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ORIGINAL ARTICLE

Denizli Travertine: A Global Heritage Stone Resource Nominee from Western Türkiye

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Abstract
A global heritage stone designated by International Union of Geological Sciences (IUGS) is a natural stone that has been widely used in significant architecture and monuments, recognized as integral aspects of human culture.The aim of this study is to evaluate the characteristics of the Quaternary travertine formations located in Western Türkiye called *'Denizli Travertine'* as a global heritage stone candidate. The Denizli Travertine have been commonly used as building stones in the ancient cities of the Lycus Valley since the second century BC. The cotton-white *Pamukkale Travertine*, which was designated as one of The First 100 Geological Heritage by IUGS in 2022, is the recent part of the Denizli Travertine. The travertine-dominated structures have given a privileged feature to the aforementioned ancient cities. In these cities, public buildings such as theatre, agora, bath basilica, monumental fountain, bridges and fortification wall were predominantly built in travertine. Since the thirteenth century, the use of the travertine also continued in the buildings of Seljuk Period, like caravanserais, monumental tombs and castle walls. The travertine consists of carbonate minerals (i.e. mostly calcite, with less amount of aragonite) and is porous. The main texture is significantly wackestone to packstone including peloid, bacterial/crystalline dendrite, and coated grain. Another type is banded travertines, which occurs as a fissure fill or vein, have a completely crystalline texture and has been mostly used for decorative purpose. Contemporarily, the stone is widely used in many areas such as flooring, cladding, stair steps, countertops, table, coffee tables and sculptures and is traded worldwide, and therefore considered to deserve to be designated as a global heritage stone resource.

Keywords Denizli Travertine · Heritage stone · Ancient quarries · Western part of Türkiye

Introduction

Türkiye, a bridge between Europe and Asia, is very rich in terms of natural stone diversity, some of which have been widely used for several thousands of years (Kazancı and Gürbüz 2014). Among these, the Denizli Travertine (Özkul 2019; Özkul et al. 2013), Diyarbakır Basalts (Dursun 2019), Afyon Marble (Çelik and Sert 2020), Marmara Marble (Attanasio et al. 2008), limestones of the Midyat Group known as local names such as Şanlıurfa Stone, Mardin Stone, Midyat Stone and Nizip Stone (Öztürk-Tel and Sarıışık 2020, Kazancı and Adıyaman Lopes 2022) could be mentioned primarily. The Denizli Basin in Western Turkey, also called as 'Çürüksu Graben' or 'Lycus Valley' in antiquity is well known for its widespread travertine occurrences, precipitated from thermal springs during the Quaternary period. (Altunel and Hancock 1993; Kele et al. 2011; De Filippis et al. 2012; Özkul et al. 2002, 2013; Claes et al. 2015; Van Noten et al. 2019 and references cited therein). The world famous Pamukkale, which has been on the UNESCO World Heritage List as a natural and cultural heritage since 1988, is one of the amazing travertine locality in the basin. Currently, Pamukkale Travertines, have been designated as one of the The First 100 IUGS Geological Heritage Sites in 28th October 2022 (IUGS 2022).

In the Denizli Basin, four ancient cities (e.g. Hierapolis/Pamukkale), Laodikeia, Tripolis and Colossae) were established in the past, dating back to at least to the 2nd to third centuries BC. The cities mentioned above are mostly located on or near the travertine occurrences and their associated hot springs. Therefore, the travertine has been the most leading

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building stone in these ancient cities for thousands of years. Also today, the Denizli Travertines are still quarried, processed, and traded in domestic and foreign markets.

Similarly, a large amount of travertines in Rome, Central Italy called as *'Lapis Tiburtinus'* has been used in the construction of both ancient and modern architectural structures (Grawehr 2022). Because the Lapis Tiburtinus travertine formed during late Pleistocene, which exposed near Tivoli, approximately 25 km east of Rome, have been quarried for more than two thousand years (Faccenna et al. 2008).

Global Heritage Stone Resource (GHSR) is a scientific designation created and managed by the Heritage Stone Subcommission–HSS (IUGS/IAEG) to enhance the geological knowledge, use and conservation of natural stones of historical importance worldwide (Marker 2015; Pereira et al. 2015; Primavori 2015; Kaur et al. 2020a, b; Lahaye et al. 2022). Until today, 32 natural stones from 17 countries have been registered by the subcommission (https://iugs-geoheritage.org/designations-stones/).

The aim of this contribution is to nominate the Denizli Travertine as a Global Heritage Stone Resource (GHSR).

Geological Setting

The Denizli basin, one of the grabens in the extensional province of western Türkiye, is famous for its Quaternary travertine formations (Altunel and Hancock 1993; Koçyiğit 2005; Alçiçek et al. 2007; Özkul et al. 2013; Van Noten et al. 2013, 2019). The basin was bounded by normal faults along its northern and southern margins (Fig. 1). The faults and their accompanying fissures are natural pathways for the meteoric waters to percolate into the subsurface and hydrothermal fluids to come upwards the surface. There are many travertine masses, including world famous Pamukkale Travertine, in different parts of the basin (Altunel and Hancock 1993; Kele et al. 2011; Özkul et al. 2002, 2013; Claes et al. 2015).

The travertine deposits of Quaternary age are unconformably underlain by the Neogene sequence called as *'Denizli Group'* that is early Miocene to Pliocene in age (Alçiçek et al. 2007). The Denizli Group was divided into three formations i.e. Kızılburun, Sazak and Kolankaya that composed of alluvial, lacustrine and fluvio-lacustrine deposits, respectively (Fig. 2).

On the other hand, older basement rocks of Paleozoic to Mesozoic age are composed mostly of schist and marble that are attributed to the cover units of the Menderes Massive (Bozkurt and Oberhänsli 2001; Erdoğan and Güngör 2004; Candan et al. 2011). The marbles exposed around the Denizli Basin were grouped into three types such as white, gray veined and gray marbles depending on color, crystal size, crystal boundaries and foliation. Under the microscope, heteroblastic polygonal and homeoblastic polygonal textures have been observed. In the marbles main minerals are calcite and dolomite, however, quartz, muscovite, pyroxene and ferric iron oxides are also evident as accessory minerals (Koralay and Kılınçarslan 2015). The second group of the basement rocks is the allochthonous Mesozoic limestone, dolomite and gypsum of the Lycian Nappes (Fig. 2), which tectonically overlies the Menderes Massive (Okay 1989). The dolomite and gypsum in the nappes are Triassic in age (Gündoğan et al. 2008). The basement rocks cropped out on the graben shoulders and in the mountainous areas up to 2570 m asl in height (Fig. 1).

The Denizli Basin is also important in terms of its seismic activity as well as geothermal potential (Utku 2009; Kumsar et al. 2015; Bozkaya et al. 2024). The ancient city of Hierapolis at Pamukkale, for example, was damaged several times by the paleoearthquakes (Altunel and Barka 1996; Piccardi 2007) with magnitudes up to 6.0 (Hancock et al. 2000) that were triggered by normal faulting and extension of the basin (Kaypak and Gökkaya 2012).

Travertine

Travertine is one of the continental carbonates precipitated from hydrothermal springs that is relatively hard, crystalline, and less porous compared to tufa (Pedley 2009; Jones and Renaut 2010; Özkul et al. 2013).

Travertine, composed of various lithotypes that are observed easily on the hand speciment, block surface, tile, slubs, quarry walls and under the microscope, have been described as banded, crystalline crust, shrub, pisoid, paper-thin raft, coated bubble, reed, and lithoclast-breccia travertine (Guo and Riding 1998; Özkul et al. 2002, 2013; Claes et al. 2015). Field properties, textural, mineralogical and environmental characteristics of the leading lithotypes have been summarized in Table 1.

Mineralogy and Petrography of the Denizli Travertine

Calcite is the main mineral in all varieties of the Denizli Travertine. However, some types of the travertine (e.g. banded or vein travertine) include aragonite in various amounts and rarely dolomite according to XRD analyses (Kele et al. 2011; Özkul et al. 2013). Although micrite (grains <4 μm in dimension) is the most common, the banded travertine, crystalline crust travertine and secondary pore fills are formed mostly of spar and microspar calcite. Other than carbonate minerals, detrital minerals (e.g. quartz, gypsum, mica, goethite, smectite and kaolinite) are also present in very small quantities (Kele et al. 2011; Özkul et al. 2013; Soete et al. 2015).

Various names have been attributed to the travertine such as 'peloidal travertine', 'micritic dendrite travertine', 'dendrite crust travertine', 'shrub travertine', 'bryophyte travertine', 'reed travertine', 'reed phyto travertine', 'gastropod travertine',…etc. depending on the ratio of

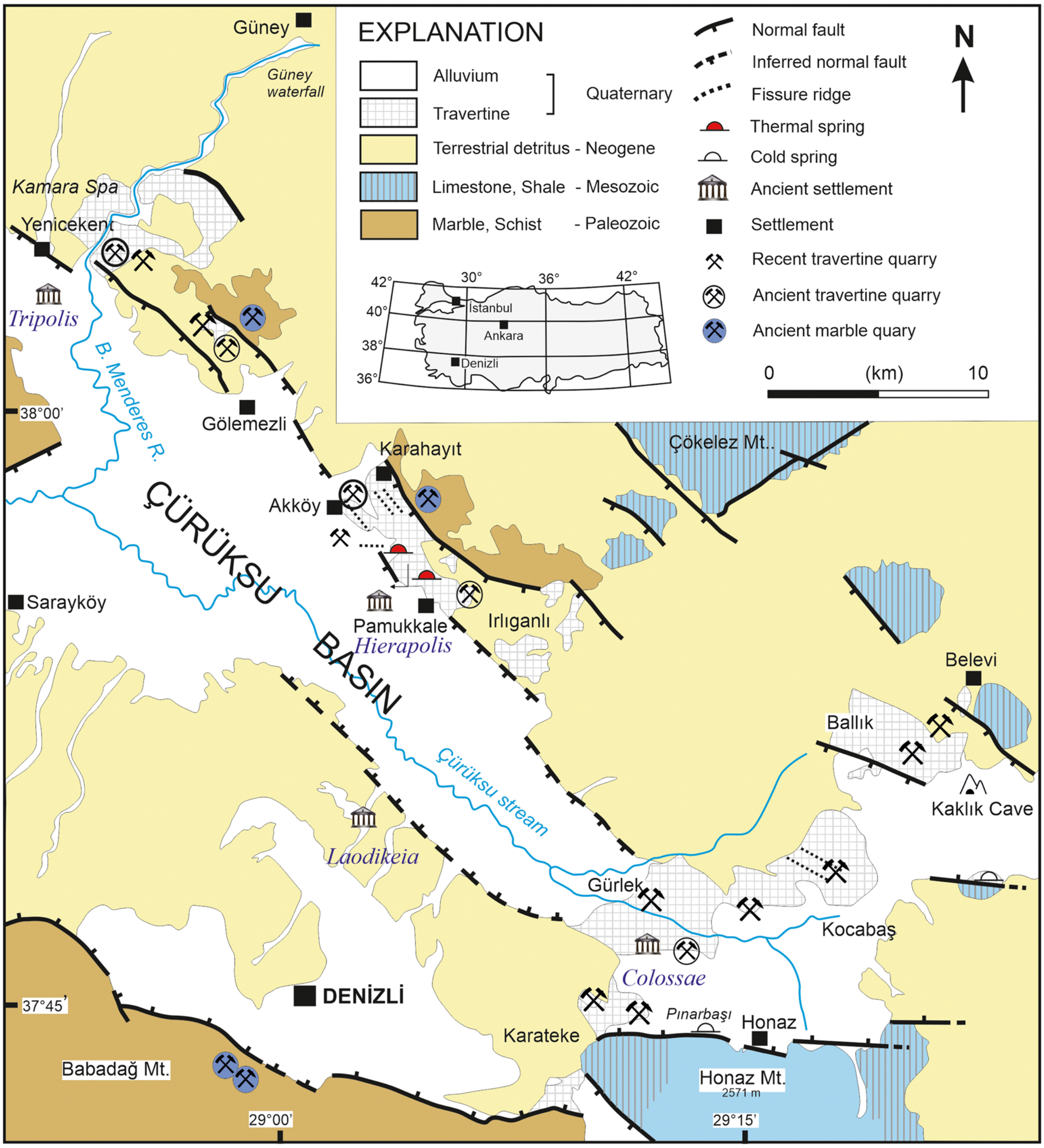


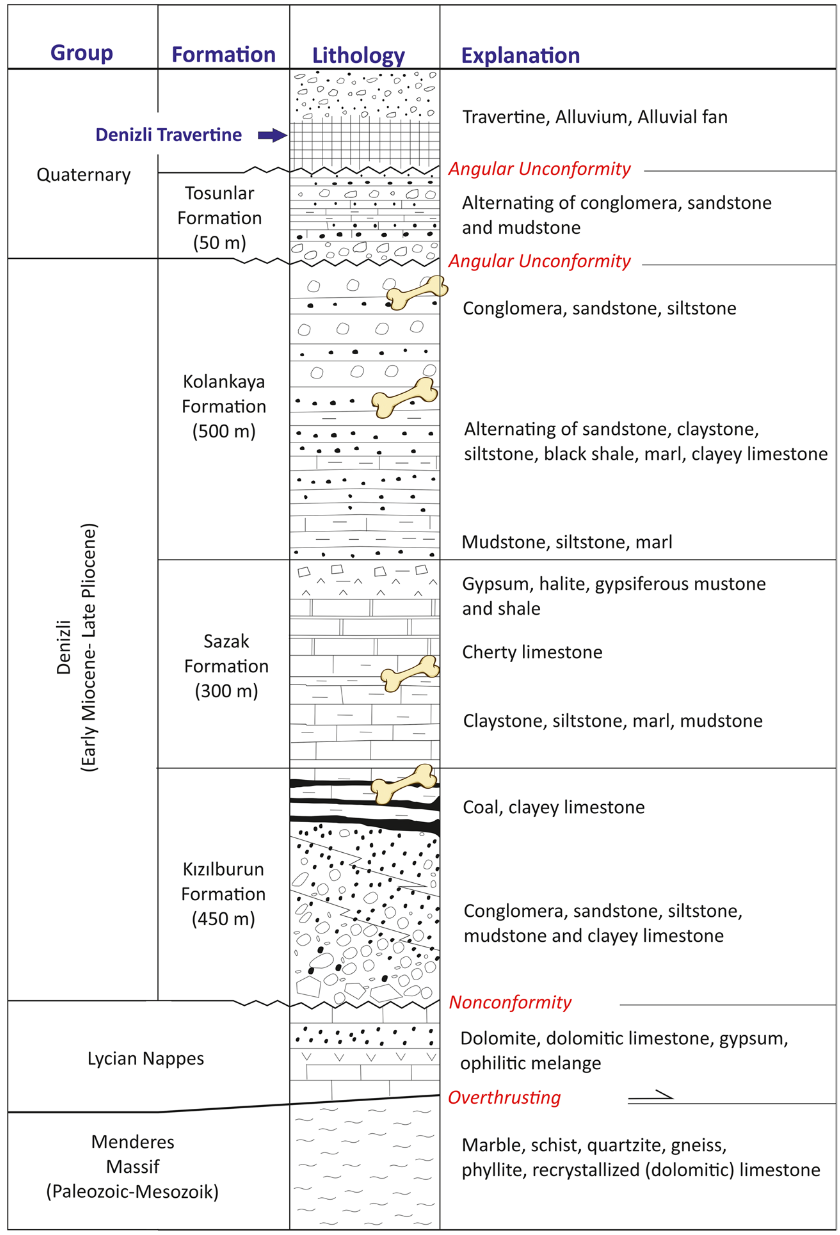
Fig. 1 Geological map showing the locations of travertine sites in the Denizli extensional basin (based on Sun 1990 and Özkul et al. 2002, 2013)

components such as peloid, phytoclast, cyanobacteria and crystalline dendrite and coated grains (e.g. pisolith, oncolith) (Table 1, Fig. 3) (see for more details Claes et al. 2015, 2017 and Aratman et al. 2020 references cited therein).

Chemical Composition

The chemical composition of the Denizli Travertine was carried out in detail in previous studies (Kele et al. 2011; Özkul et al. 2013; Lebatard et al. 2014; Claes et al. 2015, 2019; El Desouky et al. 2015). In these studies, along with major and trace elements, isotope data such as stable oxygen and carbon isotopes, Sr isotopes and fluid inclusions were also elaborated. Kele et al. (2011) focused only on the geochemistry of Pamukkale Travertine. On the other hand, the geochemical data provided by Lebatard et al. (2014); Claes et al. (2015, 2019) and El Desouky et al. (2015) are from the Ballık area. However, the geochemical data of Özkul et al. (2013) represent almost all travertine localities (Fig. 1). For this contribution, the major oxide components of the Denizli Travertine were compiled from Özkul et al. (2013) and their unpublished data (Table 2). Main component of the Denizli Travertine is CaO ranging from 50.57 to 56.36%.

Fig. 2 Stratigraphic succession of the rock units of the Denizli Province (modified from Alçiçek et al. 2007)

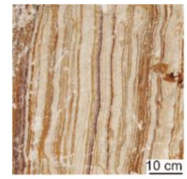
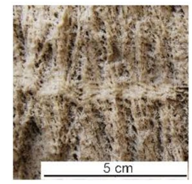
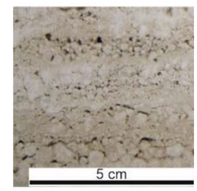
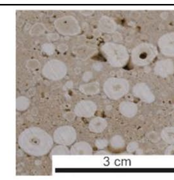
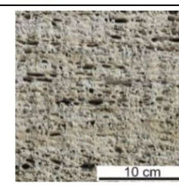
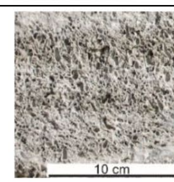
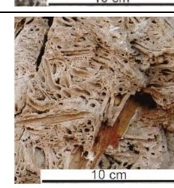
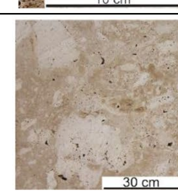


The second highest component, MgO, makes up between 0.02 and 0.84%. The Fe_2O_3 amount is 0.04 to 2.40%. In some travertines localities such as in Akköy and Karahayıt that are adjacent to Pamukkale, the iron content is higher compared to the others. In this case, the colour varies yellow–red to brown. The lowest Fe_2O_3 values were determined in the Pamukkale Travertines with 0.02–0.41%. The SiO_2 ratio appears in almost all travertines varieties between 0.01 and 0.65% (Table 2).

Technical Properties

The travertine samples collected from the different localities of the Denizli Basin (Fig. 1) have been analysed for physico-mechanical characteristics at the Rock Mechanics Laboratory of Department of Geological Engineering, Pamukkale University. Geotechnical properties of the travertine samples, which have been given in Table 3, compiled from the published data (Çelik et al. 2014; Çelik and Çobanoğlu 2019; Soete et al. 2015). Tests were conducted in accordance with the related European standards. Dry and saturated unit weights and open porosity values were determined in accordance with the TS EN 1936 (2007) standard. Water absorption values were determined in accordance with the TS EN 13755 (2003), capillary water absorption tests were conducted in accordance with the TS EN 1925 (2000) standard. Böhme and Wide Wheel abrasion tests values which are important values for building stones used as floor claddings

Table 1 Summary of the textural, mineralogical and environmental characteristics of the travertine lithotypes

Lithotype & References	Field Properties	Mineral Composition	Depositional Environment	Image
Banded Travertine (*Altunel and Hancock 1993,Özkul 2002, 2013,Capezzuoli et al. 2018*)	Dense, coarse crystalline, alternation of different colour laminae, nonporous	Mostly calcite, occasionally aragonite	Fault and/or fissure spaces	
Crystalline Crust Travertine (*Guo and Riding 1998, Özkul 2002, 2013*)	Dense, coarsely fibrous calcite feather crystals perpendicular to the depositional surface, less porous	Mostly calcite, occasionally aragonite	Slopes and cliffs from fast flowing thermal waters	
Shrub Travertine (*Guo and Riding 1998, Özkul 2002, 2013*)	Porous travertines layers dominated by small shrub-like growths, vertically orientated, 1-3 cm thick, irregular dendritic morphology	Mostly calcite	Formed mainly under microbial influence, subhorizontal surfaces in terrace pools and in depressions and flats	
Pisoid Travertine (*Guo and Riding 1998, Özkul 2002, 2013*)	Spherical, concentrically laminated, a few mm to cm in diameter	Mostly calcite, occasionally aragonite	Terrace pools, extensive pools in depressions from splashing and turbulent water.	
Paper-thin Raft Travertine (*Guo and Riding 1998; Özkul 2002, 2013; Shiraishi et al. 2023*)	Thin, delicate, brittle crystalline layers precipitated at the water surface	Calcite (common), Aragonite (less)	Formed by active $CaCO_3$ nucleation on the water surface in pools around thermal springs	
Coated Bubble Travertine (*Guo and Riding 1998; Özkul 2002, 2013*)	Gas bubbles coated by rapidly precipitated calcium carbonate	Mostly calcite, occasionally aragonite	Pool surfaces below	
Reed Travertine (*Guo and Riding, 1998; Özkul, 2002, 2013*)	Reeds coated by micrite, preserved as moulds, porous	Calcite	On mounds (reed mounds), near the bases of travertine slopes.	
Lithoclast-breccia Travertine (*Guo and Riding 1998*)	Layers tens of centimetres in thickness, interbedded with light-coloured travertines	Calcite	Penecontemporaneous erosion of slope travertines contributes significant volumes of angular grains, particularly to lower slopes to depressions	

were measured in accordance with the EN 14157 (2004) standard. Flexural strength under concentrated load and uniaxial compressive strength tests were determined in accordance with the TS EN 12372 (2001) and TS EN 1926 (2007) standards, respectively. Sonic wave velocities were measured on core samples in accordance with the ASTM D2845 (2000) standard. The Denizli Travertine has been regarded as a building stone based on the properties mentioned above.

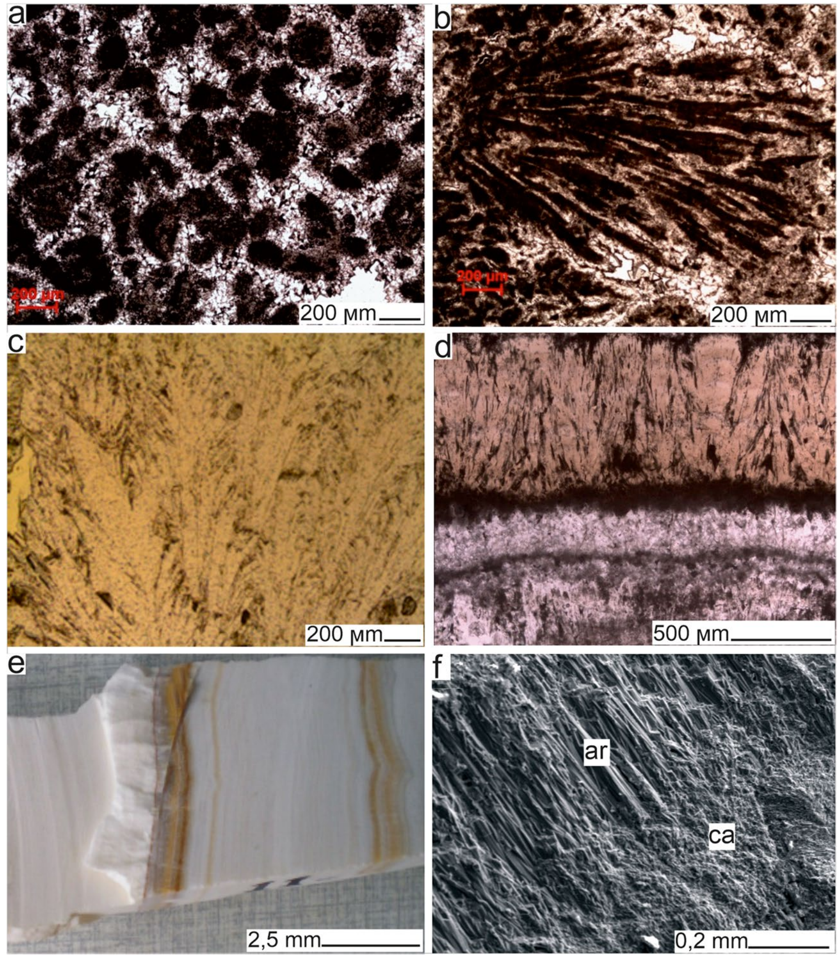


Fig. 3 Microscope and hand specimen images of the Denizli Travertine. (**a**) Peloidal travertine (peloidal micrite paches were cemented by spar calcite. PM: peloidal micrite). (**b**) Micritic dendrite travertine. Micritic dendrites in growing position to the right. (**c**) Crystalline dendrite travertine, (**d**) Crystalline banded travertine (**e**) Hand specimen of the banded travertine. White and brown layers on the cut surface composed of calcite and aragonite in different ratio, confirmed by XRD measurements. (**f**) SEM image of alternation of fibrous aragonite (ar) and rhombohedral calcite (ca) layers. (a, b, c, d from Claes et al. 2015 their Fig. 4b, e, I, k and e, f from Özkul et al. 2013, their Fig. 11a, b)

Quarries

The quarries of the Denizli Travertine have been grouped into ancient and recent quarries.

Ancient Quarries

Ancient travertine quarries are located mostly in Pamukkale, Karayıt and Yenicekent (Figs. 1, 4a-f). The field studies carried out at Pamukkale allowed to identify 21 banded travertine/alabaster quarries in a short distance from the city, within 3 km of the urban area (Scardozzi 2019; Scardozzi et al. 2019). Some of the quarries take place in the fissure ridges where particularly the banded travertine or alabaster were extracted in the central part along the ridge axis as in the Çukurbağ, Pamukkale (Fig. 4a-d) (Özkul et al. 2013; De Filippis et al. 2012; Brogi et al. 2014). In some cases, chisel marks can be observed on the quarry walls even today (Fig. 4b).

Second group of the ancient quarries are those excavated in the marbles of the Menderes Massive on the uplifted areas north and south margins of the graben (Fig. 1) (Koralay and Kılınçarslan 2015; Koralay 2017).

Recent Quarries

Recent quarries are distributed in different parts of the Denizli Basin (Figs. 1, 5). However, the quarries located mostly in the Ballık area, the number of which is around fifty there. Apart from Ballık, other travertine quarries located at Aşağıdağdere, Kocabaş, Gürlek, Karateke, Akköy, Gölemezli and Yenicekent (Fig. 1) (Özkul et al. 2013; Çelik et al. 2014). The travertine is quarried in blocks in open pit mines (Fig. 5a-d). On the other hand, the Denizli Travertine has been processed by more than 40 factories and workshops for years. In these stone processing units, the travertine blocks are cut into tiles and slabs of different sizes and shapes.

Table 2 Chemical composition of the Denizli Travertine

Locality	Sample ID	SiO_2 %	Al_2O_3 %	Fe_2O_3 %	MgO %	CaO %	Na_2O %	K_2O	TiO_2 %	MnO	LOI
(1)	1	0.18	0.07	< 0.04	0.84	55.75	0.04	0.02	< 0.01	0.03	42.9
	2	0.06	0.03	0.24	0.76	55.52	0.02	< 0.01	< 0.01	0.07	43.2
(2)	3	0.34	< 0.01	2.40	0.29	54.11	< 0.01	< 0.01	< 0.01	0.04	42.7
	4	0.02	< 0.01	< 0.04	0.02	55.50	0.03	< 0.01	< 0.01	< 0.01	43.6
	5	0.41	0.07	< 0.04	0.74	55.53	0.06	0.01	< 0.01	< 0.01	43
	6	0.11	< 0.01	< 0.04	0.54	56.36	0.04	< 0.01	< 0.01	< 0.01	42.7
	7	0.24	0.03	0.12	0.62	55.81	0.04	< 0.01	< 0.01	< 0.01	42.8
(2a)	8	0.13	< 0.01	< 0.04	0.38	55.79	< 0.01	< 0.01	< 0.01	0.15	43.3
	9	0.07	< 0.01	< 0.04	0.03	55.54	0.03	< 0.01	< 0.01	< 0.01	43.5
	10	0.15	< 0.01	0.32	0.13	55.44	0.04	< 0.01	< 0.01	< 0.01	43.2
(2b)	11	0.17	0.02	0.33	0.83	55.22	0.04	0.03	< 0.01	0.02	43.1
	12	0.41	0.11	0.87	0.38	54.84	< 0.01	0.02	< 0.01	0.03	43.2
	13	0.65	0.20	0.43	0.31	54.78	0.01	0.03	0.01	0.01	43.4
(3)	14	0.09	0.01	0.11	0.25	56.26	< 0.01 < 0.01	< 0.01 < 0.01	< 0.01	0.02	43.1
	15	0.28	0.07	< 0.04	0.54	55.30	0.01	< 0.01	< 0.01	0.01	43.7
	16	0.32	0.09	< 0.04	0.59	55.19	< 0.01	0.01	< 0.01	< 0.01	43.7
	17	0.13	0.02	< 0.04	0.54	55.53	< 0.01	< 0.01	< 0.01	< 0.01	43.7
	18	0.16	0.03	< 0.04	0.44	55.71	< 0.01	< 0.01	< 0.01	< 0.01	43.6
(4)	19	0.01	< 0.01	< 0.04	0.55	50.57	0.03	0.02	< 0.01	< 0.01	43.5
	20	0.57	0.09	0.30	0.59	50.63	0.02	0.02	< 0.01	< 0.01	42.7

Locality No: (1) Gölemezli, (2) Pamukkale, (2a) Çukurbağ, (2b) Akköy, (3) Ballık, (4) Kelkaya

Table 3 Geotechnical properties of the Denizli Travertine (Çobanoğlu and Çelik 2012; Çelik et al. 2014)

Parameter	Value Ranges	Test Standard	Reference
Dry unit weight (kN/m^3)	22.26 – 24.22	TS EN 1936 (2007)	Çobanoğlu et al. (2010); Çobanoğlu (2015); Çelik et al. (2014)
Saturated unit weight (kN/m^3)	22.75 – 24.52	TS EN 1936 (2007)	
Water absorption by weight (%) #	1.34 – 3.71	TS EN 13755 (2003)	
Water absorption by volume (%) #	3.41 – 8.71	TS EN 13755 (2003)	
Capillary water absorption (%) #	1.04 – 2.64	TS EN 1925 (2000)	
Open porosity (%) #	2.64 – 12.72	TS EN 1936 (2007)	
Böhme abrasion (cm^3/50 cm^2)	6.60 – 18.60	EN14157 (2004)	
Wide wheel abrasion (mm)	12.10 – 17.40	EN14157 (2004)	
Uniaxial compressive strength (MPa)	48.19 – 97.12	TS EN 1926 (2007)	
Flexural strength under concentrated load (MPa)	11.66 – 17.90	TS EN (1237)2. 2001	
P-wave velocity (km/s)	3.55 – 5.78	ASTM D2845 (2000)	Çelik and Çobanoğlu (2019); Soete et al. (2015)
S-wave velocity (km/s)	1.19 – 3.73	ASTM D2845 (2000)	
Poisson ratio	0.11 – 0.45	ASTM D2845 (2000)	
Modulus of elasticity (GPa)	7.92 – 68.05	ASTM D2845 (2000)	

Use of Travertine

Historical Use

In the past, the Denizli Travertine has been used widely for ornamental and building stone in ancient cities of the Denizli Basin in western Türkiye. In these ancient cities, from the first century BC, the travertine was the most leading building material in the construction of fortification, theatre, agora, stadium, street, bridge, fountain, monumental tombs and aedicula etc. (Table 4). For example, in Roman period, the Theatre, Plutonum, Frontinus Gate, Necropole and Hammam Basilica in Hierapolis (Fig. 6a-f) (D'Andria 2003); Temple A, Syrian street, southern bath-gymnasium, banded travertine columns (Fig. 7a-c) and water distribution terminal and aqueduct

Fig. 4 Some images from the ancient quarries. (**a**) An ancient quarry excavated along the fissure ridge axis in the middle part of the Çukurbağ Fissure Ridge (CFR), Pamukkale, (**b**) Close view from the quarry face, (**c**) Vertically oriented banded travertine layers at the CFR, (**d**) Close view of the vertically banded travertine layers, (**e**) An ancient travertine quarry in the south gate of Pamukkale, (**f**) An ancient quarry face located in the eastern side of the Büyük Menderes River valley, east of Tripolis, Yenice (photos—Mehmet Özkul)

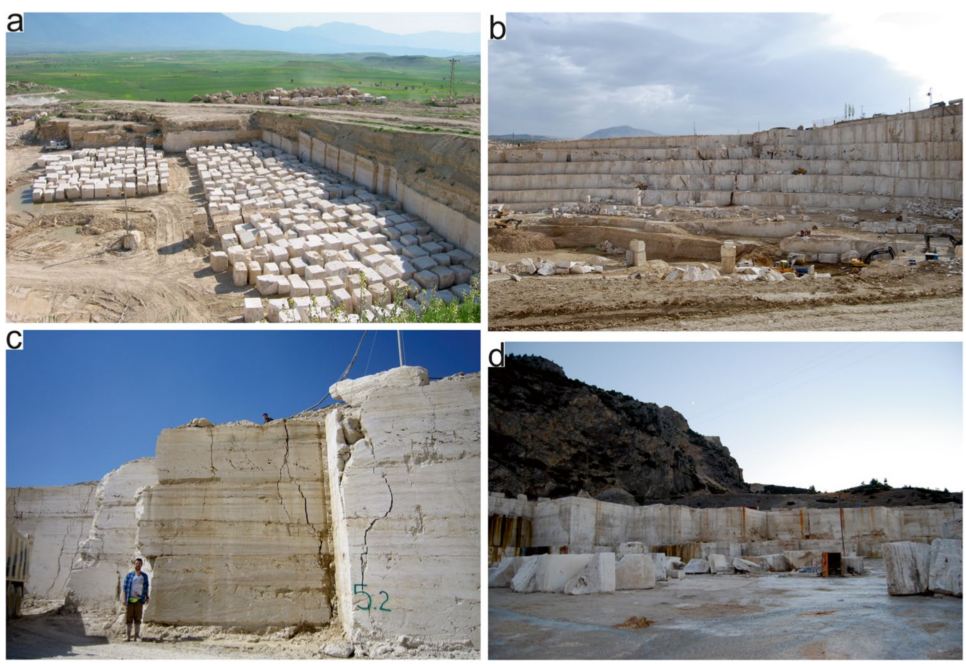


Fig. 5 Images of the recent travertine quarries from the Denizli Basin. (**a**) Travertine blocks and quarry face on the right, Çakmak quarry, southern boundary of the Ballık area, (**b**) Excavation steps from the Faber quarry, Ballık area, (**c**) Close up of a wire cut surface from the Faber Quarry, Ballık area, (**d**) A recent travertine quarry, northern apron of the Kelkaya hill, near Kaklık. Note that the Mesozoic basement limestones in the background

Table 4 List of the exemplary prominent buildings, monuments and sculptures built in the Denizli Travertine in the ancient cities of the Denizli Basin

Location	Name of Heritage buildings Monuments & coordinates	Description	References/ weblinks
Hierapolis Ancient city, Pamukkale, Denizli	Theatre 37°55′36″N, 29°07′44″E	Theatre is one of the most outstanding architectural heritages in Hierapolis that was built in third century AD (Fig. 5a). However, marble was also used as subsequent stone material, especially in the column production for the stage building	D'Andria (2003)
	Plutonium 37°55′35″N, 29°07′38″E	Plutonium, constructed in between 1st c. BC and 3rd c. AD. In front of the construction, there is a thermal spring and accompanying CO_2 degassing from cave that causes the death of living creatures. Due to these features, the cave was accepted as the entrance to the underground world (Fig. 5b)	D'Andria (2003) Pfanz et al. (2018)
	Northern Necropol 37°56′15″N, 29°07′13"	The Northern Necropolis dated back 1st c. B.C. contains characteristic sarcophagi, grave types and grave monuments from the Late Hellenistic period to the early Christian period. Mostly travertine and marble less amount were used in the Necropole structures (Figs. 5c, d)	D'Andria (2003)
Laodikeia Ancient City, Denizli	Temple A 37°50′10″N, 29°06′32'E	Mainly travertine blocks and subseently marble as column were used (Fig. 6a)	Şimşek (2007)
	Syrian Street 37°50′10″N, 29°06′30″E	The Street is extended in east–west direction. Floor of the street was paved with large travertine slabs, but, the columns on both sides along the street were made of marble (Fig. 6b)	
	Southern Bath-Gymnasium complex 37°49′53″N, 29°06′22″E	The complex, close to the stadium in the South, is made of smoothly cut travertine blocks (Fig. 6c). The travertine blocks of the walls are covered with marble. The construction year of the complex is 139 AD	
Tripolis Ancient City, Buldan, Denizli	Colonnaded Street	The Colonnaded Street called also 'Hierapolis street', 114 m in length, 10 m wide and east–west oriented and paved with large travertine slabs, in the Roman period	
	Nymphaeum *(*Monumental Fountain*)*	Monumental Fountain represents a transformation in construction technology between the Roman and Byzantine periods. Most of the columns used in the structure are made of banded travertine, except two that are granite of the Egyptian origin (Fig. 8b)	Duman (2013, 2017)
	Arched building	The Arched Building, built in travertine blocks, has rectangular structure. 10.6 m wide in N-S and 36.4 m in E-W direction. It was built in the Late Hellenistic – Early Roman period (Fig. 8d)	
	Latrina (Public toilet)	Public toilet, built in the travertine in the second century AD, is approximately 40 m^2 in size (Fig. 8c)	

Table 4 (continued)

Location	Name of Heritage buildings Monuments & coordinates	Description	References/ weblinks
Denizli, Türkiye	Akhan Caravanserai 37°49′09″N, 29°07′58″E	Built in 1253–1254 in Seljuk period by Seyfeddin Karasungur Bin Abdullah. Travertine blocks spoliated from Laodikeia were used in its construction (Fig. 9c)	Beyazıt (2017)

line made of travertine blocks (Fig. 8a, b) in Laodikeia (Şimşek 2007; Şimşek et al. 2022); the Hierapolis Street, Monumental Fountain (Nymphaeum), Public Toilet (Latrina), Arched Building (Fig. 9a-d) and Tower of the Castle complex, monumental tomb and bridge (Fig. 10a-d) all made of almost the travertine blocks in Tripolis are significant structures (Duman 2013, 2017).

On the other hand, the Tower belonging to the Castle complex in the north of Tripolis (Fig. 9a), built for defense and surveillance purposes in the thirteenth century AD (Duman 2013, 2015). Travertine, marble and schist were the main stone material used in the castle construction. The second example of the architectural heritage of the Seljuk period at Tripolis is Monumental tomb (Fig. 9b) that was

Fig. 6 Examples on the historical use of the Denizli Travertine at Hierapolis, Pamukkale (**a**) The Denizli Travertine used in Theatre, the ancient city of Hierapolis, Pamukkale, built in mostly travertine while the columns used in the stage building are made of marble (photo – Mehmet Özkul). (**b**) Plutonium built in the Denizli Travertine. Hierapolis, Pamukkale. In front of the construction (lower right), thermal water upwelling from the fault plane and CO_2 degassing from the cave to which is entered from arched gate (arrow) (photo – Mehmet Özkul), (**c**) A general view of the Northern Necropolis, close to the north gate of Hierapolis, Pamukkale (photo – Mehmet Özkul), (**d**) Close-up view of monumental tombs where travertine blocks were used in their construction (photo – Mehmet Özkul), (**e**) Hammam Basilica, Hierapolis (Pamukkale), in the construction of which Denizli Travertine was used The building was back tilted due to a paleoearthquake (photo – Hülya Özen). (**f**) Frontinus Gate (Northern Roman Gate), view to the southeast (photo – Hülya Özen)

Fig. 7 Some examples on the historical use of the Denizli Travertine at Laodikeia. **(a)** Temple A, the Laodikeia Ancient City Denizli (photo – Hülya Özen). Mainy travertine blocks and subsequently marble columns have been used, **(b)** Syrian street, the Laodikeia ancient city, Denizli. The street floor and walls on both sides are made of mostly travertine blocks, but columns along the street and a small amount of blocks were made of marble (photo – Mehmet Özkul), **(c)** The arched walls of the Southern Bath-Gymnasium where travertine was used in its construction, the Laodikeia ancient city, Denizli (photo – Mehmet Özkul). **(d)** Columns built in the banded travertine, the ancient city of Laodikeia, Denizli (photo – Mehmet Özkul)

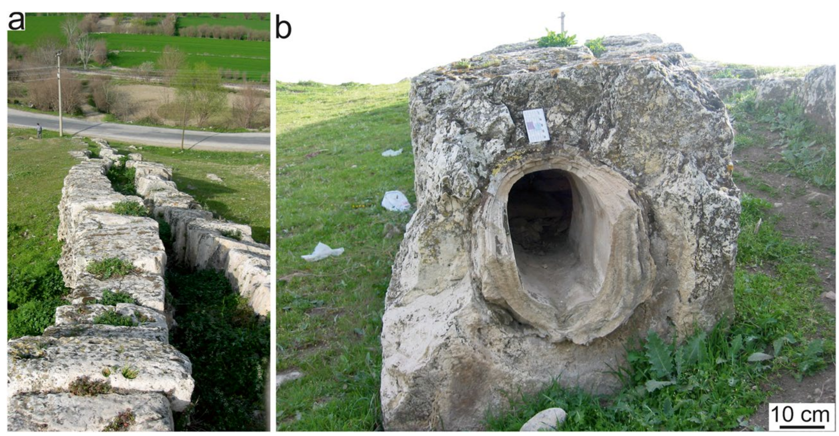


Fig. 8 **a** A historical aqueduct line made of travertine blocks to carry water in the Laodikeia Ancient City, **b** close up of the indivudual travertine aqueduct block, inside of which was scaled with calcium carbonate (photos – Mehmet Özkul)

built in fourteenth century AD (Duman 2013). The travertine and marble blocks used in these two buildings were collected from the Ancient City of Tripolis.

Other Historical Use

Apart from the buildings, some tools made of travertine such as gang saw relief that is a lid of an ancient Roman sarcophagus at Pamukkale (Fig. 11a, b) and a mortar at Karahayıt, 2 km northwest of Pamukkale (Fig. 12a) and olive oil processing stone at Tripolis (Fig. 12b) have been observed.

In addition, various marbles of the Menderes Massive, which is pre-Neogene basement rocks of the Denizli basin, shelly sandstones and pebbly sandstones from the Neogene sequences were the subsequent building stones used in the region.

The banded travertines among the travertine varieties, called also *'alabaster'* by archaeologists were commonly utilised for luxury or decorative objects. Small goods (i.e. bibelot, mosaic tables, vases of various form, bowls and dishes, drug jars) and greater objects (e.g. colossal statues, column, sarcophagi, ornamental tombs and street paving)

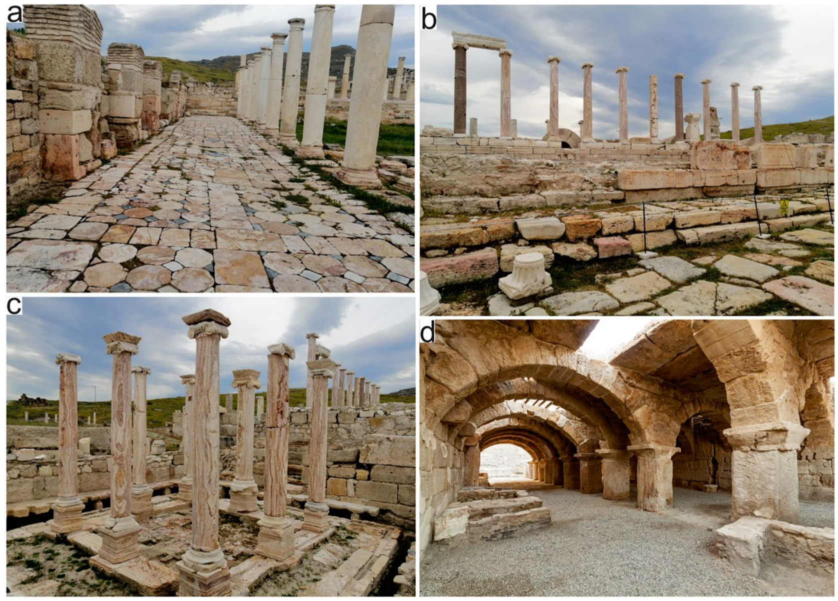


Fig. 9 Images of the historical use from the Tripolis ancient city. (**a**) Hierapolis street (photo–Bahadır Duman) (**b**) Monumental Fountain (Nymphaeum). 1st and 7th columns are granite from Egypt (photo – Mehmet Özkul), (**c**) Public toilet (Latrina) (photos – Mehmet Özkul) and (**d**) Arched building made of almost travertine blocks (photo – Bahadır Duman). Note that the main building material used in the constructions is travertine

Fig. 10 (**a**) Tower belonging to the Castle complex in the north of Tripolis, thirteenth century AD, built for defense and surveillance purposes (Duman 2013, 2015). Travertine and accompanying schist and marble were used in its construction. (**b**) Monumental tomb, fourteenth century AD, Seljuk period (Duman 2013). The travertine and marble building blocks used in the two buildings were collected from Tripolis Ancient City (photos–B. Duman). (**c**) Akhan caravanserai, Seljuk period, close the city center of Denizli (photo–M. Beyazıt), (**d**) Ahmetli bridge on the Büyük Menderes River north of the Sarayköy town (photo–B. Duman)

made up from the banded travertines, have been documented in many archaeological studies (Koralay et al. 2018). Even this variety with name of *'Coloured Hierapolis Marble'* was brought to Rome (Italy) during the Augustian period (Scardozzi 2019).

Contemporary Use

The first half of the 1980s was a milestone for the natural stone industry in Türkiye. Although Türkiye is rich in natural stone diversity, the number of stones quarried and processed until that time was quite limited. With the changes made in the mining law in these years, there has been a rapid development in the natural stone industry until today. Therefore, many quarries have been opened for various stones, factories have been established, and a significant part of the blocks and dimensional stones produced are exported worldwide. The Denizli Travertine is one of the leading stones mentioned above.

The architectural heritage built in the Denizli Travertine from two thousand years ago is still standing in the Çürüksu Graben. Influence of the semi-arid Mediterranean climate prevailing in the region is important factor in this statement. Contemporarily, a wide range of products of the travertine have emerged as a result of different processing techniques such as cuting (i.e. vein

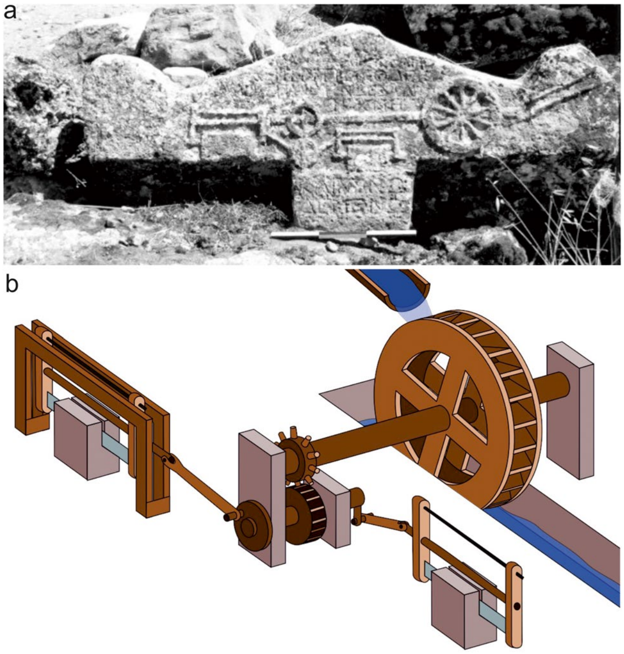


Fig. 11 (**a**) An ancient gangsaw relief on the lid of an ancient Roman sarcophagus carved into a travertine block, found in a burial chamber, which was tombstone of the craftsman, Hierapolis (Pamukkale), (**b**) fiction design of the gangsaw in **a**

cut, cross cut), filling, honing, etching, polishing, blasting, sandblasting… etc. The stone, which can be easily processed, is preferred due to its color variety, texture, soft-aesthetic appearance (Fig. 13) and price compared to the many other natural stones. In 2011, the Denizli travertine was officially registered for geographical indication on behalf of the Denizli Chamber of Commerce in Türkiye (Fig. 14). Some examples of the qualified buildings and monuments where the travertine used at home and abroad are shown in Fig. 15. Prominent constructions among these are the governor's building (Denizli, Türkiye), Forum Çamlık Shopping Center (Denizli, Türkiye), Doğramacızade Ali Paşa Mosque (Ankara, Türkiye), Yalıkavak Marina (Bodrum, Türkiye), Bahrain International Airport (Manama, Bahrain), Museum Ritter (Waldenbuch, Germany), Conservatorium Hotel (Amsterdam, Netherlands) and Miskolc University (Hungary) (Table 5, Fig. 15).

In addition to flooring and cladding, garden fountain, table, coffee table, stair, kitchen countertop and bathroom sink made up travertine could be mentioned. On the other hand, one of the natural stone companies in the Denizli province has been organizing International Sculpture Colony in front of the factory garden annually for a long time and many works of art sculptures have emerged. Some of the statues were made by carwing the travertine (Fig. 16a-d).

Fig. 12 (**a**) An ancient mortar carved into a travertine block, 1.5 m in dimension, Karahayıt to the northwest of Pamukkale (photo- M. Özkul), (**b**) Olive oil prossesing stone made of travertine block, ~ 2 m in dimension, ancient city of Tripolis (photo – B. Duman)

The Denizli Travertine is exported to many countries as blocks, tiles and slabs. The leading export countries are the United Arab Emirates, Saudi Arabia, Kuwait, Germany, Spain Poland, Greece, Romania, the U.K., the USA, Canada, Australia and New Zealand.

Conclusion

The Denizli Extensional Basin in western Türkiye has widespread Quaternary travertine exposures. These travertines are easy to process and suitable as building blocks. Petrographically, the travertine deposits are mostly porous and in micritic textures, except for several lithotypes such as the banded travertine and crystalline crust travertine. The Denizli Travertine has been widely used in many architectural heritages of the ancient cities of the Lycus Valley in western Türkiye from the third century BC to

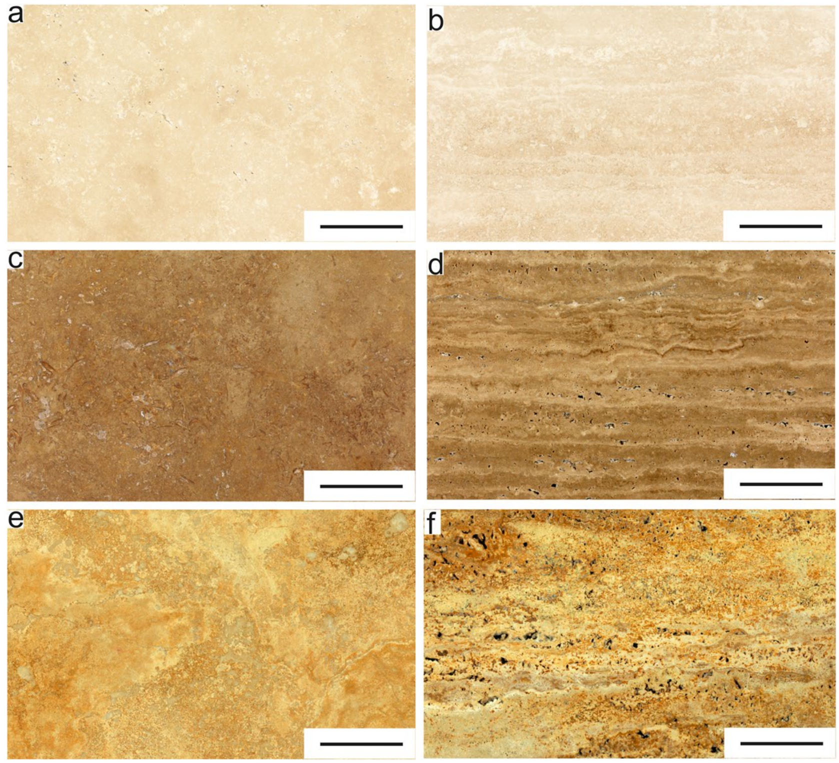


Fig. 13 Various images of the Denizli Travertine based on the color and cutting directions. (**a**) Denizli Travertine crosscut, (**b**) Denizli Travertine vein cut, (**c**), Denizli Travertine noçe cross cut, (**d**) Denizli Travertine noçe vein cut, e) Denizli Travertine-yellow travertine cross cut, (**f**) Denizli Travertine-yellow travertine vein cut. (Source: https://basaranlar.com.tr/tr/), Linear scale on each panel is 10 cm

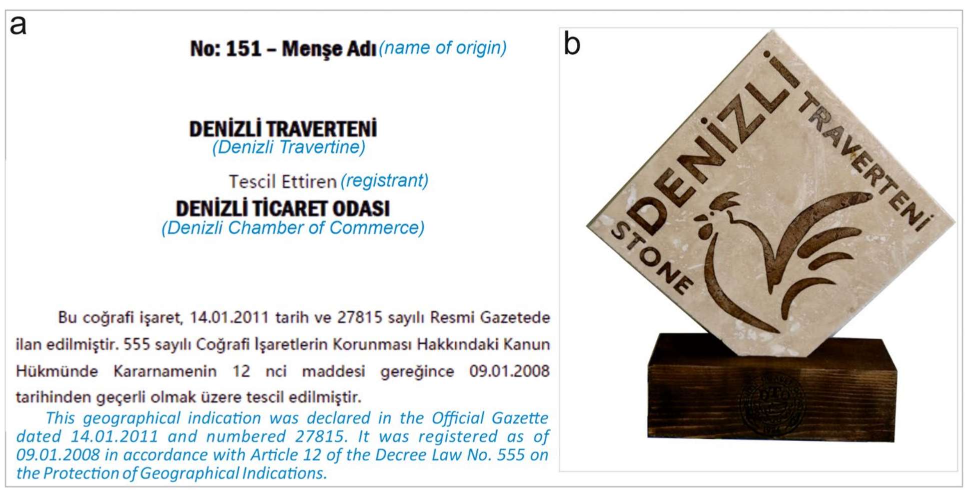


Fig. 14 (**a**) Document displaying the geographical indication of the Denizli Travertine, which was officially registered in the name of the Denizli Chamber of Commerce in 2011, (**b**) Logo of the Denizli Travertine. The logo engraved on a 15 × 15 cm travertine plate is placed on a wooden base (from Özkul 2019, his Fig. 8)

fourteenth century AD. For the last few decades, the stone increasingly demands in domestic and foreign markets due to its rich selections based on warm-feeling colours, and textures. The stone traded commonly as "Denizli Travertine" is sold as block and dimension stone including tile, slab, clad, countertop, sculpture, garden furniture, etc. It is exported to many countries from five continents i.e., countries of the Middle East and European Union, Taiwan, South Korea, the USA, the UK, Australia, Africa, and New Zealand. For the reasons mentioned above, we are encouraged to nominate the Denizli Travertine as a 'Global Heritage Stone Resource'.

Fig. 15 Views of some qualified buildings where the Denizli Travertine was used. (**a**) Governor's building (Denizli, Türkiye), (**b**) Doğramacızade Ali Paşa Mosque (Ankara, Türkiye), (**c**) Yalıkavak Marina (Bodrum, SW Türkiye), (**d**) Bahrain International Airport where the Denizli travertine was used. (https://alimoglumarble.com/projects), (**e**) Museum Ritter (Waldenbuch, Germany; https://archello.com/project/museum-ritter, (**f**) The Dubai Edition Hotel, United Arab Emirates, in which vein cut slabs of the Denizli Travertine were used (https://basaranlar.com.tr/en/references)

Table 5 Contemporary use of the Denizli Travertine

	Location	Name of Heritage buildings Monuments & coordinates	Description	References/ weblinks
1	Denizli, Türkiye	Government House 37°46′52″N, 29°05′05″E	Construction year: Completed in 2013 Archıtect: Sepin Architecture Architectures: Yavuz Selim Sepin, A. Ceylan, C. S. Gürbüz, E. Bal, T. Yüksek (Fig. 14a)	https://archello.com/brand/sepin-architecture
2	Ankara, Türkiye	Doğramacızade Ali Paşa Mosque 39°53′06″N, 32°45′40″E	Construction year: 2008 Architects: Erkut Şahinbaş, İzzet Fikirlier Oya Caymaz (Fig. 14b)	https://www.basaranlar.com.tr/
3	Bodrum, Muğla, Türkiye	Yalıkavak Marina 37°06′21″N, 27°16′57″E	Construction years: 2011–2014 Architecture: Emre Arolat Architecture (Fig. 14c)	https://www.basaranlar.com.tr/
4	Denizli Türkiye	Forum Çamlık shopping center 37°45′12″N, 29°05′27″E	Yellow travertine selection has been used for some exterior cladding. Completed in 2008	https://multi.eu/tr/portfolio/forum-camlik-turkey/; https://www.basaranlar.com.tr/
5	Manama Bahrain	Bahrain International Airport 26°15′55″N, 50°37′49″E	Construction years: Architecture: (Fig. 14d)	https://alimoglumarble.com/projects
6	Waldenbuch, Germany	Museum Ritter 48°38′20″N,9°07′18″E	Construction year: 2005 Architect: Max Dudler (Swiss). The Denizli Travertine was used in its exterior cladding (Fig. 14e)	https://www.museum-ritter.de/en/inhalt/home.html
7	United Arab Emirates	The Dubai Edition Hotel / 25°11′35″N, 55°16′50"	Some interior walls of the Hotel were covered by vein cut slabs of the Denizli Travertine (Fig. 14f)	https://www.basaranlar.com.tr/
8	Wiltingen, Germany	Van Volxem Weingut 49°38′41″N, 6°36′48"	Denizli Travertine cross cut was used in the project. Construction years: Italian architects from South Tyrol and an interior designer from Germany were commissioned for the construction	https://vanvolxem.com/en; https://basaranlar.com.tr/en/references
9	Amsterdam Netherlands	Conservatorium Hotel 52°21′30″N, 4°52′46″E	Construction year: 2012 Architecture: Lissoni&Partners	https://archello.com/project/conservatorium-hotel
10	Hungary	Miskolc University 48°04′48″N, 20°45′51″E	Construction years: Architecture:	https://www.basaranlar.com.tr/
11	South Korea	The Raum Convention Center 37°30′28″N, 127°02′22″E	Construction years: Architecture:	https://www.basaranlar.com.tr/
12	Denizli Türkiye	Forum Çamlık shopping Center 37°45′12″N, 29°05′27″E	Yellow travertine selection has been used for some exterior cladding. Completed in 2008	https://multi.eu/tr/portfolio/forum-camlik-turkey/
13	Denizli, Türkiye	Travertine sculptures 37°50′35″N, 29°08′34″E	Sculpture colony is organized annually at Denizli by the Nihat Kömürcüoğlu Culture, Art, Tourism and Promotion Foundation (Fig. 15a-d)	https://www.heykelkolonisi.com/; https://www.komurcuoglu.com.tr/

Fig. 16 Sculpture examples carved from the Denizli Travertine. (**a**) Piano, (**b**) Fish, (**c**) Feet, (**d**) Head (permission of the Sculpture Colony of Nihat Kömürcüoğlu Culture, Art, Tourism and Promotion Foundation) (https://www.heykelkolonisi.com/)

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Declarations

Conflict of Interest The authors declare no competing interests.

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