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Downstream MET-IRSL single-grain distributions in the Mojave River, southern California: Testing assumptions of a virtual velocity model

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Abstract

We use samples from a prior study (McGuire and Rhodes, 2015) to investigate the bleaching trend of Mojave River sand in more detail. We present new single grain data which provides insight into how previously presented multiple-grain luminescence signals decrease downriver. The single grain dose distributions allow for a test of the assumption that multiple-grain equivalent dose (D_e) is representative of fluvial transport down the Mojave River. For samples at the Forks, Victorville and Barstow, with laboratory luminescence sample codes J0262, J0267 and J0265, respectively, inspection of the kernel density estimate (KDE)-generated probability density function supports the assumption, though is does not prove it directly. Implementing a Kolmogorov–Smirnov (K–S) test shows that the downriver samples are statistically different from each other, suggesting bleaching as the primary mechanism for changes is dose distribution downriver. Single-grain dose distributions show that the D_e of the Afton Canyon sample (J0260) is not representative of grain travel from source to sink, but instead likely a result of local mixing of sediment populations. This result is confirmed by visual inspection of the KDE, and quantitatively using the K–S test. As has been noted by several authors, the single-grain dose distribution in active channels of rivers may represent a worst case in terms of poor bleaching, due to mixing of older-age populations (Cunningham et al., 2014; Jain et al., 2004). This observation holds for our data set and presents an opportunity to test and develop luminescence techniques to determine provenance. In particular, future sampling in the vicinity of the Afton Canyon site has the potential to identify the entry point of a poorly-bleached population.

Keywords
Mojave River
Luminescence
Geomorphology
MET-pIRIR

Introduction:

Fluvial sediments of Holocene and Pleistocene age are now routinely dated using feldspar grains due in part to the development of the post-infrared stimulated luminescence (pIRIR) protocol (Rhodes, in press; Buylaert et al., 2009; Li & Li, 2011). This technique was developed to obtain an IRSL signal from feldspar that does not fade, or fades very little over the time scale of interest (Li & Li, 2011). A possible drawback to the technique is that sequential, higher temperature measurements of the pIRIR protocol bleach more slowly in sunlight and underwater than standard IRSL signals (Kars et al., 2014). In a previous study, we took advantage of the tendency of pIRIR signals to be poorly bleached in order to

obtain information about the rate of travel of fine sand in the Mojave River (McGuire & Rhodes, 2015; Reimann et al., 2015). A fundamental assumption of that study was that fluvial transport is the dominant cause of differences in multiple-grain (MG) D_e along the river. Several workers have shown that inferences about degree of partial bleaching from MG aliquots are subject to grain sensitivity and aliquot size, both of which are difficult to control for using only MG data (Cunningham et al., in press; Arnold & Roberts 2009). In the present study, we make single-grain (SG) measurements of a subset of the samples presented previously (McGuire & Rhodes, 2015). The implementation of SG measurement techniques has allowed for analysis of poorly bleached fluvial sediments using robust statistical models (Roberts et al., 2000; Bailey & Arnold, 2006; Arnold et al., 2007). In this study, we examine SG equivalent dose (D_e) populations graphically using kernel density estimate (KDE)-generated probability distributions and quantitatively using the Kolmogorov-Smirnov (KS) test.

Samples and Methods:

Samples were collected from shallow pits in channel and point bars in the modern Mojave River. The sample locations and laboratory codes are shown in Figure 1. The depth of the samples ranged from 30 – 80 cm; the range was due to our field protocol that samples be collected only where bedding structures are present, in order to reduce the effects of recent bioturbation. The 175-200 µm grain size fraction was chosen for measurement, with the exception of sample J0266, for which there was insufficient material in the desired grain size range, and the 200 – 220 µm range was selected. Mineralogical separation was done using lithium metatungstate liquid, diluted to a density of 2.58 gcm^{-3}, as our lab had not yet implemented Super-K (2.565 gcm^{-3}) density separation (Rhodes, in press). The possible inclusion of sodic-rich feldspars after density separation may affect the changes in dose distributions downriver (see Discussion). Samples were treated with HCl to remove carbonates. The location of samples along with their laboratory codes (J0260 to J0267) are the same as previously reported and are shown in Figure 1. Single-aliquot D_e of these samples was measured and described previously (McGuire and Rhodes, 2015). In this study, we present results from single-grain (SG) MET-pIRIR measurements and thermoluminescence measurements of a subset of the samples. We implement a MET-pIRIR measurement protocol, adapted for single-grains (Fu & Li, 2013; Reimann et al., 2012). Single-grain discs from a subset of Mojave river samples were measured at temperature increments of 50, 95, 140, 185 and 230 ^{o}C; the full measurement protocol is shown in the table S1. Additionally, we measured thermoluminescence (TL) of small aliquots and the measurement protocol is shown in Table S2. It is important to note that fading corrections were not made for the SG MET-pIRIR measurements nor the TL measurements; therefore, the equivalent doses of individual grains cannot be interpreted to indicate an age.

Results:

The shape of TL D_e as a function of distance downriver differs in general from the MG MET-pIRIR trends. The concave-down shape of the TL data (as opposed to a concave-up stretched exponential) is likely a result of the reduced bleachability of feldspar TL in the water column when compared to optical luminescence bleaching (Rendell et al., 1994; Berger, 1990). The TL measurements, in conjunction with the MG MET-pIRIR trends, provide evidence for a decreasing degree of bleaching in the water column

with distance downriver. This inference is supported by hydrologic data, which shows that transmission and evaporation loss of surface water is significant downriver, even for the largest floods (Figure 3).

Single-grain data were processed using Riso's software Analyst. Rejection criteria applied to grains were >100% error in dose, >50% recycling ratio limit and the inability to fit the dose response curve with an exponential or exponential plus linear function in Analyst. Single-grain dose distributions for each temperature and sample are represented with a kernel density estimate (Figure 4). General trends from graphical inspection can be grouped into two categories: intra-sample and inter-sample. The intra-sample trends show that the grain population is progressively more poorly bleached at higher pIRIR measurement temperature. This observation is based on the widening of highest relative probability peak with increasing temperature. Additionally, the number of grains returning signal decreases with increasing measurement temperature. This may reflect a mixed mineralogy as density separation was done at 2.58 gcm^{-3} (instead of 2.565 gcm^{-3}), which can cause plagioclase feldspar to be included in the SG population (Rhodes, in press). The decreasing number of grains returning signal may also indicate a reduced probability of recombination with increasing temperature (Poolton et al., 2001), resulting in low signal to noise ratio for the lowest dose fraction of grains. While this observation casts some doubt on the extent of extrapolations that can be made from SG MET-pIRIR dose distributions, inter-sample trends show that bleaching has a first order effect on the shape of the SG MET-pIRIR D_e distributions. The SG MET-pIRIR KDE's show increased bleaching of grains at Barstow relative to the Forks, for each temperature IRSL measurement. The IR_{230} KDE for the Forks shows equal relative probability at a range of D_e (1.87 to 135 Gy), but the IR_{230} KDE for Barstow a relative probability peak (at ~18 Gy) emerges (Figure 4b), suggesting that bleaching has occurred.

Statistical Tests:

We use the two-sample Kolmogorov-Smirnov (KS) test to determine whether dose distributions are statistically different from each other. The test uses empirical cumulative distribution functions (ecdf's) for two samples and calculates the "distance" in cumulative probability between samples (see Conover, 1999). The test determines between the null hypothesis (H_0) that the distributions are the same and the alternative hypothesis (H_1) that the distributions are different, to some confidence level α (in this case, set to 0.05). The KS test for the Forks and Barstow SG distributions rejects H_0, which leads us to conclude, as expected, that the deposits are different (Figure 5). This result provides statistical justification for exploring the reason for the difference. The KS test for Barstow and Afton Canyon fails to reject H_0, which suggests (though does not prove) that the increased MG D_e at Afton Canyon relative to Barstow is due to the contribution of a few locally-sourced, poorly-bleached grains.

Roberts et al., (2000) found that it is possible to distinguish dose populations as long as there is a small number of mixture components. Since the SG data for Afton Canyon appear to be a mixture of a Barstow-provenance population and an unknown-provenance population, further sampling of the surrounding sedimentary facies and tributaries may reveal both the source and the proportion of mixing of the older population. The Afton Canyon sample was collected at a location where the Mojave River has incised through Quaternary-Tertiary fanglomerates (Reheis & Redwine, 2008). Sediment delivered through tributaries could be the source of the higher equivalent dose population, as saturated grains from the fanglomerates are partially bleached over the short transport distance to the modern Mojave River channel. Alternative explanations include entrainment fine sand fractions from Lake Manix, a Pleistocene pluvial lake that was the ancestral terminus of the Mojave River before Afton Canyon was

incised (Reheis et al., 2012; Enzel & Wells, 1997). Further sampling in the region has the potential to resolve the proportion of mixing of the Mojave River population and the older, poorly-bleached population.

Discussion:

The trends observed in SG MET-pIRIR equivalent dose distributions for the Forks and Barstow are consistent with increased bleaching of grains down the Mojave River. A 3-component finite mixture model using MATLAB function `gmdistribution.fit` function for each IR-50 ^{o}C distribution showed that the lowest mixture component shifts from 1.73 Gy at the Forks to 0.27 Gy at Barstow. The shift to lower D_e is accompanied by a reduction in the tail of the relative probability peak. This observation may be due to better bleaching of grains. However, it could also be due to the weathering of plagioclase down the river. Inclusions of plagioclase grains in the SG population may increase scatter, due to different luminescence characteristics (Lamothe & Auclair, 1997; Prescott et al., 1994). Plagioclase signals are generally less bright than K-feldspar signals, especially at higher temperatures, so it is possible that plagioclase distributions are excluded from higher temperature dose distributions. An additional factor complicating the interpretation of number of KDE plots (Figure 4) is that the number of accepted grains decreases with increasing measurement temperature. The IRSL signal's dependence on temperature is likely representative of the presence of plagioclase in the sample, as described above, but may also represent a reduction in recombination probability, resulting in rejection of more grains at higher temperature due to lower signal to noise ratio. Future sampling in the region, and density separation using Super-K (2.565 gcm^{-3}) should help resolve this issue (Rhodes, in press). The KS-test can be dependent on the number of observations and since there are more observations at Afton Canyon (n = 235) than at Barstow (n = 173) for IR_{50}, it is possible that the test is affected, however, we note that more observations tend to drive the KS-test toward rejection (Joel Saylor, pers. comm.), which is the opposite result reported here. Still, we acknowledge that the KS-test is limited in its ability to determine whether two samples are drawn from different populations.

Attributing the bleaching of grains to fluvial transport, as opposed to aeolian transport or selective weathering is a difficult task. The episodic nature of water flow on the Mojave River could allow for the majority of bleaching to occur on the surface after deposition (Gray & Mahan, 2015), resulting in similar D_e distributions for movement of grains by wind or water. The MG MET-pIRIR trends in both dose and error (Figure 2) are consistent with a theoretical model for episodic surface bleaching (Gray & Mahan, 2015). In this model, standard deviation decreases downriver along with D_e, as the grains become better mixed and bleached. In this model, the introduction of a new population causes the D_e and standard deviation to increase (Harrison Gray, pers. comm.), which is the case for our data set, specifically at Afton Canyon. We attribute the higher MG D_e and standard error at Afton Canyon to the few higher dose grains in the SG dose distribution, but note that aliquot size of the MG discs could affect the apparent trend (Cunningham et al., in press). These observations support the argument that at least a portion of the bleaching is occurring on the surface, after grains are deposited.

In a more complicated scenario, some linear combination of surface bleaching after deposition and underwater bleaching during floods could occur. One indication that surface bleaching alone cannot explain SG downriver trends is that a bimodal distribution of equivalent doses does not occur, as an episodic surface bleaching model predicts (Gray & Mahan, 2015) Another line of evidence is that a stepwise MG pIRIR model (McGuire & Rhodes, 2015) based on full-sunlight empirical bleaching curves

consistently under-predicts IR_{50}, IR_{95} and IR_{140} values down the river in all model runs. These lower temperature pIRIR signals have reached a constant value between sample J0266 and Barstow (J0265), possibly related to the pIRIR residual value, which is a function of both deposition environment and pIRIR measurement temperature (Figures 1, 2). Controlled bleaching experiments to simulate the effects of wavelength filtering in the water column have shown that residual IRSL signal increases linearly with pIRIR measurement temperature (Kars et al., 2014). It is possible that the higher than modelled (see McGuire & Rhodes, 2015) MG D_e of IR_{50}, IR_{95} and IR_{140} represents the effects of water-lain bleaching. A secondary line of evidence presented in this paper is that the downriver change in TL D_e does not follow the same stretched exponential shape of the MET-pIRIR measurements (Figure 2). Since the TL signal is much less bleachable underwater than the optical signal (Rendell et al., 1994), the lack of significant reduction in TL signals suggest that some of the bleaching is occurring underwater.

In order to test whether the single-grain distributions observed could result primarily from fluvial processes, we developed further the model presented in McGuire & Rhodes (2015). The model supposes that sediment is mobilized when river discharge is above a certain threshold (e.g. bankfull discharge). Discharge for the Mojave River is modelled using the Helendale USGS station (10260950) historical data fitted to a generalized Pareto distribution for all values greater than zero using maximum likelihood estimation. Values that are zero discharge are approximated from the data and resampled in MATLAB using an if-statement. A summary of methods for treating discharge data with excess zeros can be found in Weglarczyk et al. (2005). The model produces a random number from the Helendale generalized Pareto parameterization and applies an arbitrary threshold for bleaching: in the simluation presented in Figure 6, 10 m^3s^{-1} was used. If the number representing discharge is above the threshold, we assume the sand will bleach according to the experimentally determined bleach parameters of the general order kinetics equation (see McGuire & Rhodes, 2015). If discharge is below the threshold or zero, the sand will remain buried and the dose response curve, determined experimentally for the MG discs (see McGuire & Rhodes, 2015) is used to represent signal growth during burial (Murray and Wintle, 2003). This process was repeated for 2000 iterations, with time-steps of one month. The process was then repeated 200 times to simulate various grain histories that are possible after successive iterations. The resulting synthetic distributions are shown in Figure 6. These results suggest that it is possible to produce the trend towards better bleached samples downriver simply from random fluctuations in the frequency of bleaching. Additionally, the data can be re-produced closely, if the best-fitting iteration is selected.

Another finding of this paper is that contribution of a mixing population can have a first order effect on downriver trends of pIRIR signals, as is the case at Afton Canyon. We propose that the SG dose distribution at Afton Canyon results from a small contribution of locally-sourced grains mixed with a SG dose distribution similar to the Barstow sample (J0265). The implications of this hypothesis are that (1) tributary and/or terrace erosion exert a first order control on MG dose, and that (2) if the input population of locally sourced sand has a significantly different D_e from the main channel sand, its signature could be removed. The presence of this higher dose population may allow for future sampling along the river to pinpoint the location of the routing of these poorly bleached grains. This has important implications for provenance studies using luminescence equivalent dose distributions.

Conclusion:

Single-grain MET-pIRIR distributions are used to show that D_e populations at the Forks and Barstow differ in a statistically significant way, consistent with a trend towards better bleaching downriver. This result supports the possibility that changes in D_e down a river could be combined with theoretical models to gather information about sediment transport. The single-grain results at Afton Canyon show that using multiple-grain aliquots could be misleading, as the influence of mixed, older populations could go undetected. In this case, the model of Gray and Mahan (2015) correctly predicts that the Afton Canyon D_e is a result of mixing and not burial time. The first-order influence of mixing populations on a modern sample provide support for the use of luminescence in provenance studies (Zular et al., 2013). Jain et al., (2004) argue that modern fluvial sand D_e distributions from the Loire River represent a poorest-bleaching case. Stokes et al. (2001) and others suggest that bank erosion and tributaries may contribute older grains to the modern channel (Rittenour, 2008; Stokes, 1999). Our data supports these assertions, and we propose further that the modern river channel can be thought of as a gravity well for sediment in the immediate surroundings, routed via the drainage network. Using this general framework, the degree of partial bleaching would be dependent upon local gradient and the dose distribution of up-gradient deposits. We do not propose to test this explanation with the current data set, but rather suggest that interpretations about dose distributions of modern fluvial samples are subject to provenance and the ability of the drainage system to deliver locally sourced sediments.

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Figure 1: Map of the Mojave Desert region, showing the drainage basin of the Mojave River and the sample locations (red triangles) with sample laboratory codes. Single-grain and thermoluminescence results for a subset of these samples (J0262, J0266, J0265 and J0260) are reported in this paper (for the entire set of MG MET-pIRIR results, see McGuire & Rhodes, 2015). Map after McGuire & Rhodes (2015). Digital elevation model created using the National Elevation Dataset (Gesch, 2007; Gesch et al., 2002).

Figure 2: Multiple-grain, single-aliquot equivalent dose is plotted against distance downriver (after McGuire & Rhodes, 2015). Absolute standard error is plotted below for the samples. MET-pIRIR D_e decreases in a stretched exponential shape, then increases for all temperatures at the furthest point downriver (Afton Canyon, J0260). Only three sample were measured with TL, due to lack of material; the trend in TL D_e departs from an exponential shape, indicating that some of the bleaching over this portion of river has occurred underwater.

Figure 3: Monthly integrated discharge for the Mojave River from 1950 to 1997 is plotted with two models for transmission loss of water down the river. These models connect data points from two individual historic floods. The February, 1993 flood is one of the largest on record, and the discharge still decays down the river. The February 1973 flood is smaller and displays the more frequent discharge

shape, in which station 10263000 (Afton Canyon) receives almost no discharge (~2 m^3s^{-1}). Data from USGS National Water Information System: <http://waterdata.usgs.gov/ca/nwis/uv?site_no=10262500>

Figure 4: Kernel density estimates (KDE) of the single-grain MET-pIRIR results are plotted by equivalent dose versus relative probability. The number of grains returning signal corresponding with measurement temperature is shown in the legend. Note the scaling of both axes changes. (a) The KDE for the Forks shows several higher-dose populations that are not present at Barstow. The IR_{230} SG results show equal relative probability of a series of D_e, indicating that little to no bleaching of this signal has occurred at this location. A total of 200 grains were analyzed. (b) The KDE for Barstow shows that significant populations are not present in comparison to the Forks. Additionally the IR_{230} KDE some evidence of bleaching. A total of 400 grains were analyzed. (c) The Afton Canyon KDE shows a similar, well-bleached peak (note scaling change on rel. prob. axis) to Barstow along with inclusion of several older grains. The IR_{230} KDE also shows evidence of bleaching. A total of 600 grains were analyzed.

Figure 5: Empirical cumulative distribution function (ecdf) for IR_{50} single grains at the Forks, Barstow and Afton Canyon. The ecdf is the basis for the KS test, and, as can be seen from the deviation of the dashed curve from the other curves, a greater proportion of the Forks D_e population differs from Barstow than does the Afton Canyon D_e population.

Figure 6: Ecdf for IR_{50} single grains from the Forks and Barstow are shown (open circles) with ecdf for synthetic IR_{50} single grain distributions in a simple bootstrapped fluvial model (see text for description). One iteration is equivalent to one month of time passed on the Mojave River. The synthetic distributions show that single-grain populations should become better bleached downriver, following the trend shown in the data from the Forks and Barstow.

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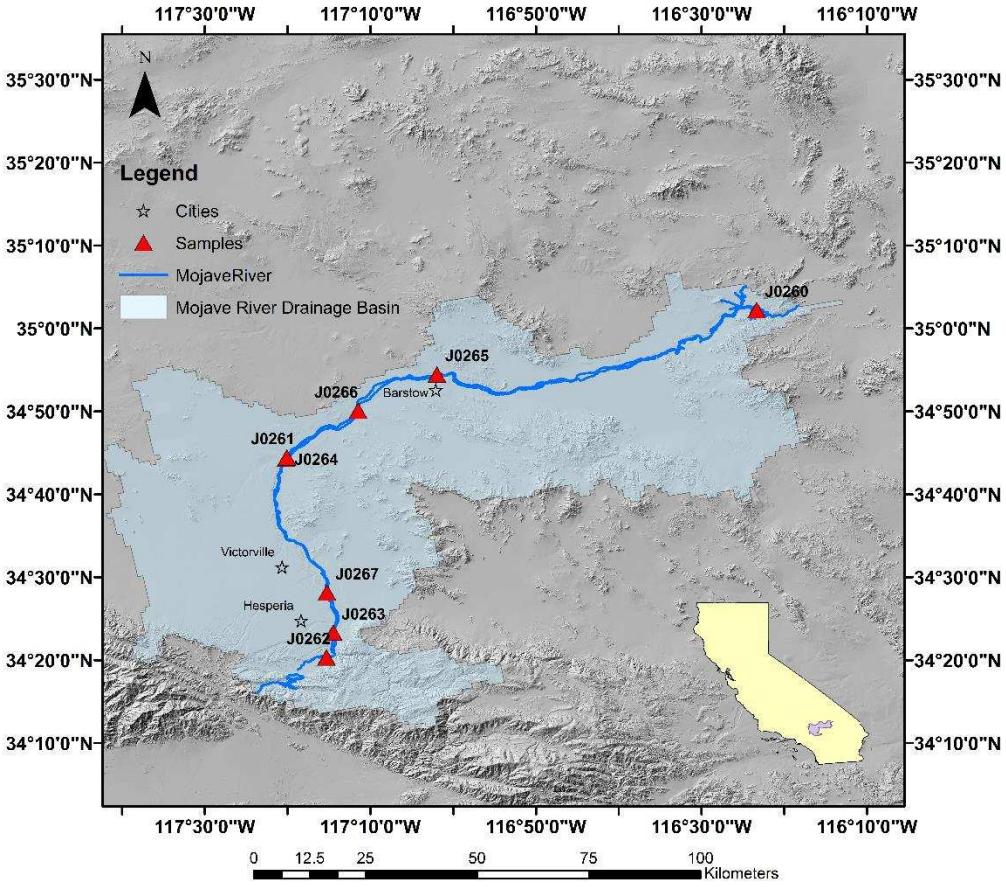
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Samples
MojaveRiver
Mojave River Drainage Basin
J0260
J0265
J0266
Barstow
J0261
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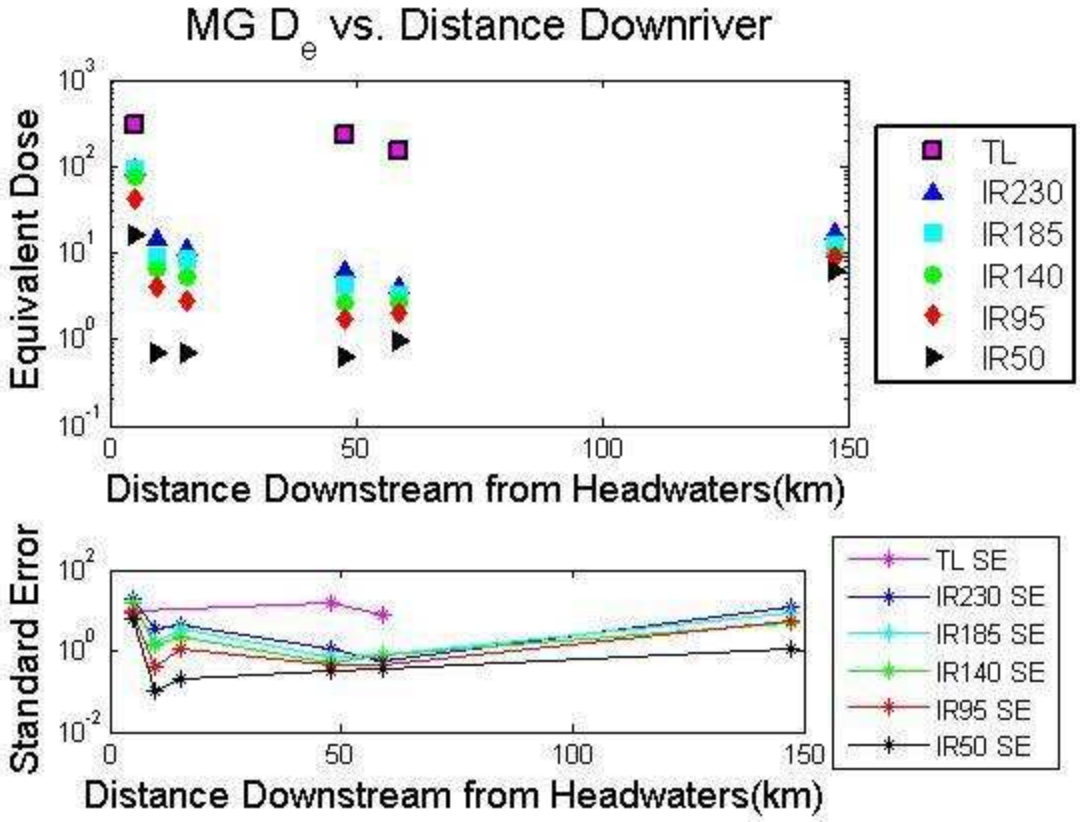
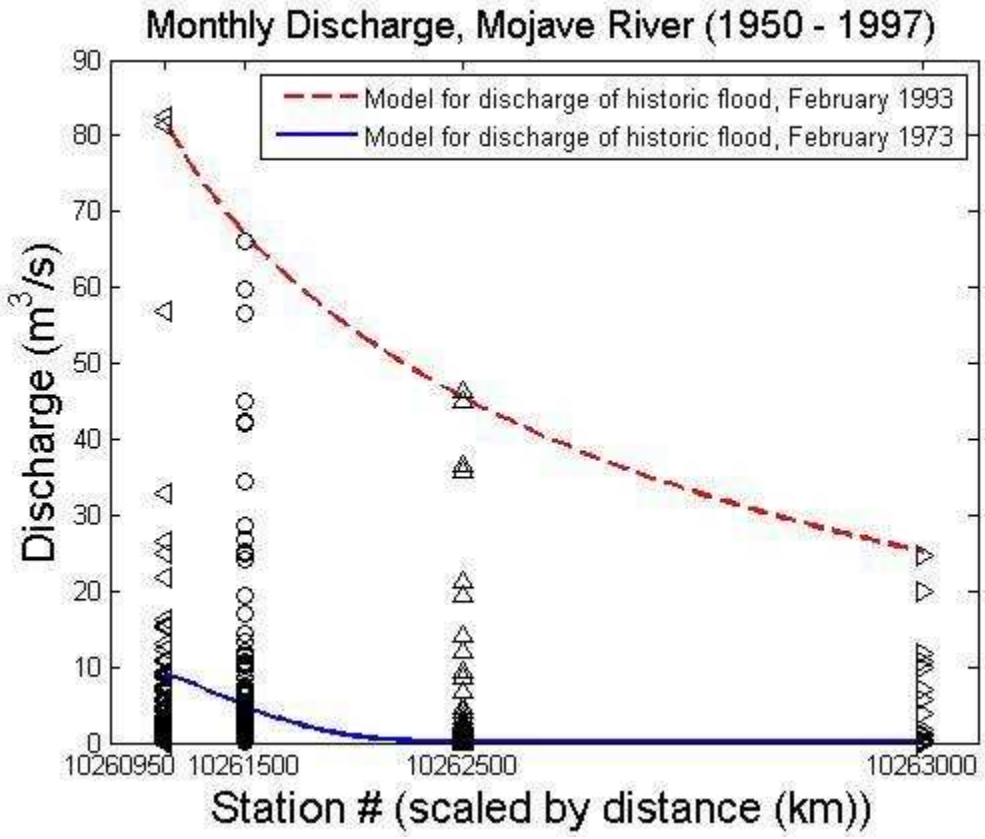
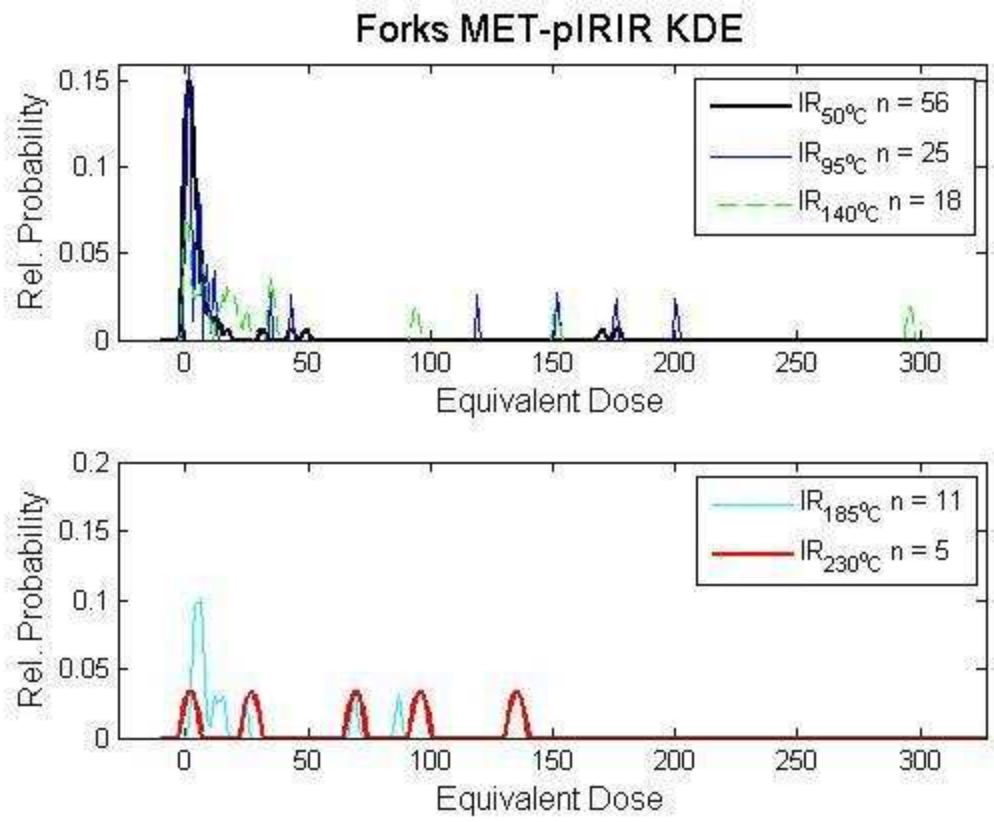

MG D_e vs. Distance Downriver
Equivalent Dose
Distance Downstream from Headwaters(km)
TL
IR230
IR185
IR140
IR95
IR50
Standard Error
Distance Downstream from Headwaters(km)
TL SE
IR230 SE
IR185 SE
IR140 SE
IR95 SE
IR50 SE

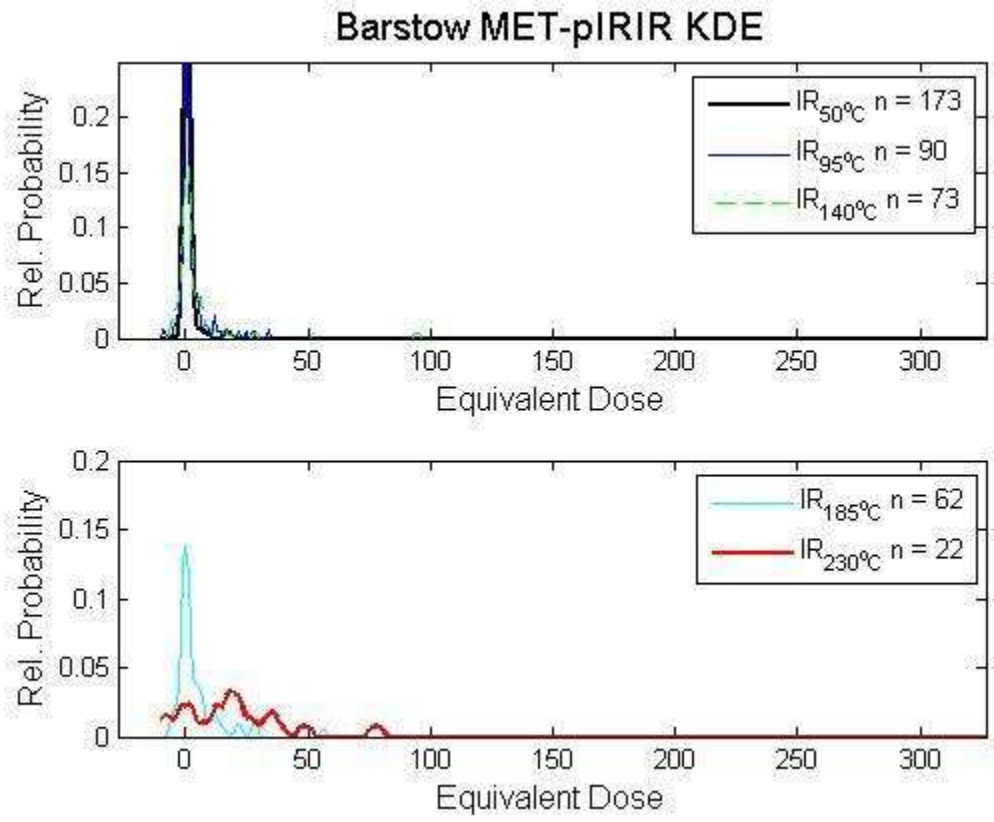
378


Monthly Discharge, Mojave River (1950 - 1997)
Model for discharge of historic flood, February 1993
Model for discharge of historic flood, February 1973
Discharge (m^3/s)
Station # (scaled by distance (km))
10260950
10261500
10262500
10263000

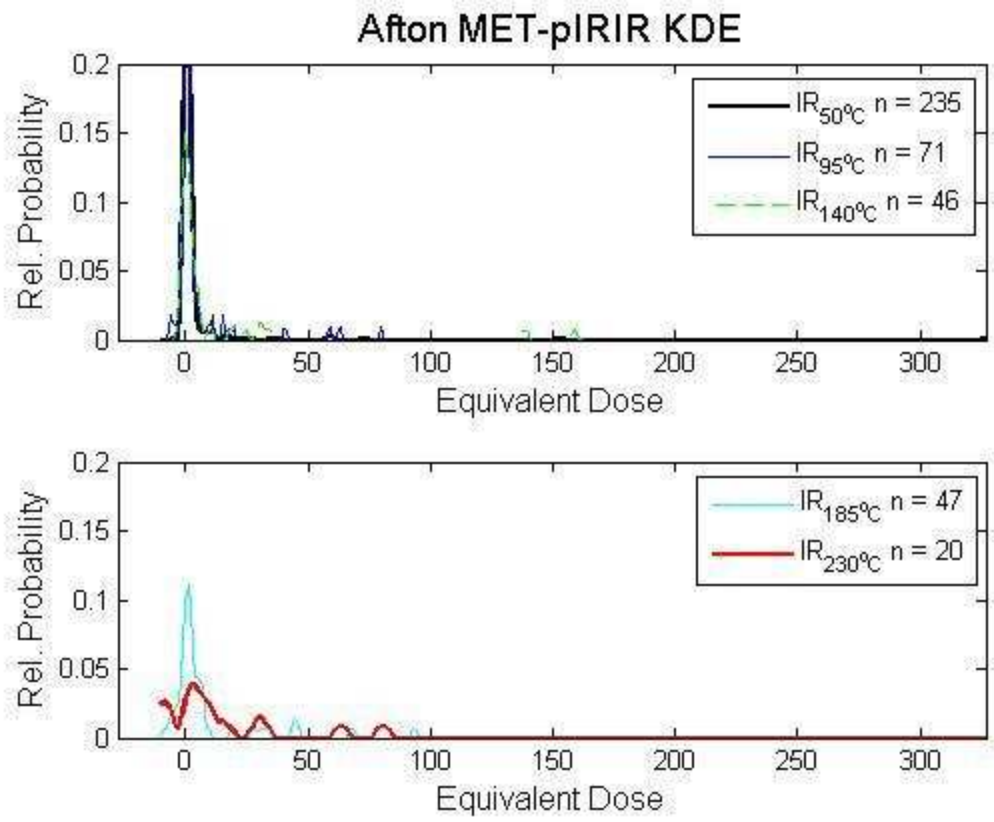
379


Forks MET-pIRIR KDE
Rel. Probability
Equivalent Dose
IR50°C n = 56
IR95°C n = 25
IR140°C n = 18
IR185°C n = 11
IR230°C n = 5

380


Barstow MET-pIRIR KDE
Rel. Probability
Equivalent Dose
IR50°C n = 173
IR95°C n = 90
IR140°C n = 73
IR185°C n = 62
IR230°C n = 22

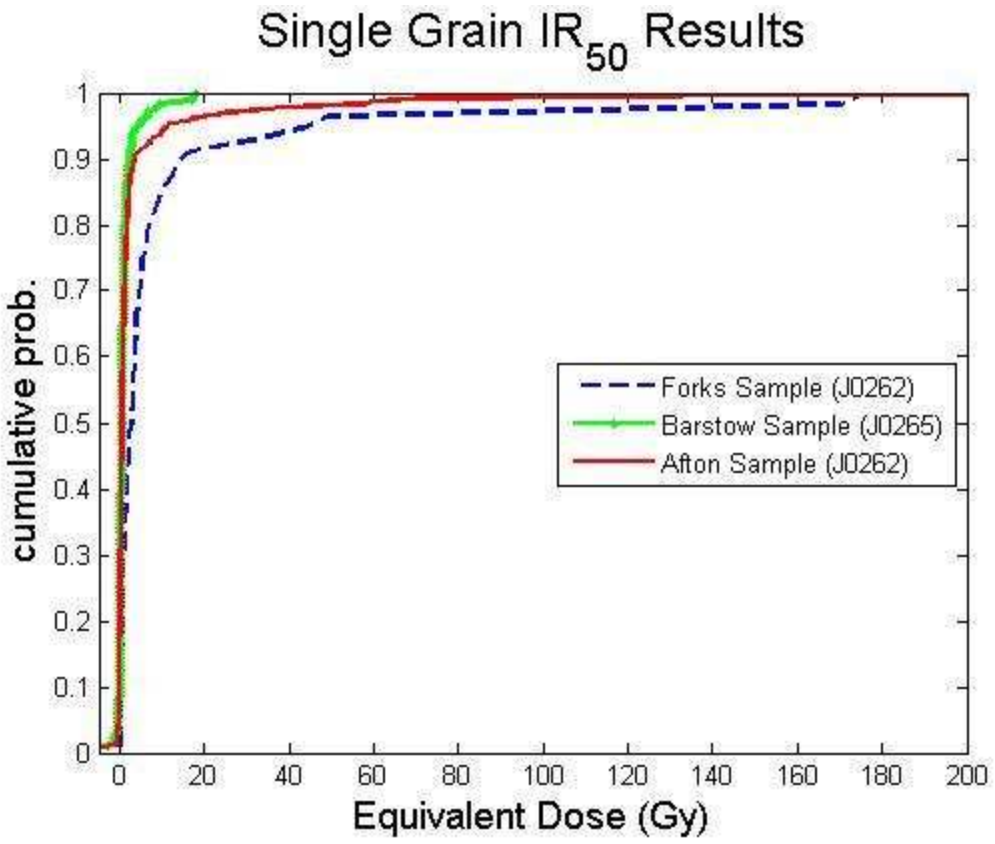
381


Afton MET-pIRIR KDE
Rel. Probability
Equivalent Dose
IR50°C n = 235
IR95°C n = 71
IR140°C n = 46
IR185°C n = 47
IR230°C n = 20

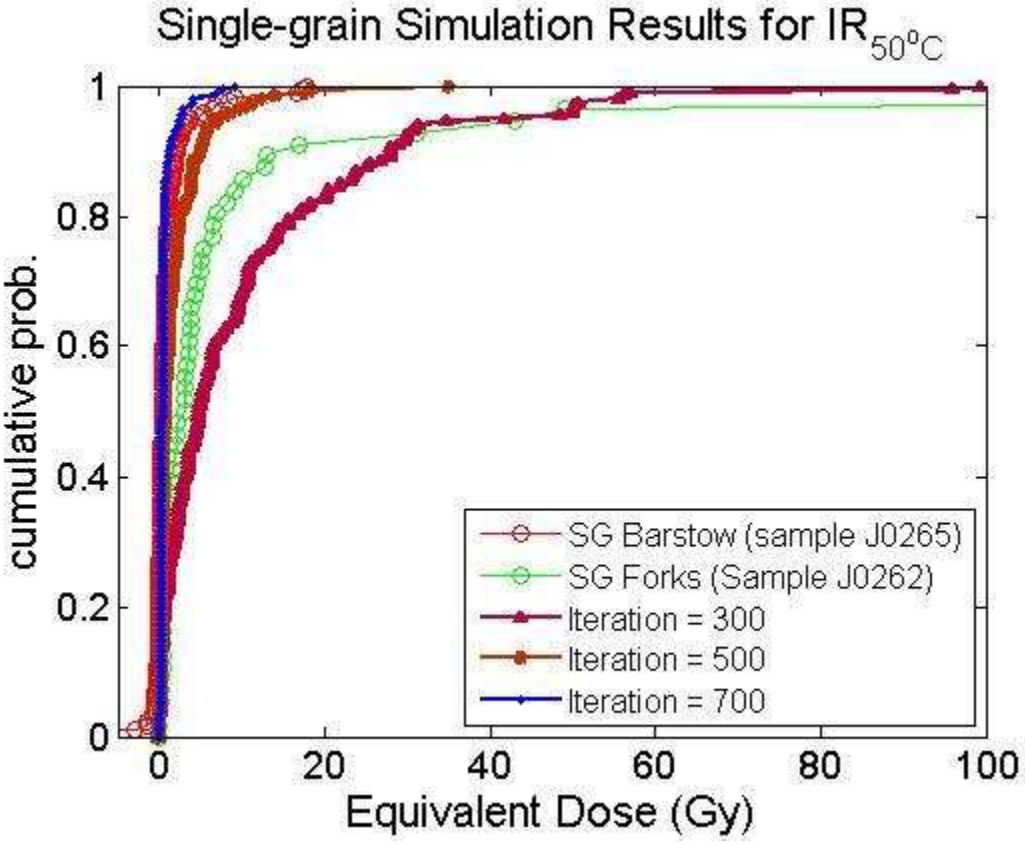
382

383

384


Single Grain IR50 Results
cumulative prob.
Equivalent Dose (Gy)
Forks Sample (J0262)
Barstow Sample (J0265)
Afton Sample (J0262)

385


Single-grain Simulation Results for IR50°C
cumulative prob.
Equivalent Dose (Gy)
SG Barstow (sample J0265)
SG Forks (Sample J0262)
Iteration = 300
Iteration = 500
Iteration = 700

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