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Holocene climate change and prehistoric settlement in the lower Danube Valley

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ABSTRACT

An analysis of the summed probability distributions of 293 radiocarbon dates from Late Glacial to mid-Holocene sites in the Danubian Iron Gates highlights the existence of well-marked ¹⁴C discontinuities at c. 9.5–9.0 ka, 8.65–8.0 ka and after 7.8 ka cal BP. These coincide with climate anomalies recorded in Greenland ice cores and palaeoclimate archives from the Danube catchment. Four possible explanations are considered: dwindling fish resources, changes in the social environment, flood-induced settlement relocations, and taphonomic effects. On present evidence, the last two factors are thought to be the most likely cause of the discontinuities observed in the Iron Gates Mesolithic–Early Neolithic radiocarbon record.

Key words: climate change, floods, radiocarbon discontinuities, Iron Gates, Danube, Mesolithic, Neolithic

1. Introduction

In a paper written in the wake of the severe flooding along the Danube and Elbe rivers in August 2002, Bonsall et al. (2002a) proposed that a 'gap' in the ¹⁴C sequences of two Mesolithic–Early Neolithic sites in the Iron Gates might be linked to a period of higher average discharge along the Danube with more frequent overbank flooding associated with generally cooler, wetter conditions in Central Europe during the 8.2 ka cal BP rapid climate change (RCC) event.

The Iron Gates sites (especially the lower-lying portions of the sites adjacent to the river) would have been vulnerable to flooding (Fig. 1). It was suggested that during prolonged periods with increased flood risk the Stone Age inhabitants of the sites likely transferred some of their activities and installations onto higher ground (areas that have been less well explored archaeologically), and that this may explain the lack of ¹⁴C dates for the period 8300–8000 cal BP.

Borić and Miracle (2004, pp. 362–363) criticized this interpretation on the grounds that

- a) there is no independent evidence of flooding along the Iron Gates reach of the Danube between 8.3 and 8.0 ka cal BP,
- b) we ‘over-interpreted’ the radiocarbon evidence by considering only ^{14}C mean/median ages and ignoring the statistical uncertainties (2σ errors) associated with them,
- c) we overlooked two ^{14}C dates from Vlasac that indicated settlement activity during the 8.2 ka event, and
- d) AMS dates from Padina and Hajdučka Vodenica obtained since 2002 ‘close the 8.3–8.0 ka cal BP gap’.

In this paper, we respond to these criticisms and review the evidence for climatic impacts during the Iron Gates Mesolithic–Early Neolithic in the light of new research.

Over the past decade there have been several important developments that have a bearing on issues raised in our 2002 paper:

- (1) A growing number of publications support a relationship between RCC events and prehistoric settlement in Europe and Near East – many of these deal with the consequences of rapid climate change for early farming communities (e.g. Bonsall et al., 2002b; Weninger et al., 2006, 2009; Gronenborn, 2007, 2009; Macklin et al., 2011), while relatively few studies have considered the effects of climate shifts on Mesolithic hunter-gatherer populations.
- (2) Many more data are available from climate proxies in Central Europe, most importantly information on Holocene lake levels and palaeotemperature records from cave speleothems and lake sediments.
- (3) The number of ‘single entity’ AMS ^{14}C dates for Mesolithic and Early Neolithic sites in the Iron Gates has increased substantially.

FIG. 1. ABOUT HERE

2. The Iron Gates radiocarbon dataset

There are now over 300 radiocarbon dates from Mesolithic and Neolithic sites in the Iron Gates region spanning the time-range from the Late Glacial to mid-Holocene (c. 15,000–5000 cal BP), which is nearly three times as many as were available in 2002.

Excluding from consideration cave sites in the mountainous hinterland, there are 313 ^{14}C dates from sites along the main trunk of the Danube, extending over a distance of more than 200 km. Of these, 20 dates are unusable in the present context because of very large errors, concerns over sample integrity, or because of suspected reservoir offsets that cannot be corrected for (e.g. human bone collagen dates with no corresponding $\delta^{15}\text{N}$ values). The remaining 293 dates comprise

- a) 59 radiometric ^{14}C dates produced in the 1960s and 1970s (57 on bulk charcoal samples, and one each on human bone and terrestrial animal bone samples), and
- b) 234 single-entity AMS ^{14}C dates on human bone (85 dates), terrestrial animal bone (148 dates) and plant macro-remains (1 date) – all obtained since 1996.

Summed probability plots of radiocarbon data have become a popular tool in archaeology for investigating long-term demographic patterns in relation to palaeoenvironmental trends. The statistical reliability of the plots depends largely on sample size relative to the time interval examined; the number of ^{14}C dates now available for the Mesolithic–Neolithic time range in the Iron Gates satisfies the

minimum reliability criteria proposed by Michczyńska and Pazdur (2004) and Williams (2012).

FIG. 2. ABOUT HERE

Fig. 2 provides a graphical representation of the calibrated ^{14}C ages generated by the *Cologne Radiocarbon Calibration and Palaeoclimate Research Package* (CalPal, version 29 May 2007) using the multiple-group calibration method (Weninger, 2000; see Weninger, 1986 for an explanation of the underlying statistical procedures). The cumulative probability distribution of the calibrated ^{14}C ages is shown as an envelope curve for the total data, with the median values of individual calibrated ^{14}C ages represented by short vertical lines. Summed calibrated probability distribution curves are presented for the full dataset (Fig. 2, dataset A), the AMS dates on terrestrial animal/plant material and human bone combined (Fig. 2, dataset B), and the AMS dates for terrestrial samples only (Fig. 2, dataset C).

The charcoal and human bone ages may introduce ‘noise’ into the analysis. Charcoal samples potentially carry an ‘old wood effect’, which can result in ^{14}C ages that overestimate the date of a cultural event by up to hundreds of years. Moreover in some cases there are doubts about the stratigraphic (hence chronological) integrity of the charcoal samples, which is why several charcoal dates from Vlasac and a date from Alibeg were excluded from our previous study (Bonsall et al., 2002a). However, all these dates have been included in dataset A (Fig. 2). Similarly, human bone ^{14}C ages from the Iron Gates sites often include a ‘reservoir effect’ resulting from consumption of freshwater and anadromous fish from the Danube (Cook et al., 2001). A reservoir correction has been applied prior to calibration based on the bone collagen $\delta^{15}\text{N}$ value (Cook et al., 2002, 2009), but the corrected ages are less precise (i.e. have larger errors). Moreover, the correction method assumes that the size of the reservoir offset remained constant over time, which may not be the case.

Radiocarbon age measurements carried out on the bones of terrestrial herbivores and short-lived plant remains do not suffer from the potential biases that can affect human bones and wood charcoal as described above. Many dates included in our analysis are single-entity measurements on humanly modified bones (artifacts, débitage, or cut-marked bones from the processing of animal carcasses), which can be considered to date human activity directly (cf. Ashmore, 1999; Tolan-Smith and Bonsall, 1999). Where unmodified animal bones were dated, they come from well-documented archaeological contexts and have a high probability of association with human activity. Arguably, therefore, the most reliable picture is provided by the ‘terrestrial’ subset (Fig. 2, dataset C), although all the curves show broadly the same pattern.

3. Discussion

There are three well-marked ‘dips’ in the summed calibrated probability distribution curve (SCPDC) for the 15000–5000 cal BP time range in Iron Gates (Fig. 2), representing phases with relatively few ^{14}C dates. There is a rough coincidence between these reductions in ^{14}C date frequency and climate shifts recorded in proxies from Greenland (Mayewski et al., 2004; Rasmussen et al., 2007), the North Atlantic (Bond et al., 1997) and Europe (Fig. 3).

- (1) The dip in the SCPDC at 9500–9000 cal BP correlates fairly closely with the climate anomaly known as the ‘9.3 ka cold event’.

- (2) The major ^{14}C discontinuity at 8650–8000 cal BP corresponds roughly with the general climatic deterioration recognized by Rohling and Pälike (2005) between 8600 and 7950 BP, which culminated in a sudden cold event ('8.2 ka event') between c. 8175–8025 cal BP (Kobashi et al., 2007). Within this phase the lowest frequency of ^{14}C dates occurs between c. 8475 and 8100 cal BP.
- (3) The dip in the SCPDC immediately after 7800 cal BP is the prelude to a long lacuna in the ^{14}C record of the Iron Gates. The initial reduction in ^{14}C dates coincides with a significant decline in sea surface temperatures (SST) in the southern Adriatic between 7800 and 7500 cal BP. This was followed by a more pronounced SST cooling between 7300 and 6300 cal BP, which at its nadir was characterized by SSTs lower than those registered during the 8.2 ka event (Siani et al. 2013).

FIG. 3. ABOUT HERE

The broad similarity in timing between centennial scale climate anomalies and the 'dips' in our SCPDC for the Iron Gates (Fig. 3) is suggestive of a correlation. However, as Behrensmeier (2006) has cautioned, establishing a causal link between climatic events and archaeological phenomena requires a convincing mechanism for transmitting cause to effect.

One possibility is that climate-related changes in river conditions had a negative impact on fish stocks, diminishing the attractiveness of the Danube as a source of food.

Fish abundance and species variety in rivers can be profoundly affected by environmental stress. Spawning and feeding behaviour can be significantly affected by sudden and/or prolonged changes in water temperature. Spawning in salmonids and wels catfish (*Silurus glanis*) may be inhibited by sudden drops in water temperature; while catfish cease to feed at temperatures below c. 10 °C and growth is impeded (Omarov and Popova, 1985; David, 2006; Copp et al., 2009). Similarly, river icing and sudden or prolonged changes in flow conditions can impact on fish populations. Periods of high flow are an important trigger for sturgeon migrations and higher water levels allow fish to pass through river stretches containing rapids or shallows. Conversely, any reduction in river discharge during the period of migration diminishes the attractiveness of the river and the number of migrants.

'Winterkill' is a phenomenon known in many temperate zone rivers caused by ice and high water flows. Ice jams and high flows cause 'scouring' of the riverbed killing aquatic insects and destroying underwater plants, which are important sources of food for many fish. Even when the surface of the river does not freeze, 'anchor ice' can form on rocks under water and may kill fish eggs and aquatic insects. Many fish species lay their eggs in gravel on the riverbed and these can be destroyed when rocks and ice scour the bottom during high water flows and even young fish may be killed. There are occasional reports of migrating Beluga sturgeons being injured by large blocks of ice in the Danube (e.g. Heckel and Kner 1858). The severity of winterkill varies year by year. One 'bad' year is unlikely to have a significant impact on the fish population of a river, but a succession of bad years could interfere with the reproduction of fish and lead to a sustained reduction in fish catches.

That said, we are not aware of any documentary evidence for prolonged major reductions in fish stocks or catches along the Danube and other major European rivers during the historical period, including the Little Ice Age, which can be unambiguously linked to climate change. However, in certain respects the Little Ice

Age was atypical among Holocene RCC events. Some Early to Mid-Holocene 'neoglacial' episodes, especially the 8.2 ka event, may have been more severe than the Little Ice Age. Moreover, the Little Ice Age coincided with a period of significant human intervention and beginnings of large-scale management of the Danube, which had an impact on fish stocks and migration as a consequence of infrastructure developments like bridges, flood defences and channelization. For example, fish and reproduction in the lower Austrian Danube were seriously affected following an ice jam and associated flooding in 1880 (Pölzl, 1906), but it is not clear whether the ice jam and flood were responsible for the marked decline of the cyprinid, Common Nase (*Chondrostoma nasus*) after 1880, or if the flood protection measures that followed this hydrological event were the cause.

More research is needed into climate change and impacts on fish species distribution and productivity in the Danube. For the time being, since no significant temporal fluctuations in the exploitation of fish resources are reflected in either the archaeofaunal or human bone stable isotope records prior to the appearance of agriculture c. 8100/8000 cal BP, it seems unlikely that the discontinuities observed in the radiocarbon record of the Iron Gates Mesolithic–Early Neolithic mirror periods of decline in river fisheries and concomitant reductions in settlement intensity.

It is generally accepted that farming spread through the Balkans between c. 8600 and 8000 cal BP. Several authors have speculated that as the agricultural frontier approached the Danube, interaction with farmers could have disrupted the Mesolithic settlement–subsistence system in the Iron Gates (Tringham, 2000; Borić, 2011; see also Bonsall, 2008, p. 277). While this might explain the ^{14}C discontinuity centred on 8.3 ka cal BP, it could not account for the reduction in the number of ^{14}C ages around 9.3 ka cal BP; while the ^{14}C discontinuity commencing after 7.8 ka cal BP, which appears to have marked a sharp decline in Early Neolithic occupation of the Iron Gates sites (Bonsall et al., 2002a; Bonsall, 2008), occurred several centuries after farming had been established in the region (there appears to have been only sporadic occupation of the Iron Gates sites between the later Neolithic and the late Pre-Roman Iron Age).

Climate-related changes in the magnitude and frequency of floods on the Danube, and the variability of flow regime, still seem the most likely explanation of the discontinuities in the Iron Gates ^{14}C record, as proposed by Bonsall et al. (2002a).

In historical times floods have occurred regularly on the Danube in spring and early summer. The main causes are excessively heavy and/or prolonged rainfall and snowmelt from upland areas within the catchment. Another historically documented cause is the build-up and then sudden collapse of ice jams formed during the break-up of river ice – ice jam formation causes a rapid rise of the river level upstream of the jam, followed by sudden flooding downstream when the jam is released. Ice jams tend to recur at significant channel constrictions (Smith and Ward, 1998). Some of the biggest floods ever recorded on the Danube were associated with the ponding and/or release of water by ice jams (which were more prevalent during the Little Ice Age), including the catastrophic flood of 1838 that devastated large areas of Budapest.

River flow data from gauging stations along the Danube are available for the last 120–150 years. Over that time major floods occurred in at least 15 separate years. The 2002 flood was the result of intense and prolonged summer rainfall over the eastern Alps and the upper Danube catchment. Two periods of sustained rainfall several days apart generated successive flood waves that travelled down the Danube at rates of up to 74 km/day (Mihailova et al., 2012).

During the combined snowmelt and rainfall spring–summer flood of 2006 the Danube at the Orșova gauging station (inside the Iron Gates gorge) underwent stage changes of 6–7 m on several occasions between late January and mid-July. Stage changes were rapid (occurring within a few days) and high river flows were maintained for periods lasting up to six weeks (Mihailova et al., 2012, fig. 5c). More extreme variations in river discharge can perhaps be expected during Holocene RCC events (especially the 8.2 ka event), given the evidence of major snowmelt and ice jam floods during the Little Ice Age.

In the area downstream of the Iron Gates I dam, which includes the important Late Mesolithic-Early Neolithic site of Schela Cladovei (V. Boronean et al., 1999; Bonsall 2008; A. Boronean and Bonsall, 2013), there is evidence for significant river incision since the Late Glacial. The 1:200,000 geological map of the area (Savu and Ghenea, 1967) shows a terrace at c. 7 m above the river, some 3 m higher than the present river flat on which the Schela Cladovei site is situated. This terrace was described as ‘Early Holocene’, but may be of Late Glacial age. Downcutting to the level of the Schela Cladovei site must have occurred before c. 9.2 ka cal BP – the earliest date for Mesolithic occupation of the site. Since Schela Cladovei is now c. 4 m above the river, further incision since the Mesolithic seems likely. This would imply that riverbed levels were higher before the 8.2 ka event, with the consequence that floods during the early part of the Holocene likely extended higher up the Iron Gates gorge walls than in more recent periods. Equally, the height of the Schela Cladovei site relative to the Danube would have been less in the earlier Holocene than today, and the site more at risk from flooding.

These observations give some idea of the likely impact of very high river flows on Stone Age settlements in the Iron Gates. Within the Iron Gates gorge any site or zone within 10 m of the mean river level could have been at risk during extreme hydrological events, while a rise in the level of the Danube of 4 m or more would have inundated Schela Cladovei and some other sites in the downstream area. Moreover flood conditions may have persisted for weeks.

Borić and Miracle (2004, p. 362) questioned whether such extreme hydrological events were characteristic of the Iron Gates reach of the Danube before the historic period. Various lines of evidence contradict this argument. At Schela Cladovei repeated overbank flooding during the early-mid Holocene is indicated by 1.5–2 m of alluvial deposits (Boronean et al., 1999) and an associated luminescence date (Fuller et al., 1994); although soil development combined with anthropogenic disturbance has erased any original stratification in these deposits, blurring the stratigraphic relationships between flood events and human occupations. At Lepenski Vir poor archaeological survival (including a lack of datable organic remains) in lower lying parts of the site nearer the river may be attributable to scour (removal of material) during flood events. Remains of stone-lined hearths are evidence that buildings had once stood in this part of the site. Srejović (1972, p. 53) observed that these hearths differ from those set within plaster floors in higher parts of the site and assigned them to an earlier phase of the Mesolithic. Since the plaster-floored structures started to be built after 8300 cal BP (Bonsall et al., 2002a, 2008), it is possible they were deliberately sited in higher slope positions in response to an increase in flood magnitude and frequency.

FIG. 4. ABOUT HERE

The historically documented floods in the Iron Gates and lower Danube were caused by climatic events in the middle and upper reaches of the Danube and its major tributaries (Fig. 4). Knowledge of Holocene climatic variations in the upper–middle Danube catchment has developed significantly over the past 15 years. Various proxy indicators reflect climatic trends during the Early and Middle Holocene that mirror those seen in climatic archives from the North Atlantic region

- (1) episodes of cooler climate at 9.3–9.1 and c. 8.2 ka cal BP are indicated by O-isotope studies of speleothems from caves in Austria (Wurth et al., 2004; Boch et al., 2009) and northwest Romania (Tămaş et al., 2005),
- (2) negative O-isotope excursions indicative of cooling and increased precipitation are registered in sediment cores from Lake Ammersee in southern Germany at c. 9.2 ka and 8.2 ka cal BP (von Grafenstein et al., 1998, 1999),
- (3) vegetation responses to climatic cooling have been recorded in high altitude peat bogs and lake sediments in the Swiss Alps (Tinner and Lotter, 2001; Kofler et al., 2005) at 8.2 ka cal BP and in northwest Romania at 9.3 and 8.2 ka cal BP (Feurdean, 2005), and
- (4) research by Magny (2004) has documented 15 episodes of higher lake level in the Alps and Jura mountains reflecting increases in annual precipitation that were broadly synchronous with RCC events recorded in Greenland ice cores, including 9550–9150, 8300–8050 and 7550–7250 cal BP (Fig. 3).

From a pan-European study of climate proxy records, Magny et al. (2003) concluded that mid-latitude Europe between 43° and 50° N experienced significantly wetter (and cooler) conditions during the RCC events of the Holocene.

Rivers tend to be very sensitive indicators of short term and rapid climate change (Macklin et al., 2006, 2012) and a likely consequence of cooler conditions and increased precipitation over the upper Danube catchment such as characterized the 9.3 and 8.2 ka events and the period after 7.8 ka cal BP would have been an increase in seasonal and/or annual discharges along the Danube and its major tributaries in Central Europe, upstream of the Iron Gates. Mathematical modelling has suggested that water discharge along the Danube and some of its major tributaries in Central Europe during the most recent RCC event of the Holocene, the Little Ice Age, was on average 10–15% higher than at present (McCarney-Castle et al., 2012).

Considering its size and importance in Europe, remarkably little work has been done on Holocene fluvial development and flood histories of the Danube and its tributaries. Research by Howard et al. (2004) and Macklin et al. (2011) along the Teleorman River in southern Romania, which flows into the Danube east of the Iron Gates, found no evidence of enhanced river activity corresponding to RCC events of the earlier Holocene between 11.6 and 5.8 ka cal BP. However, the Teleorman is a relatively small low-gradient catchment tributary of the lower Danube with very different hydro-climatic characteristics to the Danube catchment upstream of the Iron Gates.

A better proxy for hydrological patterns in the Danube catchment upstream of the Iron Gates is the behaviour of rivers draining the western Alps, where several studies have shown substantially increased discharges around the time of the 9.3 and 8.2 ka events (Miramont et al., 2000; Berger et al., 2002).

The Holocene flood history of the Danube catchment, and the Iron Gates in particular, represents a major gap in knowledge and should be viewed as a priority for future research. Potential sites for the preservation of extended Holocene flood records are likely to be found at the mouths of north and south bank tributaries in the

Iron Gates gorge, as well as in channel-margin alcoves and caves where reduction in flow velocity and flow separations during flood events results in the deposition of fine grained sediments termed slackwater deposits (Baker, 1987). The study and dating of these fluvial sediments in bedrock gorges and canyons similar to the Iron Gates have allowed both the frequency and magnitude of Holocene flood events to be reconstructed in considerable detail (e.g. Ely et al., 1993). Extending over a length of more than 200 km, the Iron Gates reach of the Danube is likely to contain a diverse range of Holocene and possibly earlier palaeoflood records, but these have yet to be investigated.

In the foregoing discussion we have sought to explain the radiocarbon record of the Iron Gates Mesolithic–Early Neolithic primarily in terms of human agency, emphasizing the likely human responses to long-term fluctuations in magnitude and frequency of flooding on the Danube. However, taphonomic processes (e.g. destruction, movement and burial of artefacts by river processes, and archaeologists’ choices of sites for investigation and samples for dating) may also have contributed to the fluctuations in the radiocarbon time series for the Iron Gates. Overbank flows could have resulted in the removal of artefacts and ecofacts from occupation surfaces – charcoal, since it floats, would be particularly vulnerable – which then would not be available for dating. However, many of the ^{14}C -dated animal and human bones from the Iron Gates sites (cf. Fig. 2) were recovered from pit features (including graves) where they would have been relatively protected from river scour. Therefore, it seems unlikely that the c. 300-year gap in the radiocarbon record at Schela Cladovei (Bonsall et al., 2002a, Fig. 2), for example, was a consequence of removal of material from the site during flood events.

4. Conclusions

Holocene climate change and its effects on ancient human populations is a complex topic, which can be investigated at different geographical scales and with a variety of analytical techniques.

We used CalPal and IntCal04 to investigate temporal trends in the radiocarbon date series from the 230 km long Iron Gates reach of the Danube valley covering the time-range from the Late Glacial to the middle Holocene, c. 15,000–5000 cal BP. The resultant summed probability distribution curves show marked discontinuities (periods with reduced frequencies of ^{14}C dates) at c. 9.5–9.0 ka, 8.75–8.0 ka and after 7.8 ka cal BP during the Mesolithic and Early Neolithic. These coincide with well-defined anomalies recorded in palaeoclimate archives from the North Atlantic region and the Danube catchment.

Changing frequencies of ^{14}C dates over time have tended to be used by archaeologists as a proxy for fluctuations in population size. In the case of the Iron Gates, however, we suggest that other factors have strongly influenced the temporal pattern. Our preferred explanation is that the ^{14}C discontinuities reflect periods of higher annual river discharge and an increase in flood magnitude during Holocene ‘neoglacial’ events, associated with generally cooler, wetter conditions in the Danube catchment upstream of the Iron Gates, and that the increased flood risk led to a reduction in the intensity with which people used certain sites or the lower parts of sites bordering the river. River scour may also have reduced the archaeological visibility of ‘neoglacial’ periods by removing material from occupation surfaces. The Holocene flood history of the Danube catchment, and the Iron Gates in particular, is poorly understood and should be viewed as a priority for future research.

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FIGURE CAPTIONS

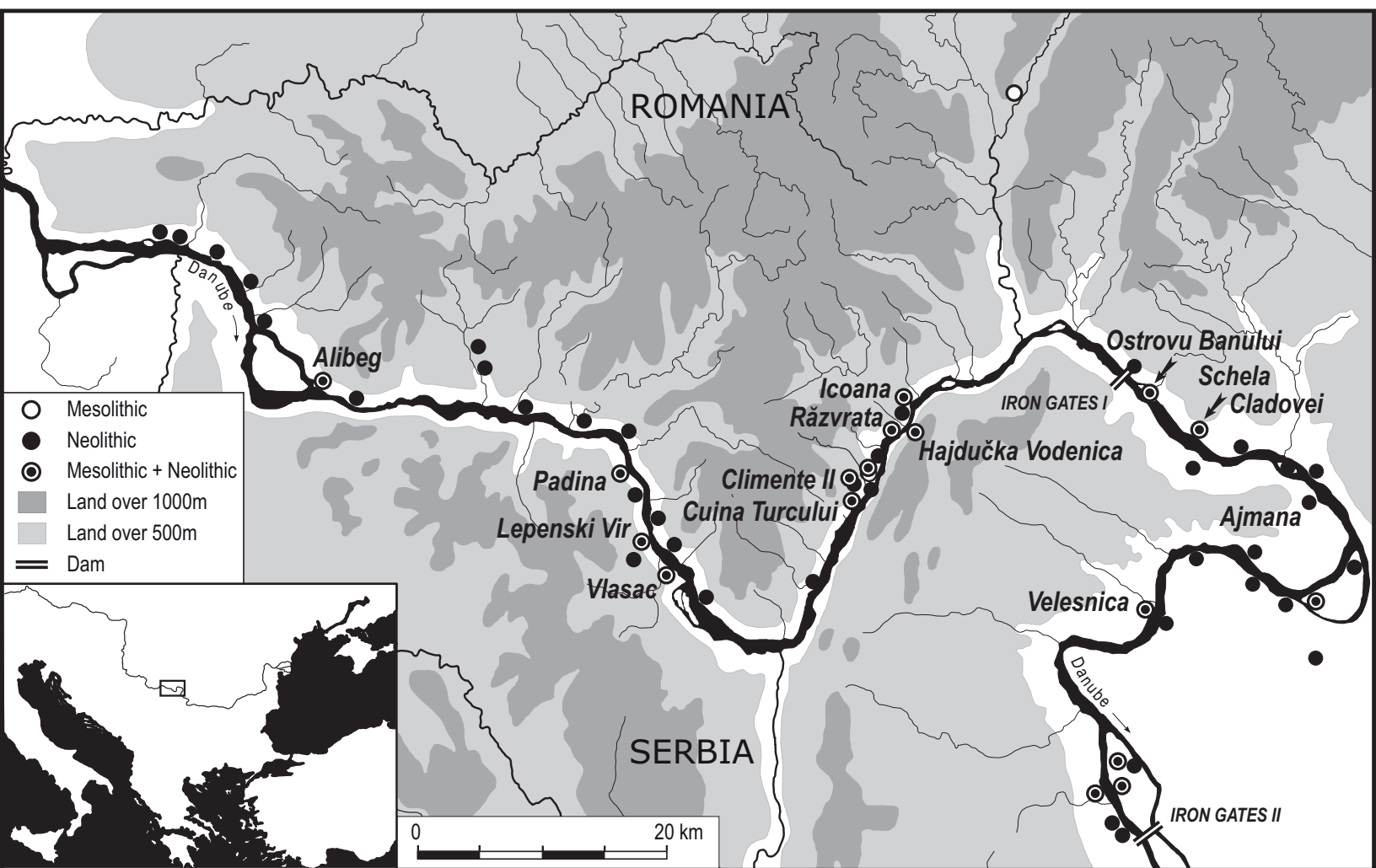
Fig. 1. Mesolithic and Early Neolithic sites in the Iron Gates. Virtually all sites along the main trunk of the Danube were located immediately adjacent to the river and would have been vulnerable (in whole or part) to inundation at times of unusually high river flows (4 m+ floods). Named sites have ^{14}C dates that were used to generate the summed probability distributions in Figs 2–3.

Fig. 2. Cumulative calibrated dating probability of radiocarbon data from Mesolithic and Early Neolithic sites along the Danube main channel in the Iron Gates. Datasets: A – all usable radiometric and AMS dates; B – AMS dates on terrestrial and human bone samples; C – AMS dates on terrestrial animal and plant samples. Calibrations performed with *CalPal* (29 May 2007) [<http://www.calpal.de>] and the IntCal04 dataset. ^{14}C data from Bonsall, 2008; Bonsall et al., 1997, 2008, 2012, 2015, unpublished; Borić and Miracle, 2004; Borić and Dimitrijević, 2009; Borić, 2011; Borić and Price, 2013; Dinu et al., 2007. Prior to calibration human bone ^{14}C ages were corrected for the ‘freshwater reservoir effect’ using Method 1 of Cook et al. (2002), assuming $\delta^{15}\text{N}$ endpoint values for purely terrestrial and purely aquatic diets of +8.3‰ and +17.0‰, respectively (cf. Cook et al., 2009).

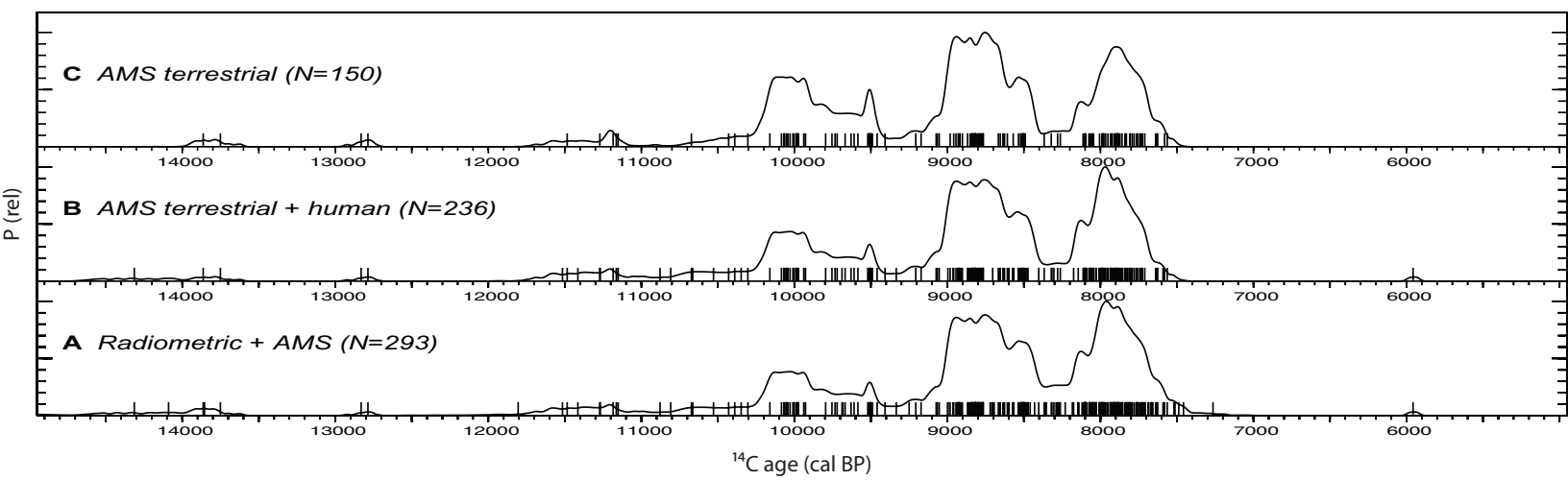
Fig. 3. Cumulative calibrated dating probability of radiocarbon data (terrestrial series) from Mesolithic and Early Neolithic sites along the Danube main channel in the Iron Gates, compared to climate proxy records from the North Atlantic and Europe 10,000–6000 cal BP. A – after Bond et al. (1997); B, D, F, G – smoothed records redrawn from Rohling and Pälike (2005); E – after Siani et al. (2013); C – horizontal bars represent cold phases recorded in $\delta^{18}\text{O}$ records from V11 Cave, NW Romania (Tămaş et al., 2005) and Katerloch Cave, Austria (Boch et al., 2009); vertical grey bars represent higher lake-level events in the Alps–Jura region (Magny, 2004).

Fig. 4. The Danube catchment showing the Iron Gates and key localities with climate proxy records for the Early to Middle Holocene: 1 – Hölloch Cave (Wurth et al., 2004); 2 – Katerloch Cave (Boch et al., 2009); 3 – V11 Cave (Tămaş et al., 2007); 4 – Lake Ammersee (von Grafenstein et al., 1998, 1999); 5 – Lake Schleinsee (Tinner and Lotter, 2001); 6 – Lake Soppensee (Tinner and Lotter, 2001); 7 – Brunnboden and Krummgampen peat bogs (Kofler et al., 2005); 8 – Preluca Tiganului and Steregoiu peat bogs (Feurdean, 2005); 9 – Alps–Jura lakes study region (Magny, 2004); 10 – Telemann Valley (Macklin et al., 2011); 11 – Durance Valley (Miramont et al., 2001); 12 – Middle Rhône Valley (Berger et al., 2002).

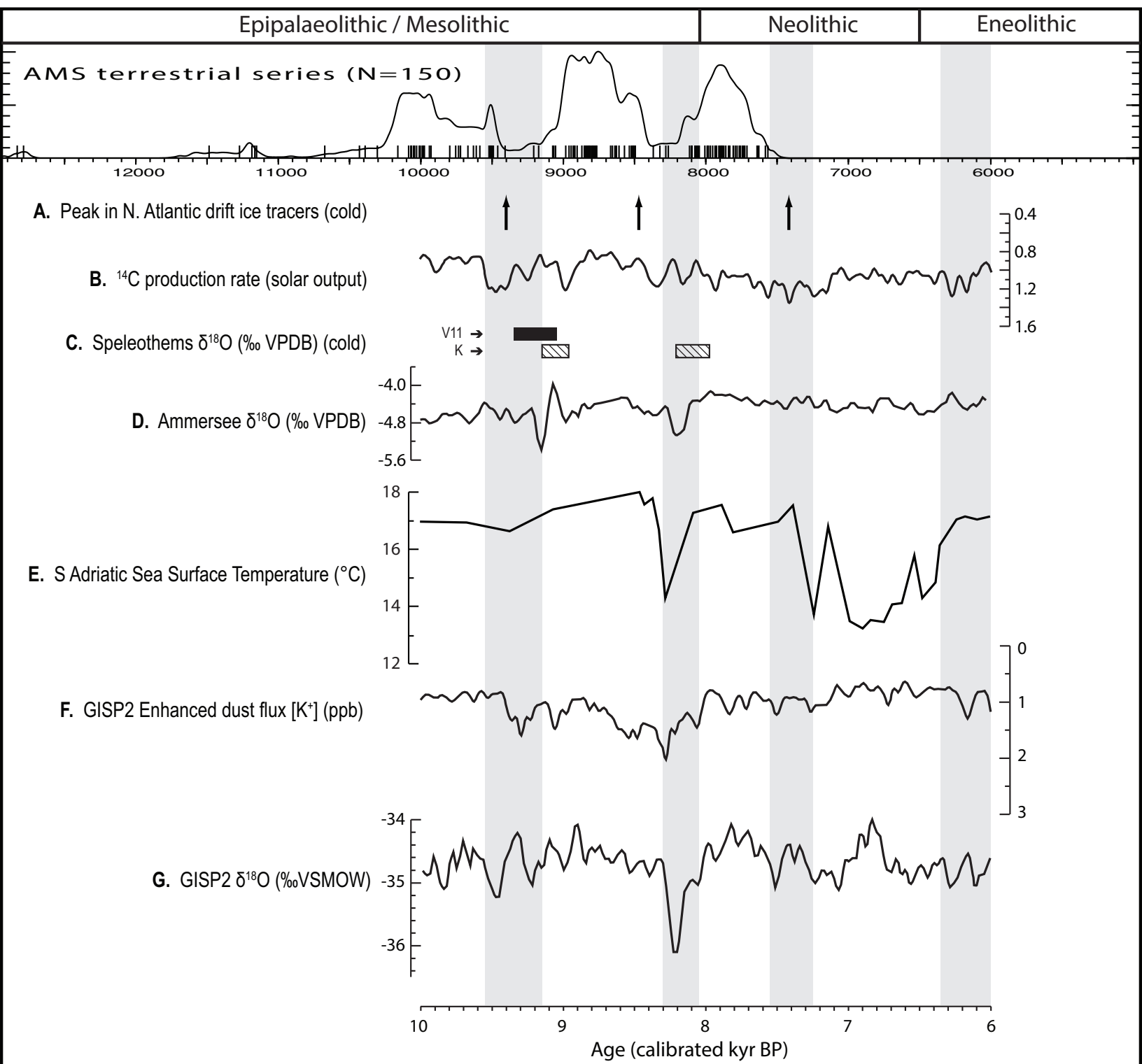
Figure



Figure



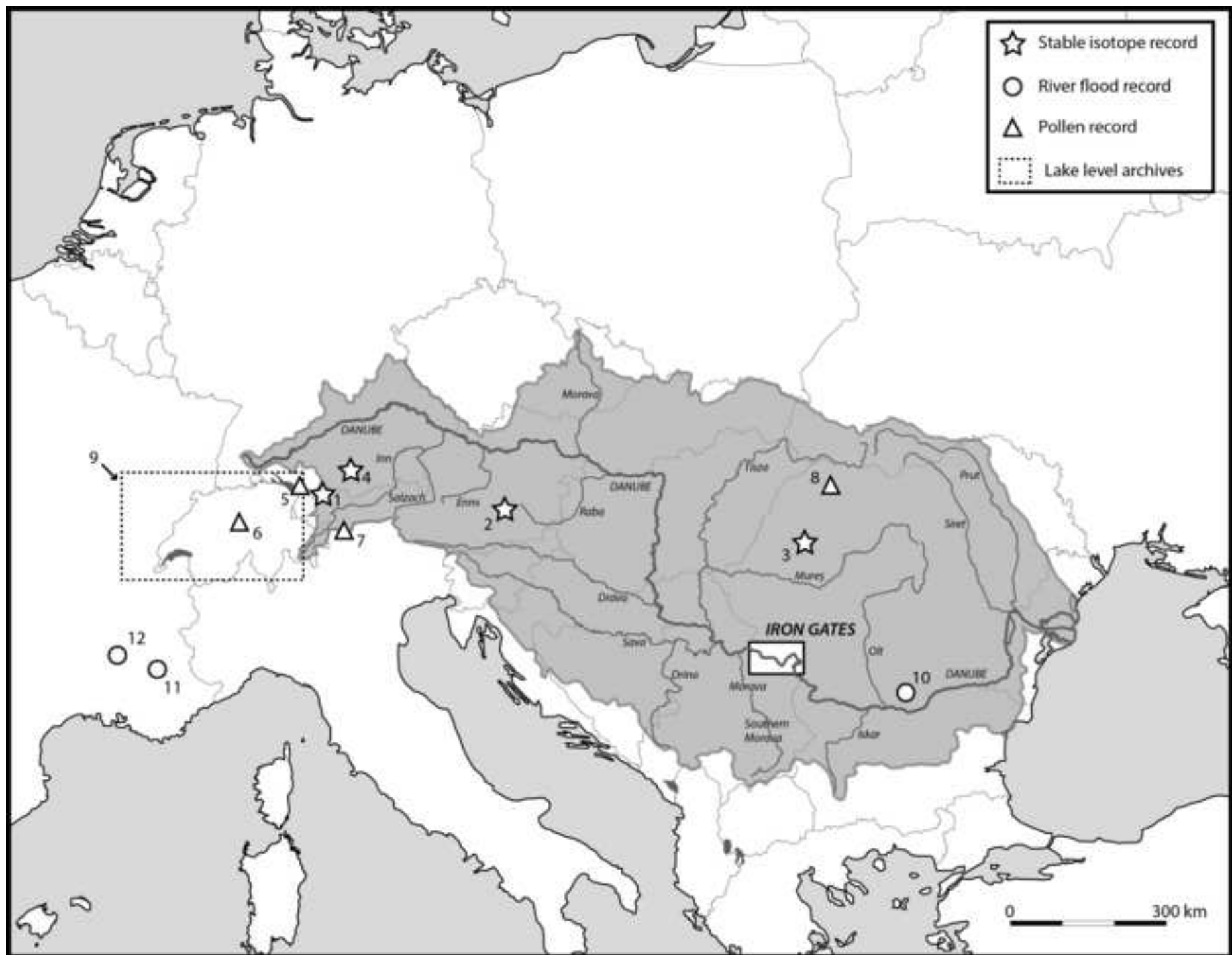
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SUMMARY OF REFEREE COMMENTS AND RESPONSES

1	<p>Vulnerability to flooding, p2, para 2, line 2</p> <ul style="list-style-type: none"> • Provide a contour map. DONE – new Fig. 1 with explanatory caption; other Figures renumbered • Where are the unpublished ^{14}C data from? From the sites shown in Fig. 1. More of the dates are now published, but in a few cases <i>details</i> can't be released by agreement with co-researchers (but will be published in due course).
2	<p>Sample size, p3, para 4, line 2</p> <ul style="list-style-type: none"> • Comment on ... and cite Williams (2012). DONE
3	<p>'Problems of calibration', p3, para 4, line 4</p> <ul style="list-style-type: none"> • Explain what is meant by 'problems of calibration'. DONE
4	<p>Freshwater reservoir effect, p4, para 2, lines 7-13</p> <ul style="list-style-type: none"> • Confirm whether or not a correction was applied to human bone dates. DONE. FRE correction was applied to <i>all</i> human bone ^{14}C ages included in the summed probability plots – this is now made clear in the text and the caption to Fig. 2.
5	<p>Stratigraphic integrity of samples dated, p4, para 3, lines 3-6</p> <ul style="list-style-type: none"> • Problematic statement. RE-WRITTEN • Stratigraphic integrity of samples? It is unclear what the referee means by 'stratigraphic integrity'. We explain in more detail the nature/provenance of our samples.
6	<p>'8.2 ka event' and shape of ^{14}C curve, p4, para 4, lines 1-6 and Figs 1-2</p> <ul style="list-style-type: none"> • Similarity between ^{14}C curve and climate trend between 8.8-8.0 ka BP. We don't agree entirely with the Referee's assessment (i.e. we don't think that it is valid to compare the finer details of curves based on quite different sets of data and statistical procedures), but we have expanded and de-simplified our discussion of the correlation between climate shifts and ^{14}C discontinuities. • Cite Rohling & Pälike (2005). DONE
7	<p>Strength of correlation between ^{14}C reductions and RCC events, p4, para 4, lines 1-6 and Figs 1-2</p> <ul style="list-style-type: none"> • ^{14}C reduction is not 'centred' on 7.5ka. Point taken; text modified (cf. #6). • Precise correlation between ^{14}C discontinuity and 9.3 ka event makes causal link more likely. We don't disagree, but a causal link requires more than coincidence.
8	<p>Related points ...</p> <ul style="list-style-type: none"> • Explanation of ^{14}C lacuna after 7.5 ka? This question was addressed in previous publications (now cited). It is beyond the scope of the present paper to revisit it, especially as we have not changed our opinion. • Have Middle Neolithic dates been excluded from the analysis? Why would the Referee think this? We state at the beginning that ALL reliable ^{14}C dates between 15–5 ka were included in the analysis.
9	<p>Climate-related impacts on fish populations, pp 4-5</p> <ul style="list-style-type: none"> • Is there evidence of technological change/simplification? The text has been expanded to address this point.
10	<p>Schela Cladovei, p6, para 6</p> <ul style="list-style-type: none"> • Association between dated material and alluvial sediments? The text has been expanded to address this point. • How many dates from SC were used in the ^{14}C curves? Odd question, given that it is stated at the beginning of the paper that ALL reliable dates between 15–5 ka were used.
11	<p>Lepenski Vir, p6, para 6</p> <ul style="list-style-type: none"> • Include more information on location/dates of plaster-floored buildings. This information can be found in our previous publications, references to which have been added.

12

Further to points 8 and 11 ...

- Changes in building traditions may affect ¹⁴C date frequency. There are many biasing factors in the construction of summed probability curves, as acknowledged in our original text (p.9). The biases in our data are unlikely to be the same as those in Crombé & Robinson's data, because building traditions, approaches to excavation and radiocarbon sampling strategies were all different. In any case, we think the referee has misquoted Crombé & Robinson (2014).

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ABSTRACT

An analysis of the summed probability distributions of 293 radiocarbon dates from Late Glacial to mid-Holocene sites in the Danubian Iron Gates highlights the existence of well-marked ¹⁴C discontinuities at c. 9.5–9.0 ka, 8.65–8.0 ka and after 7.8 ka cal BP. These coincide with climate anomalies recorded in Greenland ice cores and palaeoclimate archives from the Danube catchment. Four possible explanations are considered: dwindling fish resources, changes in the social environment, flood-induced settlement relocations, and taphonomic effects. On present evidence, the last two factors are thought to be the most likely cause of the discontinuities observed in the Iron Gates Mesolithic–Early Neolithic radiocarbon record.

Key words: climate change, floods, radiocarbon discontinuities, Iron Gates, Danube, Mesolithic, Neolithic

1. Introduction

In a paper written in the wake of the severe flooding along the Danube and Elbe rivers in August 2002, Bonsall et al. (2002a) proposed that a 'gap' in the ¹⁴C sequences of two Mesolithic–Early Neolithic sites in the Iron Gates might be linked to a period of higher average discharge along the Danube with more frequent overbank flooding associated with generally cooler, wetter conditions in Central Europe during the 8.2 ka cal BP rapid climate change (RCC) event.

The Iron Gates sites (especially the lower-lying portions of the sites adjacent to the river) would have been vulnerable to flooding (Fig. 1). It was suggested that during prolonged periods with increased flood risk the Stone Age inhabitants of the sites likely transferred some of their activities and installations onto higher ground (areas that have been less well explored archaeologically), and that this may explain the lack of ¹⁴C dates for the period 8300–8000 cal BP.

Comment [CB1]: cf. Referee comment #1

Borić and Miracle (2004, pp. 362–363) criticized this interpretation on the grounds that

- a) there is no independent evidence of flooding along the Iron Gates reach of the Danube between 8.3 and 8.0 ka cal BP,
- b) we ‘over-interpreted’ the radiocarbon evidence by considering only ^{14}C mean/median ages and ignoring the statistical uncertainties (2σ errors) associated with them,
- c) we overlooked two ^{14}C dates from Vlasac that indicated settlement activity during the **8.2 ka event**, and
- d) AMS dates from Padina and Hajdučka Vodenica obtained since 2002 ‘close the 8.3–8.0 ka cal BP gap’.

In this paper, we respond to these criticisms and review the evidence for climatic impacts during **the** Iron Gates Mesolithic–Early Neolithic in the light of new research.

Over the past decade there have been several important developments that have a bearing on issues raised in our 2002 paper:

- (1) A growing number of publications support a relationship between RCC events and prehistoric settlement in Europe and Near East – many of these deal with the consequences of **rapid** climate change for early farming communities (e.g. Bonsall et al., 2002b; Weninger et al., 2006, 2009; Gronenborn, 2007, 2009; Macklin et al., 2011), while relatively few studies have considered the effects of **climate shifts** on Mesolithic hunter-gatherer populations.
- (2) Many more data are available from climate proxies in Central Europe, most importantly information on Holocene lake levels and palaeotemperature records from cave speleothems and lake sediments.
- (3) The number of ‘single entity’ AMS ^{14}C dates for Mesolithic and Early Neolithic sites in the Iron Gates has increased substantially.

2. The Iron Gates radiocarbon dataset

There are now **over** 300 radiocarbon dates from Mesolithic and Neolithic sites in the Iron Gates region spanning the time-range from the Late Glacial to mid-Holocene (c. 15,000–5000 cal BP), which is nearly three times as many as were available in 2002.

Excluding from consideration cave sites in the mountainous hinterland, there are **313** ^{14}C dates from sites along the main trunk of the Danube, extending over a distance of more than 200 km. Of these, **20** dates are unusable in the present context because of very large errors, **concerns over sample integrity**, or because of **suspected reservoir offsets that cannot be corrected for (e.g. human bone collagen dates with no corresponding $\delta^{15}\text{N}$ values)** **problems of calibration**. The remaining **293** dates comprise

- a) **59** radiometric ^{14}C dates produced in the 1960s and 1970s (**57** on bulk charcoal samples, and one each on human bone and terrestrial animal bone samples), and
- b) **234** single-entity AMS ^{14}C dates on human bone (**85** dates), terrestrial animal bone (**148** dates) and plant macro-remains (1 date) – all obtained since 1996.

Summed probability plots of radiocarbon data have become a popular tool in archaeology for investigating long-term demographic patterns in relation to palaeoenvironmental trends. The statistical reliability of the plots depends largely on sample size relative to the time interval examined; the number of ^{14}C dates now available for the Mesolithic–Neolithic time range in the Iron Gates satisfies the minimum reliability criteria proposed by Michczyńska and Pazdur (2004) and

Comment [CB2]: The number of usable dates has increased since the MS was submitted. The summed probability distributions have been recalculated and Figs 2-3 updated.

Comment [CB3]: cf. Referee comment #3:

Williams (2012).

Fig. 2 provides a graphical representation of the calibrated ^{14}C ages generated by the *Cologne Radiocarbon Calibration and Palaeoclimate Research Package* (CalPal, version 29 May 2007) using the multiple-group calibration method (Weninger, 2000; see Weninger, 1986 for an explanation of the underlying statistical procedures). The cumulative probability distribution of the calibrated ^{14}C ages is shown as an envelope curve for the total data, with the median values of individual calibrated ^{14}C ages represented by short vertical lines. **Summed calibrated probability distribution curves** are presented for the full dataset (**Fig. 2**, dataset A), the AMS dates on terrestrial animal/plant material and human bone combined (**Fig. 2**, dataset B), and the AMS dates for terrestrial samples only (**Fig. 2**, dataset C).

The charcoal and human bone ages may introduce ‘noise’ into the analysis. Charcoal samples potentially carry an ‘old wood effect’, which can result in ^{14}C ages that overestimate the date of a cultural event by up to hundreds of years. Moreover in some cases there are doubts about the stratigraphic (hence chronological) integrity of the charcoal samples, which is why several charcoal dates from Vlasac and a date from Alibeg were excluded from our previous study (Bonsall et al., 2002a). However, all these dates have been included in dataset A (**Fig. 2**). Similarly, human bone ^{14}C ages from the Iron Gates sites often include a ‘reservoir effect’ resulting from consumption of freshwater and anadromous fish from the Danube (Cook et al., 2001). A reservoir correction **has been** applied prior to calibration based on the bone collagen $\delta^{15}\text{N}$ value (Cook et al., 2002, 2009), but the corrected ages are less precise (i.e. have larger errors). **Moreover**, the correction method assumes that the size of the reservoir offset remained constant over time, which may not be the case.

Radiocarbon age measurements carried out on the bones of terrestrial herbivores and short-lived plant remains do not suffer from the potential biases that can affect human bones and wood charcoal as described above. Thus, **provided they accurately reflect the age of the context in which they were found (and are therefore not residual)** their age measurements will most accurately date the archaeological event under study. Therefore, arguably **Many dates included in our analysis are single-entity measurements on humanly modified bones (artifacts, débitage, or cut-marked bones from the processing of animal carcasses), which can be considered to date human activity directly (cf. Ashmore, 1999; Tolan-Smith and Bonsall, 1999). Where unmodified animal bones were dated, they come from well-documented archaeological contexts and have a high probability of association with human activity. Arguably, therefore, the most reliable picture is provided by the ‘terrestrial’ subset (Fig. 2, dataset C), although all the curves show broadly the same pattern.**

3. Discussion

There are three well-marked minima in the summed probability distribution curves from the Iron Gates (**Fig. 2**) centred on 9.3 ka, 8.2 ka and 7.5 ka cal BP, respectively. The first of these ^{14}C discontinuities occurs at the boundary between the Early and Late Mesolithic (as defined by Bonsall, 2008), the second a century or so before the transition from the Mesolithic to the Neolithic, and the third during the Early Neolithic. Interestingly, **all three ^{14}C minima coincide with well defined RCC events recorded in Greenland ice cores (Mayewski et al., 2004; Rasmussen et al., 2007) and North Atlantic deep sea cores (Bond et al., 1997), which is suggestive of a correlation (Fig. 3). However, establishing a causal link between climatic events and archaeological phenomena requires a convincing mechanism for transmitting cause to effect (cf. Behrensmeier, 2006).**

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Comment [CB9]: cf. Referee comment #8

There are three well-marked ‘dips’ in the summed calibrated probability distribution curve (SCPDC) for the 15000–5000 cal BP time range in Iron Gates (Fig. 2), representing phases with relatively few ^{14}C dates. There is a rough coincidence between these reductions in ^{14}C date frequency and climate shifts recorded in proxies from Greenland (Mayewski et al., 2004; Rasmussen et al., 2007), the North Atlantic (Bond et al., 1997) and Europe (Fig. 3).

- (1) The dip in the SCPDC at 9500–9000 cal BP correlates fairly closely with the climate anomaly known as the ‘9.3 ka cold event’.
- (2) The major ^{14}C discontinuity at 8650–8000 cal BP corresponds roughly with the general climatic deterioration recognized by Rohling and Pälike (2005) between 8600 and 7950 BP, which culminated in a sudden cold event (‘8.2 ka event’) between c. 8175–8025 cal BP (Kobashi et al., 2007). Within this phase the lowest frequency of ^{14}C dates occurs between c. 8475 and 8100 cal BP.
- (3) The dip in the SCPDC immediately after 7800 cal BP is the prelude to a long lacuna in the ^{14}C record of the Iron Gates. The initial reduction in ^{14}C dates coincides with a significant decline in sea surface temperatures (SST) in the southern Adriatic between 7800 and 7500 cal BP. This was followed by a more pronounced SST cooling between 7300 and 6300 cal BP, which at its nadir was characterized by SSTs lower than those registered during the 8.2 ka event (Siani et al. 2013).

The broad similarity in timing between centennial scale climate anomalies and the ‘dips’ in our SCPDC for the Iron Gates (Fig. 3) is suggestive of a correlation. However, as Behrensmeier (2006) has cautioned, establishing a causal link between climatic events and archaeological phenomena requires a convincing mechanism for transmitting cause to effect.

One possibility is that climate-related changes in river conditions had a negative impact on fish stocks, diminishing the attractiveness of the Danube as a source of food.

Fish abundance and species variety in rivers can be profoundly affected by environmental stress. Spawning and feeding behaviour can be significantly affected by sudden and/or prolonged changes in water temperature. Spawning in salmonids and wels catfish (*Silurus glanis*) may be inhibited by sudden drops in water temperature; while catfish cease to feed at temperatures below c. 10 °C and growth is impeded (Omarov and Popova, 1985; David, 2006; Copp et al., 2009). Similarly, river icing and sudden or prolonged changes in flow conditions can impact on fish populations. Periods of high flow are an important trigger for sturgeon migrations and higher water levels allow fish to pass through river stretches containing rapids or shallows. Conversely, any reduction in river discharge during the period of migration diminishes the attractiveness of the river and the number of migrants.

‘Winterkill’ is a phenomenon known in many temperate zone rivers caused by ice and high water flows. Ice jams and high flows cause ‘scouring’ of the riverbed killing aquatic insects and destroying underwater plants, which are important sources of food for many fish. Even when the surface of the river does not freeze, ‘anchor ice’ can form on rocks under water and may kill fish eggs and aquatic insects. Many fish species lay their eggs in gravel on the riverbed and these can be destroyed when rocks and ice scour the bottom during high water flows and even young fish may be killed. There are occasional reports of migrating Beluga sturgeons being injured by large blocks of ice in the Danube (e.g. Heckel and Kner 1858). The severity of winterkill varies year by year. One ‘bad’ year is unlikely to have a significant impact on the fish

population of a river, but a succession of bad years **could interfere** with the reproduction of fish and lead to a sustained reduction in fish catches.

That said, we are not aware of any documentary evidence for prolonged major reductions in fish stocks or catches along the Danube and other major European rivers during the historical period, including the Little Ice Age, which can be unambiguously linked to climate change. However, in certain respects the Little Ice Age was atypical among Holocene RCC events. Some Early to Mid-Holocene ‘neoglacial’ episodes, especially the **8.2 ka event**, may have been more severe than the Little Ice Age. Moreover, the Little Ice Age coincided with a period of significant human intervention and beginnings of large-scale management of the Danube, which had an impact on fish stocks and migration as a consequence of infrastructure developments like bridges, flood defences and channelization. For example, fish and reproduction in the lower Austrian Danube were seriously affected following an ice jam and associated flooding in 1880 (Pözl, 1906), but it is not clear whether the ice jam and flood were responsible for the marked decline of the cyprinid, Common Nase (*Chondrostoma nasus*) after 1880, or if the flood protection measures that followed this hydrological event were the cause.

More research is needed into **climate change and impacts on fish species** distribution and productivity in the Danube. **For the time being, since no significant temporal fluctuations in the exploitation of fish resources are reflected in either the archaeofaunal or human bone stable isotope records prior to the appearance of agriculture c. 8100/8000 cal BP**, it seems unlikely that the discontinuities observed in the radiocarbon record of the Iron Gates Mesolithic–Early Neolithic **mirror** periods of decline in river fisheries and concomitant reductions in settlement intensity.

It is generally accepted that farming spread through the Balkans **between c. 8600 and 8000 cal BP**. Several authors have speculated that as the agricultural frontier approached the Danube, interaction with farmers could have disrupted the Mesolithic settlement–subsistence system in the Iron Gates (Tringham, 2000; Borić, 2011; see also Bonsall, 2008, p. 277). While this might explain the ¹⁴C discontinuity **centred on 8.3 ka cal BP**, it could not account for the reduction in the number of ¹⁴C ages around 9.3 ka cal BP; while the ¹⁴C discontinuity **commencing after 7.8 ka cal BP**, which appears to have marked a sharp decline in Early Neolithic occupation of the Iron Gates sites (Bonsall et al., 2002a; Bonsall, 2008), occurred several centuries after farming had been established in the region (there appears to have been only sporadic occupation of the Iron Gates sites between the later Neolithic and the late Pre-Roman Iron Age).

Climate-related changes in the magnitude and frequency of floods on the Danube, and the variability of flow regime, still seem the most likely explanation of the discontinuities in the Iron Gates ¹⁴C record, as proposed by Bonsall et al. (2002a).

In historical times floods have occurred regularly on the Danube in spring and early summer. The main causes are excessively heavy and/or prolonged rainfall and snowmelt from upland areas within the catchment. Another historically documented cause is the build-up and then sudden collapse of ice jams formed during the break-up of river ice – ice jam formation causes a rapid rise of the river level upstream of the jam, followed by sudden flooding downstream when the jam is released. Ice jams tend to recur at significant channel constrictions (Smith and Ward, 1998). Some of the biggest floods ever recorded on the Danube were associated with the ponding and/or release of water by ice jams (which were more prevalent during the Little Ice Age), including the catastrophic flood of 1838 that devastated large areas of Budapest.

Comment [CB10]: cf. Referee comment #9

River flow data from gauging stations along the Danube are available for the last 120–150 years. Over that time major floods occurred in at least 15 separate years. The 2002 flood was the result of intense and prolonged summer rainfall over the eastern Alps and the upper Danube catchment. Two periods of sustained rainfall several days apart generated successive flood waves that travelled down the Danube at rates of up to 74 km/day (Mihailova et al., 2012).

During the combined snowmelt and rainfall spring–summer flood of 2006 the Danube at the Orşova gauging station (inside the Iron Gates gorge) underwent stage changes of 6–7 m on several occasions between late January and mid-July. Stage changes were rapid (occurring within a few days) and high river flows were maintained for periods lasting up to six weeks (Mihailova et al., 2012, fig. 5c). More extreme variations in river discharge can perhaps be expected during Holocene RCC events (especially the **8.2 ka event**), given the evidence of major snowmelt and ice jam floods during the Little Ice Age.

In the area downstream of the Iron Gates I dam, which includes the important Late Mesolithic-Early Neolithic site of Schela Cladovei (V. Boroneanţ et al., 1999; Bonsall 2008; A. Boroneanţ and Bonsall, 2013), there is evidence for significant river incision since the Late Glacial. The 1:200,000 geological map of the area (Savu and Ghenea, 1967) shows a terrace at c. 7 m above the river, some 3 m higher than the present river flat on which the Schela Cladovei site is situated. This terrace was described as ‘Early Holocene’, but may be of Late Glacial age. Downcutting to the level of the Schela Cladovei site must have occurred before c. 9.2 ka cal BP – the earliest date for Mesolithic occupation of the site. Since Schela Cladovei is now c. 4 m above the river, further incision since the Mesolithic seems likely. This would imply that riverbed levels were higher before the **8.2 ka event**, with the consequence that floods during the early part of the Holocene likely extended higher up the Iron Gates gorge walls than in more recent periods. Equally, the height of the Schela Cladovei site relative to the Danube would have been less in the earlier Holocene than today, and the site more at risk from flooding.

These observations give some idea of the likely impact of very high river flows on Stone Age settlements in the Iron Gates. Within the Iron Gates gorge any site or zone within 10 m of the mean river level could have been at risk during extreme hydrological events, while a rise in the level of the Danube of 4 m or more would have inundated Schela Cladovei and some other sites in the downstream area. Moreover flood conditions may have persisted for weeks.

Borić and Miracle (2004, p. 362) questioned whether such extreme hydrological events were characteristic of the Iron Gates reach of the Danube before the historic period. However, the fact that Mesolithic and Early Neolithic remains at Schela Cladovei are associated with 1.5–2 m of fine alluvial sediments (Boroneanţ et al., 1999) is evidence of repeated overbank flooding during the Early to Mid-Holocene.

Various lines of evidence contradict this argument. At Schela Cladovei repeated overbank flooding during the early-mid Holocene is indicated by 1.5–2 m of alluvial deposits (Boroneanţ et al., 1999) and an associated luminescence date (Fuller et al., 1994); although soil development combined with anthropogenic disturbance has erased any original stratification in these deposits, blurring the stratigraphic relationships between flood events and human occupations. At Lepenski Vir poor archaeological survival (including a lack of datable organic remains) in lower lying parts of the site nearer the river may be attributable to scour (removal of material) during flood events. Remains of stone-lined hearths are evidence that buildings had once stood in this part of the site. Srejšević (1972, p. 53) observed that these hearths

Comment [CB11]: cf. Referee comment #10

differ from those set within plaster floors in higher parts of the site and assigned them to an earlier phase of the Mesolithic. Since the plaster-floored structures started to be built after 8300 cal BP (Bonsall et al., 2002a, 2008), it is possible they were deliberately sited in higher slope positions in response to an increase in flood magnitude and frequency.

The historically documented floods in the Iron Gates and lower Danube were caused by climatic events in the middle and upper reaches of the Danube and its major tributaries (Fig. 4). Knowledge of Holocene climatic variations in the upper-middle Danube catchment has developed significantly over the past 15 years. Various proxy indicators reflect climatic trends during the Early and Middle Holocene that mirror those seen in climatic archives from the North Atlantic region

- (1) episodes of cooler climate at 9.3–9.1 and c. 8.2 ka cal BP are indicated by O-isotope studies of speleothems from caves in Austria (Wurth et al., 2004; Boch et al., 2009) and northwest Romania (Tămaş et al., 2005),
- (2) negative O-isotope excursions indicative of cooling and increased precipitation are registered in sediment cores from Lake Ammersee in southern Germany at c. 9.2 ka and 8.2 ka cal BP (von Grafenstein et al., 1998, 1999),
- (3) vegetation responses to climatic cooling have been recorded in high altitude peat bogs and lake sediments in the Swiss Alps (Tinner and Lotter, 2001; Kofler et al., 2005) at 8.2 ka cal BP and in northwest Romania at 9.3 and 8.2 ka cal BP (Feurdean, 2005), and
- (4) research by Magny (2004) has documented 15 episodes of higher lake level in the Alps and Jura mountains reflecting increases in annual precipitation that were broadly synchronous with RCC events recorded in Greenland ice cores, including 9550–9150, 8300–8050 and 7550–7250 cal BP (Fig. 3).

From a pan-European study of climate proxy records, Magny et al. (2003) concluded that mid-latitude Europe between 43° and 50° N experienced significantly wetter (and cooler) conditions during the RCC events of the Holocene.

Rivers tend to be very sensitive indicators of short term and rapid climate change (Macklin et al., 2006, 2012) and a likely consequence of cooler conditions and increased precipitation over the upper Danube catchment during such as characterized the 9.3 and 8.2 ka events and the period after 7.8–7.5 ka cal BP RCC events would have been an increase in seasonal and/or annual discharges along the Danube and its major tributaries in Central Europe, upstream of the Iron Gates. Mathematical modelling has suggested that water discharge along the Danube and some of its major tributaries in Central Europe during the most recent RCC event of the Holocene, the Little Ice Age, was on average 10–15% higher than at present (McCarney-Castle et al., 2012).

Considering its size and importance in Europe, remarkably little work has been done on Holocene fluvial development and flood histories of the Danube and its tributaries. Research by Howard et al. (2004) and Macklin et al. (2011) along the Teleorman River in southern Romania, which flows into the Danube east of the Iron Gates, found no evidence of enhanced river activity corresponding to RCC events of the earlier Holocene between 11.6 and 5.8 ka cal BP. However, the Teleorman is a relatively small low-gradient catchment tributary of the lower Danube with very different hydro-climatic characteristics to the Danube catchment upstream of the Iron Gates.

A better proxy for hydrological patterns in the Danube catchment upstream of the Iron Gates is the behaviour of rivers draining the western Alps, where several studies

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have shown substantially increased discharges **around the time of** the 9.3 and 8.2 ka cal BP events (Miramont et al., 2000; Berger et al., 2002).

The Holocene flood history of the Danube catchment, and the Iron Gates in particular, represents a major gap **in knowledge** and should be viewed as a priority for future research. Potential sites for the preservation of extended Holocene flood records are likely to be found at the mouths of north and south bank tributaries in the Iron Gates gorge, as well as in channel-margin alcoves and caves where reduction in flow velocity and flow separations during flood events results in the deposition of fine grained sediments termed slackwater deposits (Baker, 1987). The study and dating of these fluvial sediments in bedrock gorges and canyons similar to the Iron Gates have allowed both the frequency and magnitude of Holocene flood events to be reconstructed in considerable detail (e.g. Ely et al., 1993). Extending over a length of more than 200 km, the Iron Gates reach of the Danube is likely to contain a diverse range of Holocene and possibly earlier palaeoflood records, but these have yet to be investigated.

In the foregoing discussion we have sought to explain the radiocarbon record of the Iron Gates Mesolithic–Early Neolithic primarily in terms of human agency, emphasizing the likely human responses to long-term fluctuations in magnitude and frequency of flooding on the Danube. However, taphonomic processes (e.g. destruction, movement and burial of artefacts by river processes, and archaeologists’ choices of sites for investigation and samples for dating) may also have contributed to the fluctuations in the radiocarbon time series for the Iron Gates. Overbank flows could have resulted in the removal of artefacts and ecofacts from occupation surfaces – charcoal, since it floats, would be particularly vulnerable – which then would not be available for dating. However, many of the ^{14}C -dated animal and human bones from the Iron Gates sites (cf. **Fig. 2**) were recovered from pit features (including graves) where they would have been relatively protected from river scour. Therefore, it seems unlikely that the c. 300-year gap in the radiocarbon record at Schela Cladovei (Bonsall et al., 2002a, Fig. 2), for example, was a consequence of removal of material from the site during flood events.

4. Conclusions

Holocene climate change and its effects on ancient human populations is a complex topic, which can be investigated at different geographical scales and with a variety of analytical techniques.

We used CalPal and IntCal04 to investigate temporal trends in the radiocarbon date series from the 230 km long Iron Gates reach of the Danube valley covering the time-range from the Late Glacial to the middle Holocene, c. 15,000–5000 cal BP. The resultant summed probability distribution curves show marked discontinuities (periods with reduced frequencies of ^{14}C dates) at c. **9.5–9.0 ka**, **8.75–8.0 ka** and after **7.8 ka** cal BP during the Mesolithic and Early Neolithic. These coincide with well-defined **anomalies** recorded in **palaeoclimate archives** from the North Atlantic region and the Danube catchment.

Changing frequencies of ^{14}C dates over time have tended to be used by archaeologists as a proxy for fluctuations in population size. In the case of the Iron Gates, however, we suggest that other factors have strongly influenced the temporal pattern. Our preferred explanation is that the ^{14}C discontinuities reflect **periods of** higher annual river discharge and an increase in flood magnitude during Holocene ‘neoglacial’ events, associated with generally cooler, wetter conditions in the Danube catchment upstream of the Iron Gates, and that the increased flood risk led to a

reduction in the intensity with which people used certain sites or the lower parts of sites bordering the river. River scour may also have reduced the archaeological visibility of 'neoglacial' periods by removing material from occupation surfaces. The Holocene flood history of the Danube catchment, and the Iron Gates in particular, is poorly understood and should be viewed as a priority for future research.

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FIGURE CAPTIONS

Fig. 1. Mesolithic and Early Neolithic sites in the Iron Gates. Virtually all sites along the main trunk of the Danube were located immediately adjacent to the river and would have been vulnerable (in whole or part) to inundation at times of unusually high river flows (4 m+ floods). Named sites have ^{14}C dates that were used to generate the summed probability distributions in Figs 2–3.

Comment [CB14]: NEW

Fig. 2. Cumulative calibrated dating probability of radiocarbon data from Mesolithic and Early Neolithic sites along the Danube main channel in the Iron Gates. Datasets: A – all usable radiometric and AMS dates; B – AMS dates on terrestrial and human bone samples; C – AMS dates on terrestrial animal and plant samples. Calibrations performed with *CalPal* (29 May 2007) [<http://www.calpal.de>] and the IntCal04 dataset. ^{14}C data from Bonsall, 2008; Bonsall et al., 1997, 2008, 2012, 2015, unpublished; Borić and Miracle, 2004; Borić and Dimitrijević, 2009; Borić, 2011; Borić and Price, 2013; Dinu et al., 2007. Prior to calibration human bone ^{14}C ages were corrected for the ‘freshwater reservoir effect’ using Method 1 of Cook et al. (2002), assuming $\delta^{15}\text{N}$ endpoint values for purely terrestrial and purely aquatic diets of +8.3‰ and +17.0‰, respectively (cf. Cook et al., 2009).

Comment [CB15]: REVISED plots incorporating new dates

Comment [CB16]: cf. Referee comment #1: unpublished data?

Fig. 3. Cumulative calibrated dating probability of radiocarbon data (terrestrial series) from Mesolithic and Early Neolithic sites along the Danube main channel in the Iron Gates, compared to climate proxy records from the North Atlantic and Europe 10,000–6000 cal BP. A – after Bond et al. (1997); B, D, F, G – smoothed records redrawn from Rohling and Pälike (2005); E – after Siani et al. (2013); C – horizontal bars represent cold phases recorded in $\delta^{18}\text{O}$ records from V11 Cave, NW Romania (Tămaş et al., 2005) and Katerloch Cave, Austria (Boch et al., 2009); vertical grey bars represent higher lake-level events in the Alps–Jura region (Magny, 2004).

Comment [CB17]: REVISED – with addition of Adriatic SST record.

Fig. 4. The Danube catchment showing the Iron Gates and key localities with climate proxy records for the Early to Middle Holocene: 1 – Hölloch Cave (Wurth et al., 2004); 2 – Katerloch Cave (Boch et al., 2009); 3 – V11 Cave (Tămaş et al., 2007); 4 – Lake Ammersee (von Grafenstein et al., 1998, 1999); 5 – Lake Schleinsee (Tinner and Lotter, 2001); 6 – Lake Soppensee (Tinner and Lotter, 2001); 7 – Brunnboden and Krummgampen peat bogs (Kofler et al., 2005); 8 – Preluca Tiganului and Steregoiu peat bogs (Feurdean, 2005); 9 – Alps–Jura lakes study region (Magny, 2004); 10 – Teleorman Valley (Macklin et al., 2011); 11 – Durance Valley (Miramont et al., 2001); 12 – Middle Rhône Valley (Berger et al., 2002).