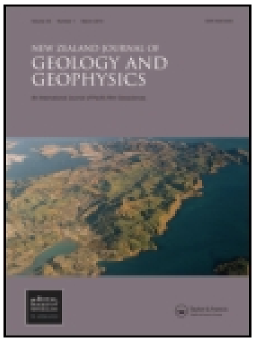

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Luminescence age estimates of Pleistocene marine terrace and alluvial fan sediments associated with tectonic activity along coastal Otago, New Zealand

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Abstract Six luminescence age estimates have been obtained from raised beach sands and loess, and alluvial fan sediments in the outboard zone of the active Otago reverse fault province, coastal Otago, New Zealand. These age estimates constrain the timing of movement of the Akatore Fault and the Titri Fault System. Five of the samples were dated by optical dating of K-feldspar in the polymineral fine silt fraction; the remaining sample was dated using thermoluminescence (TL) emitted from quartz (fine sand fraction). Raised beach sands from the lowest Pleistocene marine terrace on the upthrown side of the reverse faults (Taieri Beach) yielded ages of 117 ± 13 ka (optical dating, K-feldspar) and 117 ± 12 ka (TL dating, quartz), indicating terrace formation during the peak sea-level highstand of the last interglacial, marine oxygen isotope substage (MISS) 5e (c. 125 ka). The K-feldspar optical age has not been corrected for anomalous fading, but its consistency with the quartz TL age indicates that anomalous fading is insignificant in this sample. Samples from a raised beach sand unit and an underlying loess unit that bracket a marine terrace that has previously been associated with the c. 125 ka sea-level highstand, situated 10 km northeast of the effects of faulting (Warrington), yielded optical age (K-feldspar) estimates of 97 ± 11 and 96 ± 5 ka, respectively. These ages have not been corrected for anomalous fading and therefore the true ages might be slightly older. Two loess units within alluvial fans along the Titri Fault System in the Waihola region yielded optical age estimates of 92 ± 5 and 151 ± 5 ka (both K-feldspar), which bracket the last period of faulting along the Titri Fault System; the latter age result is consistent with geomorphic evidence that suggests fan formation during the glacial period MIS 6 (186–128 ka); this consistency also implies that there was no significant anomalous fading in these samples. Together with published radiocarbon ages, our results imply that no activity has occurred on the Akatore Fault in the period c. 125–3.8 ka and only localised activity (at Moneymore) on the Titri Fault System post-150 ka.

Keywords luminescence; optical dating; thermoluminescence; Quaternary; marine terrace; alluvial fan; active fault; Otago

INTRODUCTION

The coastal Otago region forms the outboard edge of the Otago reverse fault province, part of the c. 300 km wide Australian-Pacific plate boundary zone, diagonally crossing the South Island of New Zealand (Fig. 1). The major northeast-striking, reverse faults of the area are Quaternary-active (e.g., Bishop & Turnbull 1996; Barrell et al. 1998; Litchfield & Norris 2000; Litchfield 2001), and accordingly have significantly influenced local landscape evolution. The timing of Pleistocene fault activity has remained problematic, however, because of the lack of numeric ages.

The Titri Fault System and the Akatore Fault are together responsible for uplift of the coastal range southwest of Dunedin (Fig. 1). The structure of these faults is described by Litchfield & Norris (2000) and Litchfield (2001). In brief, they are steeply dipping (60–70°SE) reverse faults, c. 65 km (Akatore Fault) and c. 58 km (Titri Fault System) in length. The major range-bounding fault, the Titri Fault System, deforms alluvial fans along the east side of the Tokomairiro and Taieri Basins (Litchfield 2001). The Akatore Fault, which rides piggy-back on the Titri Fault System, is only partly exposed onshore, the majority lying c. 1 km offshore, parallel to the coast. The Akatore Fault is the only fault to show evidence of Holocene motion, with two c. 3 m uplift events recorded at blocked swamps and by raised marine benches along the coast. These events have been constrained by radiocarbon dating to 1150–1000 and post-3800 yr BP (Litchfield & Norris 2000).

Where radiocarbon dating cannot be applied, geochronological control has come from luminescence dating. Before this study, seven luminescence ages from sediments resting on uplifted terraces associated with movement of the Akatore Fault and the Titri Fault System have been published (Barrell et al. 1998; Rees-Jones et al. 2000). However, these ages, which are based on various techniques, have in some cases inadequate precision, and (or) are inconsistent between techniques. Furthermore, one key age was based on dating K-feldspar inclusions within quartz using infrared excitation, a technique that has not yet been shown to be generally applicable.

In this paper we report the results of six new luminescence ages, based on methods that have been well tested on deposits from various parts of the world, and discuss the results in the context of those already in the literature. Luminescence dating was applied to: (1) raised beach sediments of the

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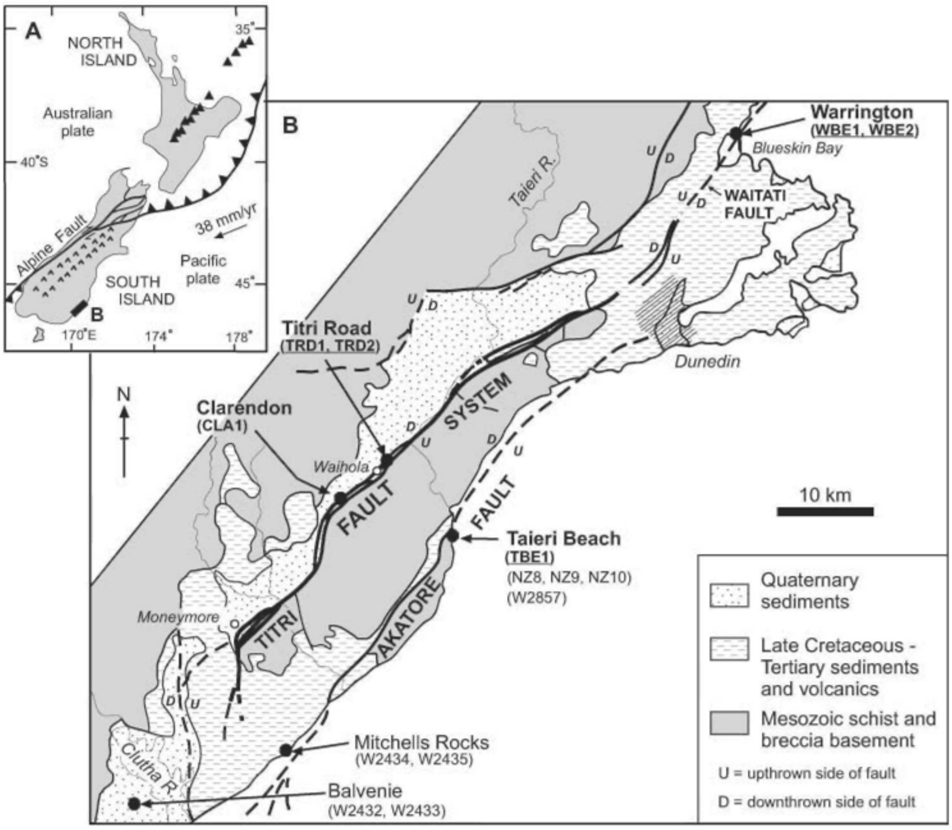

Fig. 1 **A**, Plate boundary setting of the coastal Otago area (▲ = volcanoes of the Taupo Volcanic Zone, ^ = Southern Alps. **B**, Location of luminescence samples referred to in the text; samples labelled in bold and underlined are from this study. References for the remaining samples are given in Table 3.

lowest Pleistocene marine terrace along the seaward edge of the fault blocks, and to loess underlying the terrace, and (2) loess within alluvial fans deformed by the Titri Fault System. In the following discussion, marine oxygen isotope stage (MIS) and substage (MISS) boundaries follow those used by Lee & Begg (2002).

SAMPLE SITES

Seven luminescence dating samples were collected from four sites, which included two marine cliff sections along the coast (Taieri Beach and Warrington), and two roadcut exposures in alluvial fan deposits along the Titri Fault System (Titri Road and Clarendon). The lithostratigraphy at each of our sample locations is briefly described below, while the lithostratigraphy at sites associated with previously published luminescence ages discussed in this paper (Balvenie and Mitchells Rocks sites) is discussed in Barrell et al. (1998). Locations of all the sites are shown in Fig. 1; lithostratigraphic logs are shown in Fig. 2.

Taieri Beach

Taieri Beach site (Fig. 1) is a marine cliff section that exposes c. 5 m of unconsolidated sediment resting on a shore platform c. 4 m above high sea level (a.h.s.l.) (Fig. 2). The terrace is situated 300 m east of the Akatore Fault on its upthrown side and it is the lowest of a set of Pleistocene surfaces that reach an elevation of 160 m a.h.s.l. (e.g., Bishop 1994; Barrell et al. 1998; Litchfield 2000). The 4 m high shore platform is cut into the Mesozoic schist basement (Otago Schist), and has been offset 2–4 m across the Akatore Fault (Litchfield & Norris 2000). The overlying sediments have been described and dated (Fig. 2) by Rees-Jones et al. (2000). Briefly, they consist of two quartz-rich beach sand units, together c. 3 m thick, that are overlain by a single sheet of loess c. 1 m thick. The lower sand unit was sampled for this work (sample TBE1, W2857), c. 1 m above the shore platform (Fig. 2). These samples were selected with the intention that their age would closely date the time of terrace formation.

Warrington

Northeast of Dunedin a single 4–8 m high marine terrace is preserved around the northern margin of Blueskin Bay estuary (Fig. 1). The terrace is slightly deformed, being tilted to the northeast and offset 1 m by a small northwest-striking fault. The Waitati Fault passes immediately offshore of the sample site (Fig. 1) but shows no evidence of Quaternary activity. On the basis of this lack of Quaternary displacement, and on its northwest dip, the Waitati Fault is not considered to be a part of the Titri Fault System (Litchfield 2001).

The section sampled for dating is in the modern marine cliff. Quaternary volcanic boulder beach deposits are exposed and are overlain by quartzofeldspathic beach sand. At site Warrington-1 these deposits rest on loess, while at site Warrington-2 they rest on a shore platform cut into Miocene-age volcanics (Fig. 2). This underlying loess unit crops out in other exposures and can be traced for 200–250 m southwards beneath Blueskin Bay estuary, where it is overlain by Holocene deposits (Thomas 2000). At both sites the beach sand is overlain by loess up to 5 m thick.

Based on its low elevation, this terrace has traditionally been correlated to the peak sea-level highstand of the last

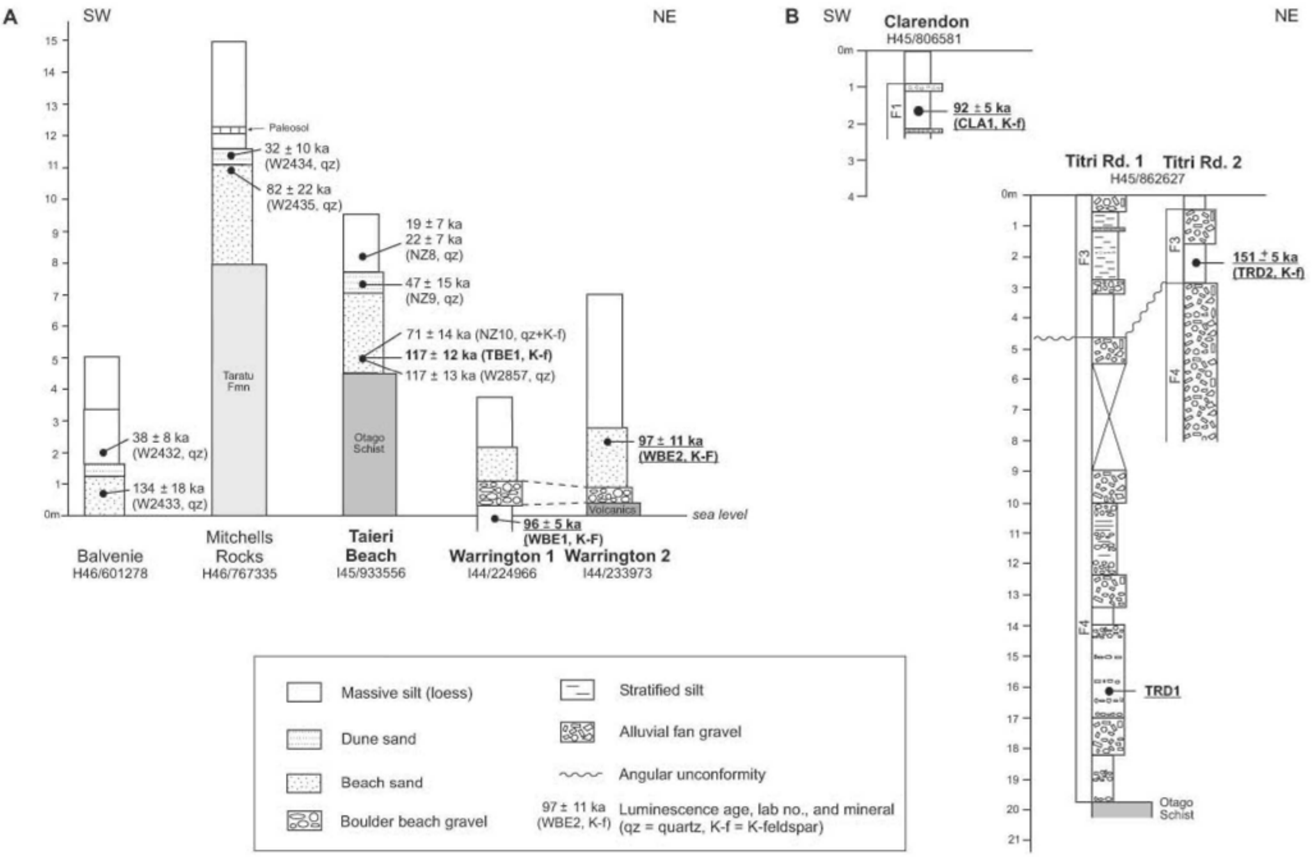

Fig. 2 Stratigraphic logs for all luminescence ages referred to in the text. Samples labelled in bold and underlined are from this study. Grid references refer to New Zealand Map Series 260 sheets (1:50 000). **A**, Marine terrace sections. **B**, Alluvial fan sections.

interglacial, MISS 5e (e.g., Landis 1983) but it has never been directly dated. If this terrace did indeed form during MISS 5e (i.e., c. 125 000 yr ago), it would indicate tectonic stability since that time (e.g., see Landis 1983; Gibb 1986; Pillans 1990).

Samples for optical dating were collected from the underlying loess at Warrington-1 (sample WBE1), c. 50 cm below its contact with the overlying beach gravel. Sample WBE2 was collected from site Warrington-2 from the beach sand c. 1.5 m above the contact with the beach gravel (Fig. 2). The age of the beach sand should approximately date the terrace, while that for the underlying loess should give a maximum age for the terrace.

Clarendon

Roadcut exposures along State Highway 1 near Clarendon (Fig. 1) expose the youngest alluvial fans mapped along the Titri Fault System (F1, Litchfield 2001). These fans have a well-preserved surface morphology and show no evidence of tectonic deformation. They are also covered in loess and show no evidence of recent deposition. At the sample site a c. 1 m thick loess unit is sandwiched between two thin (c. 10 cm) beds of greywacke and schist gravel (Fig. 2). Sample CLA1 was collected from the loess, c. 1.5 m below the fan surface (Fig. 2). These fans are undeformed everywhere except locally at Moneymore (Litchfield 2001), thus the age of the sample should predate the formation of the scarp at Moneymore but postdate the last widespread movement on the Titri Fault System.

Titri Road

Alluvial fan deposits resting on the Otago Schist basement are exposed in roadcuts along Titri Road, northeast of Waihola township (Fig. 1). The fan deposits consist of subangular schist and greywacke gravel interbedded with massive silt units which have been interpreted as loess; a detailed account of the sedimentology and stratigraphy can be found in Litchfield (2000, 2001).

The fans in this region have been uplifted and (or) deformed by a frontal fault of the Titri Fault System, Waihola 1 (Litchfield 2001). At the Titri Road site (Fig. 1), two gravel-loess sequences are separated by an angular unconformity (Fig. 2). The lowest sequence (F4) is tilted (attitude of 061/25°S), while the overlying sequence (F3) appears subhorizontal in section, but the fan surface is back-tilted towards the range (SE) between 4 and 8°. Samples from two buried loess units were collected for dating: sample TRD1 was collected from F4, c. 16 m below the fan surface, while sample TRD2 was collected from F3, c. 2 m below the fan surface (Fig. 2). These samples were collected with the intention that their ages would date alluvial fan deposition, and thus provide limiting ages for the deformation and erosion of the lower sequence (F4), and minimum age constraints on the back-tilting.

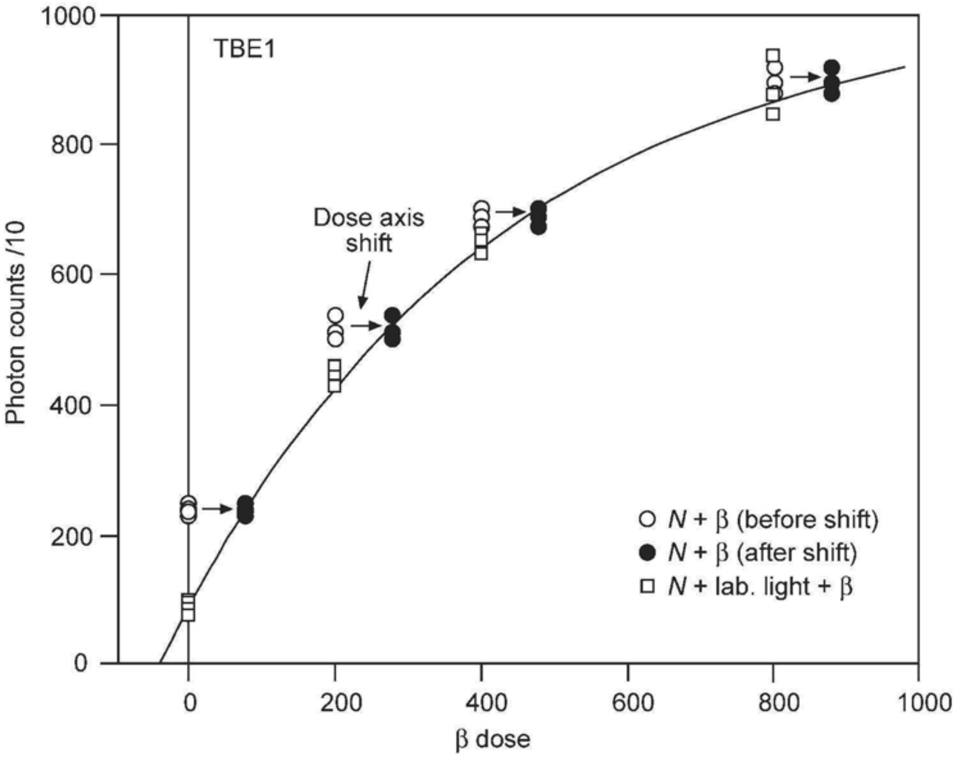

Fig. 3 Example of the regeneration method used to find the equivalent dose. Shown are the β-response curves for both the additive-dose ($N + \beta$) and regeneration (N + lab. light + β, square points) data for the first 10 s of excitation. The black dots are the $N + \beta$ data shifted along the dose axis for best fit, the shift being equal to the equivalent dose after correction for normalisation decay and incomplete laboratory bleaching. The white circles are the $N + \beta$ data before the shift. Sensitivity change is monitored by including a scaling parameter in the fit. For each sample, dose-axis shifts (in this case 94 Gy) were constant with excitation time, and thus the equivalent dose used in the age calculation was that which was determined using the luminescence integrated over the entire excitation time. Similar curves for the other samples are reported by Litchfield (2000).

OPTICAL DATING

Sample collection and preparation

Samples were collected from cleaned vertical faces either by inserting opaque plastic tubes (samples TBE1, WBE1, WBE2, W2857), or by excavating intact sediment blocks (samples TRD1, TRD2, CLA1). The samples were collected in natural daylight, and were wrapped immediately in aluminium foil and opaque black plastic. Sample W2857 was sent to University of Wollongong for thermoluminescence (TL) analysis, while the rest were prepared and analysed at Victoria University of Wellington as follows: for dating, c. 100–300 g (moist) of each sample were collected from the middle of the tubes/blocks once the outer light-exposed layers had been removed (all sample preparation was performed under subdued orange light). The bulk samples were prepared using standard methods, as outlined in Lian & Huntley (1999). For each sample, at least 50 aliquots were prepared, each holding c. 1 mg of 4–11 μm diameter (fine silt) polymineral sediment.

Determination of the equivalent dose and the environmental dose rate

Equivalent doses were determined by constructing the dose response of each sample using the violet (c. 3.1 eV, 400 nm) luminescence emitted during excitation of the K-feldspar fraction with infrared photons (c. 1.4 eV, 800–960 nm). Laboratory irradiation was at 6.7 Gy/min from a ^{90}Sr–^{90}Y β source. Before the final measurements all the sample aliquots (except some control aliquots) were heated ("preheated") together for 7 days at 140°C. All measurements were carried out using a Risø TL-DA-15 Minisys system (Bøtter-Jensen 1997) with a EMI 9135QA photomultiplier tube mounted behind Schott BG-39 and 5-59 optical filters that together selectively pass emission from K-feldspar and block the 2.2 eV (570 nm) emission from plagioclase feldspars.

Both the additive-dose with thermal transfer correction (ADTT) method and the regeneration method (e.g., Huntley et al. 1993a,b; Huntley & Clague 1996; Lian & Huntley 1999, 2001; Lian & Shane 2000; Ollerhead et al. 2001; Little et al. 2002) were used to evaluate the equivalent dose. An example of the regeneration method is shown in Fig. 3.

For each sample, the environmental dose rate was calculated from the concentrations of the parent radioisotopes ^{40}K, ^{232}Th, and ^{238}U by laboratory elemental analyses of subsamples of the bulk samples used for dating (Table 1). Radioactive disequilibrium in the U and Th decay chains at the time of sample collection was tested for in samples WBE2, CLA1, and TBE1 by thick-source alpha counting (TSAC) (Huntley et al. 1986).

Recent published work on K-feldspar samples from Canada, New Zealand, and Russia (Huntley & Lamothe 2001), and currently unpublished data from other K-feldspar samples collected from various parts of the world (D. J. Huntley pers. comm. 2003), together suggest that anomalous fading is a phenomenon that probably is common to the infrared-excited luminescence from all K-feldspars. The degree at which anomalous fading affects a calculated optical age depends on the rate at which fading occurs, and this differs between samples. It is clear, however, that for some samples anomalous fading is insignificant as far as optical dating is concerned because optical ages derived from them are consistent with independent information. To ascertain the severity of anomalous fading in our samples, fading measurements were made on each sample as described by Lian & Shane (2000). A further test for one of our samples came from comparison of its optical age with that found from TL dating of quartz sand; quartz is not known to suffer from anomalous fading.

For the beach sand samples, the water content value used for the dose-rate calculation was the average between the as-collected and saturated values, while for the better drained alluvial fan loess samples the as-collected value was used. The uncertainty used for each water content value is expected to account for wet periods and dry periods at two standard deviations (2σ) (Table 1).

The dose rate due to cosmic rays depends on the sample's depth beneath the ground surface, and can only be accurately calculated if the rate of sedimentation is known in detail and major unconformities are accounted for, which was not the case here. At the present burial depths, the contribution of cosmic rays to the total dose rate is small, accounting for only 1–8% (15% for sample TBE1) of the total dose rate. At all sample sites, the sampled units presently underlie a loess cap, which accounts for up to c. 4 m of the overburden. TL ages from the Balvenie and Mitchells Rocks sites (Barrell et al. 1998) suggest that the loess caps are much younger than the underlying units, by up to a factor of three. At all the sample sites, except for TBE1, if the thickness of the loess cap is removed from the cosmic ray dose rate calculation, the total dose rate increases by only c. 1%. For these samples, we use the present burial depths in the dose-rate calculations; for sample TBE1 we include an appropriate uncertainty (Table 2).

RESULTS

For samples WBE2 and TBE1, equivalent doses were calculated using both the ADTT and regeneration methods, and the values were found to be consistent (Table 2). For the other samples, the luminescence measured from aliquots that had received no laboratory radiation (i.e., the "naturals") was close enough to saturation so that extrapolation of the dose-response curves to the dose axis was relatively large, which resulted in equivalent dose values of low precision; for those samples, only the equivalent doses found using the regeneration method were considered (Table 2).

For the samples tested for radioactive disequilibrium, U and Th concentrations calculated from laboratory elemental analyses were consistent with those determined from TSAC, suggesting that disequilibrium was, and likely has been, insignificant in these deposits. Environmental dose rates were calculated using the more precise values found from laboratory elemental analyses (Table 1).

For all the samples, optical ages were calculated using the more precise equivalent dose values found using

Table 1 K, U, and Th concentrations, and water contents for samples introduced in this paper.

				Water content[d]		
Sample	K[a] (%)	Th[b] ($\mu g.g^{-1}$)	U[c] ($\mu g.g^{-1}$)	as collected	saturated	used
WBE2	0.70 ± 0.01	3.3 ± 0.1	0.51 ± 0.08	0.073	0.378	0.225 ± 0.076
WBE1	1.62 ± 0.03	10.7 ± 0.4	2.64 ± 0.10	0.281	0.302	0.281 ± 0.010
CLA1	1.10 ± 0.02	11.9 ± 0.3	2.84 ± 0.11	0.175	0.248	0.175 ± 0.035
TBE1	0.24 ± 0.01	3.2 ± 0.2	0.44 ± 0.08	0.091	0.305	0.198 ± 0.054
TRD2	0.89 ± 0.02	9.8 ± 0.3	2.31 ± 0.10	0.071	0.400	0.235 ± 0.082

[a] From inductively coupled plasma atomic emission spectrometry (ICP-AES).

[b] From neutron activation analysis.

[c] From delayed neutron counting.

[d] Water contents are (water mass)/(dry mineral mass).

Table 2 Equivalent doses, *b* values, dose rates, fading ratios, and optical ages for samples introduced in this paper.

	Equivalent dose (Gy)[a]					
Sample	ADTT	Regeneration	*b* value[b] ($Gy.\mu m^2$)	$\dot{D}_C$[c] ($Gy.ka^{-1}$)	$\dot{D}_T$[d] ($Gy.ka^{-1}$)	Optical[e] age (ka)
WBE2	118 ± 12	107 ± 5	0.79 ± 0.04	0.09	1.10 ± 0.11	97 ± 11
WBE1	–	270 ± 13	1.06 ± 0.09	0.12	2.82 ± 0.09	96 ± 5
CLA1	–	287 ± 7	0.79 ± 0.09	0.16	3.12 ± 0.15	92 ± 5
TBE1	89 ± 5	94 ± 3	1.06 ± 0.09	0.12	0.80 ± 0.08	117 ± 12
TRD2	–	369 ± 11	1.00 ± 0.10	0.03	2.44 ± 0.04	151 ± 5

[a] ADTT = additive dose with thermal-transfer correction method; the regeneration method used is explained in Fig. 3.

[b] *b* value (α efficiency) as defined by Huntley et al. (1988). The values listed for sample TRD1 and TRD2 are estimates. Irradiations were from ^{241}Am sources that delivered a radiation to the sample at 0.16 cm^{-2} min^{-1}.

[c] $\dot{D}_C$: Dose rate due to cosmic rays, calculated using the formula of Prescott & Hutton (1994). An uncertainty of 0.03 is included in the values for samples WBE2 and TBE1.

[d] $\dot{D}_T$: Total dose rate (that due to cosmic rays plus that due to γ, β, and α radiation). Calculated using the dose-rate conversion factors of Adamiec & Aitken (1998).

[e] In each case the equivalent dose from the regeneration method was used for the age calculation. Ages have not been corrected for anomalous fading, and must therefore be considered a lower limit; see the text for discussion. Our K-feldspar optical age for sample TBE1 is consistent with a quartz TL age for the same unit, suggesting that anomalous fading was insignificant, or did not occur, in this sample. Analytical uncertainties are ±1σ.

regeneration (Table 2), and these are all within the established c. 150 ka upper age limit for this regeneration method (e.g., Lian & Huntley 2001).

Experiments undertaken to ascertain the severity of anomalous fading in our samples yielded unusable results. This was because the luminescence intensity measured from all of the samples was low, which resulted in analytical uncertainties in the calculated fading ratios being between 2.5 and 7.2%, and this, in turn, did not allow for the calculation of fading rates of adequate precision.

DISCUSSION

In Table 3 the luminescence ages presented here are summarised together with those previously published for the study area.

Marine terrace ages

Luminescence ages of beach sands resting on the shore platforms are all consistent with deposition during MIS 5, 128–71 ka, while the luminescence ages of the overlying dune sand and loess overlap the last (Otira) glacial period (MIS 4–2, 71–12 ka). An optical age (K-feldspar) for loess underlying raised beach sediment appears to be too young (sample WBE1, discussed at the end of this section).

Limiting the marine terrace (beach sediment) ages to one of the three sea-level highstands of MIS 5 (i.e., MISS 5e (128–113 ka), MISS 5c (105–92 ka), or MISS 5a (82–71 ka)), is critical for calculating uplift rates because sea-levels during each highstand were different, possibly by as much as 25 m, from that of the present interglaciation (e.g., Chappell et al. 1996). For instance, if the lowest Pleistocene terrace along the upthrown side of both the Akatore Fault and Titri Fault System (i.e., Taieri Beach site) is c. 125 ka in age, then its relatively low elevation (c. 5–20 m strandline elevation; Litchfield 2000) implies little or no uplift has occurred on either fault in the period 125–3.8 ka (i.e., when activity resumed on the Akatore Fault; Litchfield & Norris 2000). If, instead, this terrace formed c. 80 000 yr ago, as suggested by a previously published luminescence age (sample NZ10, below) (Rees-Jones et al. 2000), then either: (1) considerable uplift has occurred since then, or (2) sea-level estimates in the coastal Otago area are too low (Rees-Jones et al. 2000).

Three separate samples of Taieri Beach beach sand, collected within 1 m of each other, have been dated using three different techniques: two of the ages are introduced in this paper (samples W2857 and TBE1), and the third (sample NZ10) was presented in Rees-Jones et al. (2000). The ages of samples W2857 (117 ± 13 ka) and TBE1 (117 ± 12 ka) are consistent, but the third, sample NZ10 (71 ± 14 ka) appears to give an age that is too young, although it overlaps slightly with the ages of samples W2857 and TBE1 at 2σ.

Sample W2857 was dated by D. M. Price at University of Wollongong using TL measured from quartz sand grains (90–150 μm diam.), and the combined additive-dose regeneration method, as described by Shepherd & Price (1990) and Nanson et al. (1991). Essentially, the method

Table 3 Equivalent doses, dose rates, and luminescence ages from all the samples in the coastal Otago region discussed in this paper.

Sample number	Depositional environment	Location	Reference	Method[a]	Equivalent dose (Gy)	Dose rate (Gy/ka)	Calculated age (ka)[g]
NZ8	loess	Taieri Beach	Rees-Jones et al. (2000)	optical[b]	39 ± 15 44 ± 15	2.038[f] 2.038[f]	19 ± 7 22 ± 7
NZ9	dune sand	Taieri Beach	Rees-Jones et al. (2000)	optical[b]	68 ± 22	1.441[f]	47 ± 15
NZ10	beach sand	Taieri Beach	Rees-Jones et al. (2000)	optical[c]	67 ± 13	0.943[f]	71 ± 14
TBE1	beach sand	Taieri Beach	this study	optical[d]	94 ± 3	0.8 ± 0.06	117 ± 12
W2857	beach sand	Taieri Beach	this study	TL[e]	72 ± 5	0.61 ± 0.01	117 ± 13
WBE2	beach sand	Warrington	this study	optical[d]	107 ± 5	1.1 ± 0.09	97 ± 11
WBE1	loess	Warrington	this study	optical[d]	270 ± 3	2.82 ± 0.09	96 ± 5
W2434	dune sand	Mitchells Rocks	Barrell et al. (1998)	TL[e]	92.1 ± 10	2.91 ± 0.04	32 ± 10
W2435	beach sand	Mitchells Rocks	Barrell et al. (1998)	TL[e]	152 ± 41	1.86 ± 0.03	82 ± 22
W2432	dune sand	Balvenie	Barrell et al. (1998)	TL[e]	153 ± 31	4.04 ± 0.04	38 ± 8
W2433	beach sand	Balvenie	Barrell et al. (1998)	TL[e]	134 ± 18	1.00 ± 0.02	134 ± 18
CLA1	loess in alluvial fan	Clarendon	this study	optical[d]	287 ± 7	3.12 ± 0.09	92 ± 5
TRD2	loess in alluvial fan	Titri Road	this study	optical[d]	369 ± 11	2.44 ± 0.04	151 ± 5

[a] See text for further discussion.

[b] Fine-grained quartz; green light excitation (514 ± 17 nm).

[c] Coarse-grained quartz; infrared (c. 880 nm) excitation. Emission presumed to be from feldspar inclusions. Age has not been corrected for anomalous fading.

[d] Fine-grained potassium feldspar; infrared (c. 880 nm) excitation. Ages have not been corrected for anomalous fading.

[e] Thermoluminescence of coarse-grained quartz using the 375°C peak.

[f] No analytical uncertainties were reported.

[g] Analytical uncertainties are ±1σ.

involves fitting a curve to the regeneration data, and plotting the natural TL on it. The additive-dose data are then plotted with respect to the natural value in order to check for sensitivity change (D. M. Price pers. comm. 2001). The TL used for construction of the dose response curves was measured at 375°C, and, although this temperature corresponds to the so-called slowly bleached TL peak, which can result in age overestimations for sediments sampled from poorly bleached environments (e.g., Spooner 1998), we do not believe that using it in this case would lead to age overestimation because the quartz grains dated are expected to have had received extended sunlight exposure while being part of an active beach.

Sample TBE1 (K-feldspar) gave an uncorrected (for anomalous fading) optical age estimate of 117 ± 12 ka (Table 2), which is consistent with that of quartz sample W2857. This suggests that either anomalous fading does not occur in sample TBE1, or that its effect is small and therefore the true age lies within the age-range defined by the analytical uncertainties. Based on the recent work of D. J. Huntley (publ. and unpubl., discussed above), we think the latter interpretation is most likely.

Sample NZ10 (Rees-Jones et al. 2000) was dated by measuring the violet (360–450 nm) luminescence resulting from the excitation of 90–150 μm diameter quartz grains with infrared (c. 880 nm) light, with the presumption that the measured emission originated from K-feldspar inclusions within the quartz. The observation that the violet emission resulting from the infrared excitation of some quartz samples could be used to produce accurate optical ages was first made by Huntley et al. (1993b). These authors tested the method on seven samples collected from independently dated aeolian dune facies of emergent coastal barriers in South Australia, ranging in age from 0 to 400 ka. These authors did not show directly that their samples contained K-feldspar inclusions, but suggested that such inclusions likely existed as the infrared-excited emission spectra included a 400 nm component that was typical of that of K-feldspar. Although these authors achieved good agreement between their optical ages and the independent age information, we stress that their apparent success should not be used alone to validate Rees-Jones et al.'s age for sample NZ10. In fact, "inclusion" ages, in general, should at present be considered with caution for two reasons:

(1) To our knowledge, no subsequent studies have been published that show that the method is generally applicable. Moreover, Godfrey-Smith & Cada (1996) showed that, for their samples (>100 quartz grains from 2 samples collected in Australia and Canada, made into a thin section for analysis), inclusions were found only in c. 65% of the grains, and, where present, accounted for only 0.05% of the grain area. Of these, only 25% were found to be K-feldspar. Based on this, Godfrey-Smith & Cada calculated that there was not enough K-feldspar in their samples to account for the measured luminescence. It must therefore be considered that, for some quartz samples, the measured infrared-excited luminescence is dominated by some other type of inclusion, or perhaps defect(s) in the quartz crystal lattice, and that they may not be appropriate for dating.

(2) Even if it can be concluded that it is K-feldspar inclusions that are being measured, the severity of anomalous fading must be properly assessed, and corrected for. If it is not, the calculated ages should serve only as lower limits. Anomalous fading can be measured with adequate precision for most feldspar concentrates, for which the intensity of the luminescence is sufficiently high (Huntley & Lamothe 2001). This is not likely to be the case for most K-feldspar inclusions using the detection apparatus presently available. Rees-Jones et al. (2000) presented results of some anomalous fading tests, and from this they suggest that their sample (NZ10) does not fade significantly. Their fading measurements are, however, too imprecise (errors of 8 and 14%) to support this conclusion.

On the basis of these arguments, we suggest that Rees-Jones et al.'s age for sample NZ10 (71 ± 14 ka) should not be considered alone in determining the age of Taieri Beach, until it can be confirmed that it is K-feldspar that is being dated, or that it can be determined that "inclusion" ages from these deposits are valid. If K-feldspar is found, the age should be considered a lower limit until the effect of anomalous fading can be properly assessed. We therefore support formation of the lowest Pleistocene marine terrace (exposed at Taieri Beach) during MISS 5e.

Barrell et al. (1998) dated a beach sand deposit from a marine terrace at Mitchells Rocks (Fig. 1) that can be correlated with the raised beach sand exposed at the Taieri Beach site, on the other (upthrown) side of the Akatore Fault. The age of their sample, W2435 (82 ± 22 ka), was determined at University of Wollongong using TL from quartz and the method described above. Unfortunately, the analytical uncertainty associated with this age is so large that, at ±2σ, the age (126–38 ka) indicates that terrace formation could have occurred during any marine highstand within MIS 5, or even during MIS 3.

The two other marine terraces in this region of southern South Island that have been dated by luminescence are situated beyond the influences of the Akatore Fault and Titri Fault System, and are considered to be in areas of relative tectonic stability. Barrell et al. (1998) reported a TL age from quartz (dated at University of Wollongong), from beach sand at Balvenie (Fig. 1, 2) that yielded an age of 134 ± 18 ka (W2433), which suggests terrace formation during MISS 5e (128–113 ka) sea-level highstand. Given the present terrace elevation close to sea level (Fig. 2), this terrace age is consistent with no tectonic uplift, or possibly even minor subsidence since that time.

The optical age of beach sand obtained from Warrington terrace during the present study (97 ± 11 ka, sample WBE2) is consistent with the quartz TL age for Balvenie terrace within 2σ. However, it is possible that the age for sample WBE2 is too young, and that this is due to anomalous fading. Unfortunately, our fading experiments yielded imprecise results, and generalisation about the severity of fading from the agreement in ages from samples W2857 (quartz) and TBE1 (K-feldspar) is risky, as sample WBE2 is at least partly derived from different bedrock (Fig. 1). The optical age for sample WBE2 can therefore be considered a lower limit. The presence of anomalous fading in sample WBE2 is supported by the optical age of a directly underlying loess unit (collected from an adjacent section, Fig. 2). The optical age of this loess unit is 96 ± 5 ka (sample WBE1). For the same reason mentioned above, this age must be considered a lower limit. However, if it is assumed that this loess formed during a glacial period, as is typical in the lower South Island (e.g., Berger et al. 2001, 2002), then sample WBE1 was probably deposited near the end of MIS 6 (186–128 ka), as it is unlikely that anomalous fading has resulted in an age underestimation of >300%, as would be the case if the sample was deposited during an older glaciation (i.e., during or before MIS 8). If this assumption is correct, then the overlying beach sand likely formed during the MISS 5e (128–113 ka) sea-level highstand. This age estimate is consistent with the interpretation of Landis (1983) and Gibb (1986), and demonstrates that the area has been tectonically stable since that time.

Alluvial fan ages

Samples from three loess units within alluvial fans were collected. Of these, only two samples, CLA1 and TRD2 (K-feldspar), were dated. The luminescence measured from a third sample (TRD1), collected from the oldest fans (F4) along the Titri Fault System (Fig. 2), was found to be c. 60% of its saturation value, so we decided not to calculate a luminescence age from it.

Sample TRD2 yielded an optical age of 151 ± 5 ka, which suggests that the second oldest fans (F3) along the Titri Fault System were deposited during the glacial period MIS 6 (186–128 ka), which is the age inferred by Barrell et al. (1998) and Litchfield (2001) on the basis of geomorphological evidence.

Sample CLA1, from the youngest fans (F1), yielded an optical age of 92 ± 5 ka, which is considerably older than the 14–24 ka (i.e., Last Glacial Maximum) age estimated by Litchfield (2001) based on geomorphological evidence. If our optical age for sample CLA1 is typical of the age of the youngest fans, then, apart from a loess cover, there has been virtually no deposition on these fans for c. 70 000 yr. This suggests that fan deposition in this region is not solely a function of climate (i.e., deposition during glacial periods), as inferred by Barrell et al. (1998) and Litchfield (2001). As an alternative, the fans may have formed in response to tectonics, during a formerly more active period of faulting along the Titri Fault System. F1 fans are everywhere undeformed, so the optical ages imply the last period of faulting on the Titri Fault System (i.e., deformation of F3 and, locally, F2 fans) occurred between c. 90 and 150 ka. This is consistent with the evidence from marine terraces on the seaward side of the Titri block for no uplift since 125 ka.

Our optical ages for samples TRD2 and CLA1 have not been corrected for anomalous fading and should therefore be considered as lower limits. However, since both these samples were collected from regions only 10 km away from Taieri Beach, from a region of similar bedrock, we expect anomalous fading to be insignificant.

CONCLUSIONS

Beach sands located on the upthrown side of the Akatore Fault at Taieri Beach gave luminescence ages of 117 ± 12 (TBE1, K-feldspar) and 117 ± 13 ka (W2857, quartz), while a beach sand sample collected beyond the limits of faulting at Warrington gave an age of 97 ± 11 ka (WBE2, K-feldspar). Together, these ages imply formation of the lowest Pleistocene marine terrace at the time of the peak sea-level highstand of the last interglacial (MISS 5e). The consistency between the K-feldspar age and the quartz age from Taieri Beach indicates that anomalous fading is insignificant in the former. The ages for Taieri Beach samples TBE1 and W2857 appear to be older than a previously reported optical age from the same site of 71 ± 14 ka (NZ10, presumed to be K-feldspar inclusions in quartz; Rees-Jones et al. 2000), but are consistent with a 134 ± 18 ka TL quartz age from Balvenie (Barrell et al. 1998). Because of the low terrace elevation, and small offset across the Akatore Fault, these terrace ages imply little or no movement on the Akatore Fault in the period c. 125–3.8 ka and no uplift on the Titri Fault System since c. 125 ka.

A sample from a loess unit directly beneath the uplifted beach gravels at the Warrington site yielded an optical age of 96 ± 5 ka (WBE1, K-feldspar). Based on stratigraphy and the luminescence ages of the overlying raised beach sand units, this loess unit is inferred to have been deposited during MIS 6 (186–128 ka), and therefore the age for sample WBE1 is too young by at least 25%, and we believe that this may be due to anomalous fading. Our data, however, support deposition of the raised marine sand at this site during the 125 ka sea-level highstand (MISS 5e).

A sample of loess collected in an alluvial fan at Clarendon along the Titri Fault System, c. 10 km from the Taieri Beach sites, gave an age of 92 ± 5 ka (CLA1, K-feldspar), while a loess sample collected from a fan at Titri Road stratigraphically below sample CLA1 gave an age of 151 ± 5 ka (TRD2, K-feldspar). These ages together indicate that the last faulting event on the Titri Fault System probably occurred between c. 90 and 150 ka, consistent with our age information from the marine terraces. The faulting event(s), which formed a 10 m high, 3 km long scarp near Moneymore (see Litchfield 2001 for details), must have therefore occurred much earlier than was inferred by Litchfield (2001).

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