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Anthropogenic Pseudokarstic Depressions on Mount Bocskor (Bakony Region, Hungary)

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ABSTRACT: Surface forms above the mine (Ármin mine) of Mount Bocskor (Southern Bakony, Hungary) were examined. We made contour maps, plan maps, morphological maps and atectonic grike (cave) maps of some of the forms and their surroundings. We examined the distribution of the depth, length, elongation ratio in case of some depressions, the relation between the depth and the diameter of some depressions, the relationship between depression group directions and mine cut directions, the standard deviation of the direction differences of depression groups and of their depressions. The forms of the mountain related to surface mining can be separated to open and closed. The former are trenches and stairs, the latter are circular, elongated, and complex depressions. The formation of these forms can be related to the balancing movements of the vault over the mountain's mine. At thin vault, stairs develop by collapses, while at the atectonic fissures of thicker vault, trenches and depressions are formed at the surface. In areas bordered by sinking (subsidence through) and downwardly cohesive faults, depression groups of diverse features are arranged in the marginal bands. Elongated depressions are formed at atectonic blocks bounded by dispersing faults in non-banded distribution. Where there is a superficial deposit, atectonic fissures can also be inherited directly by collapse to the surface and form depressions. They can also form indirectly over atectonic fissures by compaction, subsequent collapse and/or suffosion of the superficial deposit. The results of the study make it possible to analyse the material loss due to mining on the vault if the atectonic structures of the vault are partly or completely covered by superficial deposit.
KEY WORDS: mining, pseudokarstic depression, atectonic fissure, atectonic block, collapse, suffosion.

0 OBJECTIVES

In this study, we investigate the effect of mining on the formation of surface forms on Mount Bocskor near the town of Ajka (Southern Bakony, Hungary). We analyse how this effect influences landscape evolution through rock structure. We describe how mining resulted and may result in the development of various karst-like features and also the morphological, evolutionary similarities and differences between these karst-like features and natural karst features. With the knowledge of the features of the mountains we have an opportunity to understand better the processes occurring in the vault of mine extractions.

1 INTRODUCTION

Mining causes morphological (Oggeri et al., 2019; Dulias, 2016; Monjezi et al., 2009; Allgaier, 1997) and environmental (Monjezi et al., 2009; https://sites.google.com/site/miningandgeomorphology101/home/open-pit-mining) changes. The process affects the landscape evolution as well as the environment (Dontala et al., 2015; Rico et al., 2008; Rösner and van Schalkwyk, 2000; https://en.wikipedia.org/wiki/Environmental_impact_of_mining) and its equilibrium state.

Mining creates negative forms (depressions) and positive forms (dumps) on the Earth's surface (Chena et al., 2015; Mossa and James, 2013; Rico et al., 2008; Rösner and van Schalkwyk, 2000). The negative forms may be formed during surface mining (mine pits) or underground mining. The latter's forming are due to the equalisation of the material loss beneath the surface but can be distinguished from those that form due the abstraction of the water (Newton, 1987) or the lowering of the water level (Chen, 1988; Xu and Zhao, 1988; Yuan, 1987). Equalisation can be carried out by the following.

(1) Collapse of a former mining cavity, in particular on evaporites, where the intense solubility increases the size of the former mining cavity, and is inherited directly to the surface where collapse forms are formed (Móga et al., 2017, 2015; Andrejchuk, 2002; Singh and Dhar, 1997).

(2) Breccia pipes towards the surface are formed above the mining cavity by local solution/local collapse and where these reach the surface, surface features are formed indirectly (Lu and Cooper, 1997; Wassmann, 1980; Walters, 1978).

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(3) Above the mining cavity a wide area of sinking takes place and to the impact of this tension occur which results in the formation of fissures with various widths, which also cause feature development on the surface (Sütő et al., 2009; Sütő, 2001; Erdősi, 1987).

(4) The collapse of a mining cavity is inherited to the vault, where cavities are formed and their collapse causes the sinking of the surface (Wassmann, 1980).

(5) Only the superficial deposit collapses into the mining cavity and causes indirect formation on the surface (Singh and Dhar, 1997; Spooner, 1971).

Fissures and fissure caves with a width of several tens of centimeters may develop in the rock to tectonic effect. Fissure caves can also develop due to atectonic effect, when no tectonic forces occur, but for example the cooling of melt results in the development of such caves. However, as mentioned above, atectonic fissures may be formed at the margin of a sinking area due to tension. Depending on the degree of the overhanging of the vault, atectonic caves have a width of several tens of centimetres or metres, they are features with nearly parallel walls on their upper part, but wedging out downwards.

It is considered that balancing movement is sustained and prolonged when the sinking is transmitted to the surface from the vault's rocks (cavities in these collapse) (Wassmann, 1980).

The most common surface forms of the karst are dolines, which are closed depressions. Its types are the solution doline, the collapse doline, the caprock doline and the subsidence doline (Ford and Williams, 2007; Sweeting, 1973). The types of the subsidence doline are the dropout doline, the suffosion doline and the compaction doline (Veress, 2016; Waltham et al., 2005; Williams, 2004). The doline versions mentioned before are forming in different geological and morphological environment furthermore their genetics are different as well. Caprock and subsidence dolines are formed in the superficial deposit of the karst, while the solution and the collapse dolines are formed on bare or on only soil covered karst (Waltham et al., 2005; Williams, 2004; Sweeting, 1973).

The suffosion dolines sinkhole develop by suffosion, the dropout dolines develop by the collapse of the superficial deposit, the compaction dolines develop by the compaction of the superficial deposit (Williams, 2004).

In evaporits where mining is accompanied by intense solubility (which is associated with the development of large cavities) and whereas these rocks' hardness is of lower degree the collapse of the mines' vault is often and directly inherited to the superficial deposit.

Depending on the bedrock's coveredness and the quality of the superficial deposit, there may occur collapse dolines, caprock dolines and possibly subsidence dolines as well (Móga et al., 2017, 2015; Johnson et al., 2003; Andrejchuk, 2002; Johnson, 1987; Quinlan et al., 1986; Kompóty, 1908). However above the mines of the evaporites, as mentioned above, breccia pipes are often formed towards the surface (Lu and Cooper, 1997), if the cover rock above the mine is evaporite (Wassmann, 1980) it causes indirect form development in the superficial deposit. In carbonate rocks, the large mine size is less frequent henceforward the collapse and the formation of a breccia pipe is less frequent as well. But as we mentioned, the superficial deposit could collapse directly into the mine, thereby creating a subsidence doline (Spooner, 1971).

Pseudokarstic features show a morphological match with karstic formations, so they are karst-like (Halliday, 2004; White, 1988; Sweeting, 1973). So, for example the surface pseudokarstic features, just like the karstic features are areic as well. However, solubility does not play a role in their formation. Therefore, these features can develop on any rock (or on their cover). If the pseudokarstic depression is developed by anthropogenic effect (e.g., mining), it can be considered as an anthropogenic pseudokarstic depression (Veress, 2016).

2 MOUNT BOCSKOR AND ITS GEOLOGY

The Mount Bocskor on which the Ármin Mine can be found is in the Southern Bakony, to the SE from the town of Ajka, to the NW from the Kab Mountain, between the Alsó Csinger Valley, the Felső Csinger Valley and the Köves Trench (Fig. 1). In a SE direction, it passes through the mass of the Kab Mountain without a sharp limit. Mount Bocskor is one of the Bakony Region's horsts with an extent of 5 km^2 and a height of 400–438 m. It's top is almost flat, it has a minimal inclination to the NW. It lacks both epigenetic valleys and valleys developed in the superficial deposit with the exception of one which faces to the NE and is of marginal position. The steep side slopes of the block are fault scarps and valley sides. Its surface is slightly dissected by hundreds of depressions that are of varying shapes and sizes (most of them are closed form i.e., depression). Some of these are only in the bedrock (eocene limestone) some of them partly or completely into the cover as well. This is possible because there are smaller patches of non-karstic cover, which occurs in a maximum thickness of 1–2 m.

It is clayey loess that has probably reworked. Its varieties are: slightly reddish, partly coarse-grained material, yellowish clayey material and yellowish material with limestone pieces. (Many depressions were formed exclusively in this cover, others partly in the soil or in its reworked version, the thickness of which can reach 1 m.) Loess at a thickness of several m occurs only in the lower part of the mountain's slopes.

The origin of the mountain's depressions although they were formed in limestone and its cover is non-karstic. Namely, unlike karstic forms (doline), they have sharp edges (there may be soil fractures at their edges), the edges are straight, and the adjacent edges are often perpendicular to each other. It is obvious that their formation is related to mining. This statement is confirmed by the fact that in the depressions (but also on the depression-free surface) in many places in the Middle Eocene limestone (Szőc Formation) above the mine cuts there are longer or shorter fissures of several dm (possibly m), which cannot be of neither tectonic nor karstic origin. Their tectonic origin is precluded by their large number. Since there are no forms of dissolution on the walls of the fissures, the karstic origin is precluded as well. Therefore, these fissures are of atectonic origin and were created during the compensating process due to the material loss caused by mining. The beginning of the equalization dates back at least to the 70's of the 20 th century (depressions could be seen as early as 1984) and it is still ongoing nowadays.

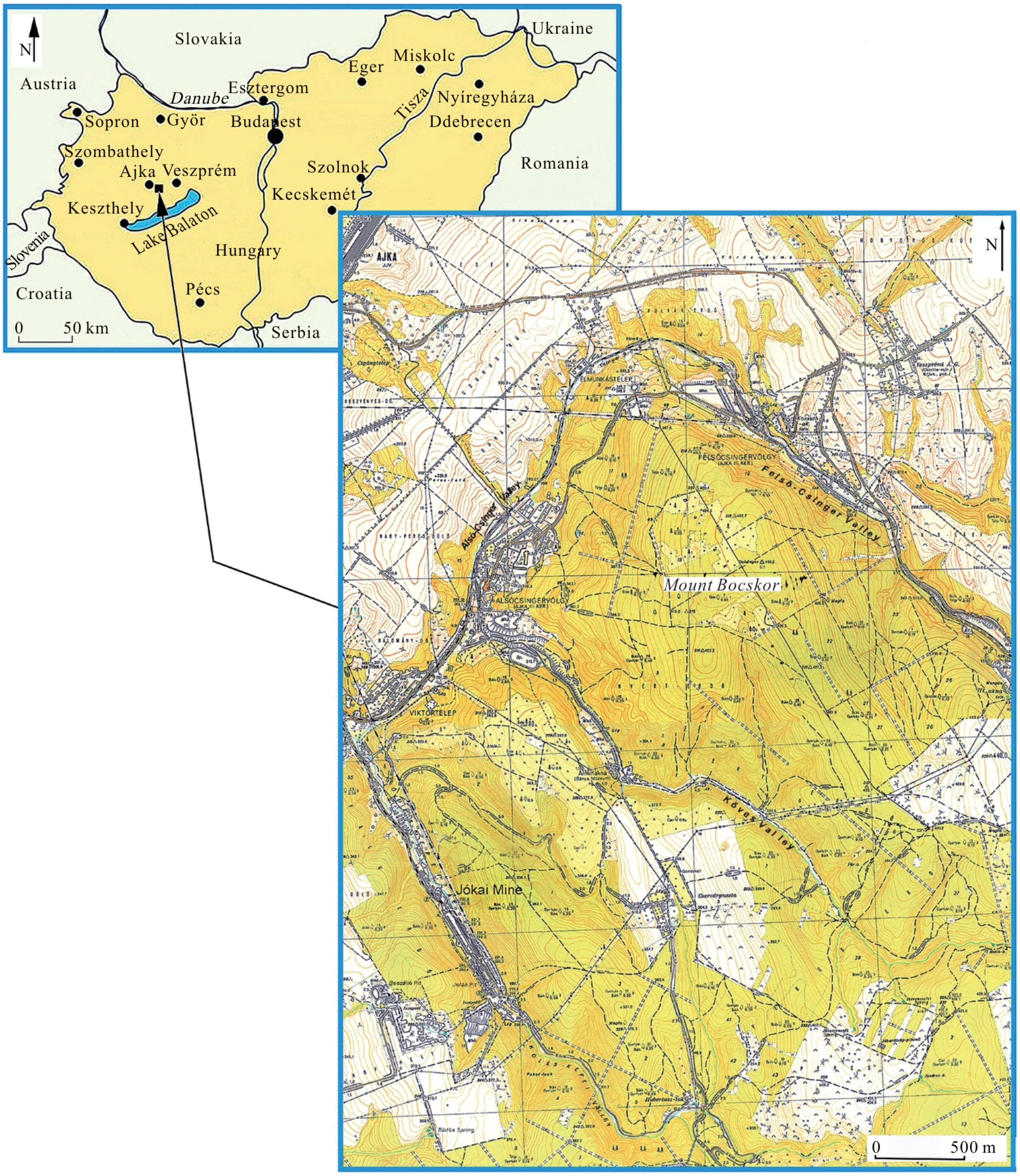

Figure 1. Location of Mount Bocskor in the area of the Bakony region (using a tourist map).

In the area of the Ajka coal basin, to which the Ármin mine also belongs (Fig. 2), production began in 1869. The Ármin mine, in the Gyula field, was started cultivated in 1877 and production lasted for 127 years (Kozma, 1991).

The coal bed sequence age was determined correctly by Miksa Hantken—the first director of the Geological Institute of Hungary—immediately with the first performed analysis and he assigned it to the Upper Cretaceous. The Hungarian Stratigraphic Committee describes and keeps in record the Ajka Coal Formation (ACF) in the Cretaceous volume (Császár, 1996) as part of the Hungarian Lithostratigraphic Units booklet series. The bedrock of this coal sequence is known from drillings, the oldest member is the Late Triassic, Norian Main Dolomite. In the area of the Ármin mine, appears as bedrock the Norian-Rhaetian Kösszeni Formation, which has a marly build up. Drilling in the Gyula field penetrated a thick Dachstein limestone formation. Jurassic formations have also been identified as bedrock, some of those are carbonates being the equivalent with the Liassic Úrkút manganese ore formation. The direct bedrock of the ACF is represented by the Upper Cretaceous (Late Santonian – Early Campanian) Csehbánya Formation in the whole area of the coal basin, which is settling on the previously mentioned formations by an unconformity.

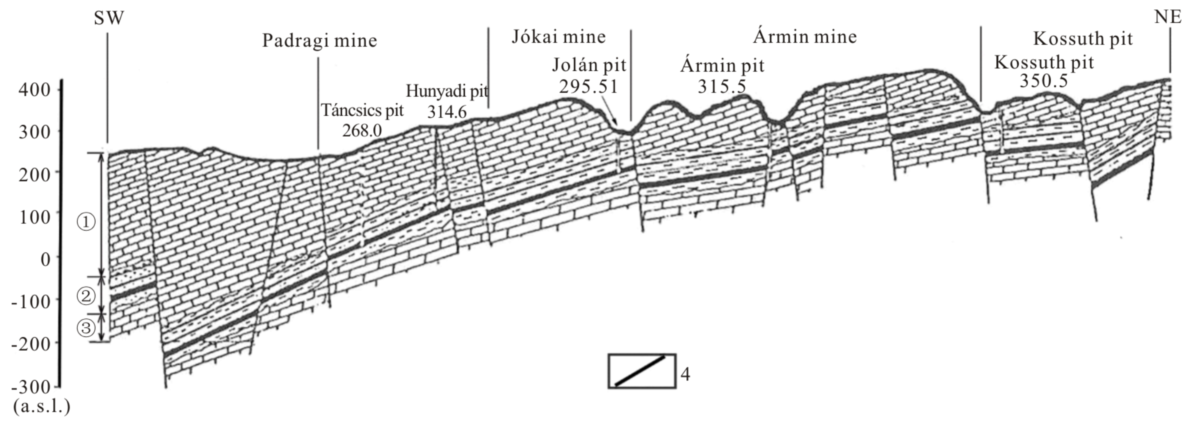

Figure 2. Geological profile of Ajka's surroundings (Kozma, 1991). 1. Eocene limestone, 2. Cretaceous rock with coal beds, 3. bedrock Triassic dolomite and limestone.

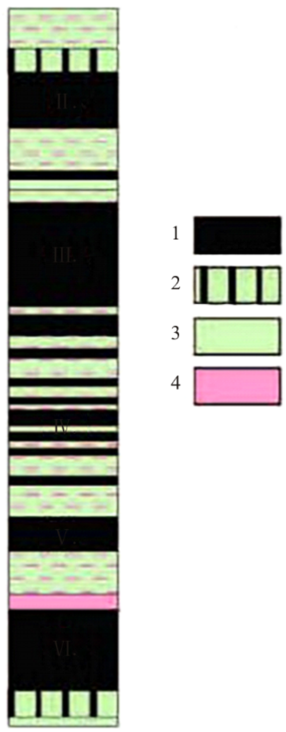

Figure 3. Coal beds of the Ármin Mine (Kozma, 1991). 1. Coal bed; 2. coaly clay; 3. clay, claymarl; 4. fossil, fossilpan.

The Ajka Coal Formation is a unit composed of a dense cyclic alternation of dark grey, grey, brownish-grey sand, siltstone, clay, clay marl, marl, light grey limy marl, limestone rock types (Császár, 1996). The coal sequence usually includes 7 coal beds, 5 of which were classified as exploitable industrial reserve (Fig. 3). Inter-laid sediments within the coal sequence are alternating sandy, clayey, marly deposits that often contain shellfish fragments. There are two characteristic horizons, the first one contains amber particles names as ajkait level, respectively the second one being the horizon with gypsum inside the field No. IV. The best quality of the coals can be found in the lower horizons with 1.5 to 3.5 m thickness. The well-developed field VI. thickness varies between 2.5–5.5 m, the thinnest coal field V. was not exploited all over the coal basin in contrary with the field IV. This latest has 2.1 to 4.5 m average thickness. Field III. is developed all over the coal basin, with thicknesses 2.45 m. The field II. thickness varies between 2.1 to 2.53 m. The field I. contains the mentioned ajkait amber horizon with restricted areal development.

The covering deposit of the ACF is the Jákó marl formation, presenting a continuous transition with it. Over this follows the Polány marl formation and the Ugod limestone formation as heteropic facies, closing the formations of the Mesozoic Era.

The Eocene Darvastó (clay-marl) and Szőc limestone formations overlaid on the Mesozoic by an unconformity. (Only the latter formation occurs on Mount Bocskor.) There is also a strong unconformity between these deposits and the Csatka Formation, which are extra-basin sediments like variegated clay and conglomerates from the Upper Oligocene–Lower Miocene, outcropping on the surface.

The structural build-up of the study area is strongly influenced by the Alpine tectonic events. The Ajka coal basin is a depression with a SW-NE axis, the infilling is the result of its re-sedimentation processes after the erosion of elevated regions. The stratigraphy sequence is characterized by unconformities and repeatedly renewable structural elements.

These are steep faults, which also mean 20–150 m offset (Fig. 2). The structural elements also show horizontal components, which proves trans-current fault with horizontal displacement of 100–150 m. Due to the sum of these effect, the formations of the area, including the coal beds, show a deepening trend towards west. Thus, the position of the structural elements and the deepening of the beds toward west was decisive in the design of the excavations, cuts and mines.

Coal was mined at 5 different horizons in the mine (two of which are inseparable) (Kozma, 1991). The exploitation horizons and fields, were established side by side but also on top of each other (Table 1, Fig. 4).

The pseudokarst features of the mount and their genetics are overviewed. With the help of the used methods (mapping, morphometry, the analysis of pseudokarst features and mine cut directions), the origin of the features from mine cuts can be given. (The applied methods make it possible to set up a relation between mine cuts and the genetics of the features. In contrast with other methods, these are suitable for presenting the effect of mine cuts to the vault even if it is partly or completely cov-

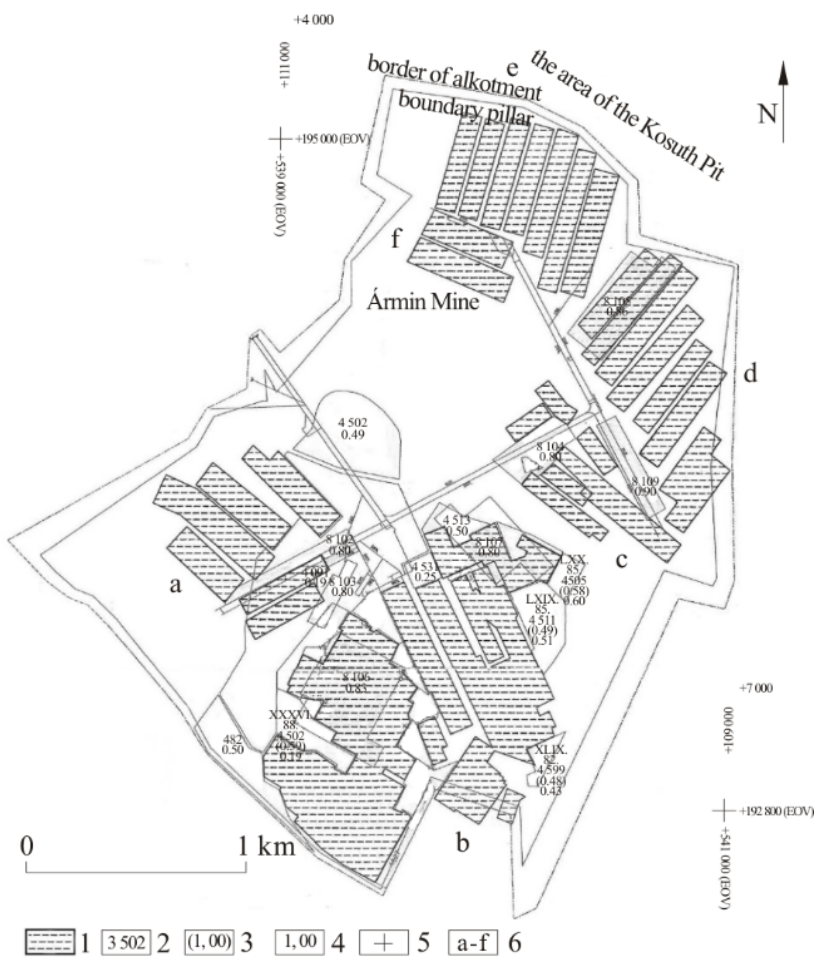

Figure 4. Map of bed IV (Bakonyi Erőmű Rt Bányászati Igazgatóság, 2004). 1. Excavation; 2. block number; 3. abandoned mineral reserves, original mineable value; 4. mineable value; 5. map coordinate; 6. identification mark of excavation blocks listed in Table 1.

ered with superficial deposit.) During the discussion, various effects of mine cuts to the surface are distinguished. Among the threefold effects, vault movement by sinking and atectonic faulting vault movements are interpreted by two models.

3 METHODS

A 1 : 2 000 scale plan map of the most extensive, contiguous depression system on the mountain was made. Furthermore, a 1 : 100 (of 1 site), 1 : 200 (of 2 sites) scale contour map of the three parts of this, on which the contour lines were constructed every 0.5 m. We made a 1 : 10 scale morphological map of some depressions and a cavity (fissure cave) of one of the depressions.

In the vicinity of depressions, using contour maps, we determined the extent of surface inclination. We examined the relationship between the magnitude of surface inclination and the size of depressions.

The directions of the depression groups of the depression system and the mine trenches were measured. The direction of depression groups was determined from a map which scale was 1 : 2 000: the depressions of the groups (at both outer margins of depressions) was delimited by tangent lines. Lines connecting the halves of the sections between the tangent lines were taken as the directions of the groups. (Where the direction of the tangent line changed, there were two axes and the group was divided into two subgroups.) The directions of the mining cuts were determined from the mining maps (for each excavation), as well as the directions, shape, number of mining parts and their area of each excavation part.

The depth distribution of circular depressions was measured (from contour maps) and plotted, as well as the depth and length distributions of elongated and complex depressions and their elongation ratio (quotient of length and width) was measured and plotted. The length distribution and elongation ratio of elongated and complex depressions were measured and plotted separately.

A function relation was looked for between the diameter (longer axis of elongated depressions) and depth of depressions plotted on contour maps.

The lowest differences in the direction of depression groups and the direction of depression were made. The standard deviation of the differences in the directions were counted.

The lowest possible differences in the direction of the depression groups and the mining cuts were made.

4 RESULTS

4.1 The Characteristics of the Ármin Mine

Excavation took place at different colonies, in different excavation blocks with different directions and shapes. Their shape is a regular geometric shape bounded by side walls per-

Table 1 Beds of the Ármin mine and some of their characteristics (Bakonyi Erőmű Rt Bányászati Igazgatóság, 2004)

Sign of the bed	Its separable part	Its shape	Its area (km^2)	Its direction[1]
I	a	Areal	0.03	150º–330º
	b	Areal	0.71	60º–240º
All	-	-	0.74	-
II	a	Areal	3.4	130º–310º
	b	Connected cuts	0.79	35º–215º
All	-	-	4.19	-
	a	Cuts	0.62	130º–310º
	b	Connected cuts	1.32	153º–333º
III	c	Cuts	0.13	125º–305º
	d	Cuts	0.66	38º–218º
	e	Cuts	0.46	13º–193º
	f	Cuts	0.16	112º–292º
All	-	-	3.19	-
	a	Cuts	0.53	130º–310º
	b	Connected cuts	1.54	153º–333º
IV	c	Cuts	0.53	128º–308º
All	d	Cuts	0.69	37º–217º
	e	Cuts	0.38	15º–195º
	f	Cuts	0.16	111º–291º
All	-	-	3.83	-
V–VI	a	Areal	1.76(?)	122º–302º(?)
	b	Areal	3.97(?)	165º–345º(?)
All	-	-	5.73(?)	-

[1] Direction of the edges delimiting the beds. The side of V–VI beds is irregular, their expansion is patch-like therefore both their area and direction can be given with an approximate value.

pendicular to each other. Therefore, the excavations can be separated into sub-excavations in more or less different directions. According to the shape (Table 1, Fig. 4) there is a rectangular cut (its width varies between 50–100 m), a connected cut (the cut is recognizable, but there is no partition between them), an areal cut (these are hundreds of m wide in all directions). The direction of the latter can only be given with uncertainty. There can be several colonies on top of each other therefore, several excavations can occur above each other. In the southern part of the mine, all six sites occur on top of each other.

4.2 Morphological Types of the Depressions

There are also various depressions on the flat roof level and partly on the side slopes of the mountain, which can range from a few m to a few times 10 m.

The depressions can be divided into two groups: closed depressions and opened depressions. Forms of both groups occur only on a surface covered with thin soil, but they can also occur on thicker soil or on a surface which is covered with superficial deposit. The features of the cover may be the same as those on the bedrock, but they may also differ significantly from it. They occur mostly in groups and if so their density is high. Many of them have now been replenished during mine recultivation. The closed depressions are karst-like forms and their morphology is similar to the subsidence dolines especially those which are formed in the superficial deposit. (We show below that for some forms, morphological similarity may also mean genetic similarity to subsidence dolines.)

The opened depressions are the trenches and the steps. The trenches are steep-sided features several m wide, 1–2 m deep, and several times 10 m long (Fig. 5a). The steps are a few meters high, steep features that have developed below each other on the side slope of the mountain. Between them there are a few times 10 m wide gentle slope parts.

The closed ones, can be circular, elongated and complex features by their ground plan. The circular ones can be gentle (slope angle less than 10º–20º, Fig. 6) steeper (slope angle 20º–60º, Fig. 7a) and steep side (than their slope is almost vertical). Depressions with steep side slopes are collapsed and similar to dropout dolines (Fig. 7b). There is no soil rupture on the edges of the first group, their diameters are larger (they can exceed 10 m) the diameters of the second and third groups are smaller (a few m in diameter).

The elongated depressions (Figs. 5b, 6, 8) are mostly steep-sided. They often show a fissure in the bedrock on their floor and sides. They are very varied in length. The longer ones are often separated into sections in different directions.

Complex forms are of two types. One variant includes those where the shape of the upper part differs from the shape of the lower part. Most often, the upper part is circular, but the bottom of it is elongated. The different shape indicates that the formation of the cover is different from and partly independent of the feature formation on the bedrock. The other variant includes those where they are smaller on the bottom of the main depression. The latter can be circular or elongated forms (Fig. 8). But there are also those whose ends show a broad circular depression character (Figs. 5c, 9). In these places, two perpendicular fissures can be observed in the bedrock. The upper part of the lateral slope of the elongated and complex depressions formed in the bedrock has a smaller inclination than the lower one. Especially in the sloping part, the rock has a crushed development. They are divided by smaller forms, such as land bridges and shafts. The shafts are elongated, vertical, downwardly widening fissures in the bedrock with a diameter of a few dm (Fig. 9). Land bridges occur above a few m of passages and cavities in the cover of elongated depressions (Figs. 9, 10). Their presence suggests recurrent collapses in elongated depression.

Depressions occur in three pattern types, which are the following.

(1) Lonely patterned depressions with a circular ground plan.

(2) Banded patterned depressions where the bands are divided into depression groups. In some places, they may be formed in several parallel lanes (Fig. 11). They can exceed 100 m in length and 20–40 m in width. Depression groups are divided into different directions, depression groups are divided into subgroups of different directions. Elongated, circular, and complex depressions also occur in depression groups. The elongated and complex depressions that occur in their area are varied in direction. The bands surround more or less areas which are poor in depressions. The elongated and complex depressions of the depression groups are on a sloping surface such that their longitudinal axis is perpendicular to the direction of inclination of the surface. Thus, on one of their edges, the de-

Figure 5. Trenches (a), elongated depression (b) and complex depression (c).

limiting surface tilts towards them, and on their opposite edge, it tilts away from them (Figs. 6, 8). This character can also be observed in trenches (Fig. 5a).

Elongated depressions, which are mainly fissures formed in the rock. These forms, developed in parallel with each other (their directions are not scattered), are widespread in some places. The surface of their surroundings is flat and has no inclination or specific direction of inclination.

The map of the fissure cave (Fig. 12) shows that the nature of the cavity is due to the fact that the soil held together by roots left in places covers the fissure. The cavity has a characteristic rock fissure with a parallel wall, the base of which is provided by fallen soil and debris. Because of this, its actual depth is unknown. Since there is soil in its continuation, the fissure is likely to extend beyond the surface depression.

4.3 Morphometry

Depths of depressions range from 0 to 8 m, and the predominant depth ranges from 0 to 2 m (Figs. 13a, 13b). Circular depressions are smaller, while elongated and complex, are greater in depth. This suggests that elongated and complex depressions are more directly related to the atectonic fissures of the bedrock. These features are hardly modified varieties of fissures (fissure caves). Therefore, the vertical expansion of fissures is more predominant here than at circular depressions. According to the diameter depth function (Fig. 14), the larger the diameter, the greater the depth. This relationship also indicates that the depressions form at fissures. The longer a fissure, the greater the chance of the rock opening up or being inherited to the surface, and thus, the depth of the depression may be greater. The value of R confirms the close relationship between these two properties $R = 0.9$ ($R^2 = 0.81$).

Depressions that fall out of this relationship population are circular or less elongated because the collapses (which may extend to the bedrock but also to the cover) developed more limitedly and thus, the resulting depressions were less lengthening. The other (elongated and complex) depressions from which the function was derived also have scattering, probably because their opening is of different degree. This is confirmed by the longitudinal section of the mapped fissure cave, where it can be seen that the part of the greater depth of depression formed by the collapse is shorter than the fissure in the bedrock.

The length of elongated and complex depressions is 0–80

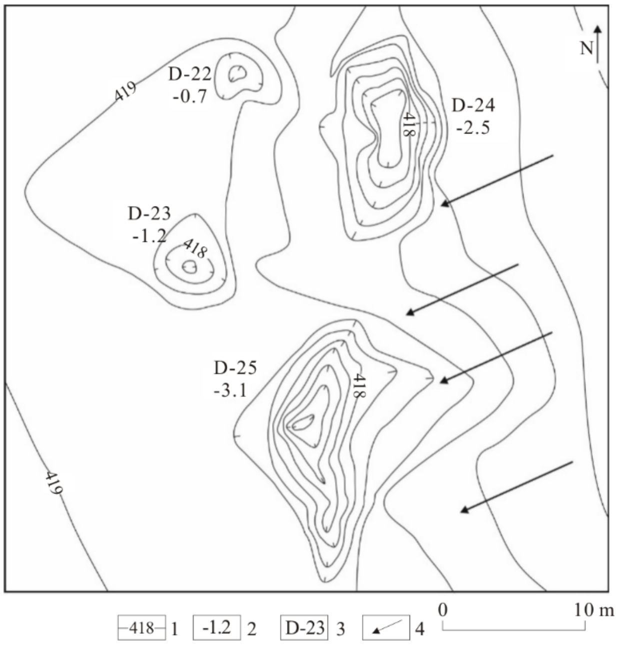

Figure 6. Topographic maps of circular depressions with gentle slope and elongated depressions (the nearly parallel dip directions of the surface developed because of the subsidence of the vault above mine cuts). 1. Contour line; 2. depth of the depression; 3. sign of the depression; 4. inclination of the surrounding surface.

m, with a length of 0–20 m predominating (Fig. 13c). The elongation rate for elongated and complex depressions is between 0–14, predominantly between 2–4 (Fig. 13d). The high rate of elongated and complex depressions in the mapped area (78 pieces) and their significant elongation value indicate that the formation of depressions is directly determined by the atectonic fissures of the bedrock.

It was mentioned that in the case of banded depressions in the vicinity of elongated and complex depressions the surface tilts locally (the magnitude of the inclination is between 2.20º–5.18º) and the direction of the longer axis of the depressions is perpendicular to the inclination (Figs. 6, 8). There is a relationship between the size (width and depth) of these depressions and the slope of the boundary surface (Table 2). Depth (average 1.8 m) and width (average 6.44 m) of depressions on a surface with a slope of less than 4º are smaller, depth (average 4.23 m) and width (average 4.23 m) of depressions on a surface with a slope greater than 4º (average 8.35 m) higher. The relationship between the size of the depression and the surface inclination is indicated by the fact that the tensile stress is greater on the more inclined surface. The greater the tensile stress, i.e., the deflection, the deeper the atectonic fissures open and thus the deeper the depressions. The width appears to be less dependent on deflection. In fact, it does, because if the D-25 depression is taken from the group with a slope of less than 4º (for which reason we will return below), the average width of the depressions on surfaces with a slope of less than 4º is 4.3 m, while with the D-25 marked depression together, the average width of depressions on surfaces with a slope greater than 4º is 9.68 m. Thus, as the tensile stress increases, the width of the opening atectonic fissures also increases.

Compared to the natural dolines of karst areas, the values of the length and elongation ratio of elongated and complex depressions show striking differences, suggesting radical genetic differences. While, for example, in Aggtelek karst (Hungary) which is covered with soil the average length of dolines is 116.38 m (Bárány et al., 2015), out of the 78 elongated and complex depressions of Mount Bocskor at 61 dolines the average length is less than 20 m and there is only one of which length reaches 74 m. Thus, on karsts larger diameter forms are characteristic. However, the elongation rate is reversed. In the Aggtelek karst, its average value is 1.63, in the case of elongated and complex depressions of Mount Bocskor the elongation rate is more than 2 by 60 depressions and is more than 12 by 2 (out of 60) depressions. The mountain's depressions show a greater correspondence with the natural subsidence dolines. Of the 34 dolines of the 3 observation plots of the West Mecsek karst's (Hungary) subsidence dolines, only 2 had a diameter of 10–20 m, 32 had a diameter of less than 10 m, and an elongation ratio of 7 to 0 (Vetési-Foith et al., 2017). Similarly, the subsidence dolines of the Bakony Region (Hungary) and Pádis (Romania) have a diameter of less than 10 m (Veress, 2016).

Comparing the lengths of elongated and complex depressions, this value is slightly higher than the latter (Fig. 15a), but there is no significant value difference between them. The elongation ratio is similarly distributed between the two form types (Fig. 15b). In terms of the elongation rate of elongated depressions, their number is decreasing in the higher value class intervals, while among the complex depressions there are also very elongated ones, so they also have an elongation rate of 8 – 14 (Fig. 15). This suggests that elongated depressions develop

Figure 7. Circular depressions. (a) With a medium slope; (b) with a steep slope (dropout doline).

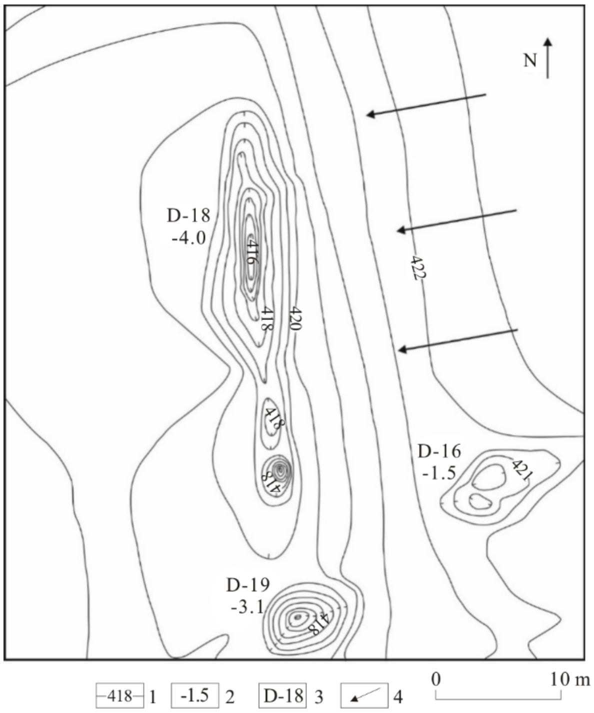

Figure 8. Topographical map of a complex depression (the nearly parallel dip directions of the surface developed because of the subsidence of the vault above mine cuts). 1. Contour line; 2. depth of the depression; 3. sign of the depression; 4. inclination of the surrounding surface.

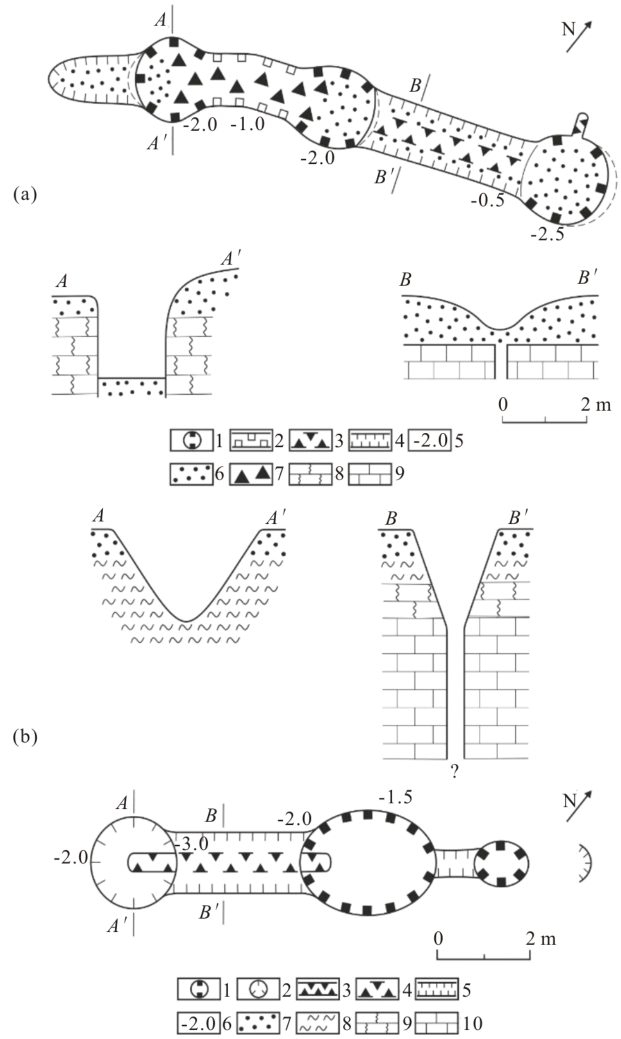

Figure 9. Geomorphological map of complex depressions. (a) Morphological map of the complex depression signed 1. 1. part of a vertical sided circular depression, 2. part of a vertical sided elongated depression, 3. fissure in the bedrock beneath the surface (under the cover), 4. part of a slopy sided elongated depression, 5. depth of the depression (m), 6. soil, 7. limestone debris, 8. clastic limestone, 9. limestone. (b) Morphological map of the complex depression signed 2. 1. part of a vertical sided circular depression, 2. part of a slopy sided circular depression, 3. vertical sided fissure in the bedrock, 4. fissure in the bedrock beneath the surface (under the cover), 5. part of a slopy sided elongated depression, 6. depth of the depression (m), 7. soil, 8. loess with soil, 9. clastic limestone bedrock, 10. limestone.

first and then elongate and separate as a result of repetitive movements, or that internal depressions form on their bottoms (repetitive elongation of the atectonic fissures of the bedrock may also contribute to their elongation). However, the value of the high elongation rate of complex depressions suggests that their elongation exceeds their widening as they develop.

By comparing the directions of the depression groups and the directions of the mine cuts, the following can be established (Fig. 16).

(1) The directions of depression groups are more diverse than the directions of mining cuts.

(2) Accordingly, there is a depression group direction range that does not include a mine cut direction. Thus, in the range of 61º–110º (241º–290º) there is one, in the range of 34º–346º (166º–210º) there are only two cutting directions (direction of the excavation parts marked IIIe and IVe). The different variability of the two directions and the separations of the direction ranges suggest that the displacements above the mine cut do not usually directly determine the directions of the depression group formed on the surface (which reflects the direction of the space growth bands or the direction of the atectonic faults).

(3) However, the direction of some depression groups or subgroups is the same as the direction of the mine cuts (e.g., subgroup marked Db and mine cut marked IVe). In other cases, the differences are very small, 2º–3º (Table 3). This suggests that the displacements of the rocks that make up the vault also had a direct effect on the atectonic fissure formation of the rock. By not sinking, or not only sinking, at these sites, atectonic faults have formed, which have contributed to the formation of atectonic fissures (see below) and thus depression.

The variance values of the direction differences (depression group and direction differences of their depressions) range from 2.52 to 43.84 (although the maximum value of 32.13 is more reliable) (Fig. 11, Table 3). Depression groups in the N with a N-S direction show a lower value, while those which are in the SE, E-W direction show a higher value. If the standard deviations for each depression group are arbitrarily set at 10.0, they can be small (less than 10.0) or large (greater than 10.0). In the depression groups with small variance, the direction difference between the depression groups and the mine cuts is larger (average 14.28º) and more varied, while in the large vari-

Figure 10. Land bridges in a complex depression.

ance it is smaller (average 6.89º) and less varied (Table 3).

4.4 Processes, Genetics

Elongated depressions, complex depressions and trenches develop at atectonic fissures, but circular depressions too. The development of circular depressions by fissures is indicated by the fact that transitions can be observed regarding the size and elongated character of small circular depressions, elongated features and very elongated features since the latter have extremely varied size and elongated nature (Figs. 13c, 13d). In addition to this, the occurrence of circular depressions among elongated (and complex) depressions makes it probable that circular depressions are transformed into elongated depressions during their growth. This is enabled by the fact that cover collapses accompany the development of the fissure of the cover in a delayed way or circular depressions already develop at a phase when the fissure that opened to the surface is still very short (its length exceeds its width only to a small degree). This is supported by the fact that the cave (Fig. 12) extends beyond the mapped depression (Fig. 9) However, it can also be observed that on the exposed bedrock walls, at the circular widenings of elongated depressions, a fracture whose direction is different from the direction of the bearing fissure can also be present. This may mean that some circular depressions develop at the intersection of fractures and fissures.

The processes that take place on the cover of atectonic fissures of the mountain are subsidence, collapse, grain shedding, compaction, and suffosion. Among them, the subsidence and collapse take place both in the bedrock and in the cover, the other processes only in the cover. The processes that take place in the cover are fast. The differences between the morphological maps, which was taken in May 2018, and the map of the cavity (which shows the ground plan of the depression) which was taken in July 2020, document this well since the values of the above maps show great differences.

4.4.1 Subsidence

We distinguish between primary and secondary subsidence. The primary subsidences occur directly due to material compensation due to the mine cuts. Therefore, they are relatively extensive. These are shown, as mentioned, by the slopes of the depression-bearing areas (Figs. 6, 8). Since the 3 contour maps were made of different parts of the same depression system, it is likely that the entire depression system is located in an area of curved sinking. The width of the sinking area (deflection) is about 10–30 m. The slope of the surface varies between 2.20º and 5.18º (Table 2). Depressions line up on this sloping (sinking) surface in particular. In the case of a sinking (deflecting) vault, the increase in space volume is limited to its edge, since here the rock has to occupy more space due to the bending and thus a tension occurs (see below).

The development of atectonic fissures (or cavities) can be of two types.

(1) Since the mapped fissure, or part of it, has no debris, this type of fissure opened to the surface of the bedrock.

(2) Depressions, based on piles of rock debris, do not reach the surface when the fissure opens, but later its vault collapses.

Depression with large-diameter, circular ground plan and with sloping-sides suggest the local subsidence of the surface. This process presumably extends to both the cover and the bedrock and is secondary. Based on their occurrence, they can develop in the bending zone thus, in the primary bending zone, but also outside this.

4.4.2 Collapses

Depression can develop by collapse on Mount Bocskor with direct and indirect inheritance. By direct inheritance the bedrock and the cover collapses together (Fig. 17I). In the case of indirect inheritance, the cover subsequently collapses into the atectonic fissure of the bedrock (which may be preceeded by the collapse of the cavity in the cover) and thus depression develops (Fig. 17III). By both processes, the developing features show similarity in morphology and in genetics with the dropout dolines of the covered karsts.

Collapses of the cover can also be observed. Their piles also occur in some depressions. The collapse of the cavities formed in the cover (and the presence of cavities) is evidenced by the wedges of the earth bridges (Figs. 9, 10) as well as the cover piles shown here. Depressions may also directly develop by collapse. Depressions formed by collapse are small in diameter, are exclusively formed in the cover, have steep (vertical) sides, and the walls are ruptured surfaces (Fig. 7b). But collapses can also occur on the slopes of steeper-sided depressions subsequently (Fig. 7a).

4.4.3 Suffosion and grain shedding

Features similar to suffosion dolines may also be devel-

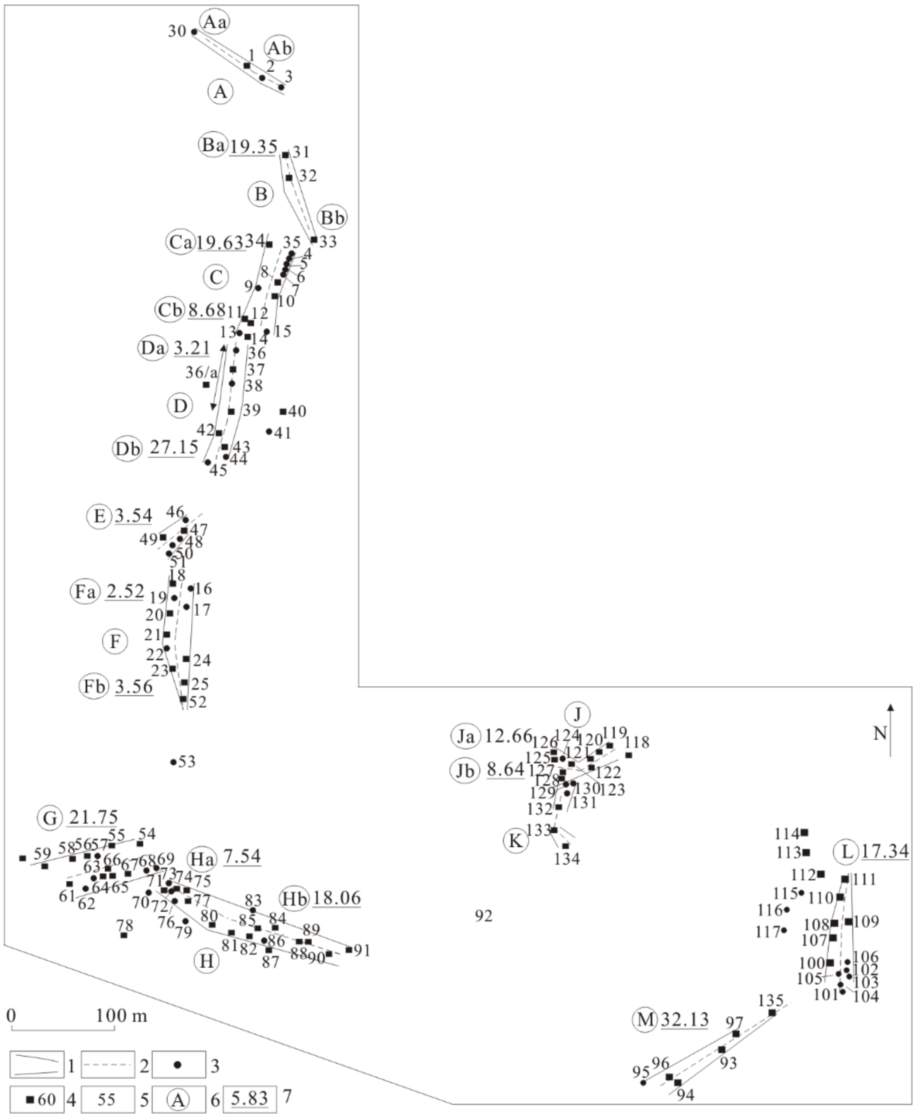

Figure 11. Depression groups. 1. Tangent line to a depressions of a depression group; 2. edited axis direction of a depression group; 3. circular depression; 4. elongated and complex depression; 5. identification number of the depression; 6. sign of the depression group; 7. standard deviation of the direction differences of depressions and of depression group.

oped by indirect inheritance. Then, the grain shedding, compaction, and suffosion act together, alternately, and cause depression to form over the atectonic fissures (Fig. 17II). Of these, grain shedding may play the largest role in the removal of the cover, followed by compaction of the cover and thus subsidence of the surface. In this way, the bottom positioned depressions of complex depressions were created (Fig. 12). Grain shedding over the gradually opening fissures of the bedrock is most significant because, according to laboratory experiments (Vetési-Foith, 2019), it occurs when the passages of the bedrock are wide enough and the grain size is small. Thus, according to the experiment, for a cover with a grain diameter of 1.0–2.0 mm, if the discharge passage is 5 mm in diameter, no material has fallen from the cover at all, but material of the same grain has already fallen into the passage's diameter has been increased to 15 mm. These processes, together with the collapse of the cover, but also afterwards, ensure that the cover is transported below the surface and that depressions (deepening and diameter increase) increase in addition to the movements of the bedrock. The flattening of the side slopes of already established depressions is caused by collapses, landslides (Fig. 7a), and pluvial erosion. The development and progression of depression are shown in Fig. 17.

5 DISCUSSION

In mines, the lack of material can be compensated by collapse, the formation of a fault structure (atectonic fault), and subsidence. Collapse can occur only on the bedrock, or only on the cover (Spooner, 1971), or both (Andrejchuk, 2002; Johnson, 1987). Surface formation is direct if it can be related to compensatory movements, in other cases it is indirect such as in cases of grain shedding, suffosion and the collapse of the cavity of the superficial deposit.

Since the number of cultivated settlements on Mount Bocskor is different in various places (or they are presumably collapsed in different rates) and they are of different sizes, the dif-

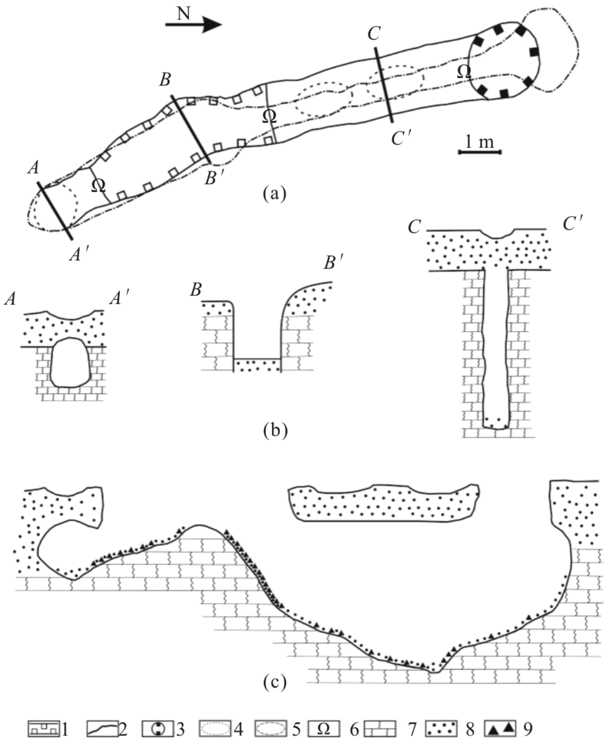

Figure 12. Ground plan (a), cross-sections (b) and longitudinal section (c) of the fissure below depression 1. 1. Part of a vertical sided depression; 2. part of a slopy sided elongated depression; 3. part of a vertical sided circular depression; 4. circular, slopy sided floor depression; 5. covered edge of fissure; 6. entrance of the cave/cavity; 7. clastic limestone; 8. soil; 9. limestone debris.

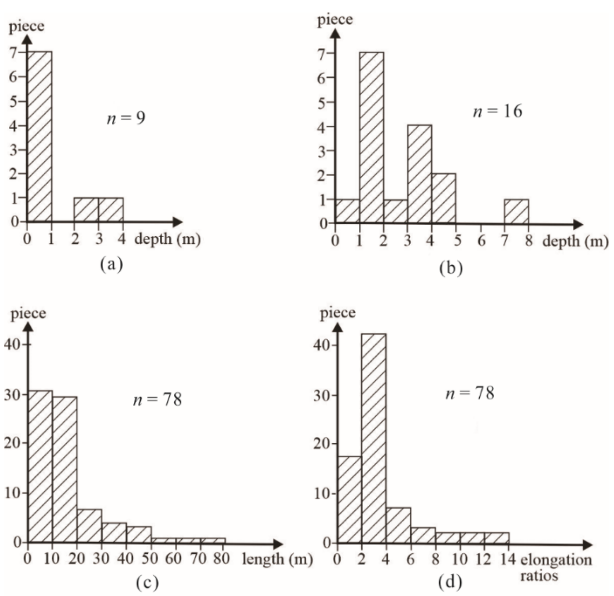

Figure 13. Depth of circular (a), elongated, and complex (b) depressions depicted on contour maps, length (c), and elongation ratio (d) of all elongated and complex depressions examined.

ferent parts of the mountain are leveled differently and the same type (subsidence) is of different magnitude and extent. However, the compensatory movements, since the cover is of

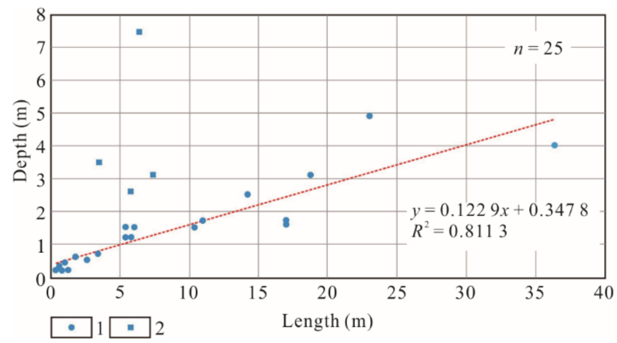

Figure 14. Function of diameter-depth of the depressions depicted on contour maps. 1. Data used to generate the function; 2. data not used to generate the function.

Table 2 Width and depth of depressions on surfaces with different slopes

Sign of the depression	Inclination of the surface	Depression's		Depression group
		Width (m)	Depth (m)	
D-8	2.20º	5.0	1.7	Ca
D-10	2.8º	3.6	1.5	Ca
D-25	2.97º	15.0	3.1	Fb
D-15	3.18º	3.8	1.2	Ca
D-13	3.83º	4.8	1.5	Ca
D-21	4.31º	11.0	4.9	Fa
D-24	4.57º	8.4	2.5	Fb
D-20	4.92º	6.0	7.5	Fa
D-18	5.18º	8.0	4.0	Fa

one type (Eocene limestone) and the vault is not plastic, are likely to be directly inherited to the surface and the formation of atectonic fractures, faults, and atectonic fissures accompanies the process.

Generally, feature development can only occur in large and horizontally extensive mine cavities. In small and non-horizontal mine cavities, as the void volume of the collapsed material increases to fill the mine cavity, surface formation can even be lacking, as in the case of natural cavities (Bull, 2011). However, the greater the verticality of the mine cavity and the thinner its vault, the higher the chance of collapse equalization. Collapse may result in surface feature development, but it does not necessarily occur. If the vault is thick and collapse takes place despite this thickness, surface feature formation can be absent as a result of the increase of pore volume of the collapsed material since it completely fills the cavity. The smaller the cavity vertically, but the wider horizontally, the greater the chance of subsidence equalization and the relating feature development.

On Mount Bocskor there is direct and indirect feature development as well. Below, feature development is interpreted by three types of movement of the vault which are collapse (1), subsidence and atectonic faulting (2), and atectonic faulting only (3).

5.1 The Collapse of the Vault (1)

In this case direct feature development (collapse) occurs. The phenomenon occurs on the slopes of Mount Bocskor.

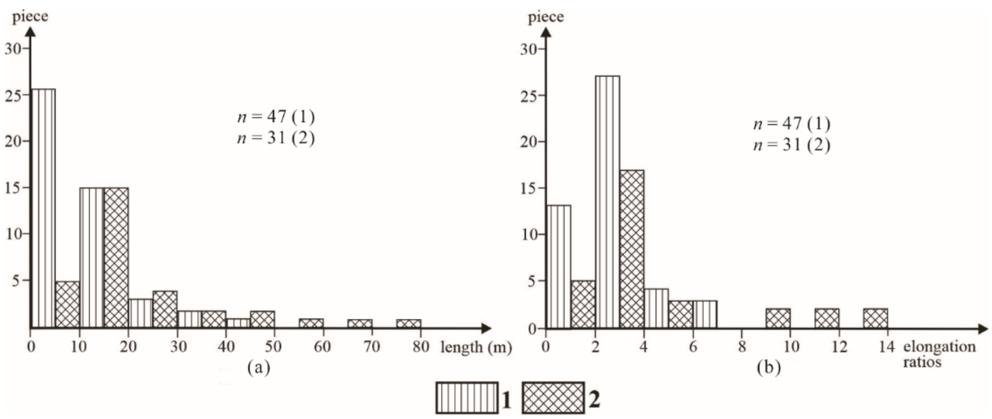

Figure 15. Length (a) and elongation ratio (b) by elongated and complex depressions. 1. elongated depression, 2. complex depression.

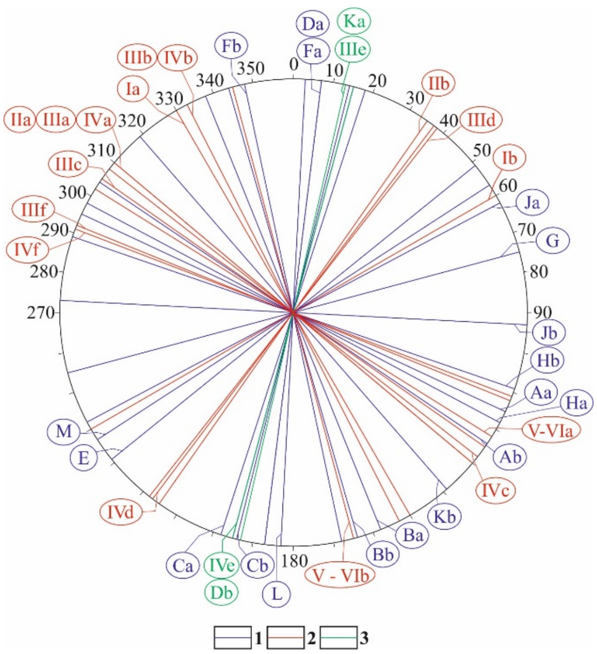

Figure 16. Directions of depression groups and mines. 1. Edited direction of a depression group; 2. direction of the mining cut; 3. the two directions match.

Steps formed in these places by collapse. This is possible where the mine cuts approached the slope of the mountain. It is likely that the collapses could have been repeated from the outside inwards, towards the inside of the mountain (step series).

5.2 Vault Movement by Sinking and Atectonic Faulting (2)

Since there are banded depressions in the interior of the mountain (Fig. 11) that surround depression-free areas, they are separated into smaller units (atectonic block, or blocks) where the balancing motion of the vault is sinking. During subsidence a subsidence trough develops. However, the subsidence, as shown below, alternates with or occurs with atectonic faults. At the outer part of subsidence trough, a folding zone is formed, where an increase in space occurs (Sütő et al., 2009; Sütő, 2001; Erdősi, 1987; Wassmann, 1980). The increase in space is followed by the formation of a tensile structure which is accompanied by atectonic fissure development. Depressions above atectonic fissures can develop by direct and indirect inheritance too (Fig. 17). The degree of subsidence can be given for coal mines with the following simplified relation in the case without a boundary angle (Sütő, 2001).

$$S = (T + M) - AT$$

where S is the subsidence, T is the thickness of the cover layers, M is the thickness of the coal layer, A is the volume growth coefficient of the coal deposit. (The boundary angle is the angle between the line connecting the edge and the surface motion boundary with the horizontal.) It is probably that the line above coincides with at least one atectonic fracture occurring at the subsidence (Fig. 18).

The maximum subsidence (according to Somosváry, 1989) is given by the following relation

$$WO = M{\cdot}s(1 - \omega t)$$

where WO is the maximum subsidence and s is the value of the subsidence factor (0.85), ωt is an embanking efficiency that is 0 in collapse mining and 0.55 in chamber and pillar mining.

According to Martos (1958), the factors influencing its subsidence above the mine are time, the size of the excavation area, the thickness, slope and depth of the excavated site, the mechanical characteristics of the side rocks, the geological, hydrological and tectonic conditions of the area. The size of the excavated area determines the undercut angle (Fig. 18). The greater its value the greater the value of the subsidence and its area (Martos, 1958), which in turn determines the rate of space increase in the deflection zone. If the undercut angle is small, the angle shanks intersect below the surface (then the subsidence is smaller in area and shallower in depth), if its larger they intersect at the surface (see Fig.18), and if they are even larger they intersect each other above the surface. The size and extent of the subsidence is the largest in the latter case. According to Wassmann (1980), the maximum subsidence above a salt mine in the Netherlands (where the size and pattern of the cavities were not known) was 1 625 mm in 4 years, with a 120 mm/10 m increase in space. According to his data, in the area of the 320 m subsidence above the salt, the space growth zone was 184 m. A maximum subsidence of 3 173 mm was measured at coal mine (Oroszlány, Hungary). There are two coal beds. Cuts were created in the lower coal bed (with a thickness of 1.7–2.5 m), from which the upper (with a thickness of 1.7–2.3 m) was reached by punching. The thickness of the cover is 100 m, con-

Table 3 Minimum differences between the axes of depression groups and the directions of mining cuts and the standard deviation of the differences between the directions of depression groups and their depressions

Sign of the depression group	Minimum differences between the direction of mining cuts and depression groups	The mining cut with the smallest difference	Standard deviation of the differences between the directions of depression groups and their depressions	The way in which atectonic fissures form
Cb	21º	IIb	8.68	
Da	22º	V-VIb	3.21	
E	9º	Ib	3.54	
Ha	4º(6)º	V-Va(IIIf)	7.54	A
Fa	22º	V-VIb	2.52	
Fb	3º	V-VIb	3.56	
Jb	19º	IIIf	8.84	
Average	14,28º	-	-	
Ba	8º	Ia	19.35	
Ca	17º	IIb	19.63	
Db	0º	IVe	27.15	
G	12º	Ib	21.75	
Hb	2º	IVf	18.06	B
Ja	2º	Ib	12.66	
Ka(?)	0º	IIIe	43.84	
L	18º	V-VIb	17.94	
M	3º	Ib	32.13	
Average	6.89º	-	-	

A. The atectonic fissure develops due to deflection; B. the atectonic fissure is the additional fault of the atectonic fault. Note: Standard deviation is small below 10.0 and is big above 10.0. For the standard deviation of Ka the depression of Kb has been used too.

stituted by Eocene limestone and Oligocene clay. The movement was measured between the dates of 6 August 1954 and 16 July 1955 (Martos, 1956). The subsidence stabilized after 200 days (Martos, 1958). The following factors affect the subsidence and its extent in the area of Mount Bocskor.

(1) Density, size, number and shape (square, rectangle, etc.) of cultivated beds (Fig. 4); (2) the thickness and inclination of the beds (Fig. 3); (3) depth of the mining; (4) characteristics of the covering rocks; (5) the value of the porosity of the collapsed material; (6) the thickness, length and number of pillars left between the mining cuts; (7) onset, intensity, nature of the subsidence (intermittent, renewable, or continuous).

Since the degree of subsidence depends on the outcome of these factors, the degree of outcome and thus of subsidence will be different in different parts of the mountain. Deflection and atectonic fault develop at the edge of the sinking area. As a result of different subsidence, the number, maturity of atectonic fissures will be different too. It is likely that the crushed, debris rock of the depression walls is formed during tensile stress. The atectonic fault, developed from the atectonic fractures, can be formed due to the shear stress due to deflection or by the vault's sinking into the mining cut. The resulting atectonic fissures (as already mentioned) also appear on the surface or are inherited in various ways to the cover, forming depression.

In the marginal, outer part of the subsidence, in the zone of deflection where space increase occurs (Fig. 18), as a result of different subsidence, the degree of space increase will also be different. According to Wassmann's (1980) calculations moving away from the edge of the deflection the rate of the space increase first grows (from 11 to 27 mm, the rate of deflection increases from 12º to 60º in 5 m) and then decreases at the edge of the compression area. The slope of the deflection (ultimately the magnitude of the subsidence) and its width determine the magnitude of the space increase. Above the Ármin mine, there are sinking areas (blocks) of different sizes on the surface next to each other, depending on the extent and area of the sinking. These, in turn, were determined by the extent and shape of the excavation areas (undercut angle). The marginal parts of the sinking areas are the sites of depression formation, which is indicated by the fact that most of them are on sloping surfaces and the depressions are located close to the strike direction of deflections (Figs. 6, 8). Depression groups are therefore grouped into bands (Fig. 16). Depressions on the bottom of the fissures indicate that depression may be associated with fissures. The different directions of depression document the different directions of atectonic fissures, their different widths and lengths, and the different development of atectonic fissures.

5.3 Models Interpreting Vault Movement

If the depressions represent the site and direction of atectonic fissures, the distribution of direction differences (Table 3, the smallest difference between the direction of the depression group and the direction of the mine cut and the standard deviation of the axis differences of the depression groups and their depressions) can be interpreted by two fissure development model (Model A and Model B). The directions of atectonic fissures and the direction of the depressions can also be interpreted by these models which are the following (Fig. 19).

5.3.1 Model A

In case of depression groups, where the standard devia-

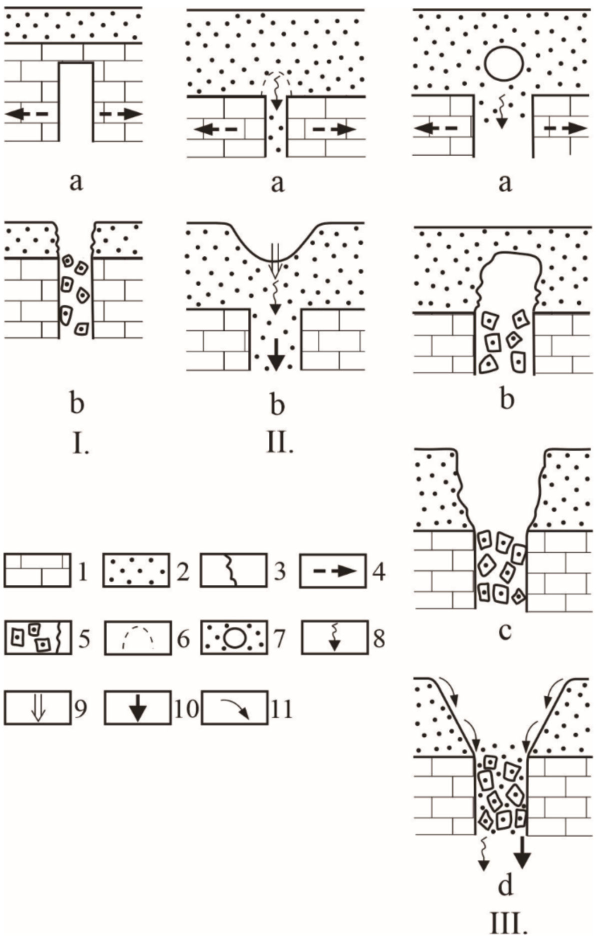

Figure 17. Development of the depressions. 1. Limestone; 2. cover and soil; 3. collapse surface; 4. development of the fissure by the displacement of the atectonic blocks; 5. collapsed material (bedrock and cover); 6. material loss in the cover; 7. cavity in the cover; 8. grain shedding; 9. compaction; 10. suffosion; 11. pluvial erosion; I.. direct inheritance to the cover by collapse: II., III. indirect inheritance to the cover; II. a. grain shedding took place into the narrow fissure; II. b. then depression forms in the cover by compaction and then subsidence; III. a. cavity formation in the cover (using the work of Waltham et al., 2005); IIIb. collapse of the material between the atectonic fissure and the cavity in the cover; III. c. collapse of the cover above the cavity; III. d. denudation of slopes of the collapsed depression by pluvial erosion.

tion of direction differences is smaller, the depressions are situated above fissures that developed by tension occurring during deflection. Therefore, the axes of atectonic fissures, depressions and of depression groups are perpendicular (or almost perpendicular) to dip directions that developed by deflection (Figs. 6, 8). This results in the low standard deviation of direction differences at these depression groups. The deflection zone has an arched ground plan, at all points the dip directions converge towards that point of the sinking area which subsides to the greatest degree (subsidence centre, Fig. 18a). The position of the deflection zone thus, the inclination of the surface at a certain site is determined by the subsidence centre. However, this site depends on the shape and size of the sinking area (on the shape and size of the excavation areas) and on the shape and size of the collapse of the vault. The axes of depression

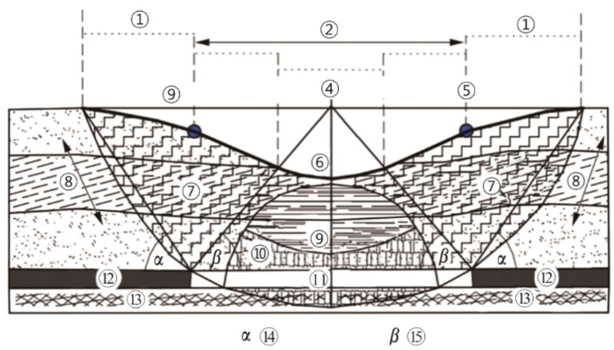

Figure 18. Subsidence trough developed by the sinking of the vault (by Sütő et al., 2009; Horányi and Kolozsvári, 1989; Erdősi, 1987). 1. Tension zone; 2. pression zone; 3. original terrain; 4. sole subsidence zone; 5. inflexion point; 6. maximum subsidence; 7. deflection zone; 8. cover layers; 9. fracture zone; 10. collapse zone; 11. excavation field; 12. coal beds; 13. bedrock layers; 14. boundary angle; 15. undercut angle.

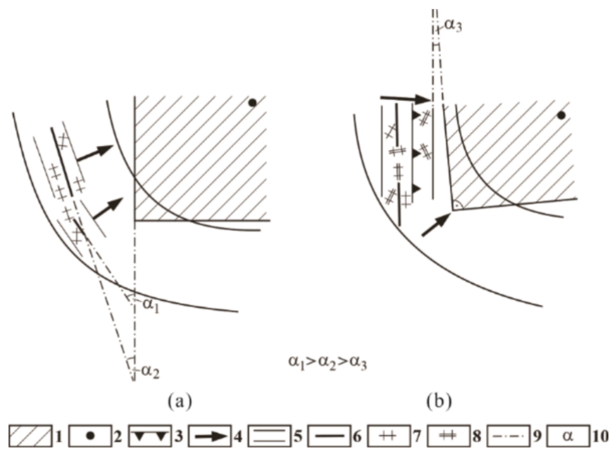

Figure 19. (a) Model A: Schematic figure of the formation of atectonic fissures due to deflection by space increase; (b) Model B: additional atectonic fissures of descending atectonic fault.

groups and the differences of mine cut directions (the mine cut whose direction is the closest to the depression group) are relatively larger (Table 3) because they are independent of the direction of a mine cut since the atectonic fissures perpendicular to the dip direction due to deflection determine the directions of the axes of depressions and depression groups.

5.3.2 Model B

At depression groups, where the standard deviation of direction differences is larger, depressions develop at atectonic fissures of more varied direction. Thus, depressions do not or not only develop to the effect of tension during deflection. Since the direction differences of the direction of mine cuts and the axis of depression groups are smaller (Table 3), the development of depression groups was affected by atectonic faults which developed during the collapse of mine cuts. The reason for a larger standard deviation is that there are several atectonic faults with different directions (as compared to the depressions of the depression groups described by Model A) in the area of the same depression group. At normal faults (Vadász, 1955) and at lateral displacements (Keller and Pintér,

1995) additional faults develop. High standard deviation refers to the fact that at the depressions of such depression groups additional faults constitute the atectonic fissures at which depressions develop. Therefore, directions of depression groups show a closer relation with the directions of the mine cuts, while higher standard deviations indicate that the development of depressions is less dependent on deflection directions, but they depend on the additional faults of atectonic faults (Fig. 18b).

The tilt values measured in the environment of each depression are consistent with the above mentioned genetic grouping. In case of the depressions of depression groups developed by deflection have a surface inclination greater than 4º, while those which developed by atectonic faults have an inclination of less than 4º (Table 2), since in the latter the equalization occurred with a lateral displacement and less deflection. Depression D-25, although here the slope of the surface is less than 4º, is still justified in the deflection genetic group, since the standard deviation of the Fb depression subgroup is small (Table 3).

Compression occurs in the inner part of the sinking areas in the upper part of the vault. Since the tensile on the lower part of the inside of the sinking area, upward wedge fissures may develop. However, these are likely to have less of an effect on surface feature formation.

The edges of the sinking zones are marked by bands formed by depression groups. There are no depressions in the inner zones, or only rarely, where the cover can be washed into the upwardly wedged fissures. Since the depression groups only partially enclose a part of the area, the subsidence of the atectonic block is only partial (tilting) and is not completely separated from its surroundings.

5.4 Vault Movement by Atectonic Fault

There are parts of the area on Mount Bocskor where depressions (these are not deep and not wide) occur in parallel and are not grouped into bands and on surface without superficial deposit, the surface around them does not tilt. Such fissures developed inside an atectonic block. Here, the increase in space was caused by the subsidence along the downwardly diverging faults.

6 CONCLUSIONS

The site, expansion and direction of 134 depressions were measured on Mount Bocskor (the longest is almost 80 m, and the deepest is 8 m), with this, their distribution and direction can be described. Detailed topographic maps of 25 depressions out of 134 were made and 6 maps are also included in this study. Morphological maps of 2 depressions were made and a map of the cave below one of them. Six exploitation horizons were separated into 18 smaller units and their area and direction were measured on horizon maps. The length, depth and elongation proportion of depressions and their distribution as well as a function relation between diameter and depth were established. Analysing the smallest difference of the directions of depressions groups, subgroups and mine cuts and the standard deviation of the axis differences of depression groups and their depression, two models were set up for the surface subsidence above the mines and feature development.

Mount Bocskor is divided into atectonic blocks. The extent and shape of each block changes dynamically depending on the extent and rate of the subsidence. The extent and duration of subsidence may be affected by the collapse of more and more beds and areas above beds over time, increasing the imbalance. The movements of the vault can be collapses and the movements of the atectonic blocks. By the latter can be distinguished sinking and atectonic block bounded by downwardly cohesive faults (here a normal fault develops), as well as sinking atectonic block by downwardly distancing faults.

In the marginal zone of subsidence, depressions can develop at the additional fissures of atectonic faults or at the atectonic fissures of the space-increasing zones of deflections. These movements are also reflected in the appearance of surface forms: stepped surfaces with collapses, mixed surface forms arranged in bands by sinking (and by downwardly cohesive faults) (circular, elongated, and complex depressions, trenches), non banded, elongated depressions by downwardly distancing faults.

Due to mining, the development of pseudocarstic depressions occurs during the following processes. Subsidences (deflections) occur (1), at the edges of which tension zones (2) are formed (also in the case of downwardly distancing faults inside the subsidence). In the tension zone, atectonic fissures in different directions are formed (3), which can be directly inherited (during the collapse of the bedrock) onto the cover (4). Where the bedrock does not collapse but opens, the cover material is transported into the atectonic fissures of the bedrock by grain sheddding or suffosion or collapse (5).

From the morphology above the mines, if it developed as a result of the mines, the nature of the compensatory movements taking place in the vault can be deduced.

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REFERENCES CITED

Allgaier, F. K., 1997. Environmental Effect of Mining. In: Marcus, J. J., ed., Mining Environmental Handbook: Effects of Mining on the Environment and American Environmental Controls on Mining. World Scientific Publishing, San Mateo. 132 – 189. https://doi. org/10.1142/

9781860943768_0005

Andrejchuk, V., 2002. Collapse above the World's Largest Potash Mine (Ural, Russia). *International Journal of Speleology*, 31(1/4): 137–158. https://doi.org/10.5038/1827-806x.31.1.8

Bakonyi Erőmű Rt Bányászati Igazgatóság, 2004. Bakony Power Plant Directorate of Mining, Map of Mine Cut, Bányavágat Térképe

Bárány, K., Márton,. K., Nelis, et al., 2015. Néhány További Adat a Hazai Karszt Dolinák Aszim-Metriájának Kialakulásához Some Additional Data on Asymmetry in the Formation of Hungarian Karst Dolines. *Karsztfejlődés*, XX: 125 – 144. https://doi. org/17701/15.125-144 (in Hungary)

Bull, P. A., 2011. Boulder Chokes and Doline Relationships. Proc. 7th. Int. Cong. Speleol., 93–96

Chen, J. P., Li, K., Chang, K. J., et al., 2015. Open-Pit Mining Geomorphic Feature Characterisation. *International Journal of Applied Earth Observation and Geoinformation*, 42: 76–86. https://doi.org/10.1016/j.jag.2015.05.001

Chen, J., 1988. Karst Collapse in Cities and Mining Areas, China. *Environmental Geology and Water Sciences*, 12(1): 29–35. https://doi.org/10.1007/BF02574824

Császár, G., ed., 1996. Kréta, Magyar Állami Földtani Intézet, Budapest. 164.

Dontala, S. P., Byragi T. R., Vadde, R., et al., 2015. Environmental Aspects and Impacts Its Mitigation Measures of Corporate Coal Mining. *Procedia Earth and Planetary Science*, 11: 2 – 7. https://doi. org/10.1016/j.proeps.2015.06.002

Dulias, R., 2016. The Impact of Mining on the Landscape: A Study of the Upper Silesian Coal Basin in Poland. Springer, Berlin, Heidelberg, New York. 209. https://doi.org/10.1007/978-3-319-29541-1

Erdősi, F., 1987. A Társadalom Hatása a Felszínre, a Vizekre és az Éghajlatra a Mecsek Tágabb Környezetében (Society's Effect to Surface, Surface Waters and Climate). Budapest, Akadémia Kiadó. 228 (in Hungarian)

Ford, D. C., Williams, P. W., 2007. Karst Hydrogeology and Geomorphology. John Wiley & Sons, Chichester. 561

Halliday, W. R., 2004. Piping Caves and Badlands Pseudokarst. In: Gunn, J., ed., Encyclopedia of Caves and Karst Science. Fitzroy Dearban, New York. 589–593

Horányi, L., Kolozsvári, 1989. Geodézia és Bányaméréstan: Bányaméréstan II (Geodesy and Mining Metrology: Mining Metrology II), Tankönyvkiadó, Budapest. 267 (in Hungarian)

Johnson, K. S., 1987. Development of the Wink Sink in West Texas due to Salt Dissolution and Collapse. In: Beck, B. F., Wilson, W. L., eds., Karst Hydrogeology: Engineeering and Environmental Implication. Balkema, Brookfield, Vermont. 127–136

Johnson, K. S., Collins, E. W., Seni, S. J., 2003. Sinkholes and Land Subsidence Owing to Salt Dissolution near Wink, Texas, and other Sites in Western Texas and New Mexico. *Oklahoma Geological Survey Circular*, 109: 183–195

Keller, E. A., Pinter, N., 1995. Active Tectonics: Earthquakes, Uplift, and Landscape. Prentice Hall, Englewood Cliffs. 338

Kompóty, J., 1908. Az Aknaszlatinai Kunigunda-Bánya Beomlásai (Collapses of the Kunigunda Mine by Aknaszlatina). *Bányászati és Kohászati Lapok*, 46: 390–392 (in Hungarian)

Kozma, K., 1991. Az Ajkai Szénbányászat Története (History of Coal Mining in Ajka). Veszprémi Szénbányák, Veszprém. 531 (in Hungarian)

Lu, Y. R., Cooper, A. H., 1997. Gypsum Karst Geohazards in China. In: Beck, B. F., Stephenson, J. B., eds., Engineering Geology and Hydrogeology of Karst Terrains. Balkema, Rotterdam. 117–126

Martos, F., 1956. A Külszíni Süllyedés Számításának Egy Közelítő Módszere (An Approximate Method for Calculating Surface Subsidence). *Bányászati Kutatóintézet Közleményei*, 1(1): 3 – 12 (in Hungarian)

Martos, F., 1958. A Külszín Elmozdulását Befolyásoló Tényezők (Factors Influencing Surface Displacement). *Bányászati Lapok*, 6: 367–372 (in Hungarian)

Móga, J., Lippmann, L., Tombor, E., et al., 2015. Az Aknaszlatinai Sókarszt Felszínalaktani Vizsgálata. *Karsztfejlődés*, XX: 185–283 (in Hungarian)

Móga, J., Szabó, J., Gönczy, S., et al., 2017. Az Aknaszlatinai-Sókarszt Dinamikusan Változó Felszínformáinak Vizsgálata Terepi és GIS Módsze-Rekkel the Study of the Dinamically Changing Landforms of Aknaszlatina Salt Karst by Field and GIS Methods. *Karsztfejlődés*, XXII: 139–161 (in Hungarian)

Monjezi, M., Shahriar, K., Dehghani, H., et al., 2009. Environmental Impact Assessment of Open Pit Mining in Iran. *Environmental Geology*, 58(1): 205–216. https://doi.org/10.1007/s00254-008-1509-4

Mossa, J., James, L. A., 2013. Impacts of Mining on Geomorphic Systems. In: Shroder, J., James, L. A., Harden, C. P., et al., eds., Treatise on Geomorphology, Vol. 13, Geomorphology of Human Disturbances, Climate Change, and Natural Hazards. Academic Press, San Diego. 74–95

Newton, J. G., 1987. Development of Sinkholes Resulting from Man's Activities in the Eastern United States. US Geological Survey Circular 968, Washington DC. 54

Oggeri, C., Fenoglio, T. D., Godio, A., et al., 2019. Overburden Management in Open Pits: Options and Limits in Large Limestone Quarries. *International Journal of Mining Science and Technology*, 29 (2): 217–228. https://doi.org/10.1016/j.ijmst.2018.06.011

Quinlan, J. F., Smith, A. R., Johnson, K. S., 1986. Gypsum Karst and Salt Karst of the United States of America. *Le Grotte d' Italia*, 4(13): 73–92

Rico, M., Benito, G., Díez-Herrero, A., 2008. Floods from Tailings Dam Failures. *Journal of Hazardous Materials*, 154(1/2/3): 79 – 87. https://doi.org/10.1016/j.jhazmat.2007.09.110

Rösner, T., van Schalkwyk, A., 2000. The Environmental Impact of Gold Mine Tailings Footprints in the Johannesburg Region, South Africa. *Bulletin of Engineering Geology and the Environment*, 59(2): 137 – 148. https://doi.org/10.1007/s100640000037

Singh, K. B., Dhar, B. B., 1997. Sinkhole Subsidence Due to Mining. *Geotechnical & Geological Engineering*, 15(4): 327 – 341. https://doi.org/10.1007/BF00880712

Somosváry, Z., 1989. Geomechanika (Geomechanics). Tankönyvkiadó, Budapest. 301 (in Hungarian)

Spooner, J., 1971. Mufulira Interim Report. *Mining Journal*, 276: 122

Sütő, L., 2001. A Felszín Alatti Bányászat Domborzatra Gyakorolt Hatásai a Kelet-Borsodi-Szénmedencében (Impacts of Subsurface Mining on Topography in the East Borsod Coal Basin). Földrajzi Konferencia, Szeged. 20 (in Hungarian)

Sütő, L., Homoki, E., Németh, G., 2009. Felszínsüllyedési és Bolygatottsági Térkép Készítése a Kelet-Borsodi-Szénmedencében (Construction of a Subsidence and Disturbance Map in the East Borsod COAL Basin). Geoinformatika és Domborzatmodellezés, HunDEM 2009 és GeoInfo Konferencia és Kerekasztal Válogatott Tanulmánya. 7 (in Hungarian)

Sweeting, M. M., 1973. Karst landforms. Columbia University Press, New York. 362

Vadász, E., 1955. Elemző Földtan (Analytical Geology). Akadémia Kiadó, Budapest. 516 (in Hungarian)

Veress, M., 2016. Covered Karst. Springer, Berlin, Heidelberg, New York. 536. https://doi.org/10.1007/978-94-017-7518-2

Vetési-Foith, S., 2019. Az Utánsüllyedéses Dolinák Képződését Befolyásoló Paraméterek Kapcsolatrendszerének Vizsgálata Modell Kísérlettel. (Analysing the Relations of the Parameters that Influences the Subsidence Dolines Formation Using Model Experiments). *Karsztfejlődés*, XXIV: 61 – 78. https://doi. org/10.17701/19.61-78 (in Hungarian)

Vetési-Foith, S., Kiss, Z., Gárdonyi, I., 2017. A Mecseki Karszt Oldódásos- és Utánsüllyedéses Töbreinek Morfometriai Elemzése (Morphometric Analysis of Dissolved- and Subsidence Dolines in the Mecsek Karst). *Karsztfejődés*, XXII: 119–138. https://doi.org/10.17701/17.119-138 (in Hungarian)

Walters, F., 1978. Land Subsidence in Central Kansas Related to Salt Dissolution, Kansas by Robert. *Bulletin Kansas Geological Survey*, 214: 74–75

Waltham, T., Bell, F., Culshaw, M., 2005. Sinkholes and Subsidence. Springer, Berlin. 382

Wassmann, T. H., 1980. Mining Subsidence in Twente, East Netherlands. *Geol. Mijnbouw*, 59: 225–231

White, W. B., 1988. Geomorphology and Hydrology of Karst Terrains. Oxford University Press, New York. 464

Williams, P. W., 2004. Dolines. In: Gunn, J., ed., Encyclopedia of Caves and Karst Science. Fitzroy Dearborn, New York, London. 304–310

Xu, W. G., Zhao, G. R., 1988. Mechanism and Prevention of Karst Collapse near Mine Areas in China. *Environmental Geology and Water Sciences*, 12(1): 37–42. https://doi.org/10.1007/BF02574825

Yuan, D., 1987. Environmental and Engineering Problems of Karst in China. In: Beck, B. F., Wilson, W. L., eds., Karst Hydrogeology: Engineering and Environmental Applikations. Balkema, Rotterdam. 1–11