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Sediment storage in the Southern Alps of New Zealand: New observations from tracer thermochronology

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ABSTRACT

Careful study of the processes transporting sediment across Earth's surface is critical for robust interpretation of the sedimentary record. Here we consider the specific influence of cyclic glaciation on the export of sediment from mountain landscapes to ocean basins. Using detrital apatite fission-track tracer thermochronology, we present new observations of sediment provenance from six large river systems draining the eastern flank of the Southern Alps, New Zealand. Detrital cooling ages in all six rivers reflect erosion of partially-reset and fully-unreset bedrock exposed in lower catchment areas and indicate that sediment is not currently contributed in proportion to long-term ($>10^6$ yr) erosion patterns. Instead, detrital cooling ages are better explained by either localized erosion along the eastern mountain front or intermontane sediment storage. Of these two alternatives, only intermontane sediment storage is further consistent with suspended sediment flux measurements in eastern rivers. Our observations are consistent with prior interpretations of Holocene sediment retention, and contrast with tracer thermochronology from continental margin deposits indicating sediment was rapidly exported to the continental shelf during the late Pleistocene. Collectively, this evidence argues for a reactive sediment routing system east of the main drainage divide that responds to cyclic glaciation by retaining sediment onshore following deglaciation and evacuating sediment reservoirs offshore during the subsequent glacial advance. Our research demonstrates the importance of intermontane sediment storage on the transmission of high-frequency ($\sim10^{4-5}$ yr) climate signals to offshore sedimentary archives while highlighting a novel approach to detailing sediment provenance in tectonically active mountain ranges.

1. Introduction

Sedimentary archives are some of our most valuable geologic records of environmental change, recording tectonic, climatic and anthropogenic signals over a wide range of timescales (Romans et al., 2016). However, accurate interpretation of environmental change from sedimentary archives requires a rigorous understanding of how environmental signals are transmitted through river systems (Jerolmack and Paola, 2010). Through careful study of sediment transport and deposition we can refine our interpretations of this geologic record, taking critical steps to understand the broader physical and chemical processes that control the habitability of Earth.

In this paper we consider the specific influence of cyclic glaciation on the export of sediment from mountain landscapes to peripheral basins. Environmental signals are primarily transmitted to offshore sedimentary archives through adjustments in river sediment supply (Romans et al., 2016). In non-glaciated landscapes, analytical models (e.g. Simpson and Castellort, 2012) concur that rivers may transmit high-frequency signals offshore with high fidelity. However, observations of widespread sediment storage (Cook and Swift, 2012) and transient (Koppes and Hallet, 2006) sediment fluxes that do not predictably increase with drainage area (Church and Slaymaker, 1989), suggest that in deglaciated landscapes, glaciation may buffer, amplify or distort environmental signal transmission (Jaeger and Koppes, 2016). Here we explore the sediment supply dynamics of six moderately large ($\sim10^3$ km^2) river systems with well-documented evidence of cyclic glaciation in a tectonically active mountain range, the Southern Alps of New Zealand.

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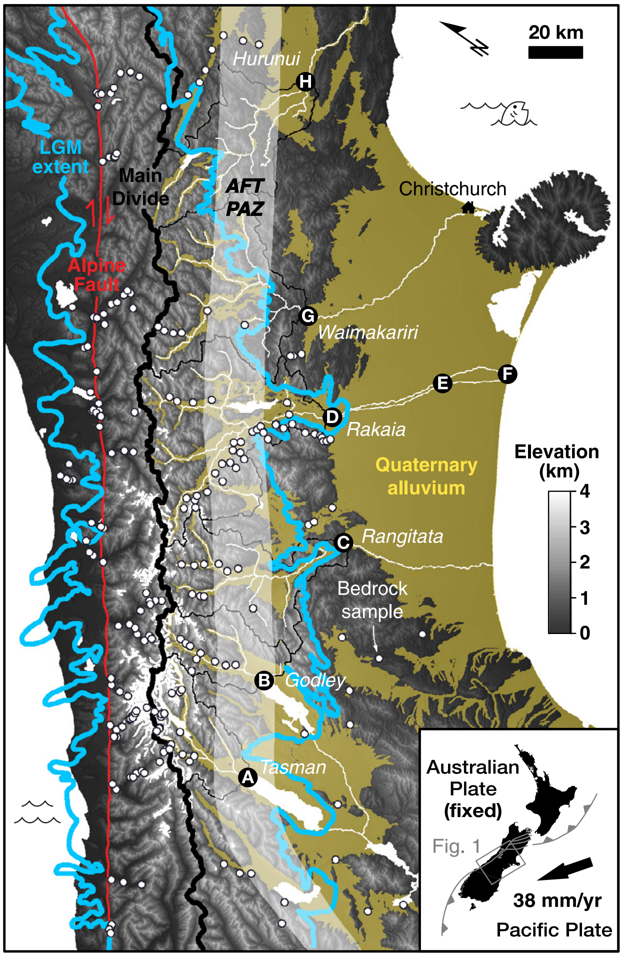

Fig. 1. The Southern Alps are a linear mountain range bound to the west by the Alpine Fault (red line) in the central South Island of New Zealand (see inset figure for location). We collected eight sediment samples from six rivers draining the eastern flank of the mountains where the results of bedrock apatite fission-track thermochronology (white circles) indicates that a partial annealing zone (AFT PAZ) is exposed. The approximate ice extent at the last glacial maximum (Barrell, 2011) is outlined in blue. River drainage areas are outlined in black. Quaternary alluvial deposits mapped at 1:250,000 scale east of the main drainage divide are highlighted in yellow (Edbrooke et al., 2015). Glaciers, lakes, and the mainstem of sampled river systems are shown in white. Bedrock thermochronology is compiled from Kamp et al. (1989), Tippett and Kamp (1993), Kamp (1997, 2001), Batt et al. (2000, 2004), Herman et al. (2009).

1.1. The Southern Alps of New Zealand

The Southern Alps are a northeast–southwest trending mountain range in the central portion of the South Island of New Zealand (Fig. 1). The mountains are uplifted by oblique convergence between the Australia and Pacific plates that developed between 10 to 8 Ma (Kamp and Tippett, 1993; Batt et al., 2004). Today an estimated 25% of plate convergence is expressed as shortening perpendicular to the Alpine Fault, a dextral oblique-slip fault marking the western boundary of Southern Alps topography, with comparatively minor shortening accommodated on antithetic faults in the eastern two-thirds of the mountains (Norris et al., 1990). Bedrock exposed within our study area comprises the Torlesse composite terrane (Edbrooke et al., 2015). This terrane is primarily composed of greywacke and argillite with semischist exposed in the headwaters of each catchment. Heavy mineral analyses indicate that the occurrence of apatite in these basement lithologies is broadly similar throughout the Southern Alps (Smale, 1990).

1.2. Impact of Pleistocene glaciation

The Southern Alps have an extensive history of Quaternary glaciation (Barrell, 2011). Direct evidence of cyclic glaciation is documented in glacial landforms (e.g. moraine sequences) and glacio-fluvial deposits that extend to the early Pleistocene (Barrell, 2011). Glaciation has had a profound influence on Southern Alps topography, shifting drainage divides (Rowan et al., 2013), modifying topographic relief (Herman et al., 2007) and valley form (Herman and Braun, 2006). Although glaciers advanced down both flanks of the Southern Alps during the last glacial maximum (Barrell, 2011, see Fig. 1 for LGM ice extent), only valleys west of the main drainage divide (hereafter Main Divide) have subsequently returned to a dendritic fluvial form (Herman and Braun, 2006). Valleys east of the Main Divide remain shallow, linear and retain over-steepened U-shaped cross sections typical of glacial excavation (Herman and Braun, 2006).

Rivers draining eastern valleys are typically braided (Reinfelds and Nanson, 1993) with estimates of suspended sediment flux based on sediment rating curves (see details in Hicks et al., 2011) ranging between 0.5–2 × 10^6 kg km^{-2} yr^{-1} in large rivers draining to the Pacific Ocean. The intermontane headwaters of eastern rivers are aggradational (Craw et al., 1999), while rivers flowing through the Canterbury Basin (e.g. the Waimakariri, Rakaia and Rangitata rivers) exhibit localized incision along the eastern mountain rangefront and within ∼15 km of the coast (Leckie, 1994). Coastal incision is interpreted to result fluvial adjustment to cliff retreat (Browne and Naish, 2003), but incision along the mountain rangefront reflects localized uplift along antithetic faults (Norris et al., 1990).

Glaciation has also had a profound influence on sedimentation offshore of the South Island. Deep-sea sediment archives from the Canterbury Basin demonstrate that the terrigenous sediment flux from the eastern flank of the Southern Alps has varied in phase with glacial–interglacial (i.e. 10^{4-5} yr) periodicities for the last 750 kyr (Nelson et al., 1985). Cyclic glaciation may regulate the offshore export of terrigenous sediment in a variety of ways. Glaciers erode bedrock more efficiently than rivers (Hallet et al., 1996) and may increase offshore sediment export by increasing sediment production during glacial advances. Glacier retreat exposes low-gradient, U-shaped valleys that may trap sediment in proglacial lakes (Carter, 1990), colluvial deposits (Hales and Roering, 2009) and aggrading rivers (Craw et al., 1999), reducing offshore sediment export following deglaciation. Moreover, a warmer, wetter climate during interglacial periods favors chemical weathering (White and Blum, 1995) and enhances periglacial processes (Hales and Roering, 2009) that comminute or dissolve sediment stored in onshore reservoirs.

In this paper, we take a novel approach to explore the dynamics of sediment supply in deglaciated river systems, detailing sediment provenance at the catchment scale with detrital apatite fission-track tracer thermochronology. This approach allows us to explicitly test the hypothesis that sediment is contributed in proportion to long-term (>10^6 yr) erosion patterns, and consider alternative hypotheses invoking sediment storage or localized incision that better explain our observations. To consider the broader influence of glaciation on offshore sediment export, we compare our observations to similar results from shelf sediments deposited during late Pleistocene glacial advances.

1.3. Tracer thermochronology in the Southern Alps

Tracer thermochronology exploits systematic patterns of mineral cooling ages in bedrock source terranes to interpret patterns of erosion from complementary analyses of detrital minerals (e.g. Stock et al., 2006). We use this approach to test the hypothesis