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ORIGINAL PAPER

Post-seismic aggradation history of the West Coast, South Island, Aotearoa/New Zealand; dendrogeomorphological evidence and disaster recovery implications

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Abstract

In the active tectonic setting of Aotearoa/New Zealand, large earthquakes are a relatively frequent occurrence and pose particular threats to infrastructure and society in Westland, on the west coast of South Island. In order to better define the medium- and long-term (annual to decadal) implications of these threats, existing dendrochronological data were supplemented by several hundred tree-ring analyses from 14 hitherto unstudied living tree stands in five catchments; these were combined to compile a regional picture of the location, extent, and timing of major prehistoric reforestation episodes on the floodplains of the area. These episodes correspond well with known dates of large earthquakes in the area (ca. 1400, ca. 1620, 1717 and 1826 AD), and their extents are thus interpreted to reflect the sediment deliveries resulting from coseismic landsliding into mountain valleys, and their reworking by rivers to generate widespread avulsion, aggradation, floodplain inundation and forest death. This regional aggradation picture can underpin anticipation of, and planning for, the medium- to long-term societal impacts of future major West Coast earthquakes. The source location of the next major earthquake in the region is unknown, so any of the Westland floodplains could be affected by extensive, up to metre-scale river aggradation, together with avulsion and flooding, in its aftermath, and these could continue for decades. Re-establishment and maintenance of a functioning economy under these conditions will be challenging because roads, settlements and agriculture are mostly located on the floodplains. The differences in floodplain vegetation between prehistoric and future episodes will affect the rapidity and distribution of aggradation; response and recovery planning will need to consider this, together with the impacts of climate changes on river flows.

Keywords Westland, New Zealand · Great earthquakes · Coseismic landslides · Dendrochronology · River aggradation and flooding · Societal impacts · Disaster recovery

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1 Introduction

While the immediate impacts of major earthquakes on society are well-known and well-studied, recent work in landscape evolution has shown that the geomorphic impacts of large earthquakes can be long-lasting and widespread (e.g. Fan et al. 2019; Davies and Stahl 2022). In particular, coseismic landsliding into the mountain reaches of rivers can give rise to extensive, long-term aggradation and avulsion across their human-occupied floodplains, with the potential for extensive disruption of societal activity for perhaps decades following an earthquake and its aftershock sequence (Stolle et al. 2019). Evidence for such impacts is accumulating from the consequences of the 1999 Chichi earthquake (e.g. Huang & Montgomery 2012), and of the 2008 Wenchuan earthquake (e.g. Liu & Yang, 2015), while in Westland, New Zealand, evidence for long-term post-seismic sediment regime disturbance was presented by Korup (2004), Wells & Goff (2006, 2007) and Robinson et al. (2016). However, study of the evidence for and implications of post-seismic river aggradation, and of its impacts on society, is still in its infancy.

In this paper we assemble new and existing regional dendrochronological evidence for post-seismic aggradation episodes in the West Coast region of South Island, Aotearoa/New Zealand (Fig. 1). This region is expected to be affected by a M8 + earthquake in the near future: recent analysis of the seismic history of the area (Howarth et al. 2021) indicates about a 75% probability of such an earthquake within the next 50 years on the plate-boundary Alpine Fault that traverses the region. While much attention has been focused on the need for response planning for the immediate aftermath of this event (Orchiston et al. 2018), little attention has been paid to longer-term planning for recovery of the area while severe river aggradation and avulsions may be taking place (Robinson et al. 2016) with consequent disruption to societal and commercial activities on floodplains. In the present work we attempt to remedy this deficiency by complementing existing dendrochronological

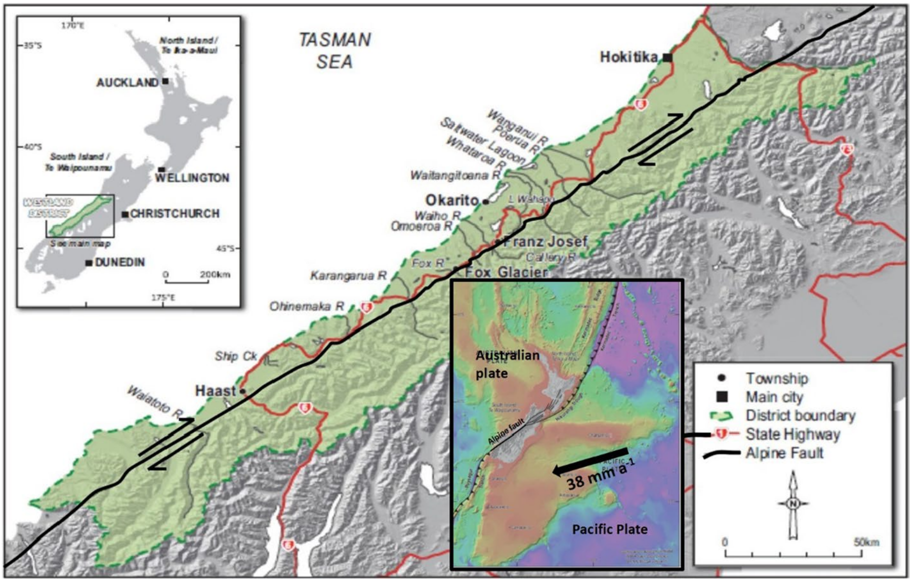

Fig. 1 Westland District (green shade), South Island, Aotearoa/New Zealand. Alpine Fault is black line, black arrows show sense of motion. Roads in red (Blagen 2021). Lower inset: tectonic setting

data with our own new data, in order to describe the extent to which post-seismic aggradation has affected the West Coast region in the past. From this we can infer the potential distribution of future events of this type, and their likely societal impacts.

We first outline the physiography of the region and what is known of its seismic history. Following this we describe the landslide-sediment cascade that can follow a major earthquake, involving reworking of the landslide debris downstream through the river system to the coast, causing aggradation, avulsion and flooding in the floodplain reaches utilised by society. We use tree-ring age data to derive a regional history of floodplain reforestation episodes. This history is then compared with the known seismic history of the area, suggesting that much of the reforestation is associated with extensive aggradation following known earthquakes. Finally, the implications of this association for the landscape response to the next major earthquake in the area are explored, including the extent, nature and duration of its impacts on society and how it may affect the response to and recovery from the event.

2 Study area—Westland, New Zealand

2.1 Physiography, seismicity and vulnerability

New Zealand's South Island lies on the active boundary between the Australasian and Pacific tectonic plates (Fig. 1); transpressive plate motion has caused the Southern Alps to rise eastward of this boundary, which is marked by the Alpine Fault. Extensive glaciations in the Pleistocene affected both the mountain landscapes east of the Alpine Fault and the lowlands west of the fault, the latter now comprising moraines interspersed with lowland floodplains (Fig. 2).

Paleoseismic investigations indicate that over the last eight millennia major earthquakes have affected Westland with a long-term recurrence interval of about 250 years (Berryman et al. 2012; Howarth et al. 2021; and references therein). In the several-hundred-year timescale at which dendrochronology is locally useful (Howarth et al. 2018), large (M7-M8+) earthquakes have occurred in ca. 1400 AD, ca. 1620 AD, 1717 AD and 1826 AD. Recent work suggests that the probability of such an earthquake occurring in the next 50 years is about 75% (Howarth et al. 2021). The rapid tectonic uplift (up to 10 mm a^{-1}) occurring in the ranges east of the fault, combined with the perhumid climate (rainfall ca. 10 m a^{-1} in

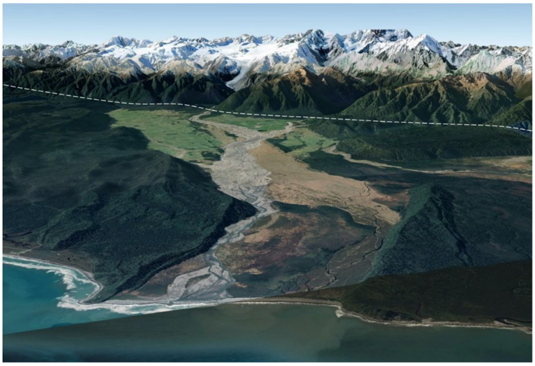

Fig. 2 The Fox River flowing in its floodplain from the Southern Alps to the Tasman Sea. Southern Alps in background; highest peaks are about 3000 m high. Alpine Fault runs along range front (dashed line). Distance from fault to sea is about 18 km. In this location the fanhead extends about halfway from the fault to the confluence between the Fox (left) and Cook (right) rivers. Modified Google Earth image

the mountains), gives rise to extremely steep valley-side slopes that are highly susceptible to landsliding, particularly in earthquakes. A number of extremely large landslides have occurred in past earthquakes (e.g. Barth 2014; Chevalier et al. 2009; Dufresne et al. 2010), and landslide-generated sediment is acknowledged to be a significant contributor to post-seismic landscape change as it is reworked by rivers to the coast (Korup 2005; Robinson et al. 2016; Croissant et al. 2019; Fan et al. 2019; Davies and Stahl 2022).

As a result of the high erosion rate and hence high sediment loads, the rivers of Westland are steep, gravel-bedded and bedload-dominated, and thus mainly braided (Fig. 2). They have infilled former glacial troughs to form alluvial fans and floodplains across which they can avulse during floods. Their characteristics and behaviour reflect the rates at which they are fed with water and sediment from their mountain catchments.

The lowlands west of the Alpine Fault (Fig. 2) comprise fan-head areas extending a few kilometres west of the range front, leading to less steep floodplains that run between hills of moraine or bedrock to the sea (Fig. 2; Beagley et al. 2020). The fan-heads and floodplains experience episodic post-seismic aggradation, as shown by buried soils that have been found beneath these areas (e.g. Berryman et al. 2001; Davies and Korup 2007). These lowland areas are the sites of most of the land-use, settlements and roads in the area, and thus are critical to the tourism and agriculture that contribute most to the ca NZ$650 M Gross Domestic Product of the area. Substantial future aggradation of the fan-heads and floodplains thus poses a serious hazard to these assets, and hence to human society in this region, and study of past episodes can yield useful information for planning the response and recovery following a major earthquake.

The floodplains of Westland were heavily forested prior to western settlement in the mid-nineteenth century, the main species being podocarps such as rimu (Dacrydium cupressinum), kahikatea (Dacrycarpus dacrydiodes) matai (Prumnopitys taxifolia) and totara (Podocarpus totara var. waihoensis), together with beech (Fuscospora and Lophozonia) forest mainly found south of the Paringa River (Fig. 1). Since western colonisation most of this forest has been cleared for pasture, and remnant stands were used for dendrochronology.

There is substantial evidence for the emplacement of deep aggradation deposits in Westland in the past. Various researchers (e.g. Berryman et al. 2001; Davies and Korup 2007; Robinson et al. 2016) have estimated anywhere from millimetre- to metre-scale post-seismic aggradation depths on alluvial fans and floodplains, although for a number of potential reasons (field site selection bias, spatially variable depth), modelled estimates seem to be generally less than the metre-scale depths recorded in the field. For example, Berryman et al. (2001) describe buried soils corresponding in age to the ca. 1620 AD event on sub-fans adjacent to the Whataroa floodplain, representing several metres of aggradation, and Davies and Korup (2007) reported a massive deposit of medium sand dating to ca. 1550 AD at an approximate depth of 4–5 m in a trench in the Waiho fan-head. It also seems likely that the scale of post-seismic aggradation depth will decrease down the floodplain towards the sea, being greatest where the river exits the mountain range front and least at the coast; however, to date there is no field evidence to support this expectation.

2.2 Post-seismic sediment cascade

As outlined by e.g. Korup et al. (2004), Davies and Korup (2007, 2010), Robinson et al. (2016), Fan et al. (2019) and Davies and Stahl (2022), a major earthquake in a mountainous region will generate substantial inputs of sediment to river systems from coseismic landsliding. The quantity of sediment introduced can correspond to between 10- and 100-years' worth of aseismically-generated sediment (Robinson et al. 2016), and thus constitutes a dramatic increase in sediment input, to which rivers will respond accordingly. In general, rivers are expected to steepen in order to increase their sediment transport capability, causing bed elevations to increase progressively downstream. A very large landslide may dam a river in a narrow valley (e.g. Fan et al. 2020; Korup & Wang, 2021). Such landslide dams are generally (but not always) short-lived and most of them fail by overtopping within a few days to years of their formation, causing in turn a dambreak flood which is followed by a pulse of aggradation as the dam sediment is reworked downstream. In either case, aggradation of rivers in their floodplain reaches may exceed metre-scale depths (Robinson et al. 2016), meaning that in high flows the river can overtop its banks and flow in a new course, or reoccupy an old course, across the floodplain, while at the same time overbank flows deposit finer sediments widely across the floodplain. The sediment that is not deposited is carried through to the coast, where longshore drift may cause substantial coastal accretion downdrift of river mouths. Wells and Goff (2007) dated beach ridges in south Westland and found that they formed several decades after the triggering earthquake, which indicates the duration of the rivers' response to the excess sediment input.

Davies and Korup (2010) and Beagley et al. (2020) suggest that following an aggradation episode the river incises back down into the elevated fan-head area adjacent to the mountain front, leaving a raised surface, while the floodplain downstream of the fan-head to the sea returns to its pre-seismic profile once the aggradation pulse has passed through.

2.3 Societal vulnerability

While normal rainstorm-driven flooding can be a serious floodplain – and hence, societal—hazard, it is a well-known one, and most settlements are either distant from present river courses or protected by flood-management structures. Roads in Westland often cross major rivers close to the mountain front, because here the rivers are usually incised into the fan-head and thus conveniently narrow for bridging; elsewhere roads are located on the floodplain itself. Downstream of the incised fan-head section most rivers flow in braided courses close to the level of the floodplain surface. Most of the fan-head and floodplain areas are used for agriculture, and where such land is threatened by flooding, floodbanks or levees ("stopbanks" in local parlance) confine the river to its presently-active bed. Thus, in normal circumstances, flooding is a reasonably well-managed hazard in Westland, and serious disruption is limited to exceptional events or specific highly vulnerable locations such as the Waiho River at Franz Josef (Beagley et al. 2020), where long-term aseismic aggradation is ongoing.

Where rivers are experiencing widespread rapid and long-term aggradation, however, flood management becomes exceptionally difficult, and may be impossible (Davies and McSaveney 2006). It might be thought that the conventional strategy of installing stopbanks, and increasing their height when necessary, would prevent flooding. The problem with this strategy is that keeping a river confined to its normal active channel means that the excess sediment deposition, which is the basic cause of the aggradation, is concentrated in the relatively small active bed area; thus, the aggradation continues unabated and is, in fact, accelerated by the flood control measures (Beagley et al. 2020). By contrast, if the river were allowed to spread over the whole floodplain area—as it would when aggrading naturally—the rate of aggradation would reduce correspondingly (Beagley et al. 2020). Further, mechanical removal of excess sediment from the river bed is unrealistic due to the quantity needing to be removed to offset aggradation and the need to dispose of this sediment economically.

It follows that in the aftermath of a large earthquake serious societal disruption is to be expected due not only to the damage caused by the earthquake and its immediate consequences (shaking, structural collapse, landsliding, infrastructure and lifeline damage), but also, and increasingly over time, due to rivers aggrading, changing course and impacting large areas with flooding and sedimentation. Major and minor roads, settlements, dwellings, farms, tracks, water supplies and drainage can all be affected by widespread inundation, sediment deposition and river erosion; and these impacts appear likely to continue for a period of decades following a major earthquake. While not every floodplain area will be badly affected, depending on which catchments suffer most from landsliding, there is no doubt that life in Westland could be severely disrupted on decadal time-scales. Given that a substantial proportion of the Westland economy depends on tourism, which in turn depends on road transport, it seems reasonable to anticipate that this industry will suffer badly (in turn impacting the economy of the wider South Island and of the nation); the same applies to agriculture, but with mainly regional impacts. Better understanding of the likely regional distribution of aggradation following the next earthquake, based on knowledge of previous events, is therefore a high priority.

3 Impact of aggradation on Westland floodplain forests

All of the previous major earthquakes in Westland took place in a pre-European landscape; significant western settlement occurred only with the 1860s gold rush and subsequently. Indigenous occupation of Westland by Māori since their arrival in Aotearoa/New Zealand in the fourteenth century was always sparse, and this, combined with the wet climate, spared the region the extensive deforestation that occurred in the east of the South Island. Thus, the aggradation episodes following previous Westland earthquakes took place on floodplains that were largely forested with native vegetation. It is known that sufficiently deep burial with sediment by rivers causes trees to die (e.g. Lowe et al. 2010), and that ancient forests in Westland have been buried beneath floodplain sediments (Korup, 2004); thus it is reasonable to assume that tracts of forest on the floodplains would have been killed by widespread post-seismic aggradation. These would have been replaced by new growth once the active aggradation had ceased, and these new trees would all have been about the same age. Thus it is possible to use tree age dating (dendrochronology) to identify, in the remaining floodplain forest where conversion to pasture has not taken place, even-aged stands that are likely to be the result of, and indicators of, prehistoric aggradation. The locations and ages of these stands can be used to interpret the aggradation history.

Not all landslides and aggradation episodes are the result of earthquakes, and not all tree deaths are the result of sediment inundation. Landsliding and aggradation can also be caused by severe storms, but are likely to be much less widespread than following a major earthquake (Howarth et al. 2018). It is, however, reasonable to interpret regional-scale simultaneous aggradation as the result of a major earthquake, and thus to interpret regional-scale contemporaneous floodplain tree mortality as the result of a major seismic event. Other than the regional extent, there is no diagnostic signature that distinguishes post-seismic aggradation from that due to other causes.

4 Dendrochronology

4.1 Previous work

While a number of dendrochronology investigations have been carried out on Westland floodplains (Veblen and Stewart 1982; Norton 1983; Stewart and Rose 1989; Cornere 1992; Duncan 1989, 1991; Rogers 1995; Stewart et al. 1998; Van Uden, 1997; Wells et al. 1998, 2001), only that of Cullen et al. (2003) attempted a regional spatio-temporal analysis of the type we present herein. Nevertheless, the combined dataset of these studies provides invaluable information, which the present study complements. Further, recognition of earthquakes as major sources of forest disturbance in the area dates only from the mid-1990s, so not all of the stands dated in the past were interpreted as the results of earthquake-induced aggradation.

4.2 Present work

The present study uses 51 of the 59 tree cohorts from Wells et al. (1999), excluding eight tree cohorts that are either too far outside the Westland district to be of good use, or from surfaces such as old moraines that are not relevant to this study. Fourteen of these 51 cohorts come from scattered sites north of the Wanganui River (Norton 1983; Stewart and Rose 1989; Veblen and Stewart, 1982; Wells et al. 1998), 28 cohorts are from the central Westland area between the Wanganui and Karangarua rivers (Cornere 1992; Duncan, 1989; Rogers 1995; Stewart et al. 1998; Van Uden 1997; Wells et al. 1998), and 9 cohorts come from south of the Karangarua River (Duncan 1991). The 51 cohorts from the Karangarua catchment (Wells et al. 2001) were also included in the present study, as were the 16 cohorts analysed by Cullen et al. (2003) in the Whataroa and Wanganui floodplains.

4.3 Methodology

4.3.1 Site selection

Sampling sites for the present study were chosen mainly to complement the prior data. Augmenting the pre-existing dataset of 118 forest cohorts are 14 new cohorts (535 trees) within five river catchments (Wanganui, Whataroa, Omoeroa, Karangarua and Waiatoto) in central and southern Westland. Relatively few prehistoric stands remain on most of the Westland floodplains, so choice of sample sites was limited; the absence of suitable stands over most of the Waiho and Fox floodplains, for example, is a notable limitation. The locations of previous and present sampling sites are shown in Fig. 3.

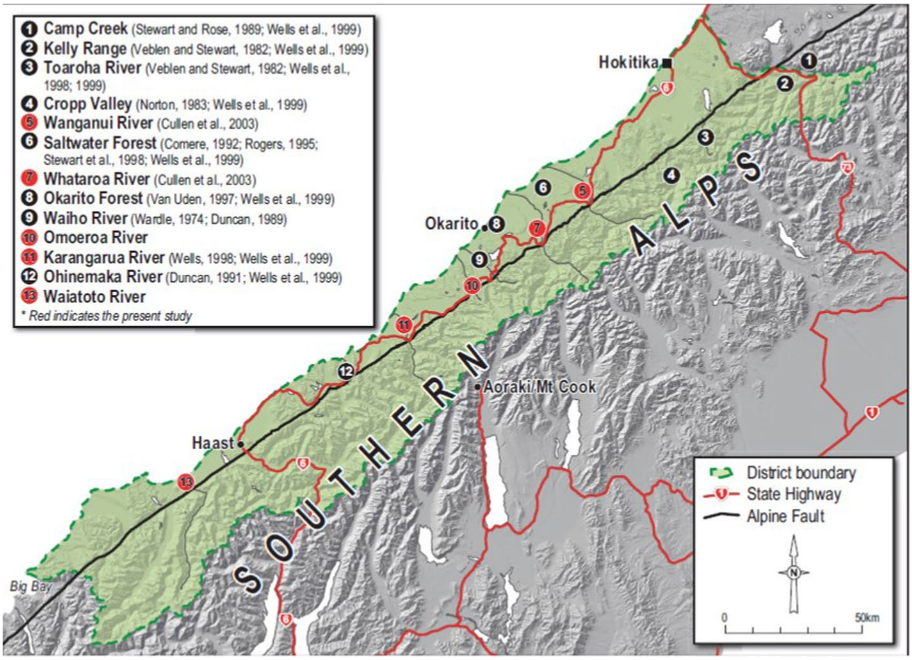

Fig. 3 Locations of previous and present dendrochronological sampling sites (Blagen 2021). The green area is Westland District, whose south-eastern boundary is the main divide of the Southern Alps

4.3.2 Sampling and analysis

The species sampled and techniques used for the present study were closely similar to those used in the previous studies, and sample analyses were likewise performed within the guidelines and limitations set out by previous researchers (Norton and Ogden 1987; Norton et al. 1987; Stokes and Smiley 1968; Wells et al. 2001; Blagen 2021). Ages of surfaces were determined from oldest living trees in the 14 sampled forest stands. Some previous work has relied on the age of quantitatively defined even-aged cohorts of trees to infer disturbance-initiated forest colonisation (Wells et al. 2001; Cullen et al. 2003), whereas others (from coastal dunes; Wells and Goff 2006) have adopted the approach used herein of dating a landform by its oldest tree. Age-frequency diagrams with 25-year bins are used herein to help distinguish cohorts, which, as outlined in Wells et al. (1998), are recognised by a distinct onset of high tree establishment. The 25-year interval was chosen to correlate with the data of previous studies, facilitating merging and comparison of datasets. The present study used two criteria described in Wells et al. (1998) to define a cohort as even-aged. The first requires that greater than 60% of the trees established within an interval of 150 years, and the second requires that greater than 90% of trees established within 350 years.

The likely original spatial extent of each aggradation event was mapped from aerial photographs and extensive field inspection as per Wells et al. (2001). Aggradation surfaces were distinguishable in the field based on uniform substrate texture and topography, with boundaries between adjoining surfaces usually marked by sharp changes in these two factors. In particular, river terrace scarps delineated older surfaces from more recent ones. An inclinometer was used to determine heights of surfaces above modern river level, and substrate texture was visually assessed at terrace scarps. Surfaces of the same height above river level and with similar substrate were assumed to be remnants of the same aggradation surface; and so the original aggradation surface was assumed to have covered the entire floodplain area between the mapped remnants, on both sides of the current river channel and between all upriver-downriver locations.

4.3.3 Errors

All tree age estimates include an addition of 28 years for conifers, and 20 years for angiosperms, to account for colonisation and growth to coring height (Wells et al. 1999). An attempt was made to minimise error due to ring growth anomalies by coring trees along the longest radius (Duncan 1989), and it was assumed that, because the early colonisation of disturbance-initiated new surfaces in Westland tends to produce trees that grow rapidly with few periods of narrow ring growth (Wells 1998), there are not likely to be many missing rings present in the conifer species cored for the present study. Date estimates of disturbance events, or the new surfaces created by them, will contain errors due to the variation in individual colonisation delay, and missing rings and estimated additional rings for cores that did not intersect the pith will limit the accuracy of estimated tree ages to about ± 0–5% of the true age (Norton et al. 1987; Duncan 1989; Stewart and White, 1998). Although dates of individual trees may have inherent errors due to growth anomalies, partial core limitations, and human error, the present study is interested in an approximate minimum age for disturbance-initiated surfaces and so these individual errors are less concerning. Wells et al. (1999) estimated that the combined error in dating a disturbance event based on tree ages could vary from about 5–55 years, with an expected range of ± 25 years for sampled cohorts that were initiated by the same disturbance event.

5 Results

The data acquired in the present study are shown in Figs. 4, 5, 6, 7, 8 and 9; these illustrate the distributions of dated stands in the Wanganui, Whataroa, Omoeroa, Karangarua and Waiototo floodplains. In addition, previous data are indicated for the Wanganui and Whataroa (Cullen et al. 2003), for the Waiho (Wardle 1974; Duncan 1989) and for the Omoeroa river mouth (Wardle 1978). The areas affected by the aggradation that caused these stands are indicated by shaded areas but are obviously approximate and limited by data sparsity.

Figures 4, 5, 6, 7, 8 and 9 also show the floodplain stands identified as dating from shortly after known West Coast earthquakes in ca. 1400, ca. 1620, 1717 and 1826 AD. When all previous data are integrated with the present data, the regional distribution of these areas is as shown in Fig. 10.

5.1 Wanganui floodplain

Cullen et al. (2003) commented that: "The age distributions of trees sampled in the lower reaches of three of the four floodplains (Ohinemaka, Wanganui, and Whataroa) are remarkably similar … All show a major pulse of establishment commencing c. AD 1650, and a consistent but much smaller peak in establishment after the AD 1717 earthquake". Our

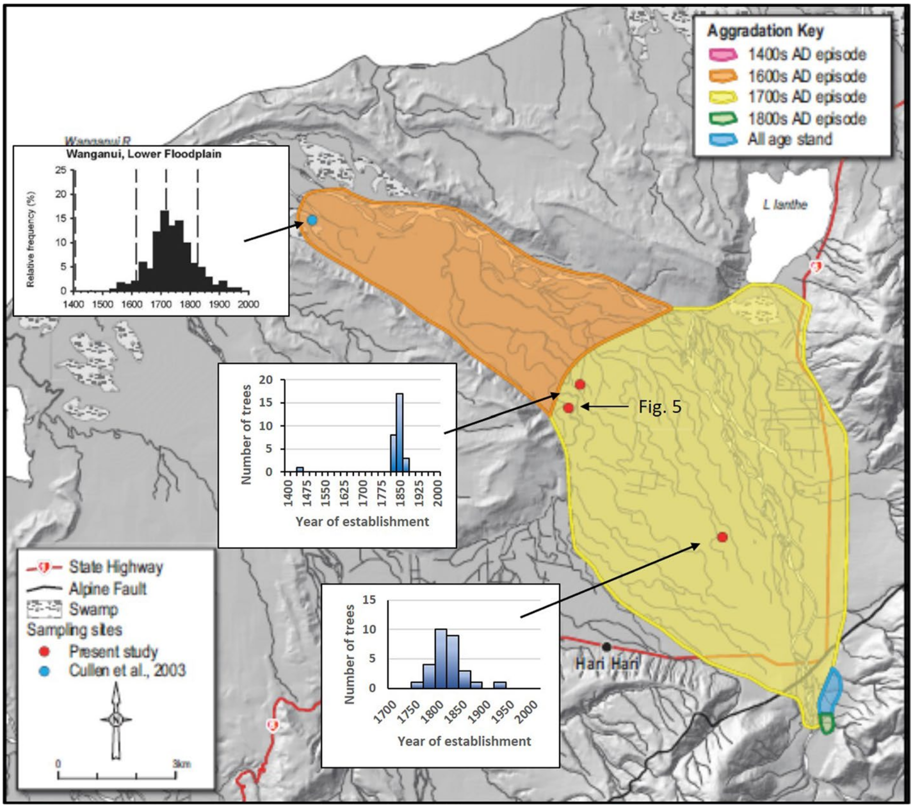

Fig. 4 Location of present and previous study sample sites on the Wanganui floodplain, indicating approximate areas inferred to be affected by aggradation episodes (Blagen 2021). Data from Cullen et al. (2003) shown for lower floodplain with earthquake dates (1400, 1620, 1717 and 1826 AD) as dashed lines

Fig. 5 Views of sample site W2 on Wanganui floodplain stand (totara and matai). Left—viewed from the east; right—interior. See Fig. 4 for location

data confirm this interpretation (Figs. 4, 6 and 8), although it is emphasised that our delineation of the different-aged aggradation areas is approximate because the data are somewhat indefinite in this regard.

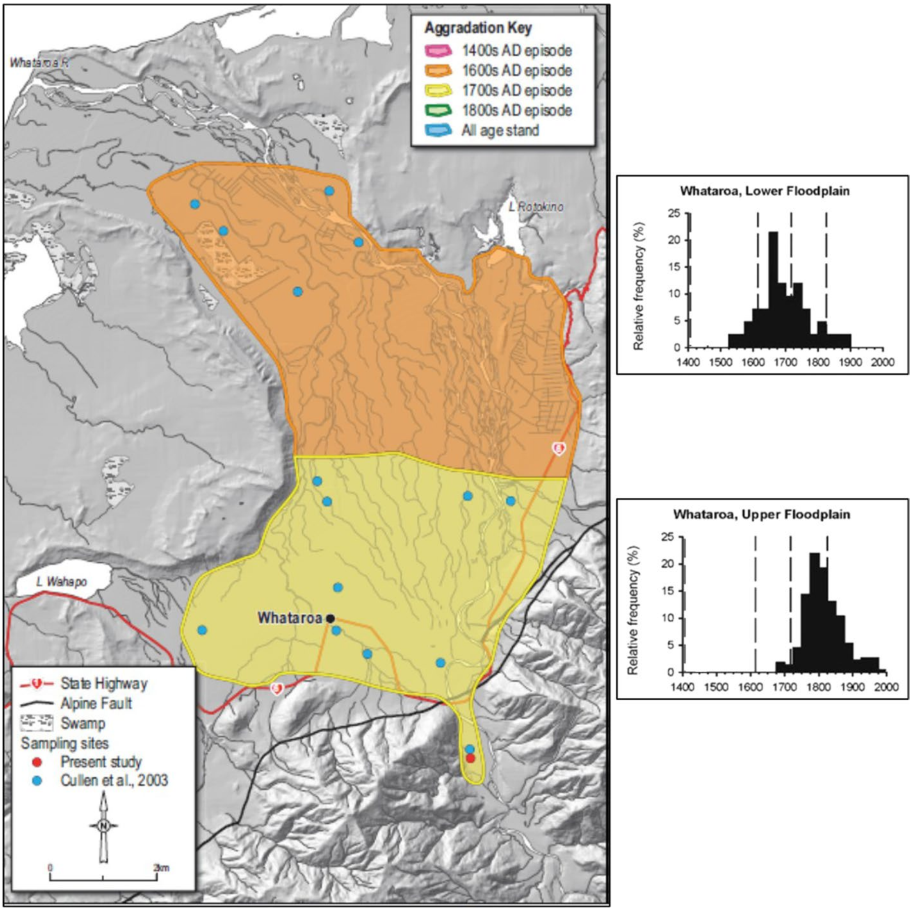

Fig. 6 Location of present and previous study sample sites in the Whataroa floodplain (sample locations from R.P. Duncan, Centre for Conservation Ecology and Genomics, Institute for Applied Ecology, University of Canberra, Australia, *pers comm.*) indicating approximate floodplain areas inferred to be affected by aggradation (Blagen 2021). Data from Cullen et al. (2003) shown at right with earthquake dates (1400, 1620, 1717 and 1826) as dashed lines

5.2 Whataroa floodplain

The Whataroa floodplain shows distinctly different frequency populations (data from Cullen et al. 2003; Fig. 6) indicating aggradation by a post-1700 AD event on the upper floodplain while the lower floodplain shows the effects of both post-1600 AD and post-1700 AD events. This distribution is interpreted to indicate that the post-1600 AD event affected the whole floodplain, but that the post-1700 AD event completely overwrote the post-1600 AD event on the upper floodplain while less intensely affecting the lower floodplain.

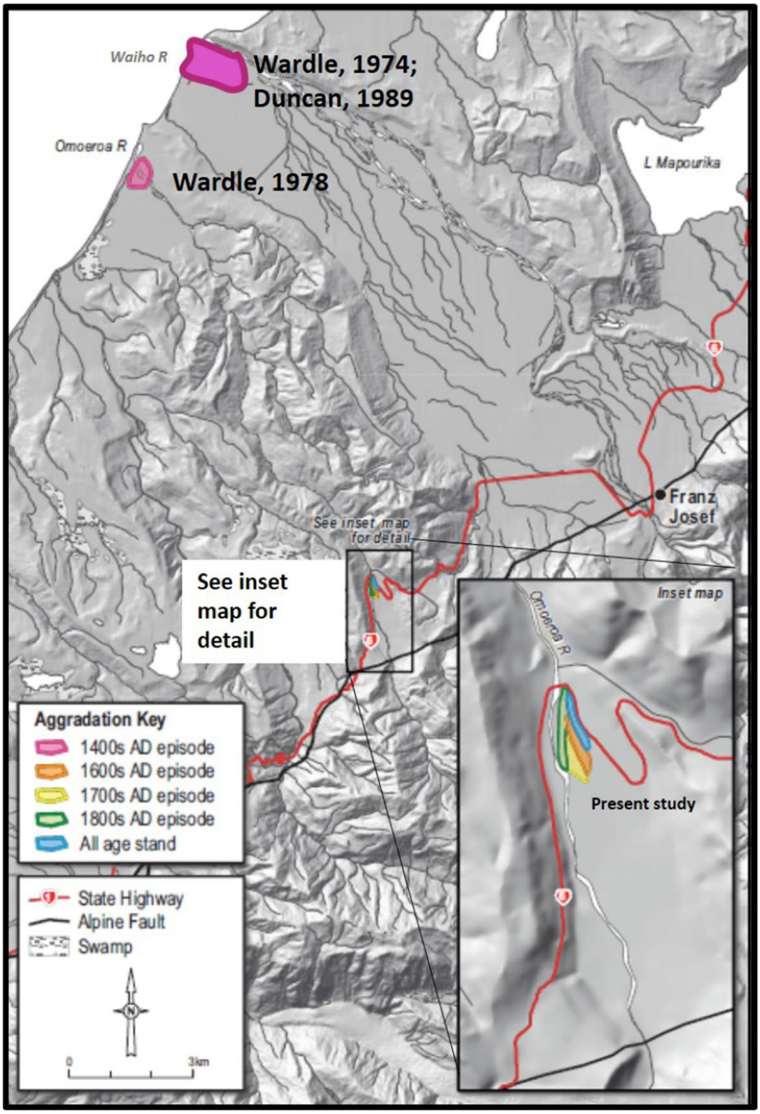

Fig. 7 Location of present and previous study sample sites in the Waiho and Omoeroa floodplains indicating approximate floodplain areas inferred to be affected by aggradation (Blagen 2021)

5.3 Waiho and Oemeroa floodplains

Data in the Omoeroa (Fig. 7 inset) indicate the impacts of several events in the small floodplain area available. No new data were acquired on the Waiho floodplain (Fig. 7) due to the lack of suitable stands. Data from Wardle (1974, 1978) and Duncan (1989) indicate that the ca. 1400 AD event extended its deposits all the way down this floodplain to the sea.

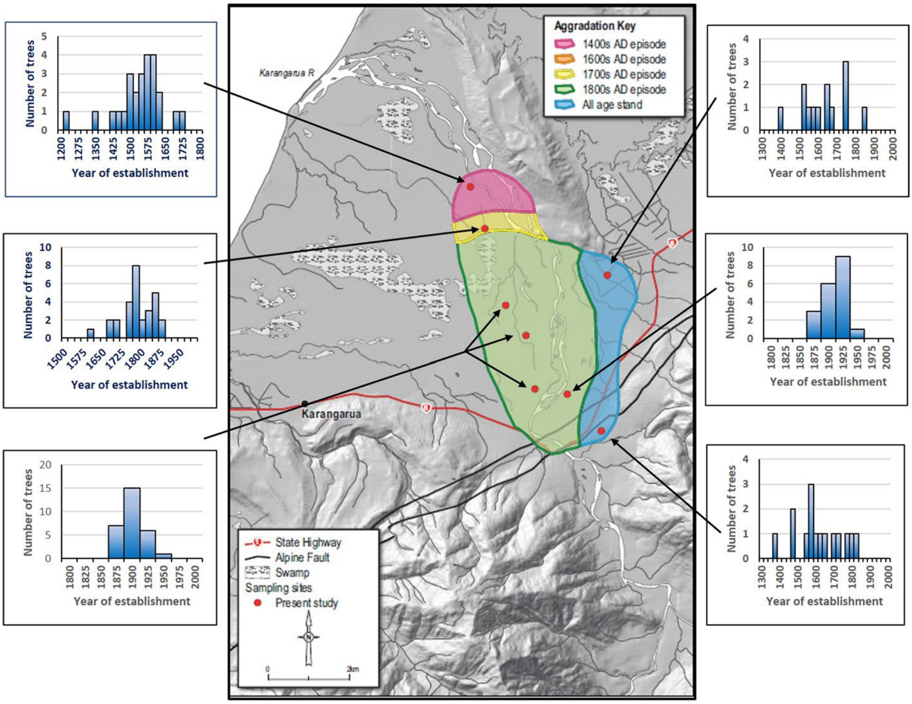

Fig. 8 Location of present and previous study sample sites in the Karangarua floodplain indicating approximate areas inferred to be affected by aggradation episodes (Blagen 2021)

5.4 Karangarua floodplain

Data from the Karangarua (Fig. 8) show that the ca. 1400 AD event extended well down the floodplain, and was overridden by the 1717 AD event; however, a post-1800 AD (presumably 1826) event appears to have overridden the previous events over much of the floodplain.

5.5 Waiototo floodplain

Waiototo floodplain data indicate the impact of the 1826 event within about 2 km of the coast, while further upstream trees of all ages are present.

5.6 All data

All of these deforestation areas are shown on Fig. 10, together with the estimated rupture lengths of the ca. 1400 AD, ca. 1620 AD and 1717 AD earthquakes (Howarth et al. 2014). These lengths are inferred from all paleoseismic data, including trenches, lake sediments, fluvial sediments and dendrochronology. Note that the 1826 AD earthquake, which was recorded by whalers in Fiordland in the far south-west of the South Island, is not included by Howarth et al. (2014) as it was not an Alpine Fault event. Similarly, recent studies (Briggs et al. 2018;

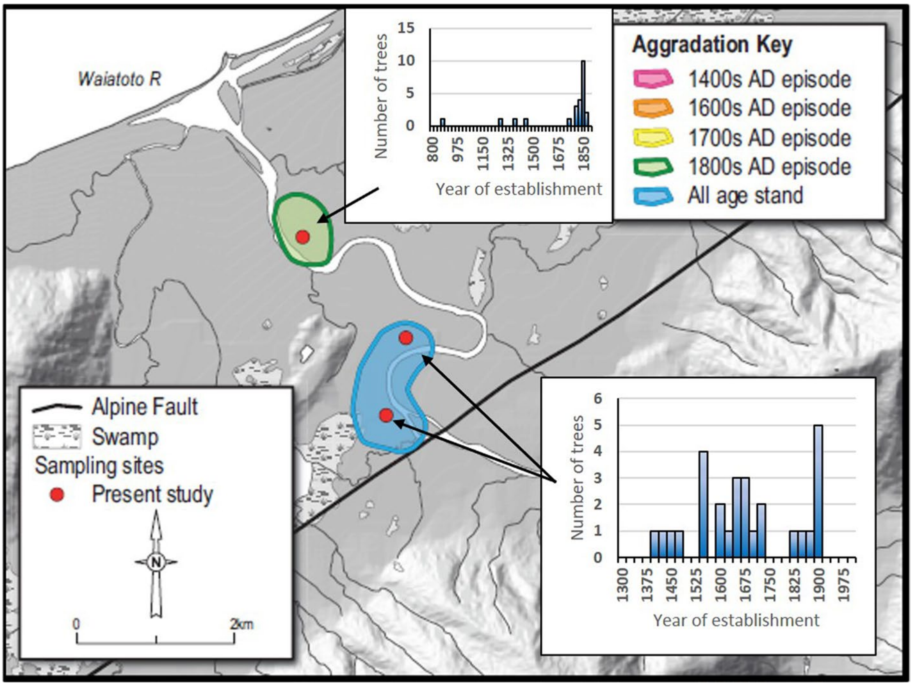

Fig. 9 Location of present study sample sites in the Waiototo floodplain indicating approximate floodplain areas inferred to be affected by aggradation (Blagen 2021)

Howarth et al. 2018) suggest that the ca. 1620 AD earthquake also appears unlikely to have been an Alpine Fault event, being located instead within the western Southern Alps.

6 Interpretation: earthquake-generated aggradation events

6.1 ca. 1400 event

Dendrochronological evidence for aggradation following this earthquake is only apparent in the Waiho, Omoeroa and Karangarua floodplains. Its aggradational surfaces are likely to have been buried and/or eroded elsewhere by subsequent events, but this distribution corresponds well with that in Fig. 10. The extreme distal location of the Waiho stand suggests that this was a very large event in the central Westland region.

Wells and Goff (2007), however, suggested that rather than a single episode at ca. 1400 AD, two regional episodes (just prior to 1450 AD and 1525 AD, respectively) better explain the cohort dates. More recently, Howarth et al. (2014) studied sediments in lakes along the Alpine Fault and derived rupture length and date estimates that are decades earlier than previously believed, placing this event at about the turn of the fifteenth century. Trees spanning these time periods are visible in the datasets as surviving remnant trees in areas with younger cohorts and as cohorts in a number of catchments, both on upstream terraces and on downstream floodplains.

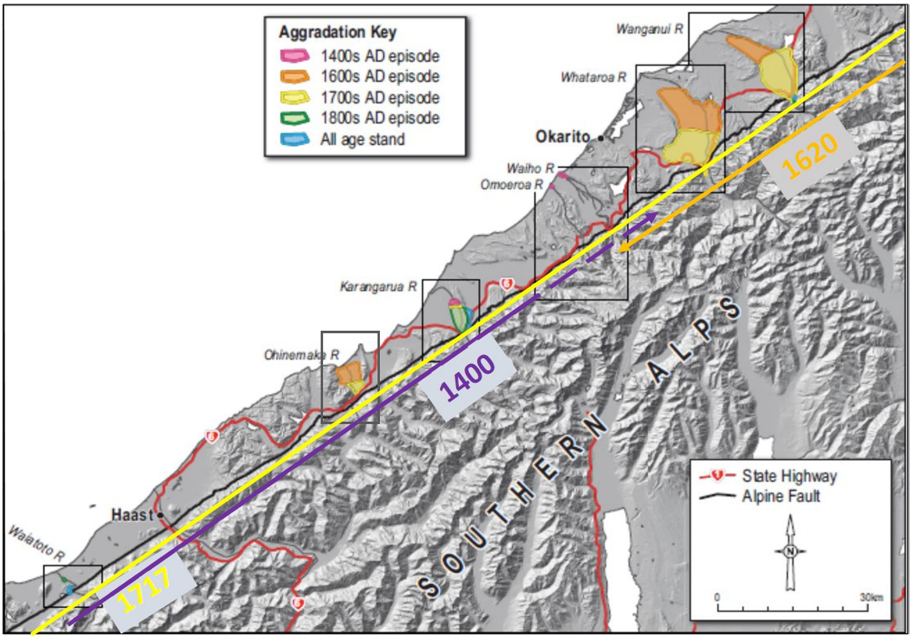

Fig. 10 Regional distribution of inferred aggradation episodes corresponding to known earthquakes (Blagen 2021). Inferred rupture lengths of previous West Coast earthquakes (from Howarth et al. 2014) shown as ca. 1400 AD – mauve; ca. 1620 AD – orange; 1717 – yellow

The northernmost catchment studied, the Wanganui (Fig. 4), did not have distinct cohorts from the 1400s AD, but there were some outlier trees dating back to 1445 AD on the lower floodplain. Note that the data corresponding to this event in other catchments were mostly found very close to the coast and likely overrun by subsequent events upstream. Initial colonisation of the current cohorts appears to have begun on the floodplain between 1525 and 1550 AD, peaking in the early 1600s AD (Cullen et al. 2003). The Whataroa shows a similar outcome with upstream terraces dating to 1425 AD and 1590 AD, and floodplain dates ranging from 1531–1669 AD (Cullen et al. 2003). These data may give credence to the idea of two events occurring within a short time of each other, the second somewhat masking the first, with the initial disturbance occurring just before 1450 AD, and a subsequent smaller aggradation event taking place 50–75 years later (Wells and Goff 2007). Evidence of disturbance at this time is also present in cohorts in the Saltwater and Okarito forests, which are north and south of the Whataroa catchment, respectively (Fig. 1; e.g. Cornere 1992; Rogers 1995; Wells et al. 1999). The possibility of one of the aggradation events in this period being climatically-induced cannot be ruled out (Howarth et al. 2018).

6.2 ca. 1620 event

Tree cohort evidence corresponding to this event is prominent and extensive in the northern Wanganui and Whataroa floodplains. The event is notably absent from the southern floodplains (Waiatoto and Karangarua), but appears in the Ohinemaka floodplain 20 km south of Karangarua (Duncan 1993), suggesting that its presence in the Karangarua may have been overrun by later events. If, as suggested by Briggs et al. (2018) and Howarth et al. (2018), the ca. 1620 AD event did not involve the Alpine Fault but was sourced on a fault farther east in the ranges, then it would be expected to generate a large volume of landslide sediment. This is because the Alpine Fault, being at the range front, radiates about half of its energy release westwards into non-mountainous terrain, while a fault within the mountains radiates all of its energy into mountainous terrain (Briggs et al. 2018). Further, if the ca. 1620 AD event took place inland from the northern half of the central Alpine Fault section (Fig. 10), it would affect the Karangarua floodplain less than those farther north.

6.3 1717 AD event

The rupture length of this event is constrained by off-fault (dendrochronology, lake sediments, fluvial deposits) as well as on-fault (Berryman et al. 2012; De Pascale and Langridge, 2012) paleoseismic indicators. It appears to have been a full-length rupture involving the whole of the Alpine Fault, and is indicated by extensive stands corresponding to this date in the Wanganui, Whataroa, Karangarua and Ohinemaka floodplains. The Wanganui (Fig. 4) has trees on the upper floodplain dating to the mid-1700s AD (1745 AD), but younger cohorts ranging from the late 1700s to early 1800s AD dominate. The Whataroa, farther south, has terraces with remnant trees dating to the 1600s AD, but the main pulse of tree growth occurs in the early 1700s AD, and the upper floodplain is dominated by young trees mostly establishing after 1720 AD (Cullen et al. 2003). The Karangarua catchment (Fig. 6) has terraces dating to the 1700s AD and tree cohorts on the upper floodplain mostly dating to the early 1800s AD. About midway down the upper floodplain, however, there is a cohort dating to 1733 AD, with what appear to be two growth pulses occurring in the late 1700s and mid 1800s AD. The Waiatoto catchment does not have cohorts dated specifically to this time-frame, but there does appear to be a pulse of tree growth on the lower floodplain occurring in late 1700s to early 1800s AD as well as beach ridges dated by tree rings to approximately 1728 AD (Wells and Goff 2007).

6.4 1826 AD event

This event was recorded by whalers in Fiordland so is the only major historical earthquake to have affected Westland. Its effects on trees are detectable in the Waiatoto, Karangarua and Omoeroa sampling sites, but—notably—not reported from the Ohinemaka. Briggs et al. (2018) reported that Mosley (1983) associated a ca. 1850 AD terrace at the Waiho-Callery confluence (recently buried by the current aggradation episode) with the 1826 AD event. However, this also could be due to an uncommon or severe weather event, an aseismic landslide in either the Waiho or the Callery, or aggradation from the Callery Gorge which is very prone to such episodes. We note also that there was a Little Ice Age advance of the Franz Josef glacier in this catchment culminating about 1750 AD (McKinzey et al. 2004). South of the Waiho, but north of the Karangarua, the Omoeroa has a cohort dating to 1857 AD on the terrace closest to the active riverbed. The fact that it is present between the major catchments supports the idea that the 1826 AD event affected catchments as far north as the Waiho, but it is hard to determine whether the small scale of the episode is due to attenuation of the disturbance intensity as it reached these catchments, or if the episode results from an extreme weather event. Farthest south, the Waiatoto floodplain also has trees dating from the mid-to-late 1800s AD, and the dune sequences at the river mouth record a range from 1831–1870 AD (Wells and Goff 2007). Approximately 80 km northeast of the Karangarua, Blagen (2021) also found cohorts on the first terrace above what might be considered active riverbed in the upper Wanganui catchment that date from 1832–1884 AD. While this may seem to show possible association with the 1826 AD Fiordland event, it is hard to say whether these cohorts are a result of a remarkably distant southern earthquake or a local severe sediment event that affected the upper reaches but did not come down onto the floodplain.

6.5 Regional summary

In spite of the spatial sparsity of data, and considerable spread in ages, it is apparent that aggradation has at times been widespread on Westland floodplains following major earthquake events. The aggradation episode that occurred in the 1400s AD was extensive in some catchments, but not seen in others, while the episode in the 1600s AD was very substantial, reaching far down the floodplain in a number of major catchments, and potentially overrunning and obscuring evidence of the 1400s AD episode in places where that episode is unseen. The more recent (1717 and 1826 AD) episodes appear to have been less extensive, but also appear on many of the floodplains studied. Although data are not available for every floodplain in Westland, the consequences of past large disturbance events in the above catchments can be extrapolated to others, which may be similarly affected after the next large earthquake.

It is notable that in the Wanganui and Whataroa floodplains the ca. 1620 AD aggradation event was substantially more extensive than that of the 1717 AD event (Figs. 4 and 6), even though the latter earthquake is thought to have been significantly larger because of its greater rupture length. Briggs et al. (2018) estimated that if the ca. 1620 AD event took place on a fault within the central section of the Alps, it would generate at least twice the aggradation depth in the Waiho and Whataroa floodplains as the range front 1717 AD event; this corresponds well with the present data. By contrast, on the Karangarua floodplain to the south the ca. 1620 AD event results in substantially less extensive aggradation, likely because the fault rupture did not extend to the Karangarua headwaters (Fig. 10). However, it is interesting that the ca.1620 AD forest disturbance was more extensive than the 1717 AD disturbance in the upper Karangarua, upstream of the Alpine Fault, and there was also a prominent ca. 1620 AD terrace there (Wells 1998), suggesting that this frontal part of the Alps may not have been much affected in ca. 1620 AD.

7 Implications for future events

While paleoseismic studies in the region have focussed mainly on the Alpine Fault (e.g. Berryman et al. 2012; Howarth et al. 2021), recently attention has broadened to encompass the possibility that some of the past events, and thus also the next major event, may relate to different faults (Briggs et al. 2018; Cox et al. 2012). Nevertheless, the paleoseismic data constraining the "Alpine Fault return period" are mostly off-fault (i.e. derived from shaking effects) so can include major earthquakes on any fault (or series of faults) within the western Southern Alps.

It is important to note that the spatial distribution of landslides in any specific future major earthquake cannot be predicted. Thus, while probabilistic forecasts can be made (e.g. Robinson et al. 2016), all we know about the next event is that large landslides can occur in any catchment, but probably not in all. This is significant because statistics reveal that despite being less numerous than smaller ones, larger landslides have dominated the production of sediment in the Southern Alps in the Holocene (Korup and Clague, 2009).

The quiescent interval since the last major earthquake in much of the area has been over 300 years—much longer than that which preceded the 1717 AD earthquake (~ 100 years). Thus not only is the magnitude of the next earthquake likely to be large (~ M_w8.2) due to the long period of accumulating tectonic stress; due to the large cumulative uplift and river incision since the last event, there will be a correspondingly large volume of source rock available for coseismic landsliding. In addition, if the next event should take place on a fault within the mountains, rather than on the Alpine Fault at the western range front, then the greater area of mountainous land exposed to severe shaking would result in a greater volume of landslide-generated sediment being available to cause downstream aggradation.

Thus, the magnitude and distribution of aggradation resulting from the next major Westland earthquake depend on.

1. When the event occurs; the longer the delay the greater the earthquake magnitude, landslide debris volume, and aggradation depth and extent.
2. Where the fault rupture is located—if it is full-length, most floodplains can be affected. If it is on the Alpine Fault the individual aggradation areas are likely to be less extensive and deep than if it is within the ranges, but more floodplains may be affected.
3. Which catchments receive large volumes of landslide debris.

The worst-case scenario (if feasible) is a long-delayed (several decades), high-magnitude (M_w8.2) earthquake within the ranges, which extends along much of the length of Westland, in which case there can be very extensive aggradation on floodplains anywhere. Figure 11 indicates areas that could be affected by aggradation following a major earthquake.

Fig. 11 Floodplains in Westland (orange) potentially vulnerable to post-seismic aggradation following the next major earthquake in the region. White line = State Highway 6

If a future event were to comprise two smaller earthquakes separated by several decades, as has been suggested for the ca. 1400 AD Alpine Fault event (Wells and Goff 2007), then each might cause as much aggradation as the ca. 1620 AD event, and each would likely affect a different part of Westland, with a similar total effect as a single event. Note that the ca. 1620 AD earthquake modelled by Briggs et al. (2018) has a magnitude of $M_w7.6$; two such events would be equivalent in energy release, and hence in sediment volume, to a single $M_w7.9$ event. Robinson et al. (2016) estimated that a $M_w8.0$ earthquake on the Alpine Fault could generate approximately 30,000–70,000 coseismic landslides, affecting close to 7,000 km^2 of the Southern Alps and generating some cubic kilometres of sediment. That study identified 16 larger river catchments as being most severely affected by landsliding, including all west-draining catchments in the central Southern Alps. The Waiho catchment near Franz Josef was anticipated to be one of the worst-affected in terms of landslide number, producing ten times more landslides than average for the size of the catchment. Once an event has occurred, river catchments and floodplains will begin to adjust immediately. Some rivers will be completely dammed for a period of time (days-decades), only for the dams to eventually overtop and fail causing downstream flooding and sediment transport. Much of the finer landslide-derived sediments will be carried out to sea in suspension relatively quickly, probably within a few months, but the larger (bedload) sediments will be mobilised and redeposited by river flow, instigating channel avulsions and aggradation as they slowly make their way through the river system. This process could take from 10 to 50 years (Wells and Goff 2006, 2007).

The Westland floodplains are no longer covered by dense podocarp forests as they were during past aggradation episodes, so the progression, depth distribution and perhaps extent of aggradation in the future are likely to be different from those inferred from previous events. It seems likely that future aggradation will be more extensive than in the past, since forests impede water flow and hence sediment movement through them; the lack of forest cover will similarly hasten the progression of aggradation over the floodplain. While aggradation will still be greater close to the mountains than farther downstream, the depth of future aggradation may be somewhat less in the upper floodplains and greater in the lower parts. Because the distance between the range front and the coast decreases to the south, southern floodplains tend to be shorter than their northern counterparts (Fig. 10). However, the width of the mountain belt from main divide to range front (Fig. 4) does not decrease in this way; this may mean that aggradation progresses more rapidly to the ocean in more southern locations. In any case, aggradation anywhere in Westland is likely to be extensive and prolonged.

The progress of aggradation following a future earthquake will be determined by river flows at the time, and given the multi-decade time-scale of aggradation, changes in river flows due to climate change can be expected to be relevant. Collins (2021) has addressed this issue, suggesting for example that under the most extreme climate-change scenarios, winter river flows in Westland may exhibit detectable increases at such timescales. However, more useable inferences await further research.

In summary, what is known about the next major Westland earthquake is that:

1. It has a probability of about 75% (29–99%) of occurring in the next 50 years (Howarth et al. 2021). However, there is no way of knowing when it will occur; this may not be for another century, or it may be today.
2. It is likely to have a magnitude greater than M_w 8.0, and may extend along the whole region, with localised ground shaking up to MM12 (maximum ground acceleration

greater than that of gravity) and shaking duration of up to a few minutes (Orchiston et al. 2018).

3. It may comprise two (or more) events of smaller magnitude ($\leq M_w 7.7$).
4. It will be followed by aftershocks up to $M_w 7+$, decreasing in magnitude and frequency over several years.
5. It will cause extensive large-scale landsliding, leading to widespread aggradation and avulsion developing in some rivers, with corresponding flooding and metre-scale sediment deposition over substantial proportions of floodplains.
6. These changes in river behaviour are likely to persist for some decades.

8 Societal impacts of the next earthquake-generated aggradation episode in Westland

The short-term (one-week) consequences of the next Alpine Fault earthquake have been investigated in some detail in the AF8 project (Orchiston et al. 2018) so will not be discussed here. Suffice it to state that there will be much damage to buildings and structures, roads, infrastructure and lifelines from shaking and landslides, such that intensive, wide-scale and coordinated emergency response measures will be needed, including evacuations of remote settlements.

At a longer time-scale, while the particular spatial distribution of severe aggradation cannot be anticipated, there will be most damage where infrastructure is located. Thus townships located on rivers close to the mountain front are likely to be worst-affected (e.g. Franz Josef and Fox Glacier, Fig. 1) while those farther from rivers or at the coast will be less threatened (e.g. Okarito and Hokitika). Roads, power lines and communications, being distributed widely across the floodplains as well as through steep country, will be widely damaged.

Once the emergency response is complete, attention will return to recovery, that is, to restoring societal and commercial activity to result once more in a flourishing Westland province. It is at this recovery time-scale (months–decades) that the aggradation processes discussed herein become important, because the river response will likely manifest itself increasingly over several months or years following the trigger event(s) as occurred with the 1999 Mt Adams landslide in Westland (Hancox et al. 2005). In this time-scale, also, it is likely that any large landslide dams formed by coseismic landslides will fail, causing sudden and brief but severe sediment-laden floods to occur in rivers. Upper-valley aggradation from the Mt Adams event appeared to peak about a decade after the landslide (Robinson and Davies 2013), but that was a relatively small, isolated event. As indicated by the time-scale of establishment of coastal sediment ridges (Wells and Goff 2006, 2007), however, the high-sediment river regime is likely to remain active for up to several decades as the excess sediment input moves through the river systems to the sea.

The recovery and rebuilding phase following the earthquake will be a very difficult time for all in Westland, due to lack of access, transport, power and communications. Restoration of these services will therefore be a high priority, and the critical requirement for this will be restoration of transport (primarily road) access throughout Westland. Since the roads frequently cross the major rivers near the range front (Fig. 10) where aggradation will be greatest (and where damage may be greatest due to proximity to the fault), it will be necessary to replace bridges with structures designed to cope with aggradation and high river bed levels over several decades. Similarly, reinstating roads of all types on floodplains across which rivers are actively avulsing, flooding and depositing sediment will be difficult, and controlling these rivers would seem to be an extremely difficult task until the aggradation starts to decline–which may take decades.

Research associated with the AF8 programme (Davies et al. 2021) has considered the time required to reinstate services from damage occurring during the earthquake and immediately afterwards. This indicates that more than six months after the mainshock State Highway 6 (SH6), the major artery running through Westland to southern New Zealand (Fig. 11), will still be impassable south of Franz Josef, as will SH73 connecting Westland with the east coast. Reinstatement of the road link southwards through the Haast Pass to Otago (Fig. 1) seems likely to require a number of years to complete, and because this through link is a major component of South Island tourism its reinstatement will be critical to the national economy. Most of the damage considered in the analysis of Davies et al. (2021) is due to landslides and rockfalls in mountainous sections of roads. This did not take into account the additional damage to SH6 due to later-onset and much longer-duration river aggradation that may affect any or many of the major Westland rivers. It is likely that these river behaviour issues will considerably increase the difficulty of and time-frame for reinstatement of the road network in Westland. Reinstatement of power and communications networks would be correspondingly delayed.

Many settlements (or townships) in Westland are located on floodplains, and usually not far distant from the mountain front (Figs. 1, 11), meaning that they are likely to be threatened with river flooding and sediment deposition soon after the earthquake as rivers start to aggrade and avulse. Being small in extent, settlements could in principle be protected by ring-levees surrounding the area, although these would bring problems of surface water drainage. Given that metre-scale aggradation is possible, these levees would also need to be at least metre-scale in height. This solution may also be applicable—but less economic—for isolated dwellings such as farmhouses and their outbuildings. While river flooding and avulsion will make the use of floodplains for agriculture (mainly grazing) more difficult, it is likely that at any time only a part of the area of any floodplain would be unsuitable for such use, but this area will be susceptible to rapid change as rivers avulse. Thus while agriculture may be feasible it would be more difficult, but as long as the farm buildings and services are secure it may be viable. However, dairy farming and forestry are the two major agricultural industries in Westland, and both require road access to transport products to main centres for processing and sale, so both will be slow to re-establish.

Since restoration of power and communications depend largely on road access, even the use of aircraft and helicopters to utilise sites with no road access will not facilitate re-opening of commercial enterprises to a significant extent. Thus it appears that post-event river aggradation has the potential to substantially delay the re-establishment of the rural economies of Westland. Given that the impacts of non-floodplain hazards (rockfall, landslides, debris flows) on the roading system will cease once aftershocks reduce to below about M_w6.2 (Hancox et al. 1997)—probably after a few years or so—it is clear that the (decade-scale) ongoing impact of aggradation will thereafter become the major impediment to rapid reinstatement of infrastructure and lifelines.

As this situation becomes apparent to officials, and with aggradation the only remaining substantial impediment to restarting the mainstream economy, it is possible that extra-ordinary measures may be undertaken to accelerate this, including perhaps large investments in stopbanking, dredging and other river control measures. Experience with trying to maintain flood risk at an acceptable level on the chronically-aggrading Waiho River (Beagley et al. 2020), however, suggests that this task would be very difficult; indeed, a proposed long-term management strategy for the Waiho is to allow it to reoccupy its natural floodplain by judiciously removing the stopbanks that have allowed its bed to aggrade far above its natural level. This suggests that alternative flood-management strategies will be worth considering, such as redeveloping infrastructure in less vulnerable locations.

9 Conclusions

We have derived, from new and previous data, a regional distribution of dated forest stands in Westland, and associated these with aggradation episodes following the occurrence of prehistoric earthquakes in the region. Our data show that these episodes following earthquakes in ca. 1400 AD, ca. 1620 AD, 1717 AD and 1826 AD varied in location and extent, and in some events aggradation on some floodplains was extensive, involving most of the total floodplain area. This suggests that following a future major earthquake, large areas of some floodplains currently used for commerce, dwelling or access may be affected for some decades by frequent flooding and sedimentation. Given that the time elapsed since the last major earthquake in the region is greater than any known previous interlude, the next earthquake is anticipated to be large in magnitude (M8 +) due to the correspondingly large accumulation of tectonic stress. Further, given the known difficulty of providing flood protection from the steep, gravel-bed rivers of the region even without post-seismic sediment inputs (e.g. Davies 1997; Davies et al. 2013; Beagley et al. 2020), the redevelopment of commerce in the region following this event is likely to be significantly affected by large-scale river management problems, possibly for some decades.

The present work allows us to suggest the potential extent of floodplain aggradation following the next major (M_w8 +) Westland earthquake, which has a 75% probability of occurrence in the next 50 years. The actual distribution will depend on the location and rupture length of the causative fault(s), which is unknowable, so it must be anticipated that, during the decades following the earthquake, any Westland floodplain can be affected by metre-scale aggradation over much of its area, in some cases to within a few km of the coast.

Planning to address this issue on the basis of knowledge of previous events (e.g. Penney et al. 2022) will, however, be complicated by two unknown factors: (i) the extent to which climate change over several decades will alter the flows and sediment transport capability of rivers, compared to those of past events (e.g. Collins 2021); and (ii), the fact that previous river aggradation and avulsion episodes took place on largely native-forested floodplains, while the next episode will take place across largely pasture-covered floodplains.

The delayed and long-term impacts of widespread river aggradation, avulsion and flooding have the potential to severely affect the recovery and redevelopment phases of response to the next major Westland earthquake, in particular by delaying reinstatement of roads and bridges, which in turn will delay reinstatement of power and communications lifelines. These hitherto neglected long-term impacts are a serious potential threat to redevelopment of the rural Westland economy and the national tourism industry.

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Data availability Processed data are available upon request to the authors.

Declarations

Conflicts of interest Competing interests (include appropriate disclosures): Not applicable.

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