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Caves in clastic rocks (Muğla, SW Türkiye)

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Research Article

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Cave, Conglomerate, Mudstone, Late Miocene-Pliocene.

ABSTRACT

Caves evolution is controlled by lithological properties, discontinuities, water, climate, and physico-mechanical properties of soluble rocks, vegetation and human impact. This study investigates the cave formation in Upper Miocene-Pliocene clastic rock in Menteşe town of Muğla. The lithology, physico-mechanical properties and hydrogeologic factors of host rocks and morphology of the caves in Asar Hill and Damlam Stream valley were examined. The caves are 1.47-9.71 m long, 2.24-19.36 m wide and 1.38-27 m high. Four joint sets and bedding planes affect the clastics in the Asar Hill area. Mudstones (low plasticity clay, sandy clay) are in soft-very soft rock, while conglomerate is in moderate-hard rock class. The mudstone removal has started the formation of the caves. The vegetation roots act as groundwater circulation paths in the Damlam Stream area. Water has eroded mudstone and muddy matrix of conglomerate following cracks and led to the formation of the caves. Water infiltration may have led to stalactite, flowstone and travertine formation in Damlam Stream caves. Possible cave collapse could threaten life and property in the Asar Hill area, and may cause the destruction of internal structures of the caves in the Damlam Stream. Thus, precautionary measures such as continuous monitoring and protection must be taken in both cave areas.

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1. Introduction

Karst features especially develop on soluble rocks such as limestone, marble, and gypsum (Ekmekçi, 2005; Ford and Williams, 2007). In addition to soluble rocks, soluble grains-clast or matrix bearing clastic rocks (conglomerate, sandstone, mudstone) may also show karstification (Busche and Sponholz, 1992; Bergada et al., 1997; Ferrarese and Sauro, 2005; Kranjc, 2005; Aubrecht et al., 2008; Breitenbach et al., 2010; Lipar and Ferk, 2011; Grimes, 2012). Caves in sandstone and conglomerate are scattered widely in many small areas across the world, but they are insufficiently studied (Dunkley et al., 2017).

Karstification in all rocks are controlled by strength, energy gradient, gravity, heat flow, micro bacteriology, discontinuities, climatic and environmental conditions, weathering, topography, grain size, and grain types, etc. (Palmer, 1991; Bergada et al., 1997; Kranjc, 2005; Breitenbach et al., 2010; Awadh et al., 2013). Active karst regions are usually associated with humid climate regimes. In karst regions precipitation and organic material in soils produce carbonic acid which dissolves karstified rocks at and below the surface over time. A wide range of international literature is available on the karst and cave studies in carbonate and evaporitic rocks (Palmer, 1991; Ford and Williams, 2007). However, the karstification in clastic rock is little studied in comparison to soluble carbonate and evaporitic rocks.

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Caves in various conglomerates which have diverse underground morphology (vertical, horizontal, circular, tectonic discontinuity controlled) have been reported and described worldwide (Değirmenci et al., 1994; Bergada et al., 1997; Lapaire et al., 2006; Lipar and Ferk, 2011; Ferk and Lipar, 2012). Caves represent ground where rock strength and bearing capacity is significantly reduced. The critical dimensions are the width of the cave and the thickness of the rock cover (Waltham, 2002).

The caves in the Pleistocene conglomerate in Slovenia were studied in detail by Ferk and Lipar (2012). Based on the literature review and field work, the caves were grouped into four different types: 1) linear stream caves, 2) shelter caves, 3) breakdown caves, and 4) vadose shafts.

Tauride Mountains in southern Türkiye composed of Palaeozoic to recent carbonate rocks is the most important karstic region of Türkiye (Güldalı et al., 1984; Nazik, 1996; Özel et al., 1996; Tuncer et al., 2005; Günay et al., 2015). Muğla is located in western Taurides in SW Türkiye (Figure 1). The city centre and surrounding area contains Jurassic-Cretaceous carbonate rocks and post Neogene clastics (Göktaş, 1998). Upper Miocene-Pliocene clastics bearing Yatağan Formation forms a flat topped, step like exposure on carbonates (Göktaş, 1998; Gül, 2015; Gül et al., 2016). Some caves were reported in conglomerate and mudstone alternation of Yatağan Formation (Gül et al., 2016). One of the most significant cave areas is located north of the Muğla city centre (Asar Hill Caves - AHC) and there are some settlements on top of it (Figure 1). The other significant cave area is located 20 km southwest of the city centre (Damlam Stream Caves - DSC) and is used for recreational purposes (Figure 1).

Detailed studies on karstification on clastic rocks like Yatağan Formation are limited. Moreover, internal

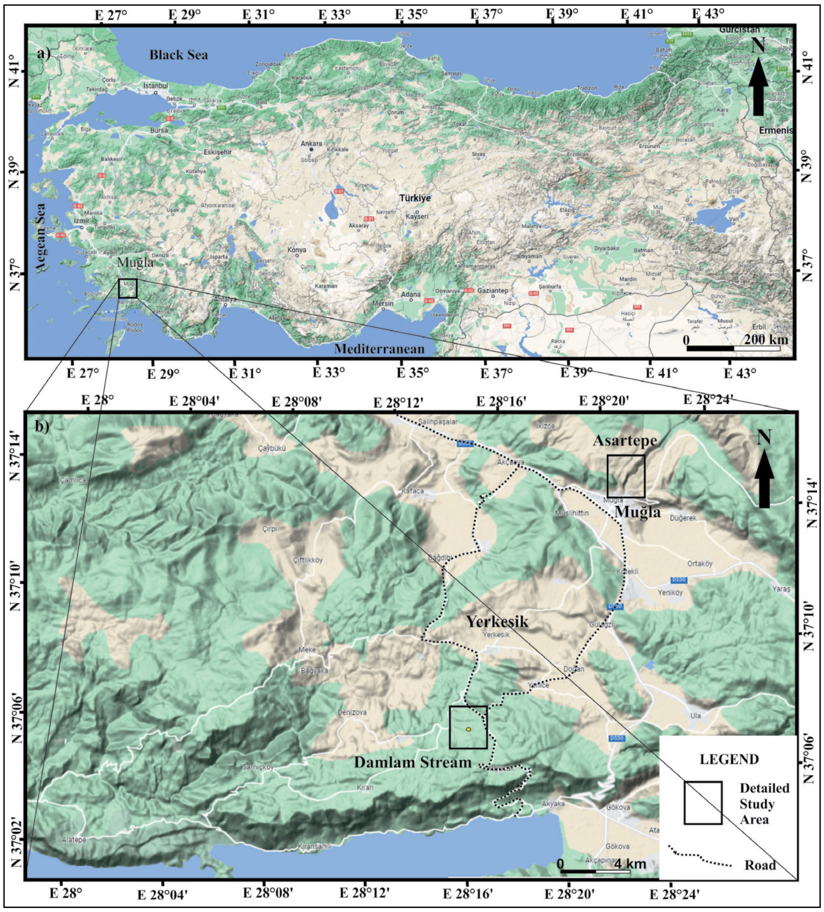

Figure 1- a) General location map of the study area, b) location map of the detailed study area (modified from Google 2022). Asartepe: Asar Hill Caves (AHC), Damlam Stream Caves (DSC).

structure differences in two significant cave areas of Yatağan Formation point to the importance of local factors. Thus, this study aims to describe the caves in Yatağan Formation, determine controlling factors of cave formation (karstification) in clastic rocks, and clarify related environmental issues. In this study physico-mechanical properties of the clastic rocks of the Yatağan formation in which caves are developed are also explained. Additionally, the formation and features of the caves are tried to be interpreted in relation with the rock properties.

2. Material and Methods

The Asar Hill and Damlam Stream, which are two significant areas with regard to cave occurrences were chosen for detailed studies (Figure 1). Each region contains numerous large and small caves. Height and width of cave mouth and length (depth through host rock interior) of cave were measured for each cave. Organic activities in caves, soil formation at the bottom of the caves and weathering were noted during the field analysis. Bed attitudes (strike-dip) and discontinuities were recorded during field studies. Two sedimentary sections were measured in both areas, and detailed lithological variations were noted. Moisture conditions of the ground, spring discharges were noted. Sieve analysis were applied to some loose samples, they classified according to Unified Soil Classification System (USCS; American Society for Testing and Materials (ASTM, 2000), D2487). Hand samples were collected during the section measurement in order to determine physico-mechanic properties of the rock material. During the office and laboratory studies, drainage network of both areas were drawn. Thin sections were prepared from fresh (limestone) and altered rocks for analysis of the petrographical properties of the rocks. Schmidt Hammer was applied to the rock for in situ rock strength determination. Schmidt Hammer was applied to stiff conglomerate part. Some geotechnical properties (porosity, density, point load, slake durability index etc.) of host rock were measured in the laboratory according to International Society for Rock Mechanics (ISRM, 2007) standard. The grain texture of studied rock was prevented from collecting standard samples during the field study. Irregular shaped block samples (for example: 20 cm (width) * 30 cm (length) *20 cm (depth)) were taken as big as possible for laboratory tests. For the Slake Durability Index experiment, a total of ten aggregate samples, each weighing between 40 and 60 g, were selected.

3. Geological Setting

The oldest rocks of the study area form highland and outcrops are Menderes Massif (including Paleozoic-Upper Cretaceous limestone-marble, schist, phyllite) in the north, Lycian Nappes (including Paleozoic-Paleocene sediments, Upper Cretaceous ophiolite-ophiolitic melange), Kuyucak Formation (Lower Miocene-Upper Oligocene conglomerates, sandstone-mudstone alternations) and Akyaka Formation (Lower Miocene-Upper Oligocene conglomerate and fossiliferous limestone) in the south (Figure 2; Konak et al., 1987; Aktimur et al., 1996; Göktaş, 1998;

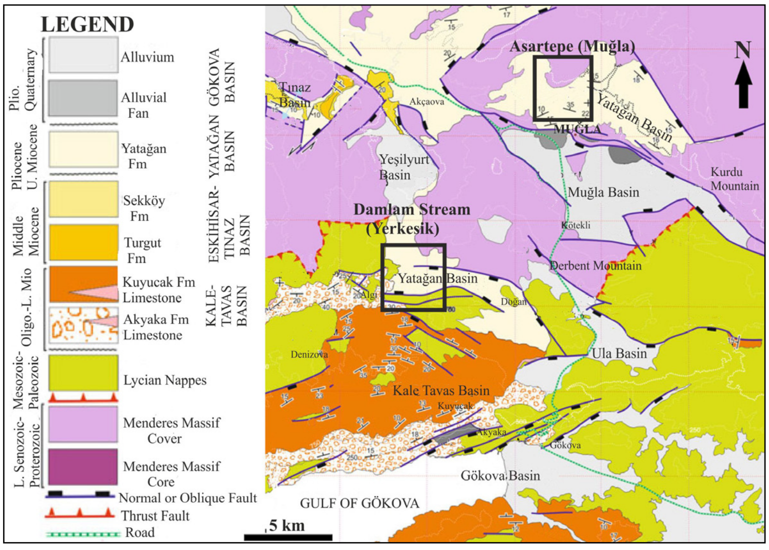

Figure 2- Geological map of the Muğla region in southwestern Anatolia (Gürer et al., 2013). Asartepe: Asar Hill Caves (AHC), Damlam Stream Caves (DSC).

MTA, 2002; Gürer et al., 2013). The Turgut Formation (Middle Miocene conglomerate, sandstoe, mudstone, marl, claystone with coal) and the Sekköy Formation (Middle Miocene limestone and marl) are exposed in Tınaz Basin (Figure 2; Gürer et al., 2013).

The Gereme Formation (Liassic carbonates), belonging to the Lycian Nappes, constitutes the higher mountains around Muğla (Figure 2) (Göktaş, 1998; MTA, 2002; Gül, 2015; Gül et al., 2021). The Yatağan Formation is reliable with the flat topography and (containing marl-limestone at the bottom, conglomerate-sandstone-mudstone at the top with caves) unconformably overlies the older formations (Konak et al., 1987; Göktaş, 1998; MTA, 2002; Gürer et al., 2013; Gül, 2015; Gül et al., 2021). This formation includes older limestone fragments (Gül et al., 2013; Gül, 2015; Gül et al., 2021), and calcite-quartz-kaolinite based on XRD test results (Gül et al., 2021). The Quaternary colluviums (breccia, mudstone) and alluviums (including conglomerates, sandstone, mudstone) filled the Muğla polje and unconformably overlie older formations (Gül, 2015; Küçükuysal et al., 2018).

The Yatağan Formation is bounded by active normal faults (Gürer et al., 2013). These faults had previously produced 4-5 magnitude earthquakes (Sezer, 2003). Tectonic history of the region locally has led to 4 different joint sets development (Gül et al., 2016).

Subtropical climate conditions are active in Muğla with average annual precipitation between 1928-2021 years was measured as 1209.1 mm (MGM, 2022). The lowest temperature is -12.6°C (04.01.1942), while the highest temperature is 42.1°C (27.07.2007), average monthly temperature varies between 5.3°C (January) and 26.4°C (July) based on 1928-2021 period measurements (MGM, 2022).

4. Caves of the Yatağan Formation

4.1. Asar Hill Caves (AHC)

4.1.1. Location, Morphology, Internal Structures

The Asar Hill is located just 500 m north of the Muğla city centre (Figure 3). The height of Asar Hill

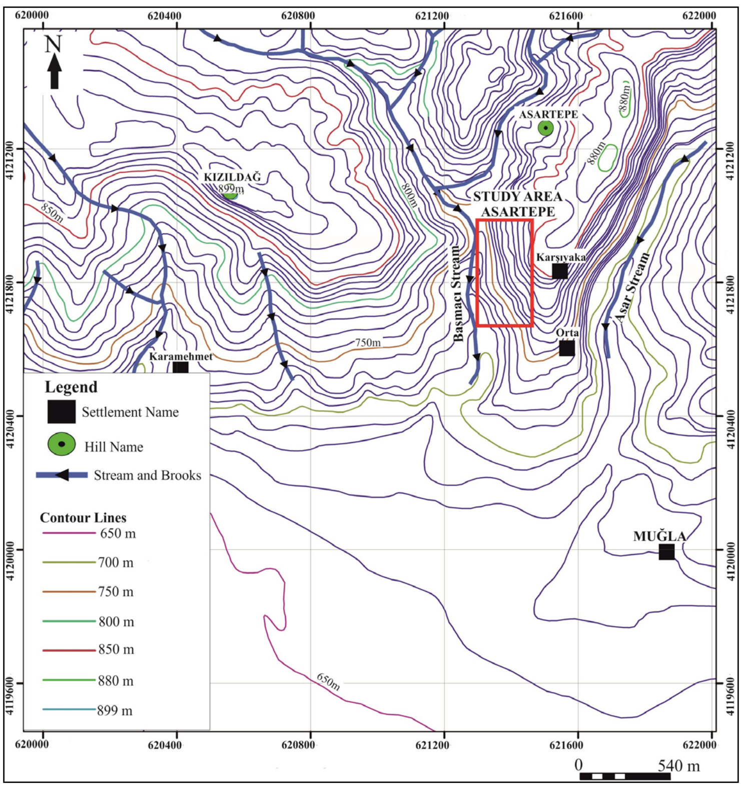

Figure 3- Topographical map and drainage network of the Asar Hill caves area was drawn from topographic raster map of Muğla province (The map is modified from a basemap of General Command of Mapping (HGK, 2016)).

is 830 m. It has 75-80° slope, and is surrounded by Basmacı or Asartepe streams. Eleven large and small caves were identified in southern skirt of the Asar Hill (Figures 4, 5; Table 1). However, number of caves is higher than this value. Some caves are inaccessible because they are either located in private property, used as barn or dense maquis. The caves in Asar Hill area differ in size, with length between 1.47 and 9.71 m, width between 2.24 and 14.89 m, and height between 1.38 and 15.88 m (Table 1). One or two storey houses

Figure 4- General field view of the Asar Hill caves (AHC) and Basmacı Stream (1-2 storey houses are on top of the caves, used for settlement and barn).

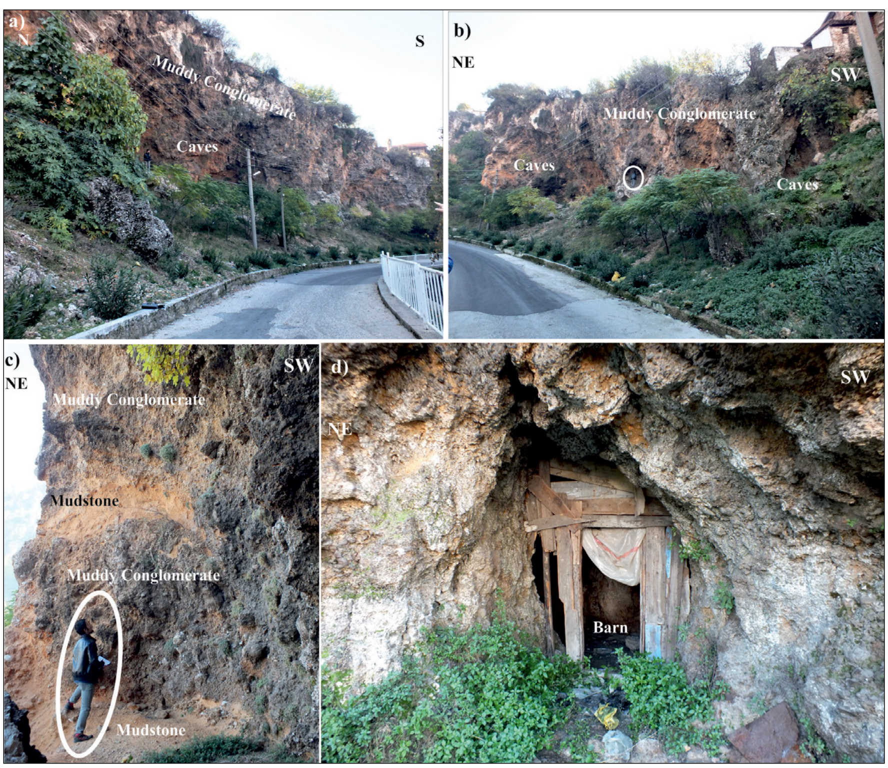

Figure 5- a) General field view of the caves on skirts of the Asar Hill, b) there are two-storey houses above the levels where the caves are located (man for scale in circle: 1.8 m), c) caves are observed in mudstone and muddy conglomerates of the Yatağan Formation (man for scale in circle: 1.8 m), d) some caves have been used as a barn for small animals.

Table 1- Dimensions of caves in Asar Hill caves area.

	Geometric Parameters		
Occurence Name	**Length (m)**	**Width (m)**	**Height (m)**
Cave 1	4.98	13.34	7.68
Cave 2	3.38	4.21	2.69
Cave 3	2.12	3.39	2.78
Cave 4	6.83	2.88	2.18
Cave 5	5.51	8.85	15.8
Cave 6	9.71	14.89	15.88
Cave 7	2.72	3.15	1.82
Cave 8	6.58	4.96	2.96
Cave 9	1.47	2.55	2.35
Cave 10	1.58	2.35	1.64
Cave 11	5.74	2.24	1.38
Statistical Evaluations			
Minimum	1.47	2.24	1.38
Maximum	9.71	14.89	15.88
Average	4.60	5.71	5.20
Standard Deviation	2.60	4.57	5.53

are located on top of the formation containing caves (Figure 4). There are no significant internal structures in AHC. Only local white coloured calcite bearing flowstone as a thin plastering were observed on host rocks. Some caves contain one or two step structures, which may have evolved due to weathering and/or human impact.

4.1.2. Local Geological Properties (Lithology, Structural Properties, Petrography)

Lithology of the Yatağan Formation on skirts of the Asar Hill is quite variable. Lower part and upper part of the section consist of poorly sorted, moderately-well indurated, cobbly, pebbly, and granule bearing muddy conglomerates, and coarse to very coarse grained sandstone alternations. The middle part of the section contains durable moderately-well sorted, pebble-granule size muddy conglomerates and coarse to very coarse grained sandstone and mudstone alternations (Figure 6). Clasts are generally Jurassic-Cretaceous Gereme Formation limestone fragments. Those

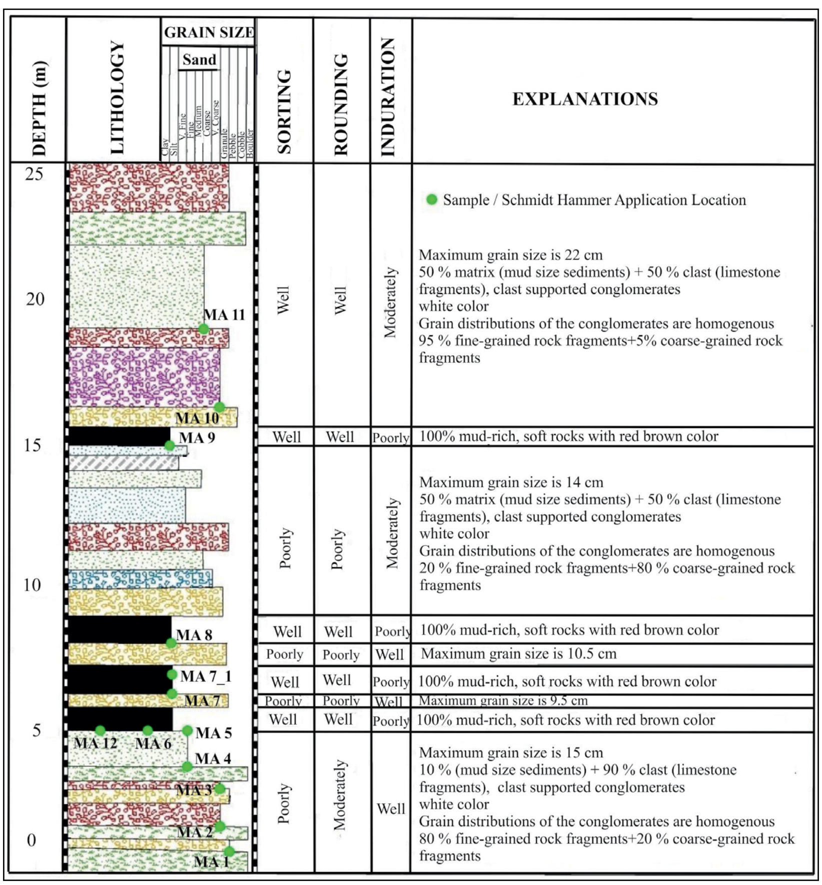

Figure 6- Detailed stratigraphic section of Asar Hill Caves (Zeybek, 2017).

fragments were binded with mud size sediments. Clast ratio (from 50 % to 90 %) and maximum clast size (from 9.5 cm to 22 cm) is highly variable along section (Figure 6). Four different joint sets in profile that comprised the caves (Gül et al., 2016) (Dip/dip direction, 60°/160°, 72°/197°, 72°/8°, 74°/331°, slope orientation 80°/257°, and bed orientation N60°E/25°-35°NW). The continuation of joints was determined as about 20 m (Gül et al., 2016). N15°-35°W/ 75°-80°SW directed joints were determined in the caves given in Figure 5c (Şahin, 2015). Their traces were also observed inside of some caves. Alignment of some joints are restricted by the caves. The joints generally have rough surfaces. Some joints are filled by clay minerals, after raining these joints show damp surfaces or water dripping occurs through them.

4.1.3. Hydrogeological Conditions

The Basmacı Stream flow west of the Asar Hill and collect water from a 5.5 km^2 drainage area. The stream is generally dry during the summer time. The caves are usually dry and hydrologically inactive. However, some small springs, and droplets were identified in some caves. The discharge of the perennial springs was 0.125 l/s (29.09.2016) and 0.143 l/s (20.01.2017). These springs reflect the current circulation of the groundwater in the karstified conglomerate which is characterized by a limited storage capacity. Şahin (2015) measured the discharge as 1.2 l/s in one fountain during the spring period. Damp areas and temporary springs were identified in caves mostly along cracks. Along those groundwater path, thin white coloured carbonate cover was formed.

4.1.4. Physico-Mechanical Properties

The dry densities of conglomerate samples from Asar Hill area fall between the 2.55 and 2.75 g/cm^3 and classified as moderate-high density class rock (Anon, 1979). Porosity values of the conglomerates are lower than 1 % and classified as very low porous rock (Anon, 1979). The strength of the examined materials (conglomerates) were classified as hard (1-3 MPa, point load strength) and mostly very hard rock (3-10 MPa, point load strength) (Broch and Franklin, 1972). The samples are in medium (60-85), medium-high (85-95) and high (95-98) durable rock classes based on Slake Durability Index after second cycle (Gamble, 1971, Sivakugan et al., 2013).

The Schmidt Hammer was applied to stiff part of the conglomerate. They have highly variable clast size from granule (2-4 mm) to cobble (64-256 mm), clast ratio, and supporting mechanism (matrix or clast supported). Moreover, application rock surface of the Schmidt Hammer is generally rough. For this reason, highly variable Schmidt Hammer rebound values were obtained even in very close areas during this study. The Schmidt Hammer rebound mumbers of the conglomerates are varying between 6.63 and 30.22. The calculated uniaxial compressive strength (UCS) values of the conglomerates from Schmidt Hammer rebound value based on the method proposed by Minaeian and Ahangari (2013) are varying from 4.5 to 20.5 MPa. Thus, one sample (MA2) was classified as very low strength (1-5 MPa) and others was classified as a low strength rock (5-25 MPa) based on ISRM (1978). Moreover, three samples (MA1, MA2, MA8) were classified as low strength (4-8 MPa), two samples (MA7, MA3) were classified as a high strength (16-32 MPa) rock, while others were classified as a medium strength (8-16 MPa) rock according to Deere and Miller (1966) classification system (Table 2). The highest strength values were obtained from the clast supported (clast ratio>80%) level. One sample from fine-grained level was classified as a SM (silty sand, 74 % sand, 26% mud) according to USCS.

Table 2- Physico-mechanical properties of conglomerate samples collected in Asar Hill area.

Sample Number	Occurrence Name	Schmidt Hammer Rebound Value	UCS = 0.678*SCH MPa	Porosity (%)	Dry Density (g/cm^3)	Point Load Strength Index (Is_{50}) (Is_{50}=Px1000/De^2) (De=50mm) (MPa)	Slake Durability Index (2nd Cycle) Id(2)=[(C-D)/(A-C)]x100	Slake Durability
MA1	**Cave 1**	9.23	6.3	0.64	2.65	7.31	90.60	Medium-High Slake Durability
MA2	**Cave 2**	6.63	4.5	0.27	2.66	4.9	89.70	Medium-High Slake Durability
MA3	**Cave 3**	25.69	17.4	0.76	2.60	4.64	86.40	Medium- High Slake Durability
MA4	**Cave 4**	12.36	8.4	0.49	2.68	8.56	95.50	High Slake Durability
MA5	**Cave 5**	17.31	11.7	0.62	2.64	5.58	89.80	Medium-High Slake Durability
MA6	**Cave 6**	20.17	13.7	0.64	2.67	4.86	90.80	Medium-High Slake Durability
MA7	**Cave 7**	30.22	20.5	0.69	2.63	4.68	88.60	Medium-High Slake Durability
MA8	**Cave 8**	11.37	7.7	0.54	2.64	4.41	92.50	Medium-High Slake Durability
MA9	**Cave 9**	21.72	14.7	0.76	2.55	1.07	74.90	Medium Slake Durability
MA10	**Cave 10**	17.56	11.9	0.99	2.61	4	87.80	Medium-High Slake Durability
MA11	**Cave 11**	17.74	12.0	0.26	2.59	2.92	79.50	Medium Slake Durability
MA12	**Cave 12**	17.31	11.7	0.81	2.58	3.73	84.20	Medium Slake Durability
Statistical Evaluations								
Minimum		6.63	4.5	0.26	2.55	1.07	74.90	
Maximum		30.22	20.5	0.99	2.68	8.56	95.50	
Average		17.74	11.7	0.62	2.62	4.72	87.52	
Standard Deviation		6.96	4.8	0.21	0.03	1.91	5.68	

4.2. Damlam Stream Caves (DSC)

4.2.1. Location, Morphology, Internal Structures

The DSC is located 20 km southwest of the Muğla city centre (Figure 1). The N-S oriented walls of the caves, with slope angles ranging between 70-85°, are composed of muddy conglomerates (Figures 7, 8 and 9). The caves in Damlam Stream area differ in size, with length between 2.01-4.73 m, width between 4.16-19.36 m, and height between 2.83-27.00 m (Table 3). The capillary root vessels of the pine and other trees hang down from cave ceiling (Figure 9). The internal structures (speleothems) of DSC are composed of stalactite, flowstone and travertine formations (Figure 9). Stalactites, which grow down from the cave ceiling, are in 1-2 cm diameter, 10-12 cm long, and hanging down ceiling. Their growth generally

Table 3- Dimensions of caves in Damlam Stream valley.

	Geometric Parameters		
Occurence Name	**Length (m)**	**Width (m)**	**Height (m)**
Cave 1	2.10	6.80	3.90
Cave 2	3.73	14.70	15.16
Cave 3	4.73	19.36	27.00
Cave 4	2.01	4.16	2.83
Cave 5	3.46	6.66	4.50
Statistical Evaluations			
Minimum	2.01	4.16	2.83
Maximum	4.73	19.36	27.00
Average	3.20	10.33	10.67
Standard Deviation	1.15	6.41	10.39

follows capillary root vessels, and they are formed by percolation and dripping of dissolved carbonate mineral loaded water from cave ceiling. Most of the flowstone covers ceiling and sidewalls of caves as a gray colored, 5 mm thick layer. The water flowing on muddy conglomerate and mudstone leads to formation of flowstone. Flowstone has low resistance against erosion and can easily be crumbleb by hand. Some thick flowstone accumulations were observed in the caves. These accumulations may be interpreted as travertine formation (Figure 9).

4.2.2. Local Geological Properties (Lithology, Structural Properties. Petrography)

The DSC area contains cobbly, pebbly, and granule bearing conglomerates with mud matrix (Figure 10). The conglomerates contain generally well sorted, well rounded and moderately and well durable sediments. The clast of the conglomerates are older limestone fragments. Those fragments were bounded with mud size sediments. Compared to the Asar Hill section, the Damlam Stream section includes thicker mudstone

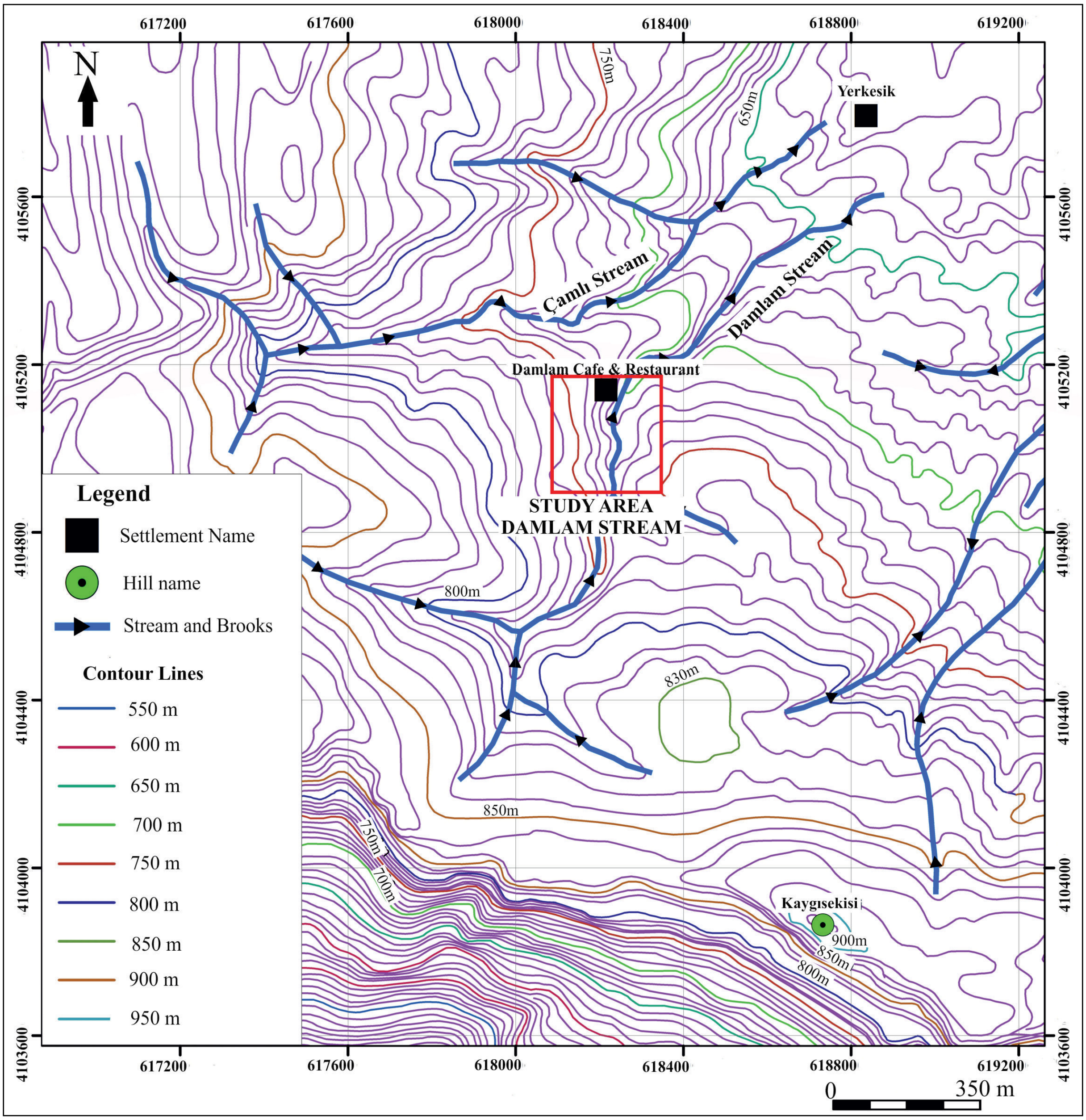

Figure 7- Topographical map and drainage network of the Damlam Stream caves was drawn from topographic raster map of Muğla province (The map is modified from a basemap of General Command of Mapping (HGK, 2016)).

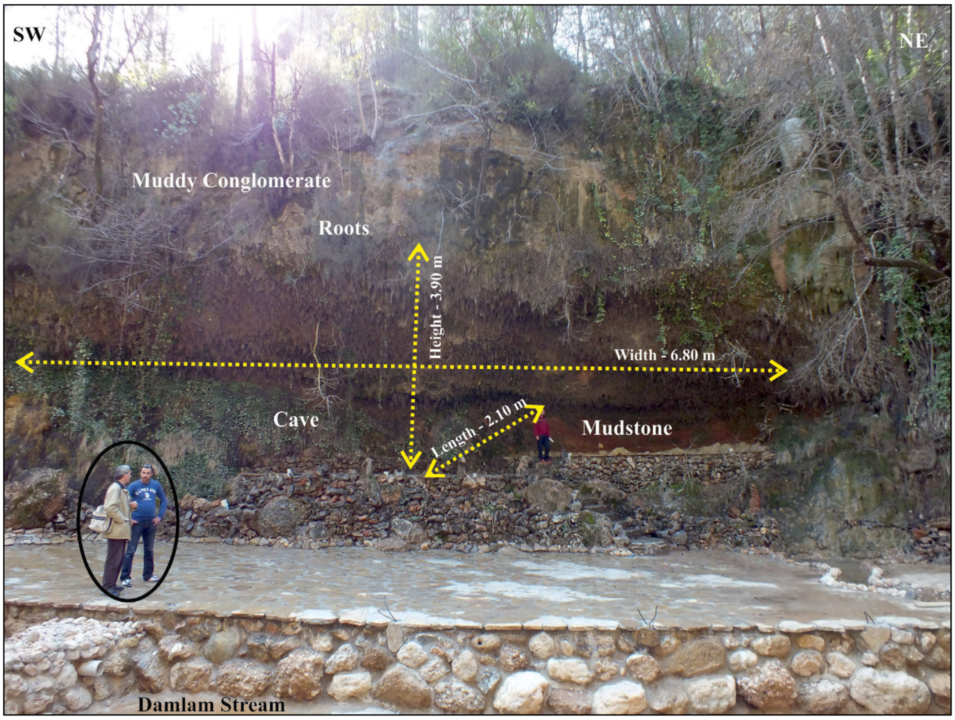

Figure 8- General field view of the cave in Damlam Stream valley. Partially interior part and in front of caves have arranged for recreation (man for scale: 1.80 m).

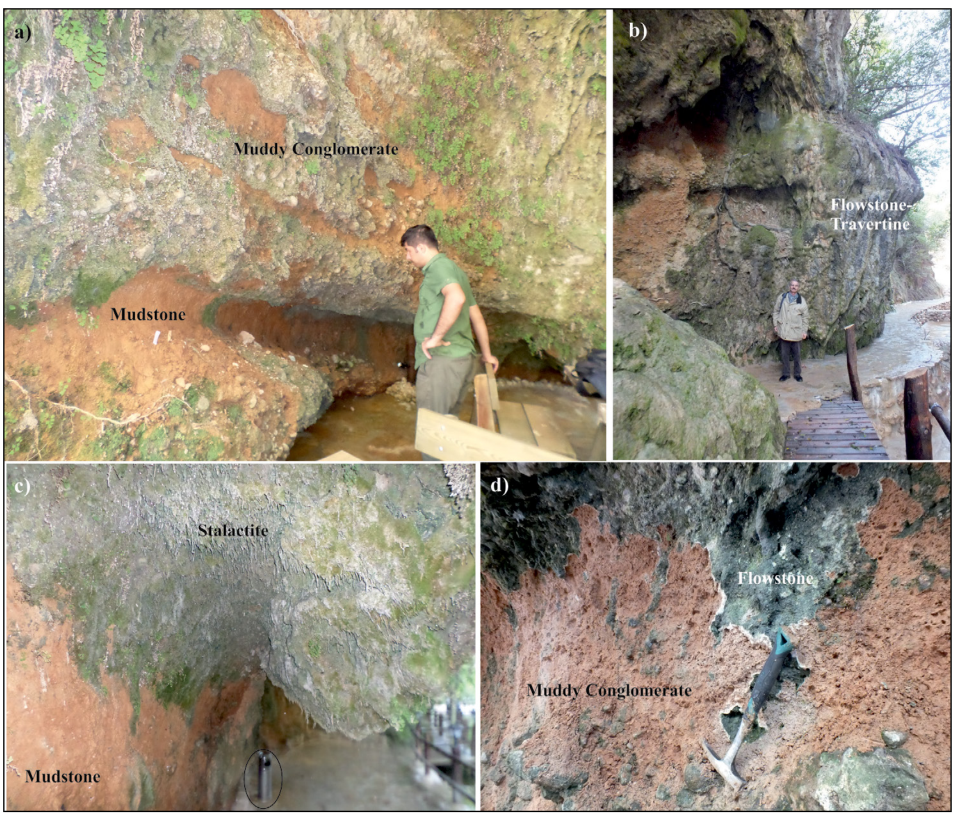

Figure 9- a) General field view of the Damlam Stream cave (man for scale in circle: 1.8 m), b) flowstone and travertine can observe on cave wall and valley side (man for scale in circle: 1.8 m), c) stalactite develop following the roots in the cave (dustbin for scale in circle: 60 cm), d) very thin flowstone cover can observe on muddy conglomerate in cave (hammer for scale: 33 cm).

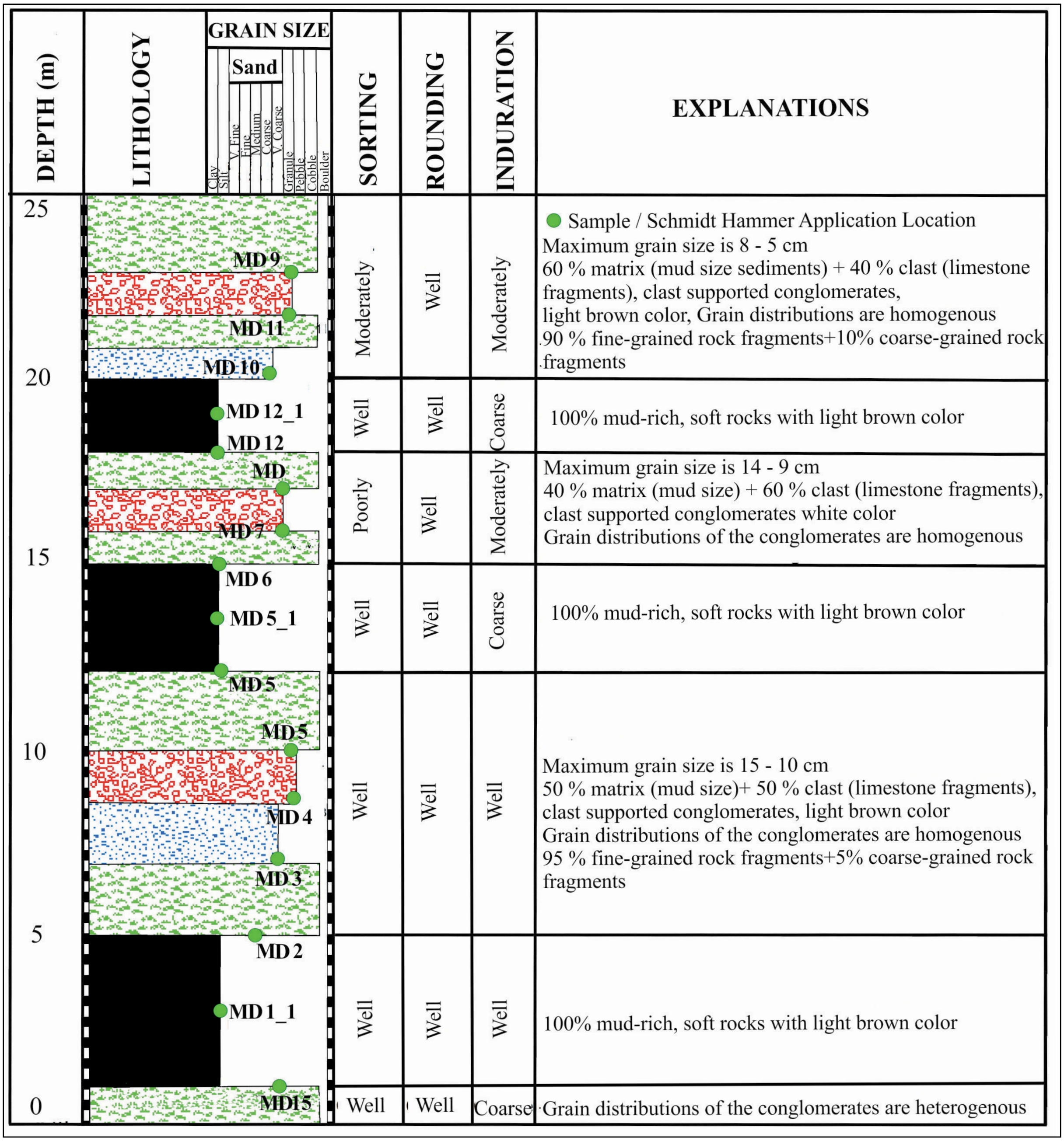

Figure 10- Detailed stratigraphic section of Damlam Stream caves area (DSC, Zeybek, 2017).

levels, and clast ratio of this region is less than the Asar Hill. Roundness and sorting of this region is better than the Asar Hill region. The maximum clast size of the Damlam Stream conglomerates is smaller than the Asar Hill conglomerates. There are no significant discontinuities determined in DSC area. The bedding plane of the conglomerate (N75°E / 18°SE) acts as weakness zone (Figure 8).

4.2.3. Hydrogeological Conditions

The DSC area has similar climatic and precipitation conditions with Asar Hill area. Damlam Stream valley is colder than Asar Hill area during the summer time due to the presence of dense vegetation and stream. Damlam Stream has a 4.8 km^2 dendritic drainage area (Figure 7), and a discharge rate of 0.5 l/s. There are permanent and temporary water leakage observed in the caves. Drippings have been observed at the edges of stalactites. The surface of cave ceilings and walls are always damp which indicates that the rock of the cave (conglomerate) is saturated to water.

4.2.4. Physico-Mechanical Properties

The dry densities of the samples from Damlam Stream area drop into the 1.83-2.62 g/cm^3 range and are classified as low-moderate-high density rock class. The porosity values vary between 1.56 and 8.26 % and they are classified as a low – medium porous rock (Anon, 1979). The point load strength index of the examined materials ranges between 0.84 and 7.78 MPa and classified as a moderate (0.3-1 MPa) - hard (1-3 MPa, point load strength) and very hard rock (3-10 MPa, point load strength) (Broch and Franklin, 1972). The samples are medium (60-85), and medium high (85-95) durable rock based on Slake Durability Index after second cycle (Gamble, 1971; Sivakugan et al., 2013).

The difficulties encountered during the Schmidt Hammer application at Asar Hill were also experienced in this field. The Schmidt Hammer rebound numbers of the conglomerates vary between 8.53 and 24.48. The calculated uniaxial compressive strength values from Schmidt Hammer rebound value based on the method proposed by Minaeian and Ahangari (2013) are varying from 5.78 to 16.60 MPa, so they are classified as low strength (5-25 MPa) based on ISRM (1978). One sample (MD5) was classified as low strength (4-8 MPa), three samples (MD1, MD2, MD4) were classified as a medium strength (8-16 MPa) and one sample was classified (MD3) high strength (16-32 MPa) according to Deere and Miller (1966) classification system (Table 4). Those conglomerates are in medium strength characteristic. Four samples were collected from mudstone, and are classified as a CL (low to medium plasticity inorganic clays) and SC (sandy clay) based on USCS (Table 5). The mudstone, observed in the lower part of the cave in the measured section is very soft, and it is easily crumbled with finger. The Schmidt Hammer test was not applied to the mudstone due to its very soft character.

Table 4- Physico-mechanical properties of conglomerate samples collected in Damlam Stream area.

Sample Number	**Occurrence Name**	**Schmidt Hammer Rebound Value**	**UCS = 0.678*SCH MPa**	**Porosity (%)**	**Dry Density (g/cm^3)**	**Point Load Strength Index (Is_{50}) (Is_{50}=Px1000/De^2) (De=50mm) (MPa)**	**Slake Durability Index (2nd Cycle) Id(2)=[(C-D)/(A-C)]x100**	**Slake Durability**
MD1	**Cave 1**	21.49	14.57	1.56	2.62	7.54	86	Medium-High Slake Durability
MD2	**Cave 2**	18.49	12.54	7.25	2.31	1.56	77.10	Medium Slake Durability
MD3	**Cave 3**	24.48	16.60	8.26	2.38	2.54	72.40	Medium Slake Durability
MD4	**Cave 4**	15	10.17	3.95	1.83	0.84	90.40	Medium-High Slake Durability
MD5	**Cave 5**	8.53	5.78	3.79	2.57	7.78	86	Medium-High Slake Durability
Statistical Evaluations								
Minimum		8.53	5.78	1.56	1.83	0.84	72.40	
Maximum		24.48	16.60	8.26	2.62	7.78	90.40	
Average		18.23	11.93	4.96	2.34	4.05	81.47	
Standard Deviation		5.26	4.18	2.74	0.31	3.34	8.19	

Table 5- Laboratory results of soil samples collected in Damlam Stream area.

Sample Number	Occurrence Name	Moisture Content W_n (%)	Natural density ρ (g/cm^3)	Specific Gravity G_s	Atterberg Limits			Grain Size Distribution (Sieve Analysis)			Unified Soil Classification System (USCS)
					LL (%)	PL (%)	PI (%)	Gravel (%)	Sand (%)	Mud (Silt + Clay) (%)	
MD1_1	**Cave 1**	27.90	1.76	2.63	37.50	24.40	13.10	0	27.01	72.90	CL
MD5_1	**Cave 5**	26.60	1.80	2.67	40.10	24.70	15.40	0	21	79	CL
MD7	**Soil 7**	20.90	1.83	2.62	36.20	23.80	12.50	8.20	22.40	69.40	CL
MD10	**Soil 10**	16.40	1.86	2.60	32.30	22.40	9.90	5.70	50.40	43.90	SC
Statistical Evaluations											
Minimum		16.40	1.76	2.60	32.30	22.40	9.90	0	21	43.90	
Maximum		27.90	1.86	2.67	40.10	24.70	15.40	8.20	50.40	79	
Average		22.95	1.81	2.63	36.52	23.82	12.72	3.47	30.20	66.30	
Standard Deviation		5.32	0.04	0.02	3.25	1.02	2.26	4.14	13.70	15.45	

5. Discussion

Large and small caves have been determined in various outcrops of the Yatağan Formation. The formation mostly consists of mudstone and conglomerate alternations, which have variable thickness. It is mostly surrounded by Jurassic-Cretaceous limestone. Combined effects of structural properties, lithological variation, strength differences, groundwater and surface water, and vegetation have created favourable conditions and led to the formation of the caves. AHC and DSC areas are composed of very soft mudstone and relatively durable conglomerate packages. The Upper Miocene-Pliocene Yatağan Formation conglomerate is the example of oligomict-single type grain bearing (only Jurassic-Cretaceous limestone fragments) conglomerates. Mudstone layers of the Yatağan Formation, especially wet parts, which are very soft, can easily be crumbled with finger. The conglomerate levels of this formation are more durable, however the strength of the matrix including mud size sediments of the conglomerate are lower than that of the clasts.

When the water circulates in the formation, especially by following the cracks, weakening of mudstone and matrix of the conglomerate occures. While the muddy material is disintegrated, they are washed away and removed from the caves. These processes then cause release of the conglomerate clasts. Increase of precipitation amount and infiltrating water may accelerate this processes and lead to enlargement of the caves. Kayan (1979) reported that Early Pliocene represented by semi-arid climatic conditions and significant erosion, and during Late Pliocene wetter climatic conditions were present in the study area that led to north directed rivers, later period under the effect of the faults uplifted and fragmented, river erosion fastened. Jiménez-Moreno et al. (2015) point out that the climatic conditions of region in south of the study area was arid and warmer than today during late Pliocene and early Pleistocene time. Early-to mid Holocene time show oscillations between aridity and humidity, whereas second half of the Holocene point out the drier conditions, recent aridity conditions started approxiamately 1300 years ago based on isotopic record from Gölhisar in SE of the study area (Eastwood et al., 2007). In the geological time period ranging between Early Pliocene and recent, in general semi-arid to arid climatic conditions were valid in the study area according to the studies of Kayan (1979), Jiménez-Moreno et al. (2015) and Eastwood et al. (2007).

There are some similarities and differences in the properties of the Asar Hill and Damlam Stream caves. Comparison of features and controlling factors of cave development in Yatağan Formation given in Table 6.

The strength of the karstic cave rocks may be reduced substantially in a short period of time by dissolution and other weathering processes mainly acting along discontinuity planes (Parise and Lollino, 2011). The Asar Hill rocks have highly variable lithology and contain weakness zones including bed planes and fractures. Water following these fractures cause to weakening, weathering and removing of mudstone and muddy matrix of the conglomerate.

Table 6- Comparison of features and controlling factors of cave development in Yatağan Formation (modified from Zeybek, 2017).

Controlling Factors and Features of Cave Occurrences	Asar Hill Caves (AHC)	Damlam Stream Caves (DSC)
Size variation ranges of caves	Length: 1.47-9.71 m, Width: 2.24-14.89 m, Height:1.38-15.88 m	Length: 2.01-4.73 m, Width: 4.16-19.36 m, Height:2.83-27 m
Internal Structure(s)	Flowstone, step	Stalactite, flowstone, travertine
Usage purpose(s)	Barn, warehouse	Recreation
Hydrogeological Condition	Temporary-seasonal (ephemeral) river, spring at the base of cave, damp ground during wet season	Permanent (perennial) river, dripping from cave roof, moist ground inside cave, surface water flowing traces on sidewall of cave.
Vegetation effect	Rare, only bushes and their roots observed at outer edge of caves	Plenty of the roots of trees (Water follows capillary cracks caused by the roots of trees)
Lithological similarities and differences	Mudstone-muddy conglomerate alternations (Maximum grain size is 22 cm), cave formations were observed in different layers.	Mudstone-muddy conglomerate alternation (Maximum grain size is 15 cm), general cave formation observed along thick muddy layer.
Structural Properties	3-4 joint sets in different direction and bedding. Active normal fault is also cut the cave bearing formation.	A few fractures were observed in cave in addition to bedding. Active normal fault is bounded the Yatağan Formation.
Strength of rocks	Without cave parts are more durable than within cave parts. Mudstone has not any strength value that means “zero” by Schmidt Hammer due to a too soft rock that can be easily crumble by finger. Mud matrix strength of conglomerate is significantly lower than clast of conglomerate (Gül et al., 2016).	Without cave parts are more durable than within cave parts. Mudstone has not any strength value that means “zero” by Schmidt Hammer due to a too soft rock that can be easily crumble by finger. Mud matrix strength of conglomerate is significantly lower than clast of conglomerate (Gül et al., 2016).
Clay type(s) (according to the Unified Soil Classification System (USCS)	SM (silty sands, sand-silt mixtures)	CL (Inorganic clays of low to medium plasticity, gravelly / sandy / silty / lean clays) and SC (Clayey sands, sand-clay mixtures)
Environmental Impact	Enlargement of cave due to both anthropogenic and natural factor cause to decrease of overburden thickness of cave so collapsing risk are increasing day by day. This risk threatens to people just settled at top of cave. The sewage system of those settlers may reach the groundwater circulating inside the cave and may lead to contamination of groundwater and spring. Continuous monitoring of cave and groundwater and spring, relocation of houses on top cave must take into consideration.	Enlargement of cave occurrences may cause to collapsing risk. Collapsing and increasing human impact due to recreation increase destruction risk of special cave structures (stalactite, flowstone, travertine, etc.). For protection of recent situation of those structures, continuous monitoring, restriction of human impact and protection of vegetation and water circulation must supply.

The clasts of the conglomerate, which are composed of Jurassic-Cretaceous limestone fragments are disintegrated by means of dissolutional weathering processes. Active weathering processes may promote progressive rock mass weakening and break down in the cave. Sometimes large rock blocks (30- 40 cm wide) fall down to the road parallel to the Basmacı Stream.

The Muğla province which is a part of the SW Türkiye, is one of the most seismically active region of the country. Seismic activities led to formation of additonal joints and rock fall in caves. Possible collapse of cave ceiling constitutes a threaten to inhabitants in AHC area. Thus, regular monitoring of caves must be made, further excavation of caves and additional settlements on top of cave area must be prohibited, and relocation of these settlements may be taken into consideration. Dewatering of the cave area must be applied with suitable drainage system to ensure the stability of the caves.

The AHC area contains numerous caves. In general, the caves of Asar Hill are isolated and have not developed a network of cave pattern. The rocks in which the caves developed are conglomerate with mud size sediment bearing matrix and mudstone alternation. Bedding planes and four joints sets are the structural features that affect those rock units. UCS values obtained from Schmidt Hammer rebound value indicate that in-situ strength of rock is largely classified as low to medium strength rock based on ISRM (1978) and Deere and Miller (1966). Laboratory tests on rock samples point out slightly porous, high density, hard rock, with medium-high slake durability. Both surface and ground water including springs, as well as damp ground were observed in the AHC area during the field studies.

Gül et al. (2016) reported that conglomerate in upper part of Asar Hill as low density (1.9 g/cm^3) and moderately porous (6.4 %) rock, while, mudstone as moderately dense (2.5 g/cm^3) and slightly porous (4.0%) rock based on Anon (1979) classification. Muddy conglomerate (matrix supported) in upper part of Asar Hill was classified as soft rock, clast supported conglomerate as hard rock and mudstone was classified as very soft rock based on insitu Schmidt Hammer Rebound Value (Gül et al., 2016).

In Asar Hill area, caves can be followed in several mudstone levels (Figure 5), while the caves follow one thick mudstone layer in the Damlam Stream area (Figure 8). The initiation of the cave formation was probably in fine-grained level of mudstones due to their relatively low resistance against weathering. Later, enlargement occured through the upper level coarse-grained muddy conglomerates. Both areas are under the effect of active normal faults. The tectonic history of the region revealed four joint sets and bedding planes have occured in Asar Hill area. However, these features (joints) are not much visible in Damlam Stream caves, because they are untraceable due to occurrence of the flowstone coverage on the cave walls.

AHC resemble shelter caves. Shelter type caves has been investigated and described by Ferk and Lipar (2012) developed in Pleistocene carbonate conglomerate in Slovenia. The authors have stated that shelter cave usually form on the edge walls of terraces or side walls of valleys or canyons. They also claim that physical weathering and corrosion are the processes that lead the formation of shelter caves in conglomerate. The length (depth) of the shelter caves of Asar Hill into the conglomerate varies from 1.5 m to about 10 m. Their width and height are usually greater than their length (Table 1). Ferk and Lipar (2012) claim that physical weathering and corrosion are the processes that form shelter caves throughout the world and these processes play a great role on the later evolution of shelter caves in conglomerate.

DSC area contains five caves. The rocks in which caves formed are conglomerate with mud matrix and mudstone alternations. Major joint sets were not detected during the field study. UCS values obtained from Schmidt Hammer rebound value indicate that insitu strength of rock is largely classified as low to medium strength rock based on ISRM (1978) and Deere and Miller (1966). Laboratory tests point out slight to moderate porous, low to high density, hard rock, with medium-high slake durability of conglomerate. The finer-grained parts of the Yatağan Formation are composed of mostly CL (low plasticity inorganic clay based on USCS) type clays.

The caves in DSC area resemble shelter caves, which were described by Ferk and Lipar (2012) in detail, developed in Pleistocene carbonate conglomerate in Slovenia. These shelter caves in DSC area have formed on the side walls of the valley. The length (depth) into the conglomerate of the shelter caves in DSC area varies from 2 m to 4.7 m. Their width and height are usually greater than their length (Table 3).

The Yatağan Formation in DSC area has highly variable lithology. Groundwater and/or surface water is quite active in this area. Water input increase into the karst rock enhances dissolution and transport of the mineral matter and may adversely modify the mechanical strength of the rock (Gutierrez et al., 2014). In DSC area, dense vegetation is present on top of the caves. The capillary root vessels of trees have penetrated into the Yatağan Formation at different places. The water follows those vessels during infiltration, and this causes weakening and disintegration of the host rock. The processes of weathering and removing of the mudstone of the Yatağan Formation, have started the formation of the caves. Then, water weakening the muddy matrix of conglomerate led to disintegration of clast, and enlargement of the caves. After the cave formation, dripping of the water along the root vessel led to the saturation of the water to calcium carbonate and formation of the stalactites, where it emerged on the ceiling of the cave. The groundwater seeping from the cave walls and flowing downwards resulted in occurrence of the flowstone as a plaster and travertine.

Human activities, such as excavation of caves for barn, storage and other purposes cause enlargement of the caves in Asar Hill area. Moreover, sewage system of the settlements on top of cave area also increase the dissolutional capacity of the water moving along fractures in AHC. Leakages from sewage may contaminate the groundwater circulating in the conglomerate of AHC. Enlargement of caves by dissolution, weakening and drop out of the rock material causes decrease in cap rock thickness (overburden thickness) in time. Recently DSC area is used as a recreation place with a restaurant. Thus human activities are threatening natural state of the caves. Continuous monitoring of the caves is necessary in DSC area. The movement of groundwater and surface water under natural conditions have to be continued and vegetation cover above the caves must be protected. Otherwise caves and their special textures may be damaged and irreversibly disappear.

The strength values of the AHC and DSC areas are very close. However, the porosity of the DSC samples is significantly higher than the AHC samples (Tables 2 and 4). The density values of the DSC samples are lower than the AHC samples (Tables 2 and 4). These features, with the contribution of groundwater and plant roots, ensured the formation of the largest cave in the DSC (Cave 3, Table 3).

Clastic rocks with various age and thickness host caves with different size in different part of world (Busche and Sponholz, 1992; Bergada et al., 1997; Kranjc, 2005; Aubrecht et al., 2008; Breitenbach et al., 2010; Lipar and Ferk, 2011; Awadh et al., 2013). Those caves are permanently or temporarily used for recreation and supplying shelter for both human and animal (Busche and Sponholz, 1992; Bergada et al., 1997; Kranjc, 2005; Aubrecht et al., 2008).

The Asar Hill and the Damlam Stream caves have some similarities and dissimilarities with the aforementioned caves. For example, Awadh et al. (2013) reported that the caves in Upper Miocene-Pliocene Injana Formation in Najaf-Karbala-Iraq area clastics. They mentioned that water circulation following the cracks led to softening, weakening and disintegration of claystone and formation of claystone balls, which are not observed in the Yatağan Formation.

Lipar and Ferk (2011) studied conglomerate caves in Udin Boršt in Slovenia which developed depending on physical weathering that evolved under the effect of karstification after deposition, thus they classified as eogenetic origin. They defined four different type of caves in conglomerates; linear stream caves (mouth of cave has 1 m high and a few meter-wide entrance, controlled by discontinuities formed as a result of temporary or permananent streams on terrain surface), shelter caves (formed in carbonate rocks, cave entrance has a few meter height and 10 m width, <10 m length (depth), matrix porosity and physical weathering is important), breakdown caves (formed as a result of collapse of previous cave), and vadose shaft (single, vertical tubular form, evolved as a result of the vertical water movement). Similar shaft occurences and enderheic plataeu collapse (doline, uvala) and small karren structures reported in Niger sandstone in Niger (Busche and Sponholz, 1992). Bergada et al. (1997) also reported vertical potholes development in Palaeocene conglomerates in Catalonia (Spain).

The caves in clastic rocks of the Yatağan Formation are example of the shelter cave (due to development in carbonate clast enriched conglomerate). Vadose shaft and other karstic structures were not detected in the study area. Absence of these structures may be explained with age (youth) of the formation and/or they may have been destroyed due to loose lithology of the Yatağan Formation. Permanent and temporary streams are located below the bottom level of the caves, so direct effects of them to cave formation were not observed.

Karst terrains may be affected by severe ground instability problems. Natural and human-induced static and dynamic loadings may trigger the collapse of the caves under marginal stability conditions (Gutierrez et al., 2014). The load imposed by heavy vehicles, drilling rigs, dumped material and engineered structures may cause dangerous sinkhole collapse events (Gutierrez et al., 2014). Impacts and hazards associated with karst are rapidly increasing as development expands upon these areas without proper planning taking into account the peculiarities of these environments (Gutierrez et al., 2014). The roof of a cave may collapse either in its natural state or under an imposed load from engineering activity. Natural collapse is by progressive failures of roof rock units, which may eventually reach the ground surface. Imposed loading may either accelerate or precipitate the natural processes of cave roof failure (Waltham, 2002).

Caves are very fragile geological occurences. Continuous monitoring of the caves, groundwater circulation, vegetation and structures are necessary for the protection of caves. Enlargement of caves and decreasing of overburden thickness may increase the collapse risk of the cave roofs. The possibility of collapse may threaten the property and human life in Asar Hill area, while in Damlam Stream valley, this may result in destruction of the specific cave structures.

6. Results

In the clastic rocks (conglomerates mainly composed of limestone pebbles) of the Yatağan Formation several caves with various size were observed in two areas. The caves in the study area differ in size, with length between 1.47-9.71 m, width between 2.24-19.36 m, and height between 1.38-27 m. The caves in the study area have the characteristics which are similar to that of shelter caves-described by Ferk and Lipar (2012).

Joint sets, bedding planes and tree roots constitute the routes for water percolation and circulation that weaken the muddy matrix of the thick and relatively low resistant conglomerate bed and mudstone. Matrix dissolution and weathering in conglomerates, results in clast-after-clast release and grain-by-grain disintegration. After the disintegration of the conglomerate, fragments have been washed. In addition to these general structural and lithologic properties, some local factors also play role in the development of the caves, (for example human impact in the Asar Hill caves and vegetation affect in the Damlam Stream caves). Human activities promote enlargement of caves in Asar Hill caves, while groundwater percolation along main and capillary vessels of the roots led to formation of small scale stalactites, flowstone and travertine deposits in Damlam Stream cave.

Surface and subsurface karstic features pose some potential hazards which must be considered for land use planning, construction, and water resource management. Caves and sinkholes present a hazard for construction processes and settlement areas. These karstic features may potentially impact the load-bearing capacity of the karstified rock. Thus, engineers and planners have to be interested in understanding the behavior of these karstic features and the potential geological hazards they may cause.

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