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GIS analysis of dissipation time of landscape in the Devil's city (Serbia)

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*The Devil's City is a unique geomorphological site well known regarding strangely sculptured stony pillars or soil (clayey) pyramids, abandoned mines and two rare hydrologic occurrences. The present landscape is partly inherited from the paleo-volcanic topography and shaped afterwards by erosion, particularly linear erosion. Soil pyramids owe their origin to the differential erosion of a more compact andesitic level on less cohesive pyroclastic material and d*isintegrate relatively quickly when they lose their protective "cap". The *pyramids are located along the two gullies, Devil's and Hell's. In the latter, also known as "The young Devil's City" the erosion process is in the beginning. The results of combined petrological and geomorphological studies permitted us to reconstruct past geological processes and predict the future evolution of the Devil's City. Geographic information system (GIS) and digital topographic modeling are becoming powerful tools not only in geographic sciences but also in geomorphological and geological modeling.*

Key word: *Devil's City, volcanic, digital topography, erosion, pyramids, GIS.*

1. Introduction

The Devil's City occupies approximately 4300 m^2 (broader area is 84404 m^2) in the south of Serbia, in the base of Radan Mountain. The altitude of the locality is 700-720 meters. The distance from the capital City, Belgrade is about 290 km and it is 29 km away from the municipality of Kuršumlija (fig. 1).The area is spatially and genetically related to the Lece eruptive complex that covers approximately 700 km^2 and represents the medium part of the Alpine-Balkan-Carpathian arc. This arc was formed through approaching and the collision of the African and the Eurasian plates, i.e. under the subjection of the Tethyan oceanic crust beneath the continental Moesian platform. The site is placed under state protection in 1959, and in 1995 was declared a natural resource of great importance and included in the first category of protected monument of nature. The site was in 2008 nominated for the Seven World Wonders of nature. The unusual shapes, known as stony pillars or soil (clayey) pyramids, abandoned mines and two rare hydrologic occurrences are prominent features of the Devil's City (fig. 2).

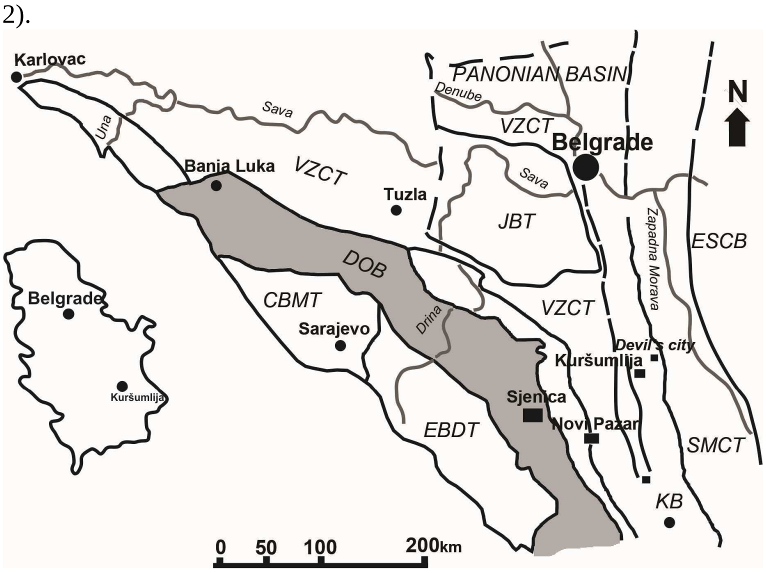

Fig. 1. The terrains in the central part of the Balkan peninsula, along with the position of the Devil's City in Serbia. ESCB - The composite terrain of Carpatho-Balkanides; SMCT - The Serbian- Macedonian composite terrain; VZCT - The Vardar Zone composite terrain; KB - The Kopaonik block; DIT - The Drina-Ivanjica terrain; DOB - The Dinaridic ophiolite belt; EBDT - The East Bosnian-Durmitor terrain; CBMT - The Central Bosnia Mts. terrain. DHCT - The Dalmatian-Herzegovinian composite terrain (Karamata, 2004).

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The soil pyramids stand from 2 -15 m in height, at the base from 4 to 6 m wide and at the summit of 1 - 2 m. These ephemeral forms disintegrate relatively quickly when they lose their protective "cap" of andesite blocks. Similar landscape defined by the isolated pinnacles known as "Fairy Chimneys" was developed in pyroclastic ignimbrites in Cappadocia [1,2].

Fig. 2. The central position of soil pyramids in the Devil's City.

2. Methods

2.1. Digital analysis

Calderas were reconstructed using methods and techniques of remote sensing. In this case we used aero-photo recordings and topographic maps of this area. We used also aero-photo recordings in a resolution of 10 meters and topographic maps which were given in the ratio 1:25,000. The digitized topographic map of the Devil's City was prepared using the open source QGIS 2.6 Bridgton software. This GIS multicriteria method is specialized to vectorize and calculate small areas on the maps. The GIS multicriteria model indicates where are the potential erosion places [3]. According to the performed digitalised topographic map were estimated the slope angles, depths and lengths of more extensive gullies. We used these values to evaluate the erosive power of water [4]. The content of elements in solution samples taken from two springs was determined by inductively coupled plasma atomic emission spectrometry (ICP-OES) in the Laboratory of the Faculty of Chemistry, Belgrade University. The ICP-OES measurement was performed using Thermo Scientific iCAP 6500 Duo ICP (Thermo Fisher Scientific, Cambridge, United Kingdom) spectrometer equipped with CID86 Charge Injector Device (CID) detector, standard glass concentric type nebulizer, quartz torch, and alumina injector. The optical system purged with argon and the Echelle polychromator thermostated at 38 ºC. Instrumental conditions were optimized to obtain sufficient sensitivity and precision [5].

2.2. Geological background

The geology of the broader area is presented on the basic geological map, sheet Kuršumlija,in theeratio ofo 1:100,000, which comprises the southern and southeastern parts of the mountain Kopaonik, the western parts of Radan Mountain and the Toplica basin [6]. The last represents the former link between the Aegean and Pannonian Sea [7,8]. The oldest rocks are Precambrian gneisses, followed with Devonian limestones occasionally marbleized. Cretaceous conglomerates and flysch products are widespread, accompanied with rocks of the Jurassic ophiolite mélange [9]. The most remarkable lithological units are volcanic and pyroclastic rocks. Volcanic rocks are dominantly andesites, built of plagioclase (andesine), amphibole, biotite and pyroxene (fig.3). Accessories are apatite and metallic minerals. Texture is porphyritic. Quartz-andesites and dacites occur sporadically with the presence of quartz. Uniform chemistry of andesites reflects on uniform volcanism.

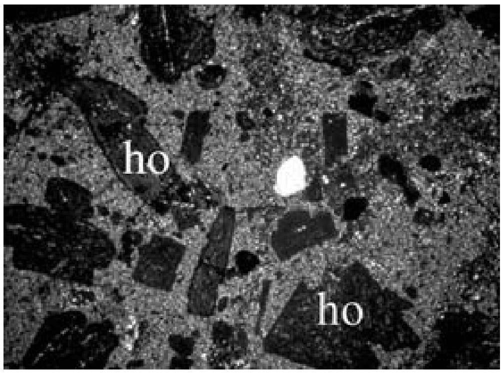

Fig. 3. Microphotography of andesite with phenocrysts of amphibolehornblende (ho). Length of microphotographs is 3 mm.

Pyroclastic rocks are mostly represented with weakly bonded volcanic breccias and tuffs. Agglomerates, volcanic bombs and blocks are less abundant. These rocks are exposed as horizons from a few meters to 100 m thick. Notable characteristics of the Devil's City are the prevailing of pyroclastic rocks over andesites and intensive hydrothermal activity.

Hydrothermal activity greatly contributed to the present morphological setting and created several quartz-brecciated zones, commonly exposed as reefs due to their higher resistance. The extension of quartz-brecciated zones is from a few tens of meters to 6 km, and their maximal width is 50 m. The most intensive hydrothermal process was silification. The zones are ore bearing, either brecciated or massive, composed of whitish cryptocrystalline to amorphous silica, opal, chalcedony, quartz, epidote, siderite, hematite, rock fragments, Pb-Zn sulphides etc. (fig.3). Variable mineral composition in distinct zones is a consequence of variable intensity of hydrothermal alteration. In relatively small areas where hydrothermal influence was lacking the superficial weathering affect all the exposed rocks and derive thin soil, known as andosols [10]. The soils are sandy with clayey compound up to 11% in abundance, slightly acidic, i.e. humus-silicate (ranker) with A-C-R horizons. Weathering indices obtained from the soil in the Devil's City using indices proposed by different authors are presented on the table 1.

Tab. 1. Weathering indices of the soil in the Devil's City. CIW-chemical index of weathering (Harnois, 1988); CIA- chemical index of alteration (Nesbitt & Young, 1982); WI – weathering indices (Parker, 1970); MWPI – modified weathering indices (Vogel, 1975).

	1	**2**	**3**	**4**
CIW	50	54	58	76
CIA	45	49	53	69
WI	84	74	74	26
MWPI	19.5	16.1	15.1	11.3

2.3. Volcanism characteristics

Volcanism in the Devil's City is related to Upper Oligocene. Regarding reference data, three phases could be distinguished.

1. Formation of stratovolcanoes
2. Formation of calderas
3. Processes inside calderas and consolidation of the complex.

1. The explosive volcanic activity during the Upper Oligocene produced several stratovolcanoes (composite or grey volcanoes). These volcanoes are known as large and long-lived volcanoes, particularly those of andesitic composition (fig. 4). They emit a combination of lava flows and tephra, building steep-sided volcanic cones. The amount of tephra exceeded the amount of lava. Lava dome probably exceeded 1000 m in height, as lava flows disabled or slowed down erosion and loss of tephra. This prediction could be confirmed by the present height of the Gajtan caldera of nearly 700 m (fig. 5). Diameters of distinct volcanoes might be over 30 km.
2. Stratovolcanoes were afterwards broken into calderas – roughly circular basins from 1 to 25 km in diameter. In general, caldera develops through collapse after the partial or complete emptying of the magma chamber, when unsupported roofs sink slowly under their own weight. Primary dimensions of calderas cannot be precisely determined due to pronounced erosion coupled with effects of subsequent endogenous motions inside the calderas themselves. The Gajtan caldera is the oldest with only preserved part on Petrova Gora. The best preserved, thus probably the youngest is the Tulare caldera with still preserved centre of effusion on Braina. The Devil's City caldera is the largest, with about 25 km in diameter and best preserved parts at Sokolovica and on the Markov Vis.
3. In the final volcanic phases already consolidated bottoms of calderas were pushed upward and ascended in the form of brachianticlines. This process was accompanied by the creation of radial fissures that will serve as paths for hydrothermal solutions.

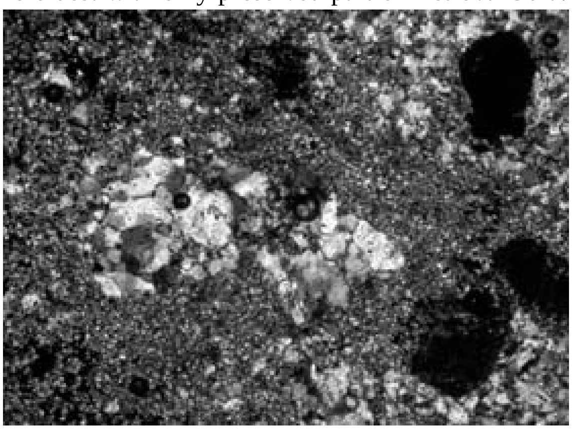

Fig. 4. Completely silicified rock. Length of microphotographs is 3 mm

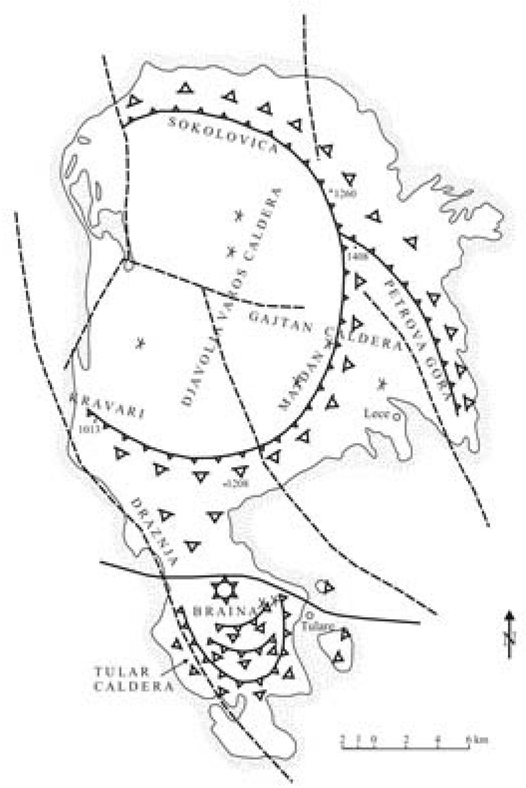

Fig. 5. The present position of calderas in present relief of Devil's City

2.4. Abandoned mines

During the Sava tectonic phase in Lece was formed Pb-Zn deposit in which was exploited Fe, Cu and Au yet in the medieval age. Famous Saxon miners were summoned by Serbian King Vladislav (1233 -1242). The descendants of the Saxon families still inhabit the village Štava, but they are completely assimilated – received Serbian names and orthodoxy. For this mine is probably genetically related extraordinary hydrologic occurrences. The springs of these waters that have many unusual properties are located at 768 m altitude. Devil's gulley with longitude $21^{\circ}\ 44'\ 42'',3$, and latitude $42^{\circ}59'53'',2$ and coordinates of the source of Hell's gulley are longitude $21^{\circ}\ 24''\ 28'',3$ and latitude $42^{\circ}\ 59'\ 51'',8$. The properties of the water itself are examined and the content of heavy metals in springs of these two gullies is given in the table 2.

Tab. 2. The properties of the water itself are examined and the content of heavy metals in springs of these two gullies.

	Fe	Co	Ni	Mn	Zn	pH
DG	308.4	297.9	102.7	8957	1147	1.5
HG	144.1	776.4	415.6	4652	1198	3.5

These waters represent the acid mine drainage (AMD) or acid rock drainage (ARD) that refers to the outflow of acidic water from abandoned Pb-Zn mines. Acid rock drainage is known to occur naturally within some environments as part of the rock weathering process, usually within rocks containing an abundance of sulphide minerals [11].

3. GIS and Digital analysis

The geo-spatial variables used in this work have been obtained from the analogue formats of the maps and we have digitized them all. We divided the area in five classes, based on the degree of erosion. The precision of the classes was determined by the super abundance and quality of data grid manipulation, the complexity of the slopes terrain and the geographic variability of the situated location. The Grid cells were put out at 25 m resolution and were validated with the ground measurement of shade tools with the help of GIS tools (Coors, 2002). Using open source QGIS 2.6 Bridgton, we divided mixed grid and put it into the software. Each data set was resampled to 25 m using a special filter into Quantum GIS 2.6. Average contour lines vector files were obtained from a digital shape when we derived data from the DEM (Digital Elevation Model [12]. The data from DEM were downloaded from the grid after digitization. The grid was rescaled from 0 (least) to the value of 1 (ideally, close to be ideal). The distance to the contour lines was given in the mixed elevation grid and after that converted to the map. Since all the data consisted of polygons, it was necessary to convert them into a grid like points in a 25 m resolution. Then, the data were standardized by 0 and 1 values. The distance between lowest and highest elevation points was 134 meters. The grid and slope directions were categorized according elevation and terrain slope. The fifth class of slope is given and also one class of grid valued in a 2,5 m resolution [13]. Other GIS data were derived from the distribution of potential erosion points with precision coordinates which were given in UTM (Universal Transverse Mercator) WGS 84 coordinate system (Fig.6). The relief map of the Devil's city region shows us that it is streams flows through the central part of the area have extreme slopes. Based on the complete processing of GIS data we divided area in fife class. Categories of degree slopes give next scores (0^0-5^0, 5.1^0-10^0,10.1^0-15.0^0, 15.1^0-20.0^0, >20.1^0). 0^0 degrees to 10^0 degrees is not active erosion, 15.1^0-20.0^0 is moderate, and more than 20.1^0 is an extremely erosion [14].

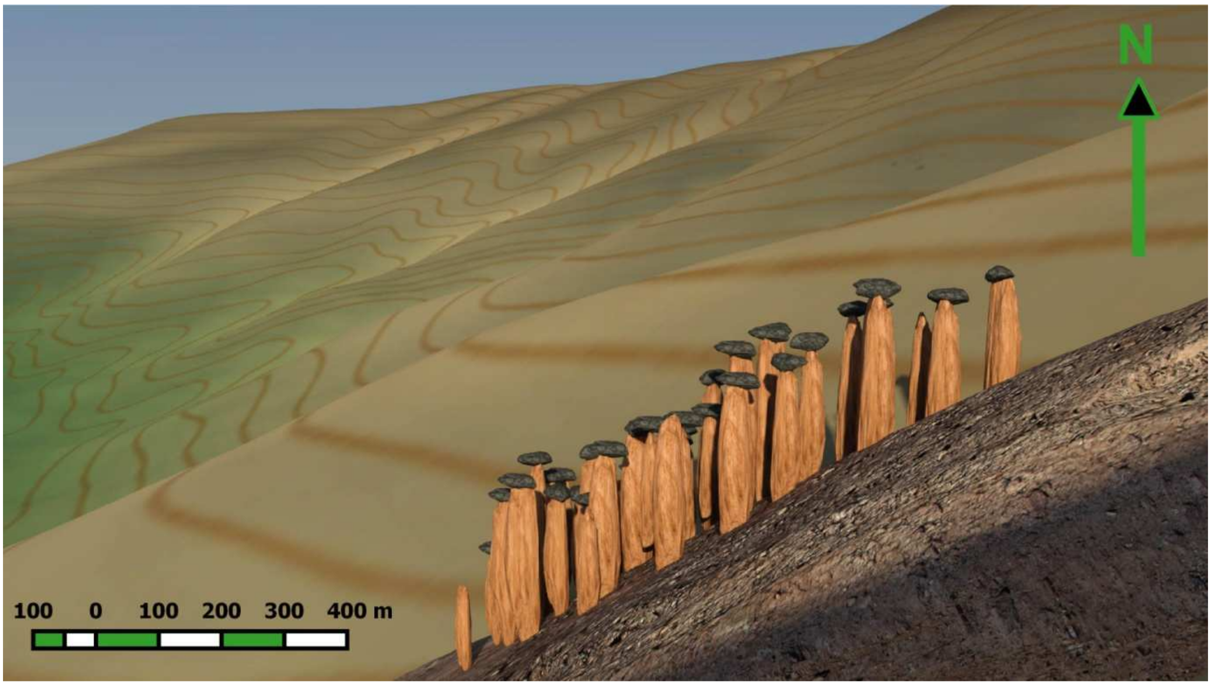

Fig. 6. Realistic model of Devil's city on the digital topographic map.

4. Results and discussion

The differences in topography and lithology in the broader area caused hydrographic differences. In the Toplica basin water flows are rare, with weak erosion and accumulation rate, whereas in the mountainous regions frequent flows cause intensive erosion and incise deeper valleys. Hydrothermally altered and partly weathered rocks in the Devil's City were additionally exposed to mass-wasting and erosion that finally shaped the present landscape. Water and wind are two important forces that effect the whole area but tend to be the most noticeable and have their main effects on slopes, i. e. banks of the two main gullies, Devil's and Hell's due to their high-angle erosional unconformity. Over 200 stony pillars are exposed in the Devil's Gully (fig. 7) In the Hell's Gully, known as "Young Devil's City", the new pyramids are forming [15].

The slope angle was calculated according to the equation, where 57. 3 is radians, $h_2 - h_1$ are the lowest and the highest points in the profile, d_m - length of the profile in meters. The very same formula is used for the slope angle expressed in percentage $\alpha^\circ = \frac{h_2 - h_1}{d_m} \cdot 100\%$. The obtained angle in the Devil's City is $\alpha^\circ = \frac{748-583}{294} \cdot 57,3 = 32,15^\circ$ in degrees, and - $\alpha\% = \frac{748-583}{294} \cdot 100 = 56,12\%$ in percentages, respectively. This is the basic parameter of the topography in the Devil's City and as the consequence linear erosion became the dominant force. Atmospheric water retains only a potential energy after hitting the Earth's surface and losing kinetic energy. However, under the influence of gravity, with an increase of the angle of motion, the atmospheric water receives kinetic energy again [16].

$$Ek = M \cdot \frac{V^2}{2} \quad (1)$$

Therefore, after converting the potential energy into kinetic energy, only one part of the water is able either to drain the surface or to swell underground. That part of liquid agent is the main factor of linear and surface erosion. In the area of Devils' City running water is moving either laminar or turbulent. The former is characteristic for surface acceleration, whereas the latter takes part in line acceleration. As the consequence of the presence of gullies between the huge pyramids of the Devil's City, the turbulent movements of water are prevailing and include approximately 95% of the disposal water. Only the rest of the 5 % are amenable. As precipitation is absorbed by the surface it fills the pore spaces, loosening pyroclastic particles and driving them apart. Subsequent water action additionally splashes the particles and included them into water-laid transport and slope movements. Pyroclastic rocks in general are of low compressibility (approximately 35 MPa). A mass amount of water that flows away from the highest points depends on the slope, the height from which this movement starts, and finally, on the depth of the channels. This can be expressed by the following formula [17].

$$V = \sqrt{2gh} \quad (2)$$

where "g" is 9. 81 m/s^2, h is the altitude. The final formula for water acceleration on the erosive plate is defined as,

$$V = 4,43\sqrt{Il} \quad (3)$$

Where "I" is an inclination angle of the terrain, " l " is the length of the channels (gullies).

In the Devil's City there are two major watersheds and more than 11 micro gullies. Along these micro gullies a linear, or rill erosion takes place. The action of runoff water through these gullies tends to separate and then isolate pyramids and enables their growing. This further accelerates the overall process. The depths of more extensive gullies are given in table 3. These values were also obtained using the performed digitized topographic map (Zhu and Lin, 2009).

Tab. 3. Depths of gullies in centimetres.

1	2	3	4	5	6	7	8	9	10	11
28cm	38cm	50cm	56cm	35cm	21cm	24cm	35cm	45cm	61cm	25cm

Their main characteristics were calculated using the arithmetic mean values.

$$A = \frac{1}{n}\sum_{i=1}^{n} a_i \quad (4)$$

Thus the average depth of gullies is A=38 cm. The digitized lengths of these gullies were also obtained and presented in the table 4. It should be noted that their names are local names.

Tab. 4. Lengths of gullies included into the Devil's City stream network.

Gully of Hell	412,8 m
Gully of Devil	222,7 m
Big gully	441,0 m
Black gully	429,1 m
Little gully	341,0 m
Gully height	875,5 m
Bad creek	377,9 m
Yellow creek	6169,1 m

In an attempt to confirm the obtained parameter of the calculated acceleration of water erosion in the Devil City, we have performed a calculation based on the Shezi constant number. The depth of the gullies and of the average inclination angle of the terrain was calculated using the following formula:

$$V = c\sqrt{RI} \quad (5)$$

where c is the Shezi coefficient and has the next oblique $C = \frac{87}{\frac{1+\frac{\gamma}{R}}{R}}$ = const. (6)

The obtained average relief parameters when the Shezi coefficient is ≈ 6.0 cm/s are: R=20 mm, I=50 %, γ=2. The average depth of the gullies R, in the Devil's City is 38 cm, the inclination angle I is 56.12 %, and the friction, γ is only 2. Finally, the water acceleration in the Devil's City is 9.76 m/s suggesting its destructive character. The used parameters for the erosive power of water in the Devil's City ($h = I \cdot l$) are: h-altitude of slope and length of slope, l. Finally, we used formula (3) and we got the erosive power [18].

5. Conclusion

Erosion phenomena are both aerial and linear character, and consist mainly of the downslope transport of loose pyroclastic deposits. Linear erosion with a geological background has to be good tools for enplaning some phenomena and some processes. Area of Devil's city presents a potential good example for destroying factor in nature. Linear and wind erosion done this landscape like natural wonder. Investigations before not give final scientific results in this area. With investigations in geomorphological, hydrological, climatological, lithological, geological and geographical area, we have better knowledge of this area. The site is placed under state protection in 1959, and in 2013 is protected like special Nature monument in Serbia. The site was in 2008 nominated for the Seven World Wonders of nature. If this erosion continues, and reflect on the pyramid itself, the process of fully informed destruction pyramids will last about 10,000 years ago. Andesite rocker caps are missing their entire system would significantly speed up the disappearance of the pyramid and shorten their lives on this topic erosion of 100-200 years.

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