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The role of earthquakes and climate in the formation of diamictic sediments in a New Zealand mountain lake

C.A. Woodward [a, b, *], A. Slee [c], P. Gadd [b], A. Zawadzki [b], H. Hamze [b], A. Parmar [b], D. Zahra [b]

[a] *School of Earth & Environmental Sciences, The University of Queensland, Australia*
[b] *Australian Nuclear Science & Technology Organisation, Lucas Heights, Australia*
[c] *Forest Practices Authority, 30 Patrick Street, Hobart, Australia*

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A B S T R A C T

We used Itrax XRF, magnetic susceptibility, grain size, and micro-CT scanning to provide a facies classification for a Late Holocene sediment sequence from Lake Chappa'ai in the Southern Alps, New Zealand. The record contained multiple diamictic layers and our objective was to determine the environmental significance of these deposits. Clast fabric analysis indicated that the diamicts comprise dropstones transported to the centre of the lake by ice rafting. Diamicts belonging to Facies 1 represent rock falls onto lake ice triggered by earthquakes that produced MMI (Modified Mercalli Intensity) > 8 shaking in the catchment. MMI >8 earthquakes may need to occur when the lake has ice cover to produce Facies 1 diamicts. MMI >8 earthquakes in the ice free season or MMI 7–8 earthquakes may also result in an increased flux of large (>1 mm) clasts to the centre of the lake, but may not produce a Facies 1 diamict. More work is required to establish the role of climate related processes on the formation of non-Facies 1 diamicts in Lake Chappa'ai. Climate change may directly lead to diamict formation by changing lake ice cover and facilitating transport of large clasts by anchor ice, or increasing the likelihood of rain on snow events in the spring. Changing ice cover conditions will also affect how mountain lakes record past earthquake events. Lakes that are ice free will not produce earthquake diamicts and lakes that have perennial ice cover may produce a single diamict representing multiple earthquakes if the lake becomes ice free. A reduction in the duration of winter ice cover will also decrease the probability of capturing primary rockfall deposits from earthquakes. Additional data, such as a diatom or chironomid record from Lake Chappa'ai may help to resolve the contribution of climate processes to diamict formation. We should consider the Lake Chappa'ai record as an indicator of minimum earthquake activity until we can disentangle the effects of climate change on non-Facies 1 diamict formation. This study highlights the multiple mechanisms that can lead to diamict formation in mountain lake sediments. These processes should always be considered before attributing the presence of diamict deposits to ice-rafted debris in a pro-glacial lake. This is particularly true in seismically active settings where earthquake triggered rockfalls may lead to diamict formation.

1. Introduction

There have been many studies on mountain lake sediment records in the northern hemisphere, including studies on past climate change (Battarbee et al., 2002; Catalan et al., 2002; Koinig et al., 2002; Lotter et al., 2002), human impacts (Hundey et al., 2014), snow avalanche records (Nesje et al., 2007) and flood histories (Glur et al., 2013). There are only a handful of records from mountain lakes in the Southern Hemisphere, including limited records from South America (Bird et al., 2011; Stansell et al., 2013; Bao et al., 2015; De Jong et al., 2016; Martel-Cea et al., 2016), Africa (Woller et al., 2000), Australia (Stanley and De Deckker, 2002), and New Zealand (Shulmeister et al., 2003; Jara et al., 2015). We therefore know little about how humans have impacted these systems, and we have just started to explore their potential as paleoenvironmental records. We also know little about lake and catchment processes in Southern Hemisphere mountain lakes.

There are many mountain lakes in New Zealand (Fig. 1) and it's geological and climatological setting makes New Zealand an

* Corresponding author. Australian Nuclear Science & Technology Organisation, Lucas Heights, Australia.
E-mail address: craigw@ansto.gov.au (C.A. Woodward).

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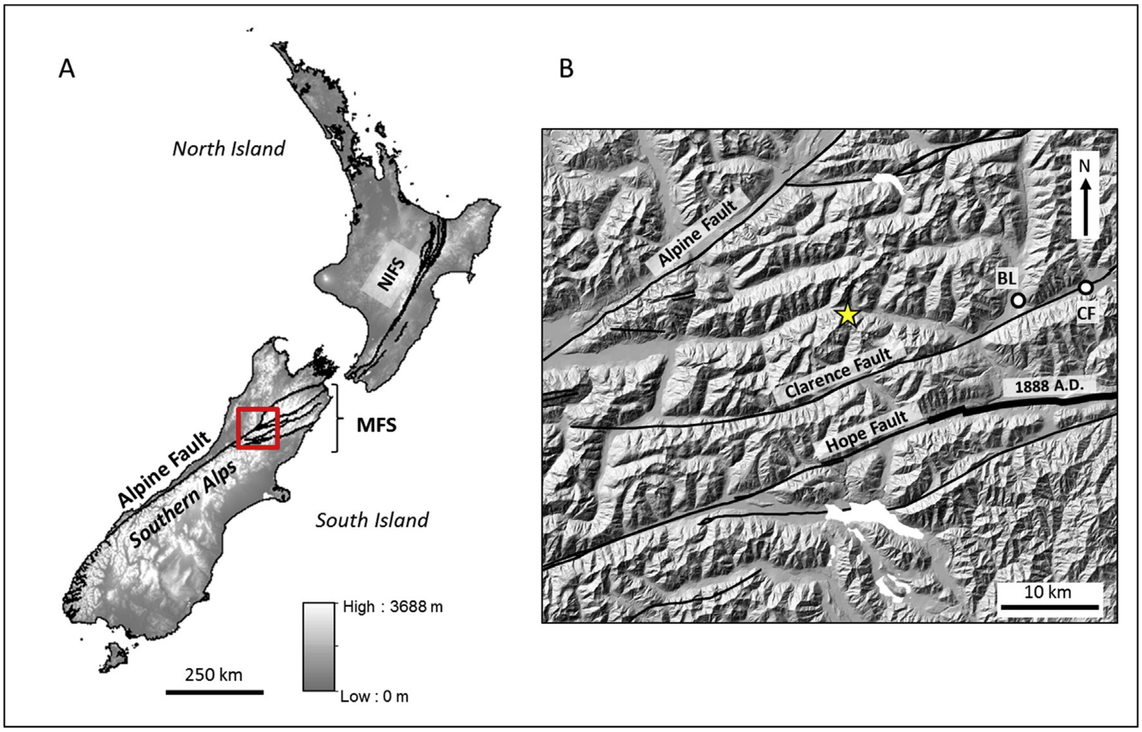

Fig. 1. The location of the study site. A. Digital elevation model (DEM) of New Zealand showing major fault lines. The red square shows the extent of Fig. 1B. MFS = Marlborough Fault System, NIFS = North Island Fault System B. DEM showing the location of the Lake Chappa'ai catchment (yellow star) and major fault lines (black lines). The thick black line on the Hope Fault shows the western limit of the fault rupture associated with the 1888 A.D. Amuri earthquake according to Khajavi et al. (2016). BL = Boyle Lodge climate station. CF = Locality of offset terraces dating the last Clarence Fault earthquake (Knuepfer, 1992). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

excellent location to study climate change and geomorphic processes. New Zealand is tectonically active, mainly due to the collision of the Pacific Plate in the east with the Indo-Australian Plate to the west. This results in uplift rates in the Southern Alps of up to 10 mm per year (Adams, 1980). The predominantly westerly airflow over the Southern Alps (Fig. 1) results in a strong orographic precipitation gradient, with up to 15 m of precipitation falling on the western side each year (Griffiths and McSaveney, 1983). Paleoenvironmental research on New Zealand mountain lakes is limited to surface sediment sampling for transfer function training sets (Woodward and Shulmeister, 2006; Dieffenbacher-Krall et al., 2007), the development of biochemical proxies (Zink et al., 2010) and a limited number of pollen records (Shulmeister et al., 2003; Jara et al., 2015).

In this paper we report the first comprehensive study of the sedimentology of a mountain lake from the South Island, New Zealand (Fig. 1). The sediments from this lake are interesting because they contain frequent diamictic layers. Sediment deposits are classified as diamicts if they comprise a poorly sorted clast-sand-mud mixture (Eyles et al., 1983). Diamicts in lake sediments are significant as they are often used to infer the deposition of ice-rafted debris in pro-glacial lakes (Smith, 2000). Diamicts in lake sediments can also be formed by other processes such as snow avalanches onto lake ice (Luckman, 1975; Nesje et al., 2007), flooding (Fouinat et al., 2017), or adfreezing of littoral lake deposits onto anchor ice (Kempema et al., 2001).

We propose and test multiple hypotheses for the formation of diamictic sediments in a New Zealand mountain lake. The diamictic sediments could represent significant regional changes or stochastic lake and catchment processes. Stochastic processes include the uneven fallout of large clasts during seasonal melting of lake ice and sporadic rockfalls onto lake ice during winter. Rockfalls can be triggered by slope instability caused by freeze-thaw cycles, frost cracking and frost wedging (Matsuoka, 2001). Alternatively, the diamictic sediments could indicate earthquake triggered rock-falls onto lake ice, or the onset of ice-rafting in a proglacial lake. Climate change could also lead to changes in thickness and persistence of ice cover and this could affect the formation of anchor ice and the transport of ice rafted debris (Adrian et al., 2009).

We use multiple techniques (Itrax XRF, magnetic susceptibility, grain size, and micro-CT scanning) to develop a lithofacies classification for sediments from a New Zealand mountain lake. Lithofacies are sediment deposits sharing similar sedimentological characteristics, such as grain size, sedimentary structures and geochemistry (Eyles et al., 1983). We use this lithofacies classification, and comparison to known regional environmental events (e.g. climate change and earthquakes) to identify the most likely cause for the formation of the diamictic sediments. We also compare the stratigraphy from two cores collected from the same lake to test whether the diamicton horizons represent the uneven fall-out of clasts during the break up of seasonal ice cover.

2. Regional setting

Lake Chappa'ai (unofficial name, 42° 31′ 55″ S, 172° 11′, 2″ E) is a small (0.02 km^2) cirque lake at an altitude of 1470 m, with a maximum depth of 6.8 m, a catchment area of 0.15 km^2 and a maximum catchment elevation of 1660 m (Fig. 2). The bedrock comprises strongly indurated greywacke and argillite (metamorphosed sandstone and mudstone) from the Triassic Torlesse Group (Gregg, 1964). The lake catchment is close to three active strike-slip faults; it is 15 km SE from the Alpine fault, 6 km NW from the Clarence Fault and 12 km NW from the Hope fault (Fig. 1). Knowledge of past earthquakes on these faults is derived from

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