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Original Research Article

Mass movements of karren slopes

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ABSTRACT

Karren and mass movements are described. Mass movements taking place on karren terrains are studied in case of bare karren and covered karren. Mass movements occur at rinnenkarren, grikes, Schichtfugenkarren, and tropical karren. This study describes that karren features increase the chance of the development of certain mass movements. It is approached in a theoretical way that in the case of different preconditions (e.g., change of slope angle), what kind of mass movements are triggered by different karren features. The most common mass movement is triggered by karren which are debris creep, gelisolifluction, rock avalanche, collapses, creep and solifluction.

Keywords: Rinnenkarren; Grike; Tropical Karren; Debris Creep; Solifluction

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1. Introduction

In this study, we describe what karren features and how they contribute to different mass movements. Karren are specific and common features of karsts. This frequency may be so significant that results in the development of karren slopes on the karst.

Karren are small features occurring on any karsts and adjusting to a given climatic environment which develop by the dissolution of the bedrock (or the surface of debris pieces). These are the smallest among karst features developing under a given climate (for example, in the temperate belt features with a depth of some decimeters are formed, while tropical karren can be several 10 m). However, on temperate karsts, other karst features may be several 10 m, while they are several 100 m in the tropical climate.

Karren are classified based on the coveredness of the bearing rock, the size, and flow conditions and on the development environment (karst type)[1–4]. Regarding the development environment, glaciokarsts, tropical karsts and coastal karsts have striking and diverse karren landscape. According to size, karren[5,6] may be microkarren (depth and width are some millimeters), mesokarren (depth and width may range from some centimeters to some decimeters or even to some meters) and megakarren (their size is several 10 m). Microkarren and mesokarren mostly include similar karren features which develop during dissolution[4]. Megakarren are mainly tropical remnant features such as stone forest, pinnacle karst, arête karst and tsingy[7–10].

Mesokarren and microkarren may develop during water flow, water percolation and to the effect of dripping water[3,4,11]. Karren formed by water flow and dripping water may develop on bare surfaces, karren of percolation origin may be formed on uncovered, but on covered terrains too. Specific karren of flow origin are rillenkarren, karren caves, meanderkarren, trittkarren, scallops and wandkarren[11,12]. **Figure 1** describes the karren of bare surfaces. Karren of percolation origin are grikes, gratekarren, kamenitzas, Schichtfugenkarren, pitkarren and notches[3,12]. Remnant features, features that developed in another way and particular transitory karren can also be mentioned[11,13]. All the above result in the fact that mass movement on karren terrain can take place on bare slopes (when the debris of the karstic rock moves) or on the covered slopes (the non-karstic rock may move).

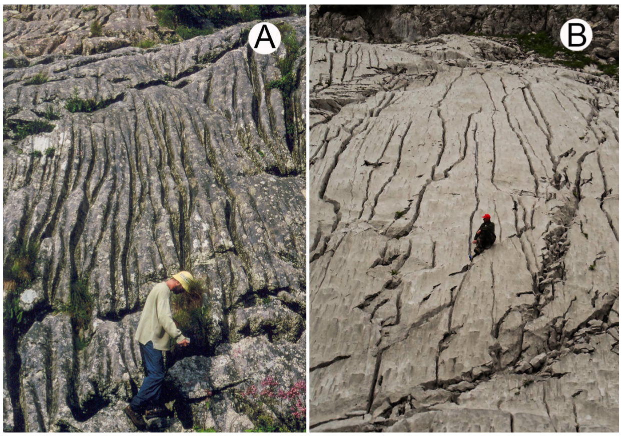

Figure 1. Rinnenkarren. A. Julian Alps; B. Totes Gebirge. Source: Photo by Veress.

On bare slopes, karren features are arranged in zones. At the upper part of the slope is the rillenkarren zone (sheet water), below that is a flat zone which is often exempt from dissolution where a trittkaren zone (local vorticity sites) may develop commonly. This is followed by the rinnenkarren zone (sheet water is replaced by rivulets). In the environment of rinnenkarren, grikes (water flow is replaced by infiltration), trittkarren, then the rinnenkarren zone turns into the meanderkarren zone (the channel line of the rivulet swings out). The meanderkarren zone may be absent and, in this case, the rinnenkarren zone is followed by the pitkarren zone (subsurface drainage). Some slopes may be characterized by only one kind of karren features (e.g., wandkarren, grikes).

On bare slopes, karren features develop in great density and size, especially on glaciokarsts. The degree of inclination, the type, density and size of karren features are related to each other. With the increase of the inclination, more and more features of flow origin (rinnenkarren, rillenkarren) develop, but their size is smaller and smaller on slopes with a larger and larger inclination (type B channels are replaced by type A channels). On slopes with extremely large inclinations (vertical or subvertical), newer features of flow origin appear (wandkarren), but newer features of percolation origin (Schichtfugenkarren) also develop. The above distribution of karren features indicates that in the case of low inclination and high inclination, the role of dissolution of percolation origin increases: at a low inclination, dissolution takes place along fractures, while at a high inclination, it takes place along bedding planes. The decrease of the size in features of flow origin (rinnenkarren) can be traced back to the increase in rivulet density[4]. As a result of this, the water flowing on the slope is separated into more and more rivulets, which does not favour the development of channel systems of great size.

On bare slopes of glaciokarsts with great extensions, a significant quantity of debris develops during karren formation. It is common that this is the only, or predominant way of debris development. This debris gets partly to the lower part of slopes and partly into the epikarst through karren. Mass movements ensure or maintain the uncovered nature of slopes and thus, further karren formation of slopes.

With the increase of slope not only the quantity and quality of karren features changes, but there is also a greater chance of the development of slopes without soil and vegetation. However, farther from the Equator and sea level, on slopes with a lower and lower dip, bare slopes are more and more extended.

1.1 Karren features

Rillenkarren, rinnenkarren, meanderkarren and wandkarren are formed by intermittent rivulets that develop and flow on the slopes. They constitute the group of linear karren features.

Rillenkarren are channels with a length of some decimeters occurring at the upper part of the slope and wedging out in slope direction. Their wedging out is due to the fact that the water flowing down the slope becomes saturated[14].

Rinnenkarren (**Figure 1**) are channels with a width and depth of some decimeters, of slope direction, their length may be several 10 m and they are areic except some varieties (type A channel, decantation channel) and develop under the rivulets of the slope[15]. They are particularly widespread on glaciokarsts where they are predominant features of bedding planes on the cuestas of glacier valleys. However, they occur on all karsts where bare rock surfaces of greater expansion are present. They may be type A and type B channels[16]. Type A channels are of V cross-section, they have a small size and small catchment area, and occur on slopes with an inclination of 30°–60°, and they do not have any tributary channels. Type B channels have a U cross-section, a greater size and a specific catchment area, and the inclination of their bearing slope is 20°(25°)–45°[4,16]. Channel systems are constituted by type B main channels and type A and type B tributary channels and are formed on slopes with an inclination smaller than 20°–25°[4] (**Figure 2**).

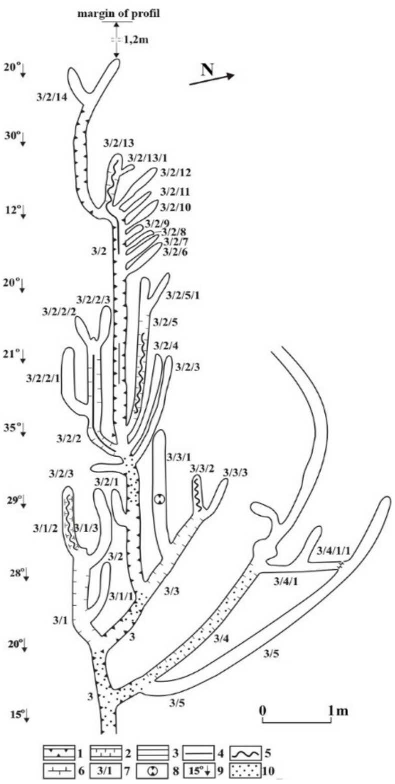

Figure 2. Rinnenkarren system. Legend: 1. main type B channel; 2. tributary type B channel; 3. type A channel; 4. internal channel (type III channel); 5. meandering type III channel; 6. floor channel divide; 7. identifying mark of the channel; 8. channel-floor pit; 9. dip direction and dip angle of the slope; 10. soil and plant on the channel floor.

Rundkarren and decantation channels are rinnenkarren varieties (**Figure 3**). At rundkarren, the interchannel ridge is rounded as a result of temporary soil cover due to dissolution. The decantation channels branch out of kamenitzas (they drain them), they are only 1–2 m long because they mostly wedge out (thus, they are not areic).

Figure 3. Giant grike that developed by the confluence of the waters of grikes (Julian Alps, Héttó Valley).

Source: Photo by Veress.

Meanderkarren are rinnenkarren with an asymmetric cross-section which develop on slopes with an inclination lower than 10°[4,17]. Asymmetry is caused by the fact that the various sections of the opposite sides of the channel side are of different gradients. This gradient is interchanged between the opposite channel sides.

Wandkarren are parallel channels with slope direction (the inclination of the slope is greater than 70°) which are not areic[18] (**Figure 4**). They are in close symbiosis with Schichtfugenkarren. They can be aligned below Schichtfugenkarren (the water leaving the Schichtfugenkarren forms wandkarren), but they can also be connected to them (in this case, wandkarren develop Schichtfugenkarren by the transmitted water) and they can also go through them. Trittkarren occur in groups on slopes of diverse inclinations (the dip of the bearing slope is 0°–40°). They are constituted by riser and tread[19–23].

Figure 4. Wandkarren (Totes Gebirge).

Source: Photo by Veress.

Karren caves are some-meter-long varieties of through caves of karsts with karren ponors and water outflow sites[11].

A grike is a system of solution longitudinal indentations with a width and depth of 1–2 m and a length of several meters[24] (**Figure 5**). Grikes develop along fractures[2,12,25], which are formed on slopes of low inclination (predominantly on slopes with an inclination lower than 10°) on both bare and soil-covered surfaces. The upper elevation limit of their occurrence is about 2,100 m in the Alps. They are very common karren features not only on glaciokarsts, but on temperate karsts and tropical karsts as well. A variety of grikes is the giant grike. This is a single large feature whose width may be several meters, its depth may be several tens of meters and its length even several hundred meters (**Figure 3**), head bed karren is also grike. At this feature, dissolution takes place along bedding planes of various inclinations which drain water. The bed bodies between the bedding planes constitute oblique or vertical mounds of some decimeters. Grate karren are morphologically similar features that are constituted by grikes being perpendicular to each other.

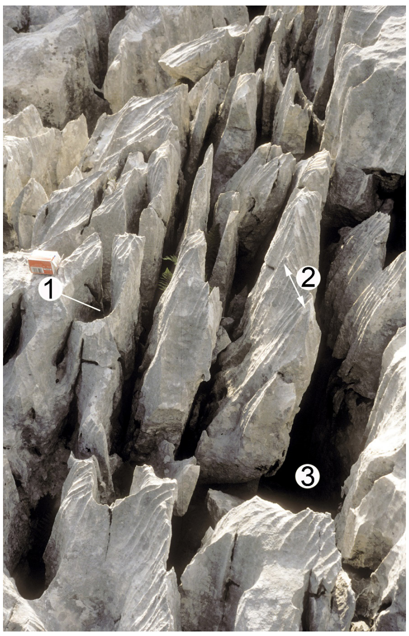

Figure 5. Grike (Totes Gebirge). Legend: 1. destroying pit; 2. rillenkarren; 3. grike.

Source: Photo by Veress.

Kamenitzas are mostly closed indentations with a diameter and depth of some decimeters which develop on low-inclined surfaces (on slopes with a dip lower than 38°)[4].

Pits are vertical features of some decimeters and meters similar to pipes, which are arranged in groups on low-inclined slopes. They may develop both on bare surfaces and soil-covered surfaces.

Schichtfugenkarren are long expanding features (they may reach a length of 10–20 m) of steep cliffs (slope inclination is 70°–85°), their height may range from 1–2 cm to some meters, and they deepen into the rock to several meters. They mainly develop along bedding planes (**Figure 6**). Notches are indentations of steep cliffs with a length of several meters and with a height of some decimeters or meters. They develop at the level of soil cover or at the water level (sea shore, cave). Haserodt[21] called features that developed at and below the level of soil cover Karrenfussnäpfe.

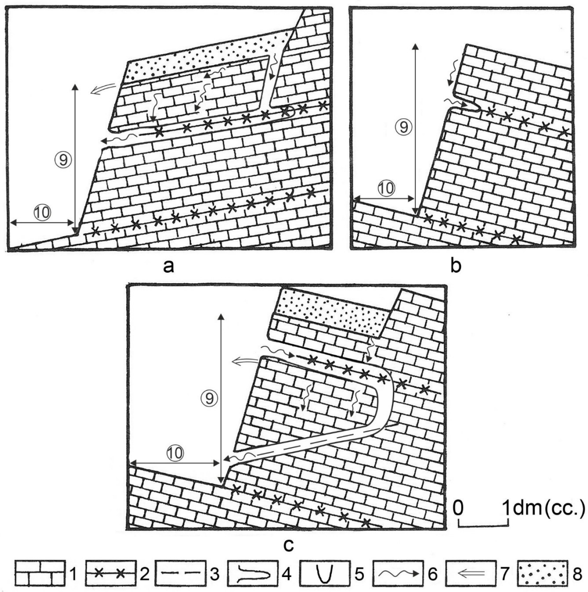

Figure 6. Genetic types of schichtfugenkarren developed on heads of beds (Veress 2010 modified). Legend: (a) inclinations of the bedding plane and the head of bed are similar; (b) inclinations of the bedding plane and the head of beds are opposite; (c) inclinations of joint and head of bed can be opposite (see top and bottom parts of figure) or similar (see middle of figure); 1. limestone; 2. bedding plane in the rock; 3. joint; 4. schichtfugenkarren; 5. grike; 6. infiltration of unsaturated water (see the bottom part of the figure); 7. clint of the movement; 8. snow; 9. head of bed; and 10. bedding plane in the surface.

During karren formation, relict landforms develop too, thus, Spitzkarren, karren tables (karren buttes), and karren inselbergs. Spitzkarren have grouped features with a height of some centimeters or decimeters ending in peaks and situated on low-inclined slopes. (Tropical karren are their large varieties.) Spitzkarren develop during the dissolutional coalescence of karren features, but they can also be formed independently of this process, thus, for example by the widening of the grikes enclosing the blocks of grate karren. Karren buttes are mounds protected by the rocks of moraine. The rock was dissolved in their environs[13]. Karren inselbergs are separated from their environment during the development of other karren features (e.g., rinnenkarren)[11].

Karren that developed in another way are thimble karren and rootkarren. Thimble karren are grouped indentations with a diameter and depth of some centimeters. They develop on bare surfaces to the effect of raindrops. Rootkarren are irregular pipe-like features that develop along the root system of vegetation to the effect of the organic acids produced by the roots.

Clints are rocks that disintegrated by fragmentation during karren formation (the rock is disintegrated along bedding planes and thus, debris of small thickness develops). When they are not disintegrated along bedding planes and therefore, debris of irregular shape is formed, it is called "clasts", and when the debris pieces are rounded by dissolution, they are called "Karrennasen"[1,25].

Adjacent karren features may coalesce by dissolution, which may be the same (e.g., pits of pitkarren and kamenitzas) or different (e.g., pit and grike or channel and grike). In the first phase of the process, the features were still separated, but in the second phase, they were not. In the former case, the two features are lined by those features that developed during the process (window and arch). In the latter case (when the features coalesce by dissolution completely), the developing feature is larger, but not new (e.g., a larger kamenitza develops by the dissolutional coalescence of kamenitzas). However, it may also happen that a newer feature is also formed during the process (e.g., inselbergs develop by the dissolution coalescence of channels).

Tropical karren are remnants of large mounds (pinnacle). The height of the mounds of the stone forest (**Figure 7**)[7,8,26,27] and the pinnacle karst, arête karst[9] exceeds 10 meters and have a small width. Arête–doline karst may be constituted by mounds with a common base. Among the mounds, there may be irregular (stone forest) or elongated (pinnacle karst) areas and dolines (arête karst). Stone forest occurs in South-China, pinnacle karst can be found in Sarawak and arête karst can be found in New-Guinea. Stone forest can be tsingy-like when it is dissected by grikes[8,28].

Figure 7. Pinnacles and wandkarren in the area of the Lunan stone forest (China).

Source: Photo by Veress.

Mesokarren like rillenkarren, rinnenkarren, kamenitzas, pitkarren (and their remnants), and wandkarren are common on the block surfaces of the tsingy. Features being the remnants of former caves (cave notches, cavity remnants, remnants of cave ceilings, and stalagmites) also occur on tsingy. These features refer to the fact that the present, giant grikes of the tsingy developed by the coalescence of surface grikes and caves[29].

Coastal karren are formed on abrasion platforms. The development of coastal karren is zonal. At the termination of the abrasion platform in the area close to the part permanently covered by water there is the intertidal platform, then towards the centre of the mainland, the phytokarst and then the zone of basins can be found[29,30].

Phytokarst is an uneven surface dissolved by algae[25]. It may occur that the phytokarst is followed by the zone of grikes[31]. However, cavities, pits, and pinnacles also occur on the coast[32]. The development and width of the zones and the size of intertidal platforms may be different in various climate belts.

2. Mass movements on the slope

The development of mass movements is affected by several factors thus, the slope angle, the elevation of the slope, the quality of the rocks building up the slope, the relationship between the spatial position of the beds and slope inclination, the degree to which the rocks are saturated by water, the extent of coveredness with vegetation, the fluctuation of the water level of the river lining the slope, earthquakes and the activity of organisms. The chance of the occurrence of mass movements is increased by a greater slope angle, the great elevation of the slope, less consolidated rocks, the similarity between the dip direction of the slope and the inclinations of the beds, the degree to which the rock is saturated with water, the lack of vegetation of the rocks, the elevated and then decreasing water level of the river and the earthquakes[33].

Classifying mass movements[34], they can be collapses (the material moves quickly, grain size is diverse), slides (there is a slide path, the motion is quick, material is unconsolidated), creeps (the material is unconsolidated and it moves slowly, grain by grain) and flows (when the material moves as a plastic liquid). Collapses may be of irregular period (bank caving, rock avalanches) and regular (falling stones and mountain collapses). In the case of slides, the slide path may develop in unstratified rock or stratified rock. According to its elevation, it can be slope slide (the slide path is above the base of the slope), and slice-like landslide (the slide path is at the base of the slope). In the case of bed slide, the slope intersects the beds, but in the case of mantle slide, it does not. Creep can be debris creep (the debris moves) and soil creeps (the fine-grained material moves). Flow can be gelisolifluction (motion takes place on frozen bedrock) and solifluction. This latter may be mud flow and debris flow (the material of the debris cone becomes fluid).

Karren may increase or decrease the chance of mass movements, but they are not determinant either in the increase or the decrease of the chance. Karren affect mass movements in two ways: they increase or decrease the mass movement of the caprock (1), during karren formation, material (debris) is formed which may be affected by mass movement (2), the developed debris contributes to the mass movement on the rocks below it due to the increase of the overburden (3), and relict landforms of karren formation are affected by mass movement (4). Karren formation of the bare slope may contribute to the occurrence of collapses and creeps, covered karsts contribute to slides, flows, and creeps. Among karren features, rinnenkarren, grikes, giant grikes and Schichtfugenkarren may contribute to mass movements. Relict landforms developing during tropical karren formation such as pillars are affected by mass movements.

2.1 Mass movement on bare slopes

In high-mountains and on glaciokarsts, ridges between the karren features are affected by physical weathering after they become separated from the bedrock and form debris barriers (**Figure 8**). This is favoured by the development and widening of rinnenkarren and grikes whose dip direction is identical with the slope. If the karren features go transversely through several beds (the beds are thin and the feature is relatively deep), the debris gets into the surrounding karren. If the karren feature goes transversely through only one bed (and the karren feature deepens into the bedrock bed, the debris can move on the slope). Debris creep, but gelisolifluction may also take place. The developed debris may feed rock avalanches. If the grike is perpendicular to the dip direction of the slope, the developing debris fills the remnants of the grike if it developed in several layers (**Figure 9I**). The debris is only able to move on the slope (debris creep) if the developed debris fills the remnants of grikes (if the grike was formed in one bed, debris movement can also take place without grike fill). However, if the grikes predominantly developed on low-inclined slopes, it does not favour debris movement.

Schichtfugenkarren may trigger collapses. In this case, the rock mass above the Schichtfugenkarren shifts. If the inclinations of the Schichtfugenkarren and the rock beds are the same and the grike reaches the Schichtfugenkarren and this section is enclosed by fractures, the block is broken away from its environment (**Figure 6a**). During its displacement, the block may be separated into larger and smaller pieces and those with outer position shift on the cliff wall. These may be rock avalanches or collapses. The process may also take place without grikes if there are two Schichtfugenkarren below each other which enclose an angle with each other (**Figure 6c**).

At tropical karren, if there are cavities below the giant grikes, grikes may not only coalesce with them by dissolution, but by collapse too. If the grike floor terminates at an aquifuge, and the inclination of the aquifuge is relatively great, pillars may even shift along this latter (**Figure 9**).

2.2 Mass movement on covered slopes

Rinnenkarren and grikes may become filled and covered, but grikes may also develop under the

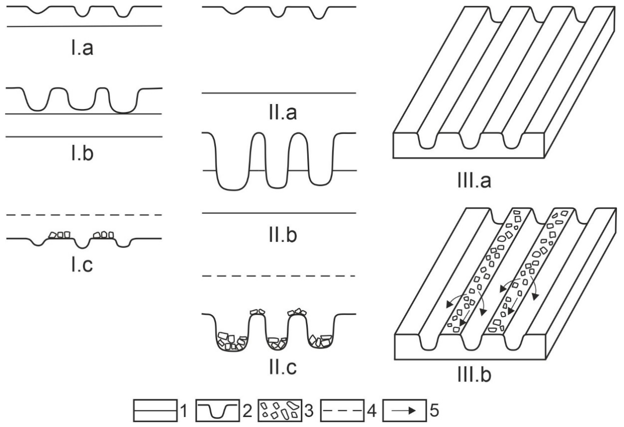

Figure 8. Debris development during karren formation on thinly bedded rock (I) and thickly bedded rock (II) (karren features are of dip direction); I-II. cross-section; III. plan view. Legend: 1. bedding plane; 2. karren feature; 3. karren debris; 4. original terrain; 5. movement of debris; Iab-IIab. development of karren feature; Ic, IIc. karren debris develops by the denudation of the ridges between karren features; IIIa. development of karren feature; IIIb. development and movement of debris.

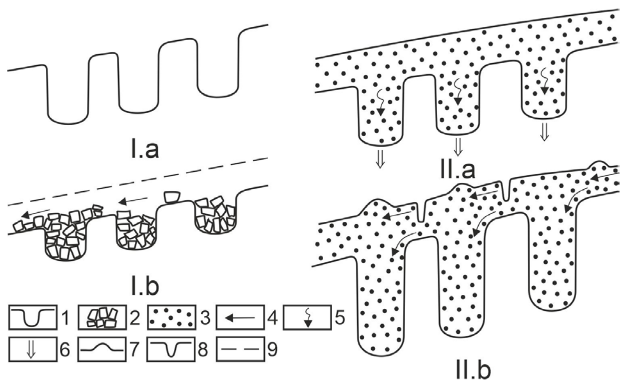

Figure 9. In case of grikes which are perpendicular to the strike direction of the slope, material motion on bare slope (I) and on slope covered with superficial deposit (II). Legend: 1. grike; 2. debris; 3. caprock; 4. material movement on the slope; 5. water motion in the fill; 6. deepening of the grike; 7. thrusting of superficial deposit; 8. grike on the caprock; 9. original surface. Notice: in case II, grikes continuously develop below the superficial deposit (deepens); a. grike development; b. debris development, and movement of superficial deposit.

cover. If the rinnenkarren is filled with clayey superficial deposit, the infiltrating water makes the fill slippery. In this case, bed slide or mantle slide takes place. Grikes perpendicular to slope inclination, if they develop below the cover, become sediment-receiving during their deepening. Thus, sections of soil creep are in the cover. At the surface, grikes may also develop on the superficial deposit (between the grikes of the bedrock) in the strike direction of the slope, humbacks develop between them due to material piling (between the grikes of the bedrock, **Figure 9II**). The superficial deposit may fold into the grikes and thus, they may also break down the movements of the cover.

In the area of rinnenkarren and grikes which are partly or completely filled with superficial deposit bands of solifluction and debris flow may develop. Debris flows of karren may contribute to the launch of large debris flows starting from alluvial cones.

Veress *et al*.[35] studied grike development in the case of filling sediments with model experiments. They claimed that the finer-grained the filling sediment (2.5–5.0 mm and finer was the fill), the larger the degree of subsidence was as compared to the subsidence of grike floors. The absolute value of the subsidence of the cover surface also exceeded the subsidence of the grike floor after a time. This was different at the various parts of the grike. This refers to lateral suffosion in the fill. Thus, it can be expected that the subsidence of grike fills and thus, the surfaces of the superficial deposit will be of different degrees. The water infiltrates in the grike fill horizontally. The finer-grained the fill (e.g., finer than 0.063 mm), the more horizontal the infiltration. The water infiltrating in the grikes leaves the grike and may cause water abundance in the superficial deposit below the termination of the grikes, where the chances of slide, creep, or perhaps flow may increase. The fine-grained sediment also promotes the widening of grikes due to lateral water drainage. This also favours the occurrence of mass movement.

Pillars that became separated by giant grikes may shift from their original position which is favoured by the fact that there is aquifuge at their floor (**Figures 10** and **11**). Buried pillars, if they become exhumed, will be unstable, and may shift on the slope. Following either natural or artificial exposures, the filling material of large-sized karren (e.g., grikes) is transported away on the steep slopes by collapse, solifluction, gelisolifluction or debris creep. On halite, the material of exposed rinnenkarren may also be transported by mass movement.

Under different circumstances, the same karren feature and different karren features have different susceptibility to trigger mass movements. In the case of a slope with larger inclination, a feature of larger size and water of a larger quantity, there is a higher chance of mass movement. In the case of the presence of all the necessary preconditions, mass movements are triggered at a higher chance by grikes, rinnenkarren and tropical karren on bare surfaces, but even on covered slopes. Schichtfugen-

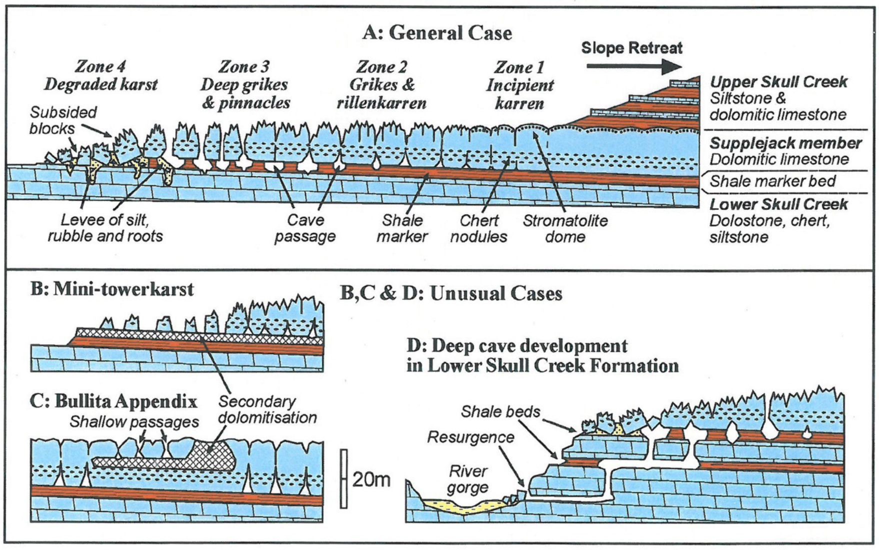

Figure 10. Grike development and landscape evolution above cave on Gregory Karst (Australia)[6].

karren increase the occurrence of mass movements on bare slopes.

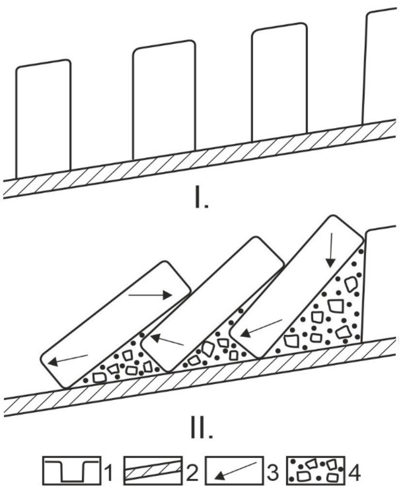

Figure 11. Denudation of pillars. Legend: 1. giant grike; 2. impermeable intercalation; 3. shift of the pillar; 4. debris and weathering residue; I. giant grikes develop; II. the pillar falls down as a result of the thinning of the rock and slides on the aquifuge (its lower and upper sides move in opposite direction).

3. Conclusions

Some karren may promote the occurrence of certain mass movements. On bare slopes, debris develops between grikes and rinnenkarren which may shift in slope direction (debris creep, and geli-solifluction). Collapses may take place at Schichtfugenkarren. At tropical karren, the slide of pillars situated between the grikes may happen, but in the case of cavities situated below the grike floors, collapses may also occur.

At covered karren, fills of grikes and rinnenkarren with dip directions may be slide paths. At grikes with strike direction, the superficial deposit may partly move into the grikes. Thus, various features may develop at the surface with superficial deposits (grike, and humback). If the features are partly filled, solifluction and debris flows may take place inside them. The instability of buried pillars increases if they are partly or completely exposed.

Conf ict of interest

The author declares that there is no conflict of interest.

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