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Source: Arctic, Antarctic, and Alpine Research, 40(4) : 685-694

Published By: Institute of Arctic and Alpine Research (INSTAAR), University of Colorado

URL: https://doi.org/10.1657/1523-0430(07-037)[MARCHI]2.0.CO;2

Arctic, Antarctic, and Alpine Research, Vol. 40, No. 4, 2008, pp. 685–694

Rocky Headwaters in the Dolomites, Italy: Field Observations and Topographic Analysis

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Abstract

Rock outcrops cover large areas of alpine headwaters and are entrenched by chutes and couloirs, which are controlled by faults in bedrock. These widespread landforms play an important role in delivering sediment to lower basin slopes. High-resolution topographical data from LiDAR surveys allow investigation of morphometric characteristics and sediment transport processes in these features. Using aerial photo interpretation, field surveys, and topographic analyses of LiDAR data, this paper quantifies the morphological characteristics of rocky couloirs and their drainage basins, and the relationship between these features and the structural setting, in a study area in the Dolomites (northeastern Italy). Rock basins are characterized by small sizes (surface area < 0.066 km^2) and high average basin slopes (up to 2.1 m m^{-1}). The analysis of contributing area and local slope outlines the difference between these rock basins, and even smaller and steeper rock faces entrenched by very shallow chutes, which were defined as interbasin areas. We consider rocky couloirs and rock basins in the headwaters of the Dolomites to be part of the channel network, since channeled flow occurs in the couloirs during storms. High-intensity rainstorms trigger debris flows as evidenced from local scouring, especially in the lower parts of the couloirs. The longitudinal profiles of the couloirs are overall linear, but the high-resolution data display distinct high-slope and low-slope stretches forming steps, that may function as localized sources and sinks for debris flows. The cross-sectional widths of the couloirs do not appear related to upslope area; this may be due to both structural control on cross-sectional geometry and complex erosion of the couloir by debris flows.

DOI: 10.1657/1523-0430(07-037)[MARCHI]2.0.CO;2

Introduction

In the alpine landscape, bedrock outcrops occupy large areas, especially in the upper parts of basin slopes. In other parts of basins, shallow and discontinuous "islands" of soil cover the rock surface; in these cases, the underlying bedrock strongly controls hydrological processes, making these situations similar to slopes with exposed bedrock. Bedrock outcrops are frequently entrenched by steep, narrow gorges banded by cliffs (termed in this paper *couloirs*, a term commonly used in the mountaineering literature). Rocky couloirs, whose origins and locations are often structurally controlled, play an important role in hydrological processes in alpine headwaters. Fractures and faults in bedrock provide preferential paths for water runoff; moreover, falling and weathering of fractured rocks provide large amounts of debris for transport by snow avalanches and debris flows.

Rock basins in the upper parts of alpine basins display a different hydrological response from soil or scree-mantled slopes. A high slope gradient, absence of vegetation and low permeability cause a fast response to rainstorms with abundant surface runoff. The quick concentration of surface runoff in upstream couloirs is also responsible for the initiation of debris flows at the interface with scree-covered slopes below. The presence of large bedrock outcrops in alpine basins also has implications for the recognition of channel heads, i.e., the points of initiation of the channel network. Understanding the physical processes leading to channel initiation in the framework of drainage basin evolution, the field recognition of channel heads, and the extraction of synthetic channel networks from digital terrain models (DTMs) has been the object of a number of studies (Smith and Bretherton, 1972; Tarboton et al., 1991; Montgomery and Foufoula-Georgiou, 1993; Dietrich et al., 1993; Pilotti et al., 1996; Hancock and Evans, 2005). Montgomery and Dietrich (1988) defined a channel head as "the farthest upslope location of a channel with well defined banks". This definition was then rephrased by Dietrich and Dunne (1993) as "the upstream boundary of concentrated water flow and sediment transport between definable banks". These authors described the geomorphic processes leading to the formation of channel heads: erosion by overland flow, seepage erosion, mass failure, and tunnel scour. Both the definition of channel heads and their genetic processes are typical of soil-mantled slopes. Most papers in the literature concern channel initiation in soil- or scree-mantled slopes. Although some contributions mention the control of bedrock properties on channel head locations (Montgomery and Dietrich, 1994), less attention is usually devoted to channel initiation on exposed bedrock. Recent investigations on bedrock channels (e.g., Rosenbloom and Anderson, 1994; Seidl et al., 1994; Whipple et al., 2000; Montgomery and Gran, 2001; Wohl and Merritt, 2001, Stock and Dietrich, 2003) mainly deal with the topography and evolution of fluvial and debris-flow dominated channels; fewer studies are devoted to the morphology of rock headwaters incised by multi-process couloirs, like those commonly observed in the upper slopes of alpine mountains.

The general morphological characteristics of alpine rock slopes and rock basins and their role as sources of clastic material are described in many studies. However, despite the importance of rock basins in the hydrological and geomorphological processes of alpine headwaters, relatively little attention has been paid to a morphometric analysis of these areas, to characterizing their topographic settings and to their relations with the channel network. Among the studies regarding the morphometry of rock basins, we mention those of Sauchyn and Gardner (1983) and Sauchyn et al. (1998) in the Canadian Rocky Mountains. In the same geographical region, Desloges and Gardner (1984) analyzed hydrologic and sediment transport processes in ephemeral headwater channels and provided a short review of previous contributions to the topic. This paper aims at describing the principal morphometric characteristics of rock basins and couloirs in alpine headwaters in an area of the Dolomites (Eastern Italian Alps) with close attention to recognizing debris transport processes and to the positions of the couloirs with respect to the channel network and the structural setting.

Methods

Study methods include aerial photo interpretation, structural and geomorphological field surveys, and morphometric analyses on digital terrain models.

Aerial photos were used for preliminary recognition of couloirs in the study area. Aerial photos taken in 1970 (scale 1:15,000), 1983 (scale 1:33,000), 1991 (scale 1:25,000), and digital color orthophotos (year 2000, scale 1:10,000; 1 m pixel resolution) were used. On the basis of aerial photo interpretation, eight rocky couloirs were selected for field investigations (Fig. 1). The principal features of the couloirs (initiation and outlet points, presence of debris on the floor, interface with scree slopes below, topographic settings) were documented through field observations. Because of difficult terrain conditions, simple and convenient topographic instruments (measuring tapes, altimeters, and clinometers) were used. The upper and lower ends of the couloirs were measured by GPS. Surveys of longitudinal profiles and representative cross sections were carried out on five couloirs. The difficult access prevented surveying of longitudinal profiles and cross sections in three more couloirs, in which only summary data (coordinates of initiation and outlet points, photo documentation) were collected. Debris-flow channels on the scree slopes located below rock cliffs were also surveyed. Field surveys made it possible to map faults and recognize their principal geometric and kinematic elements. Moreover, the principal parameters of various sets of joints were assessed along scan lines in sample areas of the rock faces. For each discontinuity, the following data were recorded: distance along the scanline; orientation (dip/dip direction); persistence (length of discontinuity along the scanline); roughness; separation; infill type (none, high-friction material, soft gouge), and thickness of infilling material. A stability analysis based on the Markland Test (Markland, 1972) was carried out; statistical analyses of joints made it possible to detect the orientations of discontinuities and to determine if their intersections with the slope led to the formation of blocks or wedges prone to fall.

LiDAR data used in the DTM analysis were acquired from a helicopter using an ALTM 3100 OPTECH, flying at an average altitude of 1000 m above ground level during snow-free conditions in October 2006. The flying speed was 80 knots, the scan angle 20°, and the pulse rate 71 kHz. The survey design point density was specified to be >5 points m^{-2}, recording up to 4 returns, including first and last. LiDAR point measurements were filtered to obtain points from the bare ground using Terrascan^{TM} software classification routines and algorithms. The point density of filtered data in the study area was ~3 points m^{-2}. Digital aerial photos at a resolution of 0.15 m were also taken using a Rollei H20 camera.

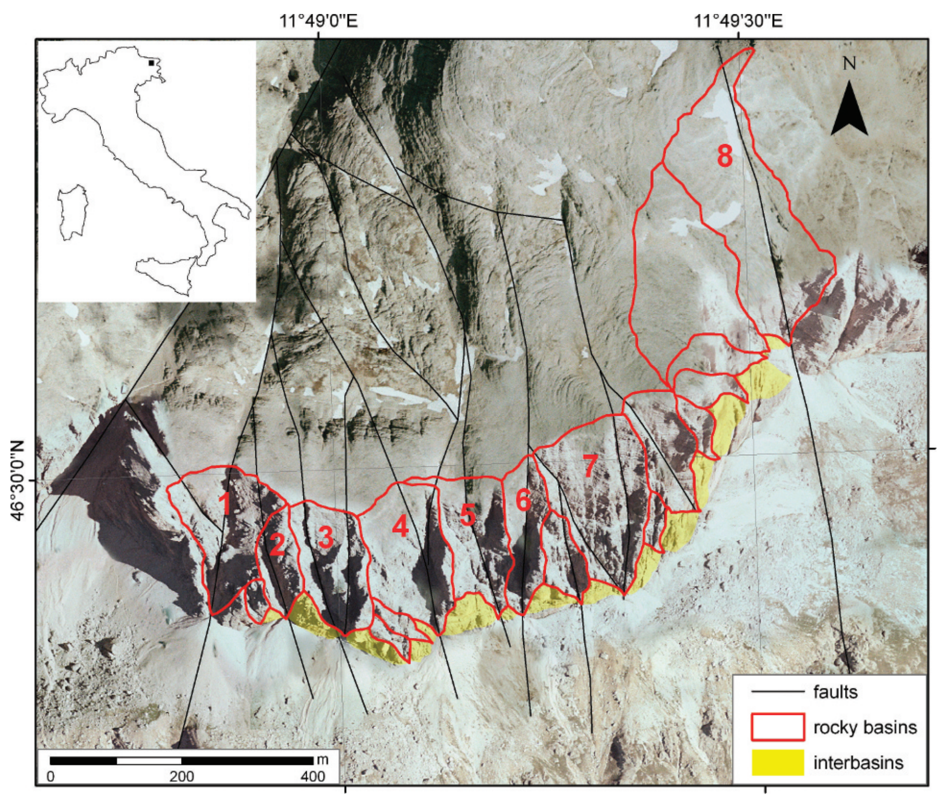

FIGURE 1 Map of the study area showing the faults that intersect the rock basins. The catchments in which field observations have been carried out are numbered from 1 to 8.

The LiDAR survey does not cover one of the studied catchments (catchment no. 1), which was analyzed using topographic data from a 1:5000 map. The LiDAR filtered points were used for DTM interpolation at a 5 m grid resolution, carried out by averaging data in 5 × 5 m windows using the Block Statistics tool of ArcGIS 9.2 Spatial Analyst extension. Topographic data of the catchment not covered by the LiDAR survey were interpolated using the Inverse Distance Weighted algorithm, available in ArcGIS 9.2, to generate a DTM with the same cell size (5 m) as the LiDAR DTM. A single flow (D8) method was used to extract the drainage basins from the DTM. Computation of D8 flow and the subsequent extraction of the drainage basins was done with open source TauDEM software packages (http://www.engineering.usu.edu/dtarb/taudem). The rock basins were closed corresponding to the outlet points measured with GPS during field surveys. A map of the upslope area was computed with a multiple flow algorithm (Quinn et al., 1991). The multiple flow upslope area was preferred for analyzing the area-slope relations, as it makes it possible to avoid grid artifacts associated with the choice of a unique flow direction. Flow dispersion, which is intrinsic to multiple flow algorithms, is consistent with multiple directions of overland flow on rock surfaces. The single-direction flow algorithm was used to compute flow path slope (McGlynn and Seibert, 2003). Flow path slope corresponds to the maximum gradient from a cell to its neighboring ones, which defines the flow direction in the single flow algorithm and the direction receiving the largest proportion of flow in the multidirectional flow algorithm.

Study Area

The study area (Fig. 1) is located on the southern flank of the Sella Group (Dolomites, northeastern Italy). This area is affected by important tectonic structures, mostly related to Tertiary NE-SW–trending Alpine compression (Doglioni and Bosellini, 1987; Mollema and Antonellini, 1999). Two different tectonic phases have been recorded: an important Triassic phase, and the Alpine deformation that shaped the actual structure and landscape (Doglioni, 1982). The rocks cropping out in the study area (Fig. 2) range from Lower Carnian to Norian in stratigraphic sequence:

The *Dolomia Cassiana* (Lower–Middle Carnian) is made up of white grayish crystalline dolomites, generally massive. It gives rise to massive rock walls.

The *Dürrenstein Formation* (Upper Carnian) consists of peritidal terrigenous-carbonate shelf deposits. In the lower part, typical stromatolitic dolomites crop out, whereas towards the top a succession of fine sandstones, siltstones and silty limestones follows with frequent pelitic intercalations, ending with a level of dolomitic limestones, dolomites and oolitic limestones.

The *Raibl Formation* (Upper Carnian) consists of siltstones and polychrome marls with subordinate limestones and dolomites, sometimes decayed, gypsum, and fine-grained sandstones.

The *Dolomia Principale* (Norian) consists of cyclical dolomites deposited in a carbonate tidal plain environment. These deposition conditions resulted in sub-horizontal dm-scale stratification. The fossil remnants of large mollusks are abundant. This formation makes up the subvertical walls on the upper slopes of the Sella Group.

In the study area, the Raibl Formation is almost completely covered by scree deposits from the overhanging cliffs of Dolomia Principale (Fig. 2). The abundant debris from the Dolomia Principale is consistent with its intense fracturing (Antonellini and Mollema, 2000) and stratification, which can be assumed to be the main joint family. In the scree belt that covers the Raibl Formation, debris cones are prominent, with apexes located at the outlet of couloirs that cut the superjacent rock slope (Fig. 2). These debris cones are a widespread landform in the Dolomites, as well as in other alpine regions (Pech and Jomelli, 2001). This study focuses on rock basins and couloirs that entrench the upper parts of dolomite cliffs, corresponding to outcrops of Dolomia Principale (Figs. 1 and 2). In most of the studied area, the Dolomia Principale has an average thickness of about 270 m, exceeding 300 m in the easternmost sector. Figure 1 shows the rock basins in the study area, and the interbasins (rock facets) between the basins and the scree slopes. The numbers 1 to 8 in Figure 1 identify the rock basins in which field observations were carried out.

With regard to vegetation cover, the cliffs of Dolomia Principale are completely unvegetated, while the scree belt and rocky slopes of Dolomia Cassiana are mostly bare, apart from sparse herbaceous vegetation. The mean annual 0°C isotherm is at about 2400 m elevation. Average annual precipitation in the study area amounts to about 1100 mm, mostly occurring as snowfall from October-November to April. On the studied rock slope, which lies between approximately 2700 and 3000 m a.s.l., precipitation occasionally takes place as snowfall during the summer. The southerly aspect causes the duration of snow cover to be shorter than in other locations at the same elevation. However, in early summer, snow avalanche accumulations are often still present on the floors of the couloirs and at their outlets on the scree slopes.

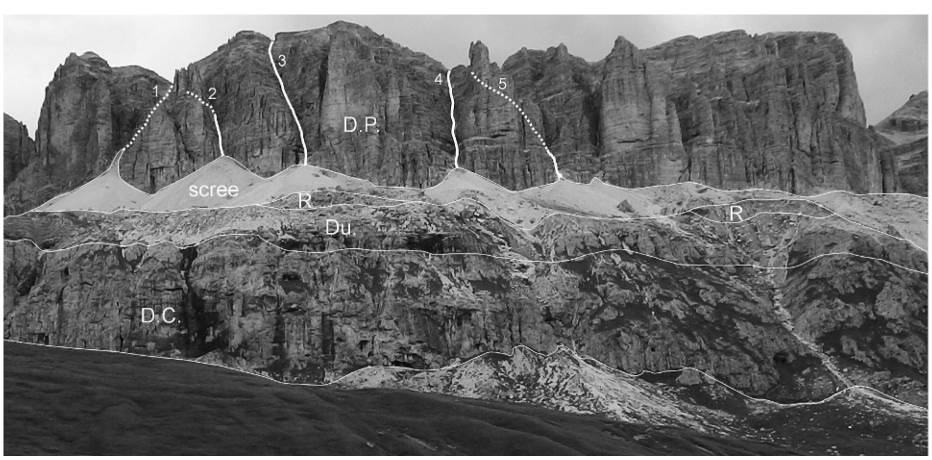

FIGURE 2. Rocks outcropping in the study area and rocky couloirs surveyed in the field (nos. 1 to 5). Dotted lines indicate couloirs hidden by rock slopes and not visible in the photo. Rock formations: D.C.: Dolomia Cassiana; Du.: Dürrenstein Formation; R.: Raibl Formation, D.P. Dolomia Principale.

Results

STRUCTURAL OBSERVATIONS

The analysis focused on couloirs that drain well-defined open rock basins in the upper part of the slope (Dolomia Principale). The adjective "open" refers to the transfer of debris from the rock basin (Sauchyn and Gardner, 1983).

Structural surveys made it possible to recognize shear elements, like Riedel shears (wedges generated by the main fault) and slickensides (parallel striations on rock surfaces produced by relative motion along opposite sides of a fault plane). These structures are associated with faults or thrusts and clearly discriminate them from fractures with no motion between the two faces. The consistency of kinematic elements observed in the couloirs (nos. 1 to 8 in Fig. 1) indicates that they are imposed on strike slip faults.

Collecting data on the joints in the rock faces along the scanlines made it possible to carry out a stability analysis to compare the stability of rock faces in rock basins with that in interbasin areas. Joint sets were identified by plotting the orientation data stereographically. The maximum point density in the contour diagram was selected to represent the orientation of each discontinuity set. Mean discontinuity spacing was calculated for each discontinuity set as the average distance between adjacent discontinuities making up the set, corrected for directional bias following the method described by Priest (1985). This correction calculates the perpendicular distance between adjacent parallel discontinuities, removing the influence of the orientation of the scanline. Figure 3 presents the pole plots with density of joints and the results of the stability analysis using the Markland Test (Markland, 1972) for a rock basin (Figs. 3a and 3b) and an adjacent interbasin (Figs. 3c and 3d). This method compares the orientation of the slope with the orientation of rock discontinuities and the internal angle of friction of the joints to assess potential instability of the rock mass. The angle of friction was calculated as 28° according to the Mohr-Coulomb criterion. The intersection of the great circle of slope face with the circle of friction angle identifies the critical zone for slope instability. The point of intersection of the great circles for the two major sets of discontinuities represents the intersection of two planes creating a wedge. If this point falls outside the critical zone (arrows in Fig. 3d), then wedge failure is not possible. If the wedge plunges more steeply than the friction angle and less steeply than the dip of the slope face in the direction of the slope face, then the point of intersection falls within the critical zone and sliding of a wedge is possible (Fig. 3b). The potential failure is proportional to the density of the joints in the critical zone. The higher propensity of blocks and wedges to falling and toppling helps explain the higher production of debris in rock basins than in the rock cliffs of the interbasins. Moreover, the detachment of rock fragments causes fresh bedrock to be exposed to weathering, further contributing to gravitational accumulation of debris.

DTM MORPHOMETRIC ANALYSIS

Table 1 summarizes the main morphometric parameters of the rock basins under study. Surface area A_s was computed for each basin as:

$$A_s = \sum_{i=1}^{n} \frac{A_i}{\cos \alpha_i} \quad (1)$$

where A_i and α_i are the planimetric area of each cell (m^2) and its slope (°), respectively, whereas n is the number of cells in the basin.

The major difference between planimetric area and surface area has to do with the high gradient of the basin slopes. A large surface area implies that large rock surfaces supply rock fragments to high-gradient couloirs, from which they are delivered to the basin outlet. This helps explain the formation of large debris cones (Figs. 1 and 2) from rock basins with small planimetric areas.

Figure 4 compares the rock basins with interbasin areas (locations shown in Fig. 1). This comparison involves all the rock basins in the study area, not only those in which field surveys were carried out. Interbasin areas, consisting of rock cliffs entrenched by shallow chutes, have slopes higher than rock basins; their highest values are typical of subvertical rock faces (Fig. 4).

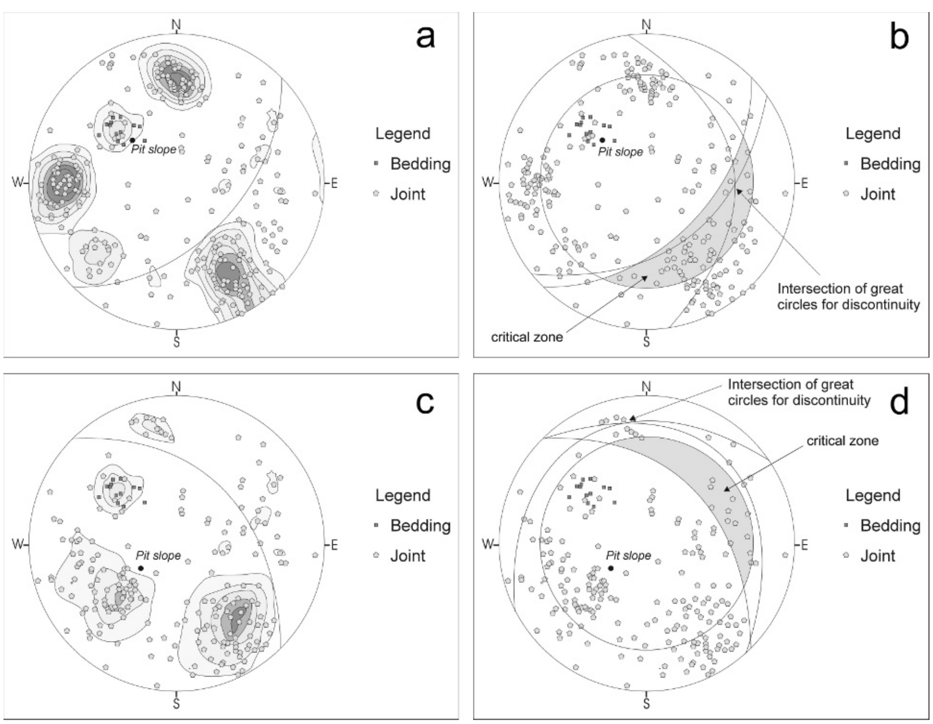

FIGURE 3. Pole plots of joints and stability analysis according to the Markland Test (lower hemisphere projection). (a) Density of joints along a couloir; (b) the same plot with the results of stability analysis; (c) density of joints in an interbasin zone; and (d) the same plot with the results of stability analysis.

TABLE 1

Principal morphometric parameters of studied rock basins. Basin 1: topographic data from 1:5000 maps. Basins 2 to 8: topographic data from aerial LiDAR.

Basin no.	Planimetric area (m^2)	Surface area (m^2)	Min–Max basin elevation (m)	Average basin slope (m m^{-1})	Average couloir slope (m m^{-1})
1	22,750	32,329	2720–2920	0.91	0.72
2	8000	18,971	2715–2921	1.60	1.20
3	18,050	35,258	2702–2920	1.60	0.91
4	23,900	46,935	2676–2914	1.62	1.08
5	17,375	32,208	2672–2893	1.47	1.06
6	12,125	29,597	2666–2885	2.13	0.90
7	31,400	53,951	2657–2929	1.34	0.90
8	47,725	65,507	2687–2964	0.80	0.67

Interbasins are located in the lower parts of the rock slopes, where the highest gradients are found, whereas rock basins extend to the upper parts of the slopes, where relative attenuation of steepness occurs in unchanneled valleys. Larger contributing areas in rock basins than in interbasins are consistent with the overall topography of these two morphological units.

The relations between upslope area and local slope are often used to compare different basins and differentiate landscape elements (hillslopes, unchanneled valleys, channels) within a basin. Figure 5 shows a scatterplot of local slope versus upslope area (computed with the multidirectional flow algorithm) for rock basins 2 to 8. Rock basin no. 1 is not included in the figure, as LiDAR data are not available. In order to reduce the scatter, data were averaged on area intervals of 25 m^2, corresponding to the grid cell size. Several authors (Montgomery and Foufoula-Georgiou, 1993; Ijjasz-Vazquez and Bras, 1995) have observed a positive gradient in the area-slope relation for very small drainage areas, followed by a decrease in slope. The change in the trend of the area-slope relation corresponds to the transition from hillslopes (divergent topography) to unchanneled valleys and channels (convergent topography). This trend is clearly visible in only one of the studied catchments (no. 6), is poorly defined in two more cases (nos. 5 and 8), and is absent in the others. This seems to indicate the absence or small extent of hillslopes in the catchments contributing to rocky couloirs, which are dominated by convergent topographies. We note that Montgomery and Dietrich (1994) stressed that the distinction between valleys and hillslopes can be irrelevant in rocky landscapes, where diffusive processes, typical of soil-mantled hillslopes, may be essentially inactive. The prevailing trends in the plots of Figure 5 show a moderate decrease in slope for increasing the contribution area. However, this relation is poorly defined for some catchments. All of the catchments show no break in slope corresponding to the transition from debris-flow to streamflow processes (Montgomery and Foufoula-Georgiou, 1993). This transition occurs for channel gradients of approximately 0.2 (Seidl and Dietrich, 1992); the high slope values in Figure 5 indicate that the rocky couloirs of the Sella Group are debris-flow dominated. Sporadically observed low gradients (0.1–0.2 m m^{-1}), corresponding to the largest drainage areas in the plots of Figure 5, do not mark a transition to streamflow processes. Their presence, intercalated with high slopes, is related to the longitudinal profiles of the floors of the couloirs, which sometimes display sequences of subvertical steps and short, low-gradient stretches reflecting the structural control due to the horizontally stratified banks of Dolomia Principale. Stock and Dietrich (2003) observed that bedrock channels scoured by debris flows have a topographic signature in the form of a curvature in log-log area-slope plots above slopes of 0.03–0.1. The rocky couloirs in the Sella Group drain smaller areas and have higher slopes than the bedrock channels described by Stock and Dietrich (2003): the limited extent of the cliff zone entrenched by the rocky couloirs does not permit the development of channels in the downstream part of the debris-flow domain. A curvature is thus not detectable in the slope-area plots of Figure 5, which cover only the upper part of bedrock channels eroded by debris flows.

OUTCOMES OF FIELD OBSERVATIONS

Longitudinal profiles and cross-sectional widths of couloir floors were surveyed through field observations. Due to terrain difficulties, detailed surveys were possible only for five couloirs (nos. 1 to 5; Fig. 1).

The morphological approach of Dietrich and Dunne (1993) for recognizing channel heads, mentioned in the Introduction, cannot be transferred to rock outcrops, and some subjectivity remains in identifying the upstream ends of rocky couloirs. Initiation points were chosen where unchanneled depressions start being confined between rock slopes, which define the banks of the couloirs. This criterion is similar to that proposed by Dietrich and Dunne for soil-mantled slopes, but differs from it because the

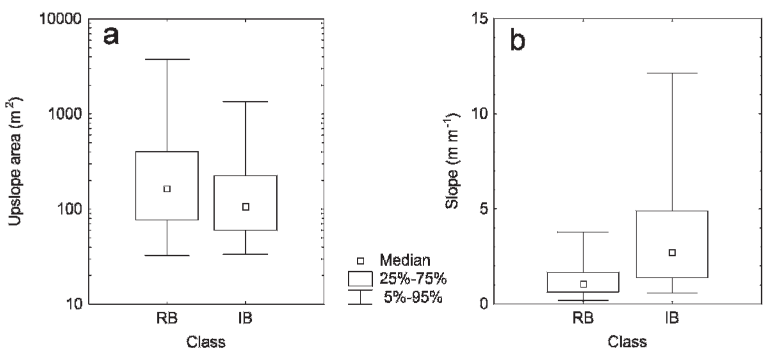

FIGURE 4. (a) Upslope area and (b) local slope: comparison between rock basins (RB) and interbasins (IB).

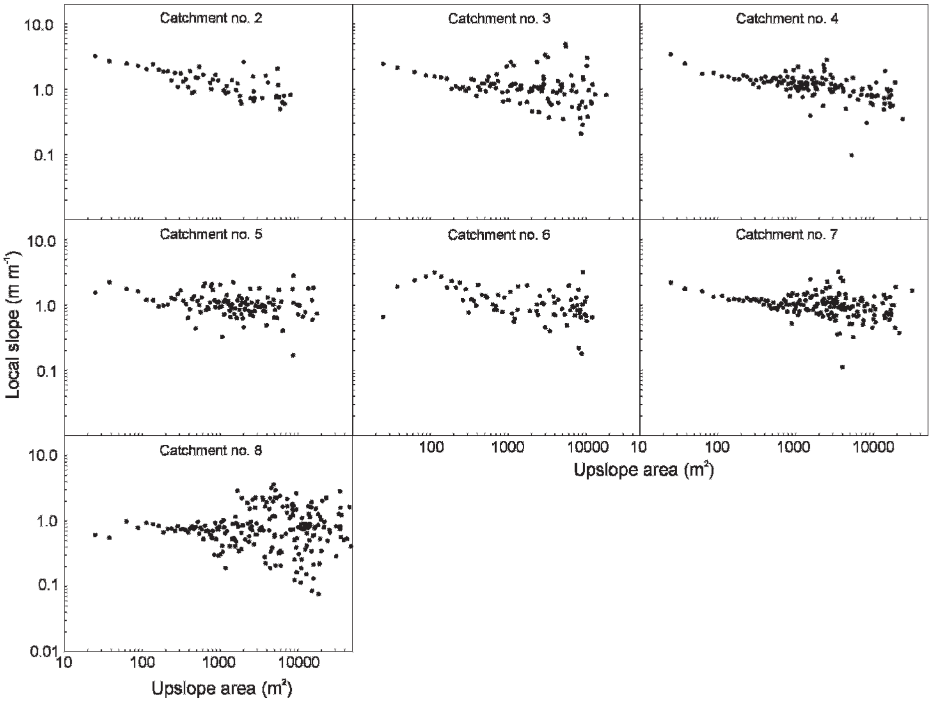

FIGURE 5. Relations between drainage area and local slope for the rock basins.

confinement of a rocky couloir between banks mainly depends on the structural settings and is less influenced by erosional and sediment transport processes in the couloir itself.

Figure 6 shows the longitudinal profiles of the studied couloirs. Total length differs remarkably between couloirs, while the patterns of the profiles remain similar. Longer couloirs (nos. 1 and 3) originate close to the catchment divide, whereas the other catchments have a longer unchanneled valley between the divide and the upper end of the couloir. Although overall profiles are roughly linear (Fig. 6), alternating stretches with different gradients, ranging from short reaches with comparatively low slopes (<0.5 m m^{-1}) to high-gradient steps, were observed in some cases (as is mentioned in the comments of Fig. 5). The floors of low-gradient reaches act as storage areas for debris coming from upstream and from lateral rock faces, while debris are often missing in high-gradient steps. The cross sections display flat floors and vertical or subvertical side slopes, resulting in rectangular or, less frequently, trapezoidal shapes (Fig. 7).

Cross sections have been subdivided into three classes on the basis of the material present on the floor: heterogeneous debris, large blocks (often stuck between rocky side slopes), and exposed bedrock (Fig. 8). A survey of several cross sections along the couloirs made an analysis of variations of cross-sectional geometry with upslope area possible. Figure 9a plots cross-sectional width versus upslope area for the five surveyed couloirs, showing a lack of a relationship between these two variables. Montgomery and Gran (2001) report positive correlation between cross-sectional width and drainage area in bedrock channels for basins extending

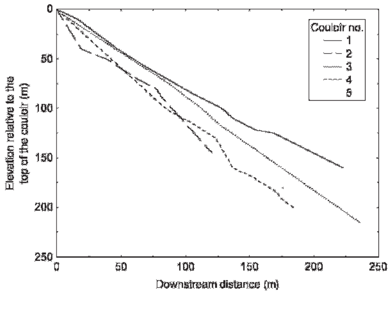

FIGURE 6. Longitudinal profiles of rocky couloirs.

FIGURE 7. Sketch of two cross-sections surveyed in the rocky couloir no. 4.

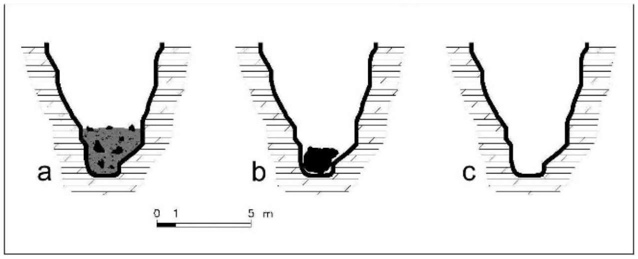

FIGURE 8. Floor material in the couloirs: (a) loose debris; (b) clogged boulder; (c) exposed bedrock.

up to tens or hundreds of km^2, i.e. in the range of fluvial processes. However, other studies (Finnegan et al., 2005; Whittaker et al., 2007) show complex trends in channel width variability for increasing drainage area and downstream distance in channels confined by bedrock: channel width may remain constant despite an increase in drainage area, or even display a decrease in steep reaches. Vianello and D'Agostino (2007) found a positive linear relation between bankfull channel width and upslope area for colluvial channels (drainage area from 0.3 to 1.0 km^2) in the upper basin of the Cordevole River, where the studied rock basins are located. As the study by Vianello and D'Agostino deals with self-formed colluvial channels, their findings do not contradict our observations on rocky couloirs. Figure 9b shows the relation between couloir slope (surveyed in the field) and floor width. For lower gradients, we observe in Figure 9b a large variability of cross-sectional widths, whereas width has a smaller variability (from 1 to 4 m) for higher gradients. We also note that debris-covered gully floors occur for slopes up to about 1 m m^{-1} (vertical dashed line in Fig. 9b), a value close to the internal friction angle of coarse angular debris in dolomite scree slopes. The widest cross sections in the couloirs analyzed in this study are associated with the presence of heterogeneous debris, which masks the actual width of the rocky floor, whereas cross sections with exposed bedrock or clogged by large boulders have smaller widths (narrow couloirs have a higher chance for clogging). Cross sections with exposed bedrock or clogged by large blocks occur both on couloir stretches where a high gradient prevents debris deposition, and on reaches with relatively low gradients ($<$1 m m^{-1}). In the last case, the absence of debris may be due to recent removal by running water or debris flows.

Debris-flow channels on the scree slopes at the outlets of rocky couloirs are not easily recognizable in some aerial photos, probably because they were obliterated by snow avalanches, but were clearly observed during field surveys carried out in the last years (2002–2007), as well as in the digital aerial photos taken in 2006 (Fig. 10).

Discussion

Field observations and DTM analyses point out three relevant topics regarding the role of rocky couloirs in Dolomite headwaters: the recognition of sediment transfer processes, the controls on the geometries of the couloirs, and their relationships with the channel network.

We recognize three main classes of processes causing solid material movement in the couloirs of the study area: detachment and gravitational accumulation of weathered rock fragments, snow avalanches, and runoff-related transport. Multiple processes are widely recognized in steep, low-order channels in mountainous regions. Gravitational accumulation of rock fragments is widespread on rock slopes and is the main geomorphic factor, directly controlled by the structural setting, leading to the formation of scree slopes at the feet of dolomite cliffs. In the rock basins of the Sella Group, side slopes are important source areas for eroded material, whereas the floor acts both as a source area and an accumulation zone. Rock fragments detached from side slopes and weathered bed material accumulate on the floors of couloirs; snow avalanches and concentrated flow (including debris flow) cause subsequent delivery to the outlets of rock basins. The role of snow avalanches in sediment dynamics mainly involves removing loose debris from cliffs, chutes, and couloirs and redistributing on the slopes below. The contribution of snow avalanches to erosion and transport of debris in mountainous basins is well known (Luckman, 1977; Ward, 1985; Ackroyd, 1986), although its relative importance in the frame of geomorphic processes is disputed. Recent papers (Heckmann et al., 2002, 2005) confirm the relevance of this research topic in alpine basins. Surface runoff occurs on rock slopes during snowmelt and as a consequence of rainstorms; runoff concentrates in convergent topographies, commonly located near fractures, and channeled flow occurs on the floors of rocky couloirs. The permeability of dolomite strongly varies from site to site and can be quite high if intense fracturing or karstic phenomena are present. However, despite rock fracturing, most dolomite slopes, like those in the study area, act as impervious surfaces in response to intense rainfall. Surface runoff removes debris from rock cliffs and transports sediment on the floors of the couloirs. Sediment transport can occur as debris flow, provided that the gradient is sufficiently high and sufficient debris is present. The first requirement is commonly met in the rocky couloirs of the study area, whereas the availability of mobilizable debris greatly varies in time and by site. Fine-grained sediment can also be transported as bedload and suspended load by snowmelt runoff and during minor storms, which do not cause debris-flow initiation. Among reports of concentrated flow on rock slopes of the Dolomites, we note the event described by Berti et al. (1999). These authors described an ephemeral cascade and surface runoff through a rocky couloir immediately after a short-duration, high

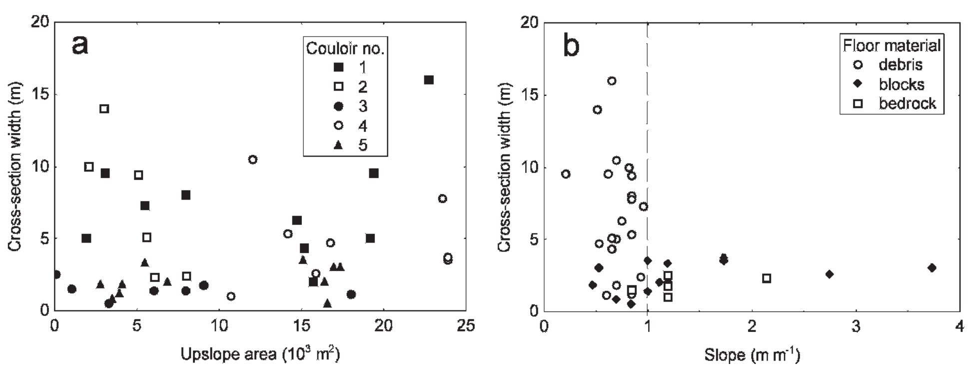

FIGURE 9. Plot of cross section width versus upslope drainage area (a), and slope of the couloir (b). The dashed line indicates the upper limit of slope for cross sections covered by debris.

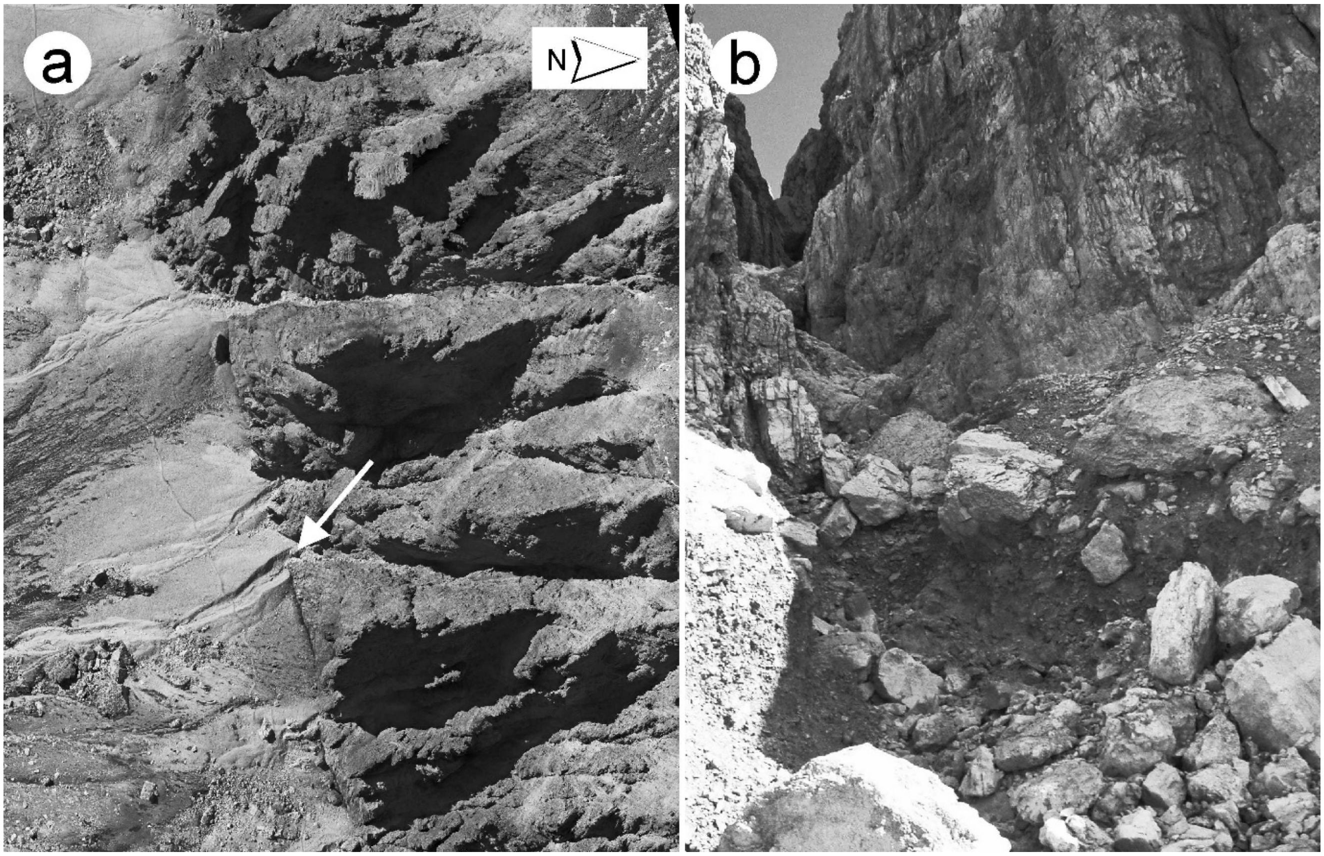

FIGURE 10. (a) Aerial photograph and (b) ground picture showing scree slope incision and initiation of a debris-flow channel at the outlet of a couloir.

intensity thunderstorm. Concentrated runoff triggered a debris flow in a channel cut into heterogeneous talus deposits at the outlet of the rock basin.

Floor width of the couloirs is independent of drainage area (Fig. 9a). We propose two possible explanations, not mutually exclusive: structural control on cross-sectional width and couloir shaping by debris flows. It is hardly possible to assess the relative importance of these two factors in controlling the geometry of the couloirs. The ephemeral occurrence of sediment transport phenomena and the obliteration of related forms and deposits by other processes, like gravitational accumulation and snow avalanches, obscures evidence of debris flows and sediment transport in rocky couloirs. Indicators of debris flow scouring (e.g., smoother surface of the floor than of the lateral walls) are seldom observed in the upper parts of the couloirs and are more common close to the outlet. This could indicate that the geomorphic effect of debris flows is relevant only in the lower part of the couloirs. The influence of structural conditions on the susceptibility of rocky couloirs to debris flows should also be noted. Fractures in bedrock favor the formation of convergent topography and the detachment of rock fragments from lateral walls. These conditions, together with steep slopes, make the couloirs prone to debris flows. Field observations and DTM analyses show that the slope gradient of the couloirs is in the range of debris-flow channels (Table 1 and Figs. 5 and 6). These features of rocky couloirs in the Dolomite headwaters indicate that these are significantly different from channels in soil-mantled slopes in the same geographical area (Vianello and D'Agostino, 2007). This leads to the third issue discussed here: Should rocky couloirs be considered to be part of the basin channel network?

Two factors could make the classification of rocky couloirs as part of the channel network questionable:

1. Sediment transport associated with water runoff and debris flows is not the only process causing solid material movement.
2. No unequivocal criteria exist for recognizing channel initiation points.

In contrast, some points suggest that rocky couloirs should be considered part of the basin drainage network:

1. Channeled flow occurs in the couloirs and is capable of entraining and transporting bed material.
2. Debris-flow erosion on scree slopes at the outlets of rocky couloirs indicates the presence of flow capable of producing channel incision in debris.
3. Scouring of bedrock by debris flows is observed in some locations, especially in the downstream reaches of the couloirs.

The occurrence of multiple transport processes can make it difficult to recognize channel bed features typical of sediment transport or debris flows, but does not imply that the studied couloirs are not part of the channel network. We note that erosion and transport due to snow avalanches in alpine catchments also affect colluvial channels, which indisputably belong to the channel network.

The impossibility of applying the geomorphological criterion of Dietrich and Dunne (1993) and Montgomery and Dietrich (1994) to recognize channel heads on rocky slopes should not lead us to state that channels are not present there. Actually, Montgomery and Dietrich (1994, p. 222) pointed out that their analysis does not apply to rocky landscapes. Channel heads in the sense of Dietrich and Dunne (1993) can be recognized at the contacts of the scree slopes with the rocky couloirs (Fig. 10). However, high slopes and lateral confinement indicate that channeled flow exerting shear stress sufficient to cause the erosion of the scree slope was already present in the upstream couloir. The observations above lead us to state that the couloirs draining open rock basins in upper slopes of the Dolomites should be considered part of the channel network of the basin.

Concluding Remarks

The presence of large bedrock outcrops is a prominent landscape feature in many alpine basins. Collecting and analyzing the data in this study has allowed us to recognize the geomorphic role of rocky headwaters in the Dolomites. The main results are summarized as follows:

The locations and morphological characteristics of rock basins and couloirs are controlled by the structural settings of the bedrock: all studied couloirs correspond to faults.

Despite the limited extent of drainage basins, large debris cones are present at the lower ends of the couloirs (Figs. 1, 2, and 10). Intense supply of debris is caused by the high susceptibility of the rock faces that border the couloirs to instability. The high gradient of the couloirs contributes to efficient delivery of debris to the outlets of the rock basins.

Multiple sediment transfer processes occur in the couloirs, including snow avalanches, gravitational detachment and accumulation of rock fragments, sediment transport by surface runoff, and debris flows. The occurrence of channeled runoff, although limited to the snowmelt period and to long-lasting or intense rainstorms, is a major influence on debris transport. For the most intense rainstorms, concentration of channeled runoff causes debris flows in the couloirs and on the scree slopes located at their outlets. The formation of water runoff in rock basins and its influence on debris-flow triggering was analyzed in a recent paper by Gregoretti and Dalla Fontana (2008). The assessment of weathering and gravitational accumulation of debris in the couloirs, as well as the evaluation of the amount of debris transported by snow avalanches, require further research.

Field measurements show that the cross-sectional widths of rocky couloirs are unrelated to the upslope contributing area. Both structural control and couloir scouring by debris flows may explain this.

Although no unequivocal criterion for identifying channel initiation points on rock surfaces can be proposed, the occurrence of channeled flow indicates that the couloirs should be considered part of the channel network of the basin.

One could argue that the spatial scale influences the relative importance of rocky headwaters in the analysis of hydrological processes and sediment dynamics: rock outcrops are usually located at the highest elevations, so their importance at the basin scale becomes smaller moving downstream. However, in small headwater basins of the Dolomites, rocky couloirs play an important role in hydrological and sediment-related processes, and their characteristics, often contrasting with those of soil- or scree-mantled slopes, must be taken into consideration in analyzing the formation and transfer of water runoff and sediment.

Acknowledgments

The authors wish to thank Alessandro Bagato for collaborating in field surveys. The authors are grateful to the editor, Anne Jennings, the associate editor, Irina Overeem, and two anonymous referees for critical reviews of the manuscript and useful suggestions. This study was partly funded by the Italian Ministry of University and Research—GRANT PRIN 2005 "National network of experimental basins for monitoring and modelling of geo-hydrological hazard."

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MS accepted May 2008