Carbonates and Evaporites (2024) 39:69
https://doi.org/10.1007/s13146-024-00981-2

ORIGINAL ARTICLE

Hydrogeological and speleological characterization of a karstic spring: the Cokragan cave system

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Accepted: 19 May 2024

Abstract
Karstic landscapes, shaped by water dissolving rocks, are unique ecosystems with complex water systems. Karst aquifers, vital for over 25% of the world's drinking water, offer a sustainable resource but are vulnerable, such as pollution and over-extraction. Therefore, it's important to understand the potential and capacity of karst springs in areas suffering from water shortages. Hydrogeological and speleological studies are crucial for understanding the unique characteristics of karst springs. Moreover, epiphreatic caves located near the water table at the interface between vadose and phreatic zones in karst landscapes, hold valuable information about past geological events. By identifying their former presence and location in uplifted limestone regions, we can reveal phases of uplift, lowering of the base level, and the rate of vertical karst development. Consequently, epiphreatic caves and associated karst processes are of considerable interest for understanding past geological changes. Here, we present an integrated study of a spring in the epiphreatic Cokragan Cave, which is an important water resource for the Uşak region, using both speleology and hydrogeology. The complex Cokragan Cave system, stretching over 2050 m, reveals multiple past groundwater levels through its geometry, with elevation differences suggesting tectonic influence. Between 2003 and 2007, Cokragan spring discharged an average of 63.5 million m^3/yr, while recharge averaged 62.37 million m^3/yr. Measured discharge ranged from a maximum of 1.488 m^3/s to a minimum of 0.108 m^3/yr. In-situ measurements and analysis of 13 samples revealed the groundwater's physicochemical characteristics, including major ions such as calcium, magnesium, and bicarbonate, and trace elements such as arsenic, boron, iron, manganese, and zinc.

Keywords Cave · Groundwater flow · Geochemistry · Karst · Speleology

Introduction

Water is vitally important for humanity to survive. However, in developing countries like Turkey, issues like overpopulation, unplanned urbanization, and industrialization have redefined the concept of "water." Simply saying "water" is no longer sufficient, requiring qualifiers like "fresh" and "usable" to indicate its safety for consumption (Moe and Rheingans 2006).

Climate change and its impacts have become prominent topics in recent decades. Managing water supplies against these negative effects is a top priority on both national and international agendas. The United Nations defined the theme of studies conducted between 2005 and 2015 as "water for life" (Hiwasaki 2011). Moreover, understanding hydrological changes in the Mediterranean region is especially important as models produced by the Intergovernmental Panel on Climate Change (IPCC) predict droughts in the next 30 years for other countries in the Eastern Mediterranean Basin, including Turkey (Collins et al. 2013). Effective water management begins with active protection. Accurately defining and evaluating the physical characteristics (geological parameters such as lithology, structure, and topography) and hydrodynamic features (precipitation, infiltration, recharge, and circulation) of water systems is crucial. Understanding these factors is essential for creating a robust protection and management model for both water quantity

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and quality within the framework of a conceptual hydrogeological model (Aydın and Ekmekçi 2005).

Karst landscapes hold significant value for four key reasons. First, as highlighted by UNESCO (Aureli, 2010), they act as one of the most crucial and secure sources of drinking water globally. Karst aquifers currently supply roughly 25% of the world's drinking water needs (Ford and Williams 2007). Second, karst landscapes contain a rich tapestry of plant, animal, and geological features that significantly contribute to the health of our planet's ecosystem (Li et al. 2021). Third, nearly half (49%) of European geoparks contain karst formations, underscoring their importance in geoheritage and geotourism (Telbisz and Mari 2020). Finally, karstic caves play a crucial role in our understanding of these landscapes (Ünal-İmer et al. 2015; Jacobson et al. 2021; Fleitmann et al. 2008). Not only do they allow for direct measurements, but they also offer unique insights into the formation and history of karst systems (Sheffer et al. 2011; Palmer 2020).

Epiphreatic caves, such as the studied Cokragan Cave, hold significant information about past geological events. Located near the water table at the interface between the vadose and phreatic zones in karst landscapes, these caves can reveal phases of uplift, lowering of the base level, and the rate of vertical karst development by identifying their former presence and location in uplifted limestone regions. This study is the first from Turkey that will investigate such links between hydrogeology, tectonics, and cave formation.

Study area and geological setting

Karstic terrain covers a third of Turkey's territory, encompassing numerous large and small springs. Karstic aquifers contribute roughly 33% of the overall water potential within Turkish surface hydrological basins (Baran et al. 1995). The Cokragan Karstic Spring, despite the region's low water potential, stands out due to its significant flow volume. The spring is located near the village of Y. Karacahisar, in the Banaz district of Uşak province, situated in the inner-western Anatolian Region of Turkey (Fig. 1). The Cokragan Spring emerges from a karstic opening known as Cokragan Cave. This cave, formed in Jurassic-aged and recrystallized

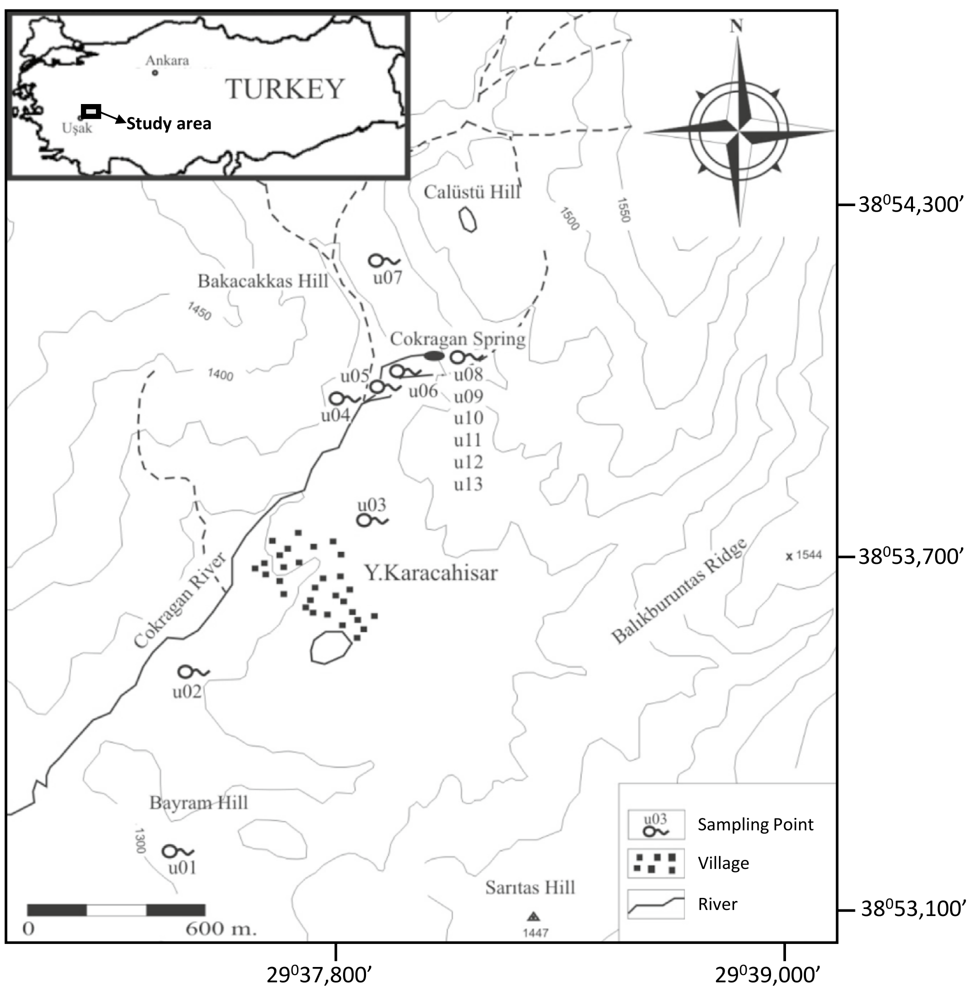

Fig. 1 The study area and the locations of the water samples

limestone, is located on Calustu Hill (1520 m) and has a total measured length of 2050 m.

The rocks in this area are composed of regional metamorphics, sedimentary rocks of the Tertiary age, ultrabasic rocks, andesite, and silicified rocks. The regional metamorphics contain sandstone, schist, green schist, schistose limestone, and recrystallized limestone (Mariko 1970, Fig. 2). The sediments of the Tertiary age, consisting of conglomerate, volcanic conglomerate, basic tuff, and sandstone, are confined to the south-eastern part of the area, where they cover the unconformable regional metamorphics and the ultrabasic rocks. It is estimated that these sedimentary rocks are of early Tertiary (Palaeogene) age because the effects of diagenesis, such as compaction and consolidation, are much more noticeable in them than in Neogene rocks, which are widely distributed throughout the south of this area.

Recrystallized limestone, which hosts Cokragan Cave, is found on Calustu Hill. Generally, recrystallized limestone is grey-white, its structure has a massif, and it is 10–20 cm thick, but it is rarely layered. The limestones have small grain shale, sandstone, and chert bands. Massif recrystallized limestones have solution structures, cavities, and fissures. Lower layers of the limestones have lateral and vertical transitive metasediments (Fig. 3).

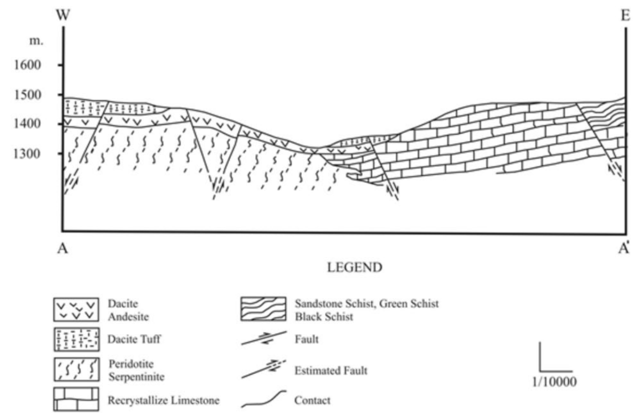

Fig. 3 A geological cross-section of the study area (© adapted from Mariko 1970)

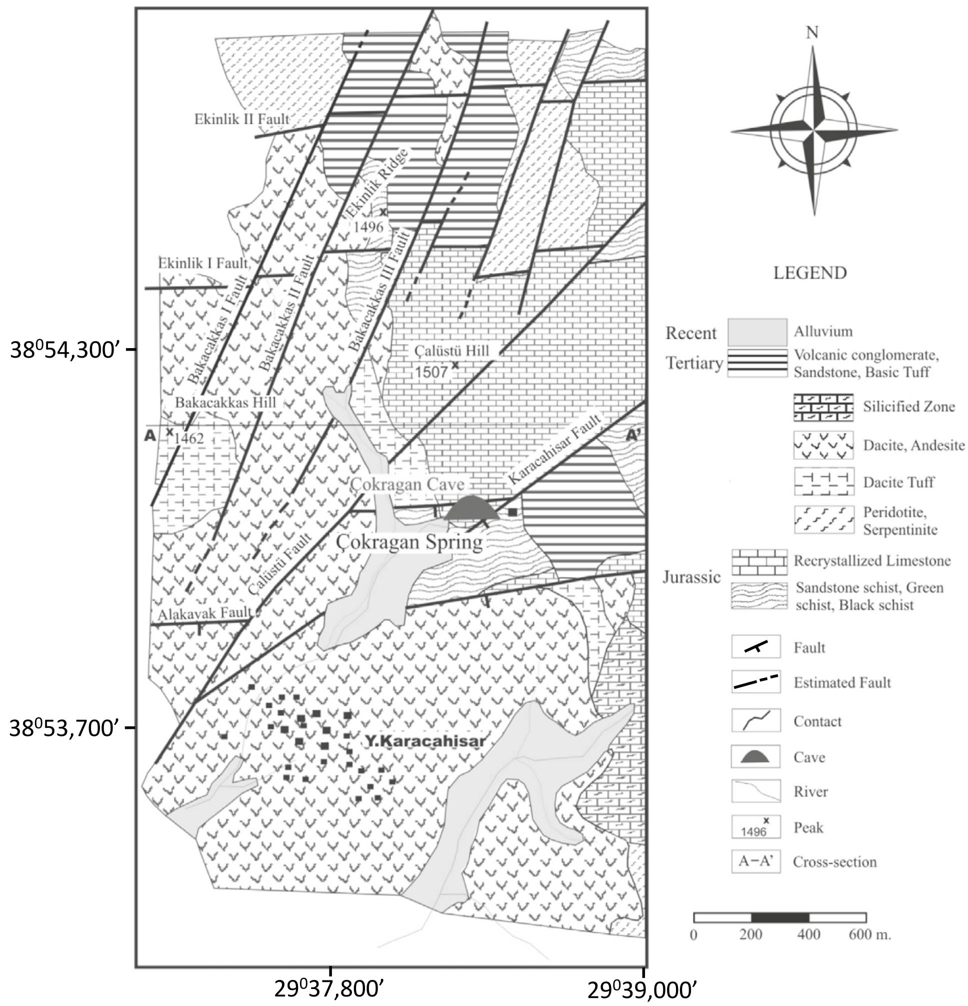

Fig. 2 Geology map of the Cokragan Spring (© adapted from Mariko 1970)

Methods

In this study, water samples were collected from the Cokragan Karstic Spring and the surrounding area to determine their hydrogeochemical characteristics. The collected water samples were analyzed at the ACME laboratory, according to APHA standards. The pH, EC, salinity, and temperature values of the water samples were measured in the field. The analyzed water samples were evaluated and interpreted using Aquachem (Calmbach 1997), Hydrowin (Calmbach 1995), and Excel.

Using the discharge data of Cokragan Karstic Spring (with at least one discharge measurement per month between February 14, 2002, and February 16, 2007) obtained from the DSI (General Directorate of State Hydraulic Works), the total amount of water discharged from the spring during each year was calculated. Then, the discharge coefficient for each dry period was determined separately using the 'Maillet Formula' (Maillet 1905) and the arithmetic average was calculated, shown in the Hydrology section. Using the discharge coefficient, the dynamic reserves of the spring at the end of each period of successive years were calculated using the formula $V(t) = Q(t)/\alpha$, and the change in dynamic reserve was determined from the difference between these reserves. By adding the change in dynamic reserve to the total amount of water discharged from the spring during each year, the amount of recharge entering the reservoir for that year was determined.

Cokragan Cave was investigated and mapped by the Dokuz Eylül University Speleological Research Society. The changes in groundwater levels caused by these movements were investigated by examining observations made inside the cave and the cave map plan and profile drawings. A steel tape measure and disto, compass and inclinometer were used to measure the cave map. The obtained measurements were entered into the 'Onstation' program (White 2019) and the map was drawn.

Results and discussion

The Cokragan Karstic Spring is placed in the UŞAK K23-a2 topographic map at 35 S 0728593/4309331 UTM coordinates and formed at the intersection point of the Karacahisar Fault and the Calustu Fault (Fig. 2). The recrystallized limestone that was formed in Calustu Hill is highly karstified, and it has in aquifer characteristics. The Cokragan Karstic Spring that emerges at an elevation of 1740 m is an important drinking water supply for the region and has been coming out from three other closer points in Cokragan Cave (Fig. 4).

Fig. 4 Underground Lake (1), underground river (2), and a view from vadose zone (3)

Although the points are very close to each other, their hydrogeochemical characteristics differ. The water that flows through the three different points is brought together by a catchment built by the DSI. Eventually, the water is conveyed to Uşak city by water pipes.

Hydrology

The analyses of spring hydrograph recession curves offer the possibility to study and define the spring flow regime and to evaluate the groundwater development potential of the spring drainage area. The hydrograph of the Cokragan Spring is obtained by subtracting the monthly flows observed by DSI. The maximum and minimum measured discharge of the spring are 1.488 m^3/s and 0.108 m^3/s, respectively. The discharge data for the spring is given in Table 1. It appears that a general recession starts around May and continues until October.

Groundwater circulation in karstic aquifers is very different to that in non-karstic aquifers. Water in karstic aquifers is gathered by fissures, caves, and channels. The hydraulic permeability of karstic aquifers is determined by the flowing water and anisotropic character (Huntoon 1995). The flow regimes of some large springs discharging from karst aquifer systems can be analyzed using discharge hydrographs. The Maillet (1905) formula, a widely-used exponential equation,

Table 1 Average discharge of the Cokragan Spring according to years (m^3/s)

	Average discharge of the Cokragan Spring (m^3/s)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2002		0.236	0.527	1.328	1.206	0.796	0.424	0.307	0.227	0.185	0.202	0.211
2003	0.289	0.269	0.276	0.481	1.156	0.596	0.395	0.253	0.241	0.193	0.161	0.146
2004	0.176	0.233	0.476	1.019	0.976	0.562	0.420	0.305	0.215	0.181	0.151	0.134
2005	0.146	0.108	0.304	0.208	1.115	0.762	0.466	0.329	0.229	0.172	0.148	0.203
2006	0.157	0.148	0.230	1.067	1.060	0.657	0.391	0.296	0.188	0.198	0.166	0.165
2007	0.149	0.154										

is an example of an analytical solution for porous media (Dewandel et al. 2003). Maillet (1905) proposed that the flow from a spring is related to the amount of water stored in the aquifer (Milanovic 1981; Ford and Williams 2007). Even though the formula was developed for aquifers with grain-like materials, it has also been used for aquifers with cracks and fractures (karst aquifers), which are non-uniform and anisotropic (Bonacci 1993). According to Bonacci (1993), Maillet's formula introduced a valuable tool for understanding recession curves during long dry periods (Aksever et al. 2021). Maillet stated that the discharge of a spring is a function of the water volume held in storage (V_s) (Maillet 1905). This simple exponential relationship (Ford and Williams 1989) describes the discharge as follows:

$$Q_t = Q_0.e^{-\alpha\,(t-to)}$$

where Q_t is the discharge (m^3/s) at time t; Q_0 is the previously measured discharge at time zero; t_o is the time elapsed between Q_t and Q_0; e is the base of the natural logarithm; and α is termed the recession (discharge) coefficient (T^{-1}). The value of the recession coefficient α derives from the hydrogeological characteristics of the aquifer, especially effective porosity and transmissivity. It represents the capability of the aquifer to release water. Analyses of the recession curves offer the possibility to study and define the flow regime of a spring, and to evaluate the groundwater development potential of the spring drainage area. Small values of α indicate a very slow rate of drainage of the aquifer and a large underground storage capacity like in the Cokragan Cave system. Springs emerging from this type of aquifer are mostly perennial. Large values of α indicate a rapid rate of drainage and a small underground storage capacity (Milanovic 1981). The magnitude of α also indicates the maturity of the flow in an aquifer. If the flow of groundwater is primarily through joints and fissures, the order of magnitude of the discharge coefficient α is 10^{-3} day^{-1}, and if the order of magnitude of α is 10^{-2} to 10^{-1} day, the flow is in massive karstic limestone primarily drained through large flow channels (Kranjac 1977) (Fig. 5).

The average recession coefficient (α) of the Cokragan Karstic Spring was detected as 0.0102 day^{-1}. The result shows that the flow of groundwater is primarily via drainage through large channels with a high permeability coefficient and/or low storage coefficient (Fig. 6). As the discharge of the Cokragan Spring changes from wet to dry seasons, it can be concluded that variations in monthly precipitation have an immediate effect on the total discharge of the spring, which is related to mature karstification and groundwater flow. According to average monthly rainfall data from 1963 to 2006, the region exhibits a typical Mediterranean climate, which is characterized by wet winters and dry summers,

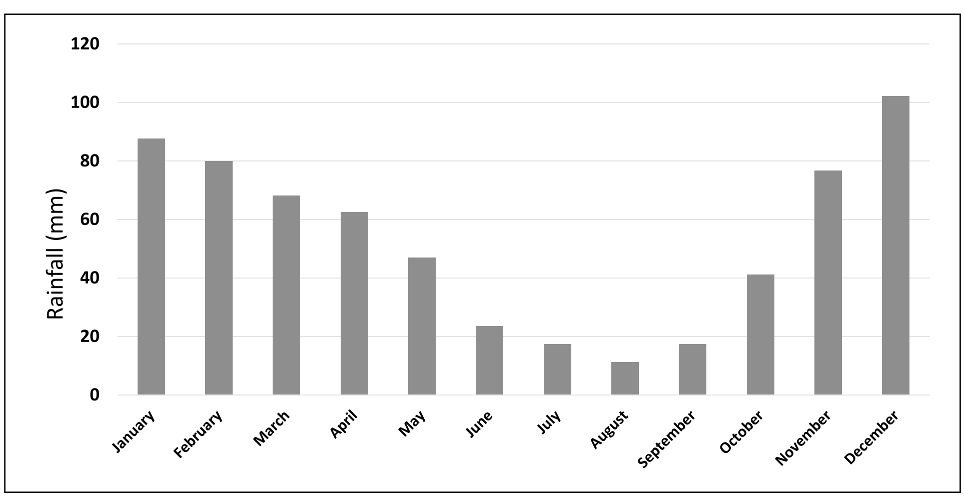

Fig. 5 Average monthly rainfall for the period 1963–2006 (mm) at Uşak Banaz Y. Karacahisar

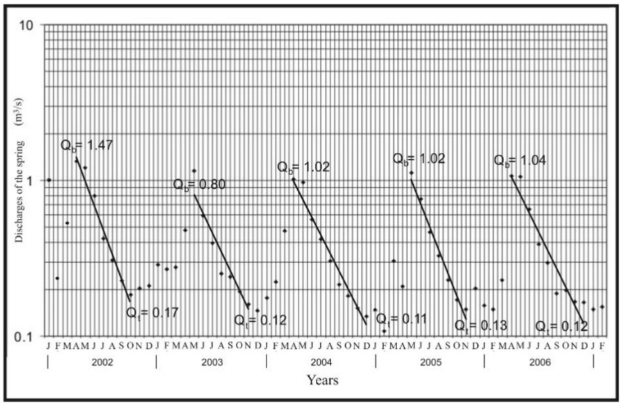

Fig. 6 The recession curves of the Cokragan Spring between 2002–2006

making seasonality of precipitation its defining feature (Fig. 5).

The recession coefficients between 2002 and 2006 are given in Table 2. The recession coefficient values can be different according to seasonal changes, temperature, and precipitation. The mean of the recession coefficient values gives the recession coefficient of the reservoir.

The recharge values between 2003 and 2007are given in Table 3. The negative (−) value of ΔV shows that the water is diminished in the reservoir compared to the former year.

Hydrogeochemistry

13 water samples were collected from the study area for chemical analyses for major ions, hardness, and heavy metal contents by using the methods suggested by APHA et al. (1981). During sampling, in-situ measurements of pH, electrical conductivity (EC), temperature (T), and total dissolved solids (TDS) parameters were taken (Table 4).

There are three dissimilar water sources named Cokragan Main Spring (CMS), Cokragan Side Spring (CSS), and Cokragan Yellow Spring (CYS) coming out of the Cokragan Karstic Spring. The samples U8–U9 (CMS), U10–U11 (CSS), and U12–U13 (CYS) were taken in summer and winter seasons to observe the effects of the circulation. The representation of the chemical composition of spring waters is shown on a Piper and Schoeller diagram (Fig. 7), regardless of the sampling period, emphasizing the homogeneity between sources.

The results of the chemical analysis water samples from the springs in the region (Fig. 1) and Cokragan Karstic Spring (CMS, CSS, CYS) are presented in Table 4. The pH values range from 6.9 to 8.9 across all samples, indicating neutral to weakly alkaline water. Temperatures vary between 5.6 and 25 °C, with the lower values measured at the Cokragan Karstic Spring. Electrical conductivity shows a wider range, spanning from 205 to 1032 µS/cm. Notably, higher conductivity is observed in samples U12–U13, which

Table 2 The recession coefficient values and the average coefficient of the Cokragan Spring according to years

Year	t (day)	Q_b (m^3/s)	Q_s (m^3/s)	R.Coef. (α) (day^{-1})
2002	180	1.47	0.17	0.0120
2003	210	0.80	0.12	0.0090
2004	240	1.02	0.11	0.0093
2005	180	1.02	0.13	0.0115
2006	240	1.04	0.12	0.0090
Mean recession coefficient (αm)				0.0102

Table 3 Recharge and discharge values of the Cokragan Spring

Water year	February Q_{s-1} (m^3/s)	February Q_s (m^3/s)	V_{s-1} (10^6 m^3)	V_s (10^6 m^3)	ΔV (10^6 m^3)	Q_{top} (10^6 m^3/year)	R_{top} (10^6 m^3/year)
2003	0.236	0.269	1.99	2.28	0.29	15.71	16.00
2004	0.269	0.223	2.28	1.89	– 0.39	11.35	10.96
2005	0.223	0.108	1.89	0.92	– 0.97	12.36	11.39
2006	0.108	0.148	0.92	1.25	0.33	11.20	11.53
2007	0.148	0.154	1.25	1.31	0.06	12.43	12.49
Total					– 0.68	63.05	62.37
Mean						12.61	12.47

Qs−1 discharge of the end of the previous water year; Qs discharge of the end of water year; V_{s-1} remained water volume; Vs storage capacity; ΔV dynamic volume; Q_{top} total annual discharge; R_{top} total annual recharge; end of the water year is taken as February

Table 4 Physicochemical characteristics of the groundwater samples

Water samples	Date dd.mm.yy	General parameters				Major cations				Major anions			Trace elements						
		T °C	TDS mg/L	pH	EC µS/cm	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	HCO_3 mg/L	Cl µg/L	SO_4 mg/L	Sr µg/L	Al µg/L	As µg/L	B µg/L	Fe µg/L	Li µg/L	Zn µg/L
U01	31.08.05	25.0	305.0	7.6	479	87.4	14.8	2.2	0.5	241.7	3	78	334.4	49	1.5	< 20	246	0.6	5.5
U02	31.08.05	18.3	124.4	8.4	205	28.5	12.9	1.3	0.4	136.6	2	12	44.5	31	< 0.5	< 20	88	0.4	4.9
U03	31.08.05	20.2	393.8	8.1	543	81.1	31.3	1.3	0.5	138.9	1	210	926.1	25	1.7	< 20	87	1.1	4.2
U04	31.08.05	13.6	812.5	7.7	963	174.1	45.4	1.2	0.5	31.3	1	573	2493.9	34	3.3	< 20	203	1.0	4.6
U05	31.08.05	15.2	842.4	7.5	1032	181.7	47.7	1.8	0.6	60.0	1	579	2408.2	35	1.1	< 20	132	1.7	5.0
U06	31.08.05	19.1	463.3	7.6	698	100.6	40.5	3.3	3.3	305.5	2	165	576.0	65	< 0.5	< 20	135	6.3	3.8
U07	31.08.05	16.2	210.0	8.9	366	4.8	55.5	0.9	0.3	282.1	1	9	15.1	33	< 0.5	< 20	182	0.4	4.8
U08(CMS)	01.07.05	11.0	502.6	6.9	500	89.3	33.9	1.2	0.7	123.9	3	249	1113.5	114	2.6	< 20	282	0.9	20.7
U09(CMS)	08.01.06	5.6	364.3	7.6	463	64.3	23.8	1.1	0.4	173.5	2	111	554.4	55	1.7	< 5	248	0.7	0.4
U10(CSS)	01.07.05	10.0	687.0	7.6	797	125.9	44.9	1.2	0.4	161.7	9	342	1527.6	19	3.4	5	414	1.3	3.0
U11(CSS)	08.01.06	8.9	601.2	7.4	780	111.4	42.8	1.4	0.6	158.1	4	309	1526.5	60	3.0	9	348	1.0	0.4
U12(CYS)	01.07.05	17.0	916.8	6.9	1026	192.7	45.6	2.1	0.7	161.1	20	492	2388.8	15	1.6	9	510	2.2	3.9
U13(CYS)	08.01.06	9.2	848.1	7.2	1028	170.9	47.1	2.0	0.8	161.9	3	468	2234.3	68	1.2	13	394	1.7	0.6

coincides with the fault zone. This suggests increased rock-water interactions (e.g., with shale, ophiolites, and clays) as the groundwater travels through this area.

A Piper and Schoeller diagram are shown in Fig. 7, summarizing major cation and anion concentrations. The change in the chemical composition of the spring water over time is related to the recharge regime, circulation, and storage of the groundwater system. The difference in chemical composition of the Cokragan spring is evaluated as an indicator of the shallow circulation spring, which is affected by the recharge area. Chemical analysis of karst springs reveals that they are suitable for drinking, agriculture, and industrial purposes. In addition, caution should be exercised when using it as drinking water due to its high iron concentration. Water samples were generally characterized as follows: cold (< 20 °C, except sample u2) and fresh (TDS < 1000 mg/L). Additionally, the waters in the study area are generally calcium-magnesium-sulfate-bicarbonate type waters. The carbonate hardness of the springs is higher than 50%, and the source of the dominant Mg, Ca, and HCO_3 ions is related to the dolomitic level of the recrystallized limestone. Major cations (calcium, magnesium, and potassium) exhibit concentrations ranging from 4.8 to 192.7 mg/L, 12.9–47.7 mg/L, and 0.3–3.3 mg/L, respectively. Bicarbonate is the dominant anion, with concentrations between 31.3 and 305.5 mg/L. Higher concentrations indicate increased dissolution of carbonate minerals, consistent with the presence of highly karstified carbonate rocks in the area. In contrast, chloride and sulfate concentrations are typically lower than bicarbonate and likely originate from halite and ophiolite formations within flysch units.

Table 4 also presents the analysis of major trace elements, with a focus on aluminum (Al), arsenic (As), and iron (Fe) due to their potential health or irrigation concerns. Aluminum concentrations typically meet the drinking water quality standard of 200 µg/L (EPA—Center for Disease Control and Prevention 2024), with sample U8 showing the highest concentration of 114 µg/L. Arsenic concentrations typically fall below the EPA's drinking water standard of 10 µg/L. Iron concentrations exhibit a wider range, varying from 87 to 510 µg/L which is below the EPA's drinking water standard. However, it exceeds the EPA's National Secondary Drinking Water Regulations (NSDWRs) of 200 µg/L in samples U1-U4-CMS-CSS-CYS. NSDWRs are established as guidelines to assist public water systems in managing their drinking water for considerations, such as taste, color, and odor. These contaminants are not considered to present a risk to human health. A positive correlation between arsenic and iron suggests the presence of iron oxides and sulfide minerals in the sedimentary rocks. Other elements like boron, lithium, and zinc all meet drinking water quality criteria (EPA). Boron, particularly important for irrigation, remains below the critical value of 700 µg/L (Ayers

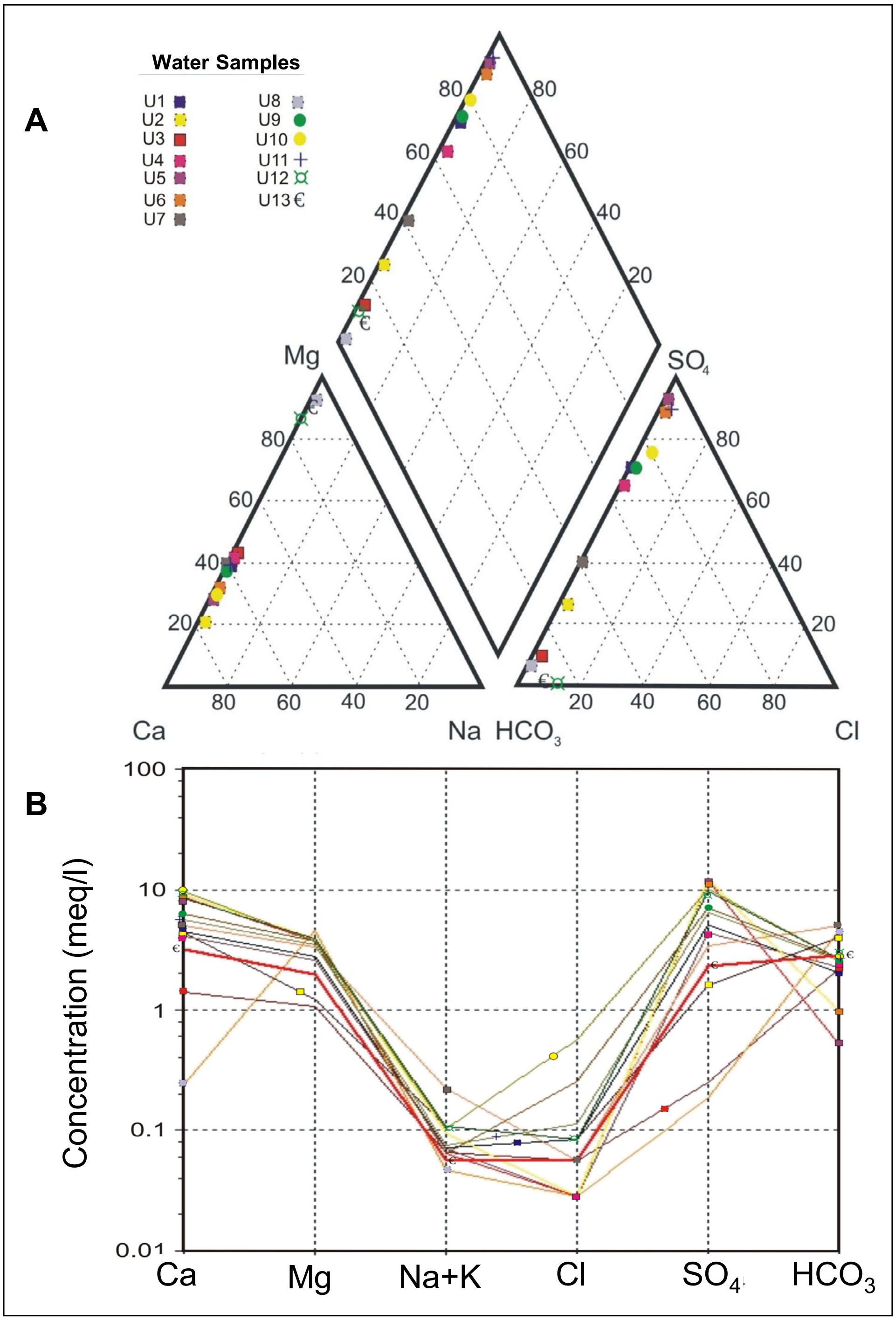

Fig. 7 Piper diagram (**A**) and Schoeller diagram (**B**) of the water samples

and Westcot 1985) in all samples. Zinc concentrations, presented in Table 4, also comply with the 5 mg/L drinking water quality standard. The change in the chemical composition of the spring water over time is related to the recharge regime, circulation, and storage of the groundwater system. The difference in chemical composition of the Cokragan spring is evaluated as an indicator of the shallow circulation spring, which is affected by the recharge area. Close monitoring of trace elements, especially iron concentrations, is important due to drinking water standards.

Speleology

The fractures resulting from tectonic forces play a crucial role in shaping cave systems (Ford and Ewers 1978; Palmer 1991; Klimchouk and Ford 2000; Tognini and Bini 2001; Faulkner 2006; Sauro et al. 2013; Becker et al. 2006). Although Turkey is a region teeming with both geologic movement and cave formations, the intimate relationship between these two phenomena has yet to be comprehensively examined (Akgöz and Eren 2015; Yamac et al. 2021; Kuzucuoğlu et al. 2019). Focusing on the Cokragan Cave system, this paper dissects the structural controls on cave passage morphology and assesses the impact of neotectonic processes on the overall cave pattern.

The Cokragan Cave is found at the exit point of the Cokragan Spring, and it is a multi-layer cave that has been developed over different periods of time. It is formed in recrystallized limestones, which were found in Calustu Hill and developed along the Karacahisar Fault. The cave has three layers. The third layer is in the phereatic zone and the current level. The first two levels are found in vadose zone because of the water level drop-offs. It can be concluded that these drop-offs reflect the three periods of faulting that occurred in the region that Mariko (1970) mentioned because the geometry of the longitudinal and cross-profiles of the caves characterize the karstic base-level changes (Fig. 8), litho-stratigraphic features, and tectonic movements (Ford and Cullingford 1978; Nazik 1989).

The Cokragan Cave was formed in recrystalline limestone, which was found on Calüstü Hill. The cave has complex passages due to limestone thickness and is bounded by impermeable sandstone schist units. Aggressive waters in the impermeable base accelerated the corrosion, and Cokragan Cave has become a complex cave system. The total length of Cokragan Cave is 2050 m, and the deepest point is 37 m based on the entrance, which was surveyed by the Dokuz Eylul University Cave Research Club (Fig. 9).

The morphology of caves, preserved much longer than surface features, allows us to reconstruct the regional history of the surrounding landscape (Audra and Palmer 2011). Cave profiles and levels reflect past base level positions (the level at which groundwater exits the aquifer) and their changes. Factors like timing, geological structure, and water recharge influence the cave profile. Phreatic passages develop below the local water table and evolve into large tubes near this level. When the base level remains stable for a long time, cave systems become intricate networks of epiphreatic tubes just above spring discharge points (Palmer 1991). During periods of tectonic stability or slow uplift, these passages can transform into low-gradient canyons filled with sediments. The zone of water table fluctuation, known as the ‘‘epiphreatic zone’’ or ‘‘floodwater zone,’’ plays a crucial role in this stage. Evidence suggests Cokragan Cave passages formed within the water table fluctuation zone, exhibiting characteristics of high-flow phreatic conduits (Fig. 8). As the regional base level dropped due to tectonic activity of The Calüstü Fault and the Karacahisar Fault, the Cokragan Karst Spring was forced to lower elevations. This drop in the water table compelled the cave passages feeding the spring to migrate downwards. In a multi-layer cave, connection with shafts indicates that the cave is keeping in step with the tectonic and geomorphologic rejuvenation of the area (Nazik 1993). The connection of the second level to the third level with shafts denotes that there is a tectonic and geomorphologic rejuvenation between these levels by tectonic movements (Piccini et al. 2003). Consequently, the highest passages represent the oldest phases of development, and the lowest represent the youngest.

The Cokragan Cave pattern is heavily influenced by tectonic features, primarily faults, and associated fractures that formed or reactivated during the late Miocene extension (Mariko 1970). These “tectonic inceptions” guided the flow of corrosive water under both phreatic and vadose conditions, sculpting passages along faults and, in some cases, bedding joints. Interestingly, younger neotectonic features have minimal impact on cave morphology, causing only minor displacements and fractures. The Cokragan Cave system has three distinct (Fig. 8) levels: Level 3: The youngest, and active passages, developing under both phreatic and epiphreatic conditions. Level 2: Inactive middle passages, formed under phreatic conditions water table cave theory (Ford and Williams 2007), with an upper section developing under epiphreatic conditions. Level 1 is the oldest, and inactive channels likely formed the water table cave theory (Ford and Williams 2007).

Cross-sections from the map of Cokragan Cave (Fig. 9) were observed to determine the geomorphological phases. During the observations, the geometry of the cavities was taken into consideration; hence, the drawings are exaggerated and schematic (Fig. 10).

The Cokragan Cave morphology is caused by a lowering of the local base level (negative shift of the Cokragan spring). This process led to old level dry and elevated as elevated cave terraces at the gorge edges. Additionally, the opening of new pools upstream led to shafts between levels due to the backward movement of water and the formation of a lower, active level.

A ‘‘cave level’’ refers to a set of passages confined to a specific vertical range, typically corresponding to past or present base levels. Rapid streambed deepening disrupts cave development, while periods of slower deepening allow passages to develop larger cross-sections, forming

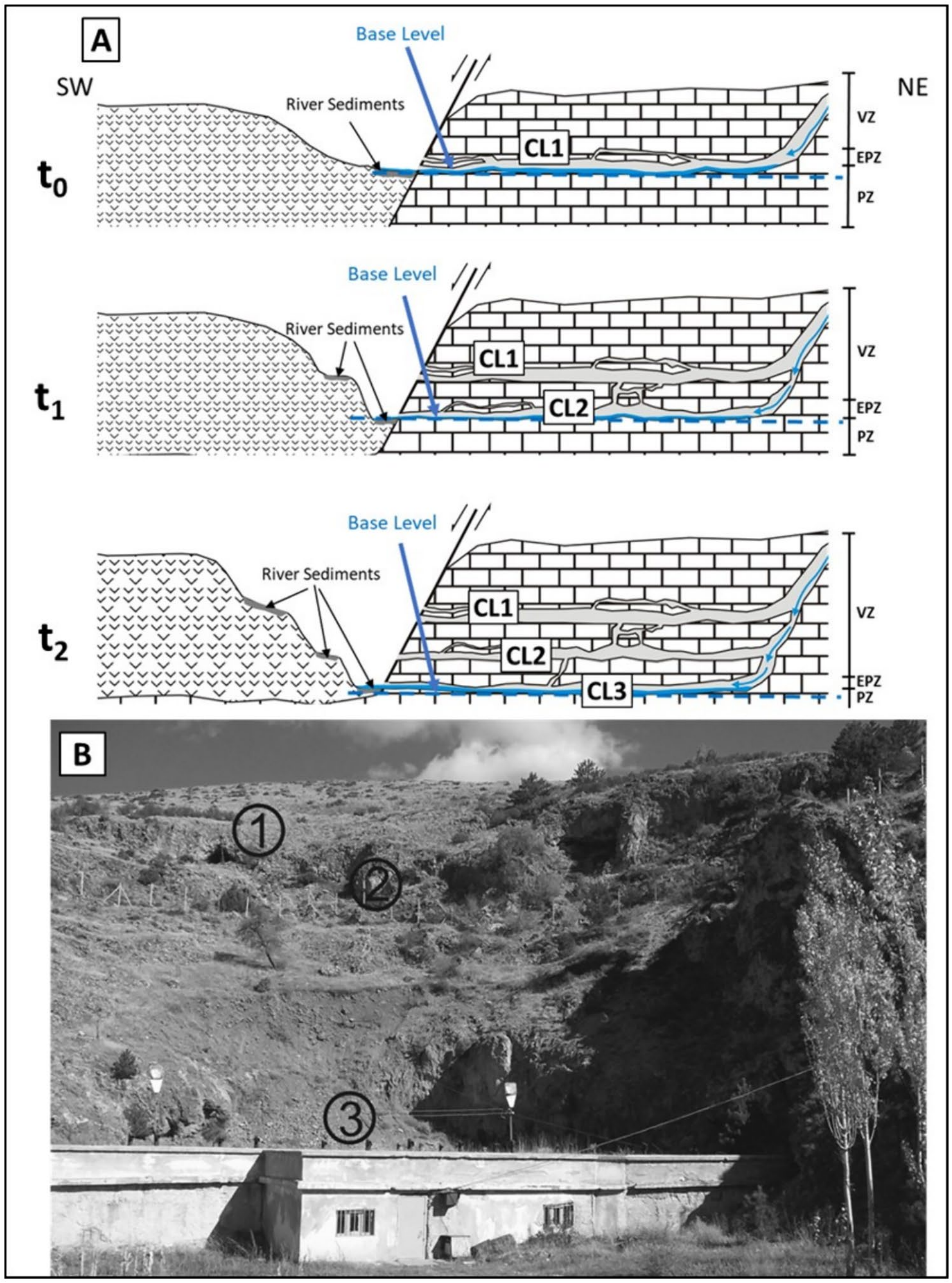

Fig. 8 **A** The commonly accepted epiphreatic speleogenesis paradigm proposes a multi-stage process for cave level development. Initially (t = t0), water dissolves rock along fissures and cracks, creating steep passages in the vadose zone (VZ). These passages connect to the epiphreatic zone (EPZ) and the phreatic zone (PZ) where the water table dictates the formation of sub-horizontal cave levels. These initial levels (CL1) become "fossil" as river incision lowers the water table (t1). This drop in the water table creates new cave levels (CL2) at the new base level, abandoning the older, higher levels (CL1). The process repeats itself (t2) with further river incision lowering the water table again. This allows for the formation of even newer cave levels (CL3) at the updated base level, while the previous level (CL2) becomes abandoned. **B** Layers of the Cokragan cave, 1st level (CL1) is the oldest paleo-spring opening, 2th level (CL2) is older than 3rd but spring opening was closed because of tectonic actions, 3rd level (CL3), the catchment, is the recent exit point of the Cokragan Karstic Spring

true cave levels. The key factor is the elevation of the past or present vadose-phreatic transition zone (the boundary between air and water-filled sections). The presence of abandoned phreatic passages (now air-filled) within the study area indicates that past base levels were situated up to 100 m higher than the current valley floor (Piccini et al. 2003). These passages serve as markers, aiding in the reconstruction of the uplift history of the Cokragan Cave Levels (refer to Figs. 8 and 10 for details). Their vertical distribution suggests two distinct periods of base-level stability: one at 1400 m above sea level (a.s.l.) and another at 1365 m a.s.l. Three different levels, which mostly reflect changes in the water table over time (Fig. 8). The highest cave terrace, situated in the dry section, is the oldest (Level 1). This terrace represents a phreatic phase where water flowed southward from the current highest dry level. With the opening of one of the vertical connections in the passage's continuation, the present-day lower level began to form. A new spring opening (Level 2) and a new bottom cut started to develop, rendering the previous Level 1 dry and elevated. This marked the beginning of the epiphreatic and vadose phases. Today, it is visible as a well-preserved 1st and 2nd level cave terrace characterized by meanders (Fig. 9).

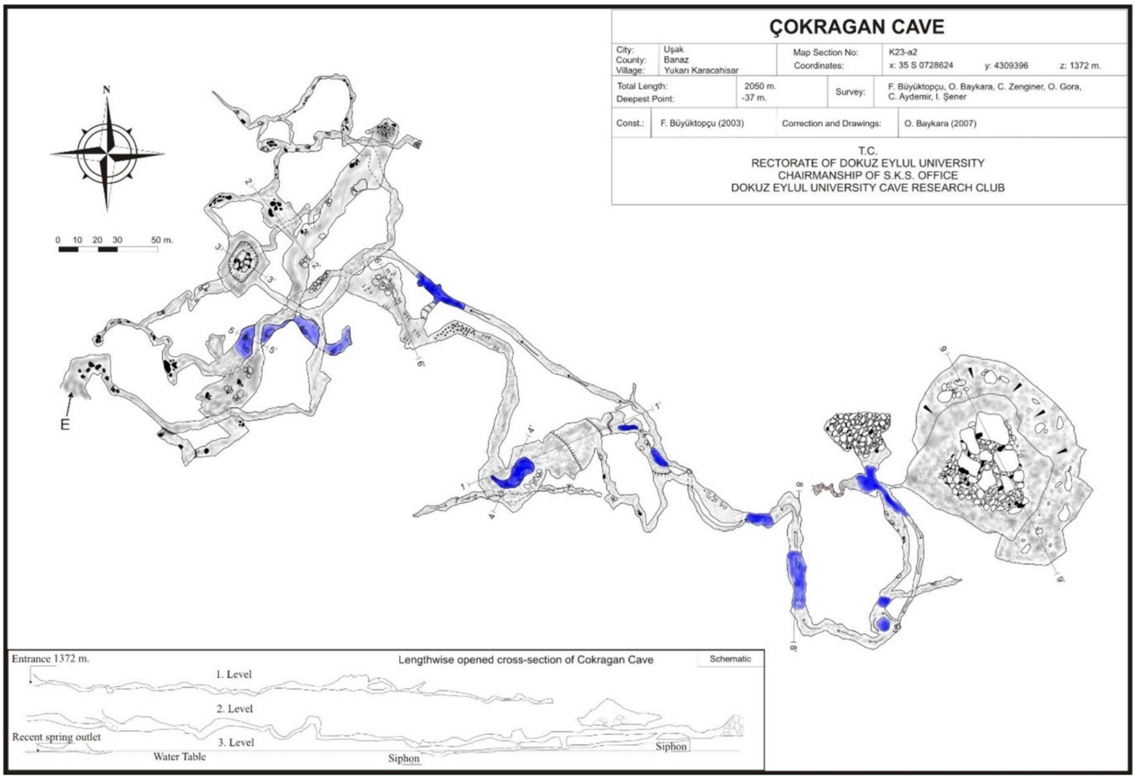

Fig. 9 Map and lengthwise opened cross-section of the Cokragan Cave

The next stage involved the widening of the fault plane (Level 2), opening a new passage. Since the cave rocky relief is an important indicator of speleogenesis (Bočić and Buzjak 1998), Cokragan Cave system has well-preserved rock relief and sediments, the hydrological conditions likely changed quite rapidly. Neotectonic movements probably triggered this activation. The ceiling slope behind Level 2 and the preserved rock relief suggest that the remaining section of the passage above was flooded (siphon). Water level horizons and wall deposits of clay indicate water level fluctuations due to inflow (Fig. 4).

Level 3's opening, also located on the fault plane, caused a further drop in water level. Currently, the active Ponor/Cokragan Karstic spring (Level 3) aligns with the impermeable rock level. In front of the 3rd layer, a human-made water catchment was constructed. Fluvial sediments are also visible within the fissures. While the narrower parts of the passages are washed out due to faster water flow, the wider sections showcase well-preserved sediments on the walls and at the bottom. In all-year-round active sections, the lower stream sediment cover differs from the rest. The cessation of water flow has led to clay washout and replacement by pebbles.

The openings of the ponors along the passages streambed resulted in a retrograde movement of water flow activity upstream. This created a steep transition profile as the earlier active transition segments behind the new ponor incision were arrested and remained as higher transition level segments (Fig. 10). However, sections of the passage that were still active continued to experience water flow interruption and passage strengthening.

Conclusions

In this study, the Cokragan Karstic Spring is characterized by using hydrogeological, hydrogeochemical, and speleological methods. Due to its volume of flow and lack of water potential in the region, the Cokragan Karstic Spring is an important one for its territory. The average recession coefficient (α) of the Cokragan Karstic Spring and the map of the Cokragan Cave shows that the flow of the groundwater is primarily drainage through large channels, and it has a high permeability coefficient and/or low storage coefficient. The discharge of the Cokragan Spring changes from wet to dry seasons, which is related to mature karstification. There are three dissimilar waters (Cokragan Main Spring, Cokragan Side Spring, and Cokragan Yellow Spring) coming out from the Cokragan Cave. The water quality of the spring is suitable for agriculture, and industrial purposes. Water samples are generally characterized as cold, fresh, and

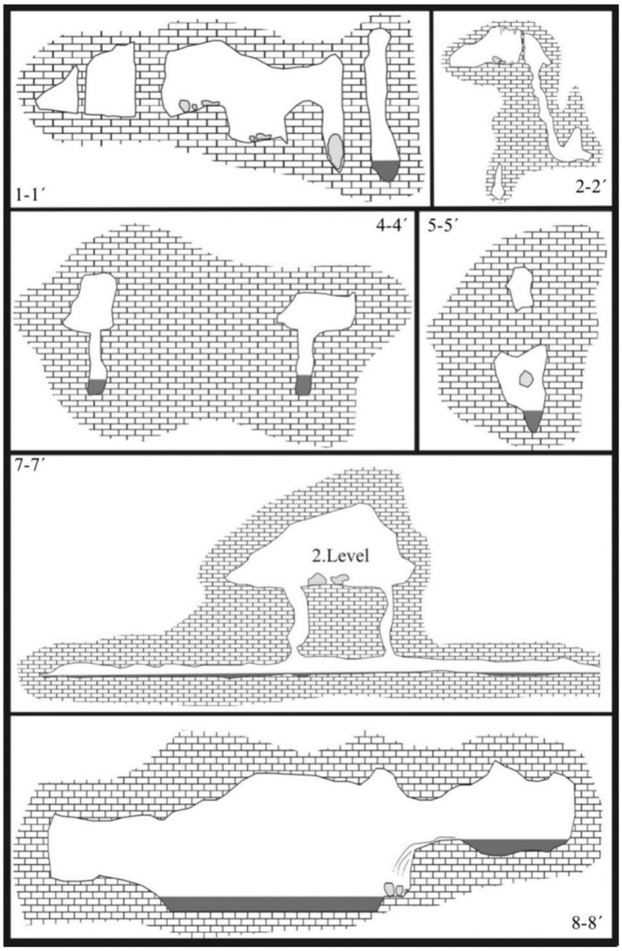

Fig. 10 The cross-Section 1-1′ states the rejuvenation. The thin and long section on the right side is the present bed of the underground river. In 2-2′, water level was decreased twice. The cavity on the top was the first groundwater level. The cavity which is at the bottom is typical for phreatic zone. 4-4′ is the best cross-section that indicates the rejuvenation. It is also called a keyhole cross-Section 5-5′ indicates the decrease of the base level through the same direction. The cross-Section 7-7′ shows the connection of the second level to the recent level by shafts after rejuvenation. 8-8′ shows a waterfall along the underground river

calcium-magnesium-sulphate-bicarbonate type waters. Cokragan Cave is a multi-layer cave which developed in different periods of time. The groundwater level dropped twice by tectonic movements in the area causing three layers in the cave. The Cokragan Cave pattern is heavily influenced by tectonic features, primarily faults, and associated fractures that formed or reactivated during the late Miocene extension. These "tectonic inceptions" guided the flow of corrosive water under both phreatic and vadose conditions, sculpting passages along faults and, in some cases, bedding joints. Fast-flowing waters in the impermeable sandstone schist units accelerated the corrosion, and Cokragan Cave became a complex cave system.

Acknowledgements We thank the anonymous reviewers for their insightful comments and suggestions. We would also like to thank Dr. Matthew J. Jacobson for reviewing the English of the manuscript. Final thanks go to the Dokuz Eylül University Caving Club members (DEÜMAK) for their help with the cave survey and investigations.

Author contributions M.O.B and Ü.G. conceived of the original idea. M.O.B. developed the research methodolgy. M.O.B collected the field data, conducted experiments. Ü.G. encouraged M.O.B and supervised the findings of this work. M.O.B created figures, tables and draft. M.O.B. and Ü.G. participated in revising and editing the manuscript.

Data availability The data supporting the findings of this paper are available from the thesis "Baykara, M. O. (2007). Çokrağan-Yukarı Karacahisar (Banaz-Uşak) Karstik Kaynaklarının Hidrojeolojik İncelenmesi (Master's thesis, Fen Bilimleri Enstitüsü)" and are also available from the author upon reasonable request.

Declarations

Conflict of interest All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

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