A 12,000-Year Probability-Based Flood Record in the Southwestern United States

By

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STATEMENT BY THE AUTHOR

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APPROVAL BY RESEARCH COMMITTEE

As members of the Research Committee, we recommend that this prepublication manuscript be accepted as fulfilling the research requirement for the degree of Master of Science.

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Abstract

River basins in the Southwestern United States are some of the most extensively studied arid land fluvial systems in the world. Since the early 1960s their hydro-climatic histories have been reconstructed from the analysis of arroyo system cut-and-fill cycles. Since the late 1970s there have also been investigations of slackwater deposits and paleostage indicators for large floods in stable-boundary bedrock reaches. Nevertheless, no studies have regionally integrated Holocene fluvial histories from these two different types of fluvial environments. The current study combines the arroyo alluvial archive with flood records from bedrock reaches to generate a probability-based, 12,000 year record of flooding in Southwestern United States. Using more than 700 ^{14}C-dated fluvial units, the analysis produces a high resolution (centennial scale) flood record. Seven episodes of increased flooding occurred at 11,250-10,400, 8800-8350, 8230-7600, 6700-5700, 5600-4820, 4550-3320 and 2000-0 cal. BP, with major peaks evident at c. 10,650, 8470, 7800, 6300, 5380, 3850, 1310 and 300 cal. BP. Bedrock reaches are found to record more frequent floods during the mid to late Holocene, while in arroyo-type systems more flood units are dated to the early and mid Holocene. These differences are primarily the result of preservation factors, since alluvial reaches tend to erode during periods characterised by very large floods. This new probability-based record of flooding correlates well with Holocene climate proxies in the Southwestern United States, including high resolution precipitation records from bristlecone pines in the White Mountains, California. The results of this study suggest that the Holocene fluvial archive can produce a highly reliable record of rapid regional hydro-climatic change.

Introduction

Rivers and streams in the Southwestern United States are some of the most extensively studied arid lands fluvial systems in the world. Since the 1960s research projects have been conducted to assess the climate history by interpreting deposits from alluvial reaches throughout the Southwest (Waters and Ravesloot, 2000; Haynes and Huckell, 1986; Onken and Joyal, 2004; Haynes, 1968; Haynes and Huckell, 1995; Johnson et al., 1997). Many of these interpretations of the alluvial record were done for their archaeological implications (Walter, 1986; Homberg and Johnson, 1991; Diehl, 1997; Huckleberry, 2005), others were conducted to better constrain the late Quaternary and historic arroyo formation (Waters and Haynes, 2001; Karlstrom 2005). Additionally, the slackwater deposit technique of analyzing large floods in bedrock reaches was pioneered in the Southwest by Dr. Victor Baker, leading to a large and thorough inventory of paleoflood frequency and magnitude (Ely, 1992; Ely and Baker, 1985; O'Connor et al., 1994; Webb, 1985; House, 1996). To date, the most comprehensive study in the Southwest based on slackwater deposits is a 5000-yr paleoflood chronology done by Lisa Ely and her colleagues (Ely et al., 1993; Ely, 1997) who identified three phases of increased flooding in the last 5000 yrs: 4800-3600, around 1000, and after 500 yrs BP.

Past researchers have tended to look at one or the other type of system. Individually these only present a partial picture of environmental change during the Holocene. Regardless of the method employed to study fluvial units, researchers have tried to demonstrate a link between a short-term history of floods and droughts and climate change in the American Southwest. Recently, better techniques for analyzing ^{14}C dated fluvial units have been developed utilizing cumulative probability density function (CPDF) plots (Macklin et al., 2005; Lewin et al., 2005; Johnstone et al., 2006; Macklin et al., 2006). These new techniques prompted a re-evaluation of the Holocene flood history in the Southwestern United States, given the very large number of dated fluvial units in the area. This study re-examines the sedimentary Holocene flood record in the Southwest and presents an even higher resolution climate record than previously published from fluvial sedimentary units in the region.

Study Region

For our study we considered 724 ^{14}C dated fluvial units from 37 locations in the Southwest (Tables 1 and 2, Figure 1). In general, bedrock reaches in this study are located at higher elevations than are the alluvial reaches. The bedrock reaches occur mainly in the mountainous regions of central Arizona, northern Arizona, southern Utah, and southwestern Texas. With few exceptions, the alluvial reaches in this study are located in southern Nevada, New Mexico, central, southern, and southwestern Arizona. Figure 2 shows the temporal distribution of dated units for both the bedrock and alluvial reaches. The distribution of ages from each system is remarkably different. The dates from bedrock reaches exhibit an almost exponential curve with over 50% of the dated units occurring in the last 3000 years. Dates from the bedrock systems are very rare until close to 6500 cal. BP, after which where they remain relatively sparse until around 2500 cal. BP. The number of dates rises steadily from 2500 cal. BP to 500 cal. BP where they seem to plateau. The largest numbers of dated units are found between 600-500 cal. BP. The alluvial curve exhibits a tri-modal distribution centered around 4500, 2500, and 600 cal. BP. In contrast to the bedrock record, the alluvial record shows many dated units from the early Holocene. Overall, most of the dated alluvial units are older than 2000 cal. BP. The difference in distribution of dates is likely related to preservation factor. Slackwater deposits in bedrock reaches record very large floods in constant-boundary river environments. When these extreme events occur they can, and often times do, remove evidence of previous floods. Thus, the bedrock record has a natural bias towards the late Holocene. However, in alluvial channels, channel migration can shift the active channel away from previously deposited sediments reducing the erosion potential from fluvial process and increasing the preservation potential.

The aim of the database of ^{14}C dated fluvial units was to: 1) establish periods of high flood probabilities in the Southwest, 2) compare the fluvial records of bedrock reaches to those of alluvial reaches, and 3) evaluate the degree to which the fluvial records are a reliable high resolution climate proxy. This was done by conducting an extensive literature search of published studies that contained ^{14}C dated fluvial units in the southwestern United States. Table 1 and 2 list the sites used in the study as well as the number of radiocarbon dates per site. Sites in the table where more than one set of dates and references refer to reaches where multiple sites were in close proximity to each other.

Methodology

Information for 724 ^{14}C dated units was collected from published, well documented studies as well as unpublished thesis and dissertation material in a similar method to that used in Johnstone et al. 2005. This information included the catchment, type of material dated, geographic location, drainage area, sedimentary context, uncalibrated ^{14}C age, depositional environment, and alluvial ensemble (Table 3). Literature that was accompanied by reliable geologic cross-sections were further analyzed to determine if each dated unit was at a sedimentary boundary and could be considered a “change” date. For this study change dates signify a marked change in depositional regime. The definition varies slightly between bedrock and alluvial reaches.

In bedrock reaches change dates signify distinct floods. The slackwater technique of analyzing floods has been proven to be a reliable method for dating individual floods (Baker et al., 1983), and reliable flood chronologies can be developed (Ely et al., 1993). For this study, each individual flood was labeled as a change date. In a particular reach where the ^{14}C dates of flood deposits overlapped and were not statistically dissimilar only one flood date was used as a change date. In all cases there were no indications that a reasonable amount of time had passed between floods (such as the development of a soil horizon or vegetation). The date selected was either the most reliable organic material dated or, if all material dated was of similar reliability, it was the oldest date.

Since the alluvial record rarely records individual floods with accuracy compared to that of bedrock-controlled systems, a slightly different definition of "change" date was applied in order to correlate the two records. As with the bedrock record, reliable cross-sections of all ^{14}C dated fluvial units were analyzed. If a date was located at a boundary between two distinct fluvial units, the date was labeled as a change date. For example, in figure 3 the ^{14}C date 4485±55 at the bottom of unit II marks the maximum date that unit II was deposited. It also marks a change in sedimentation regime and thus is considered a change date in this study. The rest of the dates are not considered change dates since they are located in the middle of the fluvial unit and not at a distinct sedimentary unit boundary. As with the bedrock reaches, if more than one date was given per unit boundary the date of the most reliable organic material was used. If all dated material was of similar origin, the oldest date was used. This method was applied to all depositional environments.

Out of the 724 fluvial units dated, 236 dates were from bedrock reaches and 488 dates were from alluvial reaches. Modern samples, samples with the age of uncertainty greater than or equal to the ^{14}C age, and samples with the uncertainty age greater than or equal to 400 were recorded in the database but not used in the analysis. A total of 625 ^{14}C dates were used to create CPDF plots. Of those 625 dates, 185 were labeled as change dates (117 from bedrock reaches and 67 from alluvial reaches).

Calculating the CPDF Curves

All dates were calibrated (INTCAL 98; Stuiver et al., 1998) and individual probability distributions were summed using OxCal version 3.9 (Bronk Ramsey, 1995, 2001). CPDF plots were then calculated from the probability distributions. In order to remove the natural bias in the ^{14}C calibration curve caused by the wiggles in the curve, each CPDF plot from the change dates was divided by the CPDF plot of the entire SW database. The large number of dates in the database served to remove the artificial peaks that are artifacts of the calibration curve as well as the peaks from the bias in the late Holocene preservation potential. Thus, it can be stated with confidence that peaks in the CPDF plots are indeed periods of increased flood activity. All probability curves were normalized to one by dividing each date by the greatest probability in the dataset.

Advantages of this method are numerous. Since river systems in the Southwest have been extensively studied for many decades the large number of published dates spanning the entire Holocene potentially make it a high-resolution fluvial record of climate change. These patterns of flood probabilities cannot be obtained from one single site. Additionally, this study integrates the fluvial records from bedrock and alluvial reaches in order to establish a more detailed hydro-climate record of the entire Holocene. By considering the whole flood record a more accurate analysis can be produced.

Limitations and Possible Sources of Error

Despite these advantages, some problems remain. The nature of the organic material that is ^{14}C dated can be a source of error. Dates from archeological structures were not considered along with many dates from charcoal and modern samples in order to decrease the potential for error. However, all ^{14}C dated material should be considered with a degree of caution. Cross sections proved to be a potential source of error as well. Many of the geoarchaeological cross sections where the dates for the alluvial units were obtained were generalized cross sections and the precise location of the organic sample radiometrically dated in the sedimentary unit was not always presented. In many cases several dates were assigned to the whole of the unit (Waters, 1986; Waters, 1987; Mabry et al., 1999). Dates from these units were not taken into consideration when determining the dates of the sedimentation changes. Moreover, in several publications cross sections did not accompany the radiocarbon dates and their precise location in the stratigraphic unit was unknown. Dates from these sources were not considered as change dates for this study. Additionally, even though steps were taken to eliminate the late Holocene preservation bias, preservation issues must still be taken into consideration. Unfortunately, these limitations may have eliminated part of the fluvial record creating gaps in the sedimentary archive. Nevertheless, with these limitations aside, this method of analysis allows for a more complete and detailed record of flood histories than has been previously been done in the American Southwest.

Southwestern US Flood Histories from Bedrock and Alluvial Reaches

A CPDF plot of all 117 bedrock change dates in the Southwest was created (Figure 4a). Four flooding episodes are evident at 7990-7550, 6700-4930, 4500-3350, and 2050-0 cal. BP. Within these four episodes many prevalent peaks are identified. Peaks are identified in the

CPDF plots by intervals where the relative probability exceeds the mean probability. The mean relative probability is 0.193 for the bedrock CPDF plots and 0.211 for the alluvial CPDF plot. Several of the largest peaks occur at 7800, 6250, 3850, 3800, 3750, 1350, 480, and 350 cal. BP. Overall, the highest flood probabilities in the Holocene occur from 7990-7550 cal. BP and from 1550 cal. BP to present. The bedrock record reflects below average flood probabilities from the early Holocene through ~ 8000 cal. BP where a brief, but very likely, period of extreme flooding is present. This brief episode of increased flooding lasts only about 440 years. After ~7550 cal. BP very few floods are recorded until ~6700 cal. BP. Aside from the brief episode of flooding ~8000 cal. BP, few ^{14}C dates are found in bedrock reaches in the early Holocene (Figure 1). This suggests one or more of the following: 1) the early Holocene had a stable, arid climate, 2) large, extreme floods did not take place in the early Holocene, or most likely, 3) if large floods did occur they were smaller in magnitude that subsequent floods and thus were not preserved in the fluvial record of bedrock reaches.

The CPDF plot of the alluvial reaches is very different than that of the bedrock reaches (Figure 4b). Roughly nine episodes of sedimentation rate changes, and thus flooding episodes, are present: >12000-11600, 11250-10390, 9150-7500, 6420-6290, 5360-4870, 4490-3700, 3480-3310, 1995-1600, and 1300-490 cal. BP. Major peaks occur at 10650, 10600, 8680-8320, 8000, 7900, 7750, 6420, 6320, and 3880 cal BP. In contrast to the bedrock record, the highest peaks in the alluvial record all occur prior to 3500 cal. BP. The alluvial record spans the entire Holocene, but records higher probabilities from the mid to early Holocene while flood probabilities are relatively low for the late Holocene, in marked contrast to the bedrock record. By examining the CPDF plot of the alluvial reaches it is clear that the early Holocene was not characterized by a stable, arid climate. It must be noted that CPDF plot of the bedrock reaches contains more dates (117 to 67) than the alluvial CPDF plot and thus interpretations must me made with caution.

When the Caps of both the bedrock and alluvial reaches are plotted together (Figure 5), many of the (~7800, 3500, 2900, 2500, 1500, 650, and 300-0 cal. BP) peaks in the bedrock CPDF correspond to troughs in the alluvial CPDF, whereas peaks in the alluvial reaches (~6400, 3250, and 2800 cal. BP) correspond to lower flood probabilities in the bedrock reaches. The latter pattern in the fluvial record reflects the fact that during a decrease in the frequency of large floods in the Southwest alluviation has been known to occur (Herford, 2002). The pattern of peaks in the bedrock CPDF plot corresponding to troughs in the alluvial CPDF plot is primarily the result of preservation factors with alluvial reaches tending to erode during periods characterised by very large floods. The nature of this relationship, as seen in the CPDF plots, establishes the fluvial record as a sensitive indicator of hydro-climate change. With this in mind, it becomes clear why the alluvial archive lacks a great number of dated units in the late Holocene; a period characterized by frequent and rapid climate change (Bond et al., 1997; Denton and Karlen, 1973; O'Brian et al., 1995) and frequent large floods. Periods where there are lows in both curves are interpreted as periods with a stable hydro-climate within the region.

Because of its arid to semi-arid climate many entrenched, ephemeral streams, or arroyos, are common in the American Southwest. Arroyo formation in the Southwest first appeared after 8000 ^{14}C BP (Karlstrom, 2005; Miller and Kochel, 1999; Waters and Haynes, 2001) and has been attributed to climate change and not human impact (Bull, 1997). Several arroyo formation episodes have been identified in the Santa Cruz River near Tucson and in the San Pedro River in southeastern Arizona near the Mexican border. Channel entrenchment in the San Pedro occurred at ~7500, 4000, 2600, 1900, 1000, and 600 ^{14}C BP and at 5600-8000, 4000, 2500, 2000, 1000, and 500 ^{14}C BP in the Santa Cruz (Waters and Haynes, 2001). At Coal Mine Wash and Red Peak Valley Wash, located in the northeastern corner of Arizona, 11 major arroyo episodes are identified at > 24,260, 11,070-10,510, 9600, 8800, 7060, 3500, 2140, 1870, 1600, 1100, and 500-600 ^{14}C BP (Karlstrom, 2005). When comparing episodes of arroyo formation in NE Arizona and SE Arizona, common entrenchment dates occur at about 7500, 2000, 1000, and 500-600 ^{14}C BP suggesting region wide changes in the hydro-climate. Since these dates of entrenchments are loosely constrained and reported in ^{14}C yrs BP without uncertainty ages, it is difficult to compare them with the fluvial CPDF plots. However, in order to make a rough comparison between the arroyo cut and fill record and the flood probability records, the entrenchments dates were constrained by the maximum age of the sedimentary unit before entrenchment occurred and the minimum age of the channel fill. All radiocarbon dates were calibrated using INTCAL 98 (Stuiver et al., 1998). By utilizing this method, the 2σ maximum and minimum common entrenchment dates occur between 7849-7553, 4786-4153, 2300-2181, 1167-565, and 659-321 cal. BP. (For raw data see GSA Data Repository item 2001044.) Periods in figure 5 where peaks are found in the bedrock CPDF and troughs are found in the alluvial CPDF suggest arroyo formation; flooding in bedrock reaches causing degradation in the alluvial reaches and thus, channel entrenchment. This is further supported by the strong correlation between region-wide arroyo formation and the divergence of the fluvial CPDF plots. There are some discrepancies in the record that can be likely attributed to the fact that the bedrock and alluvial CPDF plots are based on ~200 radiocarbon dates from the whole of the Southwest while the arroyo entrenchment dates are based on ~90 dates from northeast and southern Arizona.

A CPDF of the combined records (Figure 6) was created in order to produce a more comprehensive evaluation of flooding for the entire Holocene. Much like the previous flood probability curves shown in figure 4, the combined record indicates the flooding during the Holocene was random but clustered into distinct time intervals. Seven episodes of increased flooding are identified at 11,250-10,400, 8800-8350, 8230-7600, 6700-5700, 5600-4820, 4550-3320 and 2000-0 cal. BP, with major peaks evident at c. 10,650, 8470, 7800, 6300, 5380, 3850, 1310 and 300 cal. BP. The combined record is likely to more accurately reflect hydro-climate change than the bedrock or alluvial records alone since it spans the entire Holocene, is not affected by the reworking of the alluvial units by large floods, and covers a larger geographic area. The combined record, however, does not characterize the nature of the flooding episodes as shown in figure 5. For examples, arroyo cutting episodes cannot be distinguished from other flooding episodes in the combined record. Table 4 lists peaks in flooding phases seen in the Southwest CPDF plot, alluvial CPDF plot, and the bedrock CPDF plot. It is evident from the table that the bedrock and alluvial plots reflect somewhat divergent records of Holocene flooding. This discrepancy is likely due to preservation factors or localized flooding. However five episodes of flooding are present in all the CPDFs. This is interpreted as times when flooding affected the entire southwestern region of the United States and suggests synchronicity of hydro-climate changes. These periods are identified as peaks that are separated by <100 years and are highlighted in the table.

It should be highlighted that the flood probability from 3000-2000 cal. BP is very low; however, figure 2 shows many dates from alluvial units during this time. Those dates were not considered change dates but instead were located in the middle of fluvial deposits mainly from channel fills and overbank deposits. This can be interpreted as a period of relative stability in the fluvial environment with infrequent occurrences of large floods. During this period the Southwest experienced a wetter and cooler climate than that of today (Polyak and Asmerom, 2001) that perhaps included higher water tables and more perennial streamflow. Consequently, this period also coincided with the beginning of Early Agricultural Period in the Southwest (Huckell, 1995) and the stable fluvial environments were most likely one of the key factors for agricultural societies to develop on the floodplains in central Arizona (Huckleberry, 1999).

Relationship to Hydro-Climate Teleconnections

In figure 7 the combined CPDF of the bedrock and alluvial reaches is compared to a reconstructed precipitation record from California, a percent sand record from lake cores at El Junco Lake in the Galapagos Islands that have been strongly correlated with El Nino strength, the North Atlantic ice rafted debris (IRD) record, the Medieval Warm Period and the Little Ice Age. Comparison to the 8000 year reconstructed precipitation record from bristlecone pines in the White Mountains of California (Hughes and Graumlich, 2000) shows a relatively good correlation from the early Holocene until about 4500 cal. BP. Three out of the five episodes of increased flood probability that occur in the last 8000 years reveal a similar pattern to the precipitation record. These periods in both records that mark both an increase in precipitation and an increase in flood probability are from 8000-7600, 6700-5700, 5600-4800 cal BP. Both records show a similar pattern suggesting and increase in storminess in the West was associated with an increase in flooding in the southwestern United States. However, after ~4500 cal. BP atmospheric circulation patterns may have shifted causing major discrepancies in the two records. The “switch” in atmospheric circulation coincides with the strengthening of El Nino (Ely, 1992)

A stronger comparison is seen between SW flooding episodes and data from lake cores from El Junco Lake in the Galapagos Islands in the Pacific Ocean (Conroy, 2006). During strong El Nino months the Galapagos Islands experience a significant increase in precipitation compared to non El Nino months. Since grain size in a closed basin is a function of transport energy, higher percent sand in the lake cores signifies more severe rainfall and thus a more severe El Nino. When comparing the combined fluvial CPDF to the percent sand record five out of the six episodes of increased flooding coincide with the largest peaks in percent sand, and thus stronger El Nino and rainfall. The highest peak in the El Junco record occurs at ~2200 cal. BP and precedes the longest period of heightened flood probability in the SW by 200 years suggesting the strength of El Nino is increasing and leading to greater flood probabilities in the southwestern United States.

During the Medieval Warm Period (~900-600 cal. BP) flood probabilities in the Southwest decreased compared to the last 2000 years of the Holocene. This decrease is likely due to lower moisture levels and widespread droughts that were known to have occurred in the western US during this time period (Woodhouse and Overpeck, 1998; Stine, 1994). This decrease in flooding episodes is in sharp contrast to the Little Ice Age (~500-150 cal. BP), a period marked by increased flooding in the SW. The transition between these two climate events is marked by a step change in the fluvial CPDF indicating a reorganization of climate during this time. The increase in flooding is likely due to cooler temperatures and more moisture in the SW.

Although fluvial systems seem to have responded to the Medieval Warm Period and the Little Ice Age, and the climate reorganization between the two events, it does not seem to respond to all hemispheric climate anomalies. In figure 7 the vertical purple lines signify periods of cooler temperatures in the North Atlantic (IRD events identified in Bond et al., 1997) and have been correlated with effectively wetter conditions in the western United States (Meyer and Pierce, 2003). However, there is a weak at best correlation between these North Atlantic paleoclimate events and the Southwest fluvial record. Five out of the eight events in the last 12,000 years occur during period of increased flooding probability suggesting that perhaps these events had little or no effect on the flooding regime in the American Southwest.

Implications and Future Work

The Southwest as a region has one of the most rapidly growing populations in the United States. This significant increase in population places a great demand on water resources. Planning of these limited resources must be taken into consideration to prevent critical shortages. In addition, riparian areas are developing rapidly therefore increasing the potential economical loss if proper measures are not taken to plan for future flooding. Unfortunately, the gauged records only record data in the last ~100 years and historic records are not available beyond ~200 years. With this in mind, proper planning for future flooding cannot be assessed without the development of paleoflood records such as this one that extend the fluvial record through the early Holocene. The more data available concerning past flooding will make planning for future flooding more realistic.

This study has not only extended the fluvial record of the Southwest through the entire Holocene but also through the creation of the extensive database of fluvial units in both types of fluvial environments, bedrock and alluvial, it opens the door to numerous additional studies. By recording the depositional environments, future work can be carried out investigating the preservation potential associated with the five major depositional environments of this study; tributary mouths, alcoves or rock shelters, channel margins, flood and paleoflood plains, channel fills. In addition to preservation potential versus depositional environment, future work also need to be done to address drainage basin size related to basin sensitivity. This particular study did not categorize flood or unit boundaries into drainage basin sizes, however, work such as this would be a valuable asset to the understanding of the fluvial system. The database itself can be continuously be updated as more material become available which will act to expand the current flood probability record in addition to refining it.

Conclusion

Rivers in the southwestern United States have experienced several periods of increased flood probability during the last 12,000 years primarily related to changes in atmospheric circulation patterns and the regional hydro-climate. The record of ^{14}C dated alluvial units identifies nine episodes of increased flooding with the highest peaks occurring in the early to mid Holocene. The bedrock record is somewhat different. Radiocarbon dated flood deposits from bedrock reaches identify four major flooding episodes during the Holocene. Frequent large floods occurred with greater probability during the mid to late Holocene, with the most frequent floods occurring in the last 2000 years. Some of the discrepancies in the records between the two fluvial environments can be attributed to preservation factors. Together, the two fluvial records indicate that several times during the Holocene large floods in bedrock reaches removed some of the record in alluvial reaches, most likely from channel degradation. These instances correlate very strongly with the Southwest arroyo formation episodes identified by Waters and Haynes, 2001 and Karlstrom, 2005. This nature of the fluvial system cannot be distinguished from the bedrock or alluvial probability curves alone.

When the two records are combined seven episodes of increased flooding are identified at 11,250-10,400, 8800-8350, 8230-7600, 6700-5700, 5600-4820, 4550-3320, and 2000-0 cal. BP. An advantage to combining the record is to eliminate the “gaps” from the early and late Holocene. In addition, the combined record covers a more broad geographic area and is a more accurate representation of the fluvial history of the entire Southwest.

This probability-based record of flooding correlates well with reconstructed precipitation data from bristlecone pines in California until about 3300 cal. BP where a shift in atmospheric circulation may have caused a divergence in the records. This shift is likely attributed to the strengthening of El Nino in the last 5000 years. In conjunction with this finding, lake core sediment grain size records from El Junco in the Galapagos Islands indicate a stronger el Nino contributed to greater flood probabilities in the American Southwest during the Holocene. The fluvial systems in the Southwest also respond to hemispheric climatic events in the North Atlantic such as the Medieval Warm Period and the Little Ice Age indicating it is a sensitive, centennial-scale record of hydro-climate change.

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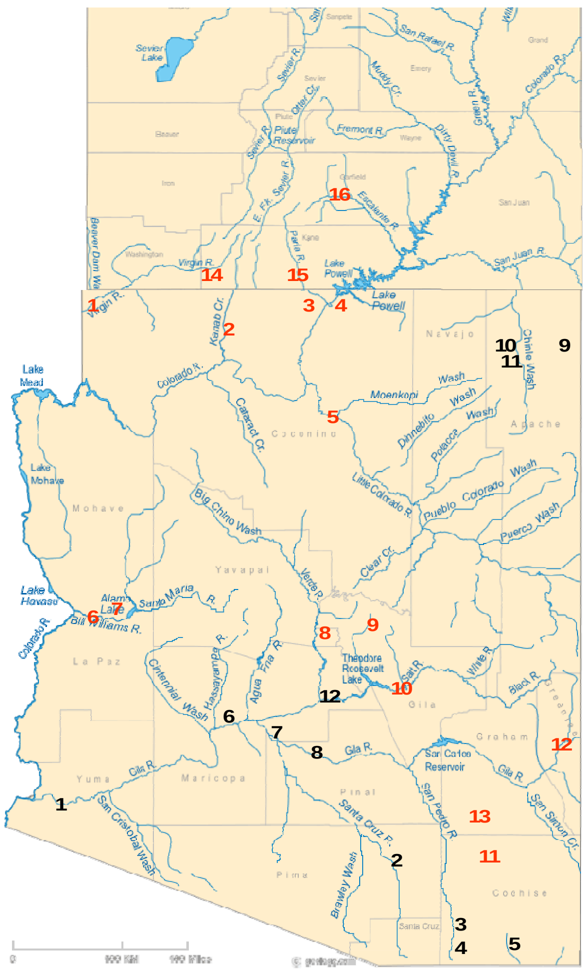

Figure 1: The bedrock (red) and alluvial (black) sites from Arizona and southern Utah that were used in this study. Refer to table 1 for site name and number of ^{14}C dated units. Not shown are sites in New Mexico, Nevada, and west Texas.

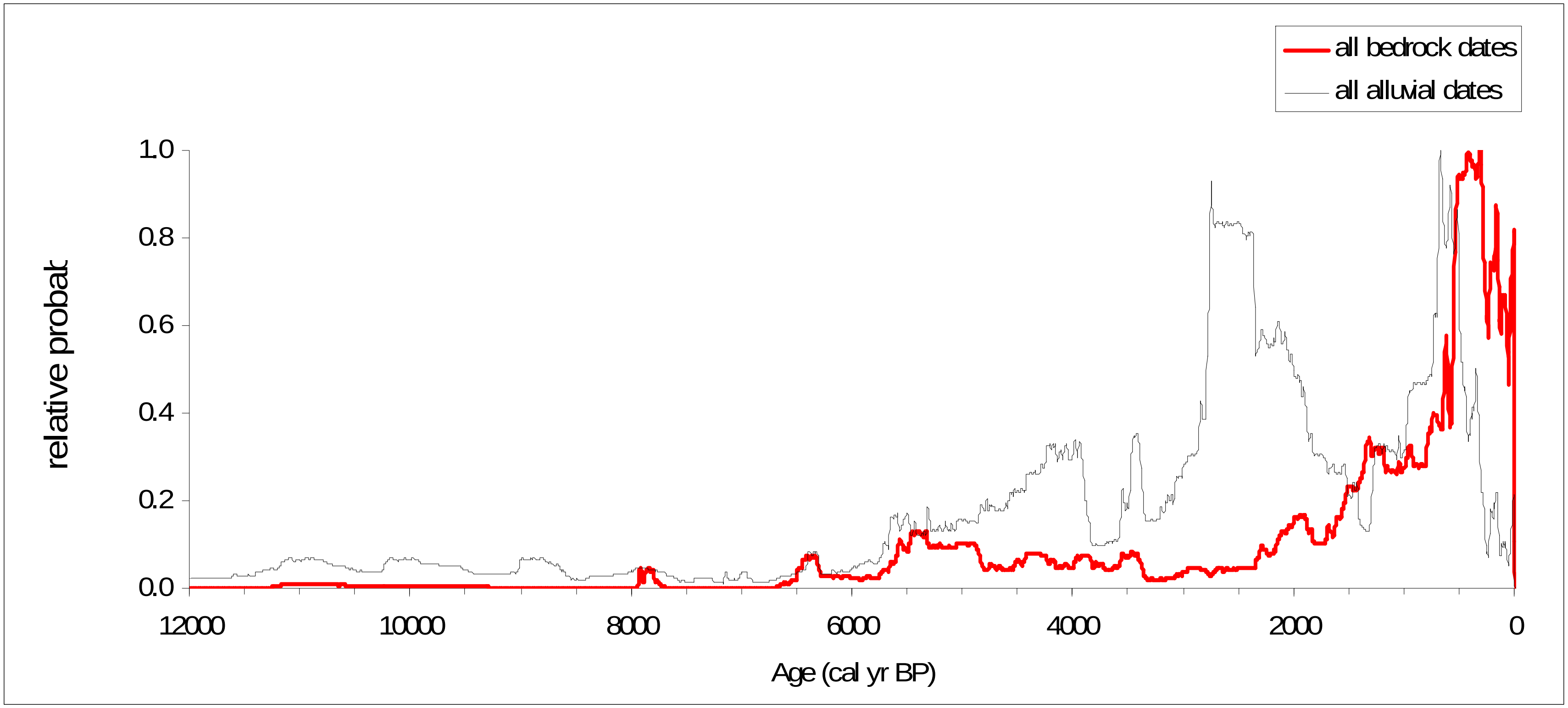

Figure 2: The summed probability distribution (normalized to one) of all dates from bedrock and alluvial reaches in this study showing the temporal distribution of ^{14}C dated units in the southwestern US. Dates from bedrock reaches are shown in red and dates from alluvial reaches are shown in black. Dates from bedrock reaches exhibit an almost exponential curve increasing toward the late Holocene while dates from alluvial reaches exhibit a tri-modal distribution with the majority of dates between 3000-1500 cal. BP.

Middle Gila River, Arizona

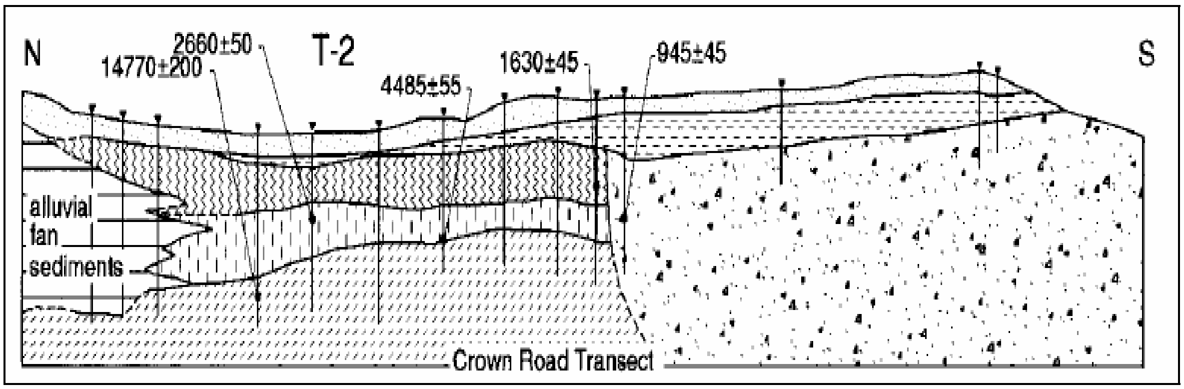

Figure 3: Geologic cross section from Waters and Ravesloot (2000). For this study the ^{14}C date 4485±55 is labeled a change date and indicates a change of sedimentation. It represents the maximum age the unit above it was deposited.

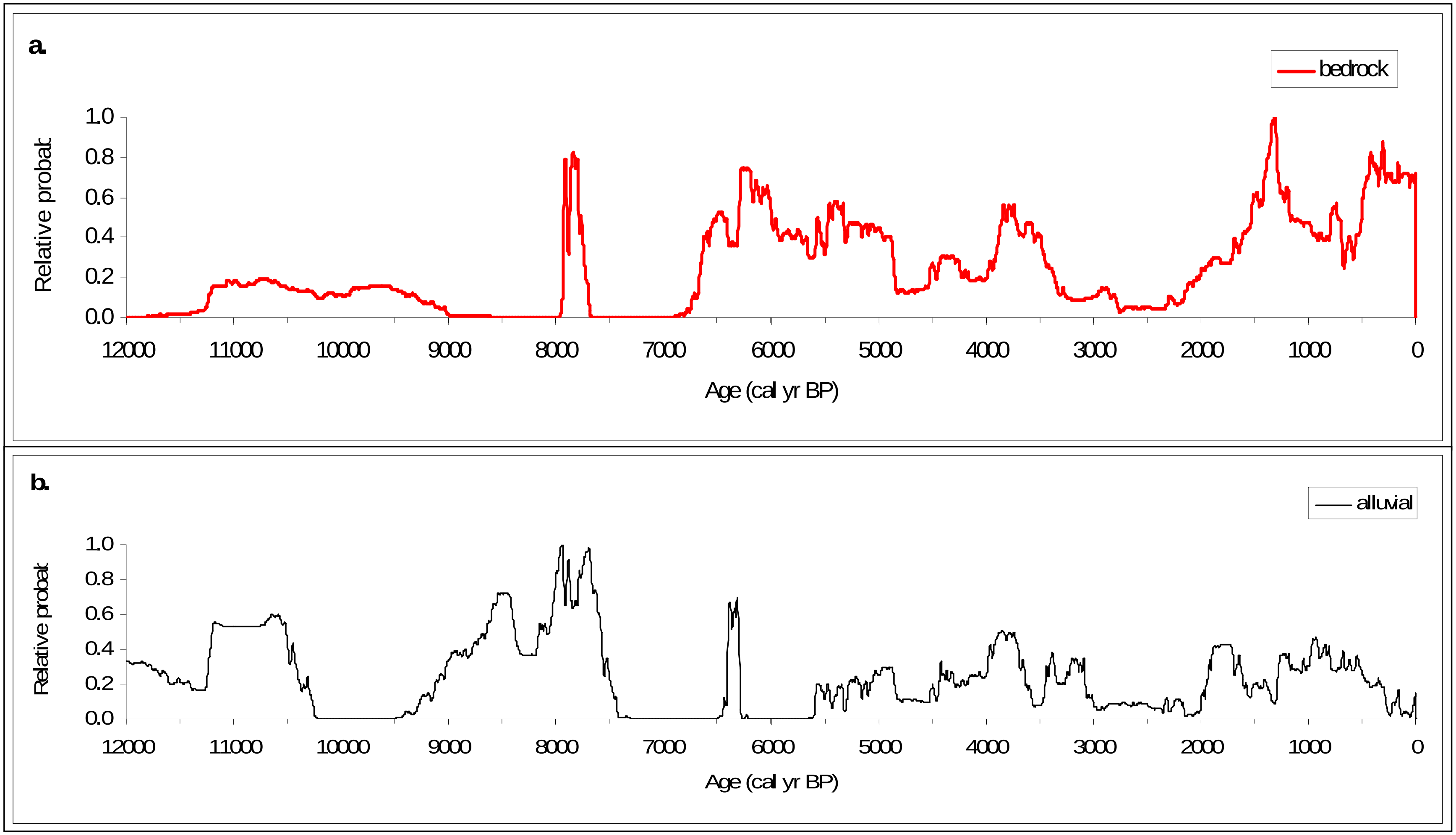

Figure 4: CPDFs of change dates in a) bedrock reaches and b) alluvial reaches used in this study.

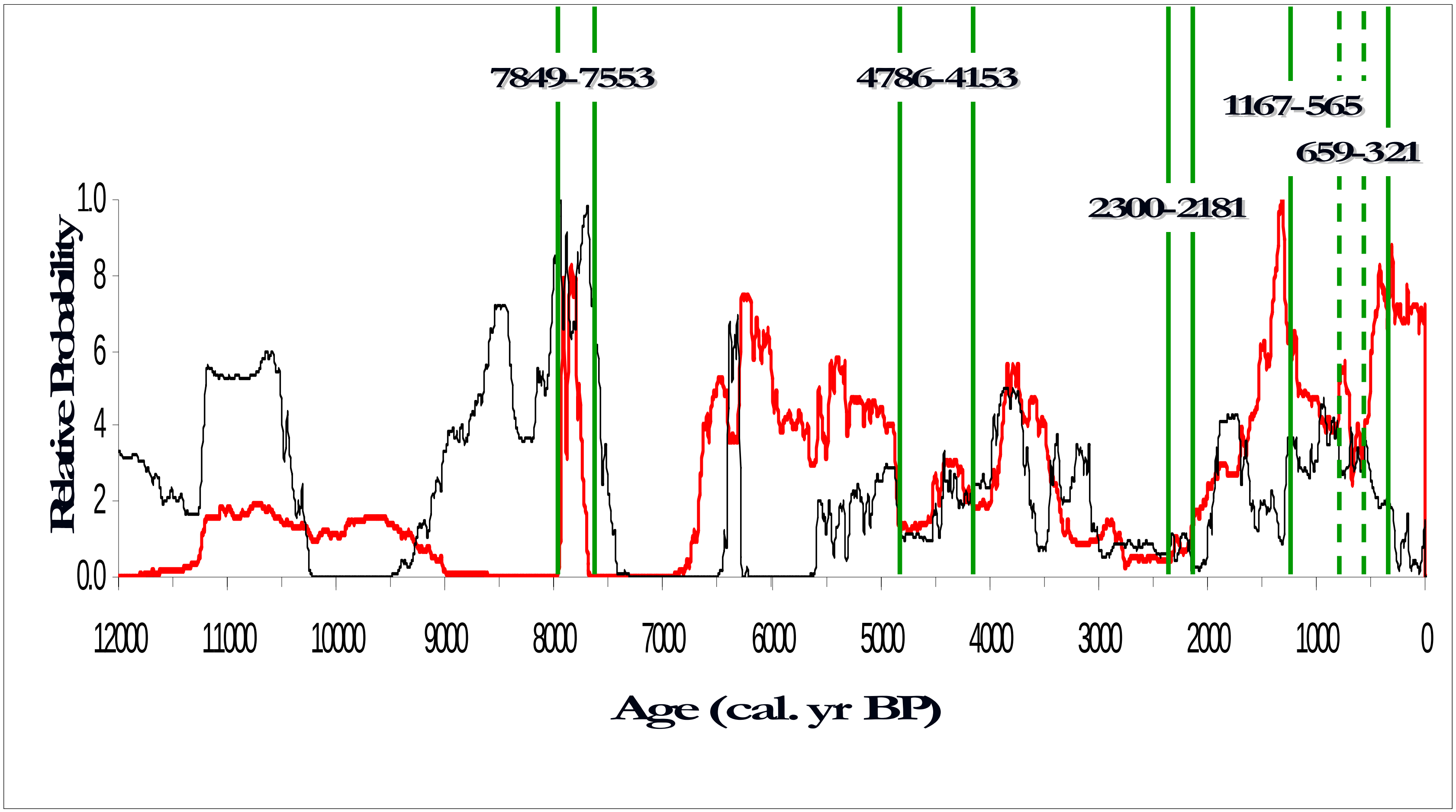

Figure 5: The bedrock CPF plot shown in red is overlain by the alluvial CPDF plot shown in black. In several places a peak in the bedrock CPDF plot corresponds to a trough in the alluvial CPDF plot indicating periods where large floods removed some of the alluvial record. The vertical green lines are region-wide arroyo formation episodes from Waters and Haynes, 2001 and Karlstrom, 2005. Dates of channel entrenchment are given in years BP.

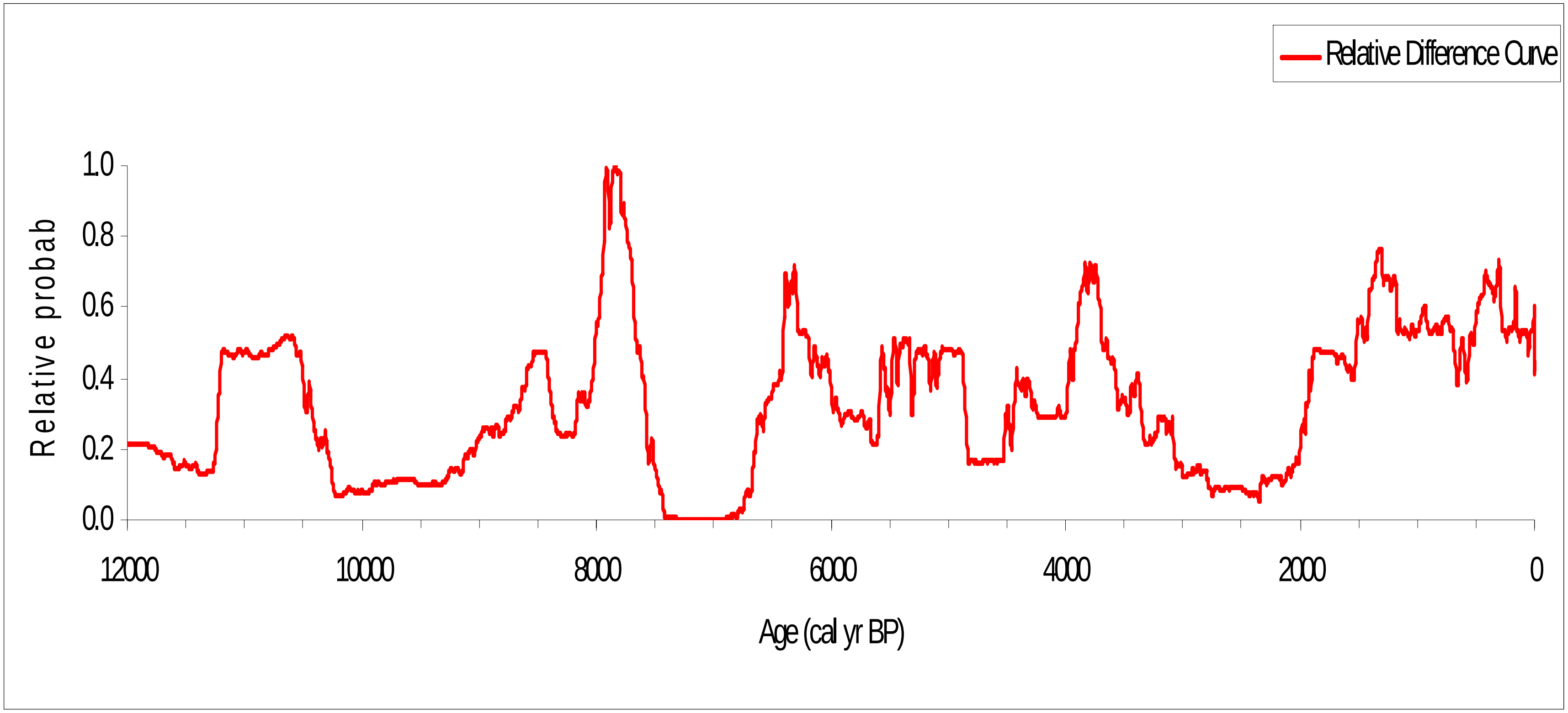

Figure 6: The combined CPDF plot of change dates from bedrock and alluvial reaches.

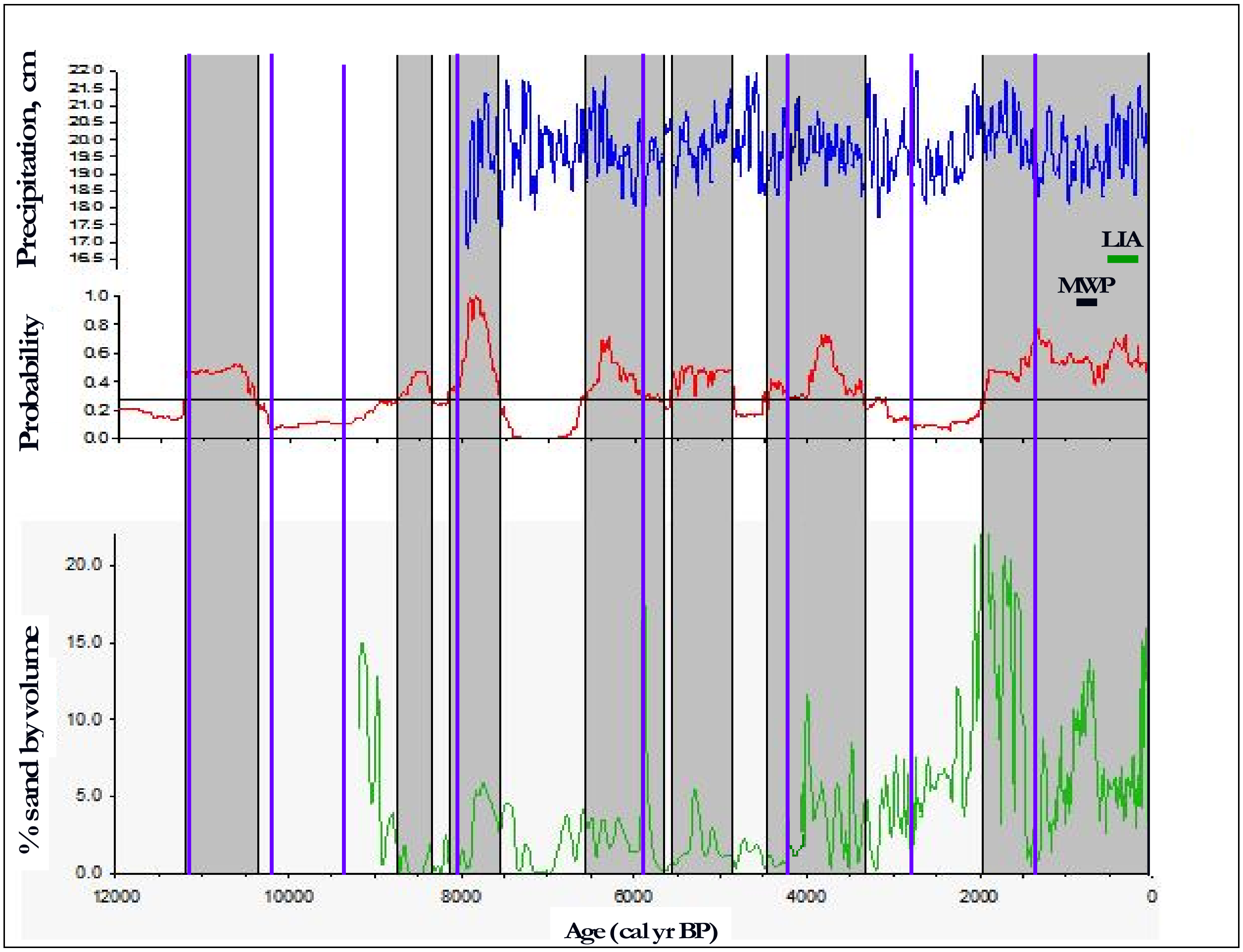

Figure 7: The combined probability curve from bedrock and alluvial reaches shown in red compared to the precipitation record from bristlecone pines in the White Mountains of California (Hughes and Graumlich, 2000) shown in blue, lake core sediment records from El Junco in the Galapagos Islands (Conroy, 2006) shown in green, the Medieval Warm Period, Little Ice Age, and IRD events (Bond et al., 1997) represented by the vertical purple lines.

Bedrock Reaches/ Rivers	Number of Radiocarbon Dates	References
1. Lower Virgin River, AZ	7	Enzel et al. 1994
2. Kanab Creek, AZ	7	Ely, 1997
3. Paria River, AZ	9, 12	Ely, 1992; Webb, 1991
4. Colorado River, AZ	6, 7, 10	O'Connor et al., 1994; Stevens NPS 1990; Ely, 1992
5. Little Colorado River, AZ	13	Ely, 1997
6.Bill Williams River, AZ	15	House, 1996
7. Maggie's Canyon, AZ	2	House, 1996
8. Verde River, AZ	19, 10, 9	House et al., 2002, Ely and Baker, 1985; O'Connor et al., 1986b
9. Tonto Creek, AZ	3	O'Connor et al., 1986a
10. Salt River, AZ	9, 9	Partridge, 1985; O'Connor at al., 1986a
11. Redfield Canyon, AZ	3	Wohl, 1989
12. San Francisco River, AZ	5	Ely, 1997
13. Aravaipa Creek, AZ	3	Roberts, 1987
14. East Fork Virgin River, UT	11	Ely, 1992
15. Buckskin Wash, UT	8	Ely, 1992
16. Escalante River, UT	23	Webb, 1985
17. Pecos River, TX	13, 16	Kochel, 1980; Patton and Dibble, 1982
18. Devil's River, TX	7	Kochel, 1980

Table 1: Bedrock river/ reaches used in this study. Reaches with multiple sets of radiocarbon dates refer to sites in close proximity to each other (<2km).

Alluvial Reaches/ Rivers	Number of Radiocarbon Dates	References
1. Gila River, AZ	9	Onken and Joyal, 2004
2. Santa Cruz River, AZ (multiple sites)	4,43, 17, 13	Haynes and Huckell, 1985; Haynes and Huckell, 1986; Waters, 1987; Freeman, 1997
2. Santa Cruz River, AZ (multiple sites cont.)	7, 9, 55, 56, 20, 13	Stafford, 1986; Huckleberry, 2005; Mabry, 1999; Freeman, 2000, Mabry, 2006; Diehl, 1997
3. San Pedro River, AZ	20, 9	Waters and Haynes, 2001; Haynes, 1968
4. San Pedro River at Curry Draw, AZ	14	Waters and Haynes, 2001
5. Whitewater Draw, AZ	16, 4	Walters, 1986; Haynes, 1968
6. Middle Gila River, AZ	5	Onken et al., 2004
7. Middle Gila River at GRIR, AZ	26	Waters and Ravesloot, 2000
8. Middle Gila River, AZ	10	Huckleberry, 1993
9. Lukachukai Creek, AZ	8	Homburg and Johnson, 1991
10. Coal Mine Wash, AZ	10	Karlstrom, 2005
11. Red Peak Valley Wash, AZ	6	Karlstrom, 2005
12. Lower Verde River, AZ	8	Johnson et al., 1997
13. Cienega Creek, AZ	14	Haynes, 1968
14. Blackwater Draw, NM	12	Haynes, 1968
15. Carrizo Wash, NM	21	Onken and Van West, 2005
16. Grants Area, NM	7	Haynes, 1968
17. Santa Anna, NM	6	Haynes, 1968
18. Tule Springs, NV	12	Haynes, 1968
19. Corn Creek Dunes, NV	5	Haynes, 1968

Table 2: Alluvial rivers/ reaches used in the study. Reaches with multiple sets of radiocarbon dates refer to sites in close proximity to each other (<2km).

ID	AUTHOR	DATE	CATCHMENT	14C MATERIAL	14C METHOD	LAB CODE
191	Ely	1992	East Fork Virgin River at Parunaweap Canyon, AZ	wood and fine grained organics transported with flood	conventional	GX-15975
238	Waters and Haynes	2001	San Pedro River at Curry Draw, AZ	carbonized plants	conventional	SMU-15
360	Kochel	1980	Lewis Canyon, Pecos River, Texas	fine grained wood, seeds	conventional	TX-3195
693	Mabry	2006	Santa Cruz River, Tucson	annual plant	N/A	Beta-193150

ID	Lat/long	ELEVATION	SAMPLE DEPTH, cm	DRAINAGE AREA, km2	SEDIMENTARY CONTEXT	UNCAL. 14C DATE	±
191	N37 10.47', W112 51.17'	4790	N/A	840	N/A	4640	75
238	N31 27.64', W110 6.48	4131	N/A	13.4	N/A	4000	130
360	N29 44.6', W101 21.8'	1143	N/A	~91,000	Organic rich fine sand	1955	70
693	N32 10.16', W110 59.39'	2400	N/A	5750	N/A	3220	40

ID	Cal. Dates (1 sd)	Cal. Dates yr (2 sd)	Cal.BP (2sd min)
191	3623-3604BC, 3523-3348BC	3634-3550BC, 3543-3314BC, 3293-3288BC, 3274-3266BC, 3238-3107BC	5641
238	2848-2813BC, 2740-2731BC, 2693-2688BC, 2679-2336BC, 2323-2308BC	2886-2197BC, 2166-2150BC	4893
360	39BC-93AD, 97-125AD	154-138BC, 112BC-227AD	2161
693	1520-1442BC	1607-1570BC, 1561-1546BC, 1541-1417BC	3614

ID	Cal. BP (2 sd) Max	BOUNDARY DATE	DEPOSITIONAL ENVIRONMENT	ALLUVIAL ENSEMBLE	ARCHAEO. MATERIAL	X-SECTION?
191	5114	Yes	slackwater deposit	narrow sandstone canyon	no	yes
238	4157	No	arroyo fill	entrenched ephemeral stream	no	generalized
360	1780	Yes	slackwater deposit in mouth of tributary	bedrock canyon	no	yes
693	3424	No	floodplain	wide entrenched ephemeral stream	no	no

Table 3: An example of four entries from the Southwestern US ^{14}C database showing all information collected for each of the 700+ entries. Information shown was obtained from Ely, 1992; Waters and Haynes, 2001; Kochel, 1980; and Mabry, 2006.

Flood probability peaks in all Southwestern reaches included in this study	Flood probability peaks in alluvial reaches	Flood probability peaks in bedrock reaches
10650	10650	
	10600	
8470	8500	
	8490	
	8200	
	8000	
7900	**7900**	**7900**
7800		7800
7790	**7750**	**7790**
6420	**6420**	**6500**
6300	**6320**	**6250**
		6100
		6020
		5590
		5400
5380		5350
		5300
3850	**3880**	**3850**
3790		3800
3750		3750
		3600
	1740	
1310		1390
		1350
1240		1200
	910	
		730
450		480
300		350
200		200
		110

Table 4: Flood probability peaks recorded in calendar years BP for all SW reaches, all alluvial reaches, and bedrock reaches in this study. Dates highlighted in bold are periods of increased flooding in all three records indicating periods of region-wide hydro-climate synchronicity.