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Research article

Fluvial terrace formation in a mountainous area (2): influence of eustatism, tectonics and altitudinal distribution of watersheds based on an allostratigraphic study (Albania)

Jean-Louis Mugnier [*, a], **Oswaldo Guzmán** [a, b], **Riccardo Vassallo** [a], **Kristina Matraku** [a, c] and **François Jouanne** [a]

[a] ISTerre, Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS, IRD, Le Bourget du Lac, France

[b] Grupo de Investigación en Ciencias de La Tierra y Clima, Universidad Regional Amazónica Ikiam, Muyuna, Ecuador

[c] Institute of Geosciences of the Polytechnical University of Tirana, Albania

E-mail: jemug@univ-smb.fr (J.-L. Mugnier)

Abstract. Terraces are highly developed along the Albanian rivers and eleven levels of terraces are recognized in the area, nine occurring during the last glacial cycle (MIS 5d to end of MIS 2). An allostratigraphy study of the fluvial terraces shows a large variety of the geometry of the sedimentary units beneath this set of terraces. This variety is controlled by the respective amount of the three parameters: lateral erosion, aggradation and difference between incision and aggradation.

Active faults offset the paleoriver profiles at throw rates locally greater than 1 $mm \cdot yr^{-1}$ and the tectonic uplift influences the long term incision: Nested strath terraces or nested filled terraces with substratum risers occur in zones of high uplift rate (greater than 0.4 $mm \cdot yr^{-1}$), superposed units and nested fill terraces with hidden substratum risers occur in the weakly uplifted zones of the intra-mountainous graben-like structures.

Most of the Albanian terraces are located above straths (nearly flat erosional surfaces) linked to phases of lateral beveling. The thickness of the sedimentary units above the strath surfaces is mostly influenced by the altitudinal distribution of the river catchments: thin strath terraces are found in the low elevation catchments, while thick fill terraces are found in large catchments and we suggest here that the deposition of fill terrace sediments occurred very rapidly at the cold-warm transitions when the high elevation areas of the large catchments were not protected by vegetation and heavily affected by hillslope processes that delivered a large volume of sediments. The thick Holocene valley fill, locally affected by fill-cut terraces, extends several tens kilometer within the mountain valleys and is probably linked to the mid-Holocene sea-level highstand.

Keywords. Strath, Fill-terraces, Strath terraces, Climatic and vegetation controls, Late glacial stage, Paraglacial.

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* Corresponding author

1. Introduction

A huge body of published works [e.g. bibliography in Cordier et al., 2017] suggests that the formation of river terraces is affected by the climate. Numerous studies show that terraces are not a simple climatic proxy [Merritts et al., 1994, Schanz et al., 2018, Pazzaglia, 2013] and tectonics, eustatism and climate interact together in terrace formation [Starkel, 1994, Vandenberghe, 2015]. Furthermore, the pathway between climate and terrace development involves several steps: the climate includes both temperature and precipitation, but also controls the type of vegetation. All together, these factors control the sedimentary supply to the river and the water flux [e.g. Vandenberghe, 2008]; these hydro-sedimentary conditions control the balance between sediment supply and transport capacity [Bull, 1991]. This balance is expressed through several geomorphologic processes [i.e. aggradation in the river channel, deposition on the overbank during flooding, sediment reworking, vertical incision and lateral erosion linked to lateral migration of the channel; Schumm, 1977] and lastly, the succession of these processes controls the characteristics of the sediment and the geometry of the sedimentary units and terrace landforms.

The relative impact of these processes strongly varies from one zone to another depending on various geomorphological parameters like basin configuration and catchment size [Vandenberghe, 2015]. In the case of the lowland rivers of northern Europe, where a very low uplift rate usually leads to the superposition of units, it has been shown that rivers generally respond simultaneously to climatic changes when the latter are enhanced by vegetation degradation or growth [e.g. Vandenberghe, 2008]. In the case of mountain belts affected by tectonics and uplift, the influence of morphological parameters remains poorly understood. Amongst the numerous questions that still need to be answered, we will particularly focus on the following point: the effects of vegetation degradation or growth are clearly found in lowland environments [Wohlfarth et al., 2008] and we wonder if the same influence of vegetation could be inferred in the case of nested terraces in a mountainous zone.

Terrace levels deposited during the last glacial stage are widely preserved along all the Albanian rivers and their morphology has been widely studied [Melo, 1961, Prifti, 1984, Lewin et al., 1991, Woodward et al., 2008, Carcaillet et al., 2009, Koçi et al., 2018]. Eleven levels of terraces in Albania, nine occurring during the last glacial stage (MIS 5d to end of MIS 2) were dated [Woodward et al., 2008, Carcaillet et al., 2009, Guzmán et al., 2023]. Albanian river catchments (Figure 1a) are located in an area where the large-scale controls (climate, tectonics or eustatism) can be considered as homogeneous: the climate is Mediterranean [Ozenda, 1975], the tectonics is controlled by the Adriatic subduction beneath South Eastern Europe [Roure et al., 2004] and all of the rivers have a base level linked to the Adriatic Sea [Lambeck and Chappell, 2001]. The catchment characteristics (size, altitude distribution) of Albanian rivers vary from ~7,000 to ~1,000 km^2 (Figure 1b), Hence, their terraces allow to study how the catchment characteristics modulate the geomorphologic fluvial response to climate fluctuations in the Mediterranean domain.

2. Concepts and methodology

2.1. *Allostratigraphy and geometry of the units*

An allostratigraphic approach [Hughes, 2010] is used here to analyze the sedimentary units and terrace landforms. Allostratigraphy is the part of sequence stratigraphy adapted to continental sediments and is one of the major unifying concepts of the geosciences indispensable to large scale studies [McLaughlin, 2005] as it provides a framework for understanding the evolution of depositional systems through time. Allostratigraphy mainly focus on the determination of the boundaries of sedimentary units whereas lithostratigraphy and sedimentology focus on the characteristics of the sediments. We consider that allostratigraphy is the most adapted method to compare the numerous terraces levels found along the more than 350 km long rivers of Albania and we systematically use the allostratigraphic approach.

In allostratigraphy, terrace surfaces, that are flat, gently dipping surfaces, are one of the types of the upper boundary of allostratigraphic units (Figure 2a). The lower boundary of the allostratigraphic units is frequently an erosional surface (strath surface) that affects the substratum or the top of a lower allostratigraphic unit. The sediment/bedrock relationships or very specific sediment form other boundaries of the

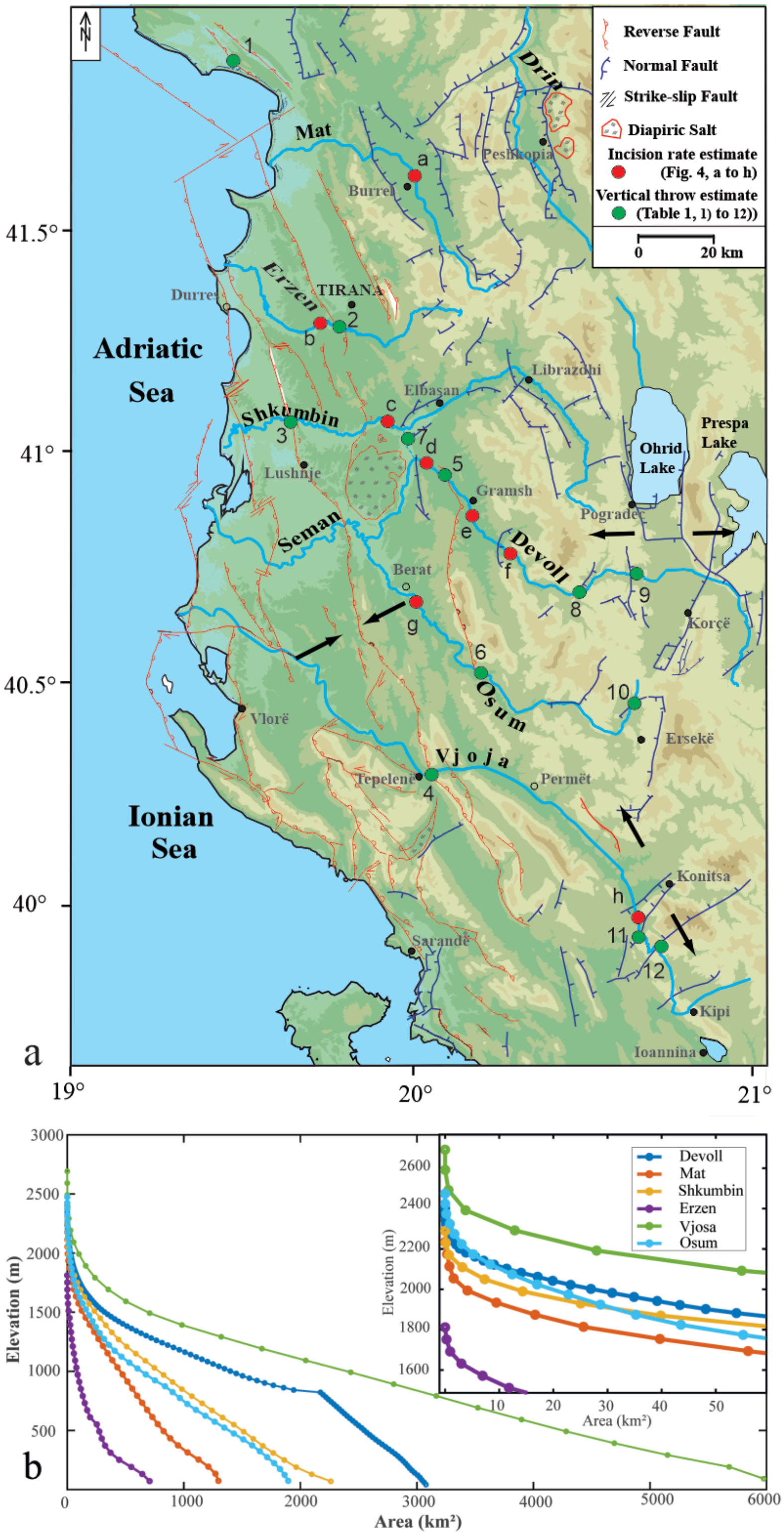

Figure 1. Caption continued on next page.

Figure 1. (**cont.**) The rivers of Albania. (a) Altitudinal and neo-tectonic map of the Albania and North-western Greece [modified from Aliaj et al., 1996 and Carcaillet et al., 2009]. Red circles (a–h) indicate location of the sites where the long-term incision rate has been estimated as far as possible from the active faults and in different tectonic compartments: (a) 1 mm·yr^{-1}; (b) 0.5 mm·yr^{-1}; (c) 1.1 mm·yr^{-1}; (d) 0.8 mm·yr^{-1}; (e) 0.8 mm·yr^{-1}; (f) 1.1 mm·yr^{-1} (see Supplementary Information, Figure 1, Appendix). The overall horizontal component of current tectonic deformation is represented by black arrows [from Jouanne et al., 2012]. Green circles (1) to (12) indicate sites where paleoriver profiles are offset by faults (see Supplementary Information, Table 1 Appendix): (1) Gornja Klezna Thrust (2.5 mm·yr^{-1}); (2) Tirana Back Thrust (0.4 mm·yr^{-1}); (3) Lushnje–Tepelenë Thrust (0.7–1 mm·yr^{-1}); (4) Lushnje–Tepelenë Thrust (0.2 mm·yr^{-1}); (5) Tomorrica Thrust (0.4 mm·yr^{-1}); (6) Tomorrica Thrust (0.3 mm·yr^{-1}); (7) Elbasan Normal Fault (>1 mm·yr^{-1}); (8) Bulcar Normal Fault Devoll (0.3 mm·yr^{-1}); (9) Korça Normal Fault (>0.8 mm·yr^{-1}); (10) West Ersekë Normal Fault (1.3 mm·yr^{-1}); (11) Konista Normal Fault (>0.4 mm·yr^{-1}); (12) Papingo fault (0.6 mm·yr^{-1}). (b) Altitudinal distribution of the different catchments. On the y-axis is altitude (m), on the x-axis is cumulative area (km^2). The window on the top right is a zoom of the hypsometry of the high areas (see Supplementary Information, Appendix 2).

allostratigraphic units. Paleosols can also form the boundary between two superposed allostratigraphic sequences and reflect periods of lack of deposition. Fluvial risers, related to river incision, may laterally limit the allostatigraphic units and induce steps characteristics of nested terraces (Figure 2b). An allostratigraphic unit may be decomposed into several sub-units depending on the texture of the sediments, itself controlled by the mode of deposition. A superposition of fine-grained, colluvial, eolian, or overflow sub-units on top of a coarse fluvial sub-unit is frequently found below terrace surfaces [Schanz et al., 2018].

The geomorphology of a mountain river valley is controlled by the long-term incision, and the allostratigraphic units express momentary fluctuations in this long-term incision due to others processes. Lateral erosion, incision and aggradation govern the geometry of the allostratigraphic units and straths, gorges and basins are respectively the three end-members geometries associated with these processes (Full line squares of Figure 3s, 3g and 3b). Depending from the succession and respective amplitude of these three processes, a large variety of allostratigraphic units' organizations can develop (Figure 3).

Difference between aggradation and incision amount is of great importance when studying nested terraces: The nested terrace geometry is formed of a succession of thick (fill) or of thin (strath-related) sedimentary units depending of the amount of aggradation. The nested units are separated by substratum risers (Figure 3s and 3f) if the vertical incision between two terraces deposition phases is greater than the sum of the sediment thickness deposited during the two phases. On the contrary, there is no substratum riser if vertical incision is smaller than the sum of the thickness of the two sedimentary units (Figure 3f-h). Fill-cut terrace is formed if the vertical incision between two terraces deposition phases is smaller than the sediment thickness deposited during the first phase of deposition (Figure 3f-c). A superposition of sedimentary units occurs when the vertical incision is almost null between two phases of aggradation (Figure 3s-u). A combination of superposed sedimentary units and nested terraces can be inferred in the case of thick fill-cut terraces (Figure 3t-f-c). When the role of lateral erosion is weak, no strath forms and aggradation occurs above the steep flank of a valley (Figure 3v). In some plain-like valleys, only aggradation is observed (Figure 3b).

2.2. *Strath versus fill terraces*

From pioneer [Gilbert, 1877] to recent [Pazzaglia, 2013] works, it is classically distinguished fill and strath terraces. A huge body of published works [see references in Cordier et al. [2017] and Pazzaglia [2013]] based on detailed sedimentological description of the deposits and application of sedimentological concepts nourish numerous discussions about their dynamic of formation.

In the following, a systematic allostratigraphic unit description, coupled with a comparison with the geometry of the actual river morphological flood plain is used and allow a very simple criteria to distinguish between strath terrace and fill terrace.

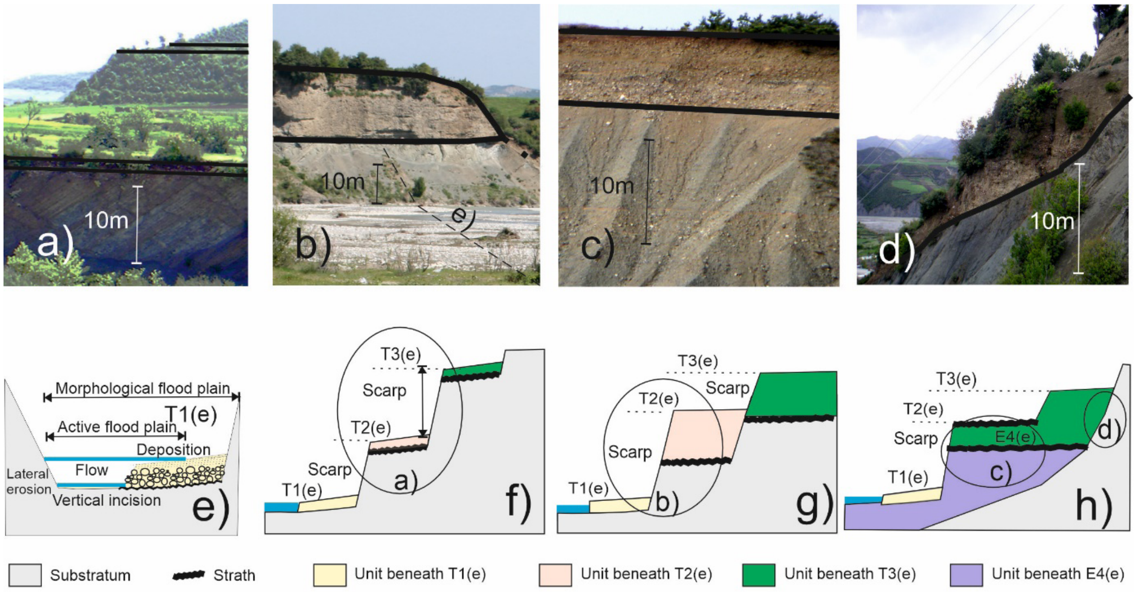

Figure 2. Examples of boundaries of allostratigraphic units in Albania. (a) Strath terrace bounded at the top by a flat terrace surface and at the bottom by a flat strath surface beveled in the substratum; (b) filled terrace limited laterally by a fluvial riser, at the top by a flat terrace surface and at the bottom by a flat strath surface beveled in the substratum; (c) Superposed units bounded by an erosional surface; (d) a valley fill laterally aggrades along the valley flank; (e) geomorphologic processes and sub-units involved during the formation of the actual flood plain terrace unit; (f) a sketch of nested strath terraces; (g) a sketch of nested fill terraces above straths with hidden substratum riser (between $T3_{(e)}$ and $T2_{(e)}$) or visible riser (between $T2_{(e)}$ and $T1_{(e)}$), respectively; (h) a sketch of a fill terrace ($T3_{(e)}$) above deposits constituted of two units aggrading on the flank of a valley and of a fill-cut terrace ($T2_{(e)}$). The circles and the dotted lin refer to the location of another part of this figure.

Fill terraces are the upper boundary of very thick allostratigraphic units (Figure 2g and 2h) that could reach thicknesses of several hundred meters [e.g. Tofeld et al., 2017] and their lower boundary type is various either valley slope, paleo-soil or strath surface.

The lower boundary of the allostratigraphic unit located beneath a strath terraces is a strath—an erosional surface—nearly parallel to the top of the terrace and located at the base of a thin sedimentary sequence [see Schanz et al., 2018]. Locally, the thickness of the unit is null [Mugnier et al., 2005, Seong et al., 2016] and the top of the strath terrace coincides with the bedrock erosional surface.

Straths are observed at the base of allostratigraphic units of very variable thicknesses (Supplementary Information, Figure 5 Appendix), and the thickness of the alluvial unit is a long-discussed criterion in the definition of a strath terrace [Pazzaglia, 2013]. From an adaptation of the work of Schanz et al. [2018], a characteristic thickness deduced from the present geometry of the morphological flood plain has been used to separate fill terraces from strath terraces.

In the case of a strath terrace, the basal strath was still beveled by lateral erosion during the high energy hydrological events [Hancock and Anderson, 2002] that remobilized the coarse deposits [Limaye and Lamb, 2016], whereas the morphological flood plain [Hauer et al., 2021] was flooded by great inundations [e.g. Vandenberghe, 2015]. The remobilization and flooding ended due to the following vertical incision phase. Therefore, the thickness of the sedimentary unit of a strath terrace scales with the

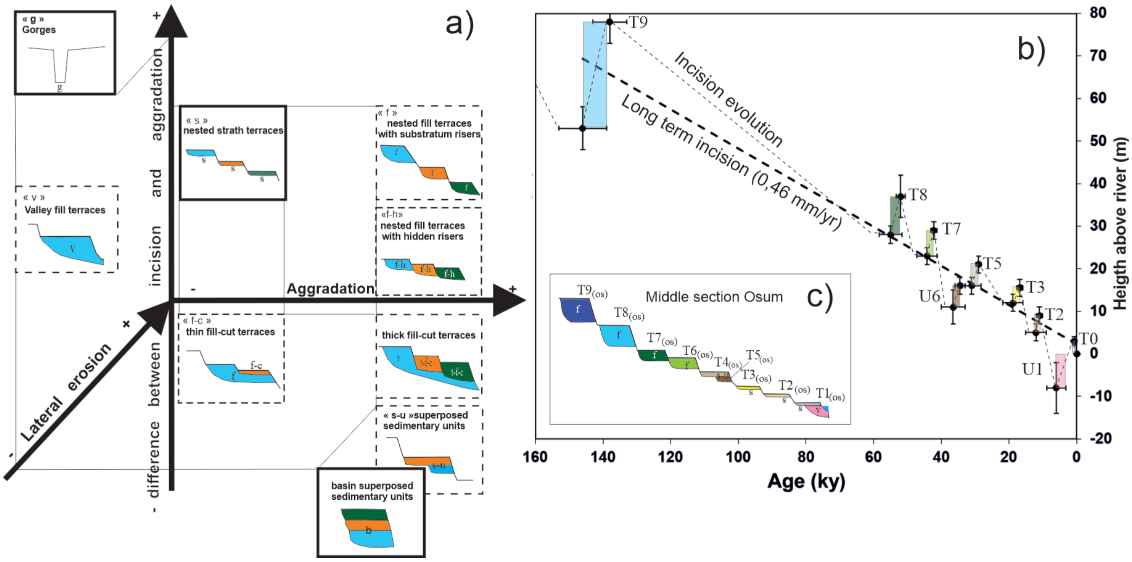

Figure 3. (a) Large scale organization and typology of the allostratigraphic units. The squares in full-lines refer to the three end-member organizations (b for basin, g for gorges and s for nested strath terraces). The squares in dashed-lines refer to examples found in Albania. f = nested filled terraces (lower Vjosa River); f-h = nested fill terraces with hidden risers; s-u = superposed units (Osum River); v = valley fill (paleo-Devoll, Cërrik plain); f-c = strath terraces cut in a previous fill terrace (upper part of the Vjosa River); t-f-c = thick sedimentary unit deposited above a strath cut through a previous fill terrace (possibly upper part of the Vjosa River). (b) Time evolution of the incision from measurements in the middle section of Osum river. Note that the tops of the terraces are dated but not their bases and it is assumed that the strath surface were mainly linked to a lateral beveling and that deposits occurred fast (see discussion). The long-term incision rate is deduced from a linear fit. (c) Simplified diagram of the terrace geometry identified along the Osum River.

scour depth of the present channel [Pazzaglia, 2013] incised through the lowermost terrace unit ($T1_{(e)}$, Figure 2e).

In the case of a fill terrace, the thickness of the sedimentary unit had increased due to the vertical aggradation and beveling of the strath ended as soon as the deposits above the strath became thicker than the thickness of sediment remobilized during high energy hydrological events [Sklar and Dietrich, 2001].

In this work, the distinction between a strath terrace and a fill terrace located above a strath surface is therefore based on the comparison of the past allostratigraphic geometry (unit thickness) with the actual dynamics of the river (height above the low flow of the morphological plain still flooded during centennial to millennial extreme flows). This height varies from one river to another and has been estimated for each Albanian river.

2.3. *Determination of the geometry of the allostratigraphic units*

Field survey have been performed along the 7 Albanian rivers to define the geometries of the allostratigraphic units from the lithostratigraphy and the geometry of the interface between Quaternary sediment and bedrock. Our database is formed of approximately one thousand sites of observations of the sedimentary units where sedimentary log, photos and precise thickness measurement were performed. The sub-unit thicknesses and the elevation of the terrace surface above the present low flow river level were measured using a laser rangefinder with an absolute accuracy of ± 0.003 m, but the actual accuracy is ~0.3 m due to the natural roughness of the surfaces considered. The terraces extends were estimated on, satellite images, a digital elevation model [DEM; SRTM, 2013] and topographic maps [Institutin

Topografik te Ushtrise Tirana, 1959–1990]. The river profiles were performed from the DEM and the paleoriver profiles were deduced from a correlation between terrace remnants of same age and from their measured elevation above the present river profile. A total of 5 river profiles and 8 paleoriver profiles were already presented by Carcaillet et al. [2009] and Guzmán et al. [2013].

3. Setting

3.1. *Paleoclimate of Albania*

The present-day Albanian climate is Mediterranean on the coast with hot and dry summers and rather mild and rainy winters. In the mountainous regions, the climate is continental with cold and snow-covered winters. The vegetation is organized into altitudinal belts: The meso-Mediterranean zone is restricted to the border of the sea [Ozenda, 1975], whereas alpine pasture lands are found over the timberline, currently located around 1900 m a.s.l. [Medwecka-Kornaś et al., 1986].

The paleo climatic records in the Albanian region [Sánchez Goñi et al., 2002, Sadori et al., 2016] correspond well with the succession of cold periods followed by rapid warm excursions [Clement and Peterson, 2008] found in the eastern Mediterranean Sea [Konijnendijk et al., 2015]. Furthermore, declines in precipitation probably occurred in Western Mediterranean area during cold periods [Kallel et al., 2000] whereas increases occurred during warm intervals [Toucanne et al., 2015]. Changes of the vegetation during interstadial events were evidenced by pronounced reductions in arboreal pollen frequencies in western Greece [Tzedakis et al., 2004, Sadori et al., 2016].

Glaciers developed in the Mediterranean mountains [Hughes and Woodward, 2017] during the last glacial stage (MIS 5d to MIS 2). Glacial features are found in the upper part of the Vjosa-Voidomatis Basin [Hughes and Woodward, 2017] where the glacial equilibrium line altitude (ELA) was close to ~2170 m a.s.l. The ELA was lower northward, reaching an altitude of ~2000 m a.s.l. in northeastern Albania [Kuhlemann et al., 2009].

3.2. *Rivers and Terraces of Albania*

The main Albanian rivers are, the Vjosa, Osum, Devoll, Shkumbin, Erzen, Mat and Drin rivers (Figure 1). The Mat and Erzen rivers are smaller and their maximum altitudes are lower (1728 m a.s.l. in the Erzen catchment) than the other catchments (2523 m a.s.l. in the Vjosa and Osum catchments).

Fluvial terrace deposition punctuates the vertical incision along the main Albanian rivers (Supplementary Information, Figure 1 Appendix). The terraces of the upper Vjosa River (Also called Voidomatis), the middle Vjosa River, the Osum River, the Erzen River and the Drin River were mapped and dated by Woodward et al. [2008], Hauer et al. [2021], Carcaillet et al. [2009], Koçi et al. [2018] and by Gemignani et al. [2022], respectively. River and paleo-river profiles of the Osum, Skumbin, Devoll and Vjoja were already presented by Guzmán et al. [2013] and the terraces of the Devoll, Shkumbin and Mat rivers were mapped by Guzmán et al. [2023]. For each river, the successions of terraces surface are called $Tx_{(river)}$. Units are nonetheless labelled $Ux_{(river)}$ when the terrace surface, fully eroded, cannot be defined.

Previous works have already shown that dating of a same terrace level by different methods generally provide consistent ages [e.g. Woodward et al., 2008, Vassallo et al., 2015] and it was therefore considered [Guzmán et al., 2023; this article] a single database formed of 47 ^{14}C, 2 ^{36}Cl, 7 ^{10}Be, 3 TL, 8 U/Th and 3 ESR dates for the Albanian river terraces. The time correlations of these terraces are based on this database (Figure 4b and Supplementary Information, Table 3 Appendix).

It is found that Holocene terrace level (T1) was related to a rapid succession of valley incisions and valley fills that occurred during the warm climatic optimum whereas nine other terrace levels (T2 to T10) formed during the last glacial stage (MIS 5d to end of MIS 2) and were nearly synchronously with interstadial transitions toward warmer and wetter conditions [Guzmán et al., 2023].

3.3. *Geology and recent tectonics of Albania*

The Albanian mountains are parts of the fold belt, which was thrusted westward [Roure et al., 2004]. The eastern side of Albanides consist mainly of Jurassic ophiolites and Mesozoic carbonates, on top of which sit continental Cenozoic extensional basins. The western side of Albanides are mainly formed of carbonates topped by Mesozoic or Cenozoic flysch deposits [Roure et al., 2004]. A foreland basin,

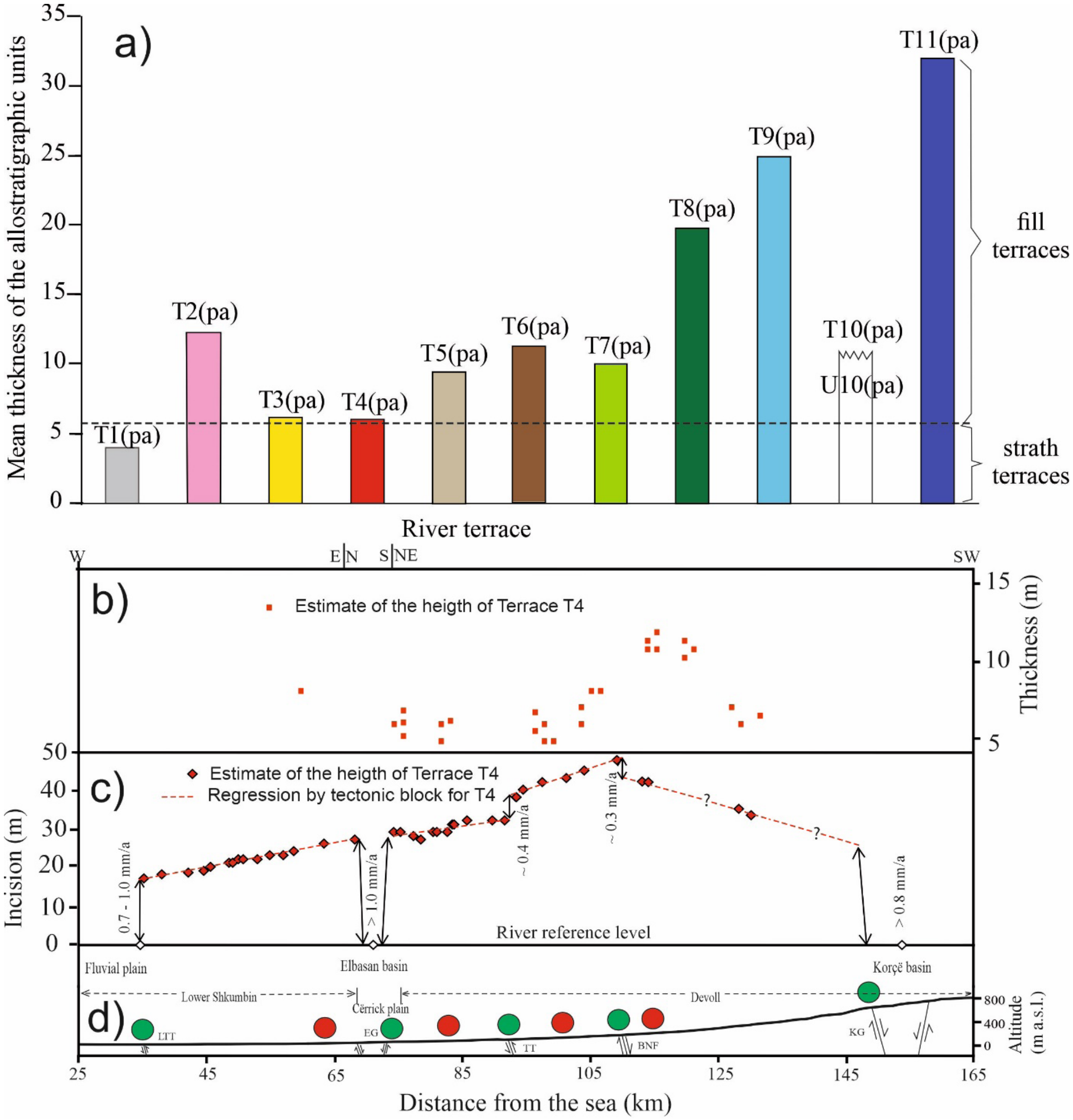

Figure 4. (a) Mean thickness of the allostratigraphic units beneath the paleo-Devoll terraces. The top of $T10_{(pa)}$ is everywhere fully eroded. The hatched line refers to the maximum height of $T1_{(pa)}$ above the low flow of the Devoll River and is the thickness limit used to separate the fill terraces from the strath terraces in the case of the paleo-Devoll. (b) Thickness of unit of $T4_{(pa)}$ (T4 in the regional nomenclature) in function of the distance from the sea. (b) Thickness of unit of $T4_{(pa)}$ (T4 in the regional nomenclature) in function of the distance from the sea. (c) Elevation of the top of $T4_{(pa)}$ (T4 in the regional nomenclature) above the actual river low flow. Green circles (3), (7), (8) and (9) indicate sites where paleoriver profiles are offset by faults; Red circles (c–f) indicate location of the sites where the long-term incision rate has been estimated (see Figure 1 for location Supplementary Information, Table 1 Appendix and Figure 1 Appendix). (d) Present day river profiles (successively Devoll and lower Skumbin) and location of the major active faults (LTT for Lushnje–Tepelenë Thrust, EG for Elbasan Graben, TT for Tomorrica Thrust, BNF for Bulcar Normal Fault and KG for Korçë Graben). Locations of the red and green dots on Figure 1.

filled with Plio-Quaternary molasse deposits, forms a coastal plain [Guzmán et al., 2023]. The synorogenic grabens crosscut the thrust system [Aliaj et al., 1996, Guzmán et al., 2013].

The Outer Albanides and the associated foredeep was controlled by a complex tectonic interplay during the Neogene between a rifting episode and the usual foredeep flexural evolution above the subducted Adriatic Sea plate [Scrocca et al., 2022]. The roles of gravitational potential energy and rheology contrasts in mountain belts is still debated in the development of subparallel thrust and normal faulting in Albania [Copley et al., 2009]. Furthermore, a clockwise oroclinal bending [Handy et al., 2019] is still in process and induces an orogen-parallel extension (NW–SE) in the deformation field [Jouanne et al., 2012]. Therefore, the recent active fault pattern is complex and delineate numerous tectonic compartments (Figure 1).

Vertical slip rates for active faults in Albania were estimated from the offset of the paleoriver profiles reconstituted from mapping of terraces (~for the last 19 ka; green circles on Figure 1 and Supplementary Data, Table 1, Appendix). Thrusts, that extend more than 120 kilometers, have throw rates that varies from 0.2 to 0.8 mm/yr [Guzmán et al., 2013, Koçi et al., 2018] but could reach locally more than 2 mm/yr [Gachelin, 1977], whereas the active faults of the extensional domain are segmented but are very active, with throw rates reaching locally 2 mm/yr [Guzmán et al., 2013]. Furthermore, an orogen-perpendicular (SW–NE) uplift gradient is found and an orogen-parallel (NW–SE) uplift gradient is locally added by the (far field) effects of major transverse fault, like the Shkodra-Peja Transverse Fault Zone (SPFZ) [Biermanns et al., 2018].

The late Pleistocene uplift rate of the compartment between faults, inferred from the long-term fluvial incision depends from the tectonic and geographic setting [Carcaillet et al., 2009]. Each compartment itself undergoes a variable uplift, linked to folding but above all to tilting (Figure 4b). The incision in the middle of the compartments are the following (Supplementary Data, Figure 1, Appendix): At the hanging wall of the major Albanides/foreland thrust boundary, the incision rate is respectively of 1.0 mm/yr along the Mat River, 1.1 mm/yr along the Skumbin River, 0.8 mm/yr along the lower part of the Devoll River, and 0.5 mm/yr along the Osum River. It is of 0.46 mm/yr at the hanging-wall of the Tirana Back thrust and 1.1 mm/yr in the upper part of the Devoll at the hangingwall of the Tomorrica Thrust. In the Elbasan and the Korçé graben sedimentation is still occurring [Prifti and Meçaj, 1987] whereas the incision rate is of 0.13 mm/yr in the Konista graben.

4. Comparison of the allostratigraphic organization of the Albanian terraces

4.1. *The Vjosa river terraces*

The Vjosa River, more than 272 km long, is made up of sections with very different morphologies [Hauer et al., 2021]. Ten terrace levels are identified along the Vjosa River [Guzmán et al., 2023]. The coarse sub-units beneath the terrace surfaces are mainly formed of rounded fluvial clasts but, angular calcareous clasts, related to debris flows, are locally intercalated within the fluvial units. Furthermore, detailed sedimentological studies [Lewin et al., 1991] show a change in the sediment dynamics linked to glacier retreats at the end of MIS2: Fine-grained slackwater sediments were deposited by large floods fed by meltwaters from glaciers sometime after 21.3 ka for $T3_{(vj)}$, and by rainfall-generated floods between 17.9 and 16.2 cal·ka for $T4_{(vj)}$ [Woodward et al., 2008].

In its upper section, the river crosses the graben structure of Konista (Figure 1) where eight units (Figure 5), including the present-day channel ($T1_{(vj)}$), were identified. All, except $T2_{(vj)}$ were dated [Lewin et al., 1991, Woodward et al., 2008]. The highest terrace $T10_{(vj)}$ was deposited by a river system with a much larger catchment that was pirated before 350 ka [Macklin et al., 1997]. The $T10_{(vj)}$ and $T8_{(vj)}$ units are related to fill terraces [Lewin et al., 1991, Woodward et al., 2008]. The substratum does not outcrop between $T7_{(vj)}$, $T6_{(vj)}$ and $T4_{(vj)}$ terraces [Woodward et al., 2008] and they are either directly deposited above the substratum or are thick fill-cut terraces formed during a process of down-cutting within the $T8_{(vj)}$ fill terrace. $T3_{(vj)}$ is superposed onto unit $T4_{(vj)}$ [Woodward et al., 2008] but is locally a thin "fill-cut" terrace cut within $T4_{(vj)}$ [Lewin et al., 1991]. Lastly, $T2_{(vj)}$ is a strath terrace.

In the middle section of the Vjosa River, the long-term incision is greater than in the upper section [Guzmán et al., 2013]. Guzmán et al. [2023] indicated

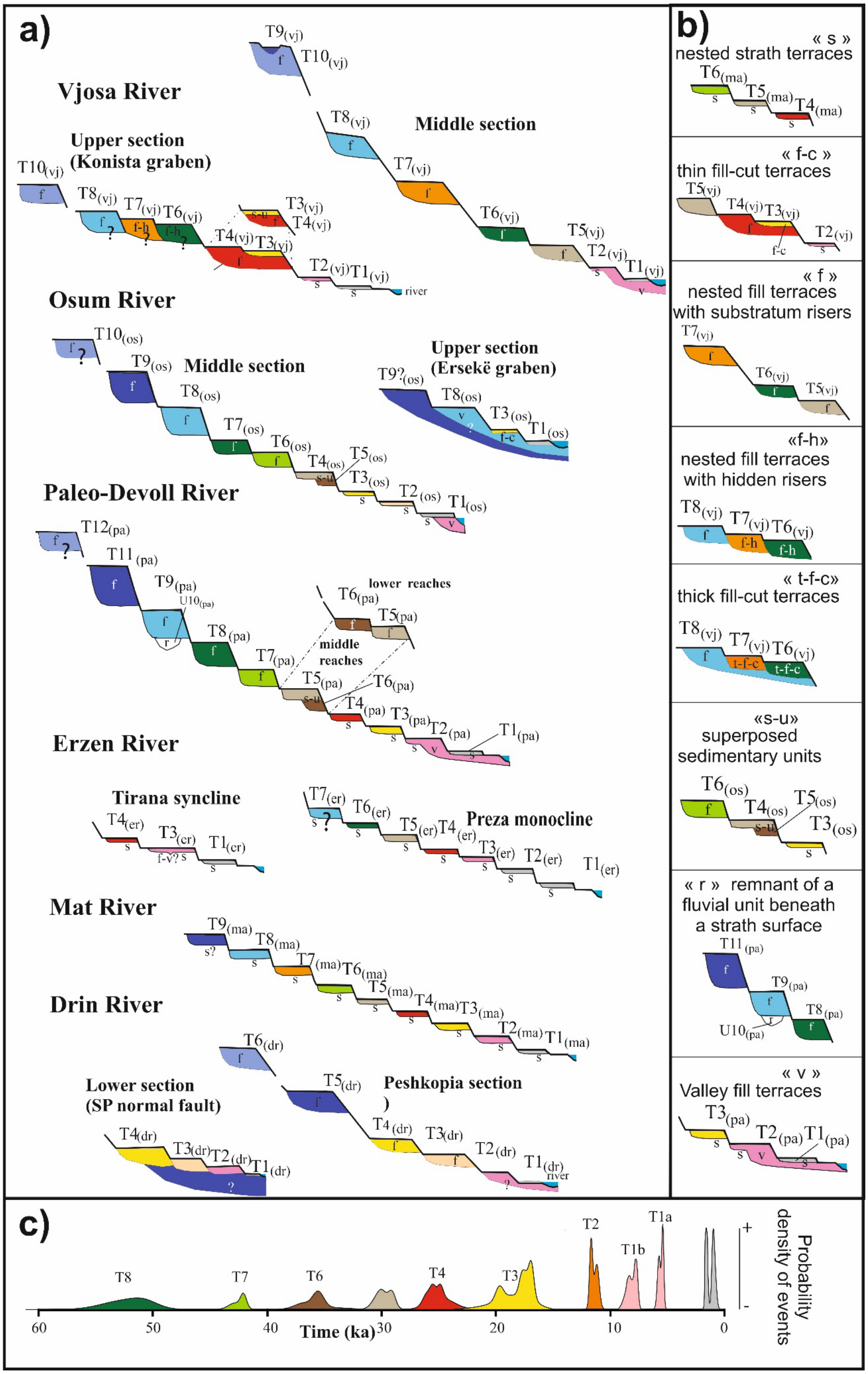

Figure 5. Caption continued on next page.

Figure 5. (**cont**.) (a) Simplified diagram of the terrace geometry identified along the 7 main Albanian rivers. The horizontal and vertical axes are not to scale. The terrace colors refer to the regional nomenclature TX (see Figure 5c). (b) Typical terrace geometries. Letters s, f-c, f, f-h, t-f-c, s-u, v refer to the types of organization of the allostratigraphic units indicated on Figure 3. (c) Age distribution of the terraces [adapted from Guzmán et al., 2023].

a level $T9_{(vj)}$ formed of paleo-meanders cut in $T10_{(vj)}$. Prifti and Meçaj [1987] mapped four fill terrace levels $T8_{(vj)}$ to $T5_{(vj)}$ and substratum frequently outcrops in the fluvial risers between the nested fill terraces. Furthermore, a large scale strath surface is clearly evidenced at the base of $T10_{(vj)}$ and $T5_{(vj)}$ thick fill terraces [Guzmán et al., 2013]. Finally, $T2_{(vj)}$ is located at the top of sediments more than 50 meters thick located below the present river [Prifti, 1981]. Geophysics would suggest that these lowest sediments could be divided into two distinct sedimentary units [Prifti, 1981].

4.2. *The paleo-Devoll River terraces*

The Devoll and Shkumbin rivers are presently separated by approximately 5 km at the level of a wind gap where a paleo-Devoll River flowed northward and was connected to the Shkumbin River till the beginning of the Holocene [Guzmán et al., 2023]. Hence, the terraces located along the middle reaches of the Devoll and the lower reaches of the Shkumbin formed a unique terrace system of eleven terrace levels [Guzmán et al., 2023].

Two superposed sub-units generally form the units: A thin upper sedimentary sub-unit (~1 m) is composed of clay, siltstone, fine sand and organic material. Nevertheless, its thickness reaches more than 2 m for the oldest terraces ($T12_{(pa)}$, $T11_{(pa)}$ and $T9_{(pa)}$) and possibly includes loess and colluvium deposited after the fluvial story. The basal sub-units consist of rounded pebbles and cobbles that are supported by a gravel and sand matrix. Clast size generally decreases towards the top, while the percentage of matrix increases. Nonetheless, the size of the coarse material shows complex variations and conglomerate sometimes alternate with horizontal stratified, fine to coarse sand levels. Sediments of the basal unit were probably deposited in a braided alluvial system characterized by cross-stratified rounded pebbles and cobble levels that alternate with horizontal stratified, fine to coarse sand levels. Nonetheless, evidence of a meandering environment is found at the base of the unit $U10_{(pa)}$ whose upper part is fully eroded (Figure 6b) and where sediments dip steeply.

The sedimentary units the paleo-Devoll River were generally deposited on straths beveled in the flysch or molasse substratum. The substratum often outcrops in the risers between the nested terraces (Figure 6). Nonetheless, from the mountain front to the Cërrik plain, the base of the allostratigraphic unit $T2_{(pa)}$ is hidden and located several tens meters lower than the present river level [Melo, 1961], suggesting here a thick valley fill.

The morphological flood plain (top surface of $T1_{(pa)}$) was measured between 2 and 6 m above the low flow river (Figure 4a). $T4_{(pa)}$ and $T3_{(pa)}$, with thicknesses between 4 and 6 m, are therefore considered as strath terraces whereas $T12_{(pa)}$, $T11_{(pa)}$, $T9_{(pa)}$, $T8_{(pa)}$, $T7_{(pa)}$, $pT6_{(pa)}$, and $T5_{(pa)}$ are fill terraces as their mean thicknesses are between 10 and 32 m (Figure 4a).

In the downstream part of the paleo-Devoll, $T6_{(pa)}$ and $T5_{(pa)}$ are stepped terraces where the substratum riser is hidden. Upstream, $T6_{(pa)}$ is not evidenced, but two allostratigraphic units are located beneath the surface of $T5_{(pa)}$ (Figure 5); the boundary between the two allostratigraphic units is an erosional surface, also expressed laterally by a strath surface beveled in the substratum (Figure 6c). The lower allostratigraphic unit extends several tens of kilometers and is formed of a gravel and pebble sediments subunit overlained by a flood plain deposit sub-unit; The lower allostratigraphic unit $U6_{(pa)}$ could be the lateral equivalent of $T6_{(pa)}$, and this upstream evolution from encased terraces to superposed units could be due to an increase in the slope of the Paleo-Devoll River between the deposition of $T6_{(pa)}$ and $T5_{(pa)}$.

Tectonics locally strongly affects the sedimentation in the Devoll-Shkumbin area. The Elbasan plain upstream of the junction between the Paleo-Devoll and the Shkkumbin, is located in a graben. The faults bounding this graben offset T1, at a rate > 1–2 mm/yr for the last 6 Ka. In the center of the graben, several

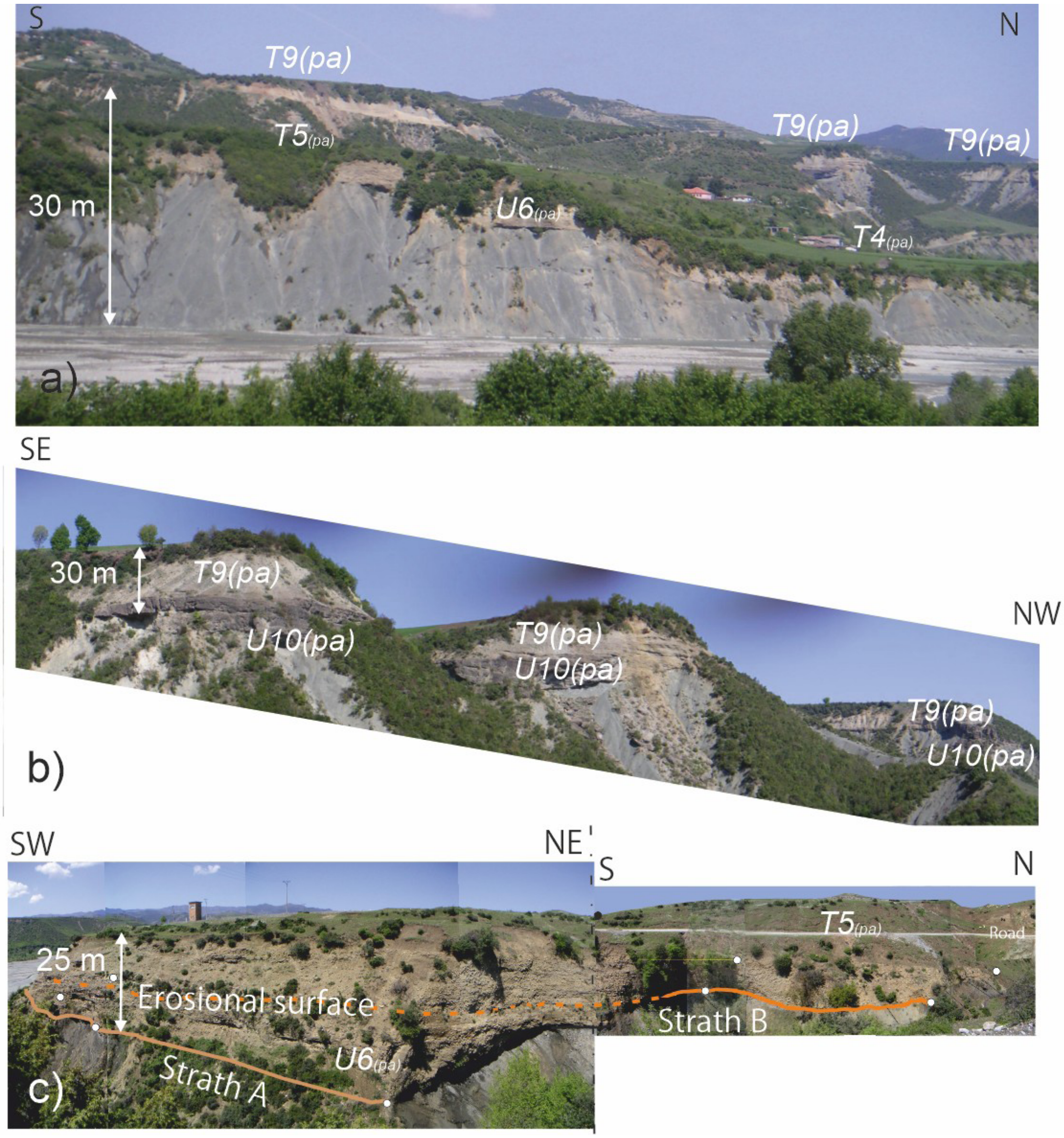

Figure 6. (a) Nested fill terraces along the Devoll. Details of $T9_{(pa)}$, $U6_{(pa)}$ and $T5_{(pa)}$ are shown on Figure 6b and 6c. (b) The remnant of the base of $U10_{(pa)}$ is located beneath the strass surface at the base of the thick $T9_{(pa)}$. (c) Superposition of the allostratigraphic units $T5_{(pa)}$ and $U6_{(pa)}$ (upper middle reaches of the Devoll River) above two distinct straths (A and B). Unit $U6_{(pa)}$ is located between the strath A and the erosional surface, in the continuity of strath B.

sedimentary units are superposed over more than 100 meters [Melo, 1961]. In the upstream part of the Devoll, a lake developed in the Korca graben till 19eme century, but the geometry of sedimentary units is here unknown.

4.3. *The Osum river terraces*

In the Osum River area, ten terraces were mapped and 5 dated [Carcaillet et al., 2009, Guzmán et al., 2023] (Figure 5). In the Ersekë graben (upper reach of the Osum River), a thick superposition od sedimentary units is observed, and $T3_{(os)}$ is possibly beveled in $T7_{(os)}$ (Supplementary Information, Figure 2 Appendix). In the middle reaches of the Osum River $T10_{(os)}$ to $T6_{(os)}$ are fill terraces [Carcaillet et al., 2009]; the sedimentary unit linked to $T4_{(os)}$ is superimposed above another allostatigraphic unit $U5_{(os)}$ whereas $T3_{(os)}$, $T2_{(os)}$ and $T1_{(os)}$ are strath terraces [Carcaillet et al., 2009]. A ~20 m thick sedimentary unit is located beneath the present-day river [Prifti and Meçaj, 1987] and is probably younger than $T2_{(os)}$ and therefore Holocene in age. This hidden unit would be in this case a T1 unit in the nomenclature of Supplementary Information, Table 3 Appendix.

In the middle reaches of the Osum River, gorges more than 50 m deep and less than ~5 m large were locally incised in a weakly extended cretaceous limestone outcrop. This zone is located between flysh outcrops where the long-term incision rate of strath terraces is 1.3 ± 0.5 mm/yr [Guzmán et al., 2013] (Supplementary Information Figure 2 Appendix) and the absence of lateral erosion in the limestone prevented any beveling during more than 30 Ka.

4.4. *The Erzen River terraces*

The terraces of the Erzen River have been mapped by Koçi et al. [2018]. An active back-thrust fault [Ganas et al., 2020; see Figure 1] offsets the domain and a time correlation between the terraces on each side allow defining 7 terraces levels [Guzmán et al., 2023]. At the transition between the plain and the first mountain relief, the morphological flood plain is very large, locally more than 13 m above the low flow river and dated at ~1.5 cal·kyr before present [Guzmán et al., 2023], suggesting a recent (less than 1.5 kyr) uplift. To consider the local development of a riser, the morphological flood plain has been separated in two parts: $T1_{(er)}$ and $T2_{(er)}$ (Figure 5). The terrace $T3_{(er)}$ is highly extended, in peculiar across a wind gap which corresponds to a paleo river that flowed close to Tirana (Figure 1a). The others terraces $T4_{(er)}$ to $T7_{(er)}$ are strath terraces as their sedimentary units are less 4-m thick and lay above strath surfaces (Supplementary Information Figure 3 Appendix).

4.5. *The Mat River terraces*

Nine terraces (Figure 5) were mapped along the Mat River [Melo, 1996] and five of these levels dated [Guzmán et al., 2023]. The sedimentary units of the terraces lie above a strath surface beveled in the bedrock. They are made up of a 3 to 5 m thick alluvium of gravel and sand that slopes upwards, and an upper sub-unit of fine sediments of fine sediments 0.5 to 1 m thick. The thickness of the alluvial unit beneath the highest $T9_{(ma)}$ is nonetheless locally greater and reaches 8 m. The top surface of the morphological flood plain $T1_{(ma)}$ was measured between 1 and 5 m above the low flow river, and the terraces of the Mat River are therefore considered as strath terraces.

4.6. *The Drin river terraces*

The Neogene-Quaternary graben structures control the drainage pattern the Drin River area [Aliaj et al., 1996]. At the hangingwall of Shkoder-Peja (SP) Normal Fault, four terraces are described [Pashko and Aliaj, 2020, Gemignani et al., 2022]. $T2_{(dr)}$ and $T3_{(dr)}$ are nested filled terraces, with hidden risers, that are cut within an older (Pleistocene or late Pliocene) lake sediment unit [Gemignani et al., 2022]. Upstream, close to Peshkopia (Figure 1), two higher terraces, $T5_{(dr)}$ and $T6_{(dr)}$ are described [Guzmán et al., 2023] and the substratum riser crop out between the thick and nested units (Figure 5). Furthermore, strath surfaces are clearly expressed at the base of $T2_{(dr)}$ and $T3_{(dr)}$.

5. Discussion

5.1. *The typology of the Albanian terraces*

Along the seven rivers of Albania, various organizations of the allostratigraphic units were observed (Figure 5b). Despite this multitude of geometries, one of the most striking result in Albania is that only the T1 Holocene valley fill units and the $U10_{(pa)}$ unit are clearly characterized by the absence of a basal strath. Straths have been found at the base of most of the allostratigraphic units, regardless of their thickness and the considered rivers. These terrace units are possibly synchronous with interstadial climatic events during the last glacial stage [Guzmán et al., 2023], and their formation can be explained by the "cold terrace" model [Vandenberghe, 2015]. In this model, vertical incision is promoted by increased transport capacity during the transition from cold, dry conditions to warmer, wetter conditions [e.g. Fuller et al., 1998, Vassallo et al., 2007, Bridgland and Westaway, 2008], while deposition of sedimentary units and beveling of straths have occurred previously.

5.2. *Why and when thick fill sedimentary units deposited above strath surfaces?*

We found that most of the terraces are thin strath terraces in the two small catchments of the Erzen and Mat rivers, but are thick fill units deposited above the strath surfaces in the larger catchments of the Vjosa, Osum, paleo-Devoll and Drin rivers.

These results arise a crucial question: what controls the difference in development between fill and strath terraces? In other words: why and when thick fill sedimentary units deposited above strath surfaces? The uncertainty associated with the proposed temporal correlation between the terraces of different rivers [Guzmán et al., 2023] is too great to determine whether the synchronism being proposed relates to sedimentary deposits or to their incision. Even superposed sample sets dated in $T4_{(vj)}$ [Lewin et al., 1991, Woodward et al., 2008] do not allow distinguishing the age of the lowest fill deposits from that of the highest ones, themselves close to the terrace abandonment age. Similar situations have already been described elsewhere in the world [Wegmann and Pazzaglia, 2009, Gunderson et al., 2014, Vignon et al., 2016]. Understanding of what controls the difference in development of fill and strath terraces therefore allows inference of when the sediments of the fill terraces were deposited.

5.2.1. *The influence of eustatism, catchment size and lithology in terrace formation*

The influences of eustatism, catchment size or lithology in terrace formation have been proposed for solving the fill versus strath terrace dilemma:

- An upstream evolution along coastal rivers has been demonstrated [Merritts et al., 1994], with strath terraces found upstream of fill terraces linked to sea-level rise. In Albania, the effect sea-level highstand is only expressed for the Holocene, with shoreline modifications [Fouache et al., 2010] and diversions of the Drin [Ganas et al., 2020], Skumbin, Seman [Guzmán et al., 2023] and Vjoja [Fouache et al., 2010] rivers above their sedimentary fans in the foreland. In the lower part of the mountain belt, the T1 terraces are linked to strong aggradations along the Vjoje, Osum, Devoll and Drin rivers (Figure 5), as well as the deviations of the Devoll and Erzen rivers; they are probably linked to the upstream influence of the mid-Holocene sea-level highstand [Somoza et al., 1991]. A late Holocene vertical incision follows the formation of fill-cut terraces beveled by lateral erosion in the thick Holocene valley fills. The T1 terrace is therefore consistent with the "warm" unit model [Vandenberghe, 2015], but it is the only one in Albania.
- In Albania the correlation found between the catchment size and the thickness of the sedimentary units suggests that catchment size is a first order parameter for the genesis of a particular type of terraces. Nonetheless, the catchment areas located upstream of the fill terraces of the upper Vjosa and upper Osum (110 km^2 and 70 km^2, respectively) are of the same order as the catchments upstream of strath terraces of the Mat and Erzen (130 and 70 km^2, respectively). Therefore, the regional distribution of the fill or strath terraces in Albania is not simply a consequence of the size of the catchments.
- Wegmann and Pazzaglia [2009] showed in the Northern Apennines that strath terraces develop in catchments with siliciclastic lithologies whereas fill terraces develop in catchments with carbonate bedrocks. In Albania, all the rivers intersect a wide variety of geological zones [Roure et al., 2004]. No clear lithology dominances are evidenced for the bedload of the different Albanian river catchments [Woodward et al., 2008, Xhaferri et al., 2020]. No relation between thickness of the sedimentary unit and clast lithology is found in Albania. Thus, the bedrock lithology does not influence the type of terraces in Albania, although strath surfaces are generally beveled in flysch formation.

5.2.2. *The influence of tectonics in terrace formation*

The tectonic settings control the long-term incision rates in the Albania-Greece area [Carcaillet et al., 2009, Guzmán et al., 2013, Biermanns et al., 2018] and the active faults locally offset the paleoriver profiles deduced from the top of the terrace fly [Guzmán et al., 2013; Supplementary Information, Table 1 Appendix; Figure 4c].

Vignon et al. [2016] have shown that displacement along faults, mainly related to earthquakes close to the surface [Mugnier et al., 2005], could affect the thickness of a sedimentary unit if it occurs during its deposition, with a thinning of the unit above the uplifted compartment. Due to the moderate seismic intensity in Albania [fewer M 6.7 earthquakes and less than a few meters of surface rupture movement, from Pondrelli et al., 2006], this influence is nevertheless weak, although observed locally at the intersection of the Devoll and Bulcar Normal Fault (Figure 4b). Therefore, active tectonics does not transform a strath terrace into a thick fill terrace.

Furthermore, the regional distribution between fill or strath terraces is not linked to differences in the long-term incision rates: Terraces in the Erzen and Mat catchments are strath terraces, although the incision rates of the latter are double than the incision rates of the former (Red dots a and b on Figure 1); the thickest fill terraces both developed in the zone with the fastest incision rate (Upper Devoll) and the zone with the smallest incision rate (Konista graben of the Upper Vjosa) (Red dots f and h on Figure 1).

Therefore, tectonics cannot explain alone the regional distribution of the fill and strath terraces in Albania.

5.2.3. *The sediment production of the glaciers and the paraglacial domain*

The sediment production of the glaciers and the paraglacial domain is of great importance and is particularly significant during the reduction of glacier size [Ballantyne, 2002]. There are several evidences of ongoing paraglacial adjustment linked to the present-day glacial retreat [Guillon et al., 2022]: Meltwater flow is greatly increased and downstream sediment discharge is influenced by sediment reworking and changes in fluvio-glacial connectivity [Tunnicliffe et al., 2012, Ravazzi et al., 2012].

Glaciers developed during the glacial stages in northwestern Greece and Albania [Hughes and Woodward, 2017]. Nonetheless, no paleo-glacier has been evidenced to date for the Osum and Devoll river catchments, whose surfaces above the 2174 m-paleo-ELA are 12 and 14 km^2, respectively. The surface above the paleo-ELA is significant only in the case of the Vjosa River where it reaches 120 km^2 (see Figure 1b and Supplementary Information, Figure 1 Appendix).

The bedrock beneath the Vjosa River glaciers is limestone, and the increased proportion of limestone clasts in T3 to T8 suggests a significant contribution from glacial erosion [Woodward et al., 2008]. Nonetheless, ice only covered less than 10% of the upper catchment during the last glacial stage (MIS 5d to 2) whereas the paraglacial domain inherited from the previous glacial stages was extended [Woodward et al., 2008]. Therefore, the great aggradation phases in the upper reaches of the Vjosa River during the last glacial stage was partly linked to the direct glacial sediment input and probably enhanced by the remobilization of paraglacial sediment.

5.2.4. *Role of the altitudinal distribution of the vegetation*

The altitudinal distribution of the vegetation could have controlled terrace formation. gkIn a general manner, vegetation changes enhance the effect of precipitation and temperature on the sediment supply and water runoff [e.g. Bull, 1991, Kasse et al., 2005]. Our data indicate that the altitude distribution of the catchments (Figure 1b) modulates the geomorphic response of the fluvial system: fill terraces develop in catchments with large high-altitude zones while strath terraces in catchments with smaller high-altitude zones (Figure 7). We suggest that this difference in terrace formation is mainly related to the vegetation contrast between the lower and higher part of the range [Tzedakis et al., 2004, Wohlfarth et al., 2008] that is enhanced during cold and dry periods [Kallel et al., 2000, Toucanne et al., 2015]:

- In the high-altitude part of the large catchments, steppe vegetation prevailed during cold and dry periods [Sadori et al., 2016] and the vegetal cover was probably not continuous. Hillslope processes heavily affected these zones and produced a lot of sediments. A pulse of sediment supply at the beginning of the warming period would correspond to a remobilization, during the latency time needed for the vegetation to recolonize

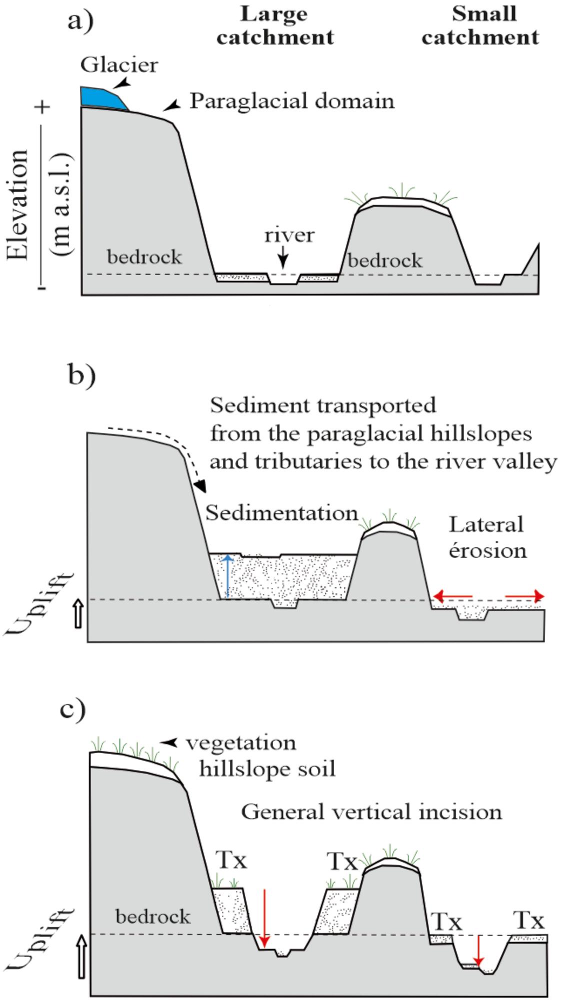

Figure 7. Diagram illustrating the relationships between hillslope-channel coupling and the succession of aggradation, vertical incision and lateral erosion during hydro-climatic cycles in the Albanian rivers. The left and right sides refer to large catchments with a large proportion above 1700 m asl and to small catchments located beneath 1700 m asl, respectively. (a) During periods of cold and dry conditions, a balance between transport capacity and sediment supply favors a large morphological flood plain in large and small catchments due to lateral erosion and sediment transfer. (b) At the very beginning of a period of warm and humid conditions, pulse of aggradation occurs in the large catchments. (c) During the period of warm and humid conditions, vertical incision occurs everywhere.

the slopes, and under the effect of the increase in runoff, of the sediments stored during the cold period on the slopes. Then, fill terraces formed rapidly during these climatic transitions.

- In the small catchments, foothills remained covered over their whole area by vegetation that protected their hillslopes from erosion as they were less dry and less cold than the high parts of the large catchments; the vegetation had a buffer effect and attenuated the evolutions of sediment supply and transport capacity. This would have maintained a near equilibrium balance in the rivers favoring the lateral beveling that led to the formation of strath terraces.

In summary, the pulses of sediment supply at the transition between cold and warmer periods in Albania may be a combination of (1) sediments provided by areas that have become ice-free as a result of glacier retreat, (2) sediments inherited from previous glaciations and remobilized by increased precipitation and erosion, and (3) hillslope sediments supplied during the latency period between climate change and vegetation change in high altitude catchments.

6. Conclusions

The geomorphologic study of the seven major Albanian rivers is presented in this work. The allostratigraphy organization of the flights of terraces is compared between these rivers. The abandonment of the Albanian terrace surfaces is possibly in phase with climatic variations but our results show that the geomorphic responses of the river systems to climatic variations are influenced by a combination of processes. The geomorphic responses of the river systems are also influenced by the lithology, the tectonic settings, the eustatism and the catchments altitudinal distribution.

- The medium strength of the bedrock lithology (mainly flysch) in numerous parts of Albania favors lateral erosion and strath development. The tectonic setting is characterized by a moderate uplift rate (0.1 to 1 mm/yr) and the rather slight difference between the amount of the successive incision and deposition events both favors the formation of nested terraces and their preservation. The exceptional succession of Albanian terraces is probably due to this combination of a medium strength of the bedrock and of a moderate uplift rate (0.1 to 1 mm/yr).

- The influence of the altitudinal distribution of the catchments on the geomorphic responses of the river system is complex and includes the vegetation spreading and glaciers size.

In the small catchments, during cold and dry periods, most of the hillslopes continued to be protected by the vegetation; an equilibrium was approached between sediment supply and transport capacity. In the upper part of the large catchments, the vegetation cover had significantly decreased, leading to increased erosion of the hillslopes; more sediment was available, while dry conditions maintained a low transport capacity of the rivers.

It is suggested that, during the rapid transition to warmer conditions, the increase in precipitation favored the supply of sediments from previously unvegetated or glaciated areas. This would induce a sedimentary impulse that would create thick sedimentary units affected by vertical incision as soon as the sedimentary stock provided by the slopes was exhausted or stabilized by the vegetation. These processes would favor the development of fill terraces in large catchments but not in small ones.

Declaration of interests

The authors do not work for, advise, own shares in, or receive funds from any organization that could benefit from this article, and have declared no affiliations other than their research organizations.

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Supplementary data

Supporting information for this article is available on the journal's website under https://doi.org/10.5802/crgeos.278 or from the author.

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