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ORIGINAL PAPER

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Erosional processes, topographic length-scales and geomorphic evolution in arid climatic environments: the 'Lluta collapse', northern Chile

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Abstract The 'Lluta collapse' of northern Chile is one of the oldest recognizable landslides (>2.5 Ma) in a hyperarid continental setting. This paper develops a conceptual landscape evolution model of the 'Lluta collapse' and analyzes the controls of mass wasting and erosion/sediment transport in channels on the topographic development. The data presented here imply that high relief along a topographic scarp, surface fracturing, elevated groundwater table during a more humid climate and an aquitard underlying permeable ignimbrites are preparatory causal factors for landsliding >2.5 Ma ago. A strong seismic event then possibly resulted in the displacement of ca. 26 km^3 of mass. Subsequent modification of the landslide scar occurred by backward erosion, resulting in the establishment of a dendritic drainage network and the removal of an additional ca. 24 km^3 of material. It appears that this mass was produced by mass wasting in the headwaters, and exported by high-concentrated debris flows in channels. In addition, morphometric information suggest that whereas the geometrical development of the 'Lluta collapse' has been controlled by gravitational mass wasting, the rates of the development of this geomorphic unit have been limited by the export rates of mass and hence by the transport capacity of the flows.

Keywords Landscape morphology · Mass wasting · Debris flows · Morphometry · Central Andes

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Introduction

It is generally accepted that except from glacial erosion, long-term erosional processes comprise channelized (e.g., fluvial processes and debris flows) and unchannelized components (e.g., hillslope processes) (Montgomery and Dietrich 1993; Tucker and Bras 1998; Stock and Dietrich 2003; Lague and Davy 2003). Among these processes, channelized erosion and sediment transport is generally anticipated to exert the first-order control on landscape evolution and formation of relief. This implies that channelized processes limit process rates on the adjacent hillslopes (e.g., Slingerland et al. 1993; Whipple and Tucker 1999). In contrast, based on a detailed study carried out in the pre-steady state Finisterre Mountains, Papua New Guinea, Hovius et al. (1998) found that the mode and rate of drainage basin modification is governed to a significant extent by hillslope mass wasting at the channel heads. The results of the Hovius et al. study imply that during transient stages, hillslope processes rather than fluvial erosion potentially dictate the evolution of a landscape for a limited time interval.

This paper extends the results of the Hovius et al. study to the situation of the 'Lluta collapse' that is located in one of the driest places in the world in northern Chile (Fig. 1). Specifically, the aim is to explore the role of hillslope mass wasting and channelized erosion/sediment transport on the initiation and the modification of the drainage network in this hyperarid climatic setting. The 'Lluta collapse' is ideally suited for the purpose of this study because it is probably the oldest well-preserved erosional/depositional system in the world, and because the abundant geomorphic markers have been explored in detail by geologic and morphologic studies (e.g., Uhlig 1999; Wörner et al. 2002; García and Hérail 2005; Kober et al. 2005). The paper will reveal that whereas the geometric development of the 'Lluta collapse' is controlled by hillslope mass wasting, the rates of landscape development are limited by the transport capacity of the channelized systems (fluvial processes

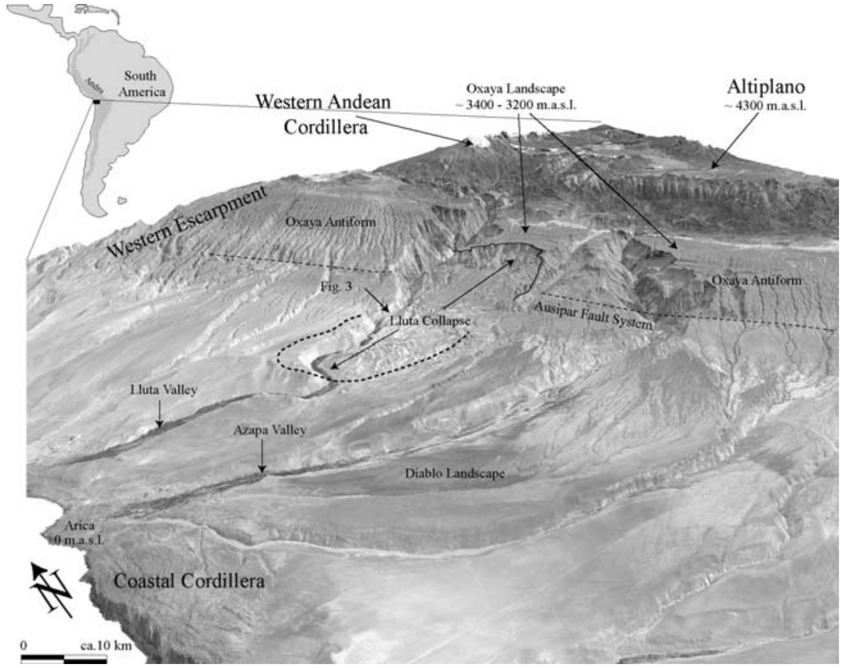

Fig. 1 Overview figure: 3D visualization of a Shuttle Radar Topography Mission–Digital Elevation Model (SRTM–DEM) (with spatial resolution of 90 m; vertical exaggeration is 2x) overlain by an autorectified LANDSAT 5 image showing the Western Escarpment of the Central Andes in northern Chile at ca. 18°S

and debris flows). The data are the results of geomorphic analyses carried out for the 'Lluta collapse', and sedimentological information collected from the landslide deposits.

Local setting

Geomorphology and bedrock geology

The western slope of the Andes of northern Chile at 18°S latitude is divided into three main longitudinal morphological units that comprise from the west to the east: the Coastal Cordillera, the Western Escarpment, and the Western Andean Cordillera (Fig. 1). The Coastal Cordillera is made up of upper Jurassic to Cretaceous tholeiitic arc rocks, plutonites and marine backarc strata of Jurassic and early Cretaceous age (Wörner et al. 2002). At the coast, the Cordillera forms a steep cliff from where it gently dips towards east forming the basement for the overlying Oligocene/Miocene fluvio-lacustrine and volcanoclastic deposits.

The Oligocene/Miocene sequence of the Western Escarpment comprises coarse-grained clastic and volcanoclastic sediments that are assigned to (from the base to the top) the Azapa Formation, the Oxaya Formation and the Diablo Formation (Fig. 2) (Salas et al. 1966). These units were deposited in a wedge-shaped basin, east of the Coastal Cordillera. The Azapa Formation, between ca. 25 Ma and 21 Ma old (Kohler 1999), consists of more than 500 m-thick succession of predominantly coarse-grained sandstones that alternate with conglomerates and mudstones and that were deposited by ephemeral braided rivers. The coarse-grained nature and the considerable thickness of these clastics document a significant topographic gradient and thus, initial uplift of the Andes at that time (Wörner et al. 2002). The Azapa Formation is overlain by a 300–1,100 m-thick sequence of welded rhyodacitic ignimbrites that are assigned to the Oxaya Formation. Ar–Ar dates yielded ages of between 22.7 Ma and 19.4 Ma for this unit (Wörner et al. 2000). These ignimbrites form to large extents the modern surface on the upper part of the Western Escarpment (e.g., Oxaya Landscape and Oxaya Antiform, Fig. 1). Between 19 Ma and 8 Ma, the Western Escarpment evolved into a large monocline due to enhanced uplift (e.g., Isacks 1988), resulting in a westward tilt and significant steepening of the landscape. Surface uplift and topographic tilting was associated by andesitic volcanism in the upper part of the northern Chilean Andes (Salas et al. 1966). Also during the same time interval, unconfined low-concentrated flows transported andesitic debris over the ramp. These sediments were then deposited in the lower portions of the Western Escarpment, resulting in construction of the Diablo Formation (García 2002). This unit, with its characteristic black andesitic clasts, onlaps the Oxaya Formation in an eastward direction. Its top forms to large extents the present surface on the lower Western Escarpment that is referred to as Diablo Landscape in the literature (e.g., García 2002; Figs. 1, 3).

The 'Lluta collapse' (Fig. 3) (Wörner et al. 2002; García 2002; García and Hérail 2005), which is the focus of this study is a prominent geomorphic feature in the landscape of the Western Escarpment of the Central Andes (Fig. 1). It is made up of three morphological domains (Fig. 3) that comprise: (i) the headwaters with a dendritic drainage network, (ii) the accumulation area with slide blocks representing the tail of the initial landslide, and small sedimentary basins dammed behind

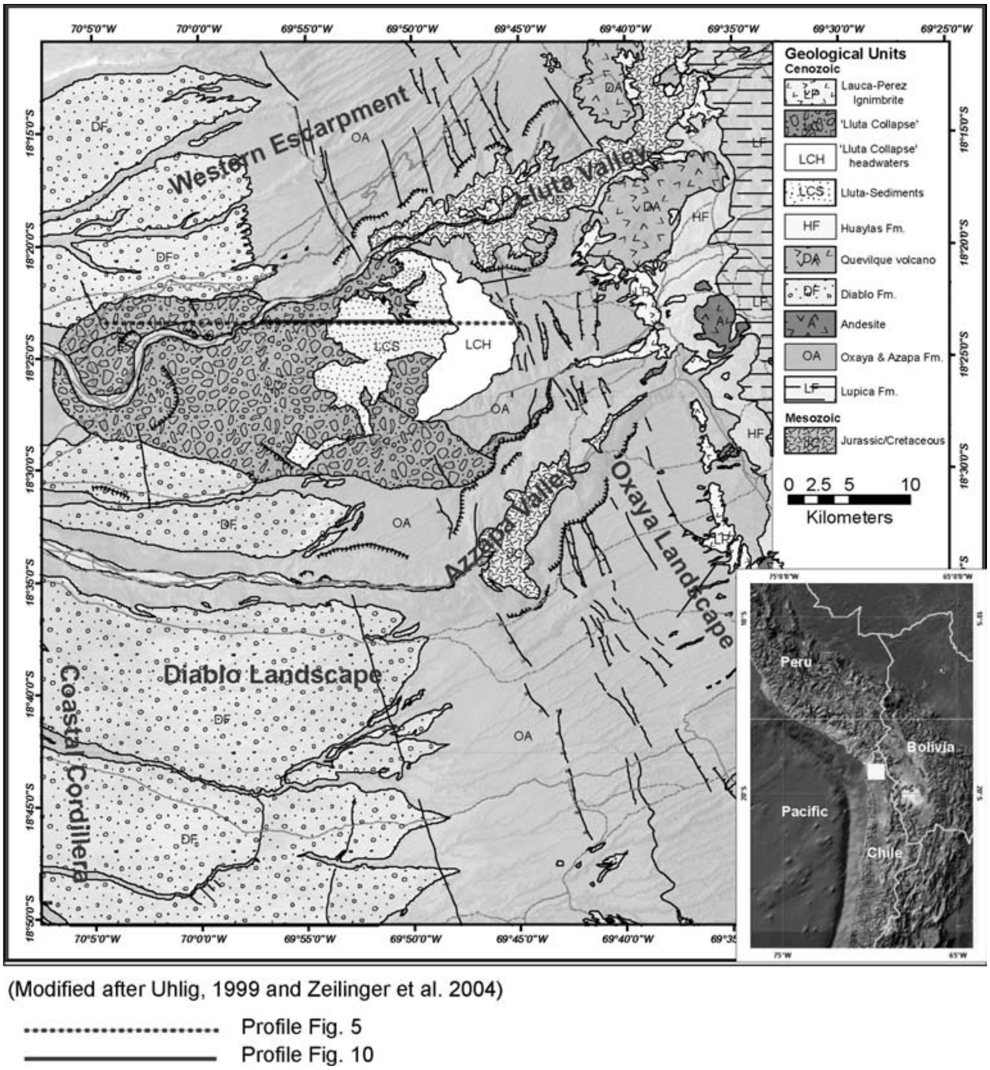

Fig. 2 Map showing overview of geological setting (modified after Uhlig 1999 and Zeilinger et al. 2005)

these blocks, and (iii) the topographic heights and corrugated surfaces at the toe of 'Lluta collapse' representing the toe of the landslide. The eastern boundary of the 'collapse' (i.e., the headwaters) is located at the edge of the western steep limb of the Oxaya antiform. Also well displayed in the landscape is the western limit of this antiform, the so-called Ausipar fault (Figs. 1, 3; Munoz and Charrier 1996), which comprises several segments of different structures developed under an E–W compressive regime (Zeilinger et al. 2005). Deformation on this fault ceased around 4.8 Ma ago (Munoz and Charrier 1996). N and S of the Azapa valley, the Ausipar fault is expressed by steep ω-verging thrusts with small offsets and therefore small amount of shortening.

At present, these morphological units are dissected by large valleys (e.g., Lluta and Azapa valleys, Fig. 1) that are sourced at the western edge of the Altiplano. Incision of these valleys started sometime between 8 Ma and 7.5 Ma as indicated by cross-cutting relationships between the valleys and dated alluvial terraces (Von Rotz et al. 2005).

Climate and hydrogeology

The study area currently experiences a hyperarid climate in the lower part (Atacama desert), and semiarid climatic conditions in the high Andes. In the location of the 'Lluta collapse', modern precipitation occurs during extremely rare episodic events, resulting in average rainfall rates of <100 mm/year. The present-day hyperaridity of the study area is induced by a combination of (i) subtropical atmospheric subsidence, (ii) the upwelling, north-flowing, cold Humboldt Current, which prevents precipitation in the coastal regions, (iii) the rain-shadow effect of the Andean Cordillera, which prevents humid air from reaching the Pacific coastline, and (iv) general global climate cooling in the late Pliocene (Hartley and Chong 2002; and references therein). In the area surrounding the 'Lluta collapse', semiarid to arid conditions are inferred to have commenced in the middle Miocene (Alpers and Brimhall 1988; Clark et al. 1990; Mortimer and Saric 1975) and persisted to ca. 3 Ma, when palaeoclimate finally shifted towards

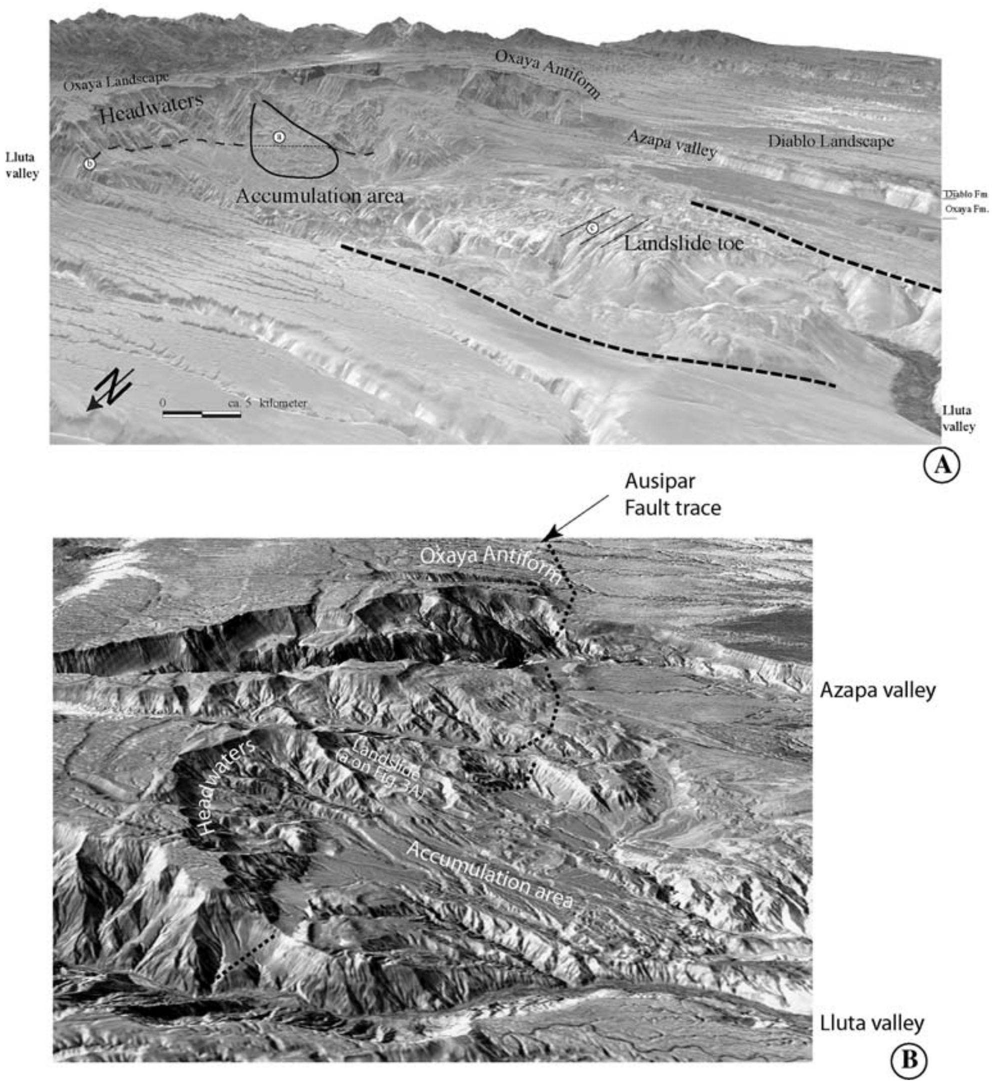

Fig. 3 **a** 3D visualization of a SRTM–DEM overlain by an autorectified LANDSAT 5 image showing the study area with its characteristic geomorphic domains. **b** displays a closer look to the headwaters and the accumulation area. Note the presence of a landslide mass that has not been completely removed

today's hyperaridity in the Atacama desert (Hartley and Chong 2002). Although climate has been hyperarid in the Atacama desert, there exist several springs at the base of the western slope south of the study area (Galli and Dingman 1962). Hoke et al. (2004) thought that these springs have been charged by groundwater with sources in the Western Cordillera or the Altiplano. These authors also argued that landsliding and the formation of steep headscarps in the Western Escarpment were controlled by groundwater sapping.

Methods

Identification and analysis of landform elements was achieved using remote sensing techniques (analysis of satellite images and aerial photographs), and standard geological and geomorphic methods in the field. Aerial photographs at a scale of ca. 1:60,000 taken in 1955 and 1956 are available from the Instituto Geographico Militar in Santiago de Chile. The landform elements were analysed visually on an autorectified LANDSAT 5 satellite image and on aerial photographs. Field work comprised sedimentological logging of representative sections in the accumulation area of the 'Lluta collapse' in an effort to reconstruct the nature of erosion and sediment transport.

The extraction of morphological properties requires a high-resolution digital elevation model (DEM). Therefore, calculation of the DEM with a grid resolution of 20 m was performed based on the standard photogrammetric methods described in detail by Kraus (1994). The data were collected from nine overlapping aerial photographs (arranged in a 3×3 pattern). Eleven ground control points were measured with a hand-held GPS to calibrate the photos. The average root-mean-square errors of the control points were in the order of 5 m in horizontal and 10 m in vertical dimension. With reference to the small-scale geomorphic elements having effective vertical dimensions in the order of 100 m, this error corresponds to a relative error of approximately 10%. The morphometric properties of the analysed drainage basin were extracted from the DEM using standard GIS.

Results

Geomorphic architecture of the 'Lluta collapse'

As outlined above, the 'Lluta collapse' is made up of three morphologically distinct landform elements that are referred to as the headwaters, the accumulation area, and the landslide toe (Fig. 3).

Headwaters

The most prominent geomorphic element in the study area is the headwaters of the 'Lluta collapse'. This unit displays an amphitheatre-like concavity with a diameter of ca. 15 km (Fig. 1, 2, 3). The eastern boundary of the headwaters is defined by a sharp scarp-line, which—at a smaller scale—is made up of smaller coalescing concave geometries. The valleys and ridges that initiate at this boundary strike perpendicular to the scarp-line resulting in a radial-symmetric texture in the satellite image. In addition, they display a dendritic network of channels and ridges at various scales. To the west, the headwaters are bordered by the gently northwestward dipping terraces of the accumulation area [line (b) in Fig. 3a].

The geology of the headwaters comprises Jurassic to Cretaceous basement rocks (Fig. 2) that crop out in some very deep and narrow canyons. These rocks are overlain by the 20–100 m-thick conglomerate–mudstone alternation of the Azapa Formation. The roof of the stratigraphic succession consists of several ignimbrite sheets of the Oxaya Formation that reach a cumulative stratigraphic thickness of 300–500 m. These welded ignimbrites reveal a NNW–SSE trending subvertical foliation, separating the strata into 1–3 m-wide columns.

The bedrock geology appears to control the morphology of the headwaters. In the highest part where the bedrock consists of the ignimbrites of the Oxaya Formation, the steep hillslopes lack any channels, or they are only slightly modified by several 100–300 m-long downslope-oriented grooves and rills with diameters of ca. 1–2 m. Headscarps are steep and scoop-shaped, and at the top they are arranged en echelon to form a staircase-like topography with offsets of ca. 10 m (Fig. 4b, c). Further downslope where the bedrock consists of Mesozoic units, the geomorphic texture is characterized by a high roughness with deeply incised and narrow valleys. The southern part of the headwaters, however, is made up of a unit with a tongue-shaped front and a smooth surface texture with convex cross-sectional geometries [(a) on Fig. 3a, and 'landslide' on Fig. 3b]. This part of the headwaters has been less affected by erosion and sediment transport in channels, and the tongue-shaped front overlays the terraces of the accumulation area (Fig. 3b).

Wörner et al. (2002) interpreted the amphitheatre-shaped concavity of the 'Lluta collapse' headwaters to result from a landslide. However, the coalescing small-scale concave geometries which define the scarp-line and the presence of deeply incised and branched valleys indicate that the headwaters have been formed by a combination of landsliding and subsequent modification by erosion and sediment transport in channels. We therefore argue that the initial landslide scar was farther west than the modern scarp-line, approximately near the present-day western termination of the headwaters [(b) in Fig. 3a]. It is important to note here that the position of the proposed initial landslide scar coincides with a topographical step in Mesozoic basement rocks, that is related to the Ausipar fault (Fig. 5). Field observations directly eastward of the proposed initial landslide scar show that the basement and overlying stratigraphic units (i.e., Azapa and Oxaya Formation) are still in their autochthonous situation. Therefore, the scar of the initial landslide cannot be farther east than line (b) in Fig. 3a.

The unit with the tongue-shaped front [(a) in Fig. 3a, see also Fig. 3b] is interpreted as a landslide that has not yet been completely modified by processes in channels, and that is younger than the terraces of the accumulation area. Elsewhere in the channel network (e.g., in the bordering catchments to the north and to the south), the processes in the channels appear to have efficiently exported the masses from subsequent landsliding, resulting in partial exposure of bedrock on the channel floor.

Lluta landslide toe

To the west of the study area, the landscape is characterized by an irregular corrugated surface (Fig. 3), which, in some places, rises up to 200 m above the undisturbed top of the Diablo Formation. A poorly defined north–south trending lineament in the satellite image corresponds to north–south trending topographic ridges [dashed lines (c) in Fig. 3a]. The unit is composed of chaotically arranged fragments and blocks (ca. 0.1–0.5 km in size) of deformed Oxaya and locally Diablo Formations. The rocks are highly disturbed and brecciated. Locally, small topographic depressions are filled by younger fine-grained diatomaceous deposits. Mapping reveals that these blocks overlay the undisturbed conglomerate/mudstone alternation of the Azapa Formation (Fig. 4d).

The north–south trending topographic ridges and the chaotic nature of the landscape are interpreted as compressional structures that occurred at the toe of the landslide mass, when material was pushed and overthrusted by the frontal part of the sliding mass (Fig. 5). Because these blocks rest on an undisturbed sequence of the Azapa Formation (Fig. 4d), the top of this conglomerate–mudstone alternation is considered as the detachment horizon. Note that because of the post-depositional faulting along a NNW–SSE striking high-angle reversed fault (Salas et al. 1966), exact identification of the lateral and frontal boundaries is thwarted.

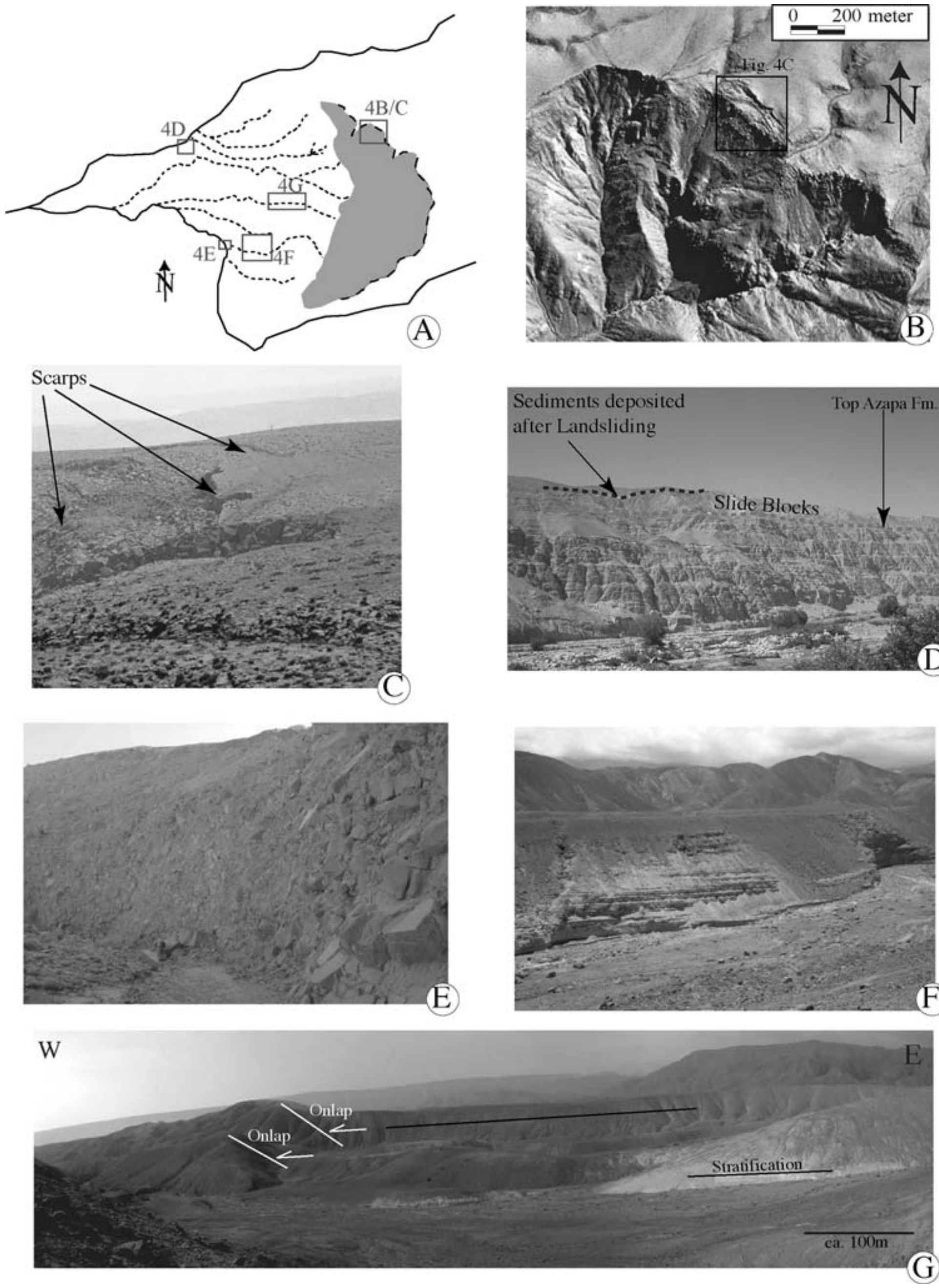

Fig. 4 **a** Overview of 'Lluta collapse' showing location of photos from the field, **b** rectified aerial photo, and **c** photo showing the headwaters with a en-echelon arrangement of incipient scarps (*arrowed*) forming a stair-case topography, **d** photo from the Lluta valley indicating the detachment horizon of the Lluta landslide, **e** slide block with brecciated ignimbrites, **f** horizontally stratified sediment dammed behind these blocks, and **g** onlap-relationship between stratified sediments and tilted slide bocks

Accumulation area

Between the headwaters and the landslide toe is the area where sediment accumulated after landsliding (Fig. 3). Here, the geomorphology and the geology are made up of two components that comprise blocks of chaotic monolithological breccias (km-scale) with a hummocky surface texture and slightly westward dipping planar surfaces and horizontally stratified clastic deposits.

The blocks are made up of ignimbrites of the Oxaya Formation. They consist of poorly sorted, clast-supported breccias with internally broken clasts and blocks with diameters of up to 3 m (Fig. 4e). The matrix also consists of lithologies of the same formations. However, detailed observations reveal that the original stratigraphic architecture is still preserved in the breccias, and that these units form asymmetrical wedge-shaped blocks (km-scale) that are tilted towards east and overlay the undisturbed conglomerate–mudstone alternation of the Azapa Formation. These blocks are partly covered by well-stratified clastic deposits (Fig. 4f) that coarsen upward from horizontally stratified fine-grained silt- and sandstones with diatomaceous layers to poorly stratified cobble-sized conglomerates with a sandy matrix. These sediments onlap the wedge-shaped brecciated blocks in a westward direction (Fig. 4g). The top of these conglomerates defines the slightly westward dipping planar surfaces behind the tilted blocks.

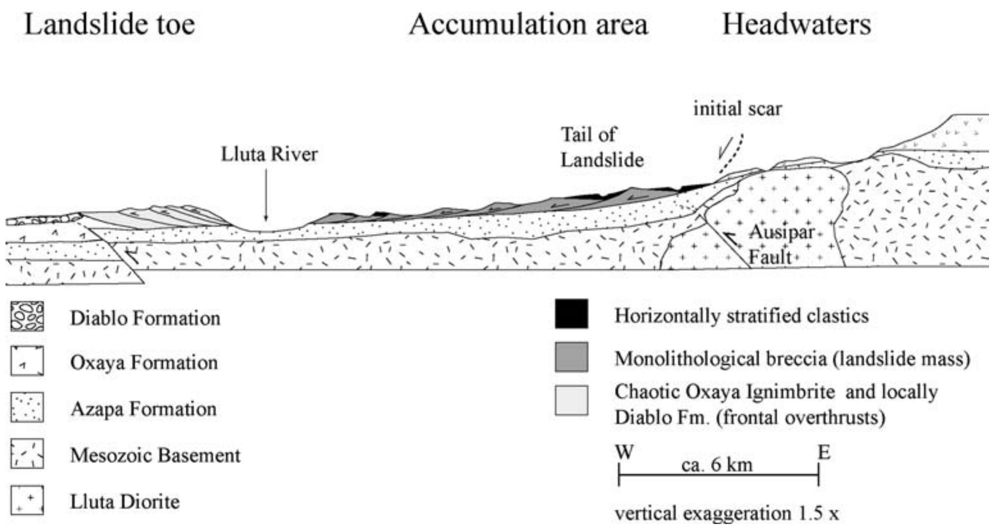

Fig. 5 Section showing the modern stratigraphic–geomorphic situation of the 'Lluta collapse'. The section runs parallel to the movement of the landslide (see *dashed line* in Fig. 2 for localization of the profile)

The observations delineated above suggest that the hummocky surfaces of the brecciated unit can be considered as edges of backward-tilted allochthonous slide blocks. Estimated total thicknesses of the tilted blocks fall in the range between 100 m and 300 m for small and larger blocks, respectively. The chaotic and disturbed structure with internally broken blocks/clasts and with a fragmented matrix is typical for gravitational slide blocks. Indeed, such a fabric has been reported to be characteristic for fragmentation during transport (e.g., Siebert 1984; Ui et al. 1986). Because these blocks rest on an undisturbed sequence of the Azapa Formation, the top of this conglomerate–mudstone alternation is considered here as the detachment horizon (see also interpretation of the Lluta landslide toe).

The well-stratified fine-grained clastic deposits and the occurrence of diatomaceous layers at the base of the sedimentary succession suggest a shallow water, lacustrine depositional environment that established in small basins behind the tilted blocks. The sedimentological trend from fine-grained clastics to cobble-sized, clast-supported conglomerates with a sandy sedimentary matrix indicates progradation of a depositional system where episodic non-cohesive high-concentrated mass flows represent the predominant sedimentary processes.

Figure 3b clearly shows that the landscape of the accumulation area has been affected by linear erosion in channels up to the present. In the upper part of the accumulation area, the depth of incision can reach 50–80 m. Further downstream towards the Lluta valley, the depth of incision increases to >500 m within short distances (see Discussion below), finally reaching the modern level of the Lluta river and exposing the detachment horizon of the landslide. It appears that ongoing dissection of the 'Lluta collapse', and especially of the accumulation area, has been controlled by the continuous lowering of the base level as incision of the Lluta river has proceeded (Kober et al. 2005). Indeed, once the small basins behind the rotated blocks are filled and the drainage network of the Lluta headwaters is connected with the Lluta river, the lowering of the Lluta valley started to control the elevation of the base level in the 'Lluta collapse' area (see Discussion below).

Volume of displaced and eroded rocks

The volume of material removed by landsliding was estimated by subtracting the DEM of the modern topography from that representing the initial landscape (i.e., prior to landsliding, Fig. 6a). Reconstruction of this initial situation was achieved by digitizing the areas surrounding the Oxaya Antiform north and south of the Lluta headwaters that have not been affected by erosion (Figs. 1, 3). Digital data from these areas (see black dots on Fig. 6a) were then used to interpolate a DEM with a grid resolution of 50 m applying the methodology of kriging (Cressie 1990). In this interpolated DEM, the offset due to thrusting along the Ausipar fault becomes readily visible (Fig. 6a). The DEM representing the modern situation (Fig. 6b) was finally subtracted from the DEM imaging the topography prior to landsliding (Fig. 6a) to assess the volume of eroded material (difference DEM of Fig. 6c). This difference model images the mass that has been removed from the study area since incision into the Diablo and Oxaya Formations started (i.e., since between 8 Ma and 7.5 Ma, Von Rotz et al. 2005).

Figure 6c shows the V-shaped erosion of the landscape in the major valleys and in the accumulation area of the 'Lluta collapse', but also the convex-upward scoop-like geometry of the headwaters. The calculated volume of eroded material in this area due to backward erosion is ca. 24 km^3 which is ca. 50% of the total mass that was mobilized in the 'Lluta collapse' area by landsliding and backward erosion (Wörner et al. 2002). The initial Lluta collapse landslide, therefore, mobilized ca. 26 km^3.

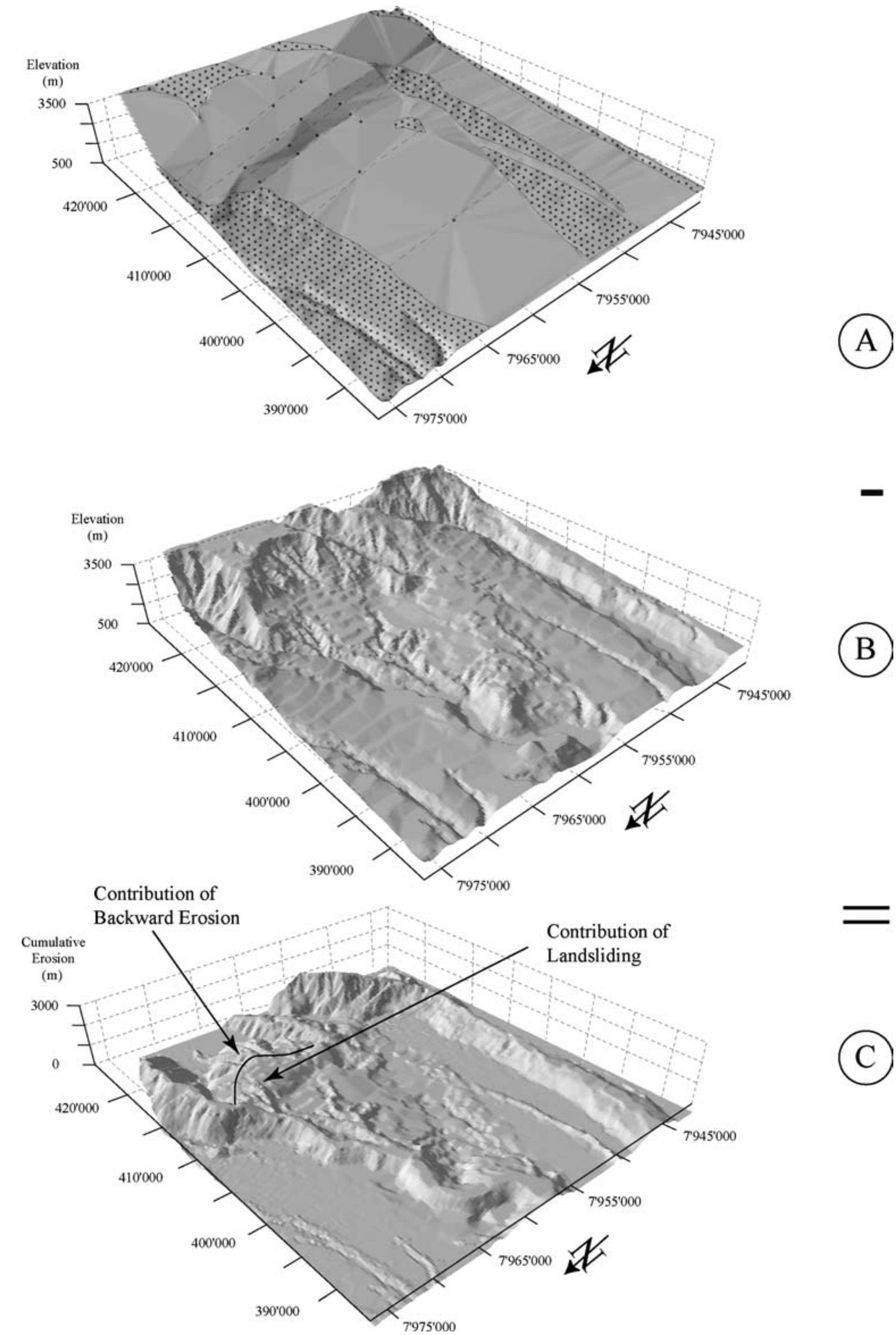

Fig. 6 Calculation of the difference model: **a** Digital elevation model (DEM) of the paleo-surface: *dotted areas* show points in the DEM of the present-day situation (**b**) that were used for the interpolation. Note that points along a line parallel to the general strike-direction of the Ausipar fault and the Oxaya Anticline were also used for interpolation. **b** DEM for the present-day situation, and **c** difference model. See text for further explanation

Topographic length-scales for landsliding

It was outlined before that the well-defined scarp-line of the 'Lluta collapse' has an amphitheatre-like, downward concave shape which, at a smaller scale, is itself defined by smaller coalescing concave geometries (Fig. 7). Here, we determine the various topographic length-scales recorded by the landscape of the headwaters. These data will bear information about the extent to which hillslope mass wasting and/or erosion and sediment transport in channels have controlled the evolution of the headwaters of the 'Lluta collapse'.

Figure 7 illustrates that topographic length-scales of at least three orders can be identified in the headwaters. The first order represents the whole escarpment that has a cross-sectional width of ca. 15 km (Fig. 7a). The sec-

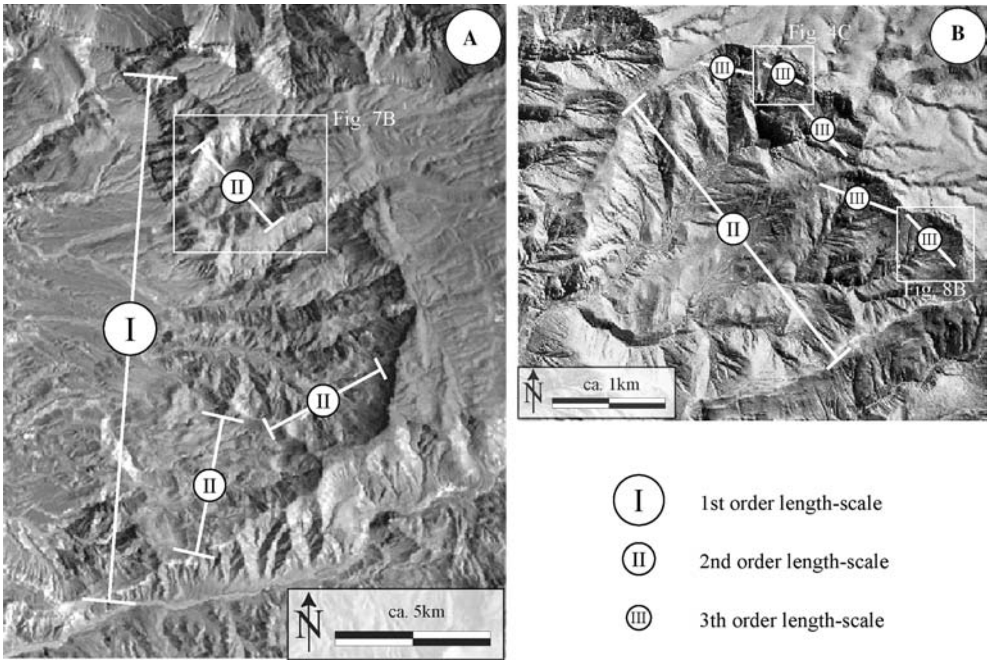

Fig. 7 (**a**) Overview of the 'Lluta collapse' scarp-line showing topographic length-scales, and (**b**) details showing lower-ordered length-scales detected in the headscarp

ond order length-scale comprises headscarps that measure between 2.3 km and 3.5 km in cross-sectional width (Fig. 7a, b). This is also the scale for which fragments of a landslide are found in the southern portions of the headwaters (a on Fig. 3a, and 'landslide' on Fig. 3b). Third- and lower-ordered geometries comprise headscarps with cross-sectional widths that range from 60 m to 1000 m. Field observations reveal that these geomorphic features have also been formed by landsliding (e.g., Fig. 4b, c).

It appears that the initial escarpment was formed by a single mega landslide event (see Discussion below). Because the modern sharp scarp-line of the 'Lluta collapse' is composed by headscarps that have been formed by landsliding at nearly all scales between 3.5 km and 60 m, we interpret that the retreat of the headwaters and hence the establishment of the drainage network has been predominantly controlled by mass wasting processes.

Topographic length-scale for erosion and sediment transport in channels

Channel profiles tend to adapt distinct gradients that are inversely related to the upstream size of the drainage basin if processes in channels control the rates of the topographic development for geologic time scales (i.e., >10 Ky) (e.g., Tucker and Slingerland 1996, and references therein), and if the bedrock lithology is to large extents constant. Consequently, segments of a drainage basin, where the rates of landscape development have been controlled by processes in channels, are identified by linear relationships between the logarithm of the channel gradient and the logarithm of the contributing area (e.g., Snyder et al. 2000; Stock and Dietrich 2003; Lague and Davy 2003; and many others). Because we aim to determine the extent of scale at which channelized erosion and sediment transport has driven the development of the Lluta headwaters, we calculated the relationships between channel gradients and size of contributing areas for catchments that originate at the scarp of the 'Lluta collapse' [which excludes some systems with sources in the Oxaya Landscape (Fig. 8)]. Systems that are occupied by landslides (e.g., a on Fig. 3a) are excluded from this analysis because of the irregular channel profiles at nearly all scales.

Figure 8a illustrates that for contributing areas $<10^4$ m^2, the data points tend to follow a horizontal line, implying that erosion and sediment transport have not been predominantly controlled by processes in channels for geologic time scales. In contrast, for contributing areas $>10^4$ m^2, channel gradients decrease with increasing drainage area, illustrating the predominant controls of erosion and sediment transport in channels on the rate of landscape development. It appears that the inflection in the log(slope)–log(area) plot observed for drainage areas with sizes between 10^4 m^2 and 10^5 m^2 represents a threshold for linear processes to exert the predominant controls on the rates of development of the analysed sub-basins. Note that this statement applies only if landslide masses have become completely removed in the catchments (see landslide a on Fig. 3 as contrasting example).

Discussion

General evolution of the 'Lluta collapse'

Integrated observations and interpretations of the geomorphic domains outlined above reveal a subdivision of the landscape evolution processes into (i) an initial mega

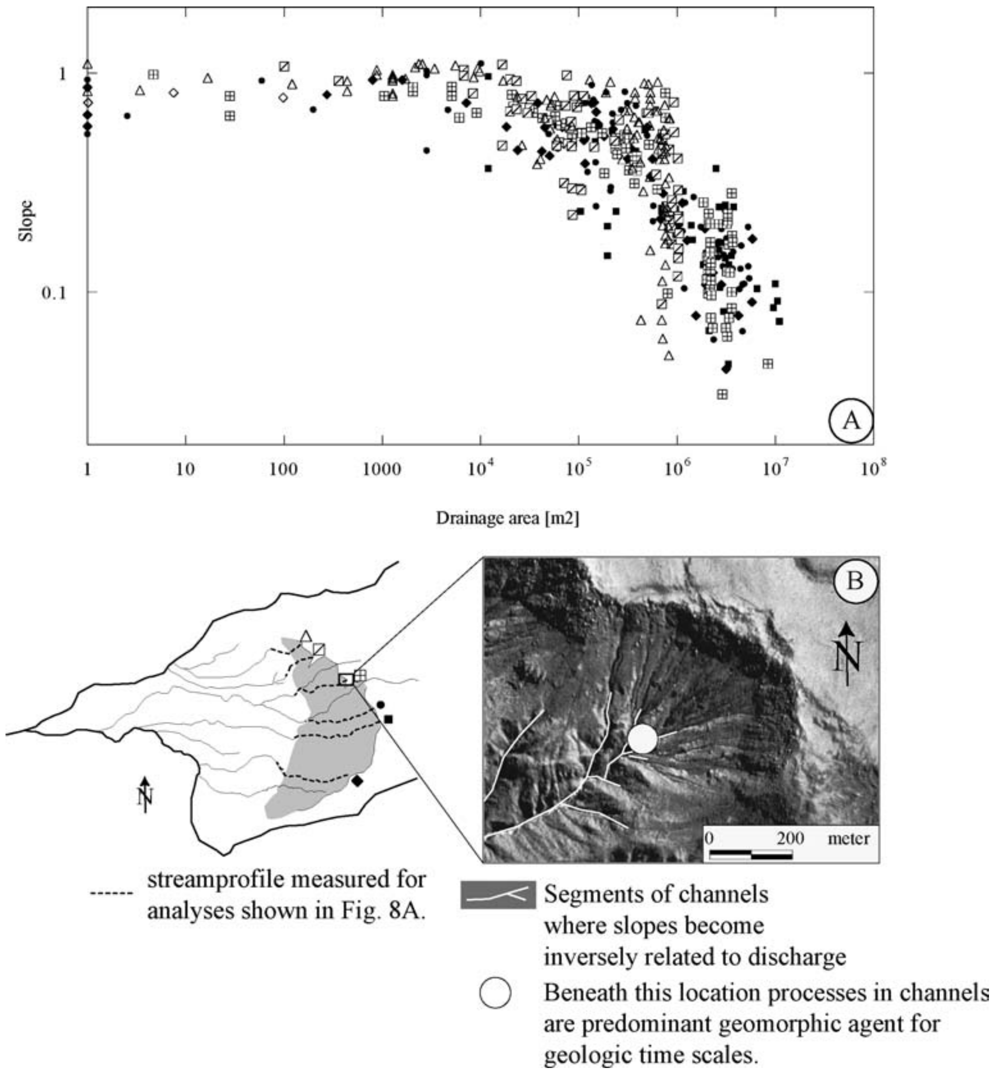

Fig. 8 **a** Relationship between slope and upstream size of the drainage area in the analysed stream profiles in the 'Lluta collapse' headwaters. **b** Example from the headwaters showing the situation where the slope becomes dependent on the size of the drainage basin (*white circle*). In locations where the upstream sizes of drainage basins are below 10^4 m^2 (NE of the *white circle*) the channel gradients are independent from the size of the contributing areas.. Above this threshold size of drainage basin, processes in channels become the predominant geomorphic agent for geologic time scales. Note that gravity-driven channelized erosion also occurs in the catchment above this critical location as indicated by abundant rills. However, channelized processes in this uppermost part of the headwaters appear not to exert a predominant control on the topographic evolution for geologic time scales. The symbols indicate the channels that were considered for calculation of the slope-area plot of (**a**)

event resulting in the formation of the 'Lluta collapse' landslide, (ii) continuous backward erosion and accumulation in small dammed basins behind the landslide masses, and (iii) enduring lowering of the Lluta river base level that has resulted in linear dissection of the 'Lluta collapse' accumulation area (Fig. 9). However, because the average elevation of the whole landslide mass lies beneath the top of the Diablo Formation and since the volume of the landslide blocks is smaller than the space between the detachment horizon and the top of the Diablo Formation (Fig. 9), material must have been removed by the Lluta river prior to landsliding. Accordingly, we interpret that erosion and base level lowering by the Lluta river increased the relief to a threshold level for landsliding. The occurrence of deformed material north of the Lluta valley in the lower part of the study area can then be explained by shortening and thrusting of material at the frontal part of the landslide mass. Note that this statement contrasts to some of the interpretation of Wörner et al. (2002). These authors argued that, because deformed material is found on both sides of the Lluta valley (Fig. 1), initiation of landsliding must predate the formation of the present Lluta valley.

As outlined above, the top of the Azapa Formation served as detachment horizon of the Lluta landslide. Nice exposures are found on the steep flanks of the Lluta valley (Fig. 4d). In addition, there is a porosity and permeability contrast between Oxaya and Azapa Formations. Whereas the ignimbrites of the Oxaya Formation are well jointed and, therefore, act as aquifer, the internally less jointed conglomerate/sandstone/mudstone alternation of the Azapa Formation is likely to be relatively less permeable and might act as an aquitard that can potentially become a saturated basal shear surface during periods of extended precipitation and elevated groundwater table. The scar area of the 'Lluta collapse' landslide was presumably located at the most distal edge of the Oxaya Antiform (Figs. 1, 3). This is also the location where we found the most proximal tilted slide block. Because of the frontal thrusts at the toe of the landslide, and the horizontal stratification of the sediments dammed behind the slide bocks, we interpret that the sliding occurred during one single

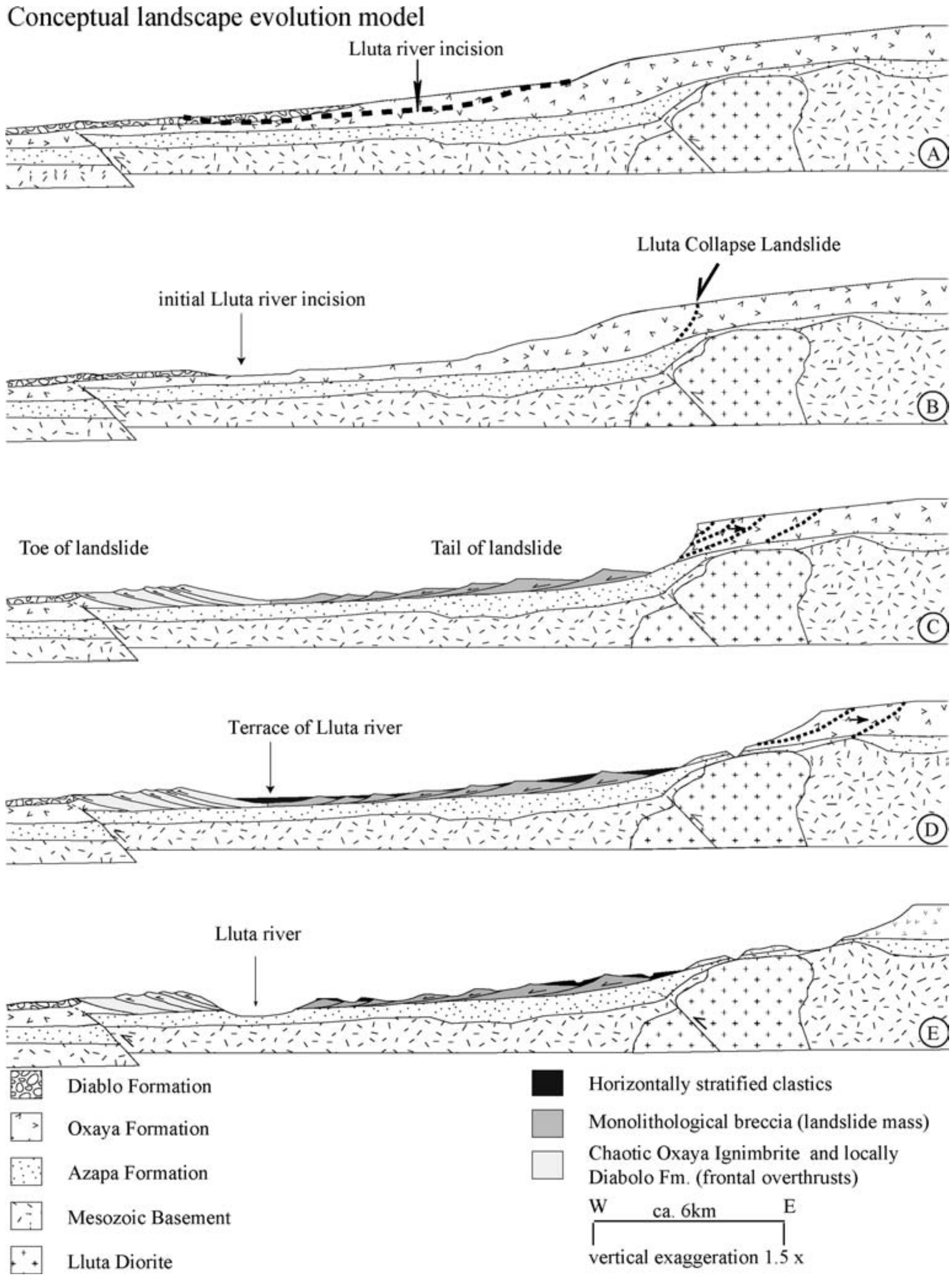

Fig. 9 Conceptual model showing different stages of the topographic evolution of the study area. The profiles have a vertical exaggeration of 1.5, and they are drawn schematically. *Dashed lines* and *arrows* indicate changes from one stage to the other: **a** initial situation showing the topographical ramp, **b** situation just prior to landsliding when incision of the Lluta river resulted in a critical relief, **c** situation just after the giant mega event. Note that the tilted slide blocks formed dammed wedge-shaped basins. Note also the frontal overthrusting at the toe of the landslide mass. **d** and **e** Continuous backward erosion and modification of the initial landslide scar due to enduring base-level fall in Lluta river. Erosional products are first deposited in dammed basins and later transported to the Lluta river. Figure (**e**) corresponds to the present-day situation

event (multiple events would have disturbed the horizontal stratification of dammed sediments).

We have no constraints on reconstructing the triggering mechanisms since, geotechnical analyses have not been performed [i.e., static and dynamic slope-stability analyses (e.g., Jibson 1996)]. Nevertheless some possible scenarios will briefly be discussed. We interpret a condition of non-frictional or cohesive strength along the basal shear plane of the landslide to allow such a gigantic mass to move over tens of kilometres (e.g., Erismann 1979). These conditions require a weak detachment horizon, which, in this case, is the top of the Azapa Formation. Accordingly, we interpret that landsliding occurred during a period of elevated groundwater table which, in turn, possibly resulted in fluidization and saturation of the basal shear zone. In the scar area of the initial Lluta landslide, pre-existing joints in the ignimbrites of the Oxaya Formation formed weak discontinuities that preferentially favoured the initiation of the landslide. Additionally, the ‘Lluta collapse’ is located in a tectonically active regime (subduction zone) that has lasted for millions of years. Hence, threshold conditions for landsliding of the over-steepened topographical step (due to lowering of the base level of the Lluta valley) were possibly exceeded during a seismic event as seen also in other areas with large landslides (e.g., Hermanns and Strecker 1999; Philip and Ritz 1999; Solonenko 1977).

The second stage of landscape development comprises a phase of backward erosion resulting in establishment of the dendritic drainage network of the headwaters. The erosional products were then accumulated behind the tilted slide blocks. In the uppermost portions of the headwaters, sediment was produced by landslides of various scales (e.g., a in Fig. 3a, scarps in Fig. 4b, c, see above). These smaller-scaled landslides have generated new concavities which, in turn, have concentrated runoff on a scale sufficient to initiate and further promote channelized processes. Export of sediment occurred by non-cohesive episodic flows, resulting in deposition of clast-supported breccias with a sandy matrix that coarsen upward. Trigger mechanisms for the smaller-scaled hillslope failure processes have possibly been similar to those discussed in the context of the giant initial event (i.e., seismic shaking, elevated water table and groundwater sapping, pre-existing surface fracturing).

Note that it is possible that during this second stage of landscape evolution, fragmented blocks in the east became eroded and the material redeposited behind slide blocks farther west. On the other hand, we are aware that the eroded and deposited mass does not balance volumetrically (Fig. 9). Instead, we interpret that most part of the eroded material was transported bypass downstream.

The determination of ages for the landsliding event is thwarted because of a lack of high-resolution chronologies in the study area. Nevertheless, Kober et al. (2005) measured the concentration of cosmogenically induced nuclides for boulders on the accumulation area, yielding a minimum age of ca. 2.5 Ma for landsliding. This makes it most probably one of the oldest and largest palaeolandslide recognized in a continental setting (cf. Philip and Ritz, 1999; and references therein). The assignment of a minimum age of 2.5 Ma and the interpretation of a more humid phase to allow landsliding at the km-scale as outlined in the previous sections is in line with the chronology of climatic shifts in this part of the Andes. Specifically, sedimentological data imply wetter climatic conditions immediately prior to 3 Ma (Hartley and Chong 2002).

Relationships between base level in Lluta valley and the geomorphic evolution of the 'Lluta collapse'

As outlined above, the slide blocks of Oxaya Formations formed small basins behind which the erosional products from the headwaters started to accumulate. However, besides this initial local control on sediment accumulation, the elevation of the base level of the Lluta river exerted a more important control on erosion and deposition in the headwaters and in the accumulation area, respectively. This interpretation is confirmed by a geometric comparison of the terraces that form the top of the basins behind the slide blocks. Indeed, Fig. 10 shows elevation profiles (extracted from the DEM with a horizontal resolution of 20 m) of the four separately analysed terrace systems. It clearly illustrates that the systems a (proximal), b (medial) and d (distal) are aligned in one convex profile with continuously decreasing gradients. Mapping shows that the deposits of systems a and b mainly consist of ignimbrite clasts revealing a local source (i.e., from the headwaters), whereas the conglomerates underlying terrace d consist of diorites, ignimbrites and andesits revealing a distal

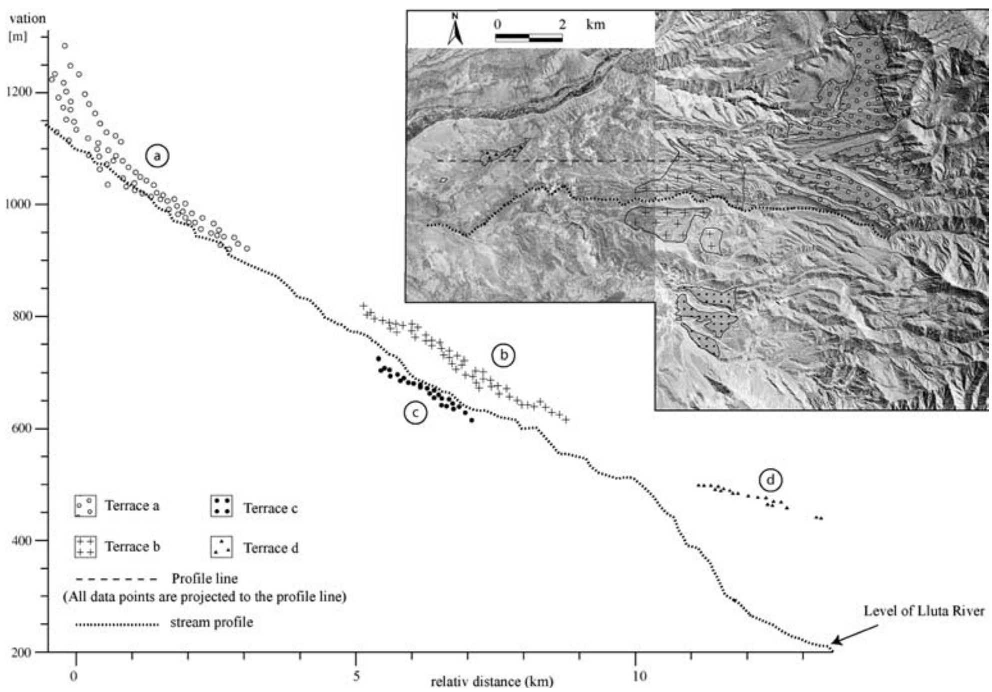

Fig. 10 Elevation profiles of four separately analysed terraces in the accumulation area of 'Lluta collapse'. All data points are projected to the profile line (see also *bold line* in Fig. 2 for localization of the profile). Vertical exaggeration is 10x. See text for further explanation. Note that the > 2.5 Ma-old exposure age was determined for terrace c, and that terrace d was deposited by the Lluta river

source (i.e., a former terrace of the Lluta river). The alignment of these terraces, therefore, reveals that the elevation of the Lluta river exerted a predominant control on the accumulation behind the slide blocks. The planar system more to the south (system c in Fig. 10) shows the same dip angle as the neighbouring terraces, but at a lower topographic elevation with an offset of ~80 m, implying a younger age than for the base level recorded by terraces a, b and d. This is also the terrace for which the minimum exposure age of ca. 2.5 Ma was measured (Kober et al. 2005). All these observations imply that the slide blocks controlled the processes in the headwaters of the 'Lluta collapse' only for a limited time interval. Once the accommodation space behind the slide blocks was filled with sediment, the transport systems broke through the barriers. Hence, it evolved in response to the base-level change of the Lluta river.

Length-scales, topographic evolution and rates of geomorphic processes

The morphometric properties of the scarp-line and field observations imply that the concave geometries presumably resulted from gravity-driven hillslope processes. Whereas the largest length-scale of the landscape (i.e., the present-day 15 km-wide dimension of the 'Lluta collapse') corresponds to the initial landslide event, lower-ordered length-scales are assigned to the smaller coalescing concavities that are generated through smaller landslides during the second stage of backward erosion. These concavities concentrated runoff at a scale sufficient to initiate channelized sediment transport and erosion (i.e., beneath the transition from landslide-dominated hillslopes to fluvial and debris flows dominated channels). These latter processes are inferred to have further reduced the initial upper length-scale, replacing the initial Lluta landslide scar with an entire drainage network. It appears that mass wasting processes of different length-scales described above have been responsible for the geometric evolution of the scar line, the formation of the downward concave-shaped landscape and the production of mass in the headwaters. In contrast, high-concentrated flows have controlled the export of mass during the second stage of landscape development. Once the landslide masses were removed from the headwaters, then processes in channels started to control the rates of relief formation in the headwaters. This is indicated by the decrease in channel gradients at increasing sizes of the contributing areas for systems that have removed large landslide masses in their catchments. If this situation has established, then processes in channels not only control the rates of relief formation, but also the rates of headward propagation of the scar line. Landsliding then occurs if erosion and sediment transport in channels has sufficiently lowered the local base levels to magnitudes to initiate further landslides. We interpret, therefore, that the rates of development of the 'Lluta collapse' headwaters have been limited by the export rates of mass and hence by the transport capacity of the flows once the large landslide masses from the initial event have been removed.

Conclusion

Hovius et al. (1998) outlined the importance of hillslope mass wasting on the geometric development of a dendritic drainage network in the Finisterre Mountains, Papua New Guinea. These authors concluded that in this mountain belt, watersheds appear to initiate by isolated gorge incision, to expand by large-scale landsliding possibly controlled by groundwater seepage, and to entrench by channelized processes of landslide scars and deposits. They also conclude that once a mountainous drainage basin with ridges and valleys is established, only major landslides can modify the drainage pattern. Although the climatic setting of the study presented here contrasts to the situation of the Finisterre Mountains, the results of the sedimentological and geomorphic analyses allow drawing almost identical conclusions. Specifically, this study outlines the significance of mass wasting for the initiation of the 'Lluta collapse' watershed and for the geometric evolution of headscarps. It also illustrates the role of sediment transport and erosion in channels on the rates of landscape evolution if the landslide masses have been removed.

Because of the geometric similarities between the shapes of concavities composing the 'Lluta collapse' scarp-line, and since these geometries result from landsliding, it is possible that this geometric similarity over different scales reflects a possible threshold parameter (e.g., mechanical strength of the bedrock) that defines critical conditions for initiation of landsliding. Hence, the results presented in this study might provide further constraints to understand gravity-driven hillslope processes as controls on the geometrical evolution of landscapes in general, and for arid climatic environments in particular.

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