Quaternary Science Reviews 94 (2014) 28–43

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Glaciers and rivers: Pleistocene uncoupling in a Mediterranean mountain karst

K.R. Adamson [a,b,*], J.C. Woodward [c], P.D. Hughes [c]

[a] School of Geography, Queen Mary, University of London, Mile End Road, London E1 4NS, UK
[b] Geography, School of Science and the Environment, Manchester Metropolitan University, Manchester M1 5GD, UK
[c] Quaternary Environments and Geoarchaeology Research Group, Geography, School of, Environment, Education and Development, The University of Manchester, Manchester M13 9PL, UK

A R T I C L E I N F O

Article history:
Received 28 October 2013
Received in revised form
9 April 2014
Accepted 16 April 2014
Available online 10 May 2014

Keywords:
Pleistocene
Mediterranean
Karst
Coupling
Glacial
Fluvial
Outwash

A B S T R A C T

Large-scale coupling between headwater catchments and downstream depocentres is a critical influence on long-term fluvial system behaviour and on the creation of the fluvial sedimentary record. However, it is often difficult to examine this control over multiple Quaternary glacial cycles and it has not been fully explored in karst basins. By investigating the Pleistocene glacial and fluvial records on and around Mount Orjen (1894 m) in Montenegro, we show how the changing connectivity between glaciated mountain headwater source zones and downstream alluvial basins is a key feature of long-term karst system behaviour – especially in relation to the creation and preservation of the surface sedimentary record. Middle and Late Pleistocene glacial deposits are well preserved on Mount Orjen. Uranium-series dating of 27 carbonate cements in fluvial sediments shows that many alluvial depocentres were completely filled with coarse glacial outwash before 350 ka during the largest recorded glaciation. This major glaciation is correlated with the Skamnellian Stage in Greece and Marine Isotope Stage 12 (MIS 12, c 480–420 ka). This was a period of profound landscape change in many glaciated catchments on the Balkan Peninsula. Later glaciations were much less extensive and sediment supply to fluvial systems was much diminished. The extreme base level falls of the Late Miocene produced the world's deepest karst networks around the Mediterranean. After MIS 12, the subterranean karst of Mount Orjen formed the dominant pathway for meltwater and sediment transfer so that the depositional basins below 1000 m became disconnected (uncoupled) from the glaciated headwaters. There is little evidence of post-MIS 12 aggradation or incision in these basins. This absence of later Pleistocene and Holocene fluvial activity means these basins contain some of the thickest and best-preserved outwash deposits in the Mediterranean.

1. Introduction

Pleistocene glaciation of the Mediterranean mountains was first recognised over a century ago (Cvijić, 1898, 1900), but it is only in the last few decades that systematic mapping and radiometric dating have begun to reveal the complexity of this record (Woodward et al., 2004; Hughes and Woodward, 2009). It is now well established that ice caps and glaciers varied greatly in size between the cold stages of the Middle and Late Pleistocene (Hughes et al., 2006a, 2010; Lewis et al., 2009; Calvet et al., 2011). Glacial sediments and landforms are especially well preserved in the limestone uplands of southern Europe. In the Pindus Mountains of Greece and the Dinaric Alps of Montenegro, we have evidence for at least four phases of glaciation: each has been dated by uranium-series (U-series) methods ($n = 59$ dates) (Woodward et al., 2004; Hughes et al., 2006a,b, 2010, 2011). These glaciations were successively smaller and occurred during three cold stages: the Skamnellian, Vlasian and Tymphian Stages. Hughes et al. (2005, 2006a) used a continuous parastratotype at Lake Ioannina in Greece to correlate these cold stages with Marine Isotope Stages (MIS) 12; 6; 5d-2, respectively. The final episode of Pleistocene glaciation took place at the end of the Tymphian Stage and is correlated with the Younger Dryas (Hughes et al., 2006b). This was marked by a climatic deterioration across Europe (12.9–11.7 cal ka BP; defined as a chronozone spanning the interval 11–10 ^{14}C ka BP by Mangerud and Donner, 1974).

* Corresponding author. School of Geography, Queen Mary, University of London, Mile End Road, London, E1 4NS, UK. Tel.: +44 (0)20 8772 6170.
E-mail addresses: k.adamson@qmul.ac.uk, k.adamson@mmu.ac.uk (K.R. Adamson).

http://dx.doi.org/10.1016/j.quascirev.2014.04.016
0277-3791/

A key objective is to establish the impact of past glacial activity on Pleistocene river basin processes across the Mediterranean, from the mountains to the coastal zone. The Pleistocene alluvial record in the glaciated catchments of the Mediterranean can form an indirect record of headwater glacial history (Lewin et al., 1991; Woodward et al., 2008). We can investigate this record to explore changes in the long-term transfer, or coupling (Harvey, 2002), between the sources of glacial outwash and river depositional settings downstream. Previous attempts to explore these interactions, over several glacial–interglacial cycles, have been hampered by limited dating control for the glacial record (Conchon, 1978; Woodward et al., 1995; Smith et al., 1997) and by limited preservation of Middle Pleistocene fluvial deposits in many river basins (Macklin et al., 2002; Macklin and Woodward, 2009, Table 1).

There is also a need to consider the role of the karst system as both conduit and store for meltwater and glaciofluvial sediment (Bočić et al., 2012). This is particularly important given that limestone karst dominates many glaciated catchments across the northern Mediterranean and in other parts of the world (e.g. Kiernan et al., 2001; Burger, 2004; Ford and Williams, 2007; Lewin and Woodward, 2009; Colhoun et al., 2010). Our understanding of glacial and fluvial system interactions within karst landscapes is currently limited (Colhoun et al., 2010). The Mediterranean is a distinctive setting in which to explore the role of karst systems on glacial–fluvial dynamics due to the extreme base level falls (>1500 m) associated with the Messinian Salinity Crisis (MSC). The MSC was a period of near complete desiccation of the Mediterranean Sea during the Late Miocene (c 5.96–5.33 Ma), when dramatic falls in regional base level produced some of the world's deepest karst drainage networks (Mocochain et al., 2006). A key aim is to examine long-term patterns of fluvial sedimentation as the boundary conditions for river basin processes (e.g. the extent of glaciation and volume of outwash) shifted over several glacial–interglacial cycles. To this end we have investigated the Pleistocene sedimentary records in a suite of alluvial depositional settings in the karst landscapes flanking Mount Orjen on the Adriatic coast of Montenegro (Fig. 1).

2. Mount Orjen Karst and the glacial record

Orjen (1894 m) comprises several peaks on a large upland limestone karst plateau (>1000 m a.s.l.) bounded by steep slopes and a radial network of poljes, valleys, and fans. The plateau has well-developed karst topography with extensive pavements, dolines, and sinkholes, which are characteristic of the classic karst landscapes within glaciated basins across Montenegro (Hughes et al., 2011; Stepišnik and Žebre, 2011) and elsewhere in the Mediterranean uplands (Gams, 1969, 1978, 2005; Lewin and Woodward, 2009; Telbisz, 2010a, b; Woodward and Hughes, 2011; Bočić et al., 2012). The area contains a well-developed network of caverns and deep subterranean passages (Stepišnik et al., 2009). Runoff from Orjen is dominated by subterranean karst flows, many of which discharge via submarine springs in the Bay of Kotor and the Adriatic Sea (Bortoluzzi et al., 2009). Some have been mapped by speleologists (Tisserant, 1974; Groupe Spéléologique Muséum National d'Histoire Naturelle, Paris, 2003), but little scientific exploration has taken place.

This part of the Balkans is one of the wettest places in Europe (Magaš, 2002; Ducić et al., 2012). Over the period 1961–1990 the meteorological station at Crkvice (937 m a.s.l.) recorded a precipitation average of 4593 mm (Ducić et al., 2012). The value is likely to be substantially higher (>5000 mm) in the nearby mountains, which reach 1894 m a.s.l. Large ice caps formed on Mount Orjen during the Middle and Late Pleistocene. There is well-preserved evidence of at least four glacial phases. These have been U-series dated ($n = 12$) and correlated to the Skamnellian Stage (MIS 12), Vlasian Stage (MIS 6), Tymphian Stage (MIS 5d-2), and the Younger Dryas (Hughes et al., 2010). The extent and thickness of these ice masses decreased significantly during the course of the Middle and Late Pleistocene (Fig. 1). During the Skamnellian Stage (MIS 12) a large ice cap covered the plateau and the highest peaks, and ice lobes extended into the valleys and poljes below 1000 m. The excellent preservation of the moraines makes an older age unlikely. Large glaciers also formed during the Vlasian Stage (MIS 6), but did not extend beyond the 1000 m contour (Fig. 1). The glaciers of the

Table 1
Examples of dated Early to Middle Pleistocene alluvial sequences in the Mediterranean.

Location	Author	Dating method	Age	MIS
Rio Aguas, southeast Spain	Candy et al. (2004)	U-Series	155 ± 9 ka	6
			207 ± 11 ka	7
	Schulte et al. (2008)	U-Series	148 ± 8 ka	6
			167 ± 7 ka	12
			169 ± 9 ka	
			>350 ka	
Guadalope, northeast Spain	Fuller et al. (1998)	IRSL	157 ± 15 ka	6
			122 ± 17 ka	
			188 ± 39 ka	
			130 ± 15 ka	
Cinca and Gallego rivers, northeast Spain	Peña et al. (2004a, 2004b)	OSL	148 ± 7 ka–156 ± 22 ka	6
			176 ± 14 ka	
			177 ± 22 ka	
			180 ± 12 ka	
	Lewis et al. (2009)	OSL	134 ± 9 ka	6
			155 ± 24 ka	
			156 ± 10 ka	
			171 ± 22 ka	
			180 ± 12 ka	
Antas and Almanzora rivers, southeast Spain	Hoffmann (1988)	ESR	421–505 ka	12
	Wenzens (1992)		1.4–1.7 Ma	45–58
			2.4 Ma	94
Gediz River Basin, western Turkey	Maddy et al. (2012)	K–Ar	1.26–1 Ma	38–28
River Tigris, southeast Turkey	Bridgland et al. (2007)	K–Ar	1.20 ± 0.02 Ma 1.31 ± 0.06 Ma	36
Wadi Zewana, northeast Libya	Rowan et al. (2000)	U-series	140 ± 10 ka	6
			179 ± 14 ka	7
			201 ± 19 ka	