**Caesium-137 dating applied to slackwater flood deposits of the Llobregat River,
NE Spain**

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Abstract

During a palaeoflood study of the Llobregat River (NE Spain), analysis of ^{137}Cs was carried out on slackwater flood deposits to obtain an improved flood chronology for the most recent flood sediments. At the Monistrol study reach, ^{137}Cs was measured in flood deposits preserved in valley side rock alcoves, with a range of ^{137}Cs concentrations of 2.80 to 10.06 mBq/g measured. The ^{137}Cs was associated with sediment mobilised from the upstream catchment by erosion and transported to the alcoves during floods. The onset of measured caesium activity in the sedimentary profiles permitted the deposits to be divided between those from floods that occurred before the mid 1950s and those from events after this period. Combining the information derived from the slackwater flood stratigraphy, the minimum discharge estimates associated with the flood deposits, ^{137}Cs analysis and the instrumental peak discharge series, it was possible to identify the particular flood events responsible for the majority of the slackwater flood units. At Vilomara, however, ^{137}Cs activity was measured in palaeoflood deposits dated to the Late Bronze Age and located at an elevation not reached by the floodwaters of the largest modern events. The data from this site indicated that the ^{137}Cs was not associated with sediments transported by floods but was rainfall-derived, the rainwater reaching the deposits through fissures in the rock. To ensure the successful application of caesium dating to slackwater flood deposits preserved within rock alcoves, or caves, some general guidelines are proposed. The technique is best applied: 1) when there is a sedimentary profile of greater than 1 m depth; 2) when the profile is sampled away from zones affected by direct percolation or springwater entering the alcove; and 3) where there are various levels of contrasting textures within the profile.

Keywords: Palaeoflood hydrology, Slackwater flood deposits, Caesium-137, Flood chronology, Mediterranean region

1. Introduction

Palaeoflood hydrology is the reconstruction of the magnitude and frequency of large floods using geological evidence (Baker et al., 2002). The most common evidence used is provided by sedimentary flood records, such as those left by sequences of slackwater flood deposits that indicate former flood stages (Baker and Kochel, 1988; Benito et al., 2003a). The methodology combines: a) stratigraphic and sedimentologic analyses to identify the number of flood units preserved within a particular sedimentary sequence; b) hydraulic modelling to calculate minimum discharge estimates from the known elevations of slackwater flood sediments; and c) dating techniques to determine the chronology of flood occurrence (e.g. Kochel et al., 1982; Ely and Baker, 1985; Partridge and Baker, 1987; Baker and Pickup, 1987; Kochel and Baker, 1988; Pickup et al., 1988; O'Connor et al., 1994; Benito et al., 1998, 2003b, 2004; Greenbaum et al., 2000; Kale et al., 2000; Yang et al., 2000; Jones et al., 2001). The most common dating technique used in these studies is radiocarbon dating, usually on charcoal preserved within slackwater flood sediments. The radiocarbon dating technique, however, has an applicable age range of between *ca.* 300 to 55,000 years BP (Trumbore, 2000) and, therefore, cannot accurately date the sediments of flood events from the most recent centuries. In fluvial geomorphology, caesium-137 dating has been used widely for determining the chronology and rates of overbank sedimentation of modern fine-grained floodplain sediments (Walling and He, 1997; Stokes and Walling, 2003). The dating technique is based on the fact that ^{137}Cs is an artificial radionuclide that was first released into the atmosphere by nuclear bomb testing in the mid 1950s and reached the land surface by atmospheric fall-out. A study analysing the post-bomb ^{137}Cs content in modern slackwater flood deposits from the San Francisco and Paria rivers in Arizona

(Ely et al., 1992) has shown that the technique can also be successfully applied to date these, generally, coarser grained fluvial sediments. Although the main aim of palaeoflood hydrology is to lengthen the flood series beyond that of the instrumental record, significant benefits can also be gained by accurately dating modern slackwater flood deposits. Firstly, because these events occurred during the instrumental period, there is the potential to correlate the modern sedimentary flood record with the gauging station data, which can a) improve the calibration of the hydraulic model developed for palaeoflood discharge estimates, and b) lead to a better understanding of the relationships between flood magnitude/frequency and the preservation of slackwater flood deposits. This is of particular importance in understanding the palaeoflood record preserved over centuries to millennia. Secondly, the ability to date individual modern slackwater flood units has a potential application in the statistical analysis of long-term flood series, where systematic gauging station data are combined with non-systematic palaeoflood discharge estimates. Accurate dating of the modern flood deposits can ensure that these events are not duplicated in the flood frequency analysis.

In this study, caesium-137 dating was carried out on slackwater flood deposits, preserved in valley side rock alcoves, of the Llobregat River in Catalonia, north east Spain (Fig. 1). The study reaches at Monistrol de Montserrat and Pont de Vilomara were considered optimal for the study for a number of reasons. Firstly, the rock alcoves are located along the study reaches at different elevations, resulting in preserved slackwater deposits from a range of flood magnitudes. Secondly, they are in close proximity to nearby gauging stations with continuous instantaneous discharge series beginning in 1942 and spanning the post-bomb period. This provided the potential for correlation between the instrumental and sedimentary flood records. Finally, the largest

flood of the 20th century, the 1971 event (with a discharge of 2300 m³/s at Monistrol) occurred during the dating range of the caesium-137 method, providing potential for comparison between this event and long-term palaeofloods.

2. Study area

The Llobregat River is located in Catalonia in north east Spain (Fig. 1). The river flows north-south from the Pre-Pyrenean Cordillera to the Mediterranean Sea, immediately south of Barcelona, draining a catchment area of 4984 km². The Llobregat River has a typically Mediterranean regime with a low mean annual discharge (21 m³/s), extreme seasonal variations and flood peaks around 100 times greater than the mean discharge. Mean annual rainfall in the catchment varies from 900-1100 mm in the headwater reaches to 500-700 mm in the middle and lower reaches. Large flood events are triggered by maximum rainfall exceeding at least 200 mm within a 24 hour period (Llasat, 1991).

The study reaches are located in the middle reach of the Llobregat River. Pont de Vilomara is located upstream of the Cardener River tributary junction and drains a catchment area of 1845 km². Discharges were first recorded at the Pont de Vilomara gauging station from 1915-23, with a continuous series from 1942 onwards. The Monistrol de Montserrat reach is located downstream of the Cardener confluence and has a catchment area of 3370 km². The reference gauging station for the Monistrol site is located approximately 3 km upstream of the study reach at Castellvell. The instantaneous discharge series began in 1942. Since this time, three flood events have been recorded with discharges greater than 1000 m³/s: 20th September, 1971 (2300

m³/s); 8th November, 1982 (1520 m³/s); and 11th June, 2000 (1200 m³/s). The river at both study reaches is confined by bedrock walls, as the river cuts north-south through the Eocene conglomerates of the Prelittoral Cordillera and the Montserrat Massif. Valley-side rock alcoves developed within the predominantly horizontal rock strata provide favourable sites for the deposition and preservation of slackwater flood sediments (Kochel and Baker, 1988; Benito et al., 2003a).

3. Materials and methods

Slackwater flood deposits provide evidence of the minimum water surface elevation of past flood events and can be used to estimate flood magnitude and frequency (Baker and Kochel, 1988; Benito et al, 2003a). Sites of slackwater flood sediment deposition were identified along the study reaches and sections were cut to expose the sedimentary sequences. Individual flood units were determined through a close inspection of depositional breaks and/or indicators of surficial exposure. The former include clay layers at the top of a unit and erosional surfaces. Surficial exposure was indicated by either bioturbation, angular clast layers where local alcove or slope materials were deposited between flood events, or fine-grained, reddish alcove sediments. For this study, six depositional sequences were investigated with a total of 40 individual slackwater flood units identified. Flood units are referred to in the text by the individual alcove code, followed by the flood unit number indicated in the stratigraphic columns (Figs. 2, 3 and 4).

The initial flood chronology was determined by radiocarbon dating carried out on charcoal samples collected from individual flood units. Necessary preparation and pre-

treatment of the sample material for radiocarbon dating was carried out by the ^{14}C laboratory of the Department of Geography at the University of Zurich (GIUZ). The dating was done by AMS (accelerator mass spectrometry) with the tandem accelerator of the Institute of Particle Physics at the Swiss Federal Institute of Technology, Zurich (ETH). Calibration of the radiocarbon dates was carried out using the CalibeETH 1.5b (1991) programme of the Institute for Intermediate Energy Physics ETH Zürich, Switzerland, using the calibration curves of Kromer and Becker (1993), Linnick et al. (1986) and Stuiver and Pearson (1993). The results of the samples discussed in this paper are presented in Table 1.

For the Monistrol site, each individual flood unit was sampled for ^{137}Cs analysis down to a reasonable depth, informed by the results of the radiocarbon dating. At site MB non-flood sediments were also sampled due to the thickness of these deposits between flood units MB2 and MB3. For the thickest flood units, such as MD6, two samples were taken. The MA site, radiocarbon dated to A.D. 1516-1642, was not sampled for ^{137}Cs analysis due to its limited thickness and subsequent potential for contamination. For the sediments of the VA alcove at Vilomara, the unit VA5 at 31-39 cm depth was radiocarbon dated to 794-554 B.C., therefore samples were collected at 5 cm intervals to obtain a sufficient number of samples from the overlying, undated, deposits. Sample ^{137}Cs activity was determined at the University of Exeter (Department of Geography), using a p-type coaxial HPGe detector. Count times were typically 30,000-50,000 seconds, providing a precision of $\pm 10\%$ at the 95% confidence level. As the slackwater flood sediments in the study reaches were located within rock alcoves, protected from direct fall-out, it was assumed that the measured ^{137}Cs originated as ^{137}Cs associated

with sediment mobilised from the upstream catchment by erosion and transported to the site during floods.

The discharge estimation for the different flood units was accomplished by computing the water surface profiles for various hypothetical discharges that were routed through the river reaches. By comparing the model-generated profiles to the palaeostage indicators, marked by the elevation of the slackwater flood deposits, palaeodischarges were specified. Discharge estimation by hydraulic modelling was carried out using the step-backwater method, the most commonly utilised method in palaeoflood hydrology (Webb and Jarrett, 2002). Computations were run using the HEC-RAS one-dimensional model (Hydrologic Engineering Center, 1995) run within a GIS environment. Cross-sections (see Fig. 1 for locations) and flood deposit elevations, the input data for the hydraulic models, were surveyed along both study reaches using a Trimble 4700 kinematic differential GPS, with additional data provided by a Sokkia total station where satellite visibility was poor.

4. Results

4.1. Monistrol de Montserrat

Fig. 2 presents the caesium and radiocarbon dating evidence for alcoves MA, MB and MC, plotted alongside the stratigraphy and the valley cross section that illustrates the relative elevations of the distinct alcoves preserving slackwater flood deposits. Also illustrated are the minimum discharge estimates calculated for the floodwaters to cover the respective alcoves during flood events. The highest elevation slackwater flood

deposits of the Monistrol study reach are those of Alcove MA, associated with a minimum discharge estimate of $4680 \text{ m}^3/\text{s}$. One flood unit, radiocarbon dated to calibrated AD 1516-1642, is preserved at this site. Just downstream is the Alcove MB site. A minimum discharge of $1500 \text{ m}^3/\text{s}$ would be needed for the river water to reach the base of the alcove and $2000 \text{ m}^3/\text{s}$ for it to cover the uppermost sediments. The stratigraphy of Alcove MB is composed of four slackwater flood units that can clearly be distinguished from the local, reddish, alcove sediments with high clay contents and occasional angular clasts that have accumulated between floods. It is likely that these deposits originate from slope wash on the valley side above the rock alcoves, the clays and silts being transported by water entering the alcoves through rock fissures. Two modern radiocarbon dates were obtained from charcoal sampled from the profile. Caesium-137 activity is recorded in flood units MB3 and MB4, with no activity in the older deposits at the base of the profile. There is also measured ^{137}Cs activity in the non-flood sediments, though the highest ^{137}Cs concentrations were recorded in the slackwater flood units with values of 4.76 and 4.73 mBq/g for units MB3 and MB4, respectively. This is also illustrated in Fig. 5 where the peak ^{137}Cs concentrations are associated with the flood deposits that have generally lower clay contents than the alcove sediments.

At Alcove MC, the lowest elevation alcove of the study reach, the stratigraphy consists of 18 individual slackwater flood units. A minimum discharge estimate of $200 \text{ m}^3/\text{s}$ is required for a flood event to cover the base of the alcove and $440 \text{ m}^3/\text{s}$ to cover the uppermost flood unit. Three modern radiocarbon dates were obtained from charcoal sampled from the profile. The first flood unit containing ^{137}Cs activity is that of MC9 located at approximately 1.25 m depth in the stratigraphic profile, with a value of 2.80

mBq/g. However, no ^{137}Cs was measured in the next two flood units. In the upper part of the profile, ^{137}Cs occurs in all the measured samples with a maximum value of 10.06 mBq/g in unit MC14. A plot of ^{137}Cs concentration and percentage clay content against stratigraphic depth is presented in Fig. 5. For the Alcove MC samples with ^{137}Cs activity, the two curves exhibit the same general pattern, with peaks in ^{137}Cs activity associated with higher clay content reflecting the positive relationship between ^{137}Cs activity and clay content frequently reported in ^{137}Cs investigations (He and Walling, 1996).

The stratigraphy, discharge estimates and ^{137}Cs concentrations for Alcove MD are presented in Fig. 3. A flood event of 1000 m^3/s would be required to cover the uppermost flood sediments at this alcove. Seven slackwater flood units were identified in the stratigraphy, with ^{137}Cs measured in the upper three flood units. The range of values of ^{137}Cs concentration for the Alcove MD sediments is 2.93 to 4.59 mBq/g. There appears to be positive relationship between ^{137}Cs concentration and clay content in units MD6-7 (Fig. 5).

4.2 Pont de Vilomara

Alcove VA, at the Vilomara reach, contains 0.95 m of slackwater flood sediments that represent eight individual flood units (Fig. 4). The alcove is located 16 m above the channel bed with a minimum estimated discharge of 3700 m^3/s required for floodwaters to reach the site and 4300 m^3/s to cover the uppermost flood unit. Two radiocarbon dates of 853-776 B.C. and 794-554 B.C. were obtained from flood units VA4 and VA5, respectively, indicating the occurrence of high magnitude flood events during the Late

Bronze Age period. The ^{137}Cs data indicates activity in six of the nine samples analysed (with values of 0.70-2.60 mBq/g) including those samples taken from the deposits dated to the Late Bronze Age. The lower elevation Alcove VB preserves two flood units, with ^{137}Cs activity recorded in the upper unit but not in the lower unit. The two samples measured from unit VB2 recorded values of 3.39 and 2.05 mBq/g. An estimated discharge of 2300 m³/s would be needed for floodwaters to cover Alcove VB.

5. Discussion

In the three sequences of slackwater flood deposits at Monistrol (MB, MC and MD) it is evident that sediments deposited by post-1955 flood events can be identified from the measured ^{137}Cs activity. This is seen most clearly at the low elevation Alcove MC. The first post-1950s event, identified by the first trace of ^{137}Cs activity in the profile, is that of MC9 indicating that the ten flood deposits MC9-MC18 all post-date this period. A comparison with the instrumental gauging data series (Fig. 6) indicates that from the mid-1950s there have been at least 15 flood events of a sufficient discharge to be able to deposit slackwater flood deposits within the alcove. With a more detailed analysis of the stratigraphy, ^{137}Cs data, gauging station record and modelled discharges, it has been possible to identify the individual floods responsible for each of the flood units MC13-MC18 (Fig. 6). This is due to the self-censoring of the flood stratigraphy that occurs due to the progressive elevation of the sediments caused by vertical depositional accretion (House et al., 2002). The key flood units are MC11 and MC13 that, as a consequence of their thickness (26 and 33 cm respectively), raised the discharge needed for the river to reach the new sedimentary surface and cause further sedimentation at the site. From the step backwater modelling calculations, the water surface elevation required to cover the

MC13 sediments is associated with an estimated minimum discharge of $345 \text{ m}^3/\text{s}$. This censoring level is indicated on the peak annual discharge series (Fig. 6) and it is evident from this graph that there have only been a limited number of flood events that exceeded this discharge and could have deposited units MC13 to MC18. These events are indicated on the stratigraphic column and are highlighted on the gauging station peak discharge series.

The different threads of evidence all come together to support the hypothesised flood chronology. The 1971 event, the largest in the instrumental record, deposited a 33 cm thick unit of fine to medium sands (MC13). The next two flood units, MC14 and MC15, have been assigned to two similar magnitude floods that occurred during the same water year (1973/74). The peak discharge of the 1973 event was $340 \text{ m}^3/\text{s}$, very similar to the discharge threshold estimated as $350 \text{ m}^3/\text{s}$, resulting in the thin sedimentary layer MC14. Flood units MC16 and MC17 are believed to be the 1982 and 1988 floods, respectively. The gauging station discharge of the latter event is lower than the threshold discharge of ca. $440 \text{ m}^3/\text{s}$ calculated by hydraulic modelling for the deposits, however, the event was recorded as a minimum discharge of $370 \text{ m}^3/\text{s}$ and not as a precise discharge value. The uppermost flood unit, MC18, was deposited during the field campaign by the June 2000 flood that registered a discharge of $1200 \text{ m}^3/\text{s}$. The sedimentary flood record prior to 1971 at site MC is incomplete, as indicated by the fact that fewer post-bomb flood units are preserved than there were flood events with a discharge of sufficient magnitude to cover the sedimentary surface. The most likely cause of this incomplete record is erosion. The largest flood on record was that of 1971, however, the stratigraphy suggests that this event was not responsible for the erosion of earlier deposits. The contact between units MC12 and MC13, a thin clay layer deposited

during the falling limb of the flood hydrograph, shows no evidence of an erosive contact. It is likely, therefore, that the sedimentary record reflects a change in preservation potential of the sediments as distinct from the erosive capability of a particular flood. During the eighteen year period 1948-1966, only two years did not witness floods of a sufficient magnitude to cover the deposits. Since 1966, however, the frequency of inundation of the deposits has been lower. In particular, after the two floods of the 1973/74 water year which only just covered the sedimentary sequence, there have only been three floods in 26 years large enough to exceed the necessary threshold discharge. This reduced frequency of inundation at the alcove could allow stabilisation of the vegetation cover and improved protection against erosion from subsequent large magnitude flood events. A frequency of one event a year would not have enabled such a high degree of stabilisation, rendering the deposits more susceptible to erosion.

At Alcove MD, ^{137}Cs activity was measured in the three uppermost flood units (Fig. 3). The sediments of MD6 and the uppermost unit MD7 belong to the 1971 and 1982 floods respectively. These floods had discharges with magnitudes over 50% greater than that needed to cover the alcove. This may have resulted in the convoluted bedding observed in these deposits (Fig. 3) as this would have been caused by high pressure exerted on the sediments (Allen, 1984). The June 2000 event also covered the alcove but did not leave deposits on top of unit MD7 due to the fact that the already *in situ* slackwater flood deposits filled the alcove. This event left a bank of sediments that, at their highest elevation, pinched out at the level indicated in Fig. 3, towards the top of unit MD6. The event responsible for the MD5 unit is, however, open to speculation as according to the Castellvell gauging station data no other event reached the threshold

discharge needed to reach the alcove. The most likely candidate is the flood of 1962, the fourth largest magnitude event within the instrumental record that reached a discharge of $1500 \text{ m}^3/\text{s}$ downstream of Monistrol at the Martorell gauging station.

At the Alcove MB site the highest ^{137}Cs activity was measured in the two uppermost flood units, MB3 and MB4 (Figs. 2 and 5). The estimated discharge for the deposits of *ca.* $2000 \text{ m}^3/\text{s}$ suggests that these two units relate to the 1971 and 1982 flood events, the two largest in the instrumental series with discharges recorded as $2300 \text{ m}^3/\text{s}$ and $1520 \text{ m}^3/\text{s}$, respectively. The discrepancy between the recorded discharge and the modelled discharge from slackwater flood sediments indicates the inherent difficulty of accurately measuring large discharges at gauging stations. This also occurred at the Pont de Vilomara site, where the 1971 flood was recorded as $1500 \text{ m}^3/\text{s}$ but modelling using slackwater flood deposits (unit VB2) containing plastic materials and with measured ^{137}Cs activity, yielded a discharge of $2300 \text{ m}^3/\text{s}$. The MB and VB flood deposits are the highest elevation modern deposits at the two study reaches. The Alcove VA and MA flood units, with events radiocarbon dated to the Late Bronze Age and Little Ice Age period, respectively, indicate that higher magnitude events occurred in the past. Modelling estimates indicate minimum discharges in the range of $3700\text{-}4300 \text{ m}^3/\text{s}$ for the Vilomara floods and $4680 \text{ m}^3/\text{s}$ for the Monistrol event.

The ^{137}Cs results for the Alcove VA deposits at Pont de Vilomara indicate problems with ^{137}Cs dating at this site, since ^{137}Cs activity is recorded in the slackwater flood units dated to the Late Bronze Age. Furthermore, the estimated discharges necessary to reach the alcove ($3700\text{-}4300 \text{ m}^3/\text{s}$) are of a greater magnitude than that of the largest modern flood event in 1971, confirming that the ^{137}Cs could not have reached the site

with flood transported sediment. Alcove VA is a small rock overhang covered by a thin soil. Rainfall infiltrates rapidly through the fissured conglomerate rock and drips onto the surface of the fine sandy silt palaeoflood deposits. This would have enabled rainfall derived ^{137}Cs to contaminate these older palaeoflood deposits. There is also evidence for ^{137}Cs mobility in the sediments of Alcove MB. Caesium-137 activity occurs in the fine-grained alcove sediments, sampled from beneath flood units MB3 and MB4, with ^{137}Cs measured *ca.* 0.5 m below MB3.

6. Conclusions

The application of ^{137}Cs dating to sequences of slackwater flood deposits preserved at two study reaches of the Llobregat River has been explored. The results indicate that the technique can be used successfully in the dating of such deposits when the ^{137}Cs reaches the site in association with sediment mobilised from the upstream catchment. This was the case at the Monistrol alcoves, where an improved chronology for the modern slackwater flood deposits was obtained. In the case of the MC alcove, a comparison between the flood stratigraphy, caesium dating evidence, the modelled discharge data and the instrumental discharge series enabled individual flood units to be assigned to specific floods from the gauging station record. Evidence from other sites, however, indicates that care is needed when interpreting the ^{137}Cs data from slackwater flood deposits. For example, ^{137}Cs activity was measured in the Late Bronze Age slackwater flood sediments of Alcove VA indicating that the source of the ^{137}Cs was not sediment transported to the site in this case. A number of general guidelines can be provided to ensure the successful application of ^{137}Cs dating to sequences of slackwater flood deposits preserved within rock alcoves or caves. In particular it is important to minimise

the potential impact of, or to interpret carefully, any profiles affected by ^{137}Cs reaching the sediments via percolation. The ^{137}Cs dating technique is, therefore, best applied: 1) when there is a sedimentary profile of greater than 1 m depth; 2) when the profile is sampled away from zones affected by direct percolation or springwater entering the alcove; and 3) where there are various levels of contrasting textures within the profile.

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Tables

Table 1. A summary of the radiocarbon dating samples and results, including calibrated ages calculated by the CalibETH 1.5b programme using the calibration curves of Kromer and Becker (1993), Linnick et al. (1986) and Stuiver and Pearson (1993).

Study reach	Flood unit	Laboratory code	Radiocarbon age (yrs BP)	Calibrated age	One sigma calibrated age range
Pont de Vilomara	VA4	UZ-4523/ETH-23673	2640 ± 55	798 ± 75 BC	853 BC, 776 BC
	VA5	UZ-4524/ETH-23674	2580 ± 75	669 ± 114 BC	794 BC, 554 BC
Monistrol de Montserrat	MA1	UZ-4605/ETH-24418	305 ± 50	AD 1585 ± 79	AD 1516, AD 1642
	MB2	UZ-4738/ETH-25509	Modern		
	MB2-3	UZ-4515/ETH-23665	Modern		
	MC2	UZ-4520/ETH-23670	Modern		
	MC6	UZ-4521/ETH-23671	Modern		
	MC11-12	UZ-4522/ETH-23672	Modern		

Figure captions

Fig. 1. Location of the Llobregat Basin in NE Spain (A). The Pont de Vilomara (B) and Monistrol de Montserrat (C) study reaches, illustrating the location of rock alcoves preserving slackwater flood deposits and surveyed cross sections.

Fig. 2. The stratigraphy, radiocarbon dating and ^{137}Cs activity of Alcoves MA-MC of the Monistrol study reach plotted alongside the valley cross-section. Also annotated on the cross-section are the calculated discharge estimates required for river floodwaters to completely cover the alcoves. Minimum discharges are also indicated on the stratigraphy for selected flood units.

Fig. 3. Stratigraphy and ^{137}Cs activity of Alcove MD of the Monistrol study reach. The calculated discharge estimates for floodwaters to reach the base and ceiling of the alcove are indicated. (See Fig.2 for the key to the stratigraphic column).

Fig. 4. The stratigraphy, radiocarbon dating and ^{137}Cs activity of Alcoves VA and VB of the Pont de Vilomara study reach plotted alongside the valley cross-section. The vertical scale of the Alcove VA column is the same as that indicated for Alcove VB. Also annotated are calculated discharge estimates associated with the two alcoves. (See Fig.2 for the key to the stratigraphic columns).

Fig. 5. Percentage clay content and ^{137}Cs activity plotted against stratigraphic depth for the slackwater palaeoflood deposits of alcoves MB, MC, MD and VA.

Fig. 6. A) The proposed chronology for the Alcove MC slackwater flood deposits illustrated alongside the stratigraphy, ^{137}Cs concentrations and minimum discharge estimates. B) The peak annual instantaneous discharge series at Castellvell. The threshold discharge of $345 \text{ m}^3/\text{s}$ needed to reach the surface of the 1971 flood sediments (unit MC13) is shown. The shaded bands illustrate the range of calculated discharge estimates, from the alcove base to ceiling, associated with Alcoves MB, MC and MD. The individual slackwater flood units deposited by a particular event are annotated. Water Year refers to the period from 1st October to 30th September.