Geomechanical and hydrogeological characterization of fracture systems in Banyoles Karst caprock units, Catalunya

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ABSTRACT: Banyoles karst systems, located in NE Catalonia, is tectonically controlled, and associated to an artesian aquifer. This karst system is formed at the surface by a cap layer of competitive marls and calcareous rocks above a highly dissolving thick unit of gypsum with depth larger than 20 m. The voids left by upward water flow of the artesian aquifer generates sinkholes at the surface. First, we analyzed aerial photographs to describe the latest karst activity from 1945 up to the present. Secondly, we performed eighteen scanline surveys to describe the cap-rock structure (Jv and RQD) and describe hydraulic aperture and transmissivity (a_c, T_f) of each joint set.
In the cap rock units, we found up to 7 fracture systems that define medium-large block size. Two fractures have the highest T_f values, order of magnitude between 10^{-1} and 10^{-3}, critical for the generation of collapses where the gypsum unit is shallow.

Keywords: hypogenic karst, cap-rock units, unitary block size, hydraulic aperture, transmissivity, Banyoles Lake.

1 GENERAL LAYOUT

In the same way as human-made underground excavations, the roof failure of caprock sinkholes is controlled by the discontinuities, their conditions, and the water inflow into them. The progressive roof failure of non-karstic units is upward until they reach the surface and causes instant or progressive subsidence (Waltham et al. 2004 and Whaltman & Fookes 2005). Therefore, in the same way as in tunnel exploration, it is important to characterize joint set orientation, the size of the loose blocks, to check for highly fractured zones, and to know discontinuity conditions for water flow and to determine the stability of the caprock units to evaluate collapse susceptibility. This study intents to geomechanically characterize the caprock units of Banyoles karst system. The study focuses on the vicinity of the sinkholes that generates the lake to evaluate potential susceptible areas through 1) the study of the historical activity (1945-2022) and 2) through geomechanical outcrop surveys of caprock units (Brady & Brown 1985) to characterize block size and mechanical aperture (ISRM 1978) for 3) to calculate hydrological characteristics of discontinuities (Singhal & Gupta 1999). The results intent to characterize how family joints define the unitary block size that collapse and how their conditions control flux of water.

2 GEOLOGICAL AND HIDROGEOLOGICAL CONTEXT

The study area corresponds to the N–S-oriented Banyoles Lake (BL) valley (Figure 1). In this site confluence two tectonic domains: the Alpine orogenic compressional phase (Late Cretaceous-Miocene) and the Neogene post-orogenic extensional phase (Late Miocene-present day), characterized by the development of down-to-the-east, NNWSSE-trending normal faults superimposed on the previous compressive structures.

The BL valley locates at the Ebro Cenozoic Basin, on the footwall of both the Vallfogona Thrust, N of the study area, and the Camós-Celrà Fault (Figure 2). At the area, the following units can be differentiated in stratigraphic ascending order: the Late Paleocene- Early Eocene carbonate unit of Girona Fm that do not outcrop at the area and contains the artesian aquifer unit that originates the karst. The Early-Middle Eocene age, Beuda Fm., ELgb, consists of white and crudely bedded Ca-sulphates, gypsum/anhydrite, with interbedded bluish marls and limestones. This is the karst formation responsible for the development of sinkholes in the area. The karst cap-rock units above Beuda Fm. are composed by Middle Eocene formations: Banyoles Fm., ELb1; the Bracons Fm, ELb2; and Bellmunt Fm., ELb3, that form a thick detrital sequence. At the top of these units, the Folguerolas Fm, EBp3, shows despositional intertidal facies. At the BL, these Eocene units are in tectonic contact with younger detritical Pliocene sediments of the Empordà Neogene basin through the Camós-Celrà normal faults and covered by Pleistocene-Holocene deposits (IGC 1996).

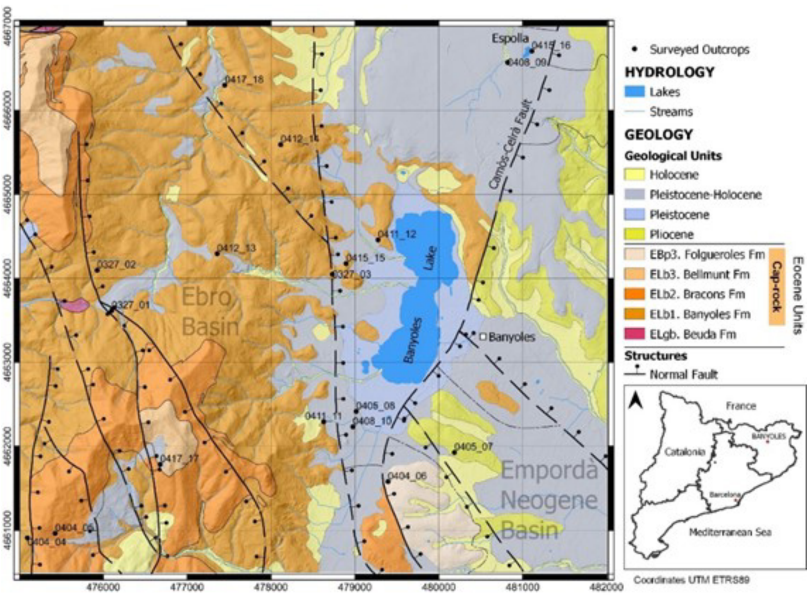

Figure 1. Schematic geological map of Banyoles Lake (BL) valley from IGC (1996).

The BL is part of the Garrotxa-Banyoles karst aquifer system (Figure 2). The recharge area locates at the Garrotxa carbonate massif (1200 m a.s.l.) north of the Fluvia River basin (1000 m a.s.l.) where most of the surface water infiltrates in bedrock outcrops and sinking streams (Vidal 1954). Groundwater flows downwards through a stack of thrust sheets and duplexes dominated by limestone formations, goes deeper through Vallfogona Thrust, and incorporates into the limestones of Girona Fm. At the Fluvia River area, this deep carbonate aquifer is confined by a thick aquiclude of evaporites and turbidites (Carrillo et al. 2014), that quickly wedges out to the south. Gutierrez et al. (2019) dismissed the Fluvia River as a drainage connected with the Garrotxa-Banyoles aquifer system and proposed its main discharge zone further south where BL is located (175 m a.s.l) and the Girona limestone is overlayed directly by the evaporitic unit. Here, the aquifer is confined in most of the area by thick impervious marls (Banyoles Fm.) and the Camós-Cerlà Fault controls its eastern boundary. The permanent BL is fed at several points in its bottom by artesian springs. The upward groundwater flow from the lower confined aquifer traverses the upper gypsum unit, causing its karstification and the development of caprock collapse sinkholes.

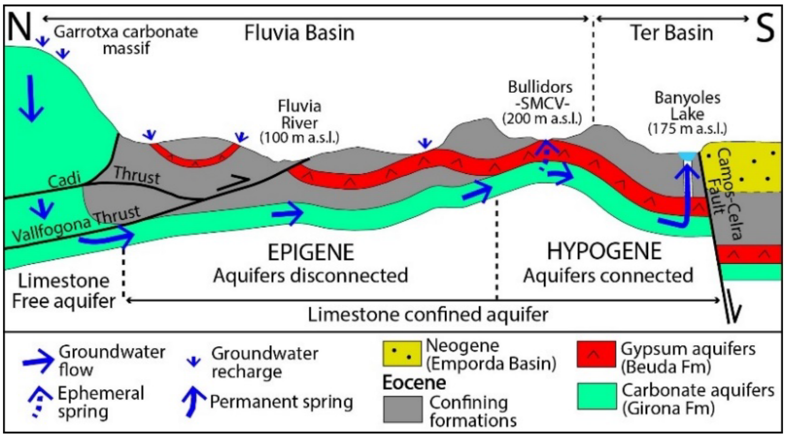

Figure 2. Schematic map of Banyoles artesian aquifer (modified from Gutierrez et al. 2019).

3 METHODOLOGY

3.1 Sinkhole evolution 1945 - 2022

A depressions map was produced through the interpretation of aerial photographs since 1945. We reviewed historical aerial photographs, detailed topographic maps, scale 1:5000 and shaded relieve from the Institut Cartogràfic i Geològic de Catalunya which were available through the Open ICGC v.1.1.8 tool (2022). Orthophotos series used in the analysis were: 1945, 1956, 1970, 1994, 2010, 2022. Local people, local publications (Abellán & Campos 2008), geotechnical and scientific reports (Brusi et al. 1987) also provided useful information on the spatial and temporal distribution of sinkholes. Then, a field survey was conducted to check and examine the preliminary mapped sinkholes.

3.2 Geomechanical rock mass structure and discontinuity transmissivity

We characterized the nature and distribution of structural features for the cap-rock units of Banyoles karst and define how many joint sets define the rock structure. For each joint set we define orientation (dip and dip direction) and surface characteristics such as spacing, persistence, curvature, roughness JRC, infilling, aperture, and water infiltration. For collecting the data, we followed the scanline methodology as explained in Brady & Brown (1985), and the characteristic of the joint sets described accordingly ISRM methods (1978).

For each outcrop in the field, corresponding to different cap rock units, we calculated the unitary block (Jv) size and Rock Quality Designation (RQD) by using equations 1 and 2 (ISRM 1978).

$$Jv = N_{f1}/L + N_{f2}/L + \ldots + N_{fn}/L \quad (1)$$

$$RQD = 115 - 3.3Jv \quad \text{for } Jv = 4.5$$
$$RQD = 100 \quad \text{for } Jv \geq 4.5 \quad (2)$$

Where N_{f1}, N_{f1}, N_{f3} is the number of fractures per joint set and L is the length of the sampling scanline. Classification of block size is given by ISRM (1978) classification.

Hydraulic aperture for each discontinuity set, a_c, and transmissivity, T_f as a volume, were calculated by identifying mechanical aperture, a_r, and Joint Roughness Coefficient, JRC. to evaluate both parameters accordingly to the equations 3 and 4, as explained by Singhal & Gupta (1999).

$$a_c = a_r^{\,2} / JRC^{2.5} \quad (3)$$

$$T_f < \approx a_c^3 \quad (4)$$

For selecting mechanical aperture and JRC, we generated for each joint set a histogram to define minimum, maximum, and modal values of a_r and JRC. Having the range of a_r values for each discontinuity and knowing the most frequent JRC interval, we calculate a range of a_c and T_f. Since the JRC was characterized in the field within an interval, from the roughness visual scale, then the maximum value of this interval was used. For example, if the JRC most frequent value was the interval (4-6) we used the largest value of JRC=6.

4 RESULTS

4.1 Sinkhole evolution

The karst activity has been manifested through generation of flooded depressions, mostly nested within or contiguous to former depressions which have changed the Banyoles Lake shore since 1945, (Figure 3).

The entire reviewed period was subdivided in shorter periods between 11-15 years depending in the availability of aerial photographs, except for the 1970-1994 subperiod (Figure 3). The subperiod between 1994-2010 shows the largest generation of terrain surface depressions with an area of about 6.8 ha.

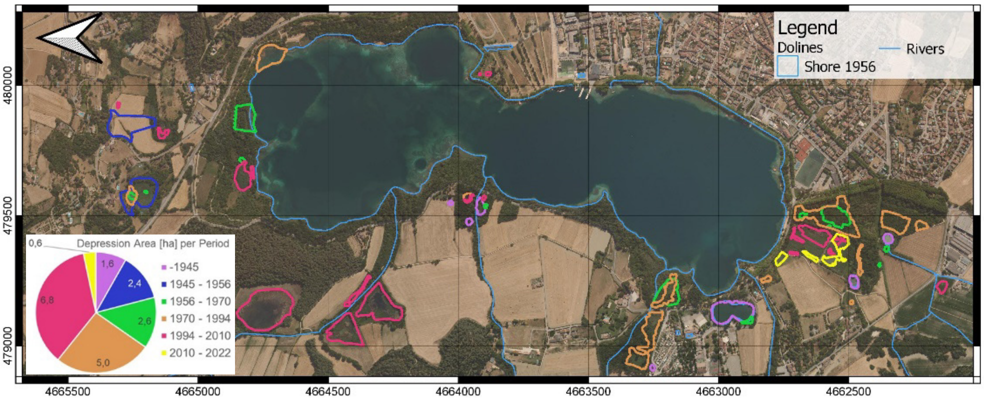

Figure 3. Sinkhole evolution 1945-2022. Pie chart shows the depression area in hectares for each reviewed sub-period.

4.2 Joint sets and rock structure

We performed 17 scanline surveys at cap rock units' outcrops. The examined geological unit and their location is shown in Figure 1. For each outcrop, discontinuities were grouped in different discontinuity sets according to their orientation, Table 1. We identified between three and four joint sets at each outcrop. Once each set was defined by orientation, we calculated the Jv and RQD for each scanline (Table 1). In general, Jv values range between 1 to 10 [joints/m^3] defining blocks of size Medium to Large (ISRM 1978). With the values of Jv we calculated the RQD index which always ranges in values close to 100% denoting Good to Excellent quality.

4.3 Hydraulic aperture and transmissivity

Reviewing the data from all 17 outcrops (n=399) we defined seven joint sets for the caprock units of BL. Table 2 shows the characteristics of each joint set. Spacing minim values in all joint sets are always closed to zero, < 0.1 m. In general, the maximum spacing ranges between 3 and 8 m. The most frequent persistence in all joint families is always less than 1 m. Maximum values of persistence range between 1.5 and 3 m. JRC values are very disperse. The largest values of a_r range between a value of zero, Closed, and a maximum of about 8 cm, Wide.

Table 1. Orientation of joint families, Jv and RQD for each surveyed scanline.

Crop ID	Formation	Dip/Dip Direction [°]				Jv [joints/m^3]	RQD [%]
0327_01	ELb1	276/80	010/76	233/79		2.7	100
0327_02	ELb1	228/72	155/75			3.9	100
0327_03	ELb1	219/78	107/82			3.2	100
0404_04	ELb1	079/75	124/60			4	100
0404_05	ELb2	158/86	079/85			4.6	100
0405_06	Ebp3	283/81	180/84	253/52		2.8	100
0405_07	NPRa	137/85	270/88	195/87		2.6	100
0408_08	Qtle	217/86	082/87	140/83	185/86	3.7	100
0408_09	Qclu	148/74	208/80	116/86	266/83	2.0	100
0411_11	ELb1	355/69	108/87	072/84		3.3	100
0412_12	ELb1	264/69	167/75			8.3	87.5
0412_13	ELb	252/77	180/88			6.8	95.5
0415_14	ELb1	114/59	081/06	049/83		5.4	97.3
0415_15	ELb1	090/80	223/78	307/80		4.0	100
0417_16	Qclu	045/86	317/76			4.0	100
0417_17	ELb3	019/85	296/85	073/88		1.7	100
0417_18	ELb1	204/84	072/63	135/46	012/70	2.1	100

Table 2. Geomechanical conditions for each fracture set and calculated hydraulic parameters, a_c and T_f.

Joint set	n Dip/Dip Direction [°]	Spacing min/max/sd class [m]	Persistence min/max/sd class [m]	JRC modal class	a_r min/max/sd class [cm]	a_c min max [cm]	T_f min max [cm3]
F1	78 272/90	02/5.0/1.1 Moderate	0/1.9/0.4 Very Low	6-8	0/5/0.8 Closed	0 1.38x10-1	0 2.63x10-3
F2	38 302/90	0.1/3.43/0.88 Closed	0/1.84/0.4 Very Low	16-18	0/5/02 Closed	0 1.8x10-2	0 6.02x10-6
F3	42 177/87	0/7.15/1.93 Moderate	0.1/2.1/0.6 Very Low	16-18	0/5/0.1 Closed	0 1.8x10-2	0 6.02x10-6
F4	80 217/87	0/8.1/1.71 Moderate	0.1/3/0.6 Very Low	12-14	0/4/0.2 Closed	0 2.2x10-2	0 1.04x10-5
F5	28 164/85	0.1/4.53/1.34 Wide	0/1.5/0.4 Very Low	2-4	0/5/0.3 Closed	0 7.8x10-1	0 4.77x10-1
F6	73 253/83	0/6.3/1.34 Closed	0.1/1.9/0.5 Very Low	8-10	0/8/0.2 Parcially open	0 2x10-1	0 8.29x10-3
F7	60 147/88	05/5.66/1.5 Closed	0/2.1/0.5 Very Low	4-6	0/8/0.1 Closed	0 7.3 x10-1	0 3.82x10-1
sd: standard deviation							

The families with the largest a_r values are F6 and F7. In this way, hydraulic aperture, a_c, according to Equation 2, shows minimum values of zero and the maximum values are of the order of 10^{-1} cm in F1, F5, F6, and F7. Calculated T_f shows that the largest values of transmissivity belong to joint sets F5 and F7 of the order of 10^{-1}.

5 CONCLUSIONS

Banyoles Lake karst has been formed by the coalescence of multiple sinkholes. The formation activity has been characterized between 1945-2022. The reviewed spatio-temporal evolution of karstic activity indicates that the lake may be expanding, especially in the northern and southern ends parallel to the trace of the major faults. Borehole correlations made by Fabregat (2013) have established the thickness of the caprock units above the gypsum which varies between 80 m and 19 m at western and northern shores of the lake, respectively. This coincides with two sites where we detected most of the historical activity.

The caprock units have Excellent quality given the high values of RQD close to 100%. The unitary block size, Jv, resulted medium size-large according to ISRM classification (1978). Depth to the gypsum unit and area of generated surface depressions give and idea of the block distribution and volume to be mobilized in case of collapse/subsidence at once. Even though, the predominance of short persistence 1 m and predominance of high JRC, above 8-10, make the caprock blocks more interlocked and do not mobilize easily. The families F5 and F7 have the largest T_f and the lowest JRC values. These two joint sets have orientations ENE-WSW almost perpendicular to the Camós-Celrà Fault trace and they might facilitate the water percolation from surface and the water flowing from below during dissolution of this hypogenic karst system at the northern, southern, and western shorelines of BL.

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