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Determining fluvial sediment virtual velocity on the Mojave River using K-feldspar IRSL: Initial assessment

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Abstract

The Mojave River of Southern California was chosen as a field site to investigate the applicability of luminescence dating to sediment transport rate problems. Grains in the active channel of the river are expected to show signs of partial bleaching and this makes it difficult to determine time since deposition accurately. A modification of the multiple elevated temperature post-IR IRSL (MET-pIRIR) procedure, (Buylaert et al., 2009; Li and Li, 2011), was used for K-feldspar grains (175-200 μm) at temperature increments of 50, 95, 140, 185, and 230 $^{\circ}\text{C}$ in order to provide more information about relative signal bleaching among samples. The measurements show an exponential decrease in equivalent dose (D_e) with distance down the Mojave River. Higher temperature pIRIR signals are bleached more slowly than lower temperature ones (Buylaert et al., 2009). The D_e for samples at 50 $^{\circ}\text{C}$ is roughly constant along the river. These results suggest cyclical bleaching and burial as grains are transported downriver and higher energy (deeper) traps are vacated. The pattern of D_e values for the Mojave River can be used to constrain the sediment transport rate for this river by building a model of growth and bleach for each temperature increment. A bleaching experiment was run with multiple aliquot samples for direct sunlight exposure times of 0, 10, 30, 300, 1000, 3000, 10,000, and 30,000 s. The MET-pIRIR procedure was applied at each temperature increment for each exposure time aliquot and the results for all exposure times were fit to the general order kinetics equation using a non-linear regression. The bleaching parameters were used in conjunction with the SAR growth curves to build a model of partial bleaching of grains during transport that is fitted with a c_2 test to the pIRIR data from the Mojave River. This model is not a unique solution, but can be used to assess the likelihood of various sediment transport regimes.

Keywords:

Geomorphology

Infrared Stimulated Luminescence

Post IR-IRSL

Mojave River

44 1 Introduction

45 The rate of fine sand ($0.125 \text{ mm} < d < 0.250 \text{ mm}$) transport has been the subject of
46 numerous theoretical studies and has implications for hillslope processes, denudation rates of
47 mountain ranges, and basin analysis (Howard et al., 1994; Paola, 2000). Despite robust theory
48 on the subject, there are few methods to measure fine sand fluvial transport in natural rivers
49 (Milan and Large, 2014). Field studies of fine-sediment transport in streams and rivers primarily
50 utilize tracer techniques (e.g., Crickmore, 1967). The tracer produces an above-background
51 signal in individual sand grains that can be measured along a reach of a river as the sediment
52 travels downstream. Individual grains with tracer are treated as a point mass using a centroid
53 whose position over time can be converted into a virtual velocity (Milan and Large, 2014).
54 Methods applied to larger sediment sizes, such as gravels and pebbles, include painting
55 individual stones (Church and Hassan, 1992) and passive-integrated transponder (PIV) tags
56 (Lamarre et al., 2005). Both of these methods are impractical for fine sand-sized particles,
57 especially in large river systems. Methods that have been applied to fine sand include coating
58 grains with fluorescent dyes (Rathburn and Kennedy, 1978) and enhancement of magnetic
59 susceptibility of iron coatings on sand grains (Milan and Large, 2014). These methods have been
60 successful in small rivers and streams, but application at the catchment scale or to large rivers
61 would be time consuming and difficult to implement.

62 We propose to use natural luminescence of K-feldspar grains from samples along the
63 Mojave River to estimate a virtual velocity of fine sediment transport. The geography of the
64 Mojave River and the sample sites for this project are shown in Figure 1. Our method is not a
65 “tracer method,” as described above, because the process responsible for transporting the
66 sediment (water flow) changes the luminescence signal we are measuring. Therefore, we create
67 a simple forward model to explain how we expect the Infrared Stimulated Luminescence (IRSL)
68 signal of fine sediment to change during water flow events. Future work will address the
69 inverse problem of determining a virtual velocity for fine sediment in a more mathematically
70 rigorous fashion.

71 Luminescence dating has proved a useful tool in geomorphology to date deposits of
72 sediment and to understand the context of the events that created the deposits (e.g., Stokes,
73 1999; Rittenour, 2008). Prior research has shown that sensitivity of quartz grains changes in
74 response to fluvial transport (Pietsch et al., 2008), and that quartz luminescence intensity
75 changes in response to tributary inputs into large river systems (Stokes et al., 2001). We
76 observe a roughly exponential decrease in multiple elevated temperature post-IR IRSL (MET-
77 pIRIR) signals as a function of distance downriver, and propose that this result is a consequence
78 of cycles of transport (signal bleaching) and deposition (signal growth) (Figure 2). This study
79 explores how these preliminary results may be used to estimate sediment virtual velocity,
80 defined as the distance travelled by the centroid of a group of individual grains (Figure 3)
81 divided by the time interval between measurement locations (Milan and Large, 2014). We focus
82 on the modern channel of the Mojave River as a case study and use a MET-pIRIR procedure
83 (Buylaert et al., 2009; Li & Li, 2011; Fu & Li, 2013).

84

85 2 Regional Setting

86 The Mojave River in southern California is a terminal ephemeral stream that transports
87 water and sediment through one of North America’s driest regions (Enzel and Wells, 1997;

88 Enzel et al., 1992). The river flows from the San Bernardino Mountains, through the Mojave
89 Desert towns of Victorville and Barstow and terminates at Silver Lake playa. Two upper
90 streams, West Fork and Deep Creek, which are located on the north-facing slope of the San
91 Bernardino Mountains, provide the majority of water flow for the entire river (Enzel and Wells,
92 1997). The confluence of the creeks is known as The Forks and the river flows from here to
93 Silver Lake playa, a distance of about 200 km (Figure 1). The Forks receives an average of more
94 than 1000 mm of precipitation per year (Enzel and Wells, 1997). However, the drainage basin
95 overall is very dry; 90% of the watershed receives less than 150 mm/year (Enzel and Wells,
96 1997). At the Silver Lake terminus, 75 mm/year is the average (Enzel and Wells, 1997).

97 Hydrologic monitoring over the past century has shown that during normal or dry years
98 water does not flow along the entire length of the river due to transmission loss and
99 evaporation (Enzel and Wells, 1997). Significant flow, defined by Enzel and Wells (1997) as a
100 peak discharge of $>90 \text{ m}^3\text{s}^{-1}$, reaches Afton Canyon and Silver Lake only during extreme flood
101 events (Enzel and Wells, 1997). The hydrologic record from USGS stream gages indicates that
102 large floods on the Mojave River are correlated with the negative phase of the Northern
103 Annular Mode (NAM) and Northern Pacific Gyre Oscillation (NPGO) southern displacement
104 (Reheis et al., 2012). However, up until 1998, large magnitude floods also correlate with the
105 positive (El Nino) phase of El Nino Southern Oscillation (ENSO) (Hereford et al., 2006). There is
106 ambiguity associated with correlating multi-decadal time scale cycles using less than a century's
107 worth of hydrologic data (Reheis et al., 2012). For the purposes of our model, the frequency of
108 flooding on the Mojave River is an essential parameter; better constraints on this time interval
109 would be useful, but are beyond the scope of this study.

110

111 3 Methods

112 3.1 Sample collection and preparation

113 Samples were collected from eight locations along the Mojave River (Figure 1). Sample
114 locations were taken over a range of 156km, from the Forks to the Afton Canyon campsite. In
115 several cases, long stretches of the river (i.e., $>50 \text{ km}$) were inaccessible due to private
116 property. Sample sites were selected in dry channel bar deposits, to ensure that the grains were
117 last transported by water rather than wind. In order to reduce the recent effects of
118 bioturbation, only samples with clear bedding structures were chosen. At each site, a hole was
119 dug 0.3 to 0.5 m deep and an opaque 3-cm-diameter tube was pushed horizontally into the
120 freshly cleaned wall of the hole. The tubes were capped and placed in a light protective bag.
121 Location was recorded using a handheld GPS (GARMIN GPSmap78s). Samples were labeled
122 according to the order of their collection. In the lab they were given numbers J0260-J0267
123 (Figure 1).

124 Samples were opened under controlled lighting conditions. The material from both ends
125 of the tube was removed. The remaining material from the middle of the tube was separated
126 by wet sieving into the desired grain size fractions. For mineralogical isolation, the grain size
127 fraction 175-200 μm was chosen for each sample except J0263, for which the 200-250 μm sieve
128 fraction was chosen due to lack of material in the desired size range. The samples were treated
129 with HCl to remove carbonates. Density separation was performed using lithium metatungstate
130 diluted to a density of 2.58 g/cm^3 . For each sample, the denser material (mostly quartz) was
131 frozen in a liquid nitrogen bath and the floating feldspar grains were poured off. The feldspar

132 grains were washed and dried. No HF treatment was given due to the light color of the grains
133 and bright signals observed in preliminary runs, indicating that grain coating was minimal. A
134 monolayer of grains was glued to 1 cm diameter aluminum discs using viscous silicone oil. Three
135 discs were made for each sample.

136

137

138 3.2 Luminescence measurements and MET-pIRIR procedure

139 Luminescence measurements were made using a Riso TA-DA-20D with blue-green filter
140 combination (BG3 and BG39), for a transmission window of 340-470 nm. IRSL was measured
141 using the MET-pIRIR procedure (Fu & Li, 2013). The MET-pIRIR procedure provides data from a
142 series of thermally assisted IRSL measurements and was initially developed to find a stable,
143 non-fading IRSL signal for K-feldspar (e.g., Li & Li, 2011). We make IRSL measurements at 50 °C,
144 95 °C, 140 °C, 185 °C, and 230 °C, with a pre-heat of 250 °C for 60 seconds. Our dose response
145 curves were created using the SAR protocol (Murray & Wintle, 2000; Murray & Wintle, 2003).
146 The measurement procedure is summarized in Table 1.

147

148 3.3 Bleaching experiment

149 In a separate experiment, we quantitatively describe how MET-pIRIR signals respond to
150 sunlight exposure. The IRSL decay signal for feldspar has been described as a stretched-
151 exponential (SE) function (Pagonis et al., 2012; Chen, 2003), and by the general order kinetics
152 shown in Equation 1, below (Bailiff and Barnet, 1994; Poolton et al., 2009). Since we are
153 interested only in the shape of IRSL decay in response to sunlight bleaching, the choice of one
154 of the approximation functions listed above is somewhat arbitrary; although the parameters in
155 these equations contain information about the underlying physical process of charge eviction
156 from traps and recombination, they do so in an approximate way. We use the general order
157 kinetics equation after Poolton et al. (2009) as a descriptive function, rather than an exact
158 model, of IRSL intensity response to sunlight exposure.

159 The bleaching experiment measured pIRIR response to increasing sunlight exposure
160 time and fit the data by varying the parameters of the general order kinetics equation:

161

$$162 \quad I = \frac{I_0}{(1+at)^p} + R \quad (1)$$

163

164 In Equation 1, parameter a is bleachability, p is order and R is residual. The parameter a
165 represents capture cross section, light intensity, and initial trapped charge population (Poolton
166 et al., 2009). The parameter p is known as the order of the reaction and contains information
167 about how the reaction proceeds (McKeever, 1985). If p is 2, then Equation 1 is described as
168 second order, indicating that luminescence emission is proportional to both trapped electron
169 concentration and the number of unoccupied recombination sites, and that these quantities are
170 exist in proportion of 1:1 (McKeever, 1985). In general order kinetics (i.e. $1 < p < 2$)
171 luminescence displays neither first nor second order kinetic behavior (Bailiff and Barnet, 1994).
172 We have modified the general order kinetics equation to include a residual term (R in Equation
173 1), which represents low intensity IRSL after long sunlight exposure time.

174 The sample from Barstow (J0265) was chosen as representative due to a lack of
175 material from other sample sites. A total of 24 discs with 2-3 mm diameter monolayer grains
176 were adhered (using silicon oil), to 1 cm diameter aluminum discs. In sets of three, the discs
177 were exposed to direct sunlight at the University of California, Los Angeles for different
178 amounts of time. The exposure times were 0, 10, 30, 300, 1000, 3000, 10000, 30000 seconds.
179 Luminescence measurements were made using the MET-pIRIR procedure (see Table 1). The
180 resulting data were fit to the general order kinetics equation using the Levenberg-Marquardt
181 algorithm, subject to the constraint $1 < p < 2$ in Equation 1. If the algorithm is unconstrained, the
182 solution for p for some pIRIR temperatures is less than 1, the physical meaning of which is not
183 immediately clear. The bleaching experiment is subject to sensitivity changes and thermal
184 transfer. Additionally, “anomalous stability,” or the observation that the signal decays more
185 slowly than expected by theory, may explain why the unconstrained solution for p is less than 1
186 (Chen et al., 2012). For the purposes of this simple model, we have decided to fit the bleach
187 curves using the $1 < p < 2$ constraint, so that comparison among MET-pIRIR fits is more
188 straightforward (see Section 4). The SAR dose response curves were fitted to an exponential
189 function (Equation 2):

$$I = a(1 - \exp(-(x + c)/b)) \quad (2)$$

193 using Riso Analyst software (Levenberg-Marquart algorithm). Some of the dose response curves
194 are actually exponential plus linear, but in order to reduce complexity of the model we chose to
195 fit all curves with an exponential.

197 4 Results

198 In general, the equivalent dose of modern channel samples (J0262, J0263, J0267, J0266 and
199 J0265) decreases downriver for each MET-pIRIR measurement (Figures 1, 2). The MET-pIRIR
200 equivalent dose (D_e) from 230 °C measurements decreases most slowly with distance
201 downriver when compared with intermediate (185 °C, 140 °C and 95 °C) MET-pIRIR D_e (Figure
202 2). The pIRSL signals are shown in Figure 2 with background subtracted, where background is
203 defined as the last 50 channels in a 250 channel IRSL decay curve for a given sample. Although
204 subsequent higher temperature pIRIR measurements are observed to decrease in an
205 exponential shape down the river, the pIRIR measurements at 50°C decrease after the first
206 sample site to a constant low level at the downriver sample sites. Laboratory experiments show
207 that subsequent higher temperature assisted IRSL signals are bleached more slowly than lower
208 temperature ones (Duller & Wintle, 1991; Buylaert et al., 2009; Li & Li, 2011).

209 A comparison of MET-pIRIR signals among a single sample site reveals that pIRIR D_e is
210 proportional to IRSL measurement temperature, suggesting that each temperature increment
211 in the MET-pIRIR removes an increasingly difficult to bleach IRSL signal (Figure 2). These pIRIR
212 results are consistent with other workers’ results (Fu and Li, 2013; Kars et al., *in press*).
213 Furthermore, the results from our bleaching experiment can explain, to first order, the
214 downriver trend of MET-pIRIR measurements as a consequence of different bleaching rates due
215 to sunlight exposure during transport. Table 2 summarizes the results of the bleaching
216 experiment for sample J0265 (Barstow) and fits are shown in Figure 4. The bleach curve for
217 each MET-pIRIR temperature exhibits first order behavior (where $p = 1$ in Equation 1) when

218 constrained to $1 < p < 2$, except for IR_{50} that is between first and second order. One rationale for
219 constraining p is to facilitate comparison of parameter a among different MET-pIRIR
220 temperatures, as parameters a and p are not independent of each other in the general order
221 kinetics equation. Parameter a for IR_{230} is about an order of magnitude lower than a for IR_{50} .
222 The unconstrained fit for IR_{230} is clearly better than the constrained fit by visual inspection of
223 Figure 4e. However, in order to maintain continuity between each thermally assisted fit, we use
224 the constrained results for a and p for IR_{230} .

225 The shape of each fitted bleach-curve is consistent with observations of modern channel
226 sand samples in the Mojave River, suggesting that cyclical exposure to sunlight could explain
227 the pattern (see Figures 2, 4). In Equation 1, parameter a , sometimes referred to as
228 bleachability, decreases from pIRIR at $50^{\circ}C$ through subsequent MET-pIRIR measurements; our
229 fitted results suggest that the bleachability parameter for pIRIR at $230^{\circ}C$ is an order of
230 magnitude less than the bleachability for pIRIR at $50^{\circ}C$.

231 We have removed three samples from the bleaching experiment and modeling due to two
232 unrelated factors. Samples J0264 and J0261 were collected from a terrace deposit in a location
233 where the main channel was inaccessible. These terrace samples have a higher equivalent dose
234 than the modern channel upriver and downriver, as would be expected; since we do not model
235 deposition and erosion of terraces explicitly, we have removed these results for the purposes of
236 this simple model. The sample furthest from the headwaters is J0260, which was taken at Afton
237 Canyon and was also removed, due to its higher pIRIR signal. A preliminary interpretation is
238 that this sample has erosional inputs from nearby Tertiary to Quaternary alluvial-fan beds
239 (Reheis and Redwine, 2008), which increases the average IRSL of small aliquot samples. For the
240 purposes of this model, again we have elected to study the reach of the Mojave River from the
241 headwaters to Barstow (Figure 1).

242 243 4.1 Model conceptual description

244 We construct a simple, first-order forward model of MET-pIRIR signal response to cycles of
245 bleaching and growth, simulating how the luminescence characteristics of grains would respond
246 to transport and deposition on the Mojave River. This forward model attempts to reproduce
247 the MET-pIRIR data collected in the field by imagining a mass of sand in the Mojave River
248 beginning at the headwaters (simulated time = 0), and travelling downriver from the
249 headwaters (Sample J0262) to Barstow (Sample J0265) (Figure 1; Figure 3). The grains are
250 assumed to come from bedrock with infinite age (signal at saturation) just upstream from our
251 headwater sample site (Figure 1).

252 The model reproduces MET-pIRIR signals after a series of hypothetical floods, the frequency
253 of which is roughly estimated to be 10 years. (We vary this parameter from 1 to 100 years in
254 iterative runs of the model). The general order kinetics equation (Equation 1), using parameters
255 shown in Table 2, represents bleaching during transport or deposition (if grains rest on the
256 surface layer) and the dose response curve derived from Riso Analyst represents signal growth
257 during burial (Figure 3). Specific steps in the algorithm for the model are shown in Appendix.

258 The pIRIR data from the Mojave River is fit to the model outputs using the assumption that
259 each sample site in space represents a point in time for our hypothetical average sand travelling
260 down the river. This forward model approximates "every flood," meaning that once the best fit
261 is calculated, the number of floods between each data point times the interval between each

262 flood is the amount of time it took for the samples to travel from one site to the next. We
 263 ignore the minor contribution of the time average sand grains spent in transport (on the order
 264 of days) since the total amount of time is dominated by deposition (on the order of years). We
 265 acknowledge that this method is heavily dependent on accurate flood frequency modeling,
 266 which is difficult to achieve at the resolution required. For this iteration of the forward model,
 267 we make major simplifying assumptions and evaluate model performance semi-quantitatively
 268 and graphically.

269

270 4.2 Model assumptions

271 Some key assumptions are necessary to simplify the model. We assume that the
 272 samples are representative of fluvial transport and that the MET-pIRIR measurements at each
 273 sample site would be repeatable if one were to directly observe the luminescence
 274 characteristics of a set of grains as it travelled the entire length of the river. Additionally, we
 275 assume weathering of feldspar grains does not contribute to changes in signal downriver. This is
 276 a potential problem given the time scales involved and either laboratory tests or statistical
 277 treatments should be implemented in a more advanced model to address this problem. We
 278 also assume that bleaching by attenuated light is analogous to a reduction in signal by direct
 279 sunlight. Recent work (Kars et al., *in press*) has shown that filtering of blue and ultraviolet light
 280 in water selectively affects the bleachability of higher temperature pIRIR signals. This
 281 observation was not accounted for in the present work. The period of bleaching time in the
 282 model is not representative of an actual amount of time that the sample has spent in the water
 283 column or on the surface of a channel bar. The model does not account for hydrologic
 284 transmission loss, which is known to occur on the Mojave River, even during large floods (Enzel
 285 and Wells, 1997). Transmission loss would decrease the frequency of transport events and
 286 increase burial time downriver, causing a relative increase in equivalent dose (in comparison
 287 with our model without transmission loss) with distance downriver. Finally, IRSL values are not
 288 corrected for anomalous fading.

289

290 4.3 Chi-squared minimization

291

292 The model calculates MET-pIRIR values for a bleach and growth pair (representing one
 293 transport, deposition and burial event) iteratively and checks how close each iteration output is
 294 to the observed Mojave River data using a χ^2 best fit. Since the distance between samples is
 295 known, the solution space within a critical χ^2 value provides upper and lower bounds on
 296 sediment virtual velocity for the river. The model implements a best fit to the data using
 297 Pearson's Chi Squared test, shown in Equation 3, modified after Davis (1973).

298

$$299 \chi^2 = \min \left\{ \frac{|IR_{model230} - IR_{data230}|^2}{IR_{230}} + \frac{|IR_{model185} - IR_{data185}|^2}{IR_{185}} + \frac{|IR_{model140} - IR_{data140}|^2}{IR_{140}} + \right. \\ 300 \left. \frac{|IR_{model95} - IR_{data95}|^2}{IR_{95}} + \frac{|IR_{model50} - IR_{data50}|^2}{IR_{50}} \right\} \quad (3)$$

301

302

303 A list of chi squared terms is calculated for each model generated point and the
304 minimum is found simply by searching the list for the lowest value (for a description of the
305 algorithm, see Appendix). A simulated time from the lowest chi squared model point is assigned
306 to each sample location. The root mean square of all minimum chi squared is the output that is
307 plotted on the χ^2 map (Figure 5). Robust error calculations were not carried out for this
308 analysis (there is error on the bleach parameters for each signal and each dose response curve
309 in addition to error in the natural IRSL intensity). The critical χ^2 value is 7.78, for 0.1 level of
310 significance and four degrees of freedom. The results of the test are plotted as contour maps in
311 a grid of the growth periods (flood intervals) and bleach times that we tested with the model,
312 as shown in Figure 5. The range of plausible values for bleach time and growth period
313 parameters is very large. Forward model results of time passed span three orders of magnitude,
314 as discussed below.

315

316

317 5 Discussion

318 Model runs that are within the χ^2 tolerance can be forward modelled, which
319 graphically outputs model generated points for comparison with measured data points (Figure
320 6). The forward model is in the space of IRSL signal as a function of simulated time in years,
321 where $t = 0$ is a hypothetical sample at the first sampling location (Figure 3, Figure 6). This
322 allows us to solve for the amount of simulated time passed between the headwaters sample
323 J0262 and samples downriver (see Figure 1). The least amount of simulated time output by the
324 model is 20 years and the maximum amount of time passed is 7500 years.

325 The time interval range is too large to describe sediment virtual velocity. However, we
326 can use other information to help constrain the problem further. Based on hydrologic data over
327 the last century, the Mojave River flows continuously from the headwaters to Barstow (sample
328 J0265, Figure 1) roughly once every decade (Enzel and Wells, 1997), although individual
329 examples of recurrence interval vary widely from 1 year to 12 years as measured by USGS
330 stream gage monitoring (USGS National Water Information System, see references). If we
331 assume that the flood frequency (and thus the growth period) has remained constant, we can
332 solve the least χ^2 for the bleach time parameter only. The solution space ranges from 1 to 8
333 seconds of cyclical bleaching and the results are shown in the inset of Figure 5. In the forward
334 model, time passed from the headwaters to Barstow ranges from 210 to 800 years. Figure 6
335 shows that the forward model only accurately models pIRIR 230°C for the entire length of the
336 river. This could be a result of not taking river flow transmission loss into account. Less frequent
337 water flow as a function of distance from the headwaters would increase the recurrence
338 interval and reduce the magnitude of transport events, thereby limiting the light exposure of
339 buried grains. The model presented in this paper overestimates how much light downriver
340 samples receive relative to samples further upriver. Another possibility is that only the largest
341 floods are responsible for channel deposits and that the frequency and magnitude of bleaching
342 is far more heterogeneous than this model represents. In general, a more advanced model and
343 more measurements are necessary to improve the accuracy of the least χ^2 forward model
344 method.

345 Our preliminary results suggest that flow is frequent enough that the IRSL signals
346 decrease downriver, overcoming signal growth during burial time, from the headwaters to at

347 least Barstow. The result at Afton Canyon, although somewhat ambiguous, may represent a rise
348 in equivalent dose due to less frequent transport. Greater sampling density, and a model with
349 robust hydrologic inputs is needed to resolve this problem.

350 The MET-pIRIR laboratory methods developed in previous studies can be applied to
351 determine a range of possible transport times for sediment in the modern channel of the
352 Mojave River. A larger data set should provide better constraints on our estimates and allow for
353 robust statistical analysis of variability. The growth period parameter is likely to remain
354 insensitive to constraint because change in signal due to growth occurs on a time scale that is
355 approximately 5 orders of magnitude greater than change in signal due to bleaching. A more
356 constructive approach may be to solve for the bleach time parameter only while using a
357 distribution of growth periods with a mean based on prior hydrologic data from the region. In
358 either case, additional sampling should improve the accuracy of the solution.

359

360 6 Conclusion

361 The MET-pIRIR measurement process used in conjunction with a model for
362 environmental changes in luminescence, such as that presented here, has the potential to
363 become a powerful new tool to assess source to sink processes. The applicability of this
364 approach to fluvial systems other than the Mojave River may be wide-reaching. Other authors
365 have noted exponential decrease in equivalent dose (or “effective dose” since the dose does
366 not represent the age of the deposit) for small aliquot quartz samples with distance from
367 source in large drainage systems (e.g., Stokes et al., 2001). However, the MET-pIRIR procedure
368 may provide richer data with which to distinguish components of sunlight bleaching, making K-
369 feldspar the preferable mineral to determine virtual velocities or sediment residence times in
370 fluvial systems.

371

372 Appendix

373 Description of Forward Model Algorithm Steps

- 374 1. Initial simulated point is IR_{230} at saturation in IRSL units (for all following iterations, IRSL
375 is from step 6)
- 376 2. IRSL value from step 1 is bleached for t_b seconds using general order kinetics equation
377 (Equation 1, see text) with IR_{230} parameters determined by experiment.
- 378 3. New IRSL value after step 2 is converted to equivalent dose units using SAR growth
379 curve (Murray and Wintle, 2003), which has been rearranged from Equation 2 (see text):

$$x = -c - b(\ln(1 - I/a))$$

- 380 4. Growth period (in D_e units) is added to equivalent dose value determined in step 3.
- 381 5. New D_e after growth is converted to IRSL units using Equation 2 in its usual form.
- 382 6. The corresponding time in Equation 1 for the IRSL value from step 5 (x-axis value on a
383 IRSL decay curve) is found by rearranging Equation 1

384

$$t = \frac{\left(\sqrt[p]{\left(\frac{I_0}{I} - R \right)} - 1 \right)}{a}$$

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7. This time is added to t_b in step 2 and we repeat steps 2 through 7 for 225 iterations (The number of iterations was determined by running the entire algorithm several times until the fastest, in total simulated time, convergence was reached.)
 8. Repeat steps 1 through 7 for IR_{185} , IR_{140} , IR_{95} and IR_{50} .
 9. Create a list with 225 repetitions of each MET-pIRIR measurement at each Mojave River sample location.
 10. Insert each list into the corresponding temperature data term in Equation 3 (i.e. $IR_{data230}$ for the IR_{230} data at each sample location).

$$\chi^2 = \min \left\{ \frac{|IR_{model230} - IR_{data230}|^2}{IR_{230}} + \frac{|IR_{model185} - IR_{data185}|^2}{IR_{185}} + \frac{|IR_{model140} - IR_{data140}|^2}{IR_{140}} + \frac{|IR_{model95} - IR_{data95}|^2}{IR_{95}} + \frac{|IR_{model50} - IR_{data50}|^2}{IR_{50}} \right\}$$

- 395
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400
11. Search every resulting chi squared value for the lowest one.
 12. Repeat 10,000 times in order to test 100 different bleach time inputs and 100 different growth period inputs.

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402
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409
410 References

411
412 Bailiff, I.K. and Barnett, S. M., 1994. Characteristics of infrared stimulated luminescence from a
413 feldspar at low temperatures. *Radiation Measurements*, 23: 541-546.

414
415 Buylaert, J. P., Murray, A. S., Thomsen, K. J., and Jain, M., 2009. Testing the potential of an
416 elevated temperature IRSL signal from K-feldspar. *Radiation Measurements*, 44: 560-565.
417
418 Chen, R., 2003. Apparent stretched-exponential luminescence decay in crystalline solids.
419 *Journal of Luminescence*, 102-103. 510-518.
420
421 Chen, R., Lawless, J. L., Pagonia, V., 2012. Two-stage thermal stimulation of
422 thermoluminescence. *Radiation Measurements*, 47: 809-813.
423
424 Church, M., Hassan, M. A., 1992. Size and distance of travel of unconstrained clasts on a
425 streambed. *Water Resources Research*, 28: 299 -303.
426
427 Crickmore, M. J., 1967. Measurement of sand transport in rivers with special reference to tracer
428 methods. *Sedimentology*, 8: 175 – 228.
429
430 Davis, John C., 1973. *Statistics and Data Analysis in Geology*. John Wiley and Sons, New York.
431
432 Duller, G. A. T. & Wintle, A., 1991. On infrared stimulated luminescence at elevated
433 temperatures. *International Journal of Radiation Applications and Instrumentation*, 18: 379 –
434 384.
435
436 Enzel, Y. Brown, W. J., Anderson, R. Y., McFadden, L. D., Wells, S. G., 1992. Short-duration
437 Holocene lakes in the Mojave River drainage basin, southern California. *Quaternary Research*,
438 38: 60-73.
439
440 Enzel, Y. and Wells, S. G., 1997. Extracting Holocene paleohydrology and paleoclimatology
441 information from modern extreme flood events: an example from southern California.
442 *Geomorphology*, 19: 203-226.
443
444 Fu, X., Li, S., 2013. A modified multi-elevated temperature post IR-IRSL protocol for dating
445 Holocene sediments using K-feldspar. *Quaternary Geochronology*, 17: 44-54.
446
447 Gesch, D.B., 2007, *The National Elevation Dataset*, in Maune, D., ed., *Digital Elevation Model*
448 *Technologies and Applications: The DEM Users Manual*, 2nd Edition: Bethesda, Maryland,
449 American Society for Photogrammetry and Remote Sensing, pp 99-118.
450
451 Gesch, D., Oimoen, M., Greenlee, S., Nelson, C., Steuck, M., and Tyler, D., 2002, *The National*
452 *Elevation Dataset: Photogrammetric Engineering and Remote Sensing*, 68: 5-11.
453
454 Hereford, R., Webb, R. H., Longpre, C. I., 2006. Precipitation history and ecosystem responds to
455 multidecadal precipitation variability in the Mojave Desert region, 1893 - 2001. *Journal of Arid*
456 *Environments*, 67: 13 - 34.
457

458 Howard, A. D., Dietrich, W. E., Deidl, M. A., 1994. Modeling fluvial erosion on regional to
459 continental scales. *Journal of Geophysical Research*, 99: 13971 - 13986.
460
461 Kars, R. H., Reimann, T., Ankjaergaard, C., Wallinga, J., *in press*. Bleaching of the post-IR IRSL
462 signal: new insights for feldspar luminescence dating. *Boreas*, doi: 10.1111/bor.12082
463
464 Lamarre, H., MacVicar, B., Roy, A. G., 2005. Using passive integrated transponder (PIT) tags to
465 investigate sediment transport in gravel-bed rivers. *Journal of Sedimentary Research*, 75: 736 –
466 741.
467
468 Li, B., Li, S., 2011. Luminescence dating of K-feldspar from sediments: A protocol without
469 anomalous fading correction. *Quaternary Geochronology*, 6: 469-479.
470
471 Milan, D. J., Large, A. R. G., 2014. Magnetic tracing of fine-sediment over pool-riffle
472 morphology. *Catena*, 115: 134 – 149.
473
474 McKeever, S. W. S., 1985. *Thermoluminescence of solids*. Cambridge University Press,
475 Cambridge.
476
477 Murray, A. S., Wintle, A. G., 2000. Luminescence dating of quartz using an improved single-
478 aliquot regenerative-dose protocol. *Radiation Measurements*, 32: 57-73.
479
480 Murray, A. S., Wintle, A. G., 2003. The single aliquot regenerative dose protocol: potential for
481 improvements in reliability. *Radiation Measurements*, 37: 337-381.
482
483 Pagonis, V., Marthekai, P., Singhvi, A. K., Thomas, J., Balaram, V., Kitis, G., Chen, R., 2012. Time-
484 resolved infrared stimulated luminescence signals in feldspars: Analysis based on exponential
485 and stretched exponential functions. *Journal of Luminescence*, 132: 2330-2340.
486
487 Paola, C., 2000. Quantitative models of sedimentary basin filling. *Sedimentology*, 47: 121 - 178.
488
489 Pietsch, T. J., Olley, J. M., Nanson, G. C., 2008, Fluvial transport as a natural luminescence
490 sensitizer of quartz. *Quaternary Geochronology*, 3: 365 – 376.
491
492 Poolton, N. R. J., Kars, R. H., Wallinga, J., Bos, A. J. J., 2009. Direct evidence for the participation
493 of band-tails and excited-state tunneling in the luminescence of irradiated feldspars. *Journal of*
494 *Physics: Condensed Matter*, 21: doi: 10.1088/0953-8984/21/48/485505.
495
496 Rathburn, R. E., Kennedy, V. C., 1978. Transport and dispersion of fluorescent tracer particles
497 for the dune-bed condition, Atrisco Feeder canal near Bernalillo, New Mexico. USGS
498 Professional Paper: 1037.
499

500 Reheis, M. C., Bright, J., Lund, S. P., Miller, D.M., Skipp, G., Fleck, R. J., 2012. A half-million-year
501 record of paleoclimate from the Lake Manix Core, Mojave Desert, California. *Palaeogeography,*
502 *Palaeoclimatology, Palaeoecology*, 365: 11 - 37.

503

504 Reheis, M. C., Redwine, J. L., 2008. Lake Manix shorelines and Afton Canyon terraces:
505 Implications for incision of Afton Canyon. Reheis, M.C., Hershler, R., and Miller, D.M., eds., in
506 *Late Cenozoic Drainage History of the Southwestern Great Basin and Lower Colorado River*
507 *Region: Geologic and Biotic Perspectives: Geologic Society of America, Special Paper 349*, pp
508 227 – 259.

509

510 Rittenour, T., 2008. Luminescence dating of fluvial deposits: applications to geomorphic,
511 paleoseismic and archeological research. *Special Issue, Boreas*, 37: 613-635.

512

513 Stokes, S., Bray, H.E., Blum, M.D., 2001. Optical resetting in large drainage basins: tests of
514 zeroing assumptions using single-aliquot procedures. *Quaternary Science Reviews*, 20: 879-885.

515

516 Stokes, S., 1999. Luminescence dating applications in geomorphological research.
517 *Geomorphology*, 29: 153-171.

518

519 USGS National Water Information System,

520 http://waterdata.usgs.gov/ca/nwis/uv?site_no=10262500 (accessed July 3, 2014).

521 Figure Captions

522

523 Figure 1: Map of field site: Samples from the Mojave River are marked with a triangle and their
524 respective laboratory codes. All samples are from point bar or channel bar structures that have
525 been preserved since deposition, with the exception of samples J0261 and J0264. These
526 samples were taken from a terrace in a location where the river was inaccessible. They are
527 excluded from the present study for this reason. Sample J0260 is also excluded, see text for
528 discussion. Topographic data from USGS National Elevation Dataset (<http://ned.usgs.gov>; Gesch
529 et al., 2002; Gesch, 2007).

530

531 Figure 2: Equivalent dose decreases with distance from the furthest upstream sample, J0262
532 (Figure 1). The subsequent higher MET-pIRIR measurements bleach more slowly than lower
533 temperature ones. Equivalent dose for IR₅₀ remains at a constant low level after the first sample
534 site.

535

536 Figure 3: Conceptual model of bleaching and growth differences for IR₅₀ and IR₂₃₀. Bleaching
537 varies significantly, while growth of the signal is similar. This allows for the signal response to
538 sunlight exposure in the environment to be measurably different. Note that the simulated time
539 scale for bleaching is greatly exaggerated in this figure. The upper half of the diagram
540 represents IRSL field measurements and the trends observed downriver. The sand patches
541 indicate an average mass of sand (centroid shown with black dot), the IRSL characteristics of
542 which are assumed to be represented by the sample discs. The lower half shows a mapping of
543 IRSL values to simulated time of the forward model. Since the number of flood events between

544 each location is unknown, the change in simulated time (Δt^*) is determined by the best fit of
545 field measurements to model outputs. The unknown amount of growth between deposition
546 and collection of the sample contributes to uncertainty in Δt^* .

547

548 Figure 4: Bleaching experiment data fitted to the general order kinetics equation (Equation 2)
549 for each temperature assisted met-pIRIR measurement. Fits are shown with residuals below. (a)
550 IR₅₀ (b) IR₉₅ (c) IR₁₄₀ (d) IR₁₈₅ (e) IR₂₃₀ fit with constraint $1 < p < 2$ and IR₂₃₀ without constraint, see
551 section 4.

552

553 Figure 5: Model χ^2 test results. The contours represent values of χ^2 test statistic for 100 bleach
554 time inputs and 1000 growth period inputs. For a 0.1 level of significance and four degrees of
555 freedom, the critical χ^2 value is 7.78, meaning that any model with input parameters falling
556 within this contour is accepted as consistent with the data. The inset shows the χ^2 for 10 year
557 growth periods (decadal) and the interval of (1,100) bleach times. The dashed line indicates the
558 0.1 significance level, below which lie acceptable model fits.

559

560 Figure 6: Forward Model. This output is for an input growth period of 10 years and an input
561 bleach time of 7 seconds. The resulting total simulated time is 270 years. IR₂₃₀ fits well, but
562 lower temperature pIRIR measurements fit less well due to decay of model to background level,
563 see text for discussion.

564

565 Table Captions

566

567 Table 1: The MET-pIRIR protocol used in this study, after Fu and Li, 2013.

568 Table 2: The results for fitted parameters of Equation 1 for each MET-pIRIR. Parameter a has
569 units of s^{-1} , p is unitless and R is arbitrary units of IRSL intensity.

570

571 Table 1

| Step | Measurement |
|--------------------|-------------------------------------|
| 1 | Natural, Regenerative Dose |
| 2 | Preheat 250°C, 60s |
| 3 | IR diodes at 50 °C |
| 4 | IR diodes at 95 °C |
| 5 | IR diodes at 140 °C |
| 6 | IR diodes at 185 °C |
| 7 | IR diodes at 230 °C |
| 8 | Test Dose |
| 9 | Preheat 250°C, 60s |
| 10 | IR diodes at 50 °C |
| 11 | IR diodes at 95 °C |
| 12 | IR diodes at 140 °C |
| 13 | IR diodes at 185 °C |
| 14 | IR diodes at 230 °C |
| 15 | Hot bleach IR diodes at 290 °C, 40s |
| Repeat from step 1 | |
| | |

572

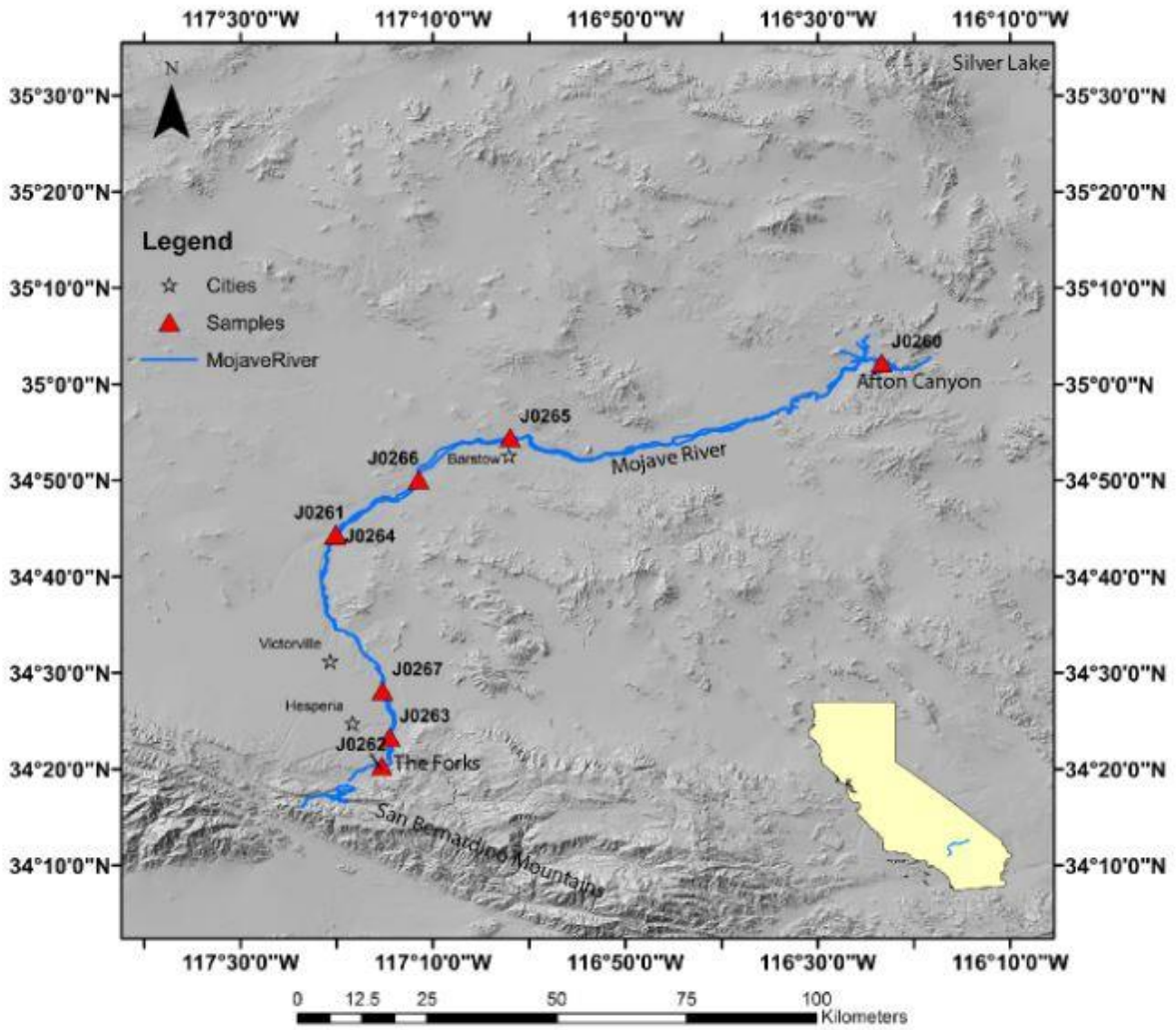
573 Table 2

574

| IR Stimulation | a | p | R |
|-------------------|--------|--------|--------|
| IR ₅₀ | 0.074 | 1.6178 | 0.0439 |
| IR ₉₅ | 0.0526 | 1 | 0.0476 |
| IR ₁₄₀ | 0.0292 | 1 | 0.1409 |
| IR ₁₈₅ | 0.0169 | 1 | 0.2513 |
| IR ₂₃₀ | 0.0064 | 1 | 0.2903 |
| | | | |

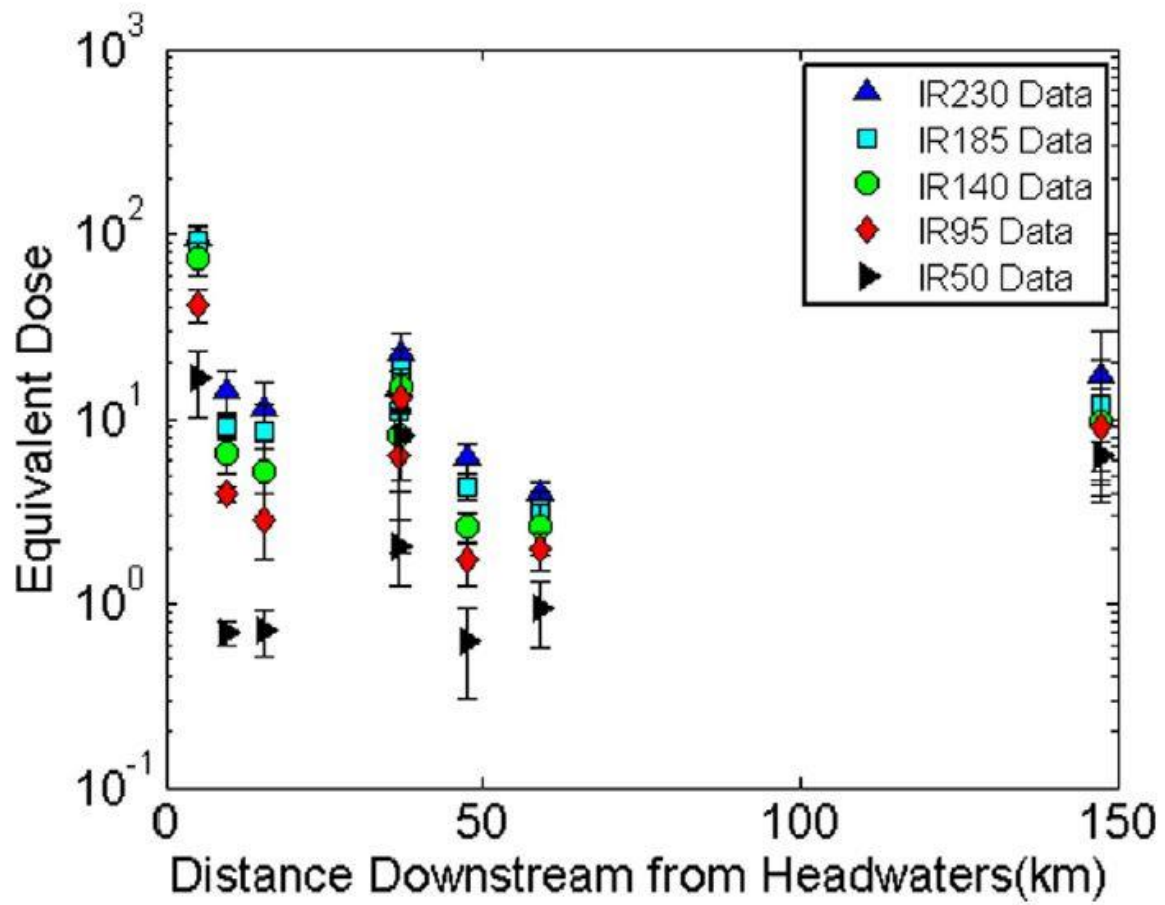
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576 Figure 1

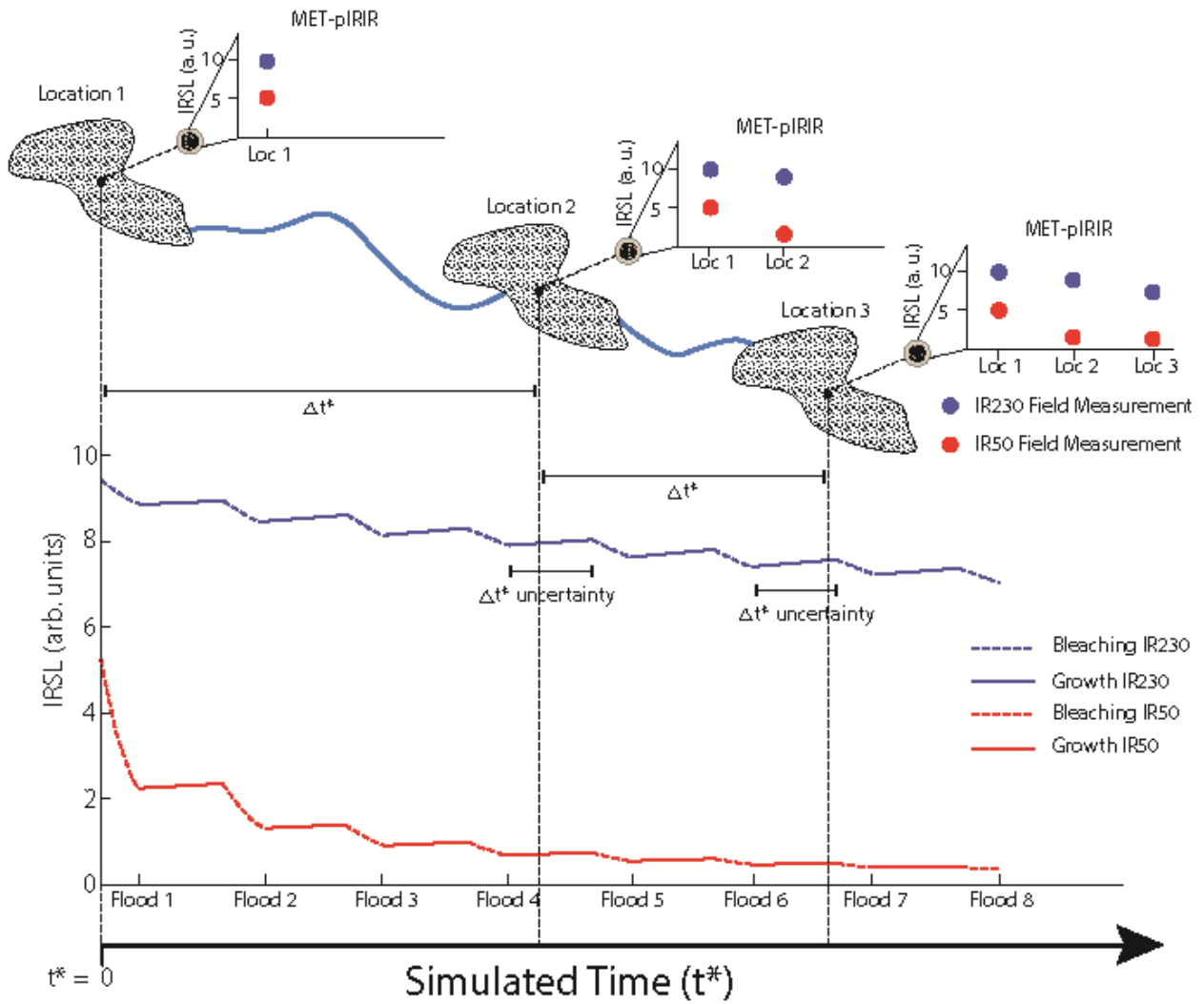


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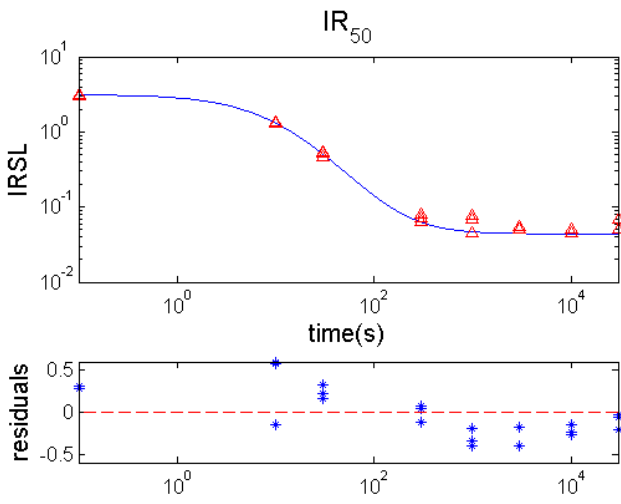
579 Figure 2
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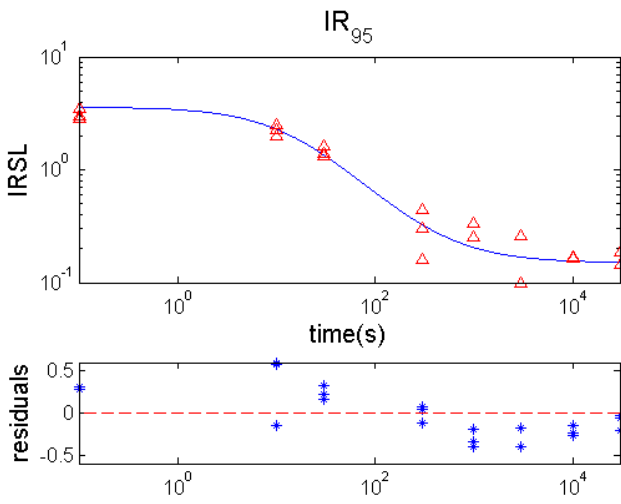
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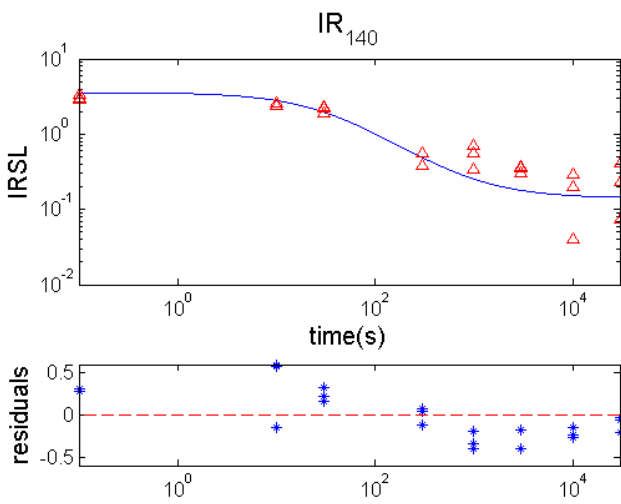
586 Figure 4 a-d



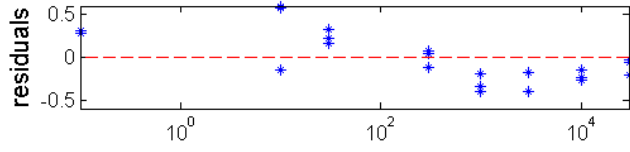
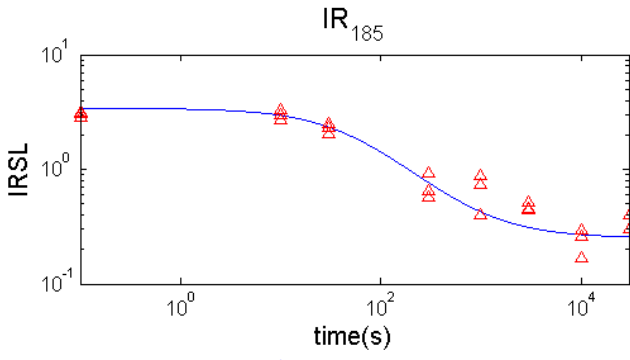
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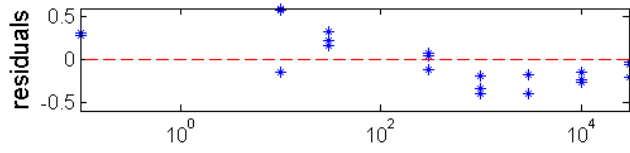
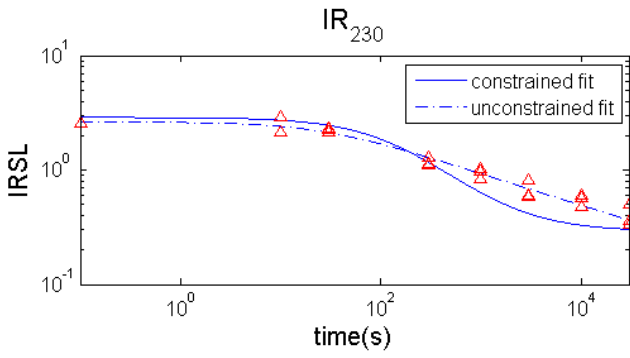
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