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Uplift and active tectonics of southern Albania inferred from incision of alluvial terraces

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ABSTRACT

In Albania, the Osum and Vjoje rivers cross the active graben system and the active frontal thrust system of the Albanides. The effects of climatic and geodynamic forcing on the development of these two rivers were investigated by the means of field mapping, topographic surveying and absolute exposure-age dating. We established the chronology of terraces abandonment from the compilation of new dating (^{14}C and *in situ* produced ^{10}Be) and previously published data. We identified nine fluvial terraces units developed since Marine Isotope Stage 6 up to historic times. From this reconstituted history, we quantified the vertical uplift on a time scale shorter than the glacial climatic cycle. Regional bulging produces an overall increase of the incision rate from the west to the east that reaches a maximum value of 2.8 m/ka in the hinterland. Local pulses of incision are generated by activation of normal faults. The most active faults have a SW–NE trend and a vertical slip rate ranging from 1.8 to 2.2 m/ka. This study outlines the geodynamic control in the development of rivers flowing through the Albanides on the scale of 10^3–10^5ka.

Introduction

In a tectonically active setting characterised by long-term uplift, Pazzaglia et al. (1998) suggest that the river incision rate equals the long-term uplift rate. Locally, rise or attenuation of the incision rate can also be interpreted as the consequence of vertical motion of the active faults. Nonetheless, the river-bed morphology can also strongly depend on climate (Bridgland and Westaway, 2008). In the Mediterranean basin, river response of glacial–interglacial climatic changes has been the subject of numerous studies (see review in Macklin et al., 2002), which outline the upstream control in continental interiors and downstream control in coastal plains and continental margins (e.g., Blum and Tornqvist, 2000). This dichotomy makes it difficult to establish general rules for terrace correlation, and the “great unifying generalisation” of terrace abandonment linked to glacial–interglacial transitions is probably an oversimplification. Recent modelling of river erosion gives clues for understanding the processes behind this dichotomy: although a fluvial system can take a thousand years to respond to a perturbation (Hancock and Anderson, 2002), the abandonment of fill terraces can be synchronous (Becel, 2004), due to the diffusion characteristics of the transport-limited processes that control the incision of fill terraces when water discharge increases (Whipple and Tucker, 2002).

We studied two rivers of the southern Albanides in order to quantify the geodynamic control on the incision of alluvial terraces. We selected the Osum and the Vjoje (Voidomatis in Greece) rivers, which flow from northwestern Greece and southern Albania across the active Dinaro–Hellenic alpine fold belt to the west. The present-day geodynamic deformation results from SW dipping of the foreland domain (the Adriatic Sea). This tilt leads to an overall shortening of the western part of the Albanides (Fig. 1a), whereas normal faults produce ~E–W trending extension in the hinterland (Roure et al., 2004).

From mapping and dating of terrace abandonment, we reconstructed both spatial and temporal variations of incision rates along the Osum and the Vjoje rivers. These reconstructions allow a quantification of the fluvial evolution at a higher resolution than a glacial–interglacial cycle (on the scale of 10^3/10^5 years), and therefore an estimation of the effect of geodynamic uplift on river incision. We identified nine preserved terraces units developed since Marine Isotope Stage 6 (MIS 6) up to historic time. Uplift seems to produce two distinct effects: an overall increase of the incision rate from west to east related to regional bulging, and local pulses of increasing incision generated by activation of normal faults.

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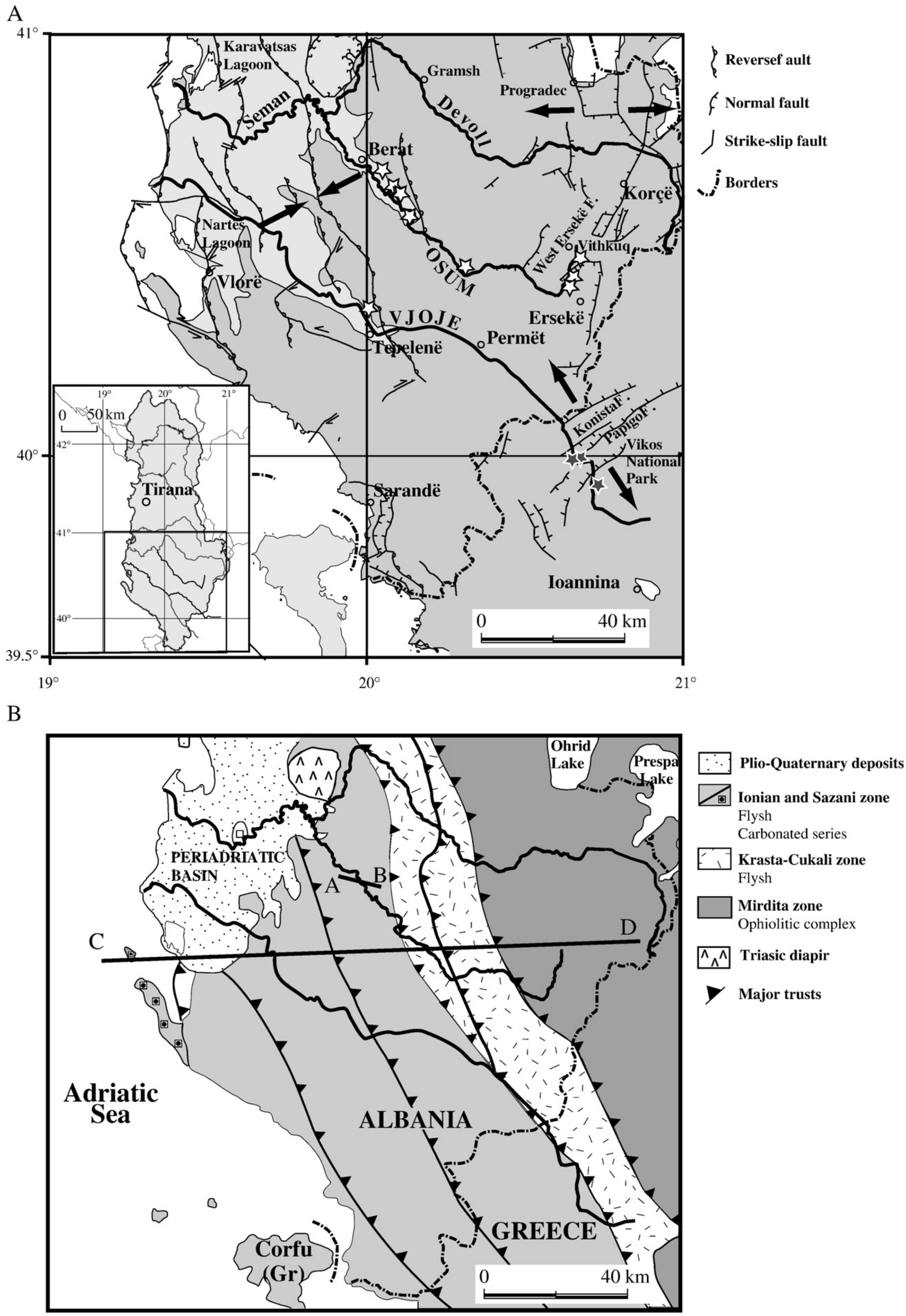
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Nartes
Lagoon
West Ersekë F.
Vithkuq
OSUM
Vlorë
Ersekë
VJOJE
Tepelenë
Permët
KonistaF.
PapigoF.
Vikos
National
Park
Sarandë
Ioannina
0 40 km
0 50 km
19°
20°
21°
42°
41°
40°
Tirana
Reversef ault
Normal fault
Strike-slip fault
Borders
B
Ohrid
Lake
Prespa
Lake
PERIADRIATIC
BASIN
A
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Adriatic
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ALBANIA
GREECE
Corfu
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Plio-Quaternary deposits
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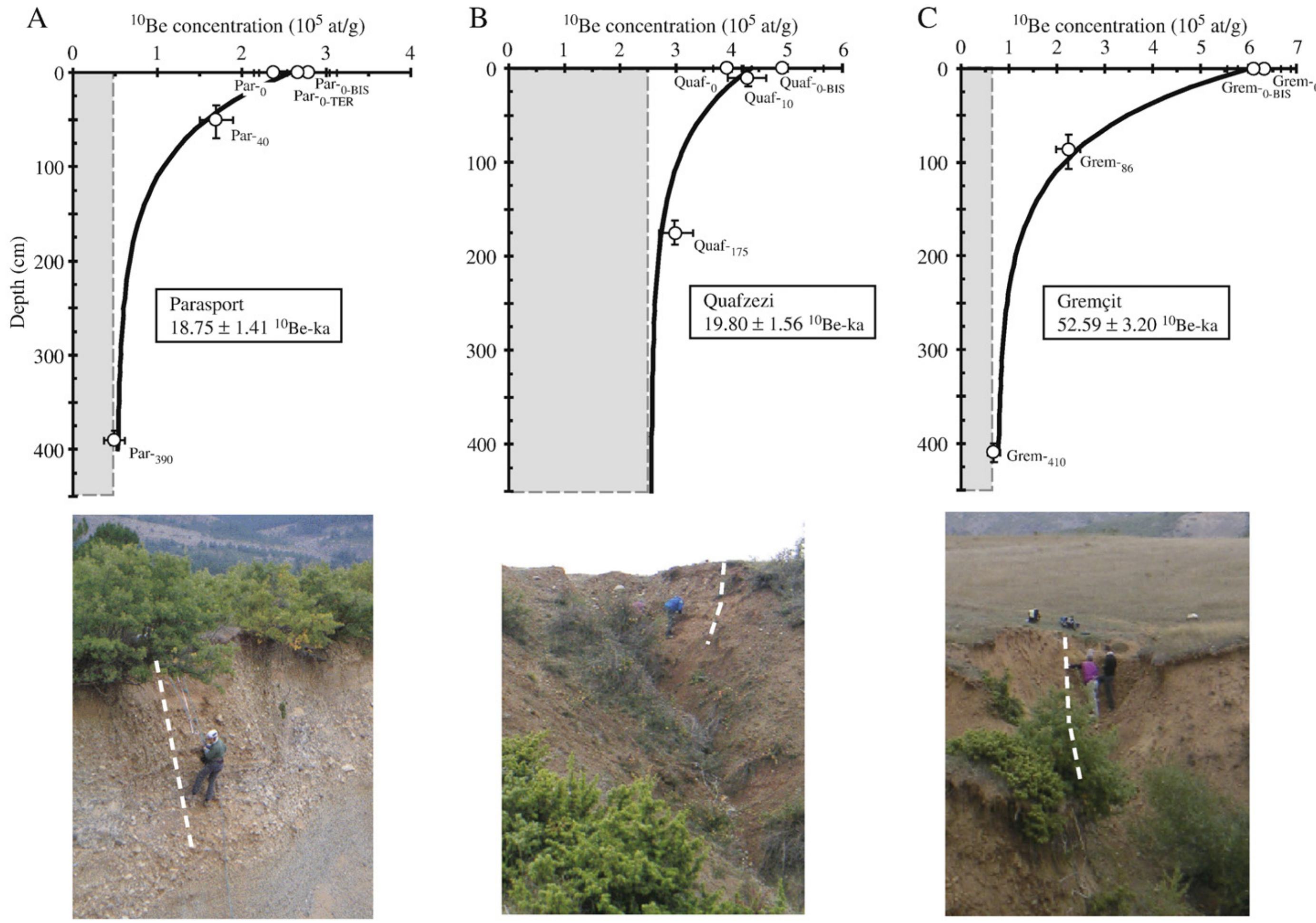

Figure 2. Depth profiles of the ^{10}Be concentration along Parasport (A), Quafzezi (B) and Gremçit (C). The depth-production best fits are in solid lines. Inherited ^{10}Be concentrations are the dashed grey zone. Details of the exposures ages calculations are in Table 1. Dashed lines on photograph localized the sampling profiles.

Geological setting

The Dinaro–Hellenic Alpine fold belt constitutes a segment of the wide Circum-Mediterranean Peri-Tethyan thrust belt. The Albanian foothills have been thrust westwards over the Adriatic foredeep during the Alpine orogeny (Roure et al., 2004). This geodynamic setting produces contrasting relief with a flexural basin filled with Plio-Quaternary deposits and forming a flat costal plain in the foreland (periadriatic basin), a thin-skinned fold and thrust belt in the midland, and a large basin and range zone in the hinterland, resulting from synorogenic Neogene–Quaternary grabens that crosscut the thrust system (Figs. 1A and B).

We concentrate our study on a zone located between two major transverse structures that cut the area: the Vlore–Elbasani–Dibra transfer zone in the central part of Albania (Roure et al., 2004), and the prolongation of the Keffalinia strike-slip transform zone at the northwestern border of Greece (Baker et al., 1997).

The area is still tectonically active and produces permanent microseismicity and frequent earthquakes reaching intensities of IX. The neotectonics (Fig. 1A) are controlled by NE–SW compressive stress in the western part connected to subduction of the Apulian lithosphere and extensional stress in the internal zones (De Mets et al., 1990, Robertson and Shallo, 2000; Kilias et al., 2001; Niewland et al., 2001; Goldsworthy et al., 2002; Roure et al., 2004). The major extension direction varies from E–W close to the Ohrid and Prespa lakes to NW–SE at the southern end of the Ersekë basins. On the regional scale the Albanides are governed by long-term uplift (Aliaj, 1997).

The Vjoje and the Osum rivers constitute two of the six main rivers of Albania. The catchments of the Osum (2.2×10^3 km^2) and the Vjoje (6.7×10^3 km^2) are rather small and close to each other; therefore, their climatic settings are comparable. Both rivers drain ophiolites of the Mirdita zone, flysch deposits of the Krasta-Cukali zone, carbonate rocks of the Ionian zone and Quaternary sediments of the Periadriatic basin (Aubouin and Ndojaj, 1964; Roure et al., 2004) (Fig. 1B).

The source of the Osum is located in nearby Vithkuq (District of Korçë) at an elevation of 1100 m. The river flows over 160 km and connects with the Devoll River in the flat plain down to the city of Berat (Fig. 1A). This confluence forms the Seman River, which flows for 80 km toward the Adriatic Sea near the Karavatsas lagoon. The Seman River and its tributaries form the longest drainage system of Albania (281 km length). Terraces of the upper Osum are cut terraces formed in Pliocene lake sediments (Aliaj et al., 2000). The terrace sediments are composed of limestone, flint stone, igneous

Figure 1. (A) Neotectonic map of the Southern Albania and North-western Greece. Areas located within 200 m above Sea level are in light grey. Dark grey stars indicate published data (Lewin et al., 1991; Hamlin et al., 2000; Woodward et al., 2001) and white stars indicate data computed in the present study. Fault types are described in the picture caption and the overall current tectonic deformation is represented by black arrows. (B) Simplified lithological map of the studied area modified from Roure et al. (2004) for the southern Albania and from Dercourt (1964) for the northern Greece. Synthetic cross sections of Figures 3B (A–B) and 6 (C–D) are represented in B.

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rocks (mainly ultrabasite), radiolarites, and flysch fragments. Most of the deposited materials presumably originated from the Krasta-Cukali and Mirdita zone formations. From the base to the top, the terraces are formed by a thick layer (>10 m) of pebbles of variable size, and are supported by fairly homogeneous fine sand matrix (see photograph, Fig. 2). The pebble size decreases upward while the granulometry of the matrix increases. The sequence is covered by a ~0.5-m mixed horizon composed of sand and organic materials. In the middle section, the Osum flows in a deep and narrow gorge that is not favourable for the formation of cut terraces, but rather indicates strong incision. In the lower part of the Osum, most of the terraces are fill terraces, except for two of them that have been interpreted as strath terraces (see below). The fill terraces are rather uniform and composed of large carbonate rock and small quartz pebbles, joined by a fine sand matrix with locally occurring large clay lenses corresponding to paleo-deposition of material during the river flow.

The Vjoje River originates in the Vikos National Park in Greece at an elevation of 1600 m, and it flows northwest for 272 km to the Adriatic Sea to the north of the Nartës lagoon. The Vjoje flows in an atypical catchment in the Mediterranean zone. Its upper part was glaciated during the last glacial maximum (LGM), as suggested by well-preserved glacial features (Lewin et al., 1991). In the middle part, the river flows over flysch deposits until it incises deep and narrow transverse (E–W) gorges along the frontal active trust, and then meanders on the costal plain to the Adriatic Sea in the west. Most of the studied terraces are located immediately at the end of the gorge, but several terrace levels have been also documented in the lower section of the river (Prifti, 1981). Terraces are organized as those of the Osum with a thick layer of heterogeneous sediments coming from upward geological formations (Fig. 1B), and a thin organic deposit on the top. A notable difference between the Vjoje and Osum river terraces is that the fraction of limestone clasts seems to be more important in the Vjoje terraces and that glacial materials locally appears (Lewin et al., 1991).

Methods

Terrace thicknesses and elevations above the present-day river bed have been measured using a laser range distancemeter. Terrace age control was obtained from data previously published by Lewin et al. (1991), Hamlin et al. (2000) and Woodward et al. (2001) as well as from *in situ* produced ^{10}Be and radiocarbon (^{14}C) dating performed specifically for this study. This implies that the age of the terrace abandonment is contemporaneous to the age of deposition of the highest terrace layer. Thus we dated organic residues and quartz-rich pebbles collected into layers developed during the ultimate flooding event and considered the value as the age of abandonment of the alluvial terrace.

Cosmonuclide (*in situ* produced ^{10}Be) age determinations have been done on siliceous-rich pebbles collected along depth profiles of three terraces of the upper Osum (Fig. 2, Table 1). Sample sites were selected to minimize post-depositional processes; we thus selected surfaces where terraces did not show evidence of strong disturbances (erosion or settling). Material was sampled along depth profiles in order to estimate ^{10}Be inherited from prior exposure. The deepest sample was thus collected deep enough to evaluate the geological blank. Beryllium oxide targets were extracted following the chemical procedure of Brown et al. (1991). Because there are no recordings of the thickness and duration of snow cover for the time of interest (i.e., the last ~50 ka), corrections for recurrent snow cover were impossible. The calculated exposure ages are thus minimum estimates (Lal, 1991). Table 1 presents exposure ages of terraces that we considered assimilated as the minimum age of terrace abandonment. In the following, the interpretation is based on ages corrected to the geomagnetic effect (intensity-corrected ages), and dates are given in ^{10}Be-ka in order to allow straightforward correction for future refinements in production rate histories.

Six ^{14}C ages have been determined from organic residues collected from clay lenses or fine sediment horizons. ^{14}C ages lower than ~21.5 ^{14}C ka BP were calibrated using the CALIB program version 5.0 (Stuiver et al., 2005), based on the IntCal04 data set (Reimer et al., 2004) and reported as intercept ages with two sigma (95%). Calibrated ages (cal ka BP) are given as a time interval linked to the related probability (Table 2). ^{14}C ages older than ~21.5 ka were corrected using the polynomial of Bard et al. (2004) and are labelled in italics and followed by ka BP (Table 2). The previously published conventional ^{14}C ages (Lewin et al., 1991 and Woodward et al., 2001) were calibrated following the same procedure.

Results

Terrace dating

The upper terrace is located on the left bank of the Osum at the Parasport locality. The surface is placed at 70 m above the present day riverbed and shows a weak dip of ~10° to the N–NW that could be the consequence of the tectonic tilt induced by the West Ersekë normal fault (Fig. 1A). The samples come from an escarpment formed by the incision of a tributary of the Osum. We assume a negligible lateral ^{10}Be production because the escarpment is still active. ^{10}Be concentrations measured in three surface samples (Fig. 2A, Par-$_{0,}$ -$_{BIS}$ -$_{TER}$) range from $2.37 \pm 0.22 \times 10^5$ to $2.79 \pm 0.25 \times 10^5$ atoms per gram of quartz (at/g.). Samples collected at depth allow drawing of an exponential curve assimilated to the evolution of production with depth. Because the lower sample (Par-$_{390}$) has been collected at 390 cm depth, we consider the measured concentration (i.e. $0.49 \pm 0.13 \times 10^5$ at/g) as the inherited ^{10}Be concentration (i.e., geological blank). We thus corrected the surface concentrations to this inherited concentration. The best fit between the theoretical depth production and our results correspond to a weighted averaged minimum age of 18.75 ± 1.41 ^{10}Be-ka and zero erosion.

Two other terraces have been sampled at ~2 km to the south from Parasport at ~29 (Quafzezi) and ~50 m (Gremçit) above the present-day river bed.

Three surface and subsurface samples (Fig. 2B, Quaf-$_{0,}$ -$_{BIS}$ and -$_{10}$ respectively) have been collected along the northern edge of Quafzezi. ^{10}Be concentrations range from $3.95 \pm 0.27 \times 10^5$ to $4.93 \pm 0.74 \times 10^5$ at/g. Because the terraces are actually used for agriculture, we assimilate the upper 20 cm as the plowing depth and consider the subsurface sample as equivalent to the surface samples. Quartz-rich materials being scarce, we only determined one ^{10}Be concentration at depth (Quaf-$_{175}$, $3.01 \pm 0.31 \times 10^5$ at/g). At the considered depth and for a density of 2 g/cm^3, post-depositional *in situ* production remains significant and represents ~11% of the surface production. A meaningful proportion of the measured concentration of Quaf-$_{175}$ can thus be regarded as inherited from prior exposure. Therefore, we considered a post-depositional production of 0.47×10^5 at/g corresponding 11% of the weighted averaged concentration of surface concentrations and an inherited concentration of 2.54×10^5 at/g. The recognition of this inheritance allows calculating a minimum age of terrace abandonment at 19.80 ± 1.56 ^{10}Be-ka.

Two quartz pebbles were sampled on the surface of Gremçit (Fig. 2C, Grem-$_{0}$,-$_{BIS}$). ^{10}Be concentrations of surface samples are $6.34 \pm 0.55 \times 10^5$ at/g and $6.12 \pm 0.55 \times 10^5$ at/g respectively and depth samples are consistent with a theoretical depth production considering zero erosion. Taking into account the measured concentration of the deepest sample (Grem-$_{410}$, $0.69 \pm 0.13 \times 10^5$ at/g) as the geological blank, the data set yields a minimum age of 52.59 ± 3.20 ^{10}Be-ka.

In addition, we sampled five organic residues embedded in terraces of the downstream section of the Osum (District of Berat)

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Table 1
In situ produced ^{10}Be dating and sampled terraces locations

Topographic setting							Geomagnetic correction (%) (c)						
Samples	Materials	Latitude (North)	Longitude (East)	Elevation (m)	Elevation/river bed (m)	Depth (cm)	Surface P_0 (a)	Geomorphic factor (b)	Value (%)	Uncertainty (%)	Corrected production rate (d)	^{10}Be concentration (10^5 at/g) (e)	Corrected age (ka)
Parasport		40°52.36	20°72.00	970	70								
Par-$_0$	Quartz					0	10.72	0.998	4.5	8.3	11.18	2.37 ± 0.22	16.86 ± 2.31
Par-$_{0\text{-BIS}}$	Quartz					0						2.79 ± 0.25	20.66 ± 2.76
Par-$_{0\text{-TER}}$	Quartz					0						2.66 ± 0.46	19.50 ± 3.90
Par-$_{40}$	Quartz					40						1.70 ± 0.20	18.16 ± 2.76
												Weighted average	18.75 ± 1.41
Par-$_{390}$	Radiolarite					390	Geological blank					0.49 ± 0.13	
Quafzezi		40°52.97	20°69.00	850	29								
Quaf-$_0$	Quartz					0	9.74	0.922	2.7	7.9	9.22	3.95 ± 0.27	15.30 ± 1.84
Quaf-$_{0\text{-BIS}}$	Quartz					0						4.93 ± 0.74	26.04 ± 4.69
Quaf-$_{10}$	Quartz					10						4.29 ± 0.34	21.75 ± 2.77
												Weighted average	19.80 ± 1.56
Quaf-$_{175}$	Flint					175	Geological blank and post-depositional production *					3.01 ± 0.31	
Gremçit		40°55.67	20°73.83	890	50								
Grem-$_0$	Quartz					0	10.06	0.922	10.5	8.6	10.25	6.34 ± 0.55	55.81 ± 5.48
Grem-$_{0\text{-BIS}}$	Quartz					0						6.12 ± 0.55	53.63 ± 5.43
Grem-$_{86}$	Flint					86						2.24 ± 0.25	46.30 ± 5.56
												Weighted average	52.59 ± 3.20
Grem-$_{410}$	Sandstone					410	Geological blank					0.69 ± 0.13	

(a) Surface production rates computed from a modern ^{10}Be production rate of 5.1 ± 0.3 at·g^{-1} SiO_2.yr^{-1} (Stone, 2000) and depth-production includes contribution of neutrons, slow and fast muons (Braucher et al., 2003) and a density of 2 g/cm^3 (Brocard et al., 2003). (b) The geomorphic scaling factor has been calculated following the method of Dunne et al. (1999). (c) Geomagnetic correction and associated uncertainties are calculated from Pigati and Lifton (2004). (d) Time integrated geomagnetic intensity production rates (at.g^{-1} SiO_2·yr^{-1}). (e) ^{10}Be concentrations were calibrated against NIST Standard Reference Material 4325 using its certified $^{10}Be/^{9}Be$ ratio of 3.06×10^{-11}. The ^{10}Be concentrations were processed from measurements calibrated against non-NIST standards, we normalized the measured ^{10}Be concentrations using a factor of 1.142 ± 0.039 (Middleton et al., 1993). Analytical uncertainties are based on counting statistics, a conservative estimate of 3% instrumental variability and a 50% uncertainty in the chemical blank correction. (f) Uncertainties on minimum exposure ages are calculated by propagating the analytical uncertainties on the measured ^{10}Be concentrations, a 6% uncertainty on surface production rate (Stone, 2000) and the uncertainties associated with the geomagnetic correction (Pigati and Lifton, 2004). * For Quafzezi, we estimated the geological blank (i.e., inherited ^{10}Be concentration) as ~89% of the ^{10}Be concentration measured for Quaf-$_{175}$ (see text for detail).

Table 2
Ages determined from various techniques and sampled terraces locations

Samples			Topographic setting			Elevation (m)			Ages (ka)					Reference
Sample	Materials	Elevation above the river (m)	Latitude (N)	Longitude (E)	Elevation (m)	Top terrace above the river (m)	Base terrace above the river (m)	Top gravel above the river (m)	Methods	Lab code	^{14}C Ages (ka BP)	Calibrated interval Cal ka BP (probability)	Ages (ka) (a)	
OSUM														
A17	Organic residue	17	40°45.08	20°28.78	349	19	12.5	17.5	^{14}C	Poz-10576	9.99 ± 0.05	11.26–11.65 (0,96)	11.45 ± 0.19	This study
A16	Organic residue	25	40°63.94	20°05.53	133	29	19	28	^{14}C	Poz-10575	29.90 ± 1.30	–	*34.47 ± 1.50*	This study
A83	Organic residue	14.8	40°68.83	20°02.31	98	18.5	14.3	17.2	^{14}C	Poz-13850	37.00 ± 0.70	–	*42.15 ± 0.80*	This study
A18	Organic residue	56	40°55.97	20°14.00	282	62	55	60	^{14}C	Poz-10578	45.30 ± 1.60	–	*50.70 ± 1.79*	This study
A14	Organic residue	33.8	40°64.03	20.05.75	139	35	27	33.5	^{14}C	Poz-10574	49.00 ± 2.50	–	*54.40 ± 2.78*	This study
VJOJE														
A28	Organic residue	–	40°33.69	19°99.78	150	–	–	–	^{14}C	Poz-8824	0.71 ± 0.03	0.64–0.69 (0,88)	0.67 ± 0.03	This study
Kipi	Silt	–	39°86*	20°78*	830	56	33	–	TL	VOI26	–	–	>150	Lewin et al., 1991
Klitonia	Charcoal	–	36°96*	20°69*	430	4.5	4.5	–	^{14}C	OxA-192	0.80 ± 0.10	0.63–0.93 (0.95)	0.67 ± 0.15	Lewin et al., 1991
Klitonia	Charcoal	–	36°96*	20°69*	430	4.5	4.5	–	^{14}C	OxA-191	1.00 ± 0.05	0.79 ± 0.99 (0.97)	0.89 ± 0.10	Lewin et al., 1991
Vikos	Sediment	–	39°95*	20°69*	600	9.7	8.3	–	TL	VOI24	–	–	19.60 ± 3.00	Lewin et al., 1991
Klitonia old	Deer tooth	–	39°97*	20°66*	400	12.4	–	–	ESR	–	–	–	24.30 ± 2.60	Lewin et al., 1991
Klitonia old	Deer tooth	–	39°97*	20°66*	400	12.4	–	–	ESR	–	–	–	25.00 ± 0.50	Lewin et al., 1991
Klitonia old	Deer tooth	–	39°97*	20°66*	400	12.4	–	–	ESR	–	–	–	26.00 ± 1.90	Lewin et al., 1991
Klitonia old	Sediment	–	39°97*	20°66*	400	12.4	–	–	TL	VOI23	–	–	28.00 ± 7.10	Lewin et al., 1991
Boila	Charcoal	~10.8	39°97*	20°66*	410	10.8	10	–	^{14}C	OxA-5246	13.81 ± 0.13	16.00–16.93 (1.00)	16.46 ± 0.47	Woodward et al., 2001
Boila	Charcoal	~10.3	39°97*	20°66*	410	10.8	10	–	^{14}C	Beta-109162	13.96 ± 0.26	15.87–17.54 (1.00)	16.71 ± 0.83	Woodward et al., 2001
Boila	Charcoal	~10.5	39°97*	20°66*	410	10.8	10	–	^{14}C	Beta-109187	14.31 ± 0.20	16.50–17.91 (1.00)	17.21 ± 0.70	Woodward et al., 2001
Boila	Calcite cement	~8.2	39°97*	20°66*	410	10.8	–	–	U series	–	–	–	24.00 ± 2.00	Hamlin et al., 2000
Boila	Calcite cement	~8.2	39°97*	20°66*	410	10.8	–	–	U series	–	–	–	25.00 ± 2.00	Hamlin et al., 2000

The sample location followed by * are estimated. (a) ^{14}C ages higher than the InCal04 calibration (Reimer et al., 2004) interval have been corrected following the Bard polynomial (Bard et al., 2004) and are in italics (ka BP). ^{14}C ages previously published by Lewin et al. (1991) and Woodward et al., (2001) have been calibrated using IntCal04.

and one from the Vjoje River (Memeliaj, District of Tepelena). Samples were collected from clay lenses or fine-grained sediment horizons that are located close to the top of the terrace, and above the top of the conglomeratic material (sample elevations and positions are summarized in Table 2). The collected organic residues were thus deposited during the ultimate phase of river alluviation. We deduce that the ^{14}C ages deduced from the organic materials are equal or close to ages of the terrace abandonment. Likewise, the ages previously published by Lewin et al. (1991) and Woodward et al. (2001) are compiled in Table 2.

Discussion

Climatic control of terrace formation and correlation of terraces levels

In a mountainous area, terrace formation has been assigned to changes in sediment supply and/or water discharge produced by climatic fluctuations (Hancock and Anderson, 2002) while the influence of sea level change is considered to be small. Fill and strath terraces are developed when sediment supply is, respectively, larger than or balanced with the transport capacity, whereas incision occurs when sediment supply is smaller than the transport capacity. Fluvial terraces of the Albanides follow these characteristics because they were developed at a distance of more than 80 km from the Adriatic Sea, and therefore the climatic control is much more important than eustatic variations. Because the climate of the Mediterranean domain strongly depends on the one of the Atlantic domain (Asioli et al., 2001; Rahmstorf, 2002), precipitation regimes in the Albanides depend on temperature variations induced by changes in Atlantic circulation. Therefore, episodes of alluviation can be related to periods of cooling, while incision is more intensive during warm and humid periods.

We correlate ages of terrace abandonment deduced from our dating and previously published data (Lewin et al., 1991; Hamlin et al., 2000, Woodward et al., 2001) with climate periods. The reconstructed timing coupled with our field investigation gives a detailed picture of river development in response to climate oscillations. This allows us to correlate terrace levels on both the individual river-basin scale and between the two river drainage systems. We identified nine terrace units formed since the late Pleistocene. These terraces units are labelled according to their topographic position from the highest (T1) to the present-day riverbed (Figs. 3A–C).

In the lower Osum, terraces of T1 and T2 units are highly elevated in the topography and are strongly degraded (Fig. 3B). The loss of the initial flat surface produced by erosive processes and evidence of anthropogenic activity prevented us from collecting samples for *in situ* produced ^{10}Be age determinations. Nevertheless, in the upper Vjoje basin one thick (>23 m) terrace relict was described close to the locality of Kipi. Thermoluminescence (TL) dating of silts gave an age of terrace abandonment older than 150 ka (Lewin et al., 1991). The position of T1 and T2 above the Kipi unit suggests that they were most likely developed during the pre-Würm glaciation (Prifti, 1981, 1984). The Kipi units, previously described in the Vjoje, could thus correspond to the lower of these two distinct episodes of alluviation. During MIS 6, two strong sea-surface cooling episodes were identified in the Mediterranean from foraminifera records (Kallel et al., 2000) and likewise connected to overall cooling of the North Atlantic (Moreno, 2000). Several terrace formations have been identified in Spanish and Libyan rivers (Fuller et al., 1998; Rowan et al., 2000) between ~138–157 and ~179–183 ka. We thus presume that T1 and T2 correspond to these alluviation episodes.

In the Osum drainage, many other terraces were mapped at an intermediate topographical level and were dated between ~54 ka and ~42 ka (Table 2). In the upper basin, Gremçit (52.6 ± 3.2 ^{10}Be-ka) can be related to terraces of the lower basin dated at 50.7 ± 1.8 *cal ka BP* (A18) and 54.4 ± 2.8 *cal ka BP* (A14). The close agreement of the ages suggests the existence of a wide and continuous T3 unit from the upper to the lower basin. A younger strath terrace (T4), dated at 42.2 ± 0.8 *cal ka BP* (A83), has been found only in the lower Osum, close to Vodica. The T3 and T4 units were deposited during the first half of the MIS 3 and correspond to alluviation phases previously described in the northern Mediterranean around ~50 ka and ~ 40 ka (Macklin et al., 2002).

In the lower Osum, two superimposed terrace units were mapped close to the locality of Vertop and Fushe. The lower one (T5), dated at 34.5 ± 1.5 *cal ka BP* (A16), corresponds to the ultimate alluviation phase of MIS 3 and was probably produced during Heinrich event 3. After a break of sedimentation accompanied by lateral erosion and development of strath surfaces, a new filling (T6) took place above T5. However, the absence of organic residues or quartz-rich pebbles prohibits direct dating. This upper unit could correspond to the Aristi unit described in the upper Vjoje (Lewin et al., 1991).

The Aristi unit reaches more than 30 km in length and constitutes a major alluvial unit deposited by an aggrading and a low-sinuosity stream. The age of the Aristi unit was estimated from ESR (Electron Spin Resonance) determination of a red deer tooth at 24.3 ± 2.6, 25.0 ± 0.5 and 26.0 ± 1.9 ka whereas TL dating of sediment gives an age of 28.0 ± 7.1 ka. Moreover, the Aristi unit forms the base of the Boila rockshelter (Woodward et al., 2001). Uranium-series determination in calcite cement located two meters beneath the top surface gave ages of 24.0 ± 2.0 ka and 25.0 ± 2.0 ka (Hamlin et al., 2000). These ages agree with those (~25 ka) deduced from four samples used for ^{14}C dating of organic residues collected in the most extended terraces of the Devoll river, which is located a few kilometres to the north of the Osum (Mugnier et al., 2006). This extended alluviation thus takes place at least along 3 rivers of the southern part of the Albanides and can be connected to Heinrich event 2.

Along the lower Osum, unit T7 corresponds to strath terraces and indicates a break in the incision of T6. In the upper Osum, T7 has been identified and dated at 18.8 ± 1.4 and 19.8 ± 1.6 ^{10}Be-ka (Parasport and Quafzezi terraces). Along the Vjoje, a unit called the Vikos unit (Lewin et al., 1991) also indicates a break of sedimentation and is characterised by a thin sediment cover (few meters) deposited above an erosional surface. These sediments were dated at 19.6 ± 3.0 ka (TL). This time interval is conformable with ^{14}C ages of slackwater sediments deposited onto the erosional surface observed above the Aristi unit in the Boila Rockshelter (16.5 ± 0.5, 16.7 ± 0.8 and 17.2 ± 0.7 cal ka BP; Woodward et al., 2001). This unit correlates with the end of the LGM, which seems to extend up to ~15.6 ^{14}C ka BP (~16.9 cal ka BP) in the southern part of the Balkan (Lawson et al., 2004). A second post-LGM unit (T8) has only been recognized and dated in the lower Osum at 11.45 ± 0.19 cal ka BP (A17). Post-LGM units (T7 and T8) correspond to periods of terrace development, which have been recorded in many Mediterranean rivers between the intervals 16 ± 3 to 19 ± 1 (corresponding to T7) and 12.5 ± 1.5 to 13 ± 2 ka (corresponding to T8) (Macklin et al., 2002).

Placed at an elevation lower than 5 m above the present-day river bed, T9 constitutes the ultimate abandonment unit. Along the Albanian section of the Vjoje, abundant evidence for T9 has been recognized by Prifty (1981), and we dated one of them (A28) at 0.67 ± 0.03 cal ka BP. In the Greek part, T9 (call Klithi unit) was dated at 0.67 ± 1.50 and 0.89 ± 0.10 cal ka BP (Lewin et al., 1991). The sedimentary facies of T9 shows close similarities with widespread "haugh loams" of Europe and "post-settlement alluvium" of North America (Lewin et al., 1991 and references therein). This historic alluviation would thus be the consequence of the deforestation and the agriculture development, leading to high erodability of upstream terrains (Knox, 1977).

The proposed chronology and the identification of overall aggradations phases (T1, T2, T3, T5, T6, T8) or lateral incision phases (T4 and T7) are compatible with climatic changes of the northern part of the Mediterranean. The only exception is the last alluviation

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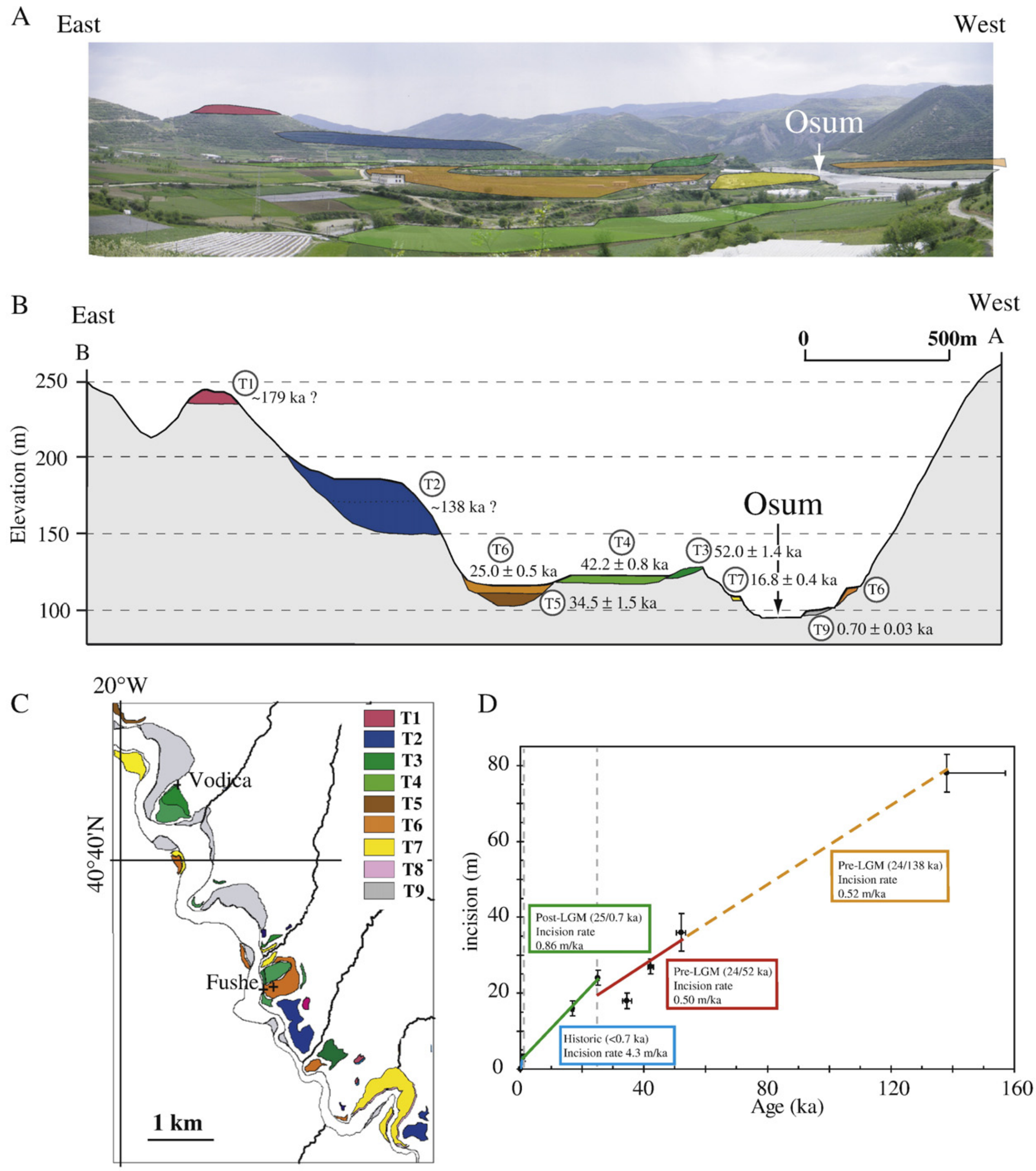

Figure 3. (A) Panoramic view of the lower Osum showing the location of terraces units. (B) Cross section through the lower Osum, Upstream of Berat (Fig. 1). The figure illustrates the incised terraces; the numbers refer to the nomenclature proposed in the present study. Ages of abandonment of T1 and T2 correspond to the end of the main periods of alluviation of MIS 6 (Macklin et al. 2002). From T3 to T9 ages are weighted averages. Note that T8 was not represented because it has not been mapped along this river section. (C) Geomorphologic map of the lower Osum, upstream of Berat. (D) Incision (m) versus ages of terrace units (ka). Breaks on slope are materialized by the vertical dashed grey lines.

episode (T9), which would be the consequence of the anthropogenic activity leading to the rise of erosion of the drainage system.

Temporal variation of the incision rate along the Osum

The contribution of our new dating combined with previously available data give a detailed picture of the incision–sedimentation pattern in rivers of southern Albania. On the bases of terrace dating, we correlate terraces that developed both along different sections of the same river catchment and along the two studied rivers. T3, which has been mapped in the lower and the upper part of the Osum, indicate a difference in age of abandonment of ~3.7 ka; T7, which was mapped in the Osum and the Vjoje indicates a lag of less than ~3.3 ka (Table 2). On the river scale, numerical modelling predicts that incision of fill terraces is synchronous when stable climate periods are longer than the transient response of the river profile evolution (Becel, 2004), but the incision becomes diachronous when the climate periods are shorter. T7 was developed during a short period of alluviation (Macklin et al., 2002) and because it shows a thin strath terrace facies, we suspect that this unit is the most diachronous. Therefore we assume the beginning of incision is nearly synchronous (less than 3.3 ka) on the scale of the river catchments, and we use our correlation scheme to estimate the incision rate for terrace remnants from their elevation above the river (Figs. 4 and 5).

The averaged incision rate of terrace units varies from 0.4 to 5.9 m/ka, which includes the temporal variations and the spatial discrepancy produced by the regional variation of surface uplift. In order to evaluate the time evolution of the incision, we compare the incision rate at a single place along the Osum upstream of Berat (Fig. 3B). In Figure 3D, we plotted ages versus elevation (above river bed) of upper terraces and evaluated the mean incision rate (using a linear fit) for different time intervals. Terrace units developed before the LGM (24–50 ka, i.e. the period supported by absolute dating) have been incised at a rate of 0.5 m/ka. This value is quite compatible with the one calculated for T2 (~0.56 m/ka) and allows us to extend it for the time period 24–138 ka. Because of the uncertainty of the age of the higher terrace (T1), we cannot discuss its incision rate in the present scheme. Incision of terraces deposited between 0.7 and 25 ka shows an increase of the incision rate of up to 0.9 m/ka. This is also evident in the upper Osum when comparing the incision rates of the pre- and post-LGM terraces at Gremçit and Quafzezi. Indeed, the incision depth varies from 50 m since 52.6 ka to 29 m since 19.8 ka. This observation suggests that incision caused by surface uplift can be estimated at ~0.64 m/ka for the time period 20–50 ka.

Since ~20 ka, the observed increase of the incision rate (1.46 m/ka) can thus be related to a modification either of the sediment supply or the transport capacity controlled by climatic changes. Because of the proximity of the Adriatic Sea and the dominant westerly winds, the Balkan region generates orographic precipitation. These particular climatic conditions let to higher moisture content in the atmosphere since the end of the LGM, which differs from the overall arid climate of the rest of Europe (Lawson et al., 2004). This regional specificity allowed the binding and stabilization of hillslopes by vegetation, and an increase in the river incision capacity by the enhancement of river flow. According to the position of the youngest terraces (T9), the incision rate extensively increases to ~5.9 m/ka during the historic periods. We suggest that the time span since the terrace abandonment is shorter than the transient response of the river to a catastrophic

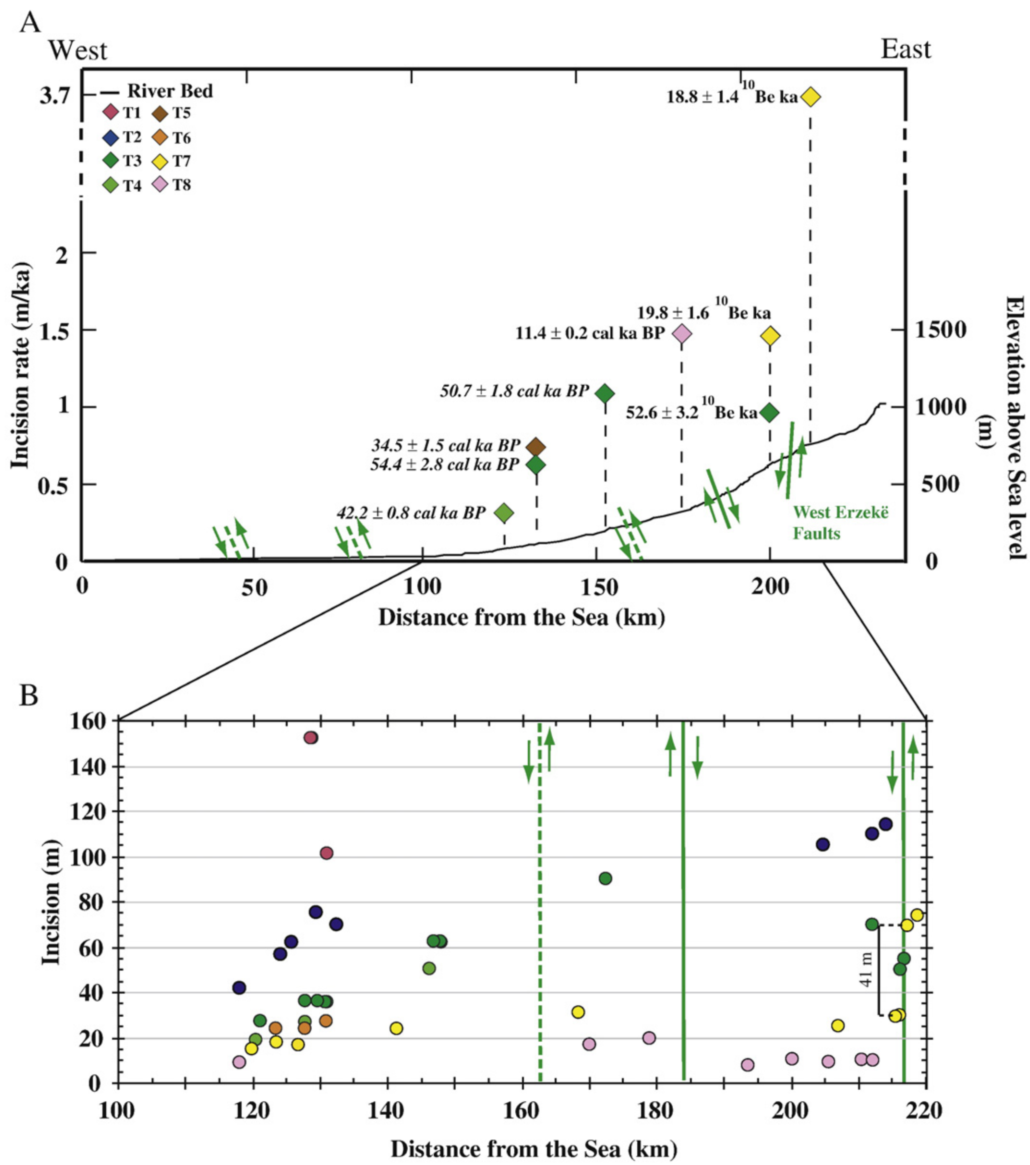

Figure 4. (A) Evolution of the incision rate along the river profile of the Osum. Right axis is the elevation of the present-day river bed; left axis is the calculated incision rate. Colour of the diamonds refers to the described terrace units (see text). Note that the ^{14}C ages in italic are corrected following Bard polynomial (Bard et al., 2004), and ages labelled cal ka BP were calibrated with IntCal04 (Reimer et al., 2004). Bold lines represent normal faults producing surface displacements. Dashed lines represent faults which would not influence in the evolution of the river profile. (B) Spatial evolution of the terrace incision (m). The *X*-axis refers to the distance from the sea.

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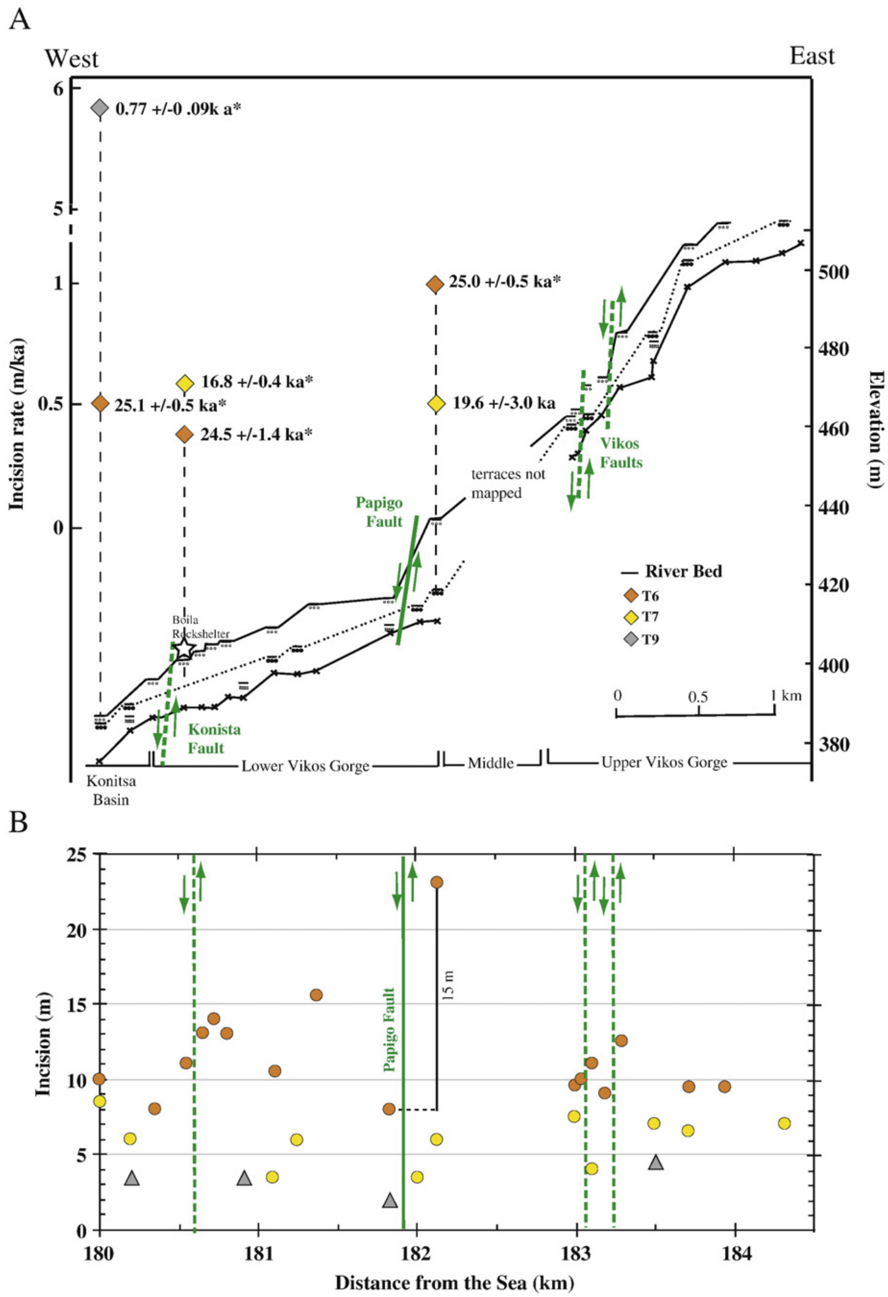

Figure 5. (A) Terraces levels mapped in the upper section of the Vjoje River (modified from Lewin et al., 1991). Dotted lines are interpolations suggested by Lewin et al., (1991). Colour of the diamonds refers to the described terrace units (see text). White star represents the Boila rock shelter. Bold lines represent normal faults producing surfaces displacements. Dashed lines represent faults that do not influence the evolution of the river profile. The ages followed by * are weighted averaged. Note that the incision rate of T2 (0.4 m/ka) is not represented because the sole remnant terrace is placed upstream at 22 km from the Konitsa basin. (B) Evolution of the incision (m) of terraces mapped by Lewin et al. (1991). The *X*-axis refers to the distance from the Adriatic Sea.

flooding event, and that unit T9 expresses the increase of sediment supply due to anthropogenic impact rather than a natural increase in the incision rate.

The temporal evolution of river incision thus agrees with the results of the numerical modelling of Hancock and Anderson (2002). We therefore consider that the uplift rate equals the incision rate only for long periods of time that exclude the late anthropogenic disruption.

Spatial variations of the incision and uplift rates

In the present study, the deconvolution of climatic control on river incision and terrace formation is a simple issue because periods of alluviation are widely spaced in time and are related to outstanding climatic periods. Because rivers cut across the main geological structures, they are located at key locations to evaluate the regional changes of incision produced by geodynamic surface uplift.

The geodynamic context of the Dinaro–Hellenic belt produces a multi-scale effect on the incision regime: the overall incision is controlled by regional surface uplift while local variations are produced by active faulting. Along the Osum (Fig. 4A), the incision rate regularly increases from 0.35 to 3.75 m/ka. However, local pulses of incision overprint the overall trend. It is particularly evident in the vicinity of the West Ersekë normal fault, which shows an offset of 41 m between the top surfaces of post-LGM terraces (Parasport and

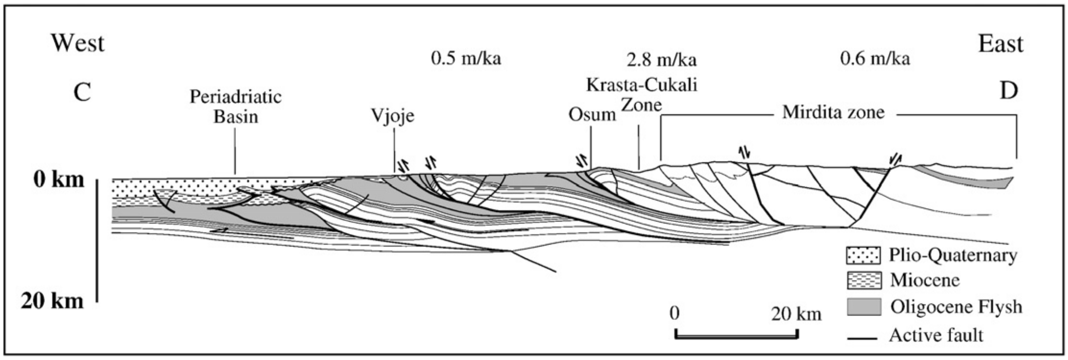

Figure 6. Simplified structural cross-section through the southern Albanides. Structures of the western part are adapted from Roure et al., 2004, middle and eastern part are adapted from Kilias et al. (2001) and from the Geological Map of Albania (1:200000, 1983). The neotectonic framework is modified from Aliaj et al. (2000). Values indicate surface uplift (m/ka) calculated in the present study.

Quafzezi terraces, ~19.3 ka) located on both sides of the fault. We suggest that this offset was produced by the vertical motion during the active faulting, leading to a displacement of 2.2 m/ka. The displacement, observed since 19.3 ± 1.1 ka, is compatible to current extensional deformation deduced from GPS measurements. The West Ersekë fault seems to be the sole active fault since the last ~19 ka. Assuming a constant vertical shift of the West Ersekë fault (2.2 m/ka) for the last 50 ka and a long-term incision rate of the hanging wall (eastern block of the fault, 0.64 m/ka), the uplift of the west side of the extensional basin and range system would thus reach 2.8 m/ka (Fig. 6).

Along the Vjoje (Figs. 5A, B), available dated terraces are located in narrow sections in the upper catchment, and the information about the spatial evolution of the incision rate is thus limited. One remnant of the T2 terrace (Kipi) mapped upstream of the Vikos gorges allows an estimation of the incision rate of ~0.4 m/ka for the last 138 ka. The most extended terrace (T6, 25.0 ± 0.5 ka) indicates an incision rate of ~0.5 m/ka in the Konista Basin and the lower Vikos gorge (Fig. 5A). In the middle section of the Vikos gorge, the surfaces of T6 terraces show an abrupt offset of 15 m. This can be connected to the vertical motion of the Papigo fault (Fig. 5B) that corresponds to an active tectonic feature defined by Waters (1993). Because terraces of the T7 unit are placed on both sides of the Papigo fault and show low and similar incision rates (~0.6 m/ka), we suggest that the fault has not been subject to significant displacements since the abandonment of T7. Taking into account a difference of ~8 ka between the ages of T6 and T7, the vertical motion along the Papigo fault reaches a rate of ~1.8 m/ka between ~25.0 and 16.8 ka. Other active faults such as the Konista fault (Waters, 1993), which delimits the southeast edge of the Konista basin, and the Vikos fault, which is located in the upper part of the gorge, do not affect the topography of the terraces. This suggests that they have been inactive since at least ~25 ka (Fig. 5B).

Conclusions

From dating and field investigations, we constrained the temporal evolution of alluvial terraces of two rivers in the southern Albania. The development of the youngest Holocene terrace unit is not climatically driven but is rather the consequence of human occupation of the catchment in historic times. Indeed, the settling of the human population led to deforestation and development of agriculture, producing an increase in soil erosion. This young terrace unit can be flooded during catastrophic precipitation and discharge events, and its sediments can potentially be remobilized. For the other terraces, ages of terrace units correlate with well-identified cold and dry climate periods that confirm the relation between terrace development and climatic changes. The two highest and oldest terrace units correspond to two periods of noticeable alleviation, which have been identified in rivers of the Mediterranean basin during MIS 6. Nonetheless, the first half of the Würm glaciation is characterized by the absence of deposits for nearly 80 ka. We mapped and dated 6 terrace units that have been formed during the second half of the Würm between ~52 to ~11 ka. A drastic rise of the incision rate occurs since the LGM and highlights the short-term response of incision evolution to climate change.

We also showed that the diachronism of the terrace abandonment is rather small (less than a few ka). The comparison of terraces deposited during the same climatic period thus allows the quantification of incision produced by surface uplift. Consequently, we identified multi-scale responses to the regional uplift. A regional bulging generates a steady increase of incision along the Osum from the west to the east, with rates reaching 2.8 m/ka in the hinterland. In the internal Albanides, the uplift decreases towards the south and reaches a value of less than 0.5 m/ka in the area of the Vikos National Park. We identified local increases in incision rate caused by active normal faulting, which allow us to estimate vertical displacements: 2.2 m/ka for the West Ersekë fault for the last ~19 ka, and 1.8 m/ka for the Papigo fault between ~25.0 and ~17 ka. These estimations give quantitative information on the mid-term evolution on both the regional uplift and the local activation of normal faults, over a scale of 10^3–10^4 yr.

The studied rivers do not cross all the neotectonic features of the Albanides, but our study outlines the importance of SW–NE trending active normal faulting in the southern part of Albania. This result is in agreement with the NW–SE extension deduced from the GPS network.

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