Research Article

Model of limestone weathering and damage in masonry: Sedimentological and geotechnical controls in the Globigerina Limestone Formation (Miocene) of Malta

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Summary. *Five types and subtypes of stone used in construction in the Maltese Islands and three problematic stone types, mostly extracted from facies within the Oligo-Miocene Valletta Basin, are identified. Their nature and geotechnical behaviour is discussed in the context of specific use in masonry. These stone types represent end members of the variations in depositional and diagenetic environments in carbonates which control their level of physical heterogeneity, and ultimately affect the nature of damage seen in Globigerina limestone masonry. A model is presented linking the level of heterogeneity to the mode of salt weathering seen especially in ancient constructions.*

Keywords: *Globigerina limestone, bioturbation, facies, salt weathering, geotechnical behaviour, Malta*

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Introduction

The mid-Tertiary succession of the Maltese Islands comprises five Formations (figure 1a), including the fine-grained sediments of the Globigerina Limestone Formation that outcrop extensively. Constructions from the Neolithic to the advent of concrete have mostly used certain facies of this Formation, which is characterised by high purity (>90% $CaCO_3$), fine grain size and small pore size. Some fine-grained facies are also found in both Coralline Limestone Formations.

Fine-grained limestone is more damaged by salt crystallization and less affected by washing of salts by rain (Kozlowski et al., 1989). This problem becomes acute in the maritime and seasonal climatic conditions of the Maltese Islands, and requires further study. Fitzner et al. (1997) have modelled salt decay in Globigerina limestone based on salt load, although Cassar (2004) alleges that marginal non-carbonate geochemical parameters can be used for 'predicting' severity of weathering.

This paper adopts a holistic approach and considers the overall nature of stone as the principal variable. A number of types of stones, considered as end members of a continuum of varieties, are for the first time systematically described on the basis of depositional environment, diagenetic potential and geotechnical properties. Pore structure is also an important control on mode of weathering (Rossi-Manaresi & Tucci, 1990). On the basis of all these factors, a model is presented that links the level of heterogeneity in stone to the diverse modes of salt weathering observed in different stone types, even when found within the same masonry construction where environmental conditions are similar.

Other forms of damage, including tensile fractures in masonry are also discussed.

Stratigraphy of the Globigerina Limestone Formation and extraction

Rizzo (1932) subdivided the Globigerina Limestone Formation into 3 Members: the Lower, Middle and Upper Members. These are separated by the ubiquitous C1 and C2 phosphorite conglomerate beds (figure 1a). The thickness of the Lower Member ranges from 0m in west Malta to >100m in central south Malta (Gatt, 2005a). Dimension stone has been won since prehistory from distinct facies within the Lower Member, which is here sub-divided into 3 palaeogeographical areas (figure 1b):

(1) The Valletta Basin facies found in central south Malta, where the Lower Member may exceed 100m in thickness and comprises a basal blue-coloured facies succeeded by pale-yellow facies showing cyclic sedimentation. The foram *Globigerinoides* is usually preserved;

(2) Cyclic sediments succeeding the basal C_0 phosphorite conglomerate bed (Gatt, 2005a) over a palaeohigh in west Malta and east Gozo, where the Lower Member becomes more condensed and may thin out considerably. Planktonic foraminifera are poorly preserved (Gianelli & Salvatorini, 1972).

(3) West Gozo palaeoslope producing some thickening of the Lower Member.

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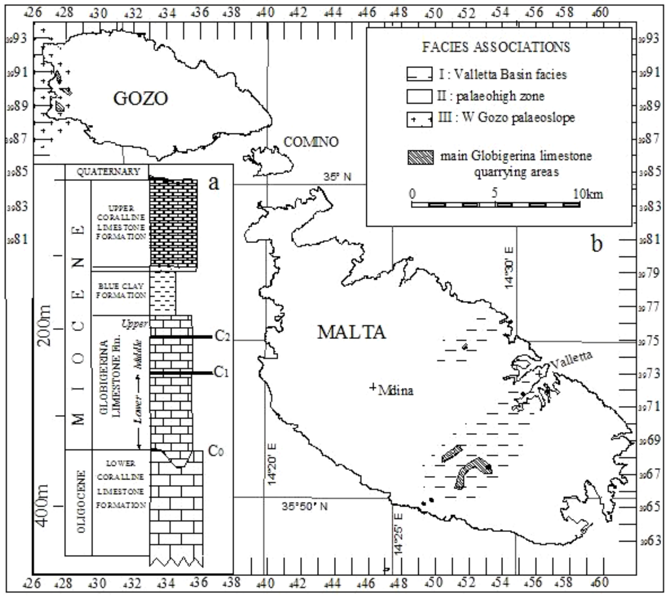

Figure 1. (a) Lithostratigraphy; (b) Localities mentioned in text.

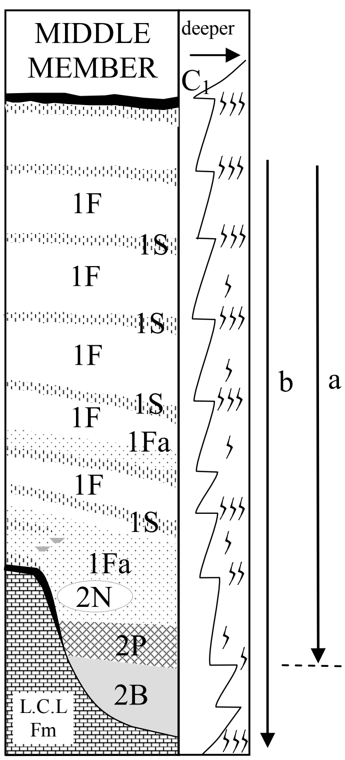

Figure 2. Highly generalized log of the Lower Member (Malta) showing stratigraphical position of stone types identified in text. Curve shows relative sea level. Symbols show level of bioturbation (a) increasing cementation; (b) increasing compaction.
(Number of sea level cycles is unknown)

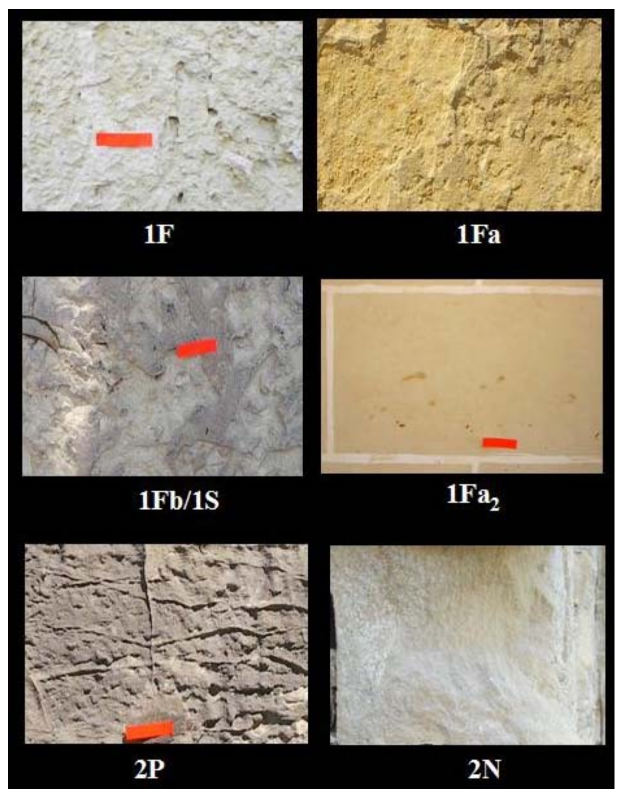

Figure 3. Photo records of masonry (exterior) classified by facies identified in text. Scale 6cm.

Localities: 1F: The Palace, Valletta;
1Fa: staircase, Association SMOM, Vall.;
1Fb /1S: Phoenicia hotel;
1Fa2: modern, Attard;
2P: S.Caterina d'Italia church, Valletta;
2N: Pinto stores, Floriana.

The main quarrying regions are found in central south Malta, coinciding with the Valletta Basin facies which has been the main source of dimension stone since prehistory, and in the west Gozo palaeoslope (figure 1b). Extraction was by splitting the rock with metal wedges, albeit the local freestone shows poor cleavage. In the 20th century, dimension stone started to be won by using rotary cutters. Most quarries lack microscale and mesoscale jointing, but may show few faults that traverse the entire quarry. Present problems include the low cost of local dimension stone, sizeable quarry waste and lack of scientific applications to quarrying leading to inadequate prospecting for good quality limestone (Gatt, 2002).

Facies of the Lower Member

Two main Facies Associations are recognised within the Lower Member, both are quarried. The stratigraphy is shown in figure 2. Specific strata within these two facies associations are used as dimension stone and here subdivided into stone types and sub-types shown in figure 3:

FACIES ASSOCIATION 1

1. Globigerinid wackestone-packstone facies – 1F

This facies is extensively used for construction and shows a wackestone to packstone texture with grains dominated by globigerinid tests (figure 4). This freestone, translated to franka in Maltese, generally has a pale yellow to white colour with few blemishes. Bioturbation includes medium sized (<50mm) burrows. SEM studies show a micritic ground mass (<2µm) with calcite spar sometimes developing in larger pores such as empty foraminiferal chambers (figures 4 & 5). The matrix includes coccoliths, although diagenetic processes may have rendered them partly indistinguishable. It has a relatively homogenized nature, although anisotropic, showing a uniaxial compressive strength normal to bedding greater by a magnitude of 1.1 to 1.2 relative to parallel to bedding.

The pelagic depositional palaeoenvironment (50 to 150m deep; Pedley, 1987) was characterised by moderate sedimentation rates and aerobic seabed conditions that allowed bioturbation. Low to moderate hydrodynamic environment produced little surface cementation, and since sediments comprise mostly calcite, there was little dissolution of metastable aragonite that could supply $CaCO_3$ for further cementation. Siliciclastic content is very low and minor accessory minerals include glauconite, quartz and phyllosilicates.

There is an overall increase in porosity in Globigerina limestone further up from the interface with the Lower Coralline Formation. This increase can be related to a number of factors including less compaction, greater preservation of empty globigerinid chambers or an overall decrease in phyllosilicates that can clog pores. Facies further up the Lower Member show higher levels of porosity (>30%) and more well-preserved coccoliths seen by SEM. A number of subtypes within 1F stone can be distinguished in ancient and modern masonry constructions. These different facies can be classified on the basis of structures within the stone that reflect depositional environment (depth of water and seabed oxygenation) and diagenesis:

a. Chondrites *facies – 1Fa:* Fine (<3mm) structures of *Chondrites* are common in franka stone and can be distinguished on the surface by brown spots in a pale yellow matrix that is usually darker than the 1F stone. *Chondrites* indicate dysaerobic depositional environments (Goldring, 1991) of deeper water where the less diverse bioturbation increases physical homogenisation in rock. A variant of this subtype (here called $1Fa_2$) recently won from certain quarries may also show medium-sized (<10mm) bioturbation with distinct brown ferruginous staining.

b. Medium to large bioturbated facies – 1Fb: On weathering, some 1F stone shows evidence of larger burrows with a width >10mm, also associated with the echinoid *Schizaster parkinsoni.* However, the difference between burrow material and surrounding is not so great as to cause significant differential weathering, although this subtype may also be a hybrid of 1S stone. Types 1Fb and 1S stone have been used for exterior boundary walls and foundations.

c. Facies with dewatering structures – 1Fc: In a few cases, bedding is disrupted by flame-structures and other dewatering structures. These sediments were disturbed by the rapid expulsion of water during compaction of the seabed sediments. A number of these structures are preserved in rock cuts in Valletta. Such internal structures can create strong anisotropies in rock which are detrimental when this stone is used in construction.

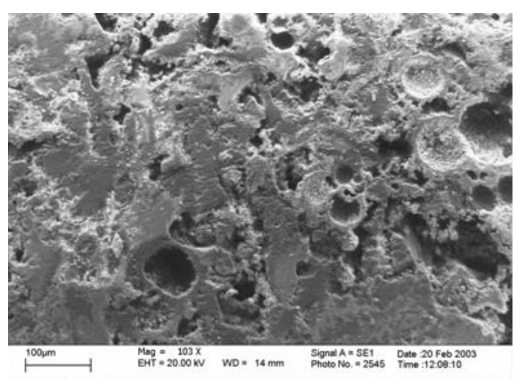

Figure 4. Lapped section of Globigerina limestone (1F stone) showing intragranular (i) and some intergranular porosity. Sample has been lapped to produce a cross-section effect (SEM micrograph by P. Gatt)

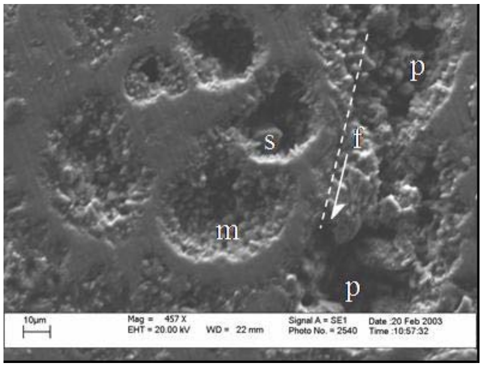

Figure 5. Trochospirally coiled shell of planktonic Globigerinacea: Intragranular porosity and precipitation of micrite (m) and spar (s) within chambers. Intergranular porosity (p) developed along Mode II failure (f). (SEM mircograph by P. Gatt)

2. Intensely bioturbated facies – 1S

Specific levels in the Lower Member consist of sediments showing anomalously dense and large bioturbation. Local quarrymen and masons use the term 'soll' to describe a problematic stone known to weather rapidly and unevenly that may have a slightly darker yellow and mottled hue, although it is also claimed to be visually undifferentiated from type 1F stone when freshly cut. Type 1S stone seen in Globigerina limestone quarries can be identified in outcrop at these stratigraphical levels:

(1) 0.3 to <3m-thick facies recurring every 2 to <10m, depending on locality. In one quarry, type 1S stone shows an increase in silica and decrease in carbonates (Testa, 1989). The repetitive intervals of 1F and 1S stone types seen in many quarries are here interpreted as cyclic sediments formed during high frequency (Milankovitch scale) climatically-driven eustatic changes.

(2) 3m from the base of the Globigerina Formation, found only on palaeohighs outside the Valletta Basin facies. The facies can be almost entirely dominated by bow-form burrows (Goldring *et al.*, 2002).

This facies is interpreted to have formed when seabed conditions were markedly aerobic during episodes of lower sea level and higher hydrodynamic levels. Under these conditions, bioturbation becomes intense and diverse, comprising large burrows of *Thalassinoides, Ophiomorpha* and *Planolites*, also associated with echinoid tests.

Animal burrows improve circulation of water in the sediments and increase the area of sediment/water interaction, resulting in the precipitation of some calcite cement. Increased cementation affects the geotechnical properties of the stone. Fitzner *et al*. (1997) confirms that 1S stone has a slightly lower porosity compared to 1F stone and Xuereb (1991) reports a higher compressive strength in 'soll' compared to franka stone, increasing to >30MPa when mottling by burrows is clearly visible (Cachia, 1985).

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Medium-depth burial, mostly related to the development of the Oligo-Miocene Valletta Basin (Gatt, 2005a) especially in south central Malta has resulted in a number of diagenetic changes that characterise facies. Further down the Lower Member, intragranular cementation increases in sediments deposited in these deeper marine palaeoenvironments, although the base (<18m) of the Globigerina Limestone Formation shows poor intergranular cementation.

1. Neomorphic facies – 2N

Neomorphism represents a more advanced form of diagenesis in Globigerina Limestone, although it is limited in extent compared to the Coralline Limestone Formations. Aggrading neomorphism can be identified in type 1F and 1Fa stone as patches having a slightly translucent and darker surface that break with a distinct conchoidal fracture. At the microscale, neomorphism sometimes results in the development of calcite crystals with curved surfaces. Figure 6 shows the front between neomorphic spar and original micrite from a 17th century dimension stone in Floriana.

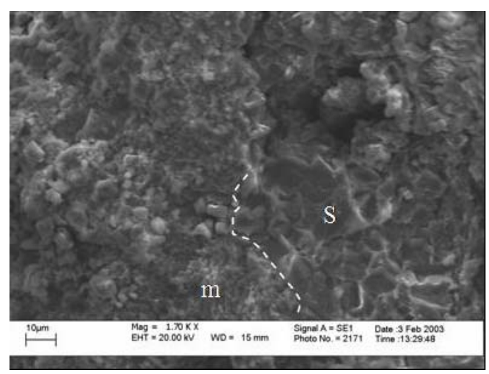

Figure 6. Growth of neomorphic spar (5-15 microns) within micrite (<4 microns) in dimension stone from 17th century building in Floriana. Dotted white line shows boundary between micrite (m) and microspar (s). (SEM micrograph by P Gatt)

Neomorphism in pelagic limestone is associated with deeper burial environments. Danish chalk in the North Sea shows the onset of pressure dissolution and the formation of microspar at depths >600m (Tucker, 1990). However, burial diagenesis in Globigerina limestone is difficult to explain since burial depths may have not been so great. The fine-grained texture and the lack of larger bioturbation structures indicates deeper water depositional environment, which may have gone through some burial diagenesis, possibly affected by elevated temperatures. Crusts (1mm thick) closely resembling neomorphic calcite are also seen on the surface of some old masonry, although their formation is unrelated to burial.

Testing of samples from the same dimension stone consisting of 1F with 2N variants show that the development of neomorphism produced a significant drop in water absorption by a magnitude of 10. This is related to a reduction in porosity by the development of neomorphism which reduces the entry of dispersed water and reduces the uptake by capillarity of solutes from the ground. Additionally, the growth of neomorphic spar also decreases hygroscopic absorption as seen in figure 7.

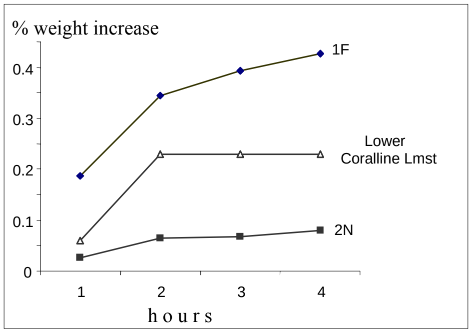

Figure 7. Hygroscopic absorption over 4 hours. Neomorphic Globigerina limestone shows only slight increase in percent weight and early levelling of trend, indicating very low hygroscopic absorption of atmospheric water compared to 1F stone.

2. Facies with cemented seams – 2P

Millimetre-thick seams of well-cemented sub-parallel horizons can be seen in the lower parts of some quarries and in ancient masonry (figure 5). These are interpreted as pressure solution seams, although without the development of stylolites. The amount of dissolution is small, distorting burrow structures only slightly. These seams may have formed by burial compaction. Alternatively, they may be extensive microcracks healed with calcite infilling, formed as a result of fracturing during tectonic activity affecting partly lithified rock. On weathering, the seams stand out, showing their stronger and more cemented nature.

3. Blue Globigerina limestone – 2B

The blue-grey coloured Globigerina limestone is easily distinguishable from other facies and is locally called ġebla l-kaħla or ħadra. Type 2B stone outcrops in dimension stone quarries of south central Malta (sometimes succeeded or replaced by an orange mottled facies) and less extensively in west Gozo. In Malta, it limits further downward excavation. This facies delimits the depocentre produced by local tectonic deepening in south central Malta linked to the formation of the Valletta Basin (Gatt, 2005a). In this relatively deeper and dysaerobic environment, 1 to >15m of carbonate and siliciclastic sediments accumulated. Metre-wide lenticular bodies of blue limestone also outcrop within the pale yellow Globigerina limestone, immediately west of the Basin at Msida and Sliema.

Non-carbonates in the Lower Member

Siliciclastic content is very low in bulk rock of the Lower Member, although it may indicate external controls that affected sedimentation throughout the Globigerina Limestone Formation. Cyclic sedimentation consisting of alternate 1S and 1F facies is accompanied by an increase in silica in the 1S beds and a peak in phosphate levels (~633ppm) just above the termination of every 1S bed (Testa, 1989). The main phosphate precipitation events in the Globigerina Limestone Formation are the C_1 and C_2 phosphorite conglomerate beds, the latter extending to SE Sicily. Carbone *et al*., (1987) associate these beds with anoxic conditions over hardgrounds. Phosphate was precipitated during shallowing events, succeeded by rare cross-bedding over the C_1 bed in Sliema (Gatt, 2005a). The increase of phosphate in recurring 1S beds is interpreted as showing greater nutrient levels during episodes of shallower marine conditions accompanied by intense bioturbation (figure 2). This culminated in the peaking of phosphate just above the 1S beds, when increased organic productivity brings the onset of low oxygen conditions resulting in a decline of bioturbation.

Clay in the Globigerina Limestone Formation is detrital in origin and correlates with quartz, comprising 0 to 25% of the rock. Its variable occurrence up the sequence represents episodes of eustatic, tectonic and climatic changes that also triggered continental erosion (John *et al.*, 2003), culminating in the deposition of the Blue Clay Formation. Superimposed on this complex mineralogical signal is clinoptilolite, which is of a volcanic origin (John *et al.*, 2003) and independent of cyclic sedimentation.

Meanwhile, tectonically-controlled deepening in the Valletta Basin produced a unique pattern of carbonate-siliciclastic sedimentation within a geographically restricted area (south central Malta). This includes type 2B stone which shows an increase in non-carbonate content recorded by Murray (1890) and confirmed by Vella *et al*. (1997) to exceed that of both 'soll' and franka (1F) stone. However, the complex and geographically diverse geochemical signals makes their use in identifying stone types highly debatable. Fitzner *et al*., (1997), Gatt (2005b) do not find a causal relationship between slight non-carbonate mineral content (e.g. non-swelling kaolinite) and severe weathering forms seen in masonry, thereby eliminating the relevance of geochemical proxies used by Cassar (2004) in 'predicting' weathering in Globigerina limestone.

Discussion

An obstacle to the scientific study of Globigerina limestone deterioration is the persistent use in literature of elusive vernacular terms utilized by masons and quarrymen, even if these terms have not been scientifically defined e.g. 'soll' (here categorised as an intensely bioturbated facies at defined stratigraphical levels).

Definition of distinct Globigerina limestone types should encompass the complexity of this material, which was deposited *circa* <25 MA and later subjected to different levels of diagenesis. These different stone types are seen to weather diversely in masonry, although, Renaissance, Baroque to early colonial age constructions show a very selective extraction of stone mainly from the Valletta Basin area (figure 1b), on the basis of their known performance in particular environmental conditions. This has resulted in relatively well-preserved ancient structures despite adverse environmental conditions and time e.g. ~2kyr Punic house at Żurrieq (Mahoney, 1988).

Depositional depth is a controlling factor in the lithification process. Together with the diagenetic potential (*sensu* Schlanger & Douglas, 1974) it accounts for the local variations in diagenetic grade of the Lower Member. These factors have direct consequences on geotechnical properties and weathering behaviour. Diagenesis starts with compaction and dewatering, affecting subtype 1Fc. Later, the dissolution of coccoliths and foraminifera with depth increased cementation and decreased porosity in type 1F stone. Increased overburden pressure brings partial dissolution, creating the 2P type of stone. Further burial leads to the ultimate end state of lithification, reached when all grains have a minimum surface-to-volume ratio (Byrne, 1965). The recrystallised type 2N stone may have partly approached this condition in absence of clay. Where clay was present, lithification was only by compaction, resulting in a stone of low strength (type 2B stone). Although burial in the Lower Member is not considered to be deep, compaction with some cementation produced stone that could be used in masonry, unlike the uncemented and less compacted Middle Member.

The complex nature of stone and response to environmental conditions has to be assessed in terms of: (1) geotechnical properties, (2) the agents of weathering of stone and (3) the forms of weathering which result from the interaction between the nature of the stone and complex environmental conditions.

1. Geotechnical properties

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The Uniaxial Compressive Strength (q_u) of the Lower Member of the Globigerina Limestone Formation ranges between 8 and >20 MPa, vaguely increasing with porosity further up the sequence (figure 8) in cores by Wardell Armstrong, (1996), although quarry samples show a negative correlation between q_u and porosity (Bonello, 1988). Type 1S stone has slightly higher compressive strength (~21 MPa) than average 1F stone (14 to 20 MPa). Bowden *et al.* (1998) also show that q_u increases with a decrease in visually assessed clay content in 'Globigerina marl'.

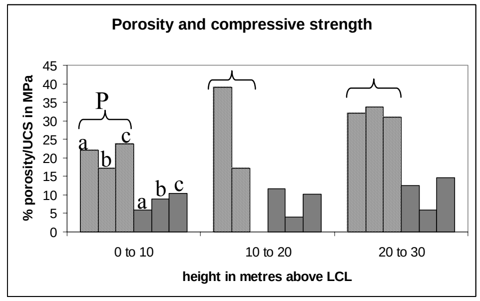

Figure 8. Rock properties varying by depth and palaeoenvironment: Porosity (P) increases further up the Lower Member; Uniaxial Compressive Strength (shaded bars) increases marginally up the section. Localities: (a) Zebbug Miocene palaeohigh; (b) Luqa palaeoslope; (c) Handaq Early Miocene palaeobasin.

The dry density of subtypes of 1F varies from 1.5 to 1.76 Mg/m^3 (Bonello, 1988). This is more comparable with the density of Tertiary chalk (*circa* 1.6 Mg/m^3) rather than limestone, indicating the medium burial depth (*circa* 200-300m) experienced by the Lower Member of the Globigerina Limestone Formation. However, type 1S may show a slightly higher density of 1.784 Mg/m^3, attributed by Xuereb (1991) to the presence of clay that permits greater compaction.

The modulus of elasticity (E) and Poisson's ratio (v) are influenced by the degree of cementation in the rock, which also influences compressional velocity in limestone (Schlanger & Douglas, 1974). Relatively higher q_u, lower porosity and palaeoenvironment indicators point to greater cementation in 1S compared to 1F stone. Figure 9 shows data for E and q_u for limestone and chalk, including that of Xuereb (1991) and Bonello (1998) who report a high E for franka stone (1F) compared to similar stone. This would also indicate an exceptionally high modulus ratio (E/q_u) of ~1000, or double that proposed by Deere & Miller (1966) for strong intact rock, comparable to that of crystalline rock e.g. massive fine-grained Taconic marble (Vermont, USA). The E for Globigerina limestone used in construction is here approximated to be ~4 to 6 GPa, on the reasonable assumption that this stone shows a low to average modulus ratio (figure 9).

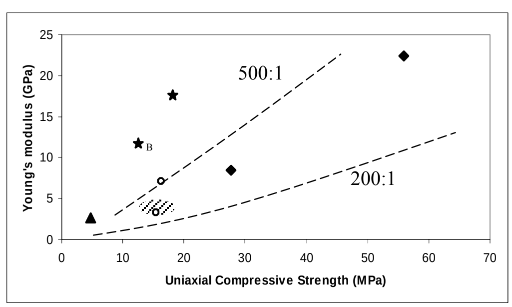

Figure 9. E and q_u for Tertiary limestone and chalk: (♦) Lower Coralline Limestone; (▲) Kent chalk (Bell, 1993); (○) Eocene chalk, Israel (Talesnick & Brafman, 1998); star symbols shows data by Xuereb (1991) and (B) Bonello (1988). Shaded area represents my approximated E for 1F stone. Dotted lines represent high and low modulus ratio limits by Deere & Miller (1966).

The tensile strength of stone has significant consequences on the integrity of masonry and construction. Because tensile strength of Globigerina limestone is always several orders of magnitude less than its compressive strength, tensile cracks can occur under many circumstances in local masonry. Mode I opening occurs initially at microscopic scale seen in figure 4, associated with Mode II failure and develops to the mesoscale. Some of the most serious damage to ancient structures is the result of tensile stress failure occurring in two types of masonry:

(a) Structures built without mortar: Neolithic to Punic age constructions, e.g. Ħaġar Qim [497 653] and Mnajdra [492 651] temples, where point load stress by overburden or by movement of masonry (due to differential settlement or erosion of surrounding stone) has resulted in tensile fracturing in megaliths of type 1F stone.
(b) Masonry with mortar: Several Medieval to Baroque buildings show erosion or deformation of mortar leading to point load stress between courses caused by masonry overburden. Depending on the stone's E, this results in the formation of vertical tensile cracks that split the dimension stone. Tensile cracks may also form at the side of the dimension stone following the removal of lateral confining pressure by loss or softening of mortar (figure 10).

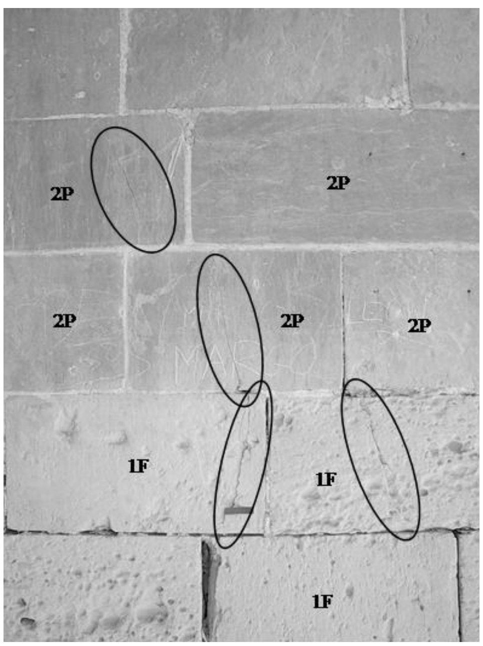

Figure 10. Auberge de Castille, Valletta, south corner: tensile fractures (circled) related to loss or differential deformation of mortar. Stone types labelled, also showing different forms of salt weathering.

FACIES ASSOCIATION 2

The geotechnical properties of types 2N and 2P stone are relatively untested. However, recrystallization and cementation reduces porosity and can increase compressive strength and E. Brittle stone have a higher E and under stress fracture at higher frequency (Gross *et al.*, 1995) e.g. rusting metal in masonry made of type 2N stone may develop tensile fractures parallel to axis of loading that lead to conchoidal fracturing.

Bioturbation in type 2B has thoroughly mixed the clay and carbonate sediments. The presence of clay reduces the potential for cementation (Matter, 1974), resulting in lithification by compaction. Since overburden pressure may not have exceeded *circa* 300m, this facies usually shows a relatively low uniaxial compressive strength of <10 MPa which makes it unreliable for use in masonry. The presence of clay can affect weathering of limestone due to its expansion on wetting and its surface charge (Gauri & Bandyopadhyay, 1999). The form of weathering seen in similar grey-coloured Globigerina limestone in the Middle Member, namely by splitting during wetting and drying cycles may be caused by the presence of clay.

2. Agents of weathering of stone

The long-term macroscale erosion of limestone is due to carbonation, although the shorter-term damage on the micro and meso-scale is controlled by salt crystallization. Cassar (2004) classifies stone by the degree of weathering and identifies 'badly' weathering stone as 'soll'. However, the degree of salt damage is also a function of environment, which is highly variable and should not be used as a basis for classifying stone types. Instead, it is the mode of weathering which reflects the intrinsic nature of the stone, independently of environment, which should partly categorize a type of stone.

The main sources of solutes in stone are capillarity rise, dispersed water and hygroscopic absorption, depending on specific environmental conditions namely, distance from the sea and water table, wind effect, diurnal temperature and humidity variations. The relationship between solute migration to stone surface and evaporation controls level of salt disruption (Rossi-Manaresi & Tucci, 1991). Fitzner *et al*. (1992) also record different damage categories for masonry and architectural decoration. The latter may show special forms of weathering due to the geometry of the stone. For example, I observed that subtype 1Fa and type 2P stone may show granular disintegration on the exterior of masonry, but result in sizeable spalling of architectural decoration on the interior (e.g. St John's co-cathedral) and exterior (e.g. Mdina gate) respectively. In this paper, damage categories refer to the most common weathering form seen on the exterior masonry.

Where environments are very hostile to local stone, as in the case of buildings close to sea level and exposed to sea spray, Globigerina Limestone was considered inadequate and was supplanted by Upper Coralline Limestone as the main dimension stone e.g. Scamp's Palace [567 720]. Type 2N stone has also been used in local constructions of the 17th and 18th century in environments that are conducive to rapid weathering of stone e.g. Forni Stores

[566 721]. In localities where capillarity rise of solutes is significant, Coralline Limestone has been used as masonry for the lower courses (e.g, in Mdina). However, in Valletta (where Coralline limestone is not readily available) this has been replaced (possibly deliberately) by type 2P stone, where dissolution seams act as inhibitors to capillarity rise.

3. Modelling mode of weathering in fine- grained limestone

A model for fine-grained limestone e.g. Globigerina limestone; Mtarfa Member, Upper Coralline Limestone (Pedley, 1987), is proposed based on the nature of the stone and the related mode of weathering (fig. 11). This is independent of salt load, which is a function of environment. This model (table 1) presents 3 conclusions based on extensive observation of external masonry in Malta:

(1) Relative intensity of salt weathering is controlled by level of; (a) uniformity of distribution of cementation; (b) physical heterogeneity, namely the distribution of pores (random or clustered) and the size of pores. Intermediate heterogeneity and cementation in stone results in least severe weathering. Weathering tests on Globigerina limestone also confirm that heterogeneity has a direct effect on loss of weight in stone (Cachia, 1999);
(2) Type of stone controls mode of salt weathering e.g. granular disintegration or alveolar weathering, as seen within the same ancient masonry (figure 11);
(3) The slight non-carbonate content especially in the problematic 1S stone has no consequence on salt weathering.

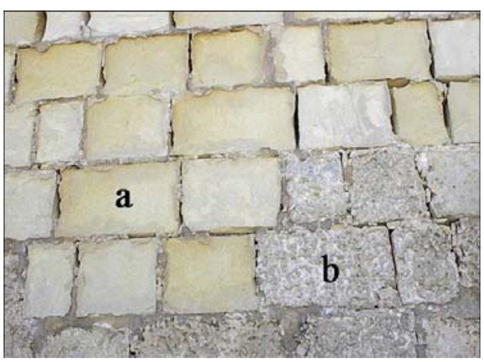

Figure 11. >200yr bastion, Mdina. Same salt load and environment; (a) Homogeneous stone (1Fa), poorly cemented, showing scaling. (b) Heterogeneous, cemented Mtarfa Member (UCL) stone develops alveolar (exichnia) mode of weathering.

Rossi-Manaresi & Tucci (1991) show that stone decay by salt crystallization occurs only in the case of particular pore structures and conclude that high crystallization pressure is associated with stone having a wide range of pore sizes, from <0.01 to 1 µm as well as larger pore sizes. Fitzner & Snethlage (1982) also associate this type of porosity with the significant development of salt decay in stone. Crystal growth in pores exerts large pressure leading to tension cracks in the stone. Cyclic wetting/drying leads to rapid disintegration of the stone. Moisture with solutes preferentially fills up smaller pores, which later supply larger pores with solute. On drying, crystallisation first occurs in the larger pores. In Globigerina limestone these include empty foraminiferal chambers (~4 to 50 µm) which are more common in type 1F stone than in type 1S stone (in the latter these are partly or completely cemented). Fitzner *et al. (*1997) confirms that pore sizes >3 µm constitute 12.2% and 5.7% in stone that weathers moderately and severely, respectively. Only after the larger pores are completely filled can crystallisation begin in the smaller pores. Heterogeneity of the stone, including the pore sizes has the following controls on salt decay in Globigerina limestone (table 1):

I. Highly heterogeneous stone:

The greater size, density and diversity of bioturbation contribute to heterogenization in 1S stone and the Mtarfa Member (shallow marine back reef facies). Larger burrows tend to be filled with coarser grain size due to the binding of grains and production of faecal pellets by burrowing fauna or because they are infilled with sand-sized grains. In type 1S stone, relatively less solute is supplied to the fewer larger pores mostly in burrows, so that more remains in the smaller pores, where salt crystallization can start at an earlier stage. Salt crystallisation is more destructive in the finer-grained matrix surrounding the burrowed areas. This explains the development of exichnia (*sensu* Martinsson, 1970) commonly seen in weathered type 1S outcrops (figure 5), also as a result of differential cementation. Exichnia protrusions break off, causing a significant loss in original volume and overall decline in strength.

II. Moderately heterogeneous stone

Type 1F stone is free from localised anomalies, hence called freestone or franka, which together with uniformly distributed cementation gives the best weathering quality to stone. Early scaling passes to granular disintegration that may later develop into poorly defined exichnia (figure 5, 1F), independently of salt load. The more common larger pores tend to block capillarity rise of water coming from smaller pores. Salt crystallization in larger pores is relatively less damaging compared to that in smaller pores. However, when larger pores close to the surface are filled with growing salt crystals, these may contribute to exfoliation and crumbling of surface crust.

III. Homogenous stone

Subtype 1Fa and type 2N stone used in masonry of the 17th century are relatively homogenous and show low diversity in burrow types. Subtype 1Fa lacks alveolar weathering by salt crystallisation. This is due to the homogenous texture of the stone that weathers uniformly by granular disintegration and scaling, although more rapidly compared to 1F stone due to its poor cementation.

	Heterogeneous	Intermediate	Homogeneous
Stone type	1S 1Fb	1F 2N	2P 1Fa
Pore size *small <3 µm*	Mostly in matrix surrounding burrows	dispersed	dispersed
larae	5.7% mostly in large burrows and connected	12.2% and dispersed (Globigerinid chambers)	dispersed
Mode of Weather-	Alveolar, distinct exichnia formed	Some alveolar, exfoliation & granular disintegration	Mostly granular disintegration and scaling
Cement-ation	moderate		low

Table 1. Model of mode of weathering controlled by stone heterogeneity (pore sizes after Fitzner et al.*, 1997)*

Conclusions

Mode of salt weathering is related to the level of physical heterogeneity of fine-grained pure limestone. This factor is fundamental to conservation and intervention and can be used to address the following problems which are endemic in the Maltese Islands:

- In cases where badly weathered stone needs to be replaced, a similar stone should be selected (figure 11 shows the effect of the contrary).

- Consolidants and non-carbonate coatings on masonry building should not be applied indiscriminately to different stone types, but are more appropriate for types with low cementation.

- Constructions in hostile environmental conditions require the selection of specific stone types that respond adequately to adverse conditions.

- Identification of stone types is fundamental in prospecting for quality limestone by the quarrying industry and can serve as a basis for a stone classification scheme and pricing of different stone types.

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