1661-8726/09/010031-11
DOI 10.1007/s00015-009-1305-5
Birkhäuser Verlag, Basel, 2009

Swiss J. Geosci. 102 (2009) 31–41

Stream profile analysis of the Koralm Range (Eastern Alps)

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Key words: Eastern Alps, geomorphology, fluvial erosion, stream profiles, exhumation

ABSTRACT

The Koralm Range at the eastern margin of the Eastern Alps shows an asymmetric topography. Steep slopes and short stream channels characterize the south-western segment, whereas gentle slopes and elongated catchments incise the mountain range towards the east. The fluvial landscape dissecting this mountain range is characterized by stream long profiles and by analyzing the power-law scaling between stream slope and drainage area. The concave-up form of the stream long profiles suggests an equilibrium state of the fluvial landscape. In accordance with a tectonic model describing the tilting of the Koralm Range as a consequence of a Miocene block rotation, slope-area data from stream channels suggest a spatial differential uplift pattern. A north-to-south-increase of the steepness values might indicate faster uplift rates in the central Koralm Range. This trend is traced by Paleogene low-temperature geochronological data and by the Late Cretaceous metamorphic field gradient. Thus, it may be explained by a long-term spatial pattern of exhumation and subsequent uplift which remained stable since the Late Cretaceous.

Introduction

The interaction of climate, endogenous and exogenous processes controls the landscape evolution of an actively deforming mountain belt (e.g. Molnar & England 1990; Gilchrist et al. 1994; Burbank & Anderson 2001; Burbank 2002; Cederbom et al. 2004). Crustal deformation, surface uplift, erosion, and exhumation occur simultaneously in many orogens. However, the causes for these processes are rarely separated from each other. The Alpine orogen is largely subjected to both north-south directed compression and lateral (orogen parallel) extension towards the east (Ratschbacher et al. 1989). As in many mountain belts, pressure-temperature-time (P-T-t) paths from the Eastern Alps document that exhumation of rocks occurred simultaneously with crustal shortening (e.g. Cliff et al. 1985). As exhumation is a direct consequence of erosion and/or extensional unroofing, Frisch et al. (1998, 2000a) explained the geomorphological evolution by exhumation and erosion during Miocene tectonic extrusion, determining the present landscape of the Eastern Alps. Based on the well-known kinematic evolution of the Eastern Alps, this model is supported by a geomorphometric analysis of a digital elevation model (Frisch et al. 2000b; Székely 2001), by a sediment budget of the Alps (Kuhlemann et al. 2002; Kuhlemann 2007), by low-temperature thermo-chronological data (Székely et al. 2002; Dunkl & Frisch 2002; Dunkl et al. 2005), and by the catchment evolution of the Alpine foreland basin (Spiegel et al. 2001; Kuhlemann et al. 2006). As a result from these studies, the present data base allows the reconstruction of the geomorphological history since the Oligocene/Miocene boundary (ca. 23 Ma) in a temporal resolution of 5 to 10 Ma.

Erosional processes and isostatic compensation are linked by a feedback mechanism (e.g. England & Molnar 1990; Stüwe & Barr 1998; Pelletier 2004). Consequently, the Late Cenozoic peak uplift in the Alps is attributed to erosionally driven uplift (Hay et al. 2003; Cederbom et al. 2004). Thus, an understanding of the elevation changes within a mountainous landscape gives rise to a better understanding of the dynamics of the lithosphere. To get an insight in this complex system it is essential to analyze high-resolution data concerning large-scale erosion rates. In the Eastern Alps, such data are not present yet.

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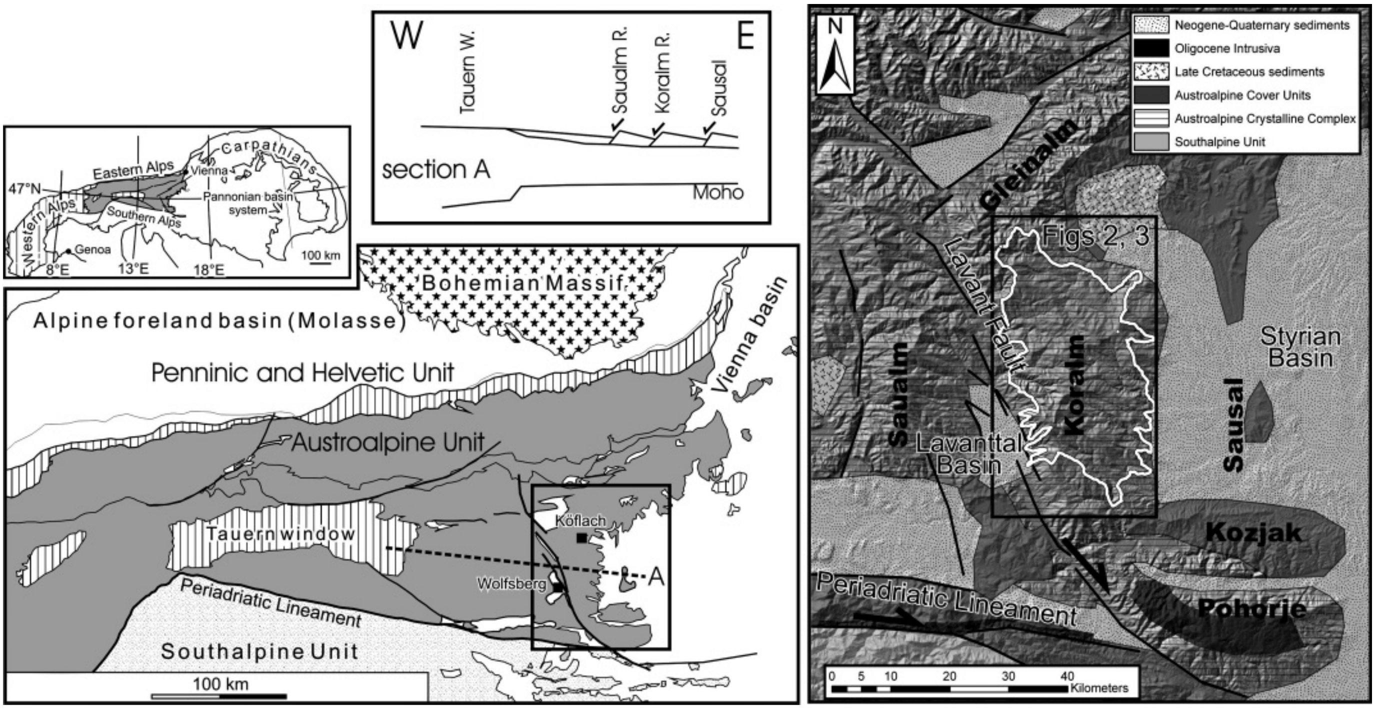

Fig. 1. Location of the Koralm Range at the eastern margin of the Eastern Alps. Section A is from Neubauer & Genser (1990).

There is much empirical evidence that topographic data from fluvial channels can be used to delineate lateral or temporal changes in the rock uplift rate (Snyder et al. 2000; Kirby & Whipple 2001; Schoenbohm et al. 2004; Wobus et al. 2006). Most studies use data from a medium-resolution digital elevation model (DEM) to estimate the power-law scaling between the local channel slope and the size of the drainage basin (Snyder et al. 2000; Kirby & Whipple 2001). A model of fluvial incision predicts a dependence of the scaling on the rock uplift rate (Willgoose et al. 1991; Howard 1994). This correlation was supported by several independent (mainly thermochronological) rock uplift estimates (e.g. Kirby & Whipple 2001), and provides therefore a simple method to map the uplift pattern of a mountain range.

In this contribution, we analyze the stream system dissecting the Koralm and Gleinalm Ranges at the eastern margin of the Eastern Alps (Figure 1). As indicated by Hejl (1998) most parts of these ranges were already close to the surface at Late Cretaceous times. P-T-paths indicate that the central part of the Koralm Range has been exhumed by larger amounts than the northern and southern parts (Tenczer & Stüwe 2003). Exhumation was closely related to Late Cretaceous to Paleogene crustal extension in higher crustal levels accompanied by a high heat flow (Kurz & Fritz 2003; Tenczer & Stüwe 2003; Rantitsch et al. 2005; Krenn et al. 2008). The Koralm Range is characterized geomorphologically by an Early Miocene paleosurface (Winkler-Hermaden 1957; Frisch et al. 1998, 2000a) which was tilted towards the east during this time (Winkler-Hermaden 1957; Neubauer & Genser 1990). Neubauer & Genser (1990) related this tilting to the Early to Middle Miocene lateral extrusion with progressive crustal thinning towards the east. Paleogene apatite fission track data give evidence for a low amount (<2 km) of exhumation since Oligocene times (Hejl 1997). Last glaciation maximum glaciers did not cover the study area (van Husen 1987). Thus, the study area experienced no vertical uplift due to isostatic rebound of deglaciation. Evidence for a steady-state landscape is presented in Székely et al. (2002). However, a strong decrease of the crustal thickness at the eastern margin of the Eastern Alps (Ebbing 2004) indicates differential uplift of the study area, being confirmed by precise vertical movement measurements as well. Consequently, it is expected that the drainage system of the study area responded to long-wavelength surface uplift, tilting and disruption of the paleosurface on a number of spatial and temporal scales. The purpose of this study is to investigate the fluvial landscape in the Koralm region to find evidence for the uplift history at the eastern margin of the Eastern Alps.

Geological setting

Miocene lateral (orogen-parallel) extrusion of the Eastern Alps resulted in the development of a prominent fault pattern which strongly moulds the present-day morphology of the Eastern Alps (Ratschbacher et al. 1991; Frisch et al. 1998, 2000a). Bordered by the Lavanttal and the Styrian Basins, the polymetamorphic Koralm Range forms a relatively rigid block in this extrusion corridor (Figure 1) and experienced major tilting during this period (Neubauer & Genser 1990). The tectonic imprint of continental escape and the consecutive events on this block has only sparsely been investigated in geological research (e.g. Kieslinger 1928; Tollmann 1976; Riedmüller & Schwaighofer 1978; Brosch 1983; Buchroithner 1984). Exploratory studies for large infrastructure projects mark the start of an increased interest in the brittle tectonics and the present-day stress regime of this region (e.g. Peresson & Decker 1998; Brosch et al. 2000, 2001; Vanek et al. 2001; Goricki & Harer 2004; Pischinger et al. 2005, 2006, 2007, 2008).

At the western margin of the Koralm Range, the NNW–SSE trending transtensional Pöls-Lavanttal Fault Zone (Figure 1) is regarded as still active with a dextral sense of shear (e.g. Fodor et al. 1998; Reinecker & Lenhardt 1999; Kuhlemann et al. 2003). The eastern boundary of the range is characterized by sets of normal faults which, for the major part, are hidden below Neogene sediments (Pischinger et al. 2008). Consequently, they are only partly reflected in the regional geological maps (Beck-Mannagetta 1980, 1991). Listric normal faults curving into foliation parallel cataclastic detachments have been frequently observed in outcrops along the eastern boundary of the Koralm (Pischinger et al. 2006). The boundary between the Koralm crystalline basement and the Neogene rocks generally trends approx. NNE to SSW, tracing the given morphology of the crystalline basement.

The study area exposes basement rocks of the Koralm and Gleinalm Range (e.g. Miller et al. 2005; Figure 1). Structurally, the Koralm Range is dominated by a 250–600 m thick, flat-lying, eclogite facies, mylonitic shear zone ("Plattengneis", Figure 2) with main displacement during Late Cretaceous times (Krohe 1987; Kurz et al. 2002; Tenczer & Stüwe 2003). It is folded into a series of open NW–SE trending syn- and antiforms (Putz et al. 2006). The "Plattengneis" is characterized by a pronounced, approx. N–S trending, lineation and a distinct mechanical anisotropy (Blümel et al. 1999; Brosch et al. 2001) related to the syn-metamorphic penetrative foliation. The Koralm Range comprises polymetamorphic micaschists and paragneisses, intercalated with marbles, amphibolites, calcsilicate rocks, eclogites and pegmatite veins (Figure 2). Cretaceous metamorphism reached amphibolite- to eclogite-facies conditions (Tenczer & Stüwe 2003). Peak metamorphic conditions of the eclogites are 15–20 kbar and 600–700 °C (Miller & Thöni 1997; Thöni 2006). From the metapelitic rocks Tencer & Stüwe (2003) determined a continuously increasing metamorphic field gradient from the north towards the central parts. Further to the south, the P-T conditions decrease (Tenczer & Stüwe 2003).

Paleogene Apatite Fission Track data between 51.3 and 26.3 Ma correlate with the altitude of the sample location (Hejl 1998). The age data suggest cooling of the Koralm Range below 100 °C in the Eocene (Hejl 1997, 1998; Rabitsch et al. 2007), and a regional variation of the uplift history, with slower erosion rates in the northern parts (Pack region, Figure 2) than in the central parts (region around the Speikkogel; Hejl 1997, 1998; Figure 2). During the Miocene, the Koralm region showed already a pronounced relief (Hejl 1998) with the formation of a Lower Miocene paleosurface on top of the Koralm-Saualm Block (Frisch et al. 2000a; Dunkl et al. 2005). Structural data and the presence of clastics previously deposited on top of the Koralm basement at an altitude of ±1100 m today, suggest that the Koralm Range was extensional-related elevated by a minimum amount of approximately 800 m, mainly during post-Sarmatian times (Pischinger et al. 2008).

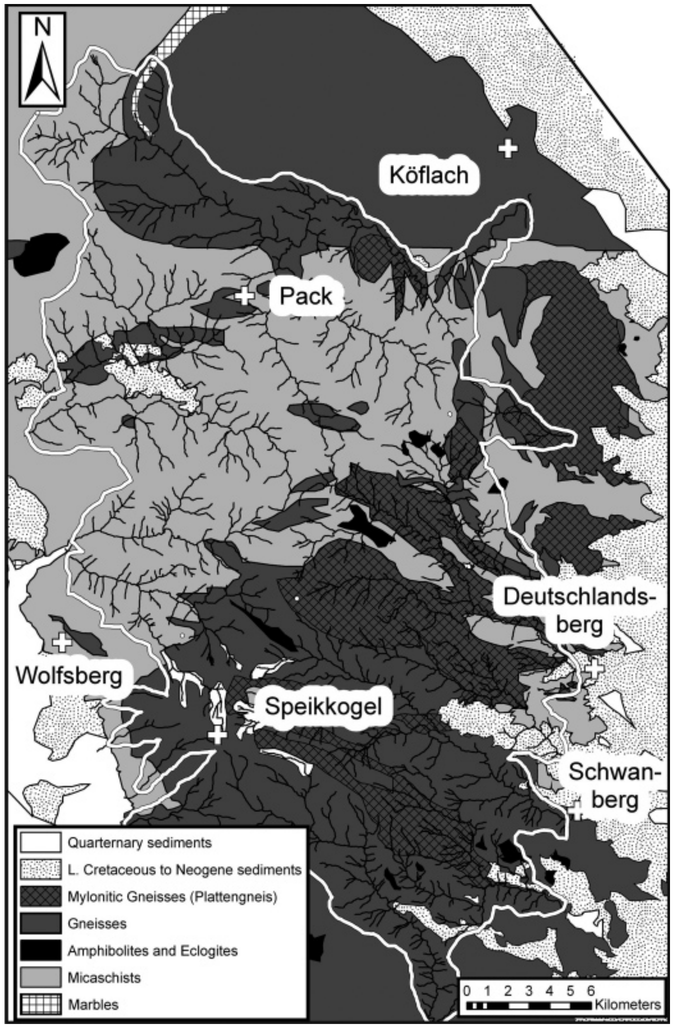

Fig. 2. Map of the study area showing generalized lithology and the streams used in the analysis.

In the southern prolongation of the Koralm Range, the Pohorje and Kozjak Mountains (Figure 1) show Middle Miocene Apatite Fission Track ages (Sachsenhofer et al. 1998) being interpreted as a result of a local rapid exhumation during this time (Sachsenhofer et al. 1998; Dunkl & Frisch 2002). From the age data, Dunkl & Frisch (2002) estimated an exhumation of 1000–1500 m in this region which is presumably dated with the Upper Miocene to Pliocene period (Sölva et al. 2005).

The evolution of a rising range may be mirrored by the produced erosional products. Therefore, the sedimentary succession in the western and eastern fordeeps, the Lavanttal Basin and the Western Styrian Basin, respectively, is reviewed here

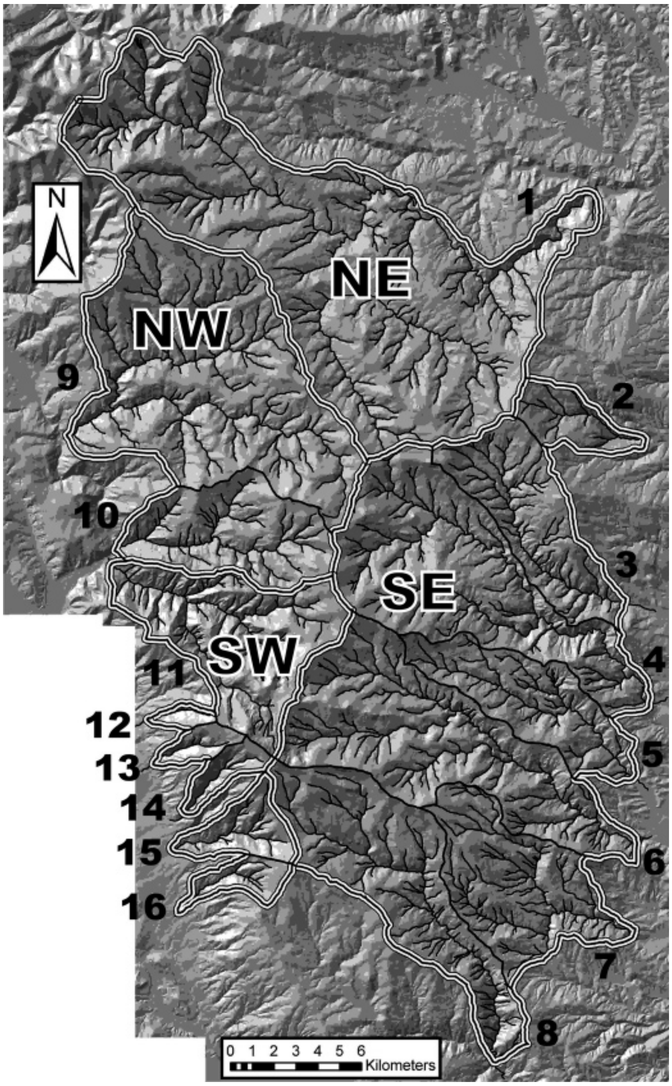

Fig. 3. Shaded relief map of the study area (see Figure 1) with the streams analyzed. Based on the stream profile analysis, the catchments of 16 streams (names in Table 1) are grouped into four zones (NW, NE, SW, SE).

shortly. East of the Koralm Block, the filling of the northern Western Styrian Basin started in the Ottnangian with coal-bearing, limnic-fluviatil sediments of the Köflach region (Figure 2; Stingl 2003). Coarse alluvial fan and delta sediments in the south (Stingl 1994) are presumably coeval. In the Karpatian, alluvial to brackish sediments were deposited along the future margins of the Koralm Block (Beck-Managetta 1952; Bechtel et al. 2007; Reischenbacher et al. 2007). Due to the onset of extensional tectonics during this time, a marine transgression east of the Sausal Block (Figure 1) caused the deposition of several 100 m thick offshore mud- and siltstones. As dated biostratigraphically, the Sausal Range was tilted during the uppermost Karpatian (Friebe 1991). By analogy, the tilting of the Koralm Range may be correlated with this event (Neubauer & Genser 1990). This is accompanied by an enhanced input of coarse debris from the Koralm and Gleinalm region into the Styrian Basin (Friebe 1990ab, 1991) and by the shift of fluviatil to marine sediments in the Lavanttal Basin (Beck-Managetta 1952; Bechtel et al. 2007). During the Badenian stage, the sea flooded the tilted Sausal Block and graded into limnic-fluviatil sediments at the coastline of the rising Koralm Block. Coarse 100 m thick mass flow deposits at the eastern margin of the Koralm Block (Nebert 1989) indicate a high erosional relief during this time. West of the Koralm Block, the Lower Badenian transgression resulted in the deposition of brackish shales (Reischenbacher et al. 2007). A seawater regression at the Badenian/Sarmatian boundary caused erosion and the progression of fluviatil sediments towards the centre of the Styrian Basin. As a consequence, no sediments younger than Badenian are exposed in the Western Styrian Basin. In the Lavanttal Basin, however, Late Sarmatian to Pliocene (?) freshwater sediments overly brackish sediments at the base of the Lower Sarmatian (Beck-Managetta 1952). Pliocene gravel is exposed locally on top of the Koralm Block (Beck-Mannagetta 1980, 1991).

Data and Methods

In this study, stream profile data of sixteen streams were examined (Figure 3). They incise the Koralm Range and the southern segment of the Gleinalm Range towards the west and east. The longitudinal river profiles were extracted from a 10 m interpolated digital elevation model (DEM) provided by the "Bundesamt für Eich und Vermessungswesen". This model is derived from a photogrammetric analysis of black and white aerial photographs with a mean scale of 1:30.000, refined by data from colored aerial photographs (1:15.000 scale). The accuracy of the DEM is specified with ±3 m for open and flat ground, ±5 m for open and hilly ground and ±20 m in forested and Alpine regions. The DEM additionally contains structural information like roads, quarries and other (Bundesamt für Eich und Vermessungswesen 2008).

From the DEM, the drainage network of the study area was delineated by using the "Flow Direction" and "Flow Accumulation" tools of ESRI® ArcGIS 9.1 software. The stream profile data (elevation and distance) were extracted from the vectorized raster of the accumulated flow in a horizontal distance of ca. 200 m with vector origins coinciding with real channel heads, mapped in a topographic map in a scale of 1 : 50.000. The local stream gradient was calculated from the extracted data. This procedure smoothes local irregularities of the DEM data and provides therefore a low-pass filtering of the stream profile.

For the main channel of each catchment (Figure 3) equilibrium stream long profiles were modeled by applying the approach of Bishop & Goldrick (2000). In this approach, a plot of the logarithm of downstream distance against the logarithm of the elevation difference provides the constraints for a mathematical description of the equilibrium stream profile flowing over lithologies of uniform erosional resistance throughout its length.

The flow accumulation raster provides a measure of the drainage area of each grid cell. However, to avoid any necessary manipulation of the DEM data (e.g. pit filling), rather than using this data set, a topographic map was used to delineate the drainage boundaries consistently in the entire study area. Depending on the local topography, sample points in a horizontal distance of 500 to 600 m were selected from the stream data. The sample points were selected to constrain the relationship between drainage areas and slope (see below). Several trials indicate the chosen distance as an optimum for a regression analysis, consistent for the entire study area. A smaller point distance does not change the fit of the calculated regression line.

Finally, the obtained drainage area (A) and slope (S) data were examined by a linear regression analysis. The regression yielded the slope of log A (as independent variable) versus log S (as dependent variable) as the concavity index Θ, and the slope-intercept as the steepness index k_s. The significance of the computed regression parameters was examined by an analysis of variance at the 95% confidence level, testing significant differences in both, the intercept and the slope. Following the recommendation of Wobus et al. (2006), a reference concavity index Θ_{ref} was calculated from a regression of a composite of all data points in the study area. In order to estimate the normalized steepness indices k_{sn}, the reference concavity index was used as a fixed parameter in the regression analysis of the individual streams. Simple models (Howard 1994; Snyder et al. 2000) predict a power-law scaling between the steepness index and the rock uplift rate (U). Despite the fact that this relation is affected by several other factors (nonlinearities in the incision process, adjustment of the channel morphology and bed state, changes in the frequency of debris flows, orographic enhancement of precipitation, Wobus et al. 2006), there is strong empirical support for a correlation between Θ and U. Therefore, k_{sn} is used here as a proxy for the local uplift rate.

Results

Stream long profiles

The long profiles of the analyzed streams have generally smooth, concave-upward curves (Figure 4). They have been described generally as equilibrium stream profiles (e.g. Hack 1957). However, abrupt discontinuities in the gradients indicate the presence of knickpoints, which may be interpreted as profile disequilibria.

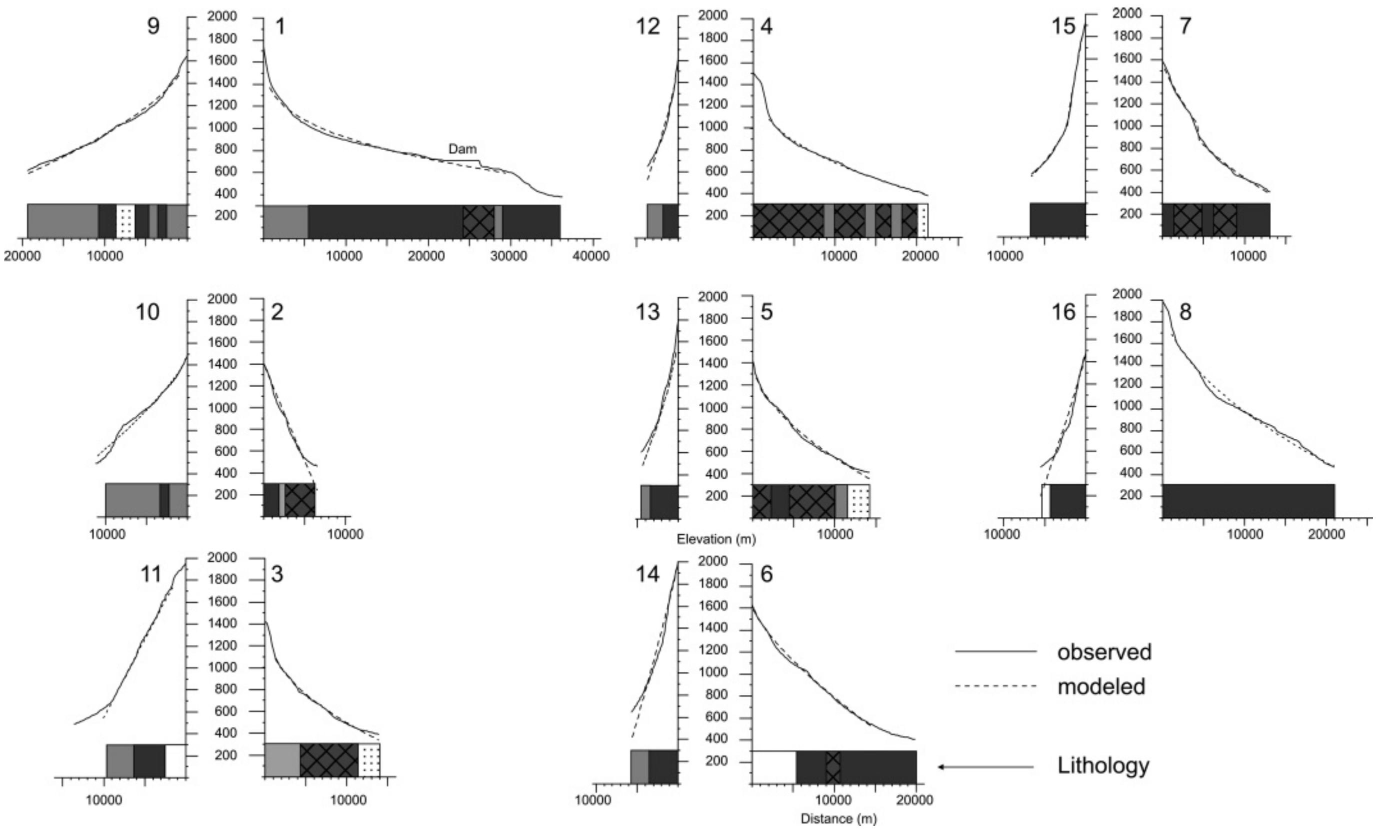

Fig. 4. Modeled and observed long profiles of the stream of Figure 3 (names in Table 1). The lithological variation along the channels is symbolized by the bars (for the symbology see Figure 2).

Table 1. Concavity and steepness index of the streams analyzed (r^2 is the Pearson correlation coefficient of the normalized regression line and N is the number of the used data points).

	stream	normalized			r^2	N
		concavity index	**steepness index**	**steepness index**		
All data		0.492	195		0.697	348
northeast						
1	Teigitsch	0.511	161	117	0.773	49
southeast						
2	Stainzbach	0.432	103	162	0.623	10
3	Wildbach	0.445	92	194	0.831	19
4	Laßnitz	0.495	206	195	0.842	45
5	Stullneggbach	0.287	6	162	0.455	11
6	Schwarze Sulm	0.316	13	222	0.734	52
7	Weiße Sulm	0.276	6	167	0.723	25
8	Krumbach	0.466	138	211	0.790	18
	All data	0.396	43	201	0.740	180
northwest						
9	Waldensteiner Bach	0.312	8	148	0.577	39
10	Fraßbach	0.267	5	190	0.748	9
	All data	0.311	9	155	0.570	48
southwest						
11	Prössingbach	0.464	222	354	0.710	16
12	Reidebnerbach	0.645	1942	227	0.931	10
13	Eitwegbach	0.518	485	331	0.709	12
14	Gemmersdorfer Bach	0.588	1593	390	0.787	10
15	Ragglbach	0.514	396	284	0.903	13
16	Rainzer Bach	0.442	122	253	0.663	10
	All data	0.438	135	304	0.768	71

Stream profile analysis

For all catchments, the regression analysis demonstrates that the data of the tributaries (Figure 3) match the regression line of the corresponding main channel. No changes in the regression parameters can be observed along individual stream profiles. Also, the observed knickpoints (Figure 4) are not reflected by a corresponding break in the slope-area plot. Therefore, stream profile data of the entire catchment were used in the analysis of the examined streams. There are no statistically significant differences between the concavities of the streams on the western and eastern slope. Consequently, the calculated reference concavity index Θ_{ref} of 0.49, falling in the typical range of concavities (Wobus et al. 2006), is a reliable estimate. The statistical comparison of the regression models for the individual streams (Table 1) indicate four zones (Figure 3) which are characterized by significantly different y-intercepts (i.e. the steepness indices, Table 1). Consequently, the data of these zones were pooled to a composite plot (Figure 5).

Discussion

The Koralm Range is a tectonically tilted block (Winkler-Hermaden 1957; Neubauer & Genser 1990). Tilting is mirrored by the asymmetric topography of this range. Steep slopes and short stream channels characterize the south-western segment, whereas gentle slopes and elongated catchments incise the

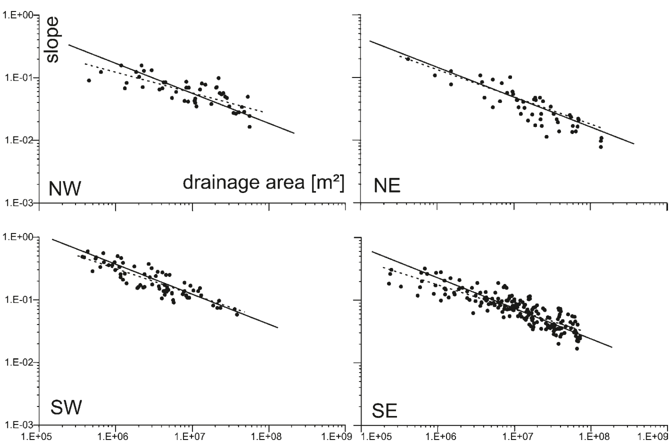

Fig. 5. Slope-area data from the zones of Figure 3. The slopes of the regression lines is the concavity index Θ and the y-axis intercept is the steepness index k_s (see Table 1). Dashed lines are fits to data with concavity as a free parameter.

Table 2. Uniaxial compressive strength (data from site investigations of the Koralm tunnel, by courtesy of the ÖBB-Infrastruktur Bau AG) of the main lithotypes of the Koralm Range (Figure 2).

Lithology	N	uniaxial compressive strength [Mpa]			
		Min	Mean	Med	Max
Mylonitic Gneiss (Plattengneis)	16	31.47	116.69	121.66	193.71
Gneiss	45	14.83	104.82	105.20	185.24
Amphibolite/Eclogite	12	29.25	135.08	121.60	301.87
Micaschist	40	16.04	71.90	67.50	143.55
Marble	5	72.15	94.12	87.63	138.55

mountain towards the east (Figures 3 and 4). The local base level at an altitude of ca. 400 m is formed by the Lavanttal Basin in the west and the Styrian Basin in the east, respectively. As the summit is given by the Speikkogel peak (Figure 2) at an altitude of 2140 m, an erosional profile of ca. 1700 m is exposed in the study area. Along the gorge like creeks, slope angles exceed 24°, indicating high relief energy (Pischinger et al. 2006). Between these, slope angles are mostly between 5° and 24°, with the mean at 14° probably reflecting the Neogene relief (Pischinger et al. 2006).

Climatic parameters may influence long-term rates of fluvial erosion in an orogen (e.g. Schlunegger et al. 2001; Schoenbohm et al. 2004). However, from the analysis of the spatial variability of precipitation data, Holawe & Dutter (1999) found no major difference in the precipitation pattern across the studied mountain range. Thus, an orographic influence on the morphometry of the Koralm Range is here excluded.

The stream channels flow to large extents on bedrock and follow more or less the dip of the landscape. Due to the exposure of highly erodible strata in the northern segment of the Koralm Mountain (Figure 2), the catchments become wider (Figure 3) and the asymmetry of the range is not longer visible. The topographic depression of the Pack region (Figure 2) can be explained by a schistose lithology as well.

Geochronological evidence and the sedimentary sequence in the fordeeps characterize the Koralm Range as a block with an increasing relief during the Ottnangian to Karpatian period. However, neither the produced orogenic debris, nor the present thermochronological data constrain the uplift path in an acceptable resolution. The analysis of stream profiles provides therefore, a promising approach to detect a regional variation of the erosion rates across the mountain range.

The comparison of the observed and modeled stream long profiles (Figure 4) indicates some excursions from the equilibrium stream profile. Apart from climate and vegetation, erodibility as the resistance against chemical and mechanical weathering, is mainly a function of the strength of the rock mass comprising the slope. The uniaxial compressive strength of the implicated lithotypes (Table 2) indicates strong erodibility contrasts at the sites of the knickpoints, attributable to the lithological variation (Figure 4). The remaining knickpoints are related to the discontinuity pattern of the rock volume. The close general relationship of drainage pattern development and preexisting discontinuity pattern has been discussed in detail by Scheidegger (2004) for several rivers resp. gorges in the Swiss Alps. Analogously, the geomorphology and the drainage pattern of the Koralm Range (Figure 3) clearly reflect the underlying geologic structures (Figure 6), related to the polyphase Miocene extensional tectonics (Pischinger et al. 2006, 2007, 2008). These are on the one hand the fault and discontinuity pattern, and on the other hand foliation fabric and the large scale regional fold structure (Figure 6 and Putz et al. 2006). Further on, pronounced anisotropic mechanical properties (Blümel et al. 1999; Brosch et al. 2000) are caused by the penetrative metamorphic foliation, and therefore differences in erodibility may be expected in areas with same lithology but different oriented foliation fabric. The relation between discontinuity and drainage pattern has already been documented by Stiny (1925) for the Teigitsch Gorge (stream 1 in Figure 3) in the northern Koralm area. Therefore, we do not see evidence for a transient system of migrating knickpoints and assume a general equilibrium state of the Koralm Range.

The analysis of the slope-area data does not indicate a downstream transition between different steepness values. However, the analysis finds statistically significant regional differences in the steepness values. In the southern segment of the study area there is a marked difference in the steepness indices across the watershed of the Koralm. This trend is accompanied by a regionally increase of the steepness values from north to south (Table 1). The south-western segment is incised by short and steep channels and shows a best-fit value of 304. This is a considerably higher value than the estimate of 201 at the south-eastern slope of the range, being characterized by lower gradients of the channels. In both areas, differences in the erodibility of the bedrocks and in the bed state of the streams are minimal (Figure 2). Consequently, we see evidence that the steepness values indicate a higher uplift rate at the western slope than on the eastern slope of the mountain range. This is in fact the expected observation by taking the eastward tilting of the Koralm into account. Towards the north, the steepness values decrease. Nevertheless, a statistically significant difference of the values between the eastern and western slope is maintained. This decrease may be partly explained by a lower strength of the bedrock lithology in the Pack region (Figure 2). However, the local concavity index is statistically indistinguishable from the concavity index of the entire study area. This suggests that steepness values are tracking the rock uplift rate. The south to north

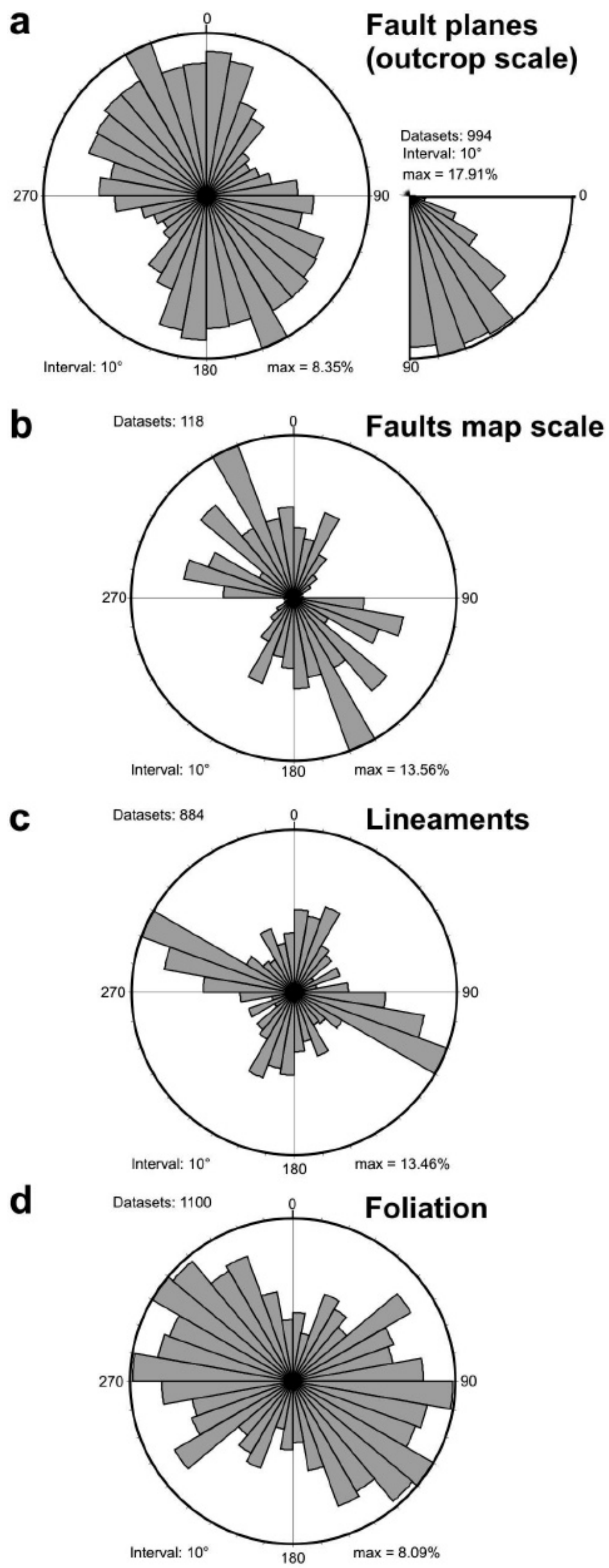

Fig. 6. Bipolar directional rose diagrams (strike direction) of (a) fault planes on the outcrop scale and the respective dip angles, (b) faults on the map scale, (c) lineaments derived from digital elevation models and (d) foliation planes from the eastern slope of the Koralm Range.

decrease of the values is in accordance with the low-temperature geochronological data of Hejl (1997, 1998), suggesting a slower uplift rate in the Pack region. Interestingly, this trend is also mirrored by the local metamorphic field gradient (Tenczer & Stüwe 2003). Peak metamorphism occurred in early Late Cretaceous times (Thöni & Jagoutz 1992, 1993; Neubauer et al. 1995; Thöni 1999, 2006) and was followed by a lateral differential, syn-convergent exhumation during the Late Cretaceous (Tenczer & Stüwe 2003; Wiesinger et al. 2006). This caused the highest amount of exhumation in the central Koralm Range (Tenczer & Stüwe 2003). These observations might indicate a spatial pattern of exhumation which remained stable from Late Cretaceous times onwards, thus pointing to a dynamic equilibrium between rock uplift and erosion (Kooi & Beaumont 1996). In response to a changing uplift rate, stream channels achieve a new steady state very rapidly (e.g. Burbank et al. 1996; Snyder et al. 2000). Therefore, it is important to note, that this supposition does not exclude short-time uplift pulses (Dunkl et al. 2005; Kuhlemann 2007), superimposing a long-term constant exhumation path. Thus, if this hypothesis is correct, the stream profile analysis of this study mirrors the long-term (time scale of 10 Ma) average rather than the short-term (time scale of 1–5 Ma) landscape evolution of the Koralm Range.

Since the early Late Cretaceous, the Koralm Range was exhumed very rapidly from deeper crustal levels (Thöni & Jagoutz 1992; Thöni 1999; Kurz & Fritz 2003; Tenczer & Stüwe 2003; Rantitsch et al. 2005; Krenn et al. 2008), exposing the surface to erosion during the Eocene (Dunkl et al. 2005; Kuhlemann 2007). Subsequently, a Miocene paleosurface (Koralm surface) was formed, not being destroyed during the Pliocene, a time interval characterized by strongly increasing erosion rates (Dunkl et al. 2005; Kuhlemann 2007). The present uplift is supposed to be compensated by erosion (Székely et al. 2002; Kuhlemann 2007). This is supported here by the observed equilibrium shapes of the stream profiles.

The Kozjak and Pohorje mountains in the southern prolongation of the Koralm Range (Figure 1) form an asymmetric block, very rapidly exhumed during the Miocene (Sachsenhofer et al. 1998; Dunkl & Frisch 2002; Janák et al. 2006). Sölva et al. (2005) found some geomorphologic evidences for a faster uplift rate in the southern part of the Pohorje Range. The asymmetry of the topography and the differential uplift rate resembles the asymmetry of the Koralm Range. However, in contrast to the transtensional nature of the Lavanttal Fault at the western margin of the Koralm Range, the Late Miocene to Pliocene transpressional tectonics (Fodor et al. 1998) in the offset zone of the Periadriatic Lineament (Figure 1), resulted in a different timing of exhumation and in a morphological disequilibrium (Sölva et al. 2005) at the Kozjak and Pohorje mountains.

Conclusions

The Koralm Range is characterized by an asymmetric topography developed during the course of Miocene continental escape tectonics. The concave-up form of the stream long profiles suggests an equilibrium state of the present fluvial landscape. Slope-area data from stream channels suggest a spatial differential uplift pattern within the Koralm Range. High steepness values indicate that the western slope was uplifted faster than the eastern slope. This is in accordance with a tectonic model which describes the eastward tilting of the Koralm Range as a consequence of a Miocene block rotation. A north-to-south-increase of the steepness values might indicate faster uplift rates in the central Koralm Range. This trend is traced by Paleogene low-temperature geochronological data and by the Late Cretaceous metamorphic field gradient. Thus, it may be explained by a long-term spatial pattern of exhumation which remained stable since the Late Cretaceous.

Acknowledgements

This study has partly been carried out during a research project (P-17697-N10) granted by the Austrian Science Fund (FWF). Rock strength data were provided by M. Blümel (Institute for Rock Mechanics and Tunneling, Graz University of Technology, by courtesy of the ÖBB-Infrastruktur Bau AG). F. Schlunegger, R. Schuster and W. Schwanghart are thanked for constructive review comments.

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Manuscript received October 10, 2007
Revision accepted October 24, 2008
Published Online first March 28, 2009
Editorial Handling: Andreas Wetzel & Stefan Bucher