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Correlation of fluvial sequences in the Mediterranean basin over the last 200 ka and their relationship to climate change

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Abstract

This paper presents a new correlation of Late and Middle Pleistocene fluvial sedimentary sequences in Greek, Libyan and Spanish river basins and evaluates river response to climate change over the Last Interglacial–Glacial Cycle. Over the past 200,000 years there have been at least 13 major alluviation episodes in the Mediterranean, although the amplitude, frequency and possibly, duration of these events varied significantly across the region. Parts of Oxygen Isotope Stage (OIS) 5 appears to have been periods of pronounced landscape change in many Mediterranean catchments with major river aggradation occurring at ~109–111 ka (during OIS 5d) and most notably at ~88 ka (OIS 5b/5a boundary). Other parts of OIS 5 appear to have been periods of relative fluvial inactivity. OIS 2 and 3 were both characterised by an apparent increase in the number of alluviation events, and this record of river behaviour parallels many other palaeoenvironmental records in the region which also show more frequent climate fluctuations between ~12 and 65 ka. There is evidence for a high degree of synchrony in major river aggradation events across the Mediterranean in catchments with very different sizes, tectonic regimes and histories. Climate-related changes in catchment hydrology and vegetation cover over the last 200 ka would appear to be the primary control of large-scale (catchment wide) sedimentation over time periods of between 10^3 and 10^4 years.

1. Introduction

More than 30 years have elapsed since the publication in 1969 of Claudio Vita-Finzi's now classic synthesis of Quaternary river development in the Mediterranean (Vita-Finzi, 1969). Yet this volume, and his 1976 paper (Vita-Finzi, 1976), remains as one of the very few attempts to systematically correlate Pleistocene fluvial sedimentary sequences in the region. This was primarily due, until relatively recently, to the difficulty of dating Pleistocene alluvial deposits older than the limit of the ^{14}C method. The 1990s, however, saw a significant increase in the number of geomorphological (e.g. Harvey et al., 1995), pedostratigraphic (e.g. Woodward et al., 1994) sedimentological (e.g. Lewin et al., 1991; Mather et al., 1995) and geochronological (e.g. Fuller et al., 1996) studies of Pleistocene alluvial sequences in southern Europe, particularly within mountain catchments that comprise much of the European part of the Mediterranean basin (e.g. Maas et al., 1998). Studies of Pleistocene alluvial geochronologies in particular were stimulated by the increasing, and successful, use of sediment-based luminescence techniques for dating fine-grained inorganic fluvial deposits. This has allowed, for the first time, Late and Middle Pleistocene river erosion and alluviation phases (Macklin et al., 1997; Fuller et al., 1998; Rose and Meng, 1999; Hamlin et al., 2000; Woodward et al., 2001) to be determined and then compared with moderate-resolution records of global climate change (Martinson et al., 1987) and high-resolution

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records of climate change that are now available for the North Atlantic region (e.g. Bond et al., 1993). What is beginning to emerge from these individual case studies is a general correspondence between Pleistocene river aggradation and periods of cooler climate, lower (total) precipitation and the development of steppe vegetation in the Mediterranean.

In this paper we present a new correlation of Late and Middle Pleistocene alluvial sequences in the Mediterranean basin, which is primarily based on very recently published research by the authors in Crete, northwest Greece, Libya, and in northeast and southeast Spain. The intention of this review is not to consider all published Pleistocene alluvial units in the Mediterranean, since earlier evaluations of these by Fuller (1995) and Maas (1998) have shown that before the early 1990s a reliance on artefacts and charcoal, of doubtful provenance for dating purposes, resulted in Pleistocene fluvial sedimentary sequences in the region being rather poorly dated. Instead we have carefully, and deliberately, selected river systems whose Late and Middle Pleistocene geomorphic development are relatively well understood, where investigations have been carried out in several reaches of a basin, and where independent dating control is available that does not use archaeological material in a secondary context or ^{14}C dates lying near to, or beyond, the age range of this technique. The purpose of this review is thus two-fold; first to construct a provisional correlation of Late and Middle Pleistocene phases of river alluviation in the Mediterranean, which can be tested and refined by later research, and second to evaluate river response to climate change in the region over the last 200,000 years.

2. Study catchments and alluvial geochronologies

Eleven catchments met our strict geomorphic and geochronological criteria for inclusion in the initial correlation exercise (Fig. 1, Table 1). River systems in the western and eastern parts of the Mediterranean basin are both represented, although there is an absence of securely dated Pleistocene fluvial sedimentary sequences within Italy and in the Mahgreb region of northern Africa. Nevertheless, in terms of drainage basin size, relief, geology and glacial history, these catchments do cover the full range of river environments found in the Mediterranean (Macklin et al., 1995) and these fall into four categories. First, the Rio Bergantes and the Rio Guadalope, northeast Spain, are the largest basins (drainage areas exceeding 1000 km^2) and both valleys have extensive flights of Pleistocene river terraces formed by episodic aggradation and quasi-continuous incision (Macklin and Passmore, 1995). The former was governed by climate-related increases in sediment delivery to trunk rivers and incision was partly a response to reduced sediment supply but also to long-term, uplift driven valley incision (Fuller et al., 1998). Second, the Voidomatis River, northwest Greece is a medium-size basin by Mediterranean standards (384 km^2) and, similar to many other mountain catchments draining the northern Mediterranean littoral (Macklin et al., 1995), its headwaters supported valley glaciers during the Late Pleistocene and probably in earlier periods (Lewin et al., 1991; Woodward et al., 1995). The third distinctive type of fluvial environment is alluvial fans, which in this paper are represented by small (<10 km^2) limestone catchments on the islands of Mallorca (Rose & Meng, 1999) and Crete (Maas et al., 1998), and along the northeastern Libyan coast (Rowan et al., 2000). Alluvial fan sequences at these sites are typical of those found throughout the Mediterranean at the margins of upland and mountain areas. Steep, bedrock confined mountain rivers form the fourth major type of fluvial geomorphic setting in the Mediterranean and the Aradena, Rapanas and Samaria gorges in southwest Crete (Maas, 1998; Maas and Macklin, in press) are some of the most spectacular examples in the region. There is no evidence that river activity in any of these 11 catchments has been affected by sea-level change over the time period considered in this review.

Dating control for all Pleistocene alluvial units, with the exception of AMS ^{14}C dates on charcoal found within fine-grained slackwater deposits in the Voidomatis River (Woodward et al., 2001), has been provided either by luminescence or uranium-series techniques. All reported dates, when taken together as part of successions or sequences, gave ages that were stratigraphically consistent; demonstrated either by superposition (in the case of vertically stacked sedimentary units) or morphostratigraphical relationships (alluviation phase separated by periods of river incision). One of the advantages of luminescence dating in an alluvial context is that it can directly give the age of a depositional event, but it is important to appreciate that effective zeroing of the luminescence signal in fluvial material has been shown to be problematic in some alluvial environments (e.g. Fuller et al., 1994; López-Avilés et al., 1998). In the Mediterranean, however, with high light levels this appears to have been less of a constraint than in other areas of Europe (e.g. Maddy et al., 1998), with probably most zeroing occurring while sediment and soil material was stored on hillslopes prior to sediment transport. Indeed, very effective bleaching would be expected to have occurred under cold and dry climatic conditions on slopes with limited vegetation cover.

In contrast to luminescence techniques, uranium-series dating of syn- or post-depositional $CaCO_3$ cements, or calcretes, provides a minimum age for a fluvial depositional event. The formation of calcretes has been shown to be governed by climate with carbonate deposition occurring under warmer or wetter conditions

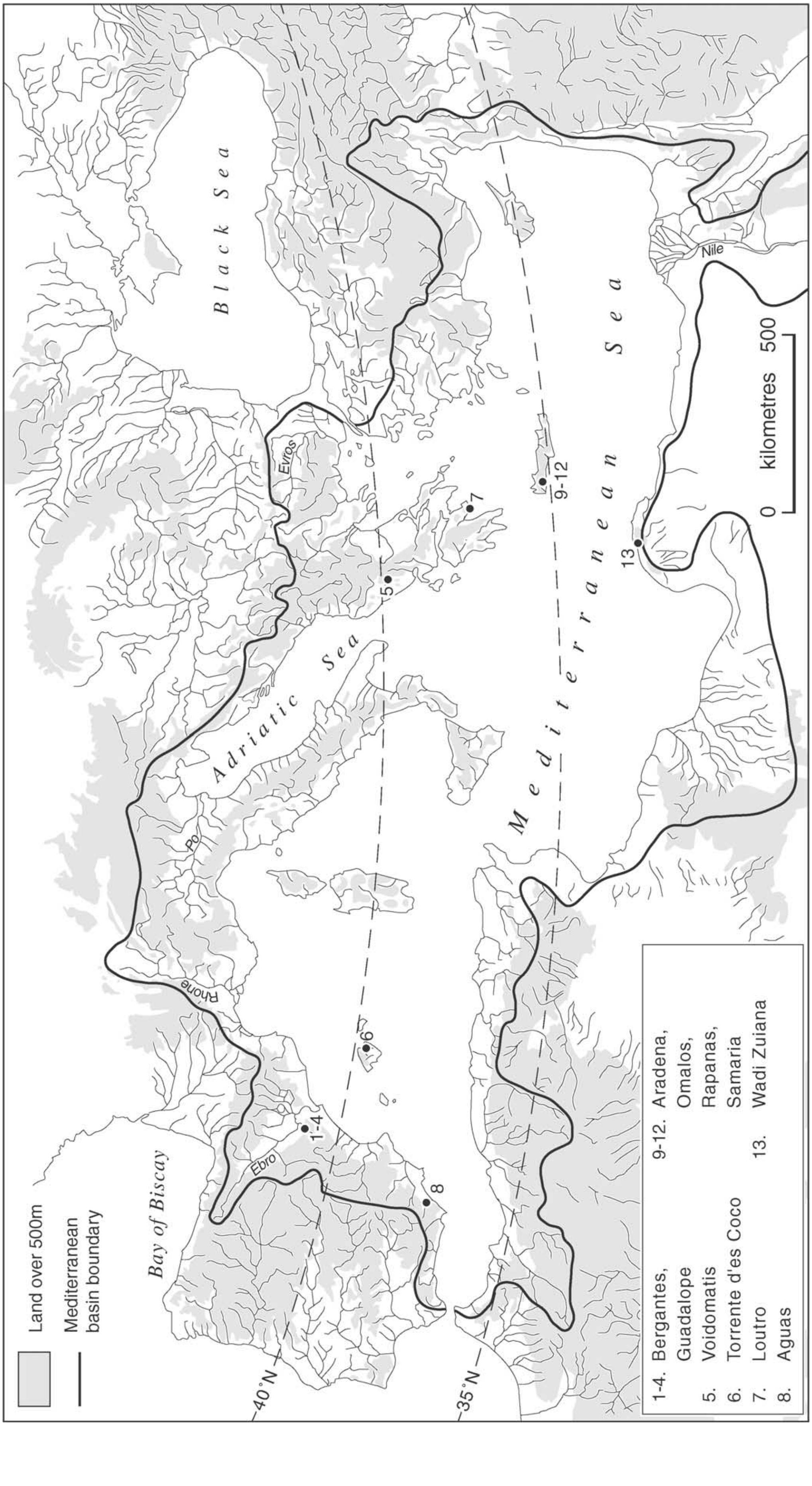

Fig. 1. Locations of Mediterranean river basins included in this review.

Table 1
Location and catchment characteristics of river systems included in this review

River basin	Latitude longitude	Basin area (km^2)	Relative basin relief at study reach (m)	Main basin lithologies	Present climate	Glaciated/non-glaciated
Guadalope, Spain	41°00 N 0°10 W	3500	1600	Sandstone/limestone/marl/conglomerate	Semi-arid	Non-glaciated
Guadalope, Spain	40°50 N 0°15 W	2500	1540	Sandstone/limestone/marl/conglomerate	Semi-arid	Non-glaciated
Bergantes, Spain	40°45 N 0°12 W	1200	1490	Sandstone/limestone/marls/conglomerate	Semi-arid	Non-glaciated
Bergantes, Spain	40°40 N 0°12 W	780	1240	Sandstone/limestone/marl/conglomerate	Semi-arid	Non-glaciated
Voidomatis, Greece	40°00 N 21°00 E	384	1950	Limestone/flysch	Humid	Glaciated
Torrente d'es Coco, Spain	39°40 N 03°19 E	3	400	Limestone/shale	Semi-arid/arid	Non-glaciated
Loutro basin, Greece	37°25 N 23°10 E	<10	<1000	Limestone/sandstone/ultrabasic	Semi-arid	Non-glaciated
Rio Aguas, Spain	37°10 N 1°52 W	1250	<500	Gypsum, sandstone, limestone, conglomerate, marl	Semi-arid	Non-glaciated
Omalos, Greece	35°19 N 23°54 E	7	974	Limestone	Semi-arid	Non-glaciated
Samaria, Greece	35°17 N 23°58 E	49	2133	Limestone	Semi-arid	Non-glaciated
Rapanas, Greece	35°15 N 23°36 E	21	1018	Phyllite/quartzite	Semi-arid	Non-glaciated
Aradena, Greece	35°13 N 24°04 E	31	2453	Limestone	Semi-arid	Non-glaciated
Wadi Zewana, Libya	32°30 N 22°00 E	10	800	Limestone	Arid	Non-glaciated

(Kelly et al., 2000). Thus uranium-series techniques, in a fluvial context, cannot provide dating control for the entire Late and Middle Pleistocene. Nevertheless, when they are used in conjunction with luminescence dating techniques there is the potential of tightly bracketing the age of an alluvial unit.

3. Towards a geochronology of river alluviation in the Mediterranean over the past 200,000 years

In Fig. 2 the ages (ka) and confidence intervals (2 sigma) of dated alluvial units are plotted for each catchment in latitudinal sequence from the northern to southern part of the Mediterranean basin. Oxygen Isotope Stages (OIS) (after Martinson et al., 1987) are also shown together with the timing of major Heinrich events (H0–H6) in the North Atlantic (Bond et al., 1993, 1997). It is immediately clear that both the number of alluvial units, and the precision to which they are dated, decrease significantly prior to the OIS 5e/6 boundary. However, when the mid-point (most likely) ages of alluviation phases in different river basins are compared, and then related to the moderate- and high-resolution continental and marine palaeoclimatic records now available for the North Atlantic and the Mediterranean region (e.g. Allen et al., 1999; Bard et al., 2000), a number of critical relationships emerge. These are discussed in detail below.

3.1. Oxygen Isotope Stage 6

In northeast Spain (Fuller et al., 1998) and northeast Libya (Rowan et al., 2000), two aggradation events can be identified within OIS 6 centred on ~138–157 and 179–183 ka. Both events correspond to particularly strong sea surface cooling episodes in the Eastern Mediterranean basin identified by Kallel et al. (2000), which on the basis of recent data from the extended Vostok ice core record in Antarctica (Petit et al., 1999), would appear to reflect periods of significant global cooling. It is noteworthy that in the Sorbas Basin, southeast Spain, gravel aggradation also occurred in OIS 6 (Kelly et al., 2000). If, as has been suggested, the main periods of groundwater-related calcrete formation are quite narrowly restricted in time (Kelly et al., 2000), the aggradation event in the Sorbas catchment may be equivalent to the younger OIS 6 alluviation phases (~138–157 ka) recognised further north in the Ebro basin and along the coast of Cyrenaica, Northwest Libya.

3.2. Oxygen Isotope Stage 5

No alluvial units have been dated to the early part of the classic interglacial substage (5e), which appears, on

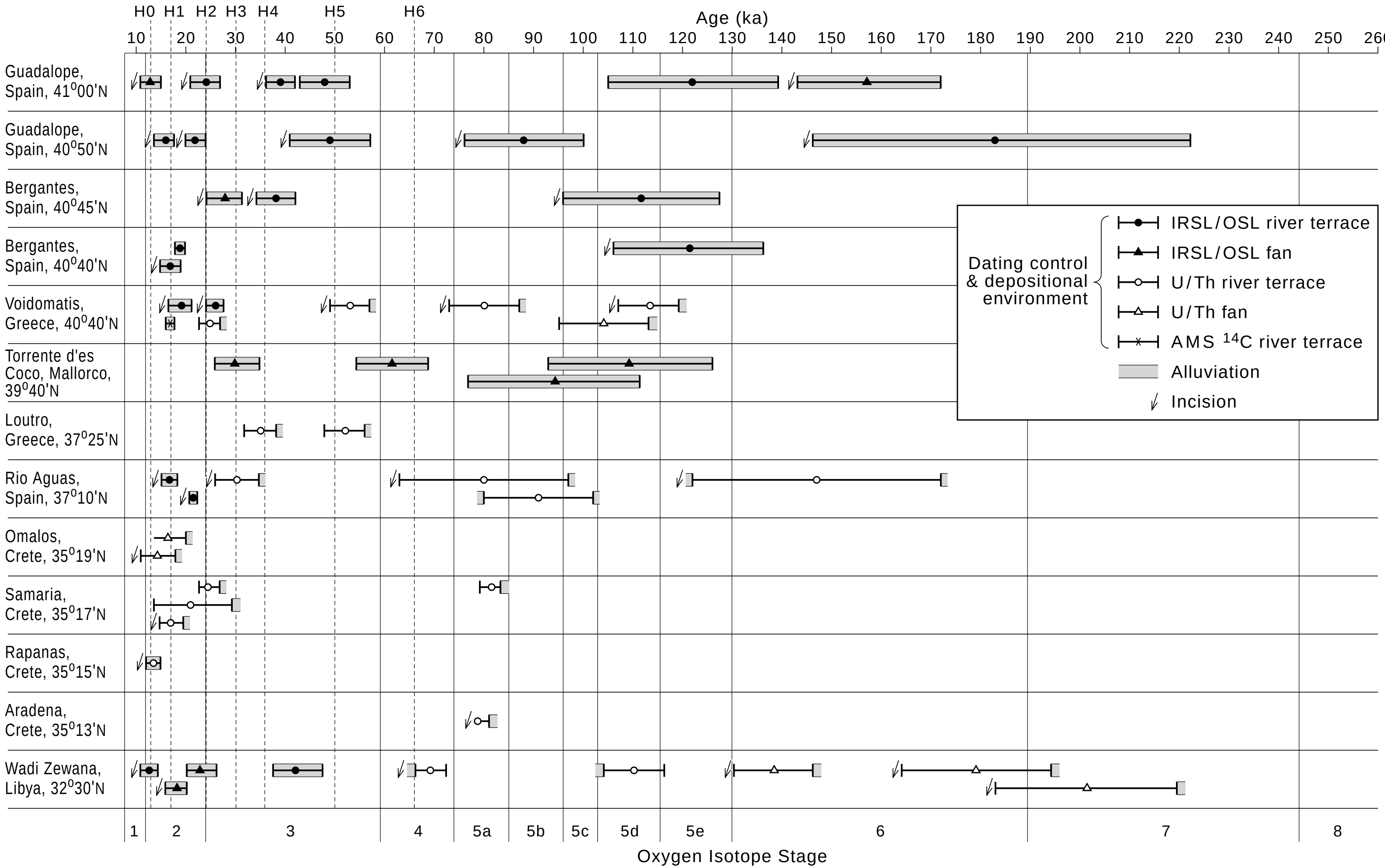

Fig. 2. Latitudinal plot of dated Late and Middle Pleistocene alluvial units in Greek, Libyan and Spanish river basins.

the basis of catchments included in this review, to have been a period of valley floor incision in the Mediterranean with soil development on stable terrace surfaces (Rose and Meng, 1999; Rose et al., 1999). At ~121–122 ka, however, gravel aggradation began in the Guadalope basin. Although there is at present limited evidence for alluvial sedimentation at this time in catchments further south than the Ebro, in the Voidomatis basin of northwest Greece (which lies at the same latitude as the headwaters of the Guadalope) there is evidence of trunk stream aggradation around this time that ended by ~113 ka, and possibly as early as 119 ka. Both marine and continental palaeoclimatic records indicate a cold and dry climate event in the middle of the Eemian at ~122 ka, which was characterised by a change in the circulation of the North Atlantic, a several-degree decline in the Nordic and Atlantic sea-surface temperatures, and an opening up of the west European forests to a mixture of steppe and trees (Maslin and Tzedakis, 1996; Adams et al., 1999). The correspondence between significant river aggradation in the northern part of the Mediterranean at ~119–122 ka and the intra-Eemian cold event would seem to be compelling, although there is no evidence at other localities such as the northwest part of Mallorca despite a record of cooling preserved in the oxygen isotope signature measured from soil cement. Indeed, parallels may be drawn with the present interglacial (the Holocene) as climatic deteriorations such as the Little Ice Age, were characterised by widespread river channel change and valley floor sedimentation in many sensitive fluvial systems such as high relief Mediterranean catchments (Fuller et al., 1998; López-Avilés et al., 1998; Maas et al., 1998).

The earliest Late Pleistocene alluviation event that is recorded in both the northern and southern Mediterranean occurred at ~109–111 ka. This coincides with the well documented, and globally significant, cooling event in OIS 5d, which shows up in the pollen record across Eurasia (Adams et al., 1999) and in the Tyrrhenian Sea surface temperature records at ~112 ka (Kallel et al., 2000). In terms of the fluvial sedimentary record, however, the 109–111 ka alluviation event was not as geomorphologically significant, or as geographically widespread, as the period of fluvial deposition that occurred around the OIS 5b/5a boundary. Taking mid-point ages for this latter event, luminescence dates indicate that it may have begun as early as ~94 ka (Torrenta d'es Coco, Mallorca), though uranium-series dates show it had ended well before 78 ka (Aradena, Crete); however, most cluster around 88 ka. High-resolution pollen records from Lago Grande di Monticchio, southern Italy show a period of very rapid cooling at, or shortly before, ~87 ka with the sudden replacement of mixed forest communities with cold steppe species and accelerated catchment erosion and lake sedimentation (Allen et al., 1999). This is also represented in the GISP2 record by a decrease in $\delta^{18}O$ values between interstadials 22–21 (Grootes et al., 1993), an increase in the relative abundance of *Neogloboquadrina pachyderma* (s.) for North Atlantic core DSDP—609 (Bond et al., 1992) and a sea surface temperature cooling in the Tyrrhenian Sea at ~87 ka (Kallel et al., 2000). The continental and marine proxy climate records and the alluvial archive presented here indicate a closely coupled Northern Hemisphere ocean-atmosphere system, which extended its influence beyond the North Atlantic and Greenland into the Mediterranean basin.

3.3. Oxygen Isotope Stage 4

Only two alluvial units from the catchments included in this review have been unequivocally dated to OIS 4. These are from Wadi Zewana, northeast Libya (69 ± 3 ka) and Torrente d'es Coco, Mallorca (61.5 ± 7.3 ka). Sedimentation in the Voidomatis and Loutro basins, Greece (Pope and van Andel, 1984), sometime before 53 ± 4 and 52 ± 3 ka, respectively, may correlate with either one, or both, of the alluviation phases recognised in Libya and Mallorca, which could equate with stadials identified at Lago Grande di Monticchio, Italy at ~69–72 and 60.5–63.5 ka (Allen et al., 1999). But confidence intervals on the alluvial unit dates overlap, and they may equally represent a single depositional phase related to Heinrich event 6 at ~66 ka (Bond et al., 1993). It is unclear at present whether the small number of alluvial units in OIS 4 reflects formation or preservation factors. Although it is interesting to note that alluviation is evident only in some of the smallest drainage basins ($<10\,km^2$) and possibly those affected by glaciation (e.g. Voidomatis), probably reflecting sensitivity levels and response rates of fluvial/slope processes to climate change. Regional temperature and moisture reconstructions from both Mallorca (Rose et al., 1999) and Italy (Allen et al., 1999) show that this was a cool and especially dry period. Limited hillslope—river channel coupling and sediment delivery to trunk rivers could account for the relatively small number of alluvial units dated to this period, although removal by later river erosion is an equally possible explanation.

3.4. Oxygen Isotope Stages 3 and 2

Two phases of fluvial sedimentation can be identified in the first half of OIS 3. The older of these events, which appears to be represented only in the most northern part of the Mediterranean, is dated to between $\sim48\pm5$ and 49 ± 8 ka. The later alluviation phase beginning at ~38–39 ka and ending sometime before 30.3 ka (though possibly as early as 34.7 ka) is recorded in both mainland Spain and Greece. In the Wadi Zewana

(Libya) alluviation at 42.4 ± 5.1 ka falls between these two periods, but given the confidence interval of this date, it is possible that it is the equivalent of either one of these alluvial units. Vegetation change at Monticchio (Italy), however, does record 3 stadials characterised by steppe biomes, at ~50–54, 40–42.5 and 36.5–37.5 ka (Allen et al., 1999), which correspond quite closely with all three alluviation phases identified here. The oldest and youngest of these coinciding with Heinrich events 5 and 4, respectively.

From around 30 ka until the beginning of the Holocene at ~11.5 ka, a clear and highly consistent picture of river activity is evident across the Mediterranean basin. In the light of a very recently published high-resolution marine sediment core from the Iberian margin (Bard et al., 2000), which demonstrates that this mid-latitude area was strongly affected both by cooling and advection of low-salinity Arctic water masses during the last 3 Heinrich events, fluvial sedimentation in the region can be correlated with some confidence to climate change. Three or possibly four (in the case of northeast Spain and Mallorca) alluviation events are recorded with each centred on ~28 ± 4–30 ± 4.7, 21 ± 0.8–26 ± 2, 16 ± 3–19 ± 1 and 12.5 ± 1.5–13 ± 2 ka. The earliest of these is represented by alluvial fan deposition in the Guadalope basin and in the Torrente d'es Coco, Mallorca, and may have formed during Heinrich event 3 (30.1 ka) or perhaps a little later during a relatively brief period of sea surface cooling in the subtropical northeast Atlantic at ~29 ka (Bard et al., 2000). The three subsequent alluviation phases correspond very closely with abrupt decreases in sea surface temperature in the northeast Atlantic between 23–26, 15.5–18 (Schulte et al., 2000) and 11.5–13 ka. This provides the most compelling evidence so far that rapid and high frequency climate change in the North Atlantic during the Last Glacial period had a profound effect not only on the vegetation of the Mediterranean region, but also on catchment erosion and river alluviation.

4. Conclusions and future research priorities

Luminescence and uranium-series geochronologies of fluvial sedimentary sequences from Greece, Libya and Spain permit for the first time robust regional correlations to be made between Late and Middle Pleistocene Mediterranean river terraces. Improvements in dating precision, and the capability to date alluvial units over the last 200,000 years, mean that phases of fluvial deposition can now be related to moderate- and high-resolution climate records in a way that would not have been conceivable even 10 years ago. What emerges from this new analysis is that Late Pleistocene river alluviation phases generally occurred during cool, dry stadials when steppe vegetation replaced forest or wooded steppe biomes. Over the past 200,000 years there have been at least 13 major alluviation episodes in the Mediterranean, although the amplitude, frequency and possibly, duration of these events varied significantly across the region. Parts of OIS 5 appear to have been periods of pronounced landscape change in many Mediterranean catchments with major river aggradation occurring at ~109–111 ka (during OIS 5d) and most notably at ~88 ka (OIS 5b/5a boundary). This is in marked contrast to western and central Europe where OIS 5d and 5b deposits are rarely reported or are limited in extent, and even fewer have been dated (Mol et al., 2000). The early part of OIS 5e appears to have been a period of stable land surfaces, dense vegetation cover and, where changes are recorded, fluvial incision. There are traces of aggradation in OIS 4, which appears to have been a period of intense cold and aridity a small number of sites. OIS 2 and 3 were both characterised by an apparent increase in the number of alluviation events and this record of river behaviour parallels many other palaeoenvironmental records in the region, which also show more frequent climate fluctuations between ~12 and 65 ka (Allen et al., 1999). In northern Europe, however, river behaviour during OIS 4–2 can at present only be correlated with moderate-resolution records of global change (e.g. Maddy et al., 1998; Mol et al., 2000) and, with the exception of the Lateglacial period (Rose et al., 1980; Vandenberghe et al., 1994), cannot be related with any precision to rapid environmental change in the North Atlantic region as documented in ice core and marine records.

This apparent sensitivity of Mediterranean river basins to Pleistocene climate change may be conditioned by a number of factors. First, catchments draining to the northern Mediterranean littoral during the Late Pleistocene lay close to the forest/steppe ecotone with northwest Spain, parts of Italy and the western Balkans (Turner and Hannon, 1988) being important refuge areas for thermophilous tree taxa. A relatively small change in climate within these areas would have large effect on slope vegetation and thus on slope stability and runoff response. This may account for widespread and large-scale river aggradation that occurred in many Mediterranean basins during OIS 5d and particularly at the OIS 5a/5b boundary, compared to the relatively subdued response of northern European river systems. Secondly, high relief steepland Mediterranean catchments have good slope-channel coupling and a ready supply of coarse bed material, which, in those river basins considered in this review, forms nearly the entire Pleistocene alluvial fill. This contrast with lowland river systems in northern and western Europe where sediment availability constraints and less effective coupling between hillslopes and channels combine to make them less responsive to climate change. The variable effects of glaciation and tectonics on the preservation of fluvial sedimentary sequences are also likely to be very important. Large-scale glaciation in northern Europe during OIS 2 appears to have removed much of the earlier Late Pleistocene alluvial record in formerly ice-covered areas. In the Mediterranean only mountain headwaters above ~ 1000 m were glaciated (Woodward et al., in press). Higher rates of crustal uplift in the Mediterranean have also played a key role in the creation of a high-resolution record of river response to Late Pleistocene climate change through valley incision and the formation of well-developed river terraces. However, one of the most important findings of this study is evidence for a high degree of synchrony in major river aggradation events across the Mediterranean in catchments with very different tectonic regimes and histories. Climate-related changes in catchment hydrology and vegetation cover, at least over the last 200 ka, would therefore appear to be the primary control of large-scale (catchment wide) sedimentation over time periods of between 10^3 and 10^4 years. This is not to downplay the very strong influence that tectonics and geological structure have on catchment morphology, drainage network development and pattern of reach scale erosion and sedimentation (e.g. Harvey and Wells, 1987), but to highlight the fact that these factors have engendered river systems in the region with a high degree of sensitivity to climate change and at the same time created conditions favourable for the preservation of temporally extended and relatively complete alluvial geoarchives.

Two priorities for future research are highlighted by this re-examination, first, there is a need to extend the geographical coverage of fluvial investigations to include important areas such as Italy, Turkey and North Africa and second, to carry out multiple dating assays of individual aggradation events. In this context, it is worth pointing out that this review, although the first of its kind for over 30 years includes only 54 securely dated alluvial units. Many of these rely on a single date, so the length of time over which deposition occurred cannot be determined. Moreover, most published dates relate to trunk river alluvial sedimentary sequences and the timing of sediment delivery from hillslopes and tributary streams, resulting from rapid environmental change has not been investigated. This information is critical if process-form relationships of the fluvial system, as it responds to climate and catchment land cover changes, are to be fully documented and modelled. Thus, while a much clearer picture of the broad phasing of Late and Middle Pleistocene river development in the Mediterranean basin is beginning to emerge, a much greater challenge will be to document the geomorphic effects of individual periods of rapid climate change. The key to establishing correct cause and effect relationships in this context will be adequate dating control of Pleistocene fluvial sequences of sufficient temporal and spatial resolution to match ice core and marine proxy climate records now available for the North Atlantic.

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