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GEOLOGICAL CHARACTERIZATION OF SIWAQA TRAVERTINE, SOUTH AMMAN, JORDAN

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ABSTRACT
Siwaqa travertine crops out, about 70 km away from Amman, just south of Siwaqa strike-slip fault. Calcite is the most dominant constituent. Travertine occurs in two main forms: laminated and vesicular (vuggy). Representative surface samples of travertine have been analyzed for the determination of their physical-mechanical properties. It was found that the pore structure, which was previously determined by the author by employing velocity of sound, porosity and degree of saturation, is the most important factor affecting the strength and other physical properties of the stone.

INTRODUCTION
The term travertine is derived from *Tivertino*; the old Roman name of *Tivoli* in Italy, where travertine forms extensive deposits. Travertine is defined as a freshwater accumulation of carbonates, precipitated from streams and spring waters, which display a wide range of conditions (Chafetz and Folk, 1984; Love and Chafetz, 1990). Creamy to white is the standard color but impurities result in yellow, brown, red and pink shades. Travertine has been used by the ancients as an ornamental stone in different parts of the world (Perath, 1984; ASTM C-119, 1987).

Travertine deposits occurring in Siwaqa area (Jordan), were studied during regional mapping and mineral exploration projects (Bender, 1968 and 1974; Sunna, 1974; Hakki and Sa'sa 1978; Khoury and Nasir, 1982; Technostone, 1984 Barjous, 1986; Moh'd 1999 a and b). The most recent work (Moh'd, 2001) has been initiated by the Natural Resources Authority of Jordan (NRA) to encourage investment in Siwaqa travertine. A second stage with detailed investigations and further drilling was recommended. The mineralogy and geochemistry of Siwaqa travertine has been studied in some detail (Moh'd and Abu Hamatteh, 2004).

The present project has been initiated to encourage investment in Siwaqa travertine. However, it has been intended that the work be reconnaissance in nature and not to drill more than nine borholes, which are to cover the whole area of travertine (16 km^2) during this stage. If positive results are obtained then more detailed investigations and drilling are to be carried out by interested parties (investors).

The present work was set to evaluate the Siwaqa travertine as a potential source for building and/or ornamental stone. It reports the exploration activities so far executed. Defining a geological framework for travertine (in terms of its geology, petrography, geochemistry, and extension) was seen to be very crucial for the subsequent evaluation of its geotechnical properties.

GEOLOGICAL SETTING
The study area is situated 70 km south of Amman and about 10 km east of the Amman-Desert Highway. Travertine, cropping out mostly east of the Hedjazi Railway

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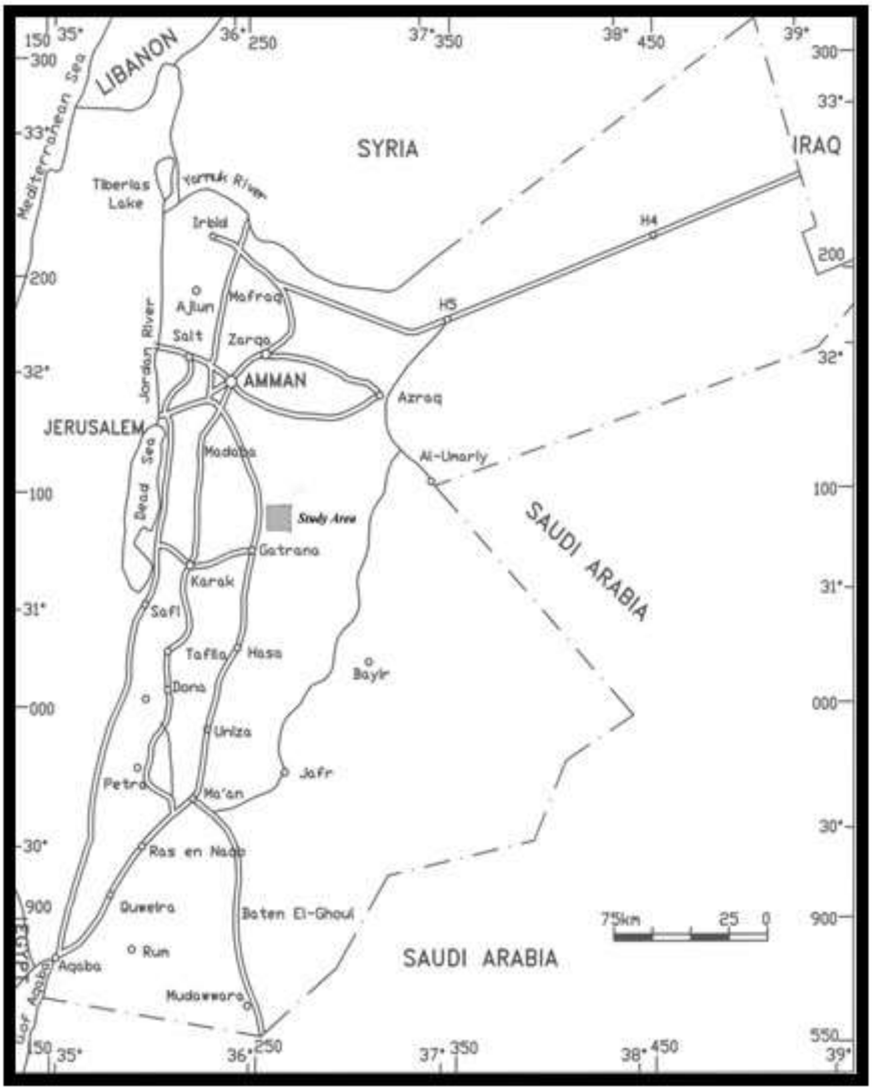

Figure 1 Location map of the study area.

Line, is limited in the north by the E-W trending, sinistral strike-slip Siwaqa Fault Zone. The eastern boundary is a major normal fault tending NW-SE east of which the Eocene chalks (Umm Rijam Formation) and the Mio-Pliocene Daba'a marbles are cropping out. The travertine deposit extends for 5 km in the E-W direction and 3-4 km in the N-S direction, thus covering an area of 16 km^2. Travertine occurs in a flat to undulating area and is divided by E-W wadi courses into four blocks. As travertine is relatively hard in comparison with the underlying chalk-marl lithologies (Muwaqqar Chalk Marl), it stands against erosion forming gentle hills. A summarized litho-stratigraphic succession of the subject area and adjacent areas is presented in Table 1.

Table 1 Lithostratigraphy of Siwaqa area.

Stage	Group	Formation/Unit	Lithology
Holocene		Siwaqa, alluvial	Travertine, conglomerate
Pleistocene			
Pliocene			
Miocene		Daba'a	Metamorphic marble
Oligocene			
Eocene	B a l q	Umm Rijam	Chalk, chert, limestone

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Paleocene		Muwaqqar	Chalk, marl, oil shale
Maestrichtian		Al-Hisa	Phosphorite, coquina, chert
Campanian		Amman	Chert, limestone
Santonian		Umm Ghudran	Chalk, chert, tripoli, dolomite
Coniacian			
Turonian	Ajlun	Wadi As Sir	Limestone, dolomite

FİELD WORK
Before drilling was started, all outcops of travertine in Siwaqa sheet were visited to select the best areas for further exploration. Some outcrop areas were dropped because of one or more of the following reasons: limited outcrop area, high degree of silicification, extensive weathering and/or fissuring, inconsistency of thickness, color, and hardness and unsuitability for mining.

Emphasis has been placed upon the area just south of the Siwaqa Fault Zone. Of this area, travertine outcrops lying west of the Railway are thin, and have poor quality as a source of marble panels. A quite big outcrop of coquina (about 1 km south-west of Mahattat Siwaqa) has erroneously been mapped as travertine. So from practical point of view this area is unsuitable for travertine extraction.

Most of the time has been spent in checking travertine outcrops lying east of the Railway. This area according to Siwaqa Goelogical Map (Barjous, 1986) constitutes the best and most continuous travertine outcrop. However, our fieldwork proved that the travertine outcrop area shown on Siwaqa sheet is highly exaggerated and some mixing up has been made between travertine and the MCM chalk and chalky limestones. This necessitated re-mapping the lower contact of travertine.

SAMPLES AND METHODS
Following our reconnaissance field visits, it was decided to execute the work in the following stages:
1) Re-elaboration of the lower boundary of travertine.
2) General geological investigation of outcrops and boreholes.
3) Drilling 9 boreholes covering the outcrop area (16 km^2) and penetrating the full thickness of travertine.
4) Characterization of the mineralogy, chemistry of the deposit by the drilled holes and 5 outcrop block samples.
5) Carrying out some engineering tests on 5 outcrop block samples.
6) Evaluation of the obtained results.

RESULTS
Re-elaboration of the lower boundary of travertine
For the purpose of our study bedrock ranging from Wadi As Sir Formation (WSL) to MCM has been considered as one unit referred to as pre-travertine bedrock (PTB). Furthermore, outcrops of travertine less than 2m in thickness (especially if their horizontal extension is small) have been ignored. A geological map of a scale 1: 50 000 was prepared to emphasize the lower boundary of travertine. Mapping was based on data obtained from field work, surveying by a distomat, drilling activities, aerial photographs analysis, and the information obtained from the available geological data of NRA (Hakki and Sasa, 1978, Barjous, 1986) and other sources (Technostone, 1984). The newly established map (Figure 2) shows a smaller outcrop area and higher base of travertine in comparison to that of Barjous (1986).

Pre-travertine bedrock **(PTB)** on the geological map includes Wadi As Sir **(WSL)**, Umm Ghudran **(WG)**, Amman **(ASL)**, Al-Hisa **(AHP)**, and Muwaqqar **(MCM)**, Umm Rijam **(URC)** and Daba'a formations/Units. Umm Rijam and Daba'a units are absent in the Siwaqa travertine area and outcrop dominantly near the eastern boundary fault.

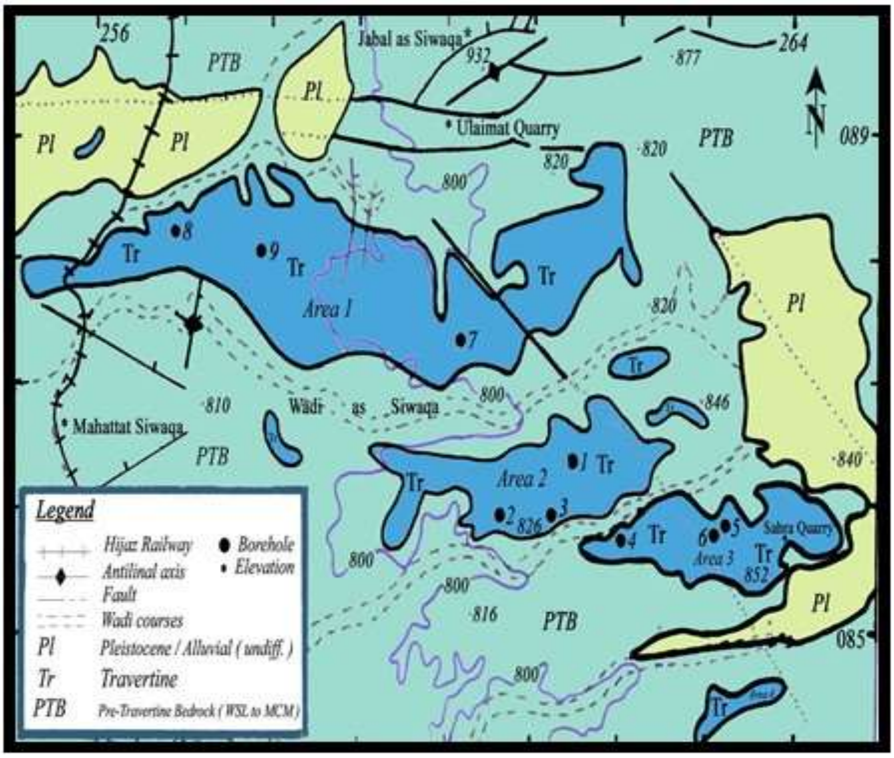

Figure 2The newly prepared map of Siwaqa travertine.

PALEOTOPOGRAPHY OF THE DEPOSİTİONAL BASİN

The lower contact of travertine is erosional and locally marked by lenses of conglomerate. As paleotopography is one of the most important factors controlling the deposition of travertine, it will be useful to get an idea about the nature of the surface above which travertine was deposited. A structure contour map was prepared for the base of travertine using 100-reference outcrop points (surveyed by a Distomat) in addition to outcrop data and subsurface information (obtained by drilling 9 boreholes). An east-west cross section of travertine is shown in Figure 3. It can be seen that in a two kilometers distance, the lower contact drops in elevation from 850 m in the eastern part to 756.5 m in the western most part to. As seen in the cross section ABC, there are three benches. The benches, from east to west, occur at 845-.

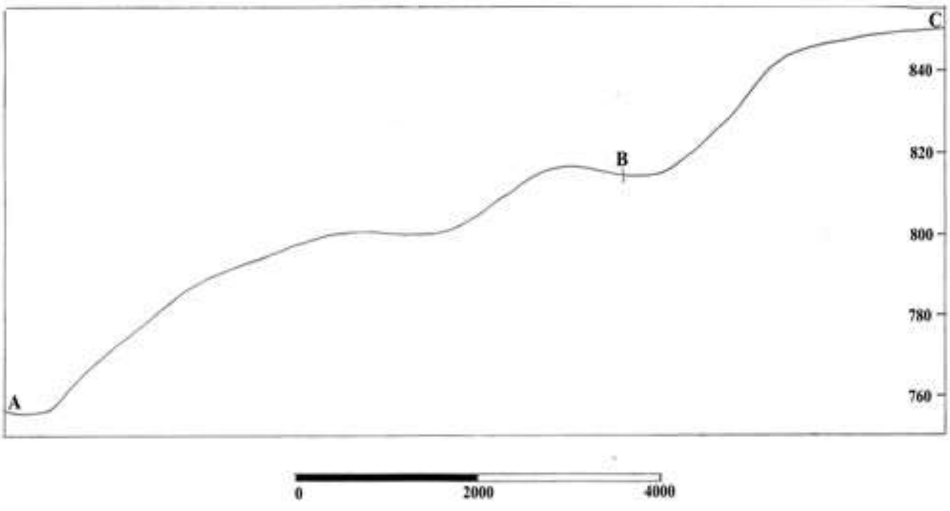

Figure 3An east-west cross-section in travertine

850 m, 815 m and 800 m, above sea level and extend for the following distances: 0.8 km, 0.6 km, and 0.5 km, respectively. the gradients of the slopes separating the benches, from east to west, are as follows: 0.045, 0.025, and 0.019, respectively

Drilling of boreholes
The boreholes were drilled to give a general idea about the quality and extension of the deposit. Most of the boreholes have been located in the central part of the study area where travertine thickness is the highest. Core drilling was executed by the Drilling Division/Exploration Directorate of the Natural Resources Authority using a Tuna drill rig.

The results of drilling activities are summarized in Table 2. It can be seen that 9 boreholes were drilled to evaluate the extension of travertine (in addition to two boreholes drilled in 1999 as part of the Grey Limestone Project).

TRAVERTINE LITHOFACIES
Siwaqa travertine unit is up to 20 m in thickness. The interbedded conglomerate is up to 7 m in thickness. Travertine consists of the following varieties (Figure 5): massive (vuggy), and laminated. These varieties are interbedded with conglomerate. Massive vuggy travertine with plant remains (reeds?) is the most dominant lithofacies. Finely laminated travertine is less common. Conglomerate marks the lower erosional contact of travertine unit. It also occurs as horizontal interbeds with the different varieties of travertine. Oligomictic and polymictic conglomerate types are common.

Table 2 Summary of drilling results.

Bore Hole No.	East.	North.	Elevation (m)	Travertine Thickness (m)	Total Depth (m)	Remarks
TRS1	261.482	86.374	830.45	19.5	20.0	+7.0m conglomerate
TRS2	260.679	85.904	825.67	11.2	39.0	+2.5m of conglomerate
TRS3	261.232	85.939	825.70	14.0	19.0	+6.0m of conglomerate
TRS4	262.043	85.730	833.32	14.0	19.0	+4m conglomerate
TRS5	263.263	85.844	850.40	13.5	20.0	Very little conglomerate.
TRS6	263.188	85.788	849.36	14.0	18.0	No conglomerate
TRS7	260.206	87.374	817.14	+7.0	7.0	2.0m of conglomerate
TRS8	256.913	88.242	778.50	1.5	10.0	NO conglomerate
TRS9	257.931	88.031	795.12	5.0	20.0	NO conglomerate
SIGL10	261.592	88.954	847	2.5	12.0	NO conglomerate
SIGL11	261.624	89.228	852	7.5	17.0	NO cong., good RQD

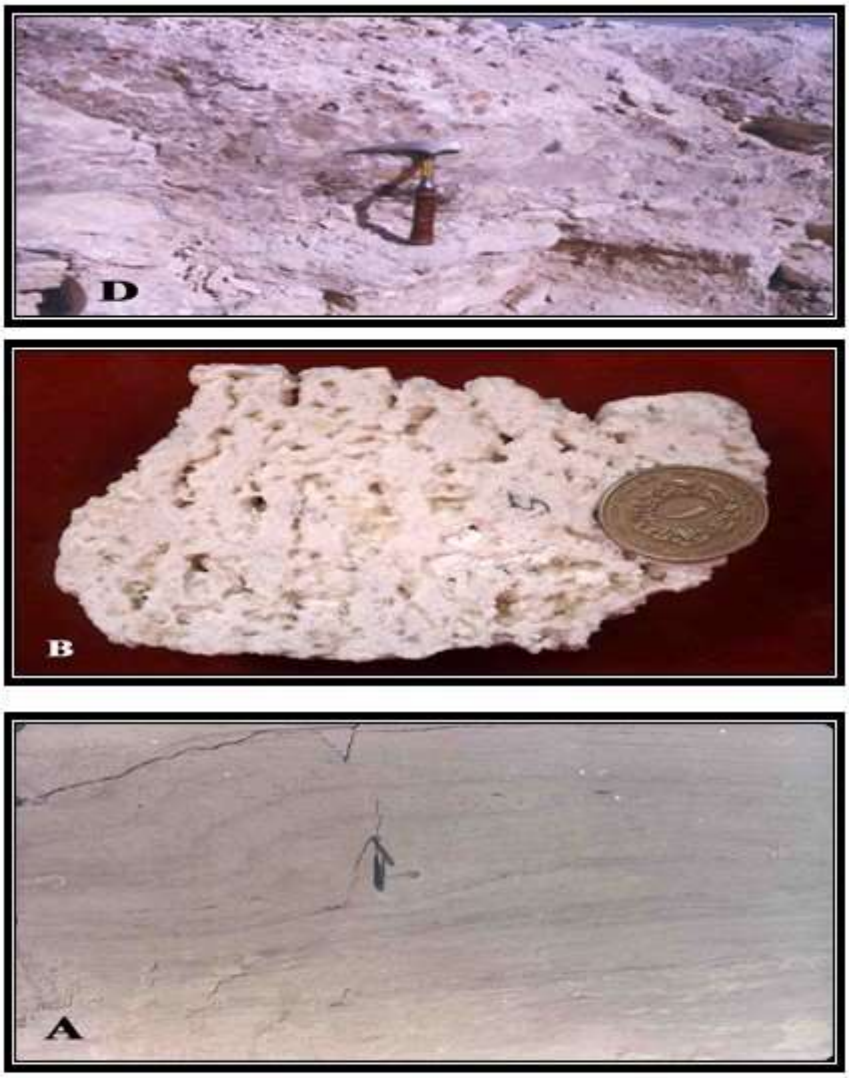

FIGURE 5 LAMINATED TRAVERTINE A (LOWER), VUGGY TRAVERTINE B (MIDDLE), AND CONGLOMERATE CEMENTED BY TRAVERTINE D (TOP).

MINERALOGY AND GEOCHEMISTRY

Results of XRD analyses indicate that calcite is the predominant phase. However, traces of quartz, gypsum, bassanite, apatite, kaolinite, dolomite and hematite are also present. Quartz is a primary component in the alluvial facies interbedding with travertine, as well as a silicification product of travertine itself. Gypsum and bassanite constitute irregular thin bands in some boreholes and forms a secondary product that fills joints and fractures. Apatite, dolomite and kaolinite phases are most dominant in the country rock underlying travertine. These phases are present in very low amounts in travertine. Hematite is slightly enriched in the conglomeratic alluvial phase. Leaching of the latter has presumably resulted in different degrees of pink-red color and departure of travertine from its cream-white color.

CaO, and SiO_2 are considered to be major oxides whereas Al_2O_3, total iron, MgO, Na_2O, K_2O, and P_2O_5 are considered as minor oxides. The CaO content varies between 39.4 and 54.9% with an average of 50.19%. CaO is present almost exclusively in the form of $CaCO_3$.

The MgO (0.09 to 1.7%) content of limestone generally reflects the presence of dolomite, but may also be associated with some clay minerals. Al_2O_3 is generally present at levels of less than 2%, this being associated with higher levels of MgO, SiO_2, total iron and Na_2O, indicating the presence of clay minerals. TiO_2 is present at concentrations of less than 0.05%. The total iron content of most samples is less than 1%. P_2O_5 content is not significant. SiO_2 ranges from 0.04 to 12.53%, the average being 3.88. SiO_2 in limestone is generally associated with clay minerals, the silicification of particles (e.g., fossils) and/ or the matrix, or with the presence of detrital quartz. Siwaqa travertine is relatively rich in some trace elements, which reach levels similar to those found in oil shale and some marble varieties (Khoury and Nasir, 1982). An example of this is chromium in volkonskite mineral which imparts a green color to the creamy white Siwaqa travertine. For further details on the mineralogy and geochemistry of Siwaqa travertine see Moh'd and Abu Hamatteh (2004).

PHYSICAL-MECHANICAL PROPERTIES

There are wide variations in all the properties tested. These variations may be ascribed to one or more of the following factors: holes and cavities, original texture, irregular distribution of impurities, thickness of bedding, and degree of diagenesis (the latter greatly affects hardness). Table 3 shows the statistical parameters of the measured physical-mechanical properties including density (dry and bulk), water absorption, total porosity, water saturation, and crushing strength. The author (Moh'd, 2007) characterized perophysically the secondary porosity of some Jordanian building limestones amongst them Siwaqa travertine. Laminated variety has fracture type secondary porosity as indicated by < 2 cementation exponent m value, whereas the vesicular type has vuggy secondary porosity (with >2 cementation exponent m value).

There are contradictory results when using different properties to classify travertine into stone groups. Using the bulk density values of the tested samples, they are classified, according to the Jordanian Standard of Building Stone No. 851/1992, as:

- 43% as class A (minimum 2.56 g/cm3)
- 57% as class B (minimum 2.56 g/cm3)

All the values are above 2.305, which is the minimum value, required for travertine to be used as a marble stone according to the Jordanian Standard for Natural Marbles No. 618/1989.
According to the Jordanian Standard of Building Stone (No. 851/1992), Class A has a 3% maximum value of water absorption, whereas Class B maximum water absorption value 4.2%. The tested samples are classified as follows:

- 32% as Class A
- 29% as Class B
- 39% as classes C&D

On the other hand, based on the crushing strength (the Jordanian Standard of Building Stone No. 851/1992), the tested samples lie in classes B (minimum 285.4) and C (minimum 122.3 kg/cm^2).

Table 3 Statistical parameters of the measured physical-mechanical properties.

	Dry density	Bulk density	Water absorption.	Effective porosity.	Total porosiy	saturation	Crush. Str.
Unit	g/cm^3		%	%	%		MPa
Mean	2.27	2.55	4.99	10.84	16.28	0.63	217.40
Standard Error	0.03	0.01	0.59	1.13	1.16	0.03	36.94
Median	2.29	2.55	3.24	7.53	15.50	0.65	231.00
Mode	2.27	2.55	#N/A	17.88	16.24	#N/A	#N/A
Standard Dev.	0.17	0.05	3.10	5.98	6.16	0.14	82.60
Sample Variance	0.03	0.00	9.59	35.72	37.97	0.02	6823.3
Kurtosis	-1.55	-0.93	-1.55	-1.60	-1.55	-1.51	-1.75
Skewness	-0.25	-0.11	0.58	0.54	0.25	-0.21	-0.35

Range	0.47	0.19	8.42	16.15	17.34	0.42	200.00
Minimum	2.02	2.45	1.87	4.60	8.12	0.40	109.00
Maximum	2.49	2.64	10.29	20.75	25.46	0.82	309.00
Sum	63.53	71.26	139.82	303.59	455.72	17.76	1087.0
Count	28.00	28.00	28.00	28.00	28.00	28.00	5.00

Discontinuities and Suitability
Travertine is intersected by a network of joints, fractures and veins. Two joint sets (almost vertical: northwest- and northeast trending) are, more or less consistent. Fractures occur in any direction. Some of these systematic (joints) and random fractures are filled with calcite, thus forming veins a few mms to 2cm in width.

In the Sahra quarry, travertine is extracted from two benches. The lowest, around 4m thick, is a massive, vesicular cream, yellow, and green travertine. It contains brecciated clasts of chert, limestone, chalk, or marble up 30 cm in length. The upper bench is 4-5 m in thickness with dominantly vesicular travertine alternating with finely laminated travertine. Occasionally, there are discontinuous conglomerate bodies. The topmost 2-3 m is thinly bedded travertine, which is unsuitable for extraction. The quarry produces blocks 1mx1.5mx2m. The Schmidt hardness of two blocks ranges from 35-58 MPa with an average of 47.7 MPa.

Siwaqa travertine has been extensively used in building the walls of the stations between Jiza and Qatrana along the Hedjazi Railway in the early 20th century.

CONCLUSIONS & RECOMMENDATIONS

Conclusions

1) The lower contact of travertine constitutes an ESE-WNW depression, roughly parallel to the present drainage, with a difference in elevation of almost 100 m.
2) The higher eastern margins grade to the lower western end by a step-like section consisting of three horizontal benches and three gentle slopes.
3) Vuggy travertine (with plant remains) is dominant.
4) Travertine biochemical deposits (3-19.5 m thick) were interrupted by three cycles of clastic sedimentation (represented by up to 7.5 m of monomictic and polymictic conglomerate) and karsting.
5) Calcite is the most dominant constituent.
6) Dolomite, quartz, kaolinite, gypsum, bassanite and hematite (that present in minor amounts), in addition to volkonskoite (a chromium-rich clay mineral) may have resulted in the departure of travertine from its creamy white color.
7) The better quality of travertine in area 3, in comparison to that of central part of area 2, is ascribed to the absence or low proportion of conglomerate.
8) Pore structure controlled the quality of travertine. Laminated travertine in comparison to the vuggy variety is stronger, denser, and with lower values of porosity and consequently water absorption and water saturation.
9) The vuggy variety may be used as is indoors. For outdoor uses it is highly recommended that its vugs being filled by epoxy or other fillers.

RECOMMENDATIONS

For the purpose of decoration stone exploration, it is recommended that a few more boreholes be drilled outside the concession area of the Sahra Quarry in Block 3 as well as, the area lying between boreholes TRS1, TRS3, and the Gray Limestone Quarry in Block 2. The suggested program of drilling will also be useful for evaluating of travertine in industrial applications.

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