread production of glacially-derived loessial materials despite the pervasive occurrence of glacial and glacio-fluvial deposits that have frequently inundated large tracts of this landscape during the Quaternary. Given the lack of loess cover-beds that have traditionally assisted in the relative dating of glacial episodes prior to the Late Quaternary, surface exposure dating techniques could provide another chronological alternative to address this issue. However, there have been two main obstacles to successfully apply this dating technique in Patagonia. First, minimum exposure ages may be obtained on moraines older than the last glacial cycle due to erosion, although dating outwash plains is more robust. Second, on the wet western side adjacent to the Andes, persistent vegetation cover during both glacial and post-glacial times, as well as widespread inundation by volcanic mass-flows, appear preventive. We make a case that soil genesis within this region appears to be dominated by a constant flux of intermittently erupted Andean-sourced tephra which has continued to upbuild soils at the ground surface separated by intervals where topdown weathering processes are intensified. As already demonstrated by New Zealand studies, multisequal soil successions have a clear implied connection to coupled glacial and interglacial climate cycles of the

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https://doi.org/10.1016/j.quascirev.2018.04.005

Quaternary. On this basis, similar sequences in northwest Patagonia provide a relatively untapped archive to enable Quaternary glacial and environmental changes in this pervasively glaciated volcanic region to be constructed.



## 1. Introduction

Southern continental Chile and South Westland, New Zealand, share similar southern mid-latitude positions within the southern westerly wind (SWW) belt and are located immediately westward of north-south trending high (>2000-m above sea level) mountain ranges that form significant topographic barriers influencing precipitation in these regions. At both locations, evidence for extensive and repeated glaciations during cold climate phases of the Quaternary is manifested in the landscape by an impressive array of glacial drift deposits with corresponding outwash plains.

In South Westland (~43°S), densely forested, fluvio-glacial landforms and associated soil cover-bed successions have been studied in detail (Almond, 1996; Almond and Tonkin, 1999; Almond et al., 2001) and this research has contributed to the formulation of a robust regional glacial chronostratigraphic framework (e.g. Nathan et al., 2002; Cox and Barrell, 2007). Across the Pacific Ocean and at similar southern latitude, the configuration and internal architecture of ice lobes in southern continental Chile (northwest Patagonia) is well-known based largely from seminal glacial morphologic maps (i.e. Caldenius, 1932; Andersen et al., 1999; Denton et al., 1999a,b). In contrast to the South Westland glaciated landscape, however, the soil cover-bed stratigraphies that mantle this glacial sequence have not been documented in any detail. The closest related studies are well to the south on the east arid side of the Andes (Douglass and Bockheim, 2006). In our study, we identify the first occurrence of multisequal soils mantling these glacial landforms in southern continental Chile, and develop a soil-stratigraphic model based on soil genesis analogues from South Westland (~43°S) and Taranaki-Wanganui (~39°S) regions in New Zealand, to provide new insights to better characterise and define the glacial chronostratigraphy in southern continental Chile.

## 2. Soil and loess stratigraphy

Soil formation is most often presented as occurring in a top-down sense, i.e., a set of processes acting on a pre-existing body of sedimentary or volcanic deposits or rock (the parent material) such that the degree and depth of alteration increases with time with a downward moving 'front' (Simonson, 1959). Such a scenario is clearly a simplification that nevertheless can hold true for many situations, but in aggrading landscapes where material is intermittently added to the ground surface this conceptual scheme is generally unsuitable (Nikiforoff, 1949; Raeside, 1964). Soils on surfaces incrementally mantled by loess, tephra, overbank deposits, colluvium or other materials form contemporaneously with the geological additions (of sediment, tephra, etc.), i.e. these soils formed by upbuilding (Nikiforoff, 1949). The degree of soil expression is dependent on the relative rates of geological accumulation and pedogenic alteration. Where the former dominates, the latter deposits are minimally modified and the geological material thickens without significant soil alteration. This scenario has been referred to as retardant upbuilding (Johnson and Watson-Stegner, 1987). Where rates of geological accumulation are low but where environmental factors drive high rates of pedogenesis (such as in warm and moist climates) coeval geological accumulation and soil modification result in thick, strongly expressed soils (developmental upbuilding: Johnson et al., 1990; Lowe and Tonkin, 2010; Lowe et al., 2015). An important feature of upbuilding pedogenesis is that all depth increments of an upbuilding soil have experienced processes characteristic of surface horizons, such as melanisation, acidification, intense bioturbation and eluviation. As a surface soil horizon (typically an A horizon) becomes progressively buried by ongoing sediment or tephra accumulation it moves into a zone characterized by subsurface pedogenic processes (e.g. illuviation) and different moisture, temperature and bioturbation regimes. Moreover, features inherited from the near-surface pedogenic processes may modulate subsurface pedogenesis (McDonald and Busacca, 1990). Phases of upbuilding and topdown pedogenesis alternated during climatically modulated loess accumulation in the Quaternary. In relatively dry continental regions with extensive loess sources, loess accumulation in cold periods resulted in retardant upbuilding, which was followed by topdown pedogenesis in the warm periods when loess accumulation effectively ceased. These circumstances yielded the so-called loess-paleosol sequences of Europe, China, North America and the drier eastern side of the Andes (i.e. Chaco–Pampean plains and the northwest mountain environments of Argentina, Paraguay, Brazil, Uruguay, Bolivia; see Zárate, 2003 and references therein). In maritime New Zealand, particularly on the western side of the two main islands, high rainfall results in rapid pedogenesis, and, where loess accumulation rates have been relatively low (Eden and Hammond, 2003), loess accumulation phases resulted in developmental pedogenesis. In these circumstances there is no clear distinction between loess and paleosols; all the loess is altered by pedogenesis to a greater or lesser extent and at times there is pedogenic overprinting between loess sheets (Lowe et al., 2015). On the western side of North Island multiple incremental contributions of weatherable andesitic tephra have enhanced pedogenesis. During cold phases, developmental upbuilding occurred during accumulation of mixed andesitic tephra-aeolian deposits (Sy beds of Alloway et al. (1992a), now manifested as weak-to moderately-structured, yellowish-brown moderately allophanic Bw horizons). Occurring within intervening warm phases, developmental tephra upbuilding continued but the intensity of pedogenesis increased. This scenario resulted in the accumulation of strongly weathered andesitic tephra soil material now manifested as well-structured, reddish-brown highly allophanic Bw horizons (Sr beds of Alloway et al. (1992a)).

On the West Coast of New Zealand's South Island, very high rainfall rates (>3-m annually) promote rapid pedogenesis (Tonkin and Basher, 2001) and consequently the relatively thin loess sheets characteristic of the region are strongly pedogenically altered from the overprint of developmental upbuilding and top-down pedogenesis. In well-drained environments, buried soils are identified by the occurrence of repeating E-Bs horizon pairs (Almond et al., 2001) (Fig. 1). At these sites, mineralisation 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 the New Zealand Soil Classification, (NZSC: Hewitt, 2010), or Eb horizon in 'Soil Taxonomy' (Soil Survey Staff, 2014); see Fig. 1 caption for further explanation). Further addition of loess