Sedimentary Geology 377 (2018) 17–33

Contents lists available at ScienceDirect

Sedimentary Geology

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

Controls on patterns of liquefaction in a coastal dune environment, Christchurch, New Zealand

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ARTICLE INFO

Article history:
Received 24 April 2018
Received in revised form 9 September 2018
Accepted 10 September 2018
Available online 13 September 2018

Editor: J. Knight

Keywords:
Liquefaction
Paleoliquefaction
Fluidization process
Coastal environment
Canterbury Earthquake Sequence

ABSTRACT

Liquefaction features in the geological record are important off-fault markers of moderate to large (>5 Mw) paleoearthquakes. The study of contemporary liquefaction features provides a better understanding of where to find past (paleo) liquefaction features which, if correctly identified and dated, can provide information on the occurrence, magnitude and timing of past earthquakes. This is particularly important in areas with blind active faults. This paper describes liquefaction features in the coastal setting of Christchurch (South Island of New Zealand), and explores the role of liquefaction and fluidization in the surface soil profile and their role in controlling surface ejection. The paper also compares the styles of liquefaction surface manifestation in the alluvial and coastal settings, and the role played by the sedimentary architecture in both environments. This analysis contributes to our understanding of which of the two environments provides a better target for paleoliquefaction studies, and which geomorphic setting within those environments is most likely to host paleoliquefaction features. The coastal setting (in particular, young coastal areas, <300 years old) is especially prone to liquefaction because near surface soils are dominated by well-sorted sandy aeolian deposits and a shallow water table exists. Fluidization within the near surface sandy layer that liquefied and in horizons above, due to upward moving pore water, resulted in a very disrupted soil stratigraphy, making it difficult to identify paleoliquefaction features. Therefore, young coastal areas are not the best target for identifying individual paleoliquefaction events. In comparison, the alluvial setting is characterized by sandy point-bar and channel deposits capped by cohesive overbank and abandoned-channel deposits. As a consequence, sand dikes that form in the alluvial settings are well defined, with preservation of the original soil stratigraphy and distinct cross cutting relationships. These conditions make the alluvial setting, along with older coastal deposits (>1000 years old), a better target for paleoliquefaction studies.

1. Introduction

Alluvial, deltaic and coastal dune systems have been recognized worldwide and for several decades as liquefaction-prone settings (Youd and Hoose, 1977; Youd and Perkins, 1978; Ziony, 1985; Amick et al., 1990; Holzer, 1998; Tinsley et al., 1998; Tuttle, 1999; Holzer et al., 2010) yet dune systems have received relatively little attention. Liquefaction investigations in the coastal setting of the eastern United States have been conducted in a back-beach lagoonal environment where sandy beach deposits were capped by organic-rich lagoonal deposits (Amick et al., 1990; Obermeier et al., 1990; Talwani et al., 1999; Talwani and Schaeffer, 2001). In this setting, large diameter sand blows were formed with central craters attributed to an "explosive" phase during liquefaction (Amick et al., 1990). This surface manifestation of liquefaction differs from that in the alluvial setting where liquefaction features typically align with point bar deposits or paleochannels (Tuttle, 2001; Almond

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https://doi.org/10.1016/j.sedgeo.2018.09.005

et al., 2010; Wotherspoon et al., 2012; Alessio et al., 2013; Bastin et al., 2015; Civico et al., 2015; Villamor et al., 2016; Tuttle et al., 2017) and no explosive origin is inferred or has been observed.

Studies of the Canterbury Earthquake Sequence (CES) (Almond et al., 2012; Quigley et al., 2013; Bastin et al., 2015; Villamor et al., 2016) together with other recent liquefaction events (Alessio et al., 2013; Civico et al., 2015; De Martini et al., 2015; Fontana et al., 2015) have focused on the alluvial setting. Liquefaction in the coastal setting of Christchurch, South Island of New Zealand, is the focus of this paper for the following reasons: i) the coastal setting was severely affected by surface ejecta; ii) the surface manifestation varied across the coastal fringe of Christchurch; and iii) the few studies that have investigated surface manifestation of liquefaction in the coastal setting did not provide an opportunity to study the potential for preservation of paleoliquefaction features (Brackley et al., 2012; Townsend et al., 2016).

In the present study of the coastal setting of Christchurch, three sites were selected with different combinations of dune ages, soils, water table conditions and levels of human modification. This range of dune characteristics was sought to provide variation in susceptibility to liquefaction and preservation of liquefaction features. At all sites we conducted GPR surveys (2D and/or 3D), excavated trenches, took hand-piston cores and vibracores, collected sediment samples for grain-size analysis and organic material for radiocarbon dating. At one site (Featherston Avenue Reserve), we outlined the stratigraphy, in order to understand the influence of the latter on the patterns of surface manifestation of liquefaction.

In this paper we characterize the pattern and style of surface manifestation of liquefaction across our study sites, describing the different types of features observed; document the effects on near surface soil profiles; and draw contrasts with the liquefaction features in the alluvial setting. Thereby, this research gives insights into which sedimentary setting (alluvial or coastal) is a better target for preserving paleoliquefaction features, and hence, which may better inform paleoseismic investigations and hazard assessment. Our conclusions present an assessment of the potential of the coastal environment to preserve paleoliquefaction features and also address controls on liquefaction susceptibility, mechanisms of ejection of liquefied sediment and its effects on soil profiles.

1.1. Liquefaction during the Canterbury Earthquake Sequence (CES)

The CES began with rupture of the Greendale Fault on 4 September 2010 (Fig. 1) causing the Mw 7.1 Darfield earthquake (Cubrinovski et al., 2010; Basher et al., 2011; Van Dissen et al., 2011; Quigley et al., 2012). The best estimate of the timing of the penultimate event on this fault is 20–30 ky ago (Hornblow et al., 2014).

The sequence continued with the Mw 6.2 Christchurch event on February 22, 2011, the Mw 6.0 Christchurch event on June 13, 2011 and the Mw 5.9 offshore event on December 23, 2011 (Bannister and Gledhill, 2012). The Canterbury Plains is underlain by Holocene fluvial sediment and on the eastern side of the city the fine grained sediment is particularly susceptible to liquefaction. Consequently, during the earthquake sequence, at least 10 liquefaction events were identified (Quigley et al., 2013; Bastin et al., 2015; Tuttle et al., 2017). Liquefaction affected residential houses near waterways or streams, wetlands throughout the city of Christchurch and the town of Kaiapoi, as well as rural areas near streams and former channels of the Waimakariri River (Orense et al., 2011; Almond et al., 2012; Brackley et al., 2012; CGD0200, 2013; Townsend et al., 2016; Villamor et al., 2016). Liquefaction and associated lateral spreading caused major damage to buildings and infrastructure in Christchurch, the town of Kaiapoi (~14 km north of Christchurch) and the Selwyn District (~25 km south-west of Christchurch).

For details on the liquefaction surface mapping, the reader can refer to Brackley et al. (2012), and Townsend et al. (2016), and for a review of the liquefaction investigations conducted during the CES the reader can refer to Villamor et al. (2016) and Tuttle et al. (2017).

1.2. The coastal environment of Christchurch and selection of study sites

The modern coastal environment of Christchurch comprises dunes, estuaries, lagoons and swamps making up the seaward part of a progradational coastal plain, which formed since the culmination of

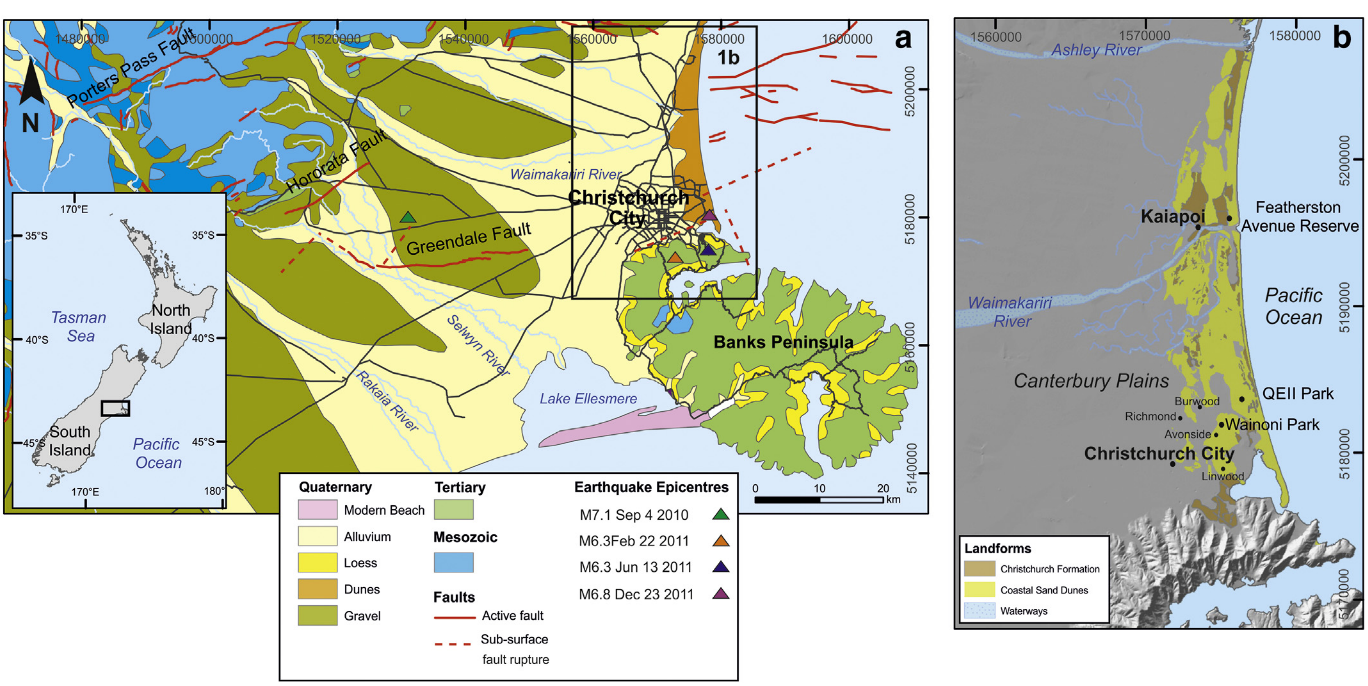

Fig. 1. Location of the study site (a) Geologic map of the Canterbury Plains showing locations of the main earthquakes of the CES and mapped faults (Langridge et al., 2016); (b) Geomorphology of the coastal fringe of the Canterbury Plains and location of the coastal study sites investigated in this study. Note, a and b use NZTM coordinate system.