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Geohistorical Structural Design Tables for the Building Stones of the Maltese Archipelago

Abstract

The engineering properties of building materials are essential knowledge when it comes to structural design. In 1885, the Crown Agents for the Colonies published a study on the resistance of Malta stone to cracking and crushing, in an attempt to develop stress design tables for local masonry. This article addresses the evolution of geological maps in the nineteenth century and, then, introduces the content of this publication. The geological formations described in the latest map are still used to this day. Finally, it discusses the usefulness of these tables in establishing the mechanical properties that Maltese stone can withstand. To identify the quality of the stone discussed in this publication, a geological map available at the time, namely that published by Andrew Leith Adams in 1870, which proved to be moderately accurate, was used. The testing procedures applied followed the accepted laboratory practice at the time. A retrospective analysis of the contents of this publication reveals that the results contained some mathematical errors.

Keywords: *stress design table, stone testing, Malta stone, Andrew Leith Adams, Crown Agents for the Colonies, Malta*

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Geohistoryczne strukturalne tabele projektowe kamieni budowlanych Archipelagu Maltańskiego

Abstrakt

Właściwości inżynieryjne materiałów budowlanych są niezbędną wiedzą przy projektowaniu konstrukcji. W 1885 roku agenci koronni ds. kolonii opublikowali badanie dotyczące odporności kamienia maltańskiego na pękanie i kruszenie, próbując opracować tabele obliczeniowe naprężeń dla lokalnego kamieniarstwa.

W artykule omówiono ewolucję map geologicznych w XIX wieku, a następnie przedstawiono treść niniejszej publikacji. Formacje geologiczne opisane na najnowszej mapie są wykorzystywane do dziś. Na koniec omówiono przydatność tych tabel w ustaleniu właściwości mechanicznych, jakie może wytrzymać kamień maltański. Do określenia jakości omawianego w tej publikacji kamienia wykorzystano dostępną wówczas mapę geologiczną, a mianowicie opublikowaną przez Andrew Leitha Adamsa w 1870 r., która okazała się umiarkowanie dokładna. Zastosowane procedury badawcze były zgodne z przyjętą wówczas praktyką laboratoryjną. Retrospektywna analiza zawartości tej publikacji pokazuje, że wyniki zawierały pewne błędy matematyczne.

Słowa kluczowe: *tabela projektowa naprężeń, badanie kamienia, kamień maltański, Andrew Leith Adams, agenci koronni kolonii, Malta*

1. Introduction

Geological maps represent not only the locations of geological structures but also the distribution of mineral resources. Such maps are the primary source of information on a given terrain. Oldroyd undertook a comprehensive survey of their development.[1] As Ciancio and Laurenza note, he made "an optimal use of the method of searching for the economic interests involved in mapmaking".[2] The oldest surviving geological map, the Turin Papyrus Map, is dated 1150 BCE, during the reign of Ramesses IV (1151–1145 BCE); it was discovered around 1824.[3] This map not only depicts the distribution of sedimentary and igneous/metamorphic rocks but also includes important landmarks. According to Harrell and Brown, "it predates by 29 centuries the next oldest known geological map" and was drawn "as an aid to or a record of one of this king's bekhen-stone quarrying expeditions to Wadi Hammamat".[4]

The French geologist Jean-Étienne Guettard (1715–1786), the author of the *Carte Mineralogique de Pologne*,[5] published a memoir in 1746.[6] Accompanying it is a map of the chalk distribution around the Paris Basin extending to southern Britain. This is a drawing of the distribution of just one formation and thus some geologists do not consider it to be a geomap.[7] A major milestone in the history of mapping geology was in 1815, when British geologist William Smith (1769–1839) produced a geological map of Britain — *A Delineation of the Strata of England and Wales, with part of Scotland*[8] — that included more than one formation shown in different

[1] Oldroyd 1996; Oldroyd 2013.
[2] Ciancio, Laurenza 2018, p. 404.
[3] Harrell, Brown 1992a; Harrell, Brown 1992b.
[4] Harrell, Brown 1992a, p. 3.
[5] Guettard 1764, p. 336.
[6] Guettard 1746.
[7] Bentley at al. 2023.
[8] Smith 1815.

colors.[9] Furthermore, Smith introduced a conceptual geologic cross-section illustrating the overall geological structure and how the various strata relate to one another.

Smith's map was published in the same year the Congress of Vienna affirmed Malta's status as a British Crown colony. Malta here refers not only to the main island which bears this name but also its dependencies, including the islands of Gozo and Comino. Malta became a British protectorate voluntarily in 1800, but Britain failed to comply with the Treaty of Amiens of 1802 which obliged it to vacate the island. In 1813, Britain established Malta as a Crown Colony, a position confirmed by the Treaty of Paris in 1814.[10] This gave rise to a public administration and an educational system which increasingly reflected developments in Britain. The result was a colonial mentality which persists in today's Malta, six decades after gaining independence in 1964. The structures of education and practice in the arts and sciences closely follow the Anglo-Saxon model.[11] Malta still relies on expertise from Britain in numerous spheres, including the mapping of the geology of the Maltese Islands.

With respect to the earliest geological mapping of the Maltese Archipelago, this article addresses a chart — presented in table format — issued in the latter part of the nineteenth century by the Crown Agents for the Colonies, which states the thrusting stress, that is compressive stress in contemporary terminology, of the limestone of the Maltese Islands.[12] Such mapping is relevant to relate the quality of limestone to the geological formations identified at the time. The structural engineering properties of the stones of Malta were a legitimate concern. Although works commenced on the Rotunda of Mosta in 1833 and were completed in the 1860s in local stone,[13] the erection of the Anglican pro-cathedral in the capital Valletta, which commenced in 1839, was halted and work already completed had to be removed and rebuilt due to cracking and crushing of the local stone.[14] The objectives of this article are (i) to outline the findings and (ii) assess and interpret them with respect to the geological and engineering knowledge of the time. Thus, the article presents a historical overview of the development of the geological map of the archipelago and discusses the main contents of the chart with respect to the latest map available at the time of its publication.

2. Historical overview of the geological mapping of Malta

The earliest geological maps, published between 1843 and 1890, were reviewed by Gauci and Schembri.[15] These versions were authored by Thomas Abel Brimage Spratt (1811–1888), Lord Henry John Reynolds-Moreton (1827–1921), Fredrick Wollaston Hutton (1836–1905), Andrew Leith Adams (1827–1882), and Sir John Murray (1841–1914). Spratt, the first pioneer to work on the geology of the Maltese Islands,[16] produced the first geological map of the archipelago based on systematic descriptions of its geological features less than three decades after Smith's map.[17]

[9] Schneiderman 2015.
[10] Pirotta 1996.
[11] Pirotta 1997.
[12] Crown Agents for the Colonies 1885.
[13] See, Bianco 2019.
[14] Borg 1982; Caruana, Gingell Littlejohn 1998.
[15] Gauci, Schembri 2017; Gauci, Schembri 2019; Gauci, Schembri 2022.
[16] Zammit-Maempel 1989.
[17] Spratt 1843.

A second was published in 1852[18] and reprinted with variations in 1854,[19] the year Reynolds-Moreton's map was published, although it appeared after Spratt's map. Hutton's map is based on his 1863 visit to Malta;[20] Gozo and Comino were not included. Adams revised the classification of the map made by Reynolds-Moreton;[21] the latter is considered to be "the first complete geological map showing both the structure and the lithology of the Islands".[22] Adams's map (Fig. 1),[23] the first to be published in color, included five strata. He published a revised version in 1874;[24] his 'sand' formation was integrated as part of the Upper Limestone (UL), a point also noted by Zammit-Maempel.[25] The geological map produced to accompany the publication authored by Murray[26] is the datum to the twentieth-century maps. The geological formations as included in these nineteenth-century maps are given in Table 1.

The 1955 geological map — known as the British Petroleum (BP) map — was published by the Ordinance Survey,[27] the UK's national mapping agency. It is based on a survey undertaken by Sir Kingsley Charles Dunham (1910–2001), Michael Robert House (1930–2002) and Albert Aloysius Wilson. The Greensand formation was integrated as part of the Upper Coralline Limestone (UCL). The resurvey of this map by Hugh Martyn Pedley[28] was published in 1993 by the Oil Exploration Directorate (OED), Office of the Prime Minister of Malta. This map subdivided the following formations into a number of lithostratigraphical members: UCL, Globigerina Limestone (GL) and Lower Coralline Limestone (LCL). UCL is composed of the Ġebel Imbark, Tal-Pitkal, Mtarfa and Għajn Melel members; GL is composed of Upper Globigerina Limestone, Middle Globigerina Limestone and Lower Globigerina Limestone (LGL), whilst the LCL is composed of Il-Mara, Xlendi, Attard and Magħlaq members. Printed on two sheets by the British Geological Survey (BGS),[29] the OED map was subsequently digitized in 2016 by the Continental Shelf Department (CSD) (Fig. 2). The latest geological map, issued by the CSD in 2022,[30] is a resurvey by the BGS of the 1993 map;[31] it differs from the nineteenth- and twentieth-century versions as it introduced a sixth formation, the San Leonardo, and a further member in the UCL formation, namely, Tal-Mas. Alongside Murray's, the geological formations, inclusive of the relative members, as included in the twentieth- and twenty-first-century versions of the map, are given in Table 2.

[18] Spratt 1852.
[19] Spratt 1854.
[20] Hutton 1866.
[21] Earl of Ducie 1854
[22] Continental Shelf Department b.
[23] Adams 1870.
[24] Adams 1874.
[25] Zammit-Maempel 1989.
[26] Murray 1890.
[27] British Petroleum Co. Ltd 1955a; British Petroleum Co. Ltd 1955b.
[28] Continental Shelf Department b.
[29] Oil Exploration Directorate 1993a; Oil Exploration Directorate 1993b.
[30] Continental Shelf Department 2022.
[31] Continental Shelf Department b.

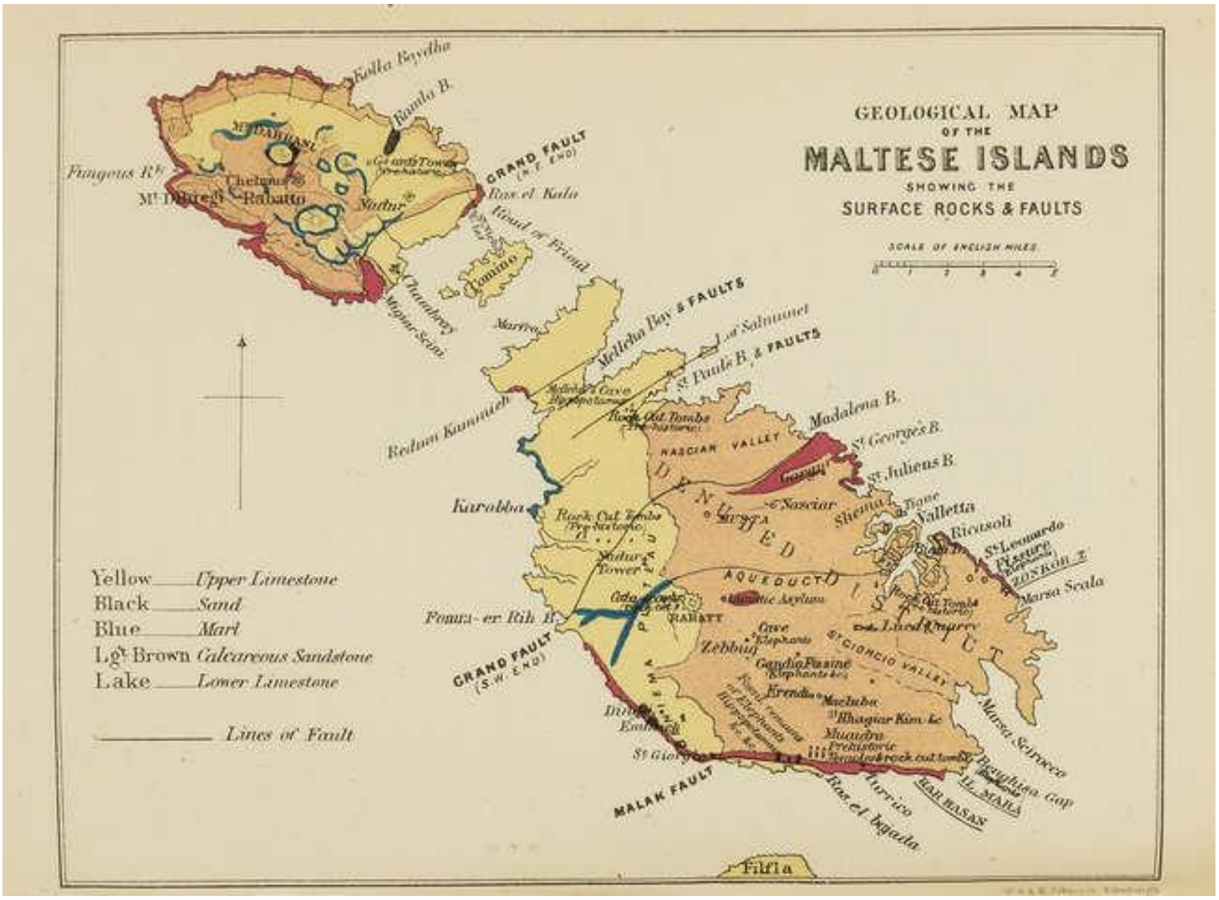

Fig. 1 Geological map produced by Adams.
Source: Adams 1870.

Table 1.[32]

Spratt[33]	**Spratt**[34]	**Hutton**[35]	**Adams**[36]	**Murray**[37]
				Alluvium
Coral Limestone	Coralline Limestone and sandstone	Upper Limestone	Upper Limestone (UL)	Upper Coralline Limestone (UCL)
Yellow sand or sandstone; Marl (dark blue clay)		Heterostegina Bed	Sand	Greensand
	Marl	Marl	Marl	Blue Clay
Freestone: Calcareous sandstone (white); Marl (blue-grey or fawn); Calcareous freestone (pale yellow or white); Calcareous sandstone;	Calcareous sandstone (white)	Freestone	Calcareous Sandstone (CS)	Globigerina Limestone (GL)

[32] Table 1 is based on Gauci, Schembri 2022.
[33] Spratt 1843; Spratt 1852.
[34] Spratt 1854.
[35] Hutton 1886.
[36] Adams 1870.
[37] Murray 1890.

Calcareous freestone (yellow white)				
Semi-crystalline sandstone	Semi-crystalline sandstone	Lower Limestone	Lower Limestone (LL)	Lower Coralline Limestone (LCL)

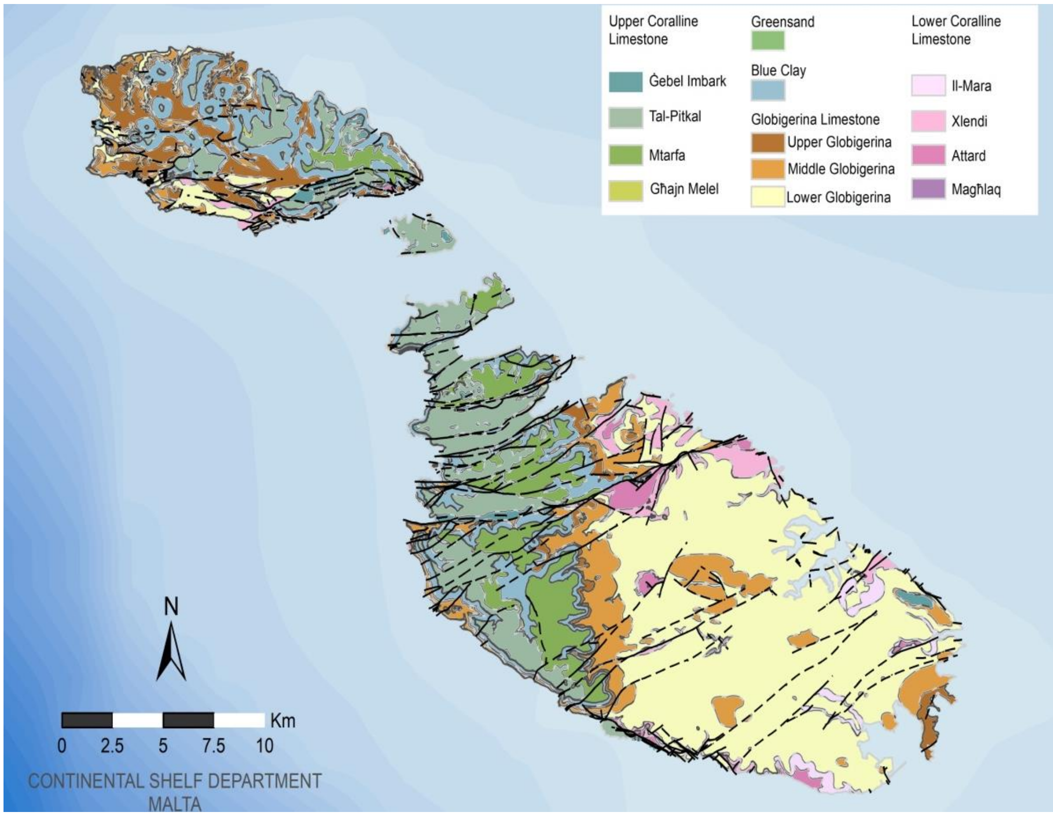

Fig. 2 Geological map digitized in 2016 by the Continental Shelf Department, Malta. Source: Continental Shelf Department a.

Table 2.

Murray[38]	**BP**[39]	**OED**[40]	**BGS**[41]
Alluvium		Alluvial	Alluvial
			San Leonardo
Upper Coralline Limestone (UCL)	UCL	UCL Members: 1. Ġebel Imbark 2. Tal-Pitkal 3. Mtarfa 4. Għajn Melel	UCL Members: 1. Ġebel Imbark 2. Tal-Pitkal 3. Mtarfa 4. Tal-Mas 5. Għajn Melel
Greensand	Greensand	Greensand	Greensand
Blue Clay	Blue Clay	Blue Clay	Blue Clay

[38] Murray 1890.
[39] British Petroleum Co. Ltd 1955.
[40] Oil Exploration Directorate 1993a; Oil Exploration Directorate 1993b.
[41] Continental Shelf Department 2022.

Globigerina Limestone (GL)	GL	GL Members: 1. Upper Globigerina Limestone 2. Middle Globigerina Limestone 3. Lower Globigerina Limestone (LGL)	GL Members: 1. Upper Globigerina Limestone 2. Middle Globigerina Limestone 3. Lower Globigerina Limestone (LGL)
Lower Coralline Limestone (LCL)	LCL	LCL Members: 1. Il-Mara 2. Xlendi 3. Attard 4. Magħlaq	LCL Members: 1. Il-Mara 2. Xlendi 3. Attard 4. Magħlaq

Given that the chart of the Crown Agents was issued in 1885, from all the maps published in the nineteenth century only the one preceding this date, namely Adams's 1874 version, was the most recent at the time of its publication. Given that this map (i) was not specifically about geology, and (ii) served to plot the locations of beds, faults, ossiferous caves and fissures, it is not considered a geological map.[42] Thus, to meet the objectives of this article, Adam's 1870 version was considered (Fig. 1). Furthermore, to evaluate the Crown Agents' publication with respect to the latest geological maps, the digitized version of the OED map was used (Fig. 2). Thus, one will be able to read the contents of the chart with respect to the geomap at the time and nowadays. This further gives insight into the awareness of geological literature by engineers researching the mechanical properties of the building stones of Malta.

Nowadays, various terms with respect to stone quality are used in the local building industry. Traditionally, quarrymen in Malta classified the limestone of the islands into five types:[43]

1. first quality, known as żonqor (or qawwi) tal-prima;
2. second quality, known as żonqor (or qawwi) tas-sekonda;
3. third quality, known as franka;
4. second-class, third quality, known as soll or tas-sekonda; and
5. heat-resistant, known as tal-kwiener or tan-nar.

The first-quality outcrops occur in the Upper and Lower Coralline Limestone strata. Generally, the second quality occurs within both. Franka, soll and tan-nar are present in what, following Murray,[44] is known as the GL formation. Similarly, the qargħajja and the kaħla occur in this formation; neither are utilized in the building industry due to their weak properties for civil engineering works.

The building stone of Malta has long been sought in other countries.[45] It is a resource still utilized in both new construction and in the restoration of the significant stock of heritage buildings in Malta, some of world heritage significance,[46] including the national capital in its entirety.[47] Indeed, given the rapid depletion of this industrial mineral resource, the Government of Malta made

[42] Gauci, Schembri 2019.
[43] Bianco 1995.
[44] Murray 1890.
[45] Ellul 2010.
[46] UNESCO a.
[47] UNESCO b.

a case to retain the status quo regarding the exportation of stone during the country's European Union accession procedure.[48]

3. The publication of the Crown Agents for the Colonies

Prepared by the Crown Agents for the Colonies, then located at Downing Street, London, the chart entitled *Resistance of Malta and Gozo stone to thrusting stress* was published on 3 July 1885 by David Kirkaldy & Son of 99, Southwark Street, London.[49] This Agency played a central role in the crown colonies. By order, this publication was issued in Malta on 21 April 1886 by the Lieutenant-Governor and Chief Secretary to Government, Walter Hely-Hutchinson (1849–1913). On behalf of the colonial government, the responsibility of the Crown Agents included the supply of non-locally available building materials.[50] This publication states the thrusting stress of 39 stone samples retrieved from 30 different quarries — not classified in terms of hardstone and softstone — from around the Maltese Islands.[51] They fell into three unspecified batches: samples 1 to 14 from Malta, 15 to 32 from Gozo, and 33 to 39 from 'Tal Kali', Malta. The publication includes three tables, one next to the other (Fig. 3) showing:

(1) the result of experiments to ascertain the resistance of thrusting stress (measured in imperial units, pounds (lb) or tons per square (sq.) inch (in.) or sq. foot (ft), respectively), that is, the maximum compressive strength of the stone per unit area that a given sample withstood without failing;
(2) the order of merit of the stone in terms of its resistance to cracking, that is, the maximum loading (lb or tons) at which a given sample cracked divided by the area (sq. in. or sq. ft, respectively) of its load bearing face; and
(3) the order of merit of the stone in terms of its resistance to crushing, that is, the maximum loading (lb or tons) at which a given sample crushed divided by the area (sq. in. or sq. ft, respectively) of its load bearing face.

All the samples were bedded between pieces of pine ⅜ in. in thickness which tallies with the method to test resistance to crushing as outlined by William Dent:[52] "subject 6-inch cubes, bedded between pieces of pine three-eighths of an inch in thickness, to uniaxial compressive load, noting the amount of force obtained when the first crack makes its appearance, and also when the crushing takes place".[53]

[48] Lino Bianco and Associates 2000.
[49] Crown Agents for the Colonies 1885.
[50] Sunderland 2004.
[51] Crown Agents for the Colonies 1885.
[52] This was Dent's second lecture on building materials, delivered in February 1887 as a Cantor Lecture of the Royal Society of Arts. He was a Fellow of the Chemical Society (an organization established in London in 1841) and a Fellow of the Institute of Chemistry (an institute founded in 1877 and granted its first Royal Charter in 1885).
[53] Dent 1887, p. 846.

RESISTANCE OF MALTA AND GOZO STONE TO THRUSTING STRESS.

Result of Experiments to ascertain the resistance to Thrusting Stress, of thirty-nine Cubes of Stone, received from the Crown Agents for the Colonies.

Marked	Name of Quarry	Test No.	Dimensions	Bed Area	Cracked slightly: Stress	Cracked slightly: per sq. in.	Cracked slightly: per sq. foot	Crushed, steelyard dropped: Stress	Crushed, steelyard dropped: per sq. in.	Crushed, steelyard dropped: per sq. foot
In paint			Inches	sq. ins.	lbs.	lbs.	tons.	lbs.	lbs.	tons.
1	'Imdaura', Quarry 'Ta Marcel' ...	1,617	5·95 5·95 × 5·98	35·58	239,520	6,731	432·8	262,690	7,383	474·7
2	Do. do. 'Tal-Lilla' ...	1,618	6·02 6·05 × 6·04	36·54	303,570	8,299	533·6	353,360	9,670	621·8
3	'Wied Id-Dis'	1,619	6·02 6·05 × 6·01	36·48	339,800	9,314	598·9	371,620	10,186	655·0
4	Do.	1,620	6·02 6·04 × 6·02	36·34	267,000	7,347	472·4	304,710	8,384	539·1
5	'Imdaura'	1,621	6·00 6·03 × 6·00	36·30	127,820	3,521	226·4	127,820	3,521	226·4
6	'Wied Id-Dis'	1,622	6·03 6·06 × 6·04	36·60	112,130	3,063	196·9	112,130	3,063	196·9
7	'Inghieret', Quarry 'Gnien tal Cmand'	1,623	5·97 5·98 × 6·00	35·[illegible]8	101,890	2,839	182·5	101,890	2,839	182·5
8	Tad-daul', Quarry 'Tal Ghauci'	1,624	6·00 6·00 × 6·00	36·00	128,400	3,537	227·4	137,210	3,811	245·0
9	'Ta Candia', Quarry 'Tal Giabra' ...	1,625	5·96 6·00 × 5·98	35·88	97,400	2,714	174·5	104,110	2,901	186·5
10	'Tal Balal', Quarry 'Ta Maroz' ...	1,626	5·95 5·98 × 5·90	35·28	92,000	2,607	167·6	102,270	2,898	186·3
11	'Marsa', Harbour extension ...	1,627	5·90 5·90 × 5·92	34·93	89,400	2,559	164·5	93,190	2,641	169·8
12	Lia, near St. Antonio Gardens	1,628	6·00 6·02 × 5·94	35·76	80,200	2,242	144·1	86,480	2,451	157·6
13	'Marsa', Harbour extension ...	1,629	5·96 5·98 × 5·98	35·76	105,980	2,963	190·5	105,980	2,963	190·5
14	Lia, near St. Antonio Gardens	1,630	5·96 5·90 × 5·86	34·57	118,500	3,427	220·3	131,420	3,801	244·4
15	'Tal Kighan', Ghain Sielem...	1,631	6·00 5·90 × 5·92	34·93	284,800	8,153	524·3	316,870	9,071	583·3
16	'Ta Ghar id-dorf', Kala ...	1,632	5·88 5·98 × 6·02	36·00	226,200	6,283	404·0	258,390	7,177	461·5
17	'Tal Fortin', Kala	1,633	6·02 6·05 × 6·02	36·42	307,700	8,448	543·2	373,660	10,259	659·7
18	'Tal Miliar', Kala	1,634	6·00 5·98 × 5·96	35·64	302,000	8,473	544·8	363,720	10,205	656·2
19	'Ta Handak ir-Rummien', Kala ...	1,635	5·98 5·98 × 6·00	35·88	314,600	8,768	563·8	382,950	10,673	686·3
20	Do. do.	1,636	6·00 6·00 × 6·00	36·00	233,800	6,494	417·6	264,270	7,340	472·0
21	'Tal Ferfux', Kala	1,637	6·00 5·97 × 5·94	35·46	288,200	8,127	522·6	289,670	8,168	525·2
22	'Ta Verdala', Xaghra ...	1,638	6·00 6·00 × 5·96	35·76	282,000	7,885	507·0	351,840	9,838	632·6
23	'Ta Ghain Barrani', Xaghra ...	1,639	5·93 5·94 × 5·96	35·40	174,600	4,932	317·1	192,410	5,435	349·5
24	'Tal Kortin, Xaghra	1,640	5·93 5·90 × 6·00	35·40	302,000	8,531	548·6	310,390	8,768	563·8
25	'Tal Belligha', Xaghra ...	1,641	5·94 5·92 × 5·88	34·80	62,640	1,800	115·7	62,640	1,800	115·7
26	'Ta Dorell', Sannat	1,642	5·90 5·96 × 5·92	35·28	71,290	2,020	129·9	71,290	2,020	129·9
27	'Ta Ghain Chelment', Sannat ...	1,643	5·96 5·80 × 5·95	34·51	46,180	1,338	86·0	46,180	1,338	86·0
28	'Ta Gnien Imriek', Xaghra ...	1,644	5·98 6·06 × 6·00	36·00	166,400	4,622	297·2	178,220	4,950	318·3
29	'Ta Gidi', Xeuchia	1,645	5·97 5·97 × 6·00	35·82	76,900	2,146	138·0	82,760	2,310	148·5
30	'Tal Bardan', Sannat... ...	1,646	5·97 6·00 × 6·00	36·00	162,500	4,513	290·2	173,820	4,833	314·0
31	'Tac-cnus, Xeuchia	1,647	5·98 6·00 × 6·00	36·00	279,500	7,763	499·2	348,390	9,677	622·3
32	'Tat-Taflin', Rabato	1,648	5·98 5·90 × 5·98	35·33	73,880	2,091	134·4	80,510	2,278	146·4
None	'Tal Kali' No. 1	1,649	5·59 6·04 × 5·97	36·05	71,400	1,980	127·3	80,260	2,226	143·1
do.	Do. No. 2	1,650	5·88 5·84 × 5·62	32·82	65,550	1,997	128·4	65,550	1,997	128·4
do.	Do. No. 3	1,651	5·80 5·92 × 5·92	35·04	68,220	1,946	125·1	77,980	2,225	143·0
do.	Do. No. 4	1,652	5·85 6·00 × 5·98	35·88	75,860	2,114	135·9	86,610	2,414	155·2
do.	Do. No. 5	1,653	5·74 5·82 × 5·88	34·22	72,120	2,107	135·4	80,510	2,352	151·2
do.	Do. No. 6	1,654	5·84 5·80 × 5·78	33·52	71,600	2,136	137·3	79,820	2,381	153·1
do.	Do. No. 7	1,655	5·95 5·90 × 6·00	35·40	68,470	1,934	124·3	68,470	1,934	124·3
				Mean	70,460	2,031	130·6	77,030	2,218	142·6

All bedded between pieces of pine ½ inch thick.

Order of Merit of the Stone derived from the various quarries as to its resistance to Cracking.

No. in Order of Merit	No. of Sample	Quality	Quarry	Cracked Tons per sqr. foot	Crushed Tons per sqr. foot
1	3	Limestone, 'Kaunia'	'Wied Id-dis', Gargur, Malta ...	598·9	655·0
2	19	Do. do.	'Ta Handak Ir-rummien', Kala, Gozo	563·8	686·3
3	24	Do. do.	'Tal Kortin', Xaghra, Gozo	548·6	563·8
4	18	Do. do.	'Tal Miliar', Kala, Gozo	544·8	656·2
5	17	Do. do.	'Tal Fortin', Kala, Gozo	543·2	659·7
6	2	Do. do.	'Tal-Lilla', Imdauura, Malta ...	533·6	621·8
7	15	Do. do.	'Tal Kighan', Ghain Sielem, Gozo ...	524·3	583·3
8	21	Do. do.	'Tal Ferfux', Kala, Gozo	522·6	525·2
9	22	Do. do.	'Ta Verdala', Xaghra, Gozo... ...	507·0	632·6
10	31	Sandstone, 'Franca'*	'Tac-cnus', Xeuchia, Gozo	499·2	622·3
11	4	Limestone, 'Kaunia'	'Wied Id-dis', Gargur, Malta ...	472·4	539·1
12	1	Do. do.	'Imdaura', 'Ta Marcel', Malta ...	432·8	474·7
13	20	Do. do.	'Ta Handak Ir-rummien', Kala, Gozo	417·6	472·0
14	16	Do. do.	'Ta Ghar Id-dorf', Kala, Gozo ...	404·0	491·5
15	23	Do. do.	'Ta Ghain-Barrani', Xaghra, Gozo...	317·1	349·5
16	28	Sandstone, 'Safra' ...	'Ta Gnien Imriek,' Xaghra, Gozo ...	297·2	318·3
17	30	Do. 'Franca'	'Tal Bardun', Sannat, Gozo... ...	290·2	314·0
18	8	Do. do.	'Tal Ghauci', Tad-daul, Malta ...	227·4	245·0
19	5	Limestone, 'Seconda'	'Imdaura', Malta	226·4	226·4
20	14	Sandstone, 'Karghain'	Lia, near St. Antonio Gardens, Malta	220·3	244·4
21	6	Limestone, 'Seconda'	'Wied Id-dis', Gargur, Malta ...	196·9	196·9
22	13	Sandstone, 'Cahla' ...	'Marsa', Harbour Extension, Malta...	190·5	190·5
23	7	Do. 'Franca'	'Gnien tal Cmand' Inghieret, Malta	182·5	182·5
24	9	Do. do.	'Tal Giabra, ta Candia', Malta ...	174·5	186·5
25	10	Do. do.	'Ta Maroz, Tal Balal', Malta ...	167·6	186·3
26	11	Do. 'Karghaia'	'Marsa', Harbour Extension, Malta...	164·5	169·8
27	12	Do. do.	'Lia', near St. Antonio Gardens, Malta	144·1	157·6
28	29	Do. 'Franca'...	'Tal Gidi', Xeuchia, Gozo	138·0	148·5
29	None	Do.	'Tal Kali', (No. 6) Malta	137·3	153·1
30	"	Do.	Do. (No. 4) do.	135·9	155·2
31	"	Do.	Do. (No. 5) do.	135·4	151·2
32	32	Do. 'Tan-nar'	'Tat-Tafla', Rabat, Gozo	134·4	146·4
33	26	Limestone, 'Seconda'	'Ta Dorell', Sannat, Gozo	129·9	129·9
34	None	Sandstone	'Tal Kali', (No. 2) Malta	128·4	128·4
35	"	Do.	Do. (No. 1) do.	127·3	143·1
36	"	Do.	Do. (No. 3) do.	125·1	143·0
37	"	Do.	Do. (No. 7) do.	124·3	124·3
38	25	Limestone, 'Kaunia'	'Tal Belligha', Xaghra, Gozo ...	115·7	115·7
39	27	Do. 'Seconda'	'Ta Ghain Chelment', Sannat, Gozo	86·0	86·0

* This test cannot safely be accepted as a criterion of the average quality of the stone from the quarry.

Order of Merit of the Stone derived from the various quarters as to its resistance to Crushing.

No. in Order of Merit	No. of Sample	Quality	Quarry	Cracked Tons per sqr. foot	Crushed Tons per sqr. foot
1	19	Limestone, 'Kaunia'	'Ta Handak Ir-Rummien', Kala, Gozo	563·8	686·3
2	17	Do. do.	'Tal Fortin', Kala, Gozo	543·2	659·7
3	18	Do. do.	'Tal Miliar', do.	544·8	656·2
4	3	Do. do.	'Wied Id-dis', Gargur, Malta ...	598·9	655·0
5	22	Do. do.	"Ta Verdala', Xaghra, Gozo ...	507·0	632·6
6	31	Sandstone 'Franca' *	'Tac-cnus', Xeuchia, Gozo	499·2	622·3
7	2	Limestone 'Kauuia'	'Tal-Lilla', Imdaura, Malta	533·6	624·8
8	15	Do. do.	'Tal Kighan', Ghain Sielem, Gozo...	524·3	583·3
9	24	Do. do.	'Tal Kortin', Xaghra, Gozo	548·6	563·8
10	4	Do. do.	'Wied Id-dis', Gargur, Malta ...	472·4	539·1
11	21	Do. do.	'Tal Ferfux' Kala, Gozo	522·6	525·2
12	1	Do. do.	'Ta Marcell', Imdaura, Malta ...	432·8	474·7
13	20	Do. do.	'Ta Handak Ir-rummien, Kala, Gozo	417·6	472·0
14	16	Do. do.	'Ta Ghar Id-dorf', Kala, Gozo ...	404·0	461·5
15	23	Do. do.	'Ta Ghain Barrani', Xaghra, Gozo...	317·1	349·5
16	28	Sandstone, 'Safra' ...	'Ta Gnian Imriek, Xaghra, Gozo ...	297·2	318·6
17	30	Do. 'Franca'	'Tal Bardan', Sannat, Gozo	290·2	314·0
18	8	Do. do.	'Tal Ghauci', Tad-daul, Malta ...	227·4	245·0
19	14	Do. 'Cahla'...	Lia, near St. Antonio Gardens, Malta	220·3	244·4
20	5	Limestone, 'Seconda'	'Imdaura, Gargur, Malta	226·4	226·4
21	6	Do. do.	'Wied Id-dis', Gargur, Halta ...	196·9	196·9
22	13	Sandstone, 'Cahla'...	'Marsa', Harbour Extension, Malta...	190·5	190·5
23	9	Do. 'Franca'	'Tal Giabra', Ta Candia', Malta ...	174·5	186·5
24	10	Do. do.	'Tal Balal', Ta Maroz', Malta ...	167·6	186·3
25	7	Do. do.	'Tal Gnien tal Cmand, Inghieret', Malta	182.5	182·5
26	11	Do. 'Karghaia'	'Marsa', Harbour Extension, Malta...	164·5	169·8
27	12	Do. do.	Lia, near St. Antonio Gardens, Malta	144·1	157·6
28	None	Do.	'Tal Kali', (No. 4), Malta	135·9	155·2
29	"	Do.	Do. (No. 6), do.	137·3	153·1
30	"	Do.	Do. (No. 5), do.	135·4	151·2
31	29	Do. 'Franca'	'Ta Gidi', Xeuchia, Gozo	138·0	148·5
32	32	Do. 'Tan-Nar'	'Tat-Taflin', Rabat, Gozo	134·4	146·4
33	None	Do.	'Tal Kali', (No. 1), Malta	127·3	143·1
34	,	Do.	Do. (No. 3) do.	125·1	143·0
35	26	Limestone, 'Seconda'	'Ta Dorell', Sannat, Gozo	129·9	129·9
36	None	Sandstone	'Tal Kali' (No. 2) Malta	128·4	128·4
37	"	Do.	Do. (No. 7) do.	124.3	124·3
38	25	Limestone, 'Kaunia'	'Tal Belligha', Xaghra, Gozo ...	115·7	115·7
39	27	Do. 'Seconda'	'Ta Ghain Chelment', Sannat, Gozo	86·0	86·0

* This test cannot safely be accepted as a criterion of the average quality of the stone from the quarry.

The Crown Agents for the Colonies,
Downing Street,
London, S.W.

99 Southwark Street,
London S.E., 3rd July 1885.
David Kirkaldy & Son.

By Order,

Malta, 21 April, 1886.

Walter Hely-Hutchinson,
Lieutenant-Governor
and Chief Secretary to Government.

[Price 6d.]

Fig. 3 Resistance of Malta and Gozo stone to thrusting stress.
Source: Crown Agents for the Colonies 1885.

The results of the experiments with respect to cracking and crushing are given in Table 3 and Table 4, respectively, which are a transcription of Fig. 3. The contemporary terminology for the term 'stress' (measured in lb), as used in the chart, is load (nowadays measured in metric units, N). Table 3 states the maximum uniaxial impact load (stress) (lb) generated on impact after a steelyard was dropped onto it in an impact test — a measure of the toughness of the stone — until the sample cracked divided by the area (sq. in.) of the bearing face of the sample. Table 4 states the maximum uniaxial compressive load (lb) applied to the sample in a crushing machine prior to failure divided by the area (sq. in.) of the bearing face of the sample. In both Table 3 and Table 4, the value in tons/sq. ft was computed with respect to each value in lb/sq. in. Given that the last seven samples, which were from 'Tal Kali' quarry, were not numbered (although each had a unique test number, ranging from 1649 to 1655), the respective sample numbers, included in brackets, were introduced by the author of the present article. Also, in the publication of the Crown Agents, Table 3 and Table 4 include a column describing the quality of the stone. A footnote to both highlights that the test for sample 31 "cannot safely be accepted as a criterion of the average quality of the stone from the quarry". The quality of the 39 stone samples is given in Table 5.

For each sample, the published values of the relative stresses (lb/sq. in. or tons/sq. ft) were checked for arithmetical errors using Excel[54] by applying the following conversion factors:

British [long] ton: 2,240 lb (1 lb is equivalent to $4.46\text{x}10^{-4}$ tons (British));

ft: 12 in. (1 in. is equivalent to $8.\overline{3}\text{x}10^{-2}$ ft); and

sq. ft: 144 sq. in. (1 sq. in. is equivalent to $6.9\overline{4}\text{x}10^{-3}$ sq. ft).

The values which differed from those stated in the chart are stated in brackets.

Table 3.[55]

Sample No.	Name of Quarry	Test No.	Dimensions			Base Area (sq. in.)	Cracked		
			Height (in.)	Length (in.)	Breadth (in.)		Stress (lb)	Stress (lb) per sq. in.	Stress (tons) per sq. ft
1	'Imdaura', Quarry 'Ta Marcel'	1617	5.95	5.95	5.98	35.58	239,520	6,731 (6,732)	432.8
2	'Imdaura', Quarry 'Tal-Lilla'	1618	6.02	6.05	6.04	36.54	303,270	8,299	533.6 (533.5)
3	'Wied id-Dis'	1619	6.02	6.05	6.03	36.48	339,800	9,314	598.9 (598.8)
4	'Wied id-Dis'	1620	6.02	6.04	6.02	36.34 (36.36)	267,000	7,347 (7,343)	472.4 (472.1)
5	'Imdaura'	1621	6.00	6.03	6.02	36.30	127,820	3,521	226.4
6	'Wied id-Dis'	1622	6.03	6.06	6.04	36.60	112,130	3,063	196.9
7	'Inghieret', Quarry 'Gnien tal Cmand'	1623	5.97	5.98	6.00	35.88	101,890	2,839 (2,840)	182.5 (182.6)
8	'Tad-daul', Quarry 'Tal Ghauci'	1624	6.00	6.00	6.00	36.00	128,400	3,537 (3,567)	227.4 (229.3)
9	'Ta Candia', Quarry 'Tal Giabra'	1625	5.96	6.00	5.98	35.88	97,400	2,714 (2,715)	174.5
10	'Tal Balal', Quarry 'Ta Maroz'	1626	5.95	5.98	5.90	35.28	92,000	2,607 (2,608)	167.6
11	'Marsa', Harbour extension	1627	5.90	5.90	5.92	34.93	89,400	2,559 (2,560)	164.5 (164.6)
12	Lia, near St. Antonio Gardens	1628	6.00	6.02	5.94	35.76	80,200	2,242 (2,243)	144.1 (144.2)
13	'Marsa', Harbour extension	1629	5.96	5.98	5.98	35.76	105,980	2,963 (2,964)	190.5
14	Lia, near St. Antonio Gardens	1630	5.96	5.90	5.86	34.57	118,500	3,427	220.3
15	'Tal Kighan', Ghain Sielem	1631	6.00	5.90	5.92	34.93	284,800	8,153 (8,154)	524.3 (524.2)
16	'Ta Ghar id-dorf', Kala	1632	5.88	5.98	6.02	36.00	226,200	6,283	404.0 (403.9)
17	'Tal Fortin', Kala	1633	6.02	6.05	6.02	36.42	307,700	8,448	543.2 (543.1)
18	'Tal Miliar', Kala	1634	6.00	5.98	5.96	35.64	302,000	8,473	544.8 (544.7)
19	'Ta Handak ir-Rummien', Kala	1635	5.98	5.98	6.00	35.88	314,600	8,768	563.8 (563.7)
20	'Ta Handak ir-Rummien', Kala	1636	6.00	6.00	6.00	36.00	233,800	6,494	417.6 (417.5)
21	'Tal Ferfux', Kala	1637	6.00	5.97	5.94	35.46	288,200	8,127	522.6 (522.5)
22	'Ta Verdala', Xaghra	1638	6.00	6.00	5.96	35.76	282,000	7,885 (7,886)	507.0
23	'Ta Ghain Barrani', Xaghra	1639	5.93	5.94	5.96	35.40	174,600	4,932	317.1 (317.0)
24	'Tal-Kortin', Xaghra	1640	5.93	5.90	6.00	35.40	302,000	8,531	548.6 (548.5)
25	'Tal Belligha', Xaghra	1641	5.94	5.92	5.88	34.80 (34.81)	62,640	1,800	115.7
26	'Ta Dorell', Sannat	1642	5.90	5.96	5.92	35.28	71,290	2,020 (2,021)	129.9
27	'Ta Ghain Chelment', Sannat	1643	5.96	5.80	5.95	34.51	46,180	1,338	86.0
28	'Ta Gnien Imriek', Xaghra	1644	5.98	6.06	6.00	36.00 (36.36)	166,400	4,622 (4,576)	297.2 (294.2)
29	'Ta Gidi', Xeuchia	1645	5.97	5.97	6.00	35.82	76,900	2,146 (2,147)	138.0
30	'Tal Bardan', Sannat	1646	5.97	6.00	6.00	36.00	162,500	4,513 (4,514)	290.2
31	'Tac-cnus', Xeuchia	1647	5.98	6.00	6.00	36.00	279,500	7,763 (7,764)	499.2 (499.1)
32	'Tat-Taflia', Rabato	1648	5.98	5.90	5.98	35.33 (35.28)	73,880	2,091 (2,094)	134.4 (134.6)

[54] Microsoft®, Excel® 2019.

[55] Based on Crown Agents for the Colonies 1885; the values which differed from those stated in the chart are stated in brackets.

(33)	'Tal Kali' No. 1	1649	5.59	6.04	5.97	36.05 (36.06)	71,400	1,980	127.3
(34)	'Tal Kali' No. 2	1650	5.88	5.84	5.62	32.82	65,550	1,997	128.4
(35)	'Tal Kali' No. 3	1651	5.80	5.92	5.92	35.04 (35.05)	68,220	1,946 (1,947)	125.1
(36)	'Tal Kali' No. 4	1652	5.85	6.00	5.98	35.88	75,860	2,114	135.9
(37)	'Tal Kali' No. 5	1653	5.74	5.82	5.88	34.22	72,120	2,107	135.4 (135.5)
(38)	'Tal Kali' No. 6	1654	5.84	5.80	5.78	33.52	71,600	2,136	137.3
(39)	'Tal Kali' No. 7	1655	5.95	5.90	6.00	35.40	68,470	1,934	124.3
						Mean	70,460	2,031	130.6

Table 4.[56]

Sample No.	Name of Quarry	Test No.	Dimensions			Base area	Crushed		
			Height (in.)	Length (in.)	Breadth (in.)	(sq. in.)	Stress (lb)	stress (lb) per sq. in.	Stress (tons) per sq. ft
1	'Imdaura', Quarry 'Ta Marcel'	1617	5.95	5.95	5.98	35.58	262,690	7,383	474.7 (474.6)
2	'Imdaura', Quarry 'Tal-Lilla	1618	6.02	6.05	6.04	36.54	353,360	9,670	621.8 (621.6)
3	'Wied id-Dis'	1619	6.02	6.05	6.03	36.48	371,620	0,186 (10,187)	655.0 (654.8)
4	'Wied id-Dis'	1620	6.02	6.04	6.02	36.34 (36.36)	304,710	8,384 (8,380)	539.1 (538.7)
5	'Imdaura'	1621	6.00	6.03	6.02	36.30	127,820	3,521	226.4
6	'Wied id-Dis'	1622	6.03	6.06	6.04	36.60	112,130	3,063	196.9
7	'Inghieret', Quarry 'Gnien ta Cmand'	1623	5.97	5.98	6.00	35.88	101,890	2,839 (2,840)	182.5 (182.6)
8	'Tad-daul', Quarry 'Tal Ghauci'	1624	6.00	6.00	6.00	36.00	137,210	3,811	245.0
9	'Ta Candia', Quarry 'Tal Giabra'	1625	5.96	6.00	5.98	35.88	104,110	2,901 (2,902)	186.5
10	'Tal Balal', Quarry 'Ta Maroz'	1626	5.95	5.98	5.90	35.28	102,270	2,898 (2,899)	186.3
11	'Marsa', Harbour extension	1627	5.90	5.90	5.92	34.93	93,190	2,641 (2,668)	169.8 (171.5)
12	Lia, near St. Antonio Gardens	1628	6.00	6.02	5.94	35.76	86,480	2,451 (2,418)	157.6 (155.5)
13	'Marsa', Harbour extension	1629	5.96	5.98	5.98	35.76	105,980	2,963 (2,964)	190.5
14	Lia, near St. Antonio Gardens	1630	5.96	5.90	5.86	34.57	131,420	3,801	244.4
15	'Tal Kighan', Ghain Sielem	1631	6.00	5.90	5.92	34.93	316,870	9,071 (9,072)	583.3 (583.2)
16	'Ta Ghar id-dorf', Kala	1632	5.88	5.98	6.02	36.00	258,390	7,177 (7,178)	461.5 (461.4)
17	'Tal Fortin', Kala	1633	6.02	6.05	6.02	36.42	373,660	10,259	659.7 (659.5)
18	'Tal Miliar', Kala	1634	6.00	5.98	5.96	35.64	363,720	10,205	656.2 (656.0)
19	'Ta Handak ir-Rummien', Kala	1635	5.98	5.98	6.00	35.88	382,950	10,673	686.3 (686.1)
20	'Ta Handak ir-Rummien', Kala	1636	6.00	6.00	6.00	36.00	264,270	7,340 (7,341)	420.0 (471.9)
21	'Tal Ferfux', Kala	1637	6.00	5.97	5.94	35.46	289,670	8,168 (8,169)	525.2 (525.1)
22	'Ta Verdala', Xaghra	1638	6.00	6.00	5.96	35.76	351,840	9,838 (9,839)	632.6 (632.5)
23	'Ta Ghain Barrani', Xaghra	1639	5.93	5.94	5.96	35.40	192,410	5,435	349.5 (349.4)
24	'Tal-Kortin', Xaghra	1640	5.93	5.90	6.00	35.40	310,390	8,768	563.8 (563.7)
25	'Tal Belligha', Xaghra	1641	5.94	5.92	5.88	34.80 (34.81)	62,640	1,800	115.7
26	'Ta Dorell', Sannat	1642	5.90	5.96	5.92	35.28	71,290	2,020 (2,021)	129.9
27	'Ta Ghain Chelment', Sannat	1643	5.96	5.80	5.95	34.51	46,180	1,338	86.0
28	'Ta Gnien Imriek', Xaghra	1644	5.98	6.06	6.00	36.00 (36.36)	178,220	4,950 (4,902)	318.3 (315.1)
29	'Ta Gidi', Xeuchia	1645	5.97	5.97	6.00	35.82	82,760	2,310	148.5
30	'Tal Bardan', Sannat	1646	5.97	6.00	6.00	36.00	175,820	4,883 (4,884)	314.0
31	'Tac-cnus', Xeuchia	1647	5.98	6.00	6.00	36.00	348,390	9,677 (9,678)	622.3 (622.1)
32	'Tat-Taflia', Rabato	1648	5.98	5.90	5.98	35.33 (35.28)	80,510	2,278 (2,282)	146.4 (146.7)
(33)	'Tal Kali' No. 1	1649	5.59	6.04	5.97	36.05 (36.06)	80,260	2,226	143.1

[56] Ibid.

(34)	'Tal Kali' No. 2	1650	5.88	5.84	5.62	32.82	65,550	1,997	128.4
(35)	'Tal Kali' No. 3	1651	5.80	5.92	5.92	35.04 (35.05)	77,980	2,225	143.0
(36)	'Tal Kali' No. 4	1652	5.85	6.00	5.98	35.88	86,620	2,414	155.2
(37)	'Tal Kali' No. 5	1653	5.74	5.82	5.88	34.22	80,510	2,352 (2,353)	151.2
(38)	'Tal Kali' No. 6	1654	5.84	5.80	5.78	33.52	79,820	2,381	153.1
(39)	'Tal Kali' No. 7	1655	5.95	5.90	6.00	35.40	68,470	1,934	124.3
						Mean	77,030	2,218	142.6

Table 5.[57]

Stone quality	**Sample no.**	
	Malta	Gozo
Limestone, kauuia	1, 2, 3, 4	15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25
Sandstone, franca	7, 8, 9, 10	29, 30, 31
Sandstone, safra		28
Limestone, seconda	5, 6	26, 27
Sandstone, karghaia	11, 12, 36, 37, 38	
Sandstone, cahla	13, 14	
Sandstone, tan-nar	32, 33, 35	
Sandstone, seconda	34, 39	

Quarry names, which include their location and the terminology for stone quality used by the Crown Agents, are in old Maltese. Their original names are given alongside those used under the modern system of Maltese orthography introduced in 1924[58] in Table 6.

Table 6.

	Old orthography	**Modern orthography**
Name of Quarry	'Imdaura', Quarry 'Ta Marcel'	'Imdawra', Quarry 'Ta' Marcel'
	'Imdaura', Quarry 'Tal-Lilla'	'Imdawra', Quarry 'Tal-Lilla'
	'Wied id-Dis'	'Wied id-Dis'
	'Inghieret', Quarry 'Gnien tal Cmand'	'Ingiered', Quarry 'Ġnien tal-Kmand'
	'Tad-daul', Quarry 'Tal Ghauci'	'Tad-dawl', Quarry 'Tal-Gauci'
	'Ta Candia', Quarry 'Tal Giabra'	'Ta' Kandia', Quarry 'Tal-Ġabra'
	'Tal Balal', Quarry 'Ta Maroz'	'Tal-Balal', Quarry 'Ta' Maroz'
	'Marsa', Harbour extension	'Marsa', Harbour extension
	Lia, near St. Antonio Gardens	Lija, near Sant' Anton Gardens
	'Tal Kighan', Ghain Sielem	'Tal-Qigħan', Għajnsielem
	'Ta Ghar id-dorf', Kala	'Ta' Għar id-Dorf', Qala
	'Tal Fortin', Kala	'Tal-Fortin', Qala
	'Tal Miliar', Kala	'Tal-Miliar', Qala
	'Ta Handak ir-Rummien', Kala	'Ta' Hondoq ir-Rummien', Qala
	'Tal Ferfux', Kala	'Tal-Ferfux', Qala
	'Ta Verdala', Xaghra	'Ta' Verdala', Xagħra
	'Ta Ghain Barrani', Xaghra	'Ta' Għajn Barrani', Xagħra
	'Tal-Kortin', Xaghra	'Tal-Qortin', Xagħra
	'Tal Belligha', Xaghra	'Tal-Belligħa', Xagħra
	'Ta Dorell', Sannat	'Ta' Dorell', Sannat
	'Ta Ghain Chelment', Sannat	'Ta' Għajn Kelment', Sannat

[57] Ibid.
[58] Għaqda tal-Kittieba tal-Malti 1924.

	'Ta Gnien Imriek', Xaghra	'Ta' Ġnien Imriek', Xagħra
	'Ta Gidi', Xeuchia	'Ta' Ġidi', Xewkija
	'Tal Bardan', Sannat	'Tal-Bardan', Sannat
	'Tac-cnus', Xeuchia	'Taċ-ċnus', Xewkija
	'Tat-Taflia', Rabato	'Tat-Taflija', Rabat
	'Tal Kali'	'Tal-Qali'
Stone Criteria	kauuia	qawwija
	franca	franka
	safra	safra
	seconda	sekonda
	karghaia	qargħajja
	caħla	kaħla
	tan-nar	tan-nar

4. Discussion

4.1. Representative sampling

All samples, except Sample 31 from 'Taċ-ċnus' quarry, were considered representative of the mean quality of the stone from a given respective quarry. The sampling method used in selecting the specimens followed Dent's advice that:

> … much care may be taken in the examination of specimens, it must never be forgotten that it is absolutely necessary, before deciding on the relative merits of different kinds of stone as to their suitability or otherwise for any special purpose, that the quarries should be visited, and the several beds carefully inspected, for in almost every quarry, whatever the description of stone may be, a very material difference will be found to exist in the quality of the stone yielded by its several beds.[59]

4.2. Chart not checked prior going to print

Until the advent of hand-held scientific calculators in the 1970s, logarithms were universally used in engineering for long division. This was the method used by the operators calculating the base area and stresses included in the Crown Agents' chart. The minimal discrepancies between these figures and the computations with Excel[60] can be attributed to the software's higher accuracy. Major discrepancies, however, are due to miscalculations on the part of those working out the long divisions, for example, the stress measured in lb/sq. in. for samples 8 and 28. Such errors reflect a lack of rigor and, if more than one individual was involved, possibly incompetence. Whilst the computations are optimal in nearly a fifth of the samples — namely, 5, 16, 14, 27, 34, 38 and 39 — the rest contain some errors. For example, with sample 28, someone made a mistake in a simple long multiplication to compute the surface area of the bearing face of the sample subject to compressive stress; this particular calculation is not a complicated one and could be generated without the use of logarithms. The errors in the published chart of the Crown Agents prove that the calculations were not rechecked but merely endorsed.

[59] Ibid., p. 847.
[60] Microsoft®, Excel® 2019.

4.3. Location of quarries

Applying the information contained in the topographical maps of the Maltese Islands,[61] the present geographical localities of the quarries where the samples were collected were plotted on a Google Earth map (Fig. 4). Although these maps are dated, they are the most accurately represented and labeled to date. Plotted at scale 1:25,000, they were originally constructed, drawn and photographed in 1962 by the British Directorate of Overseas Surveys, and were revised in 1984 using aerial photography taken by the Istituto Geografico Militare, Florence, in 1983. From the mineral resource assessment completed in the mid-1990s,[62] none of the quarries mentioned by the Crown Agents are operational; yet the original locality or limits thereof is still retained in the topographical maps.

4.4. Retrospective assessment of building stone quality

Dent distinguished between two types of stone for construction: those belonging to geological formations such as igneous rocks or deposits resulting from such formations, and sedimentary rocks, such as sandstones or limestones:

> The finer descriptions of sandstone come under the designation of ‘freestone’, a term that has no very distinctive meaning, but one which is commonly employed when speaking of any stone, whether it be a sandstone or a limestone, that is capable of being easily tooled, quite irrespective of its chemical composition.[63]

Concerning stone testing, Dent argued for chemical analysis to determine the composition and ascertain whether it was sandstone, limestone or something that “partakes of the character of both”.[64] With reference to Table 5, all the tested samples from Malta and Gozo were sedimentary, but fell under both types specified by Dent. No records were found by the author indicating whether the stone quality of the samples was ever derived by identifying their chemical composition. As Dent observes, determining composition chemically is useful in distinguishing between igneous and sedimentary rocks; however, the results are less contrasting in the case of limestone and sandstone. The first known chemical analysis of the geological formations of Malta was undertaken few years later by Murray;[65] his results appeared in subsequent literature.[66] A comprehensive study of the oldest member of the CS/GL (which refers to Adams/OED maps, respectively), namely LGL in modern stratigraphy (Table 2), was undertaken over a century later.[67] The rock type in the Crown Agents’ publication was derived from the map by Adams (Fig. 1) which indicates that all the sandstone lithotypes are CS, that is, pertaining to the GL formation. In the case of Malta, I outcropped in the Denuded District. Tests undertaken by Charles Henry Colson (1864–1939) — a civil engineer with the Admiralty Department of Civil Engineering[68] — proved that Adams’s

[61] Government of Malta 1984a; Government of Malta 1984b; Government of Malta 1984c.
[62] Wardell Armstrong 1996.
[63] Dent 1887, pp. 841–842.
[64] Ibid., p. 846.
[65] Murray 1890, pp. 14, 21.
[66] For example, Rizzo 1932, pp. 9, 14; Hyde 1955, pp. 39–40, 53–54.
[67] Bianco 1993; Bianco 2022.
[68] Cited in Murray 1890, p. 468. Colson authored a number of technical articles including Colson, Colson 1893.

limestone is much less absorbent than his sandstones. The distribution of the quarries covered by the publication of the Crown Agents for the Colonies was plotted on a contemporary geographical map (Fig. 4).

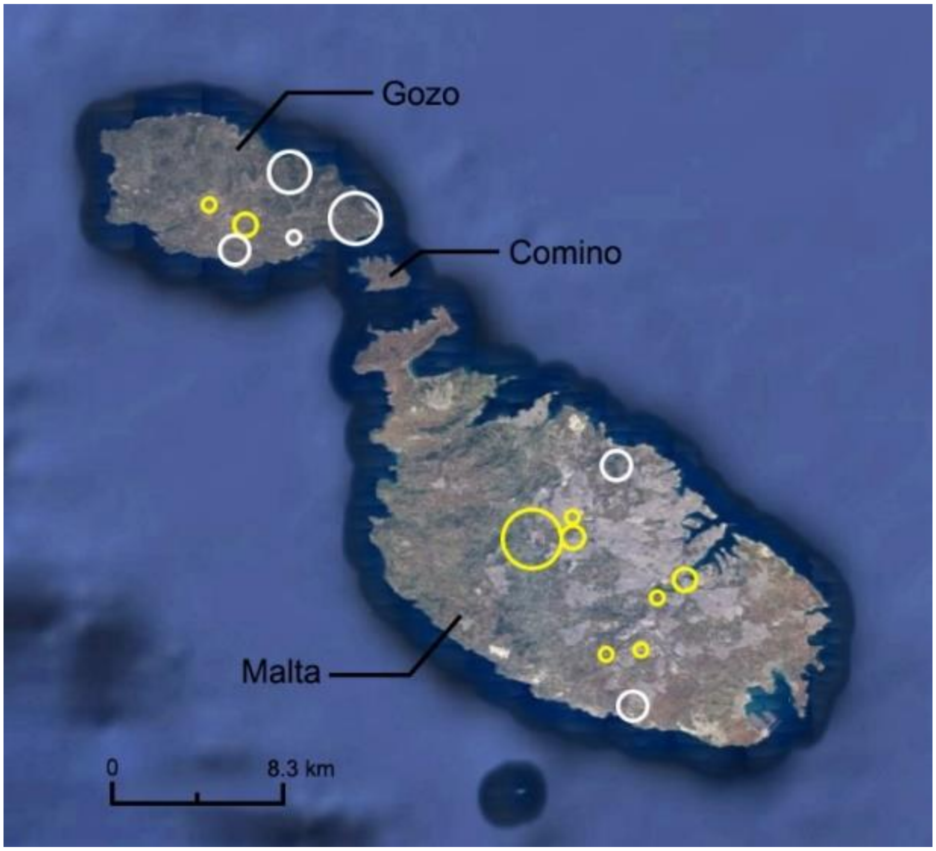

Fig. 4 Distribution of quarries covered by the publication of the Crown Agents for the Colonies: UL/UCL and LL/LCL are circled in white; CS/GL are circled in yellow; the area of each circle corresponds to the number of sampled quarries. Source: For base map, Google Earth.

Whilst taking note of modern orthography (Table 6), reference is made to Table 3 and Table 5. Where applicable, for a given stone quality identified by the Crown Agents, the range when the stone failed — that is when it cracked slightly — under stress (σ) in N/mm^2 (conversion factor from ton/sq. ft to N/mm^2 is 0.107) is given in Table 7. Through locating the approximate position of a given quarry, the respective geological formation based on the maps by Adams (Fig. 1) and by the OED (Fig. 2) is also included. The following analysis refers to Table 1/Table 2 and the acronyms contained therein. The qawwija samples, with the exception of 25, were all UL/UCL from Gozo (samples 15, 22, 23, 24); the others were LC/LCL (Malta samples: 1, 2, 3, 4; Gozo samples: 16, 17, 19, 20). Given the rough approximation of the location of the quarries where samples 18 and 21 were collected, these samples could have been from either formation. Whilst the samples of UL and UCL are mainly from the Mtarfa Member, the LL and LCL samples are predominantly from the Attard Member. The σ for sample 25 conclusively indicates that it is not qawwija. Most of the remaining samples were CS/GL, specifically from the LGL member, except for samples 5, 6, 26, 27, which are limestone sekonda quality from LL/LCL.

Table 7.

Stone quality[69]	**Range** (N/mm^2)	**Geological formation**		**Comments**
		Adams[70]	OED[71]	
Limestone, qawwija	$34.0 \leq \sigma \leq 64.2$	UL/LL	UCL/LCL	Sample 25 ($\sigma = 12.4$) was not considered
Sandstone, franka	$14.8 \leq \sigma \leq 24.6$	CS	GL	Sample 31 ($\sigma = 53.6$) was not considered
Sandstone, safra	–	CS	GL	Only sample 28 ($\sigma = 31.6$) is in this category
Limestone, sekonda	$9.2 \leq \sigma \leq 24.3$	LL	LCL	
Sandstone, qargħajja	$14.5 \leq \sigma \leq 23.6$	CS	GL	
Sandstone, kaħla	–	CS	GL	Only samples 13 ($\sigma = 20.4$) and 14 ($\sigma = 23.6$) are in this category
Sandstone, tan-nar	$13.4 \leq \sigma \leq 14.4$	CS	GL	
Sandstone, sekonda	–	CS	GL	Only samples 34 ($\sigma = 13.3$) and 39 ($\sigma = 13.3$) are in this category

If the safra sandstone sample is included with the franka sandstone samples, the limit to cracking is $14.8 \leq \sigma \leq 31.6$ N/mm^2, which is close to the range for uniaxial compressive strength for oven-dried LGL samples established by Cachia,[72] that is, $15.0 \leq \sigma \leq 32.9$ N/mm^2. The quarry at 'Ta' Dorell' (sample 26) was used to extract limestone for making lime,[73] an important inorganic material widely used until the later part of the twentieth century in Malta; likewise, samples 5, 6 and 27 are of similar quality. With respect to sample 31, the σ is typical for either UL/UCL or LL/LCL; it is definitely not a CS/GL. In general terms used in the contemporary quarrying industry, UL/UCL or LL/LCL is referred to as hardstone and the CS/GL as softstone. However, builders were aware of the hard and soft characteristics centuries earlier.[74] The distribution of the samples in terms of stress (N/mm^2) when cracking occurs is given in Fig. 5.

The publication of the Crown Agents includes the mean resistance to cracking and crushing.[75] If the mean is an arithmetic one, then it is the average of the sum of a set of values divided by the number of values. This is the best reading of the central tendency of a given distribution. The mean values given in Table 3 and Table 4 do not tally with the arithmetic one. Given that the resistance values vary significantly — from very large to very small — the arithmetic mean is not a useful tool to apply; it is impacted by this wide distribution. In the earlier part of the nineteenth century, the notion of the median was introduced as an alternative;[76] this is the figure around which half the values of a data sample are above whilst the other half is below. The stated 'mean' values in the publication of the Crown Agents neither correspond to the median nor a quartile thereof. Furthermore, the stone quality varied significantly and thus a scientifically valid arithmetic mean

[69] Crown Agents for the Colonies 1885.
[70] Adams 1870.
[71] Continental Shelf Department a.
[72] Cachia 1985; Cachia 1988.
[73] Victor Hili, Director, Road Construction Co. Ltd, personal communication.
[74] For example, see Bianco 1999; Bianco 2017a; Bianco 2017b.
[75] Crown Agents for the Colonies 1885.
[76] Bakker, Gravemeijer 2006.

should be the average of like with like and not the average of mixed samples. The same applies to the median.

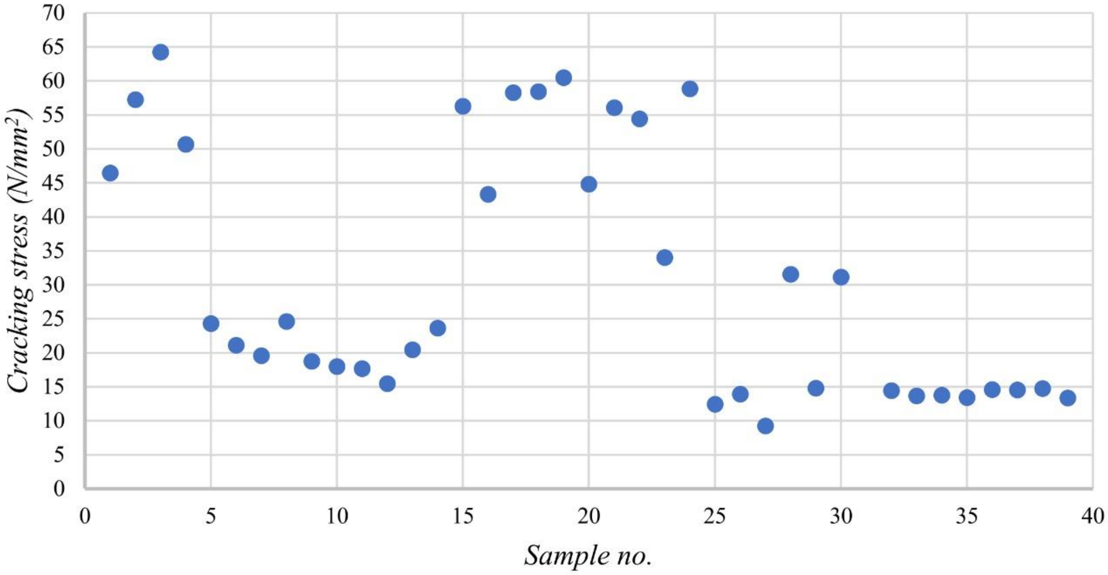

Fig. 5 Variation in cracking stress (N/mm^2) of stone samples.

5. Final comments and conclusions

The contemporary relevance of the Crown Agents' publication, *Resistance of Malta and Gozo stone to thrusting stress*, is that it states the compressive strength of limestone from quarries utilized in various buildings, some of which are monuments of cultural heritage significance still standing today. It also underpins the assessments undertaken by local architects and civil engineers when making calculations regarding the structures of buildings they designed. Such information is relevant when it comes to comprehending the materials selected by, for example, the Royal Engineers in Malta when erecting civil and military masonry structures in local limestone. This knowledge is required in restoration and conservation of cultural heritage erected in this fabric. The topics of stone preservation and stone substitutes were themes addressed in Dent's second lecture;[77] he referred to the durability of stone, the prevention of rusting of iron, and a description of granite and sandstone used in the building industry during his first lecture, held on 14 February 1887.[78] The Building Research Station — established in 1921 under the aegis of the Buildings Research (Materials and Construction) Research Board of the Department of Scientific and Industrial Research — undertook research on Malta limestone which included studies on its use,[79] its properties and behavior,[80] and its durability and the effectiveness of silicone treatment.[81]

This article aimed to assess and interpret the compressive strength of the building stones of Malta stated in the publication of the Crown Agents for the Colonies[82] with respect to the geological

[77] Dent 1887, pp. 847–851.
[78] The Editor 1887, p. 113.
[79] Building Research Station 1958.
[80] Building Research Station 1964.
[81] Building Research Station 1963.
[82] Crown Agents for the Colonies 1885.

and engineering knowledge of the time. From this publication — essentially elementary structural design tables for local masonry — the following main conclusions were drawn:

1. In attributing the lithological description of the samples, the Crown Colonies made use of the 1870 geological map produced by Adams.
2. According to the terms used in Adams's map and the corresponding one generated by the OED, the samples fell into two categories: (i) UL/UCL or LL/LCL, and (ii) CS/GL. This is indicative of the relative accuracy of the 1870 map.
3. Some individuals involved in computing the test results were either not rigorous or incompetent, as there were several miscalculations. It is highly likely the computations were not double-checked prior to printing the chart.

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