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1 **Testing the accuracy of feldspar single grains to date late Holocene cyclone and tsunami**
2 **deposits**

3

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14

15 **Abstract:** Quartz is the preferred dosimeter for luminescence dating of Holocene sediments as
16 optically stimulated luminescence (OSL) signals reset rapidly upon light exposure, and are stable over
17 time. However, feldspar is required where quartz luminescence properties are inappropriate for
18 dating, as is often the case in geologically young mountain ranges and areas with young volcanism.
19 Here we aim to evaluate the potential of single grain feldspar luminescence dating applied to late
20 Holocene cyclone and tsunami deposits, for which complete signal resetting can *a priori* not be
21 guaranteed. To address potential problems of feldspar dating of such deposits associated with
22 heterogeneous bleaching, remnant doses and anomalous fading, we use a low-temperature post
23 infrared infrared stimulated luminescence protocol (pIRIR₁₅₀) on single grains.

24 For most samples, good agreement between fading corrected IR₅₀ and non-fading corrected pIRIR₁₅₀
25 ages is observed. Both feldspar ages generally also show good agreement with age control provided
26 by historical data and quartz luminescence ages. pIRIR₁₅₀ remnant ages in modern analogue samples
27 are shown to be <50 years, indicating that dating accuracy might be negatively affected by insufficient
28 signal zeroing only for sediments younger than ~500 years. As these minor remnant ages are
29 interpreted as being caused by unbleachable luminescence residuals, slight age overestimation for
30 young samples can be overcome by subtracting the remnant ages.

31 The good agreement between pIRIR₁₅₀, IR₅₀ and quartz ages, indicates that a significant number of
32 grains must have experienced relatively complete signal resetting during or immediately prior to
33 transport, as the three signals are known to bleach at different rates. Since light exposure during the

34 event is expected to be limited, we deduce that a significant portion of the grains in the cyclone and
35 tsunami deposits was already bleached prior to the event of interest. These well-bleached grains were
36 likely eroded the beach, while other grains with larger remnant ages probably originate from the
37 shallow subtidal, coastal barriers or even further inland sources. Additional signal resetting during
38 storm and tsunami transport is indicated by slightly younger quartz than feldspar ages for grains with
39 incomplete pre-transport resetting that were eroded at the Holocene coastal barrier.

40

41 **Keywords:** single grain dating; feldspar dating; post infrared infrared stimulated luminescence;
42 tsunami deposit; cyclone deposit; transport processes

43

44 **1. Introduction**

45 Flooding by tsunamis and tropical cyclones (TCs) poses a major risk for low-lying and densely populated
46 coastal areas worldwide. Since instrumental and historical records of tsunamis and TCs are often
47 limited to a few decades or centuries (Sugawara et al., 2008; May et al., 2013) – time periods usually
48 too short to predict long-term variations of TC activity (Donnelly and Woodruff, 2007) or the
49 recurrence intervals of large tsunamis (Cisternas et al., 2005) – interpreting sedimentary onshore
50 evidence is crucial for reconstructing long-term magnitude-frequency patterns of coastal flooding
51 events. This requires chronological information on identified event deposits. While the use of
52 radiocarbon and U/Th dating is often impeded by reworking or the absence of datable material (May
53 et al., 2015), optically stimulated luminescence (OSL) dating is more widely applicable.

54 If applied to sediments of mid- to late Holocene age, quartz is typically the preferred dosimeter for OSL
55 dating. Given the presence of a dominant fast component (cf. Jain et al., 2003), which is usually stable
56 at ambient temperature and easier to reset than feldspar signals (e.g. Wintle, 2008) this enables
57 successful dating of sediments as young as a few years using quartz OSL (Ballarini et al., 2003; Madsen
58 et al., 2005). Unfortunately, tsunamis are particularly frequent in areas with poor quartz properties (cf.
59 Tsukamoto et al., 2003). The majority is triggered by submarine earthquakes along geologically young
60 subduction zones associated with volcanism, such as in Japan, Chile or Indonesia. Likewise, volcanic
61 island arcs such as the Philippines and Japan are among the most TC affected regions worldwide. In
62 these regions, minerals typically originate from freshly eroded plutonic, metamorphic or volcanic
63 bedrock and thus experienced a restricted number of transportation cycles. In consequence, quartz is
64 often affected by dim luminescence signals (Lukas et al., 2007) and significant contributions of unstable
65 signal components (Preusser et al., 2006; Steffen et al., 2009).

66 As an alternative, optical dating of feldspar may give insights into the long-term frequency of tsunamis
67 and TCs in such regions (e.g. Huntley and Clague, 1996; Riedesel et al., 2018). However, feldspar
68 luminescence signals show slower resetting by sunlight compared to quartz OSL. Significant signals
69 that were not bleached in nature (remnant doses) may remain even after prolonged light exposure (Yi
70 et al., 2016). In environments prone to light exposure during sediment transport, feldspar signals
71 measured with a conventional infrared stimulated single aliquot regenerative dose (SAR) protocol at
72 50 °C (IR₅₀) have been proven to bleach sufficiently well to be useful even for very young deposits (e.g.
73 Gaar et al., 2013). However, incomplete signal resetting is assumed to be challenging for dating
74 tsunami and TC deposits which are usually transported under turbulent flow conditions, over short
75 distances, and sometimes even at night (e.g. Jaffe et al., 2012). In particular for young deposits with
76 ages of only a few hundred years or less, the remnant doses of feldspar may be large compared to the
77 relatively low natural doses accumulated since deposition (Reimann et al., 2011; Reimann and
78 Tsukamoto, 2012). Moreover, signal loss due to anomalous fading may cause large age
79 underestimation in feldspar dating (Huntley and Lamothe, 2001). Fading correction is possible, but
80 may be related to large uncertainties and/or inaccuracies (Wallinga et al., 2007; Trauerstein et al.,
81 2012).

82 Age underestimation due to fading in feldspar can be avoided or at least significantly reduced by using
83 more stable post-infrared infrared (pIRIR) signals (Thomsen et al., 2008; Buylaert et al., 2012).
84 Unfortunately, the most stable pIRIR signals measured at high temperatures >200 °C (i.e. pIRIR₂₂₅ and
85 pIRIR₂₉₀) are usually much harder to bleach than the IR₅₀ signal and may suffer from large residual doses
86 of several Gy (Kars et al., 2014). This impedes accurate dating of Holocene deposits, particularly if they
87 are incompletely bleached. Residual doses can be reduced by means of pIRIR signals measured at lower
88 temperatures (below ~200 °C) that are easier to reset and often still not significantly affected by fading
89 (Reimann et al., 2011; Fu and Li, 2013). Well-bleached and incompletely bleached feldspar grains may
90 be separated using single grain measurements (Reimann et al., 2012).

91 The combination of low-temperature pIRIR protocols with single grain measurements offers the
92 potential to isolate low or non-fading feldspar signals that are sufficiently bleached to enable dating of
93 young and incompletely bleached TC and tsunami deposits. By overcoming some of the main
94 drawbacks related to quartz dating of coastal flooding deposits, which are often accumulated in
95 stratigraphically complex near-shore archives affected by water table variations, these feldspar signals
96 may even be advantageous to those of quartz with adequate luminescence properties. In case of storm
97 sediments composed of mixtures of coral rubble, shell hash, and sand-sized quartz and feldspar, for
98 example, external dose rates are hard to reconstruct (Brill et al., 2017). The higher internal dose rate
99 of potassium feldspar can reduce the uncertainties of dosimetry assessment (Davids et al., 2010).

100 This study aims to evaluate the potential of feldspar luminescence dating to reconstruct late Holocene
101 coastal flooding events younger than 3000 years. For this, we apply single grain dating of sand-sized
102 potassium feldspar using both conventional IR₅₀ and low-temperature pIRIR signals to TC and tsunami
103 deposits from Northwest Australia, Southwest Thailand, East Japan, and the Central Philippines. We
104 compare the resulting feldspar ages with independent age control in the form of quartz OSL ages,
105 radiocarbon data, and regional records of historical tsunami and TC impacts to test the completeness
106 of signal resetting and the robustness of fading correction. Finally, the degree of resetting of feldspar
107 signals is used to infer information on the sources and the transport conditions of sediments within
108 tsunami and TC waves.

109

110 **2. Material and Methods**

111 **2.1 Tsunami and cyclone deposits dated in this study**

112 The tsunami and TC deposits investigated in this study originate from four different regions (Fig. 1a):
113 Eastern Japan (JSH, 3 samples), the Central Philippines (TOL, 2 samples), Southwest Thailand (KPT, 2
114 samples), and Northwest Australia (PLY, 16 samples). Selection criteria were the existence of robust
115 age control in form of quartz luminescence ages, radiocarbon ages, and/or historical records, as well
116 as deposition less than 3000 years ago.

117 Two samples were collected from sand sheets in marsh deposits of the Shirasuka lowlands, Japan (Fig.
118 1b). The discontinuous sand layers are interpreted to reflect sedimentation during tsunami and/or
119 typhoon inundation within the last 1000 years (Komatsubara et al., 2008). Samples for luminescence
120 dating were taken from a sediment drill core described in detail by Garrett et al. (2018). Since quartz
121 turned out to have inappropriate luminescence properties (Riedesel et al., 2018), optical dating of
122 tsunami and typhoon recurrence had to be based on feldspar. Here we use sand layers at core depths
123 of 120 cm (JSH 1-7) and 230 cm (JSH 1-18), for which radiocarbon dating yields ages younger than 1000
124 cal years BP (Garrett et al., 2018). Correlation with the stratigraphy described by Komatsubara et al.
125 (2008) points to deposition by the AD 1605 Keichō tsunami and the AD 1361 Shōhei tsunami,
126 respectively. As a modern analogue for the best-bleached sediment source of the investigated tsunami
127 deposits, a sample was collected at the modern beach (JSH mod).

128 In the Philippines, two samples for feldspar dating were collected from sandy onshore deposits of the
129 2013 Typhoon Haiyan that were accumulated in a back-barrier marsh near Tolosa, northern Leyte (Fig.
130 1d). Samples for feldspar dating originate from a suspension-settled sand sheet (TOL 8), deposited
131 during the inundation of the back-barrier marsh by the storm surge, and from a laminated washover
132 unit (TOL 5, Fig. 1e) formed by swash-dominated flooding (Brill et al., 2016). Due to very dim

133 luminescence signals not dominated by the OSL fast component (Fig. S1 in the supplement),
134 comparison of feldspar data with quartz OSL ages is not possible.

135 In Thailand, two samples were taken from tsunami-laid sand sheets deposited during the last 3000
136 years and archived in the swales of a beach-ridge plain on Phra Thong Island (Jankaew et al., 2008; Brill
137 et al., 2012a; Fig. 1f). One sample was dated from deposits of the 2004 Indian Ocean Tsunami (KPT 2).
138 Another sample originates from a palaeotsunami deposit (KPT 20) that was dated to 550 years using
139 radiocarbon dating (Jankaew et al., 2008) and quartz OSL (Brill et al., 2012a, b). This points to
140 deposition by a tsunami triggered by a Sunda Arc rupture at about AD 1450 (Meltzner et al., 2010).

141 Finally, a total of 15 samples were dated from TC deposits forming washover fans at the south-eastern
142 margin of the Exmouth Gulf, Northwest Australia (Fig. 1h). The washover fans are composed of
143 successions of sandy TC deposition separated by palaeosols (Fig. 1i), which are interpreted to reflect
144 phases of varying TC activity within the last 3000 years (May et al., 2017). Samples for feldspar dating
145 were collected from sandy TC deposits at trenches PLY 8 (3 samples), PLY 16 (3 samples), PLY 19 (4
146 samples) and PLY 25 (5 samples). Age control is available in form of single grain quartz OSL ages, which
147 indicate relatively well-bleached sediments affected by micro-dosimetry and sediment mixing during
148 transport, and, therefore, were calculated using the central age model (CAM; Galbraith et al., 1999)
149 and the finite mixture model (FMM; Galbraith and Green, 1990), respectively (Brill et al., 2017). As a
150 modern analogue, a modern beach sample (PLY 18) that is assumed to reflect the best-bleached
151 sediment source of local TC deposits was collected.

152

153 **2.2 Sample preparation and instrumentation**

154 Samples for dating were collected from trenches using steel cylinders at PLY, KPT and TOL, or from
155 opaque plastic drill cores split in the laboratory in case of JSH. Subsequently, samples for palaeodose
156 determination were pre-processed under dimmed red light in the Cologne Luminescence Laboratory
157 (CLL) using standard procedures to separate coarse grain potassium feldspar. This included sieving to
158 fractions of 100-200 μm or 150-200 μm , chemical treatment with HCl (10%), H₂O₂ (10%) and sodium
159 oxalate to remove carbonates, organics and clay, as well as density separation to extract potassium-
160 rich feldspar (<2.58 g/cm³). Samples for dose rate determination were dried to determine in-situ water
161 contents. Uranium, thorium and potassium concentrations were assessed by means of high-resolution
162 gamma spectrometry at the CLL and the VKTA – Strahlenschutz, Analytik & Entsorgung Rossendorf e.
163 V. (Tab. S1 in the online supplement). To account for the reduced efficiency of alpha particles in
164 generating IRSL signals, a-values of 0.15±0.05 are adopted from Balescu and Lamothe (1994). Beta
165 counting conducted at the Aberystwyth luminescence laboratory was used to estimate the bulk
166 internal potassium contents of feldspar extracts from all sites. The results suggest that adopting the

167 value of $10\pm 2\%$ determined by Smedley et al. (2012) is appropriate for our samples. For more details
168 concerning sample collection at the individual sites see also Brill et al. (2012a, b) for KPT, Brill et al.
169 (2016) for TOL, Riedesel et al. (2018) for JSH, and Brill et al. (2017) for PLY.

170 Potassium feldspar grains were measured on single grain discs with hole diameters of $300\ \mu\text{m}$ at the
171 Wageningen luminescence laboratory to perform equivalent dose (D_e) measurements, residual dose
172 determination, dose recovery tests, and fading experiments for all samples. Single grain discs of all
173 samples were randomly checked for the number of grains in each hole under the microscope. More
174 than a single grain was observed very rarely. Only for protocol validation and additional fading
175 experiments, 1 mm-diameter aliquots mounted on steel discs using silicon oil were used. All
176 measurements were carried out on automated Risø TL/OSL readers equipped with $^{90}\text{Sr}/^{90}\text{Y}$ beta
177 sources delivering 0.11-0.13 Gy/s at the hole position. Signals were stimulated by an IR laser centred
178 at 830 nm in case of single grains, and an array of IR LEDs ($870\pm 40\ \text{nm}$) for the 1 mm aliquots. All
179 feldspar signals were separated from stimulation light using an interference filter with peak
180 transmission at 410 nm.

181 The measurements followed a modified version of the pIRIR protocol proposed by Thomsen et al.
182 (2008) (details are provided in section 3.1). The signals for D_e determination were derived by
183 subtracting a background estimated from the last 20 s of the decay curve from the first 4 s of the decay
184 curve in case of multi grain aliquots, and the last 0.33 s from the first 0.2 s of the decay curve for single
185 grains. All measured grains and aliquots that passed the rejection criteria in terms of recycling ratio
186 ($0.85\text{-}1.15$) and recuperation ($0.2\ \text{Gy}$ for IR_{50} and $0.4\ \text{Gy}$ for pIRIR₁₅₀ signals, i.e. 5% or 10% of the largest
187 regenerative dose) were considered for palaeodose estimation. In terms of relative recuperation (in %
188 of the natural dose), the thresholds of 0.2 and 0.4 Gy used in this study are larger than those adopted
189 in most other studies (e.g. Smedley et al., 2016), but we demonstrate that this has no effect on the
190 palaeodose (see section 3.2). To calculate palaeodoses we applied the bootstrapped minimum age
191 model (MAM_{bs} ; Cunningham and Wallinga, 2012) (for details on age model selection see section 3.5).
192 Sigma_{b} values (σ_{b}) of 0.40 ± 0.05 (PLY, JSH) and 0.35 ± 0.05 (KPT) are based on the smallest over-
193 dispersion of each sample set as the best estimate for the over-dispersion of a well-bleached sample
194 (see section 3.4). Age calculation was performed with the Adele software (Kulig, 2005). Finally, samples
195 with g -values larger than 1 %/decade (i.e. mainly the IR_{50} ages) were fading corrected using the
196 approach of Huntley and Lamothe (2001). G -values $< 1\ \text{\%/decade}$ (all pIRIR₁₅₀ ages) are assumed to be
197 laboratory artefacts and not corrected for, following Buylaert et al. (2012).

198

199 **3. Results and interpretation**

200 3.1 Selection of a pIRIR protocol

201 On the basis of 1 mm aliquots from one of the Australian samples (PLY 25-3), a series of preheat
202 experiments were performed to select the ideal combination of thermal treatments. We tested pIRIR
203 measurement temperatures between 110 and 290 °C, where the preheat temperature was always 25
204 °C above the corresponding pIRIR temperature. It can be observed that the natural doses form a
205 constant dose plateau for pIRIR temperatures ≥ 150 °C (Fig. 2a), indicating insignificant fading (this
206 assumption is supported by low g -values < 1 %/decade, see section 3.2). At the same time, residual
207 doses after 24 h of solar simulator bleaching remain below 0.1 Gy for pIRIR temperatures of 110-180
208 °C, while they increase significantly for higher temperatures (Fig. 2b). Finally, laboratory doses applied
209 after 24 h of solar simulator bleaching are successfully recovered within ± 10 % for pIRIR temperatures
210 of 110-290 °C, if corrected for their residual doses (Fig. 2c). However, given the large residuals for pIRIR
211 temperatures > 200 °C, the uncertainties increase significantly for this temperature range. A pIRIR
212 temperature of 150 °C provides a reasonable compromise between low residual doses and signal
213 stability (shaded area in Fig. 2). Hence, all further measurements follow a pIRIR protocol with
214 stimulation at 150 °C, a preheat at 175 °C for 10 s, and an IR bleaching at 190 °C for 100 s at the end of
215 each SAR cycle (pIRIR₁₅₀ protocol in Tab. 1). Test doses are kept constant at ~ 5 Gy, and each sequence
216 includes measuring 2-4 regenerative doses, the repeated first regenerative dose (recycling ratio), and
217 a zero dose (recuperation). This protocol selection is backed by preheat experiments performed on the
218 Japanese samples (Riedesel et al., 2018). For the samples from Thailand and the Philippines dose
219 recovery ratios of 1.0 ± 0.04 and 0.9 ± 0.05 measured on samples KPT 2 and TOL 8, respectively, indicate
220 the validity of the pIRIR₁₅₀ protocol.

221 Multi grain aliquots (1 mm) of sample PLY 25-3 are further used to evaluate the comparability of IR₅₀
222 signals as part of the selected pIRIR₁₅₀ protocol, with those measured by means of a standard IR₅₀ SAR
223 protocol (see Tab. 1 for protocol details). Mean equivalent doses of 1.53 ± 0.05 Gy (conventional IR₅₀)
224 and 1.54 ± 0.05 Gy (IR₅₀ measured in pIRIR₁₅₀ protocol) are identical within 1- σ errors. This indicates that
225 the IR₅₀ signal measured within the applied pIRIR₁₅₀ protocol can be used as a substitute for
226 conventionally measured IR₅₀ signals. Consequently, both signals measured within the pIRIR₁₅₀
227 protocol are considered when deriving ages for the tsunami and TC deposits.

228

229 3.2 Feldspar luminescence properties

230 Both IR₅₀ and pIRIR₁₅₀ are characterised by sufficiently bright signals for single feldspar grains from PLY,
231 KPT, and JSH (at least several 100 counts for ~ 5 Gy test doses of accepted grains; Fig. 3a). Between 31%
232 (JSH) and 53% (KPT) of the grains provide 90% of the cumulative IR₅₀ and pIRIR₁₅₀ signals (Fig. 3c). A

233 total of 46-68% (IR_{50}) and 31-56% ($pIRIR_{150}$) of the grains pass the rejection criteria. The $pIRIR_{150}$ signals
234 show no significant fading at all three locations, regardless if measured on single grains or 1 mm
235 aliquots (g-values of 0.2 ± 0.3 to 0.7 ± 0.4 %/decade; Fig. 3a). The IR_{50} signals yield larger g-values
236 suggesting that fading correction is required. Multi grain aliquots (3 aliquots per sample) indicate g-
237 values of 1.5 ± 0.3 %/decade at KPT, 3.0 ± 0.3 %/decade at PLY and 2.8 ± 0.4 %/decade JSH. Single grain
238 data show extremely large scatter and suggest higher mean g-values of 5-8 %/decade at PLY and JSH,
239 and lower ones around zero at KPT (Fig. 3a).

240 Feldspar from the Philippines (TOL), on the other hand, is completely insensitive to IR stimulation. No
241 significant IR_{50} and $pIRIR_{150}$ signals were recorded after measuring ~ 200 grains (Fig. 3a). At the same
242 time, beta counting points to very low potassium contents of only $\sim 1.5\%$ for bulk feldspar samples
243 from this site, while the respective potassium concentrations of feldspar extracts from all other
244 locations exceed 7%. Feldspar extracts from TOL, thus, seem to contain no significant amounts of
245 potassium feldspar and are not further considered in this study.

246 To test the sensitivity of dose determination towards variations of the selected rejection criteria, mean
247 equivalent doses based on a successively increasing number of grains are plotted (Fig. 3d). The grains
248 are ordered with regard to the difference between recycling ratio and unity (from good = recycling
249 ratios of 1, to poor = recycling ratios of 0.85 or 1.15) and recuperation (from low to high recuperation
250 doses) (cf. Thomsen et al., 2016; Fig. 3d). Within the defined acceptance limits, no dependency on
251 recycling ratios is observed for all measured samples. Likewise, rejection of additional grains due to
252 recuperation by successively tightening the initial acceptance criteria of 0.2 Gy (IR_{50}) and 0.4 Gy
253 ($pIRIR_{150}$) does not lead to systematic changes of the final palaeodose. The rejection of further grains
254 due to recuperation relative to their natural doses would lead to biasing towards older grains (by
255 systematically excluding lower D_e values; Fig. S2a online supplement) and was not conducted. Instead
256 the dose response curve was forced through the origin for all samples.

257

258 **3.3 Over-dispersion in dose recovery tests**

259 To collect information on the dose scatter of well-bleached samples from each site that were not object
260 to significant dose rate heterogeneity during burial, the over-dispersion values of dose recovery
261 experiments are determined using the CAM. For this, β -doses of ~ 5 Gy are applied to (i) samples
262 artificially bleached in a solar simulator for 24 h (PLY 18, KPT 2, JSH 1-7); and (ii) samples of presumably
263 modern age – and therefore assumed to have insignificant remnant doses compared to the 5 Gy
264 laboratory dose – from the modern beach (PLY 18, JSH mod) and the 2004 Indian Ocean Tsunami (KPT
265 2). While the $pIRIR_{150}$ and IR_{50} over-dispersions are similar for individual locations, the over-dispersion

266 values of modern samples are slightly larger than those of artificially bleached samples in case of both
267 IR₅₀ signals (13-15% compared to 8-13%) and pIRIR₁₅₀ signals (12-16% compared to 9-13%) at all sites
268 (Fig. 4a). This suggests that apparently not all grains in the natural reference samples have been
269 completely bleached prior to their last deposition, especially the 2004 tsunami deposit from KPT. Thus,
270 part of the over-dispersion is caused by heterogeneous luminescence signal resetting of the grains (see
271 also section 3.4). The dose-recovery ratios support this assumption. Those of modern samples show
272 only appropriate ratios between 0.9 and 1.1 if the natural remnant doses are subtracted (dose-
273 recovery ratios of 0.98-1.03 instead of 0.99-1.12). The dose-recovery ratios of artificially reset samples
274 are acceptable without any correction (0.95-1.02). However, the differences between sites and signals
275 are small compared to the dose scatter of natural D_e distributions (see section 3.5). Over-dispersion
276 values of 8-16% for both signals are therefore a reasonable estimate for the internal scatter caused by
277 experimental uncertainties for all dated samples.

278

279 **3.4 Natural remnant doses and laboratory residuals**

280 For the same samples that have been analysed for equivalent dose scatter in dose recovery tests
281 (section 3.3), the IR₅₀ and pIRIR₁₅₀ signals after resetting in nature (remnant doses of modern
282 sediments) and those of samples artificially bleached in a solar simulator (residual doses) are
283 determined. Residual doses allow for the estimation of charge transfer to the natural luminescence
284 signal during the measurement procedure and should, thus, be considered when interpreting the
285 dating accuracy of samples with unknown age. The equivalent dose of modern analogues provide
286 information on the degree of signal resetting in nature, and may be used to correct feldspar ages by
287 subtracting these natural remnant doses (e.g. Ollerhead and Huntley, 2011; Kars et al., 2014).

288 Residual doses that remain after signal resetting in the laboratory – as the result of thermal transfer
289 and/or re-trapping of charge – were calculated using the CAM, because bleaching in the solar simulator
290 zeroed all grains more or less homogeneously. Values vary between 0.01-0.04 Gy (PLY and KPT) and
291 0.14 Gy (JSH) in case of IR₅₀ signals, and between 0.05 Gy (PLY) and 0.3-0.4 Gy (KPT and JSH) in case of
292 pIRIR₁₅₀ signals (Fig. 4b). While these laboratory residuals are insignificant for the equivalent doses of
293 most samples from PLY and KPT, they account for up to 20% of the equivalent doses in case of JSH.

294 The D_e distributions of the 2004 tsunami deposit and the modern beach samples from Japan and
295 Australia (i.e. the modern analogues) show indication of partial bleaching. All these samples are
296 mixtures of well-bleached grains with low equivalent doses, and insufficiently bleached grains with
297 larger equivalent doses (see Fig. S5 in the supplement). Since dating of samples with unknown age in
298 this study is only based on the best-bleached grains of each sample, corresponding natural remnant

299 doses should be estimated from the best-bleached grains of the modern analogues only. To extract
300 the palaeodose of these best-bleached grains we use the MAM_{bs} . Crucial for its application is the
301 estimation of a robust σ_b value. In absence of non-modern, well-bleached sediments, σ_b is derived by
302 using the smallest over-dispersion from each sample set as the best estimate for that of a well-
303 bleached sample. The obtained σ_b values are 0.40 ± 0.05 (PLY, JSH) and 0.35 ± 0.05 (KPT) for both the IR_{50}
304 and $pIRIR_{150}$ data sets (Fig. 5). Similarly large σ_b values (up to 0.50) have been reported for IR_{50} and
305 $pIRIR$ single grain equivalent dose distributions of well-bleached feldspar samples from glacial settings
306 (Smedley et al., 2016). Given the composition of the deposits used in this study (a few feldspar grains
307 embedded in mixtures of quartz sand and carbonates), values in the range of 0.30-0.45 are assumed
308 to be realistic.

309 The calculated natural remnant doses of the best-bleached feldspar grains vary between 0.025 ± 0.01
310 Gy (PLY 18) and 0.07 ± 0.02 Gy (KPT 2) for IR_{50} signals, and between 0.035 ± 0.02 Gy (PLY 18) and
311 0.19 ± 0.03 Gy (JSH mod) for $pIRIR_{150}$ signals (IR_{50} and $pIRIR_{150}$ nat in Fig. 4b). The lack of significant
312 differences between laboratory residuals and natural remnant doses suggests that at least for the best-
313 bleached grains both IR_{50} and $pIRIR_{150}$ signals have been well reset in nature. We calculated remnant
314 ages for all modern analogue samples by considering remnant doses, dose rates, multiple grain g -
315 values (only for IR_{50}) and the corresponding age control (i.e. by subtracting the time difference
316 between deposition and sample collection). The natural remnant ages of all three samples vary
317 between 0 and 27 years for the IR_{50} signal (KPT = 0 years, JSH = 19 years, PLY = 27 years) and 2 and 48
318 years for the $pIRIR_{150}$ signal (KPT = 2 years, JSH = 48 years, PLY = 36 years; Tab. 2). These remnant ages
319 are astonishingly small compared to previously published data, especially for the $pIRIR_{150}$ signal (e.g.
320 Reimann et al., 2012). Interestingly, two of the $pIRIR_{150}$ remnant ages agree with their fading-corrected
321 IR_{50} counterparts within $2\text{-}\sigma$ uncertainties. For the third one (JSH mod), the $pIRIR_{150}$ remnant age is only
322 slightly older than the IR_{50} age within $2\text{-}\sigma$. Since both signals bleach at different rates, a significant
323 percentage of grains in these samples may have experienced significant light exposure during or prior
324 to transport (Reimann et al., 2015). The measured remnant doses rather seem to reflect unbleachable
325 residuals (particularly since laboratory residuals have approximately the same size) and should be
326 subtracted from the feldspar ages of palaeosamples to improve dating accuracy (e.g. Ollerhead and
327 Huntley, 2011; Kars et al., 2014). The source of these residuals may be competition between signal
328 resetting and retrapping at low dose levels during light exposure (Ollerhead and Huntley, 2011), or a
329 dose-dependent charge carry-over effect from regenerative dose cycles to the adjacent test dose
330 cycles (Colarossi et al., 2018; Riedesel et al., 2018).

331 The observation of complete bleaching at the $2\text{-}\sigma$ level (a grain is classified as completely bleached
332 when its dose overlaps with the expected dose of the sample within $2\text{-}\sigma$ errors) applies to nearly 100%
333 of the grains in case of modern beach deposits from PLY 18 (Fig. S5). In case of the 2004 tsunami

334 deposits from Thailand (KPT 2) only ~40% of the grains are well-bleached. The modern beach sand
335 from JSH mod yields ~70% of well-bleached grains for the IR₅₀ signal. But only ~15% of the grains yield
336 well-bleached pIRIR₁₅₀ signals.

337

338 **3.5 Palaeodose and age calculation for tsunami and cyclone deposits**

339 All data relevant for palaeodose and age calculation are summarised in Table 2. For D_e datasets of both
340 signals, very similar over-dispersion values of 35-155% (IR₅₀) and 34-143% (pIRIR₁₅₀) are observed. The
341 majority of the samples from all three sites show unimodal distributions with moderate to large over-
342 dispersion between 35 and 110% (Fig. 6a, b, d). Only some samples from the Australian site (PLY 8-1,
343 2; 16-1-3; 19-1, 2) are characterised by bimodal D_e distributions with larger over-dispersion values of
344 70-155% (Fig. 6c).

345 Since at least some of the over-dispersion is interpreted to reflect incomplete bleaching, the MAM_{bs}
346 was applied to estimate burial doses for all samples. For appropriately selected σ_b values (particularly
347 since applied with an uncertainty, in this study 0.35 ± 0.05 and 0.40 ± 0.05), the MAM_{bs} should also be
348 adequate for well-bleached deposits (Fig. 5b; Chamberlain et al., 2018). This should also be valid for
349 samples with bimodal D_e distributions (as shown in Fig. 6c). These distributions most likely reflect
350 mixing of different sediment sources during TC and tsunami transport and not post-depositional mixing
351 (see also section 4.2.). Thus, the grain population with the lower equivalent doses, which is dated by
352 the MAM_{bs}, reflects the more recently bleached and therefore younger sediment source (i.e. the best-
353 bleached grains) for all corresponding samples.

354 The pIRIR₁₅₀ ages and the IR₅₀ ages from KPT are not corrected for fading, because all measurements
355 indicate supposedly insignificant g-values <1 %/decade (cf. Buylaert et al., 2012). The IR₅₀ ages from
356 PLY and JSH, on the other hand, are fading corrected. Since 1 mm aliquots and single grains indicate
357 different g-values at all sites, fading corrected ages using both g-values are presented at this stage
358 (Tab. 2). Eventually, all feldspar ages are corrected by subtracting the remnant ages determined for
359 modern analogue samples.

360

361 **4. Discussion**

362 **4.1 Comparison of single grain feldspar ages with age control**

363 To test the validity of the luminescence age estimates, we compare the dating results obtained using
364 the different signals with each other and with independent age control. When results of different
365 luminescence signals are compared, we need to take into account that these methods are not entirely

366 independent, as they are partly based on the same measurements and assumptions; e.g. the external
367 dose rate is the same, as well as beta-dose rate calibration. To avoid overinterpretation of our data,
368 we eliminate all shared errors prior to comparing IR₅₀, pIRIR₁₅₀ and quartz ages (i.e. 3.5% machine
369 reproducibility on single grain D_e determination, uncertainties on external gamma and beta radiation).
370 In case of most samples investigated in this study, a good agreement between IR₅₀ ages corrected for
371 fading using multi grain g-values and pIRIR₁₅₀ ages not corrected for fading (both after subtraction of
372 remnant doses) is observed (Fig. 7a). Even for samples younger than 800 years, pIRIR₁₅₀ and IR₅₀ ages
373 agree at the 1-σ level (Fig. 7b). Likewise, both IR₅₀ and pIRIR₁₅₀ feldspar ages generally match historical
374 records and quartz ages for all samples within 2-σ errors (Fig. 7c, d, f, g). Even at the 1-σ confidence
375 level, the majority of the samples agree with age control. Notable exceptions are the pIRIR₁₅₀ and IR₅₀
376 ages older than 2000 years (PLY 25-1, 25-2, 19-4), which show a systematic trend of underestimating
377 the age control (Fig. 7c, f).

378 If the single grain g-values of 5.0±0.8% (JSH) and 6.7±0.8% (PLY) are used, fading corrected IR₅₀ ages
379 tend to overestimate both pIRIR₁₅₀ ages and age control (Fig. S6). Similar trends towards over-
380 correction of young feldspar samples when applying g-values >5% were already reported by Reimann
381 et al. (2011). The reason for the erroneously large single grain g-values of our samples is not yet clear,
382 presumably related to a bias in the large scatter of the measured single grain g-values (Fig. S4).
383 Therefore, we use multi-grain g-values to fading correct IR₅₀ ages in the following.

384 The general agreement with age control for very young samples of only a few centuries is in line with
385 the low IR₅₀ and pIRIR₁₅₀ remnant doses measured on the best-bleached feldspar grains of modern
386 analogues from Thailand (KPT) and Australia (PLY). These indicate more or less complete signal
387 resetting at the time of deposition. At both sites, the feldspar remnant ages of 0-36 years agree within
388 1-σ uncertainties with those of quartz reported for the same sites (15-25 years; Brill et al., 2012a,
389 2017). They are also well in the range of quartz remnant ages reported for tsunami (e.g. Eipert, 2004;
390 Murari et al., 2007), storm (e.g. Cunningham et al., 2011; May et al., 2015) and beach deposits (e.g.
391 Armitage et al., 2006) elsewhere. Slightly larger remnant ages of ~50 years for the pIRIR₁₅₀ signals were
392 obtained using the best-bleached grains of modern beach deposits from JSH. However, after remnant
393 dose subtraction (see section 3.4.) the Japanese samples (JSH 1-7 and JSH 1-18) agree with age control
394 as well.

395 While discussing potential reasons for slightly over- or underestimating the age control at the 1-σ
396 confidence level, it should also be taken into account that the systematic discrepancies observed for
397 samples older than 2000 years from PLY could also be an issue of inaccurate quartz ages. Differences
398 might at least partly result from the different age models used for quartz and feldspar dating. While
399 the use of the MAM_{bs} is in line with the age model selection for published quartz ages at KPT (Brill et

400 al., 2012a), different age models were used for the quartz ages at PLY (Brill et al., 2017). The quartz
401 dose distributions at PLY show the same patterns as the respective feldspar dose distributions
402 described in this paper (section 3.5). But the authors argued (i) that the FMM should be used to deal
403 with the distinct populations of bimodal dose distributions (Fig. 6c), since they may reflect sediment
404 sources with different pre-transport resetting; and (ii) that the CAM should be used for all samples
405 with unimodal dose distributions, since their over-dispersion values are rather assumed to reflect dose
406 rate heterogeneity than partial bleaching (Brill et al., 2017).

407 The use of different age models despite the similarities of the quartz and feldspar dose distributions
408 might explain the systematic discrepancies between both datasets observed for IR₅₀ and pIRIR₁₅₀ ages
409 older than 2000 years at PLY. It can be observed that bimodality of dose distributions due to mixing of
410 sediment sources during transport tends to affect only the samples younger than 2000 years, while
411 older samples show relatively broad unimodal peaks. This might point to increasing significance of the
412 burial dose compared to the remnant doses and thus to overprinting of the pre-depositional grain
413 populations by micro-dosimetry and other sources of D_e scatter. In this case, the application of the
414 CAM might lead to a systematic overestimation of the quartz ages. The previously published quartz
415 ages for these samples (Brill et al., 2017), which are based on the CAM, should therefore be interpreted
416 as maximum ages. Since we assume the MAM_{bs} as the most appropriate age model in such settings,
417 we also apply it to the quartz dose distributions of these samples to exclude any biasing of our
418 conclusions by age model selection (Fig. 7e, h). As demonstrated in Figure 7e and 7h, any systematic
419 offset between quartz and feldspar ages is successfully removed, when the MAM_{bs} is applied to both
420 quartz and feldspar samples from PLY.

421

422 **4.2 Implications for sediment sources and transportation processes in tsunami and cyclone waves**

423 The good agreement between MAM_{bs}-based quartz, fading corrected IR₅₀ and uncorrected pIRIR₁₅₀
424 ages – although all signals are known to bleach at different rates (Godfrey-Smith et al., 1988; Kars et
425 al., 2014) – points to relatively complete signal resetting in the best-bleached grains of the investigated
426 tsunami and TC deposits. Despite slight discrepancies of pIRIR₁₅₀ and fading corrected IR₅₀ ages
427 compared to the age control within 1- σ uncertainties for some samples, a systematic trend of age over-
428 estimation due to less complete bleaching cannot be observed. These conclusions are, however, only
429 true for the best-bleached grain population in each sample (i.e. the MAM_{bs} palaeodose). This applies
430 to nearly 100% of the modern beach grains at PLY regardless of signal type (quartz, IR₅₀ and pIRIR₁₅₀).
431 But only ~40% (IR₅₀ and pIRIR₁₅₀) and ~70% (quartz) of the 2004 tsunami grains from KPT are well
432 bleached. At JSH, only 70% (IR₅₀) and 15% (pIRIR₁₅₀) of the grains from the modern beach yield well-
433 bleached grains.

434 This well-bleached grain fraction reflects a sediment source with well reset signals prior to tsunami or
435 TC transport, a phenomenon described as pre-bleaching. The littoral zone is the most likely source of
436 these pre-bleached grains, since beach deposits are usually characterized by both well-bleached quartz
437 signals (Armitage et al., 2006) and feldspar signals (Madsen et al., 2011). With feldspar remnant ages
438 of only 27-36 years, sediments from the littoral zone at PLY clearly satisfy this requirement. Likewise,
439 the slightly larger remnant ages of 19-48 years in beach deposits at JSH are in line with the reasonable
440 agreement of IR_{50} and $pIRIR_{150}$ ages with age control if only the best-bleached grains are used for
441 dating.

442 In addition to the well-bleached feldspar grains originating from the beach, grains or entire grain
443 populations with ages significantly overestimating the age control are present in all samples. Modern
444 tsunami deposits from Thailand reveal right-skewed D_e distributions indicating incomplete resetting of
445 the luminescence signal in some grains eroded at the beach prior to deposition (Fig. 8a). With
446 increasing age of the TC and tsunami deposits, the remnant ages of these incompletely bleached grains
447 become rapidly insignificant and seem to reflect the beach as a single well-bleached sediment source
448 (Fig. 8b). On the other hand, the bimodal D_e distributions observed for some PLY samples suggest
449 mixing of pre-bleached grains from the beach with older grains. Considering the dimensions of the
450 respective remnant doses calculated with the FMM (i.e. 2000-5000 years), the Holocene beach barrier
451 is the most likely source of the older grains (Fig. 8c). The comparison of both grain populations reveals
452 similar proportions for all three signals (i.e. ~65% of the grains in population 1 and ~35% in population
453 2). The peaks of the older grain population tend to shift towards younger ages for the more rapidly
454 bleaching quartz signals compared to both feldspar signals (Fig. 8d). While the latter points towards
455 the influence of signal resetting during sediment transport in tsunami and storm waves, the
456 combination of a shifting peak position but unchanging proportion of the older grain population
457 suggests that this resetting was rather limited due to transport under turbulent conditions.

458

459 **5. Conclusions**

460 Our investigations demonstrate that in general both IR_{50} and $pIRIR_{150}$ signals of a significant number of
461 potassium feldspar grains are sufficiently reset to accurately date Holocene tsunami and tropical
462 cyclone deposits with ages between 3000 years and 500 years from a variety of coastal settings. These
463 best-bleached grains can be reliably extracted using the bootstrap Minimum Age Model. After
464 subtraction of remnant ages obtained from modern analogue samples (in the order of 2-48 years), no
465 significant age discrepancies at the 1- σ level compared to age control are observed even for sediments
466 younger than 500 years. For samples older than 500 years, where residuals and remnant doses are
467 insignificant compared to the natural dose of the best-bleached grain population, reasonable

468 agreement at the 1- σ level was observed for both fading-uncorrected pIRIR₁₅₀ and fading-corrected
469 IR₅₀ ages, when using the bootstrapped minimum age model and without residual dose subtraction.

470 We argue that the reason for the good agreement between pIRIR₁₅₀ and IR₅₀ feldspar ages and age
471 control observed in this study is that a significant portion of the grains are derived from sediment
472 sources sufficiently reset prior to transportation, most likely the beach. Additional, but rather limited
473 resetting seems to take place during tsunami and cyclone transport. However, this is not the decisive
474 factor for the low remnant ages of the best-bleached grains. These conclusions demonstrate the power
475 of multiple luminescence signal datasets to inform not only on chronology, but also to provide valuable
476 insights into earth-surface processes such as the sediment transport dynamics related to highly
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478

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490

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651 **Figures and tables**

652 Fig. 1: Study sites selected for feldspar single grain dating. a) Location of the four study sites Point Lefroy (PLY) in
653 NW Australia, Phra Thong Island (KPT) in SW Thailand, Shiraska (JSH) in Japan, and Tolosa (TOL) in the Philippines
654 (based on ESRI base maps). b) Shiraska lowlands with position of sediment core JSH 1 and the modern beach
655 sample JSH mod (based on Google Earth/Digital Globe 11/10/2016). c) Stratigraphy of sediment core JSH 1. d)
656 The coastal plain at Tolosa with positions of luminescence samples (based on Google Earth/Digital Globe
657 23/02/2012). e) The storm-typical planar lamination at TOL 5 sampled for luminescence dating. f) The beach-
658 ridge plain on Phra Thong Island with locations of luminescence samples (based on Google Earth/Digital Globe
659 08/10/2015). g) Tsunami sand sheets sampled for luminescence dating in trench KPT 20. h) Supra-tidal back-
660 barrier mudflat at Point Lefroy with locations of luminescence samples from washover fans (PLY 8,16,19,25) and
661 the present beach (PLY 18) (based on Google Earth/Digital Globe 22/11/2014). i) Stratigraphy of the washover
662 fan at PLY 25 with existing quartz OSL chronology (Brill et al., 2017).

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664 Fig. 2: Protocol evaluation based on sample PLY 25-3. a) Preheat-plateau test with successively increasing pIRIR
665 temperatures (110-290 °C) and preheat temperatures (always 25 °C higher than the pIRIR temperature). b) pIRIR
666 residual doses after 24 hours of solar simulator bleaching for the same temperatures as used in (a). c) Residual
667 corrected dose-recovery ratios for the same temperature range.

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669 Fig. 3: Feldspar luminescence properties of the samples dated in this study. a) Feldspar single grain signals (IR_{50}
670 and $pIRIR_{150}$) in response to ~5 Gy test doses for samples from PLY, KPT and TOL. Insert: Fading rates of sample
671 PLY 25-3 shown as a boxplot. Open circles indicate outliers; vertical lines show the mean. b) Dose-response curves
672 of feldspar samples in this study. While D_e determination is unproblematic for both signals and most samples
673 (represented by JSH IR_{50}), some of the younger PLY samples (represented by PLY $pIRIR_{150}$) suffer from large
674 recuperation, particularly in case of the $pIRIR_{150}$ signal. c) Representative light-sum curves for samples from PLY,
675 KPT and JSH. d) Running average dose of accepted grains in order of the difference between recycling ratio and
676 unity (from left unity, to right 15% difference) and recuperation (from left low, to right large).

677

678 Fig. 4: Over-dispersion in dose recovery tests, laboratory residuals and natural remnant doses measured on
679 modern analogue samples. a) Over-dispersion of dose recovery tests with 5 Gy laboratory doses administered to
680 modern age samples (PLY 18, KPT 2, JSH mod: squares) and solar simulator bleached samples (PLY 18, KPT 2, JSH
681 1-7: circles). b) Residual doses after 24 h of solar simulator bleaching and natural remnant doses of the same
682 modern analogue samples without solar simulator resetting.

683

684 Fig. 5: Over-dispersion distributions for samples from PLY, JSH and KPT. For both, IR_{50} (a) and $pIRIR_{150}$ signals (b)
685 the lowest values are in the range of 35% in case of KPT, and 40% in case of PLY and JSH.

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687 Fig. 6: Equivalent dose distributions of selected samples from each locality shown as Abanico plots. (a) Thailand.
688 (b) Japan (b), and Australia (c, d).

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690 Fig. 7: Correlation of age control (historical data and quartz ages), fading corrected IR₅₀ ages using multi-grain g-
691 values, and fading-uncorrected pIRIR₁₅₀ ages (all corrected for natural remnant doses, i.e. the column "Age rc" in
692 Table 2). a) IR₅₀ ages plotted against pIRIR₁₅₀ ages. b) Zoom into the last 800 years (grey box in a). c) IR₅₀ ages
693 plotted against age control. d) Zoom into the last 800 years (grey box in c). e) IR₅₀ ages plotted against age control
694 but with quartz ages from PLY calculated with the MAM. f) pIRIR₁₅₀ ages plotted against age control. g) Zoom into
695 the last 800 years (grey box in f). h) pIRIR₁₅₀ ages plotted against age control but with quartz ages from PLY
696 calculated with the MAM.

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698 Fig. 8: Indication for sediment sources and transport conditions of tsunami and cyclone deposits in single-grain
699 data. While unimodal D_e distributions point to the beach as the only sediment source (a, b), bimodality of D_e
700 distributions at PLY is explained by mixing of well-bleached beach sand with sediment from the mid- to late
701 Holocene barrier (c). Incomplete bleaching of beach sediments can only be observed in very young event deposits
702 (a). Besides that, the ages of the older grain population provided by different signals point to additional signal
703 resetting during tsunami and cyclone transport (d). Compared to the more rapidly resetting quartz signals (older
704 grain population indicated by peak at S2b), both IR₅₀ and pIRIR₁₅₀ signals provide systematically older ages for
705 grains derived from the barrier (peak at S2a).

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a) pIRIR₁₅₀ protocol

Step	Treatment	Observed
1	Preheat (175 °C for 10s)	
2	IRSL (laser, 1.65s @ 50 °C)	L _x (IR ₅₀)
3	IRSL (laser, 1.65s @ 150 °C)	L _x (pIRIR ₁₅₀)
4	Test dose	
5	Preheat (175 °C for 10s)	
6	IRSL (laser, 1.65s @ 50 °C)	T _x (IR ₅₀)
7	IRSL (laser, 1.65s @ 150 °C)	T _x (pIRIR ₁₅₀)
8	IRSL (LEDs, 100s @ 190 °C)	
9	Dose (R1-R4, R0, RR)	
10	Return to step 1	

b) IR₅₀ protocol

Step	Treatment	Observed
1	Preheat (190 °C for 10s)	
2	IRSL (LEDs, 200s @ 50 °C)	L _x (IR ₅₀)
4	Test dose	
5	Preheat (190 °C for 10s)	
6	IRSL (LEDs, 200s @ 50 °C)	T _x (IR ₅₀)
8	IRSL (LEDs, 100s @ 220 °C)	
9	Dose (R1-R4, R0, RR)	
10	Return to step 1	

717 Tab. 1: The pIRIR₁₅₀ (a) and conventional IR₅₀ (b) protocols applied in this study. Note, in case of dose recovery
718 experiments and determination of laboratory residuals, solar simulator bleaching for 24 h and application of a 5
719 Gy laboratory dose was performed prior to step 1. R1-R4 – regenerative doses, R0 – zero dose (for measurement
720 of recuperation), RR – recycled dose (for measurement of recycling ratio).

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Site	Sample	Signal	N _{ac}	OD (%)	σ _b	Palaeodose (Gy)	Age unc. (yrs)	Age cor. SA (yrs)	Age cor. SG (yrs)	Age rc (yrs)	Age contr. (yrs)
Thailand	KPT 2	IR ₅₀	213	111±10	0.35±0.05	0.07±0.02	8±2	8±2	8±2	-	8*
		post-IR ₁₅₀	147	88±9	0.35±0.05	0.10±0.02	10±6	10±6	10±6	-	
	KPT 20	IR ₅₀	243	35±2	0.35±0.05	4.26±0.17	456±31	515±38	456±31	515±38	564*
		post-IR ₁₅₀	242	34±2	0.35±0.05	5.25±0.18	546±35	546±35	546±35	544±35	
Japan	JSH 1-7	IR ₅₀	103	40±3	0.40±0.05	1.35±0.09	336±31	413±41	494±65	394±41	410*
		post-IR ₁₅₀	68	54±5	0.40±0.05	2.01±0.25	502±105	502±107	502±107	454±107	
	JSH 1-18	IR ₅₀	122	38±5	0.40±0.05	1.59±0.06	486±41	601±56	722±93	582±56	650*
		post-IR ₁₅₀	79	43±4	0.40±0.05	2.55±0.31	780±104	780±104	780±104	732±104	
	JSH mod	IR ₅₀	230	-	0.40±0.05	0.06±0.02	16±5	19±6	24±8	-	0*
		post-IR ₁₅₀	177	-	0.40±0.05	0.19±0.03	48±7	48±7	48±7	-	
Australia	PLY 8-1	IR ₅₀	147	115±7	0.40±0.05	0.28±0.07	240±60	298±76	405±114	271±76	380±30**
		post-IR ₁₅₀	83	109±9	0.40±0.05	0.50±0.05	426±56	426±56	426±56	390±56	
	PLY 8-2	IR ₅₀	133	76±8	0.40±0.05	0.67±0.07	582±83	733±109	1020±197	705±109	922±51**
		post-IR ₁₅₀	93	67±5	0.40±0.05	0.84±0.06	720±87	720±87	720±87	684±87	
	PLY 8-3	IR ₅₀	143	44±3	0.40±0.05	1.39±0.16	910±140	1154±183	1627±332	1127±183	1362±57**
		post-IR ₁₅₀	104	40±2	0.40±0.05	1.88±0.18	1238±171	1238±171	1238±171	1202±171	
	PLY 16-1	IR ₅₀	114	128±10	0.40±0.05	0.15±0.03	114±28	140±35	186±52	113±35	130±10**
		post-IR ₁₅₀	103	117±10	0.40±0.05	0.17±0.02	128±19	128±19	128±19	92±19	
	PLY 16-2	IR ₅₀	171	105±6	0.40±0.05	0.23±0.03	178±26	220±33	296±54	193±33	204±12**
		post-IR ₁₅₀	125	103±7	0.40±0.05	0.34±0.03	268±34	268±34	268±34	232±34	
	PLY 16-3	IR ₅₀	177	93±6	0.40±0.05	0.22±0.04	144±31	178±39	237±59	151±39	206±14**
		post-IR ₁₅₀	89	86±8	0.40±0.05	0.35±0.10	268±34	232±67	232±67	196±67	
	PLY 18	IR ₅₀	108	-	0.40±0.05	0.02±0.01	22±4	27±5	39±9	-	0*
		post-IR ₁₅₀	92	-	0.40±0.05	0.04±0.02	36±18	36±18	36±18	-	
	PLY 19-1	IR ₅₀	268	155±16	0.40±0.05	0.23±0.02	172±23	213±30	286±50	184±30	342±33**
		post-IR ₁₅₀	157	143±19	0.40±0.05	0.27±0.07	200±57	200±57	200±57	164±57	
	PLY 19-2	IR ₅₀	205	126±13	0.40±0.05	0.58±0.03	498±54	626±71	867±140	599±71	788±75**
		post-IR ₁₅₀	144	85±6	0.40±0.05	0.72±0.04	620±71	620±71	620±71	584±71	
	PLY 19-3	IR ₅₀	181	53±3	0.40±0.05	1.09±0.06	898±101	1140±134	1605±275	1113±134	1284±66**
		post-IR ₁₅₀	127	62±4	0.40±0.05	1.25±0.07	1026±116	1026±116	1026±116	990±116	
PLY 19-4	IR ₅₀	178	58±3	0.40±0.05	1.73±0.18	1390±201	1776±266	2536±517	1749±266	2264±101**	
	post-IR ₁₅₀	95	57±4	0.40±0.05	2.30±0.26	1844±277	1844±277	1844±277	1808±277		
PLY 25-1	IR ₅₀	154	43±3	0.40±0.05	2.66±0.09	1750±156	2243±215	3227±529	2216±215	2826±124**	
	post-IR ₁₅₀	101	37±3	0.40±0.05	3.66±0.14	2412±222	2412±222	2412±222	2376±222		
PLY 25-2	IR ₅₀	169	40±3	0.40±0.05	1.93±0.08	1222±127	1558±169	2216±374	1531±169	1956±87**	
	post-IR ₁₅₀	112	54±4	0.40±0.05	2.61±0.11	1654±173	1654±173	1654±173	1618±173		
PLY 25-3	IR ₅₀	250	39±2	0.40±0.05	1.49±0.04	948±83	1204±113	1699±262	1177±113	1230±83**	
	post-IR ₁₅₀	183	40±3	0.40±0.05	1.65±0.05	1046±92	1046±92	1046±92	1010±92		
PLY 25-4	IR ₅₀	176	41±3	0.40±0.05	0.79±0.04	622±64	785±85	1093±175	758±85	904±52**	
	post-IR ₁₅₀	95	44±4	0.40±0.05	0.88±0.06	690±80	690±80	690±80	654±80		
PLY 25-5	IR ₅₀	163	52±3	0.40±0.05	0.73±0.07	568±78	715±101	995±189	688±101	858±69**	
	post-IR ₁₅₀	104	47±4	0.40±0.05	0.95±0.06	742±85	742±85	742±85	706±85		

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735 Tab. 2: Feldspar single-grain luminescence data for all samples measured in this study. N_{ac} - number of accepted
736 grains, OD – over-dispersion, Age unc. – uncorrected ages, Age cor. SA – fading corrected ages using mean 1-mm
737 diameter single aliquot g-values of 1.5±0.3% (KPT), 2.8±0.4% (JSH) and 3.0±0.3% (PLY) for the IR₅₀ data, Age cor.
738 SG – fading-corrected ages using mean single grain g-values of 5.0±0.8% (JSH) and 6.7±0.8% (PLY) for the IR₅₀
739 data, Age rc – fading-corrected ages using multi-grain g-values after subtraction of remnant ages determined on

740 modern analogue samples (section 3.4. for details), Age contr. – age expected from age control (*historical record
741 or modern, **quartz ages in Brill et al., 2017). All uncertainties provided reflect the 1- σ confidence level. Dose
742 rate data are provided in the online supplement.