Paper

Vulnerability of buildings in Malta to earthquake, volcano and tsunami hazard

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Synopsis

Malta being situated in the centre of the Mediterranean, the natural disasters discussed are earthquakes and related perils, volcanism, and tsunamis.

The anticipated damage for a particular type of structure subjected to a defined earthquake intensity is presented in a matrix giving the relative mean damage ratio (MDR)[1]*. The MDR is then adjusted according to the stiffness and irregularity of the structure by constants quoted in the paper. The damage probability matrix (DPM)*[1] *for buildings then follows, as potential damage could be much higher than the MDR. The percentage deathrate*[1] *for earthquake intensity is also presented, after taking into account the proportion of damage due to non-structural causes. This gives an interesting insight into the number of casualties occurring, depending on grade of damage to building.*

Recorded damage from volcanoes and tsunamis[1] *is then given, with particular emphasis on the Mediterranean region. The information provided makes structural engineers aware of the various perils that exist; they may utilise their expertise in the area of disaster management by advising on setting parameters prior to the calculation of a risk assessment, for reducing the risks.*

In conclusion, to evaluate the various risk hazards, the Maltese Islands are split into four regions, according to geological relief formation and population density.

Introduction

The Maltese Islands, situated between Sicily and Tunisia, occupy an area of 315km^2, with a shoreline 137km long and a current population of nearly 380 000. The islands lie in the middle of an extensive fault system trending approximately NW–SE affecting the central Mediterranean from Tunisia to Sicily. The Sicily Channel forms part of the relatively stable northernmost platform of the African continent, separating the island of Sicily from the North African coast.

The geology of Malta consists of a limestone sedimentary formation (Table 1) that was originally deposited at the bottom of a warm, shallow sea during the *oliga miocene* period of the Tertiary Era.

The building material used most widely in Malta is the globigerina block known as 'franka'. A mortar is used that consists of one part cement, two parts sand, and 10 parts stone dust, which corresponds to a grade IV mortar (BS 5628), whilst characteristic crushing strengths for globigerina limestone (GL) and lower coralline limestone (LCL) (see Table 1) are 20N/mm^2 and 75N/mm^2, respectively. The difficulty of dressing LCL makes its use very limited at present, for economic reasons. Old buildings close to the sea may have the lower storey in LCL, owing to its greater resistance to deterioration.

TABLE 1 – The geology of Malta

Malta's geological succession	Max. thickness	Use
Upper coralline limestone (UCL)	175m	Lime production or known as 'Gozo marble'
Greensand	16m	Deteriorates but may be found in rubble walls
Blue clay	75m	
Globigerina limestone (GL)	227m	Easily working, used as a building block
Lower coralline limestone (LCL)	120m (visible)	Crushed for concrete aggregate or road base

Because of the absence of available timber, floor slabs were in 1.0m length masonry slabs, supported on masonry arches at ground level, with timber beams used at upper levels. During the middle of the 19th century, the timber beams could have been replaced by steel joists. Since World War 2 this form of construction has been gradually replaced by reinforced concrete slabs.

The majority of Maltese buildings consist of a loadbearing masonry system with floor slabs supported on 225mm- or 150mm-thick limestone walling. At the lower level, framing concrete beams or precast, prestressed slabs may be introduced to present an open layout for carparking or commercial use.

The Islands lie in the middle of an extensive fault system affecting the central Mediterranean from Tunisia to Sicily. The faults, along which earthquakes occur, are continuous through Malta and Gozo. Some of the faults are extinct, but others are young and still active.

John Shower, writing 5 days after the 1693 earthquake[2], mentioned 'that the roof of the church of Our Lady Tal-Pilar was thrown down, with part of that of St Lawrence. The Church and College of the Jesuits also suffered very much, but the Cathedral and St Paul's Church in Rabat received the greatest damage and are so ruined that they can hardly be repaired. Most of the houses are extremely shattered and deserted by the inhabitants who now live in grottos and under tents in the fields'. Further, 'the Grand Master was hunting and was in great danger by the falling of a mountain near him'. During the same 1693 earthquake, Agius De Soldanis in his manuscript (*Gozo Antico and Moderno*) recounts how 'at Gebel Sannat, a slice of rock was detached to the sea below, whilst the sea at Xlendi rolled out to about 1 mile and swept back a little later'. Considering the above damage, rock falls, and tsunami, it appears that the intensity of the 1693 earthquake registered MSK VII.

In *Seismic Hazard in the Maltese Islands*[3] it is concluded that observations of recent earthquake activity around the Islands indicate, at first sight, a low level of activity, with small-magnitude events (<3.5) occurring at low rates. The occurrence of a magnitude 4.5 event close to Malta in 1972, together with the reported 1693 earthquake, shows that it would be irresponsible to dismiss the hazard as negligible.

Current earthquake design

The design of normal modern buildings generally follows rules laid down in Codes, which specify minimum requirements that are gross simplifications and generalisations that incorporate uncertainties of sometimes considerable magnitude. The basic philosophy of design is the protection of human life and the avoidance of major structural damage, not the reduction of damage. 'Structures in general should be able to resist minor earthquakes without damage, resist moderate earthquakes without structural damage, but with some non-structural damage, resist major earthquakes of severity without collapse but with some structural as well as non-structural damage.'[4]

Currently, no Building Regulations are in force in Malta, but a draft[5] is being proposed to become operational. In this draft for design, a predicable level of seismic action is to be catered for, dealing with special categories of construction works. These are to comprise hospitals and ambulance depots, main utility buildings (e.g. power stations), fire engine depots, fuel and gas storage installations, bridges and underpasses on major arterial routes, buildings designed to accommodate people who have some impairment in mobility, free-standing buildings of 20.0m heights, and buildings used by large assemblies of people.

Evaluation of damage and loss to earthquake exposure

The most important factors to be borne in mind are:

- subsoil in which the risk has been built or erected
- material used in building (discussed in section 'Earthquake engineering parameters')

TABLE 2 – Recommended damping values for various materials

Material	Damping level (%)
Reinforced concrete	4
Prestressed concrete	2
Steel welded or friction-grip bolts	2
Steel bolted joints	4
Timber	12

- workmanship (discussed in section 'Earthquake engineering parameters')
- regularity and symmetry (a method of catering for this effect according to handbook by Swiss Re[1] is outlined in section 'Anticipated damage matrix')
- non-structural damage (referred to in sections on 'Engineering earthquake parameters' and 'Anticipated damage matrix')
- sensitivity (relates to machinery, plant and equipment that go into a factory, chemical plant or power station)
- fire exposure (due to the increased probability of ignition, of the escape and spread of inflammable material, and of the failure of fire-fighting facilities)

Engineering earthquake parameters

The basic vibration frequency equation for a single-degree-of-freedom system is given by:

$$f = \sqrt{(k/m)}$$

Where damping occurs, the frequency is approximated to:

$$f_D = f\sqrt{(1 - \varepsilon^2)}$$

further approximated by $\varepsilon = c/2mf$

(for earthquake motion, with displacement measured relative to the ground, the solution of the equation of motion involves the solution of a standard Duhamel integral, with the same parameters)

where

f is the frequency for simple motion
f_D is the frequency for damped motion
k depends on the stiffness of the structure occurring, to material adopted
m is the modal mass of the structure under vibration
ε is the fraction of damping
c is a damping constant of the material

From the above the static and dynamic parameters to be estimated include mass, stiffness, damping, and parameters derived therefrom, such as the natural frequencies of the building, etc.

The mass of a building may appear easy to calculate, but differences always exist between masses according to drawings when compared with actual constructions; also, the use of the building may change during its life.

The stiffness issue is complex for a number of reasons. In the first place, the stiffness designed into the structure of a building may look perfect from the point of view of static load, but possibly not for a dynamic process such as earthquake shaking. Stiffness is also affected by quality of material. Good masonry set in normal lime mortar will not produce walls as stiff as where cement mortar is used. It is known that, in earthquake zones, old houses built of poor rubble masonry, but which had received a new coat of plaster, fared better than those that had not[1].

Damping, the third important parameter, has an effect on building deformation in connection with its amplification. Recommended damping values as a percentage of the critical damping are given in Table 2.

Natural frequencies and modes of vibration play a central role in the analysis of the dynamic response of the structure. Most building Codes give an indication of how to estimate the fundamental period of buildings. The most primitive rule is provided by a formula like

$$T = aN$$

where

T is the natural fundamental period (in s)
N is the number of storeys
a is a constant, given a value varying from 0.1–0.05

The evaluation of the natural frequency of an actual structure requires possibly a more sophisticated approach. An error in frequencies could bring a building nearer to the predominant frequencies of the site, where the amplification of building response due to resonance effects may occur with substantial damage.

TABLE 3 – Types of building

Type	Description	Base shear design % of gravity
A	Building of fieldstones, rubble masonry, adobe, and clay. Buildings with vulnerable walls because of decay, bad mortar, bad state of repair, thin cavity brick walls, etc.	–
B	Ordinary unreinforced brick buildings, buildings of concrete blocks, simple stonemasonry and such buildings incorporating structural members of wood	–
C	Buildings with structural members of low-quality concrete and simple reinforcements with no allowance for earthquake forces, and wooden buildings, the strength of which has been noticeably affected by deterioration	–
D_1	Buildings with a frame (structural members) of reinforced concrete	2–3
D_2	Buildings with a frame (structural members) of reinforced concrete	3–4
D_3	Buildings with a frame (structural members) of reinforced concrete	6
D_4	Buildings with a frame (structural members) of reinforced concrete	12
D_5	Buildings with a frame (structural members) of reinforced concrete	20

NOTE: The subscript to a D building denotes the base shear to be resisted given in adjacent table.

Eventually, it is the displacement that causes damage to the structural and non-structural parts. If buildings could be made sufficiently strong that they moved with the ground, without being distorted, they would survive an earthquake very successfully. This is a practical possibility with a structure of only a few storeys, but such extreme rigidity is not attainable for tall buildings. If, for instance, one- or two-storey buildings were as stiff as a container used for shipping goods, they would ride out the earthquake with a very low MDR.

Compatibility of materials used in construction is a decisive factor in damage. A flexible and ductile steel structure may absorb a considerable amount of deformation without serious damage. If, however, brittle (i.e. non-compatible) in-fill walls are attached to such a structure, they are bound to suffer dramatically, affecting items built into or affixed to them. This explains why so-called soft structures, designed for considerable flexure, produce severe non-structural damage, even if earthquake intensity is not very high.

Steel is defined as a 'ductile' material, whilst masonry, on the other hand, is defined as a 'brittle' material. A ductile material would enter the plastic range, whilst, with a brittle material, deflection would lead to a sudden or abrupt explosive shattering failure, as in the case of glass or masonry. A building designed for high ductility would probably mean substantial non-structural losses, especially if the non-structural parts are brittle. Buildings with supporting parts of steel and with walls of metal sheets or other elastic material are good risks. Buildings in rubble masonry, masonry and blockwork or prefabricated parts are, in general, susceptible to the highest risks. Masonry walls are brittle and easily shattered, whilst prefabricated parts are rarely interconnected properly.

Building types found in Malta

Rubble masonry buildings, as found in old buildings in Valletta or in the villages, being over 200 years old, are brittle. These buildings are made of stone set in earth, and such structures tend to fall apart even if shaking is moderate at MSK V.

Damage to plain masonry is often concentrated around openings following the mortar joints. Cavity double walling poses a further problem, as the bondstone may not be sufficient for the resultant pop-out of one skin owing to little strength in the plane of earthquake distortions. Reinforced block masonry, especially at corners tying in with the reinforcement of the con-

TABLE 4 – Mean damage ratio (MDR) for building type against earthquake intensity

Building type	A	B	C	D_1	D_2	D_3	D_4
Earthquake intensity	MDR (%)	MDR (%)	MDR (%)	MDR (%)	(%)	(%)	(%)
V	4	2					
VI	10	4	1				
VII	45	20	10	3	2		
VIII	60	45	25	12	6	3	1
IX	80	60	45	30	17	12	6
X	100	80	65	55	35	25	17
XI	100	100	100	85	60	50	35

The present majority range of Maltese buildings fall within types B–D_1

TABLE 5 – Amplification factor for anticipated damage to structures, depending on irregularity and asymmetry*

(a) Irregularity and asymmetry effects on damage in relation to building elevation

Shape	Elevation	Fr_1
A1	L-shaped frame with increased height	1.3
A2	A soft structure introduced at ground level for majority of foot print area, overlying a rigid masonry structure above	

(b) Irregularity and asymmetry effects on damage in relation to floor plan

Shape	Floor plan	Fr_2
B1	A trapezoidal or L-shaped plan as opposed to rectangular	1.3
B2	A T-shaped plan	1.5
B3	A U-shaped plan	1.8

(c) Irregularity and asymmetry effects on damage in relation to internal features

Shape	Internal properties	Fr_3
C1	Different spans of irregular arangements of substantial internal walls	1.5
C2	Continuous window-bands interrupt fill-in wall, producing a short pier effect or substantial transitions in stiffness at ground level, due to large open spans	2.5

*Abridged version of tables obtained from Appendix A of Swiss Re Handbook[1]

crete floor slab, together with good workmanship in grouting up the reinforcements, would be a drastic improvement over Malta's present state of the art in the construction of masonry buildings.

The concrete buildings constructed to date generally fall short of recommendations given by earthquake Codes for detailing methods of reinforcement, mostly in the tying of column–beam joint layouts and in the positioning of stirrups in beams and columns. Special care is also needed with prefabricated buildings, as their very design is often deficient as regards adequate interconnection. If the workmanship also leaves much to be desired, the compounded effect could lead to particularly severe damage.

Anticipated damage matrix for Maltese property types founded on rock and being moderately asymmetrical and irregular

The method depends on the 12° MSK intensity scale[6] which is roughly equivalent to the MM scale in actual values, varying as to degree of sophistication, including building types (Table 3), damage grades and quantities. The arrangement of the scale includes the effects on humans, natural objects, and the damage to buildings.

In Malta, a few buildings are classified as type B. These would be restricted to old, deteriorated rural dwellings exceeding 150 years in age or old, deteriorated buildings in Valletta in which, owing to little maintenance, stability has been impaired because of water ingress. Type A are limited to old, deteriorated agricultural sheds found in fields.

TABLE 6 – Amended damage ratio matrix for higher irregularity and asymmetry

Building type	C	D_1
Earthquake intensity	(%)	(%)
V	10	5
VI	30	18
VII	60	40
VIII	100	72
IX	100	95

Most masonry buildings and most concrete frame buildings would be classified as conforming to type C. The more rigid buildings, satisfying stiffness regularity and symmetry in plan/elevation layout, are classified D1. The mean damage ratio (MDR)1 (Table 4) is the average damage to buildings of roughly similar vulnerability and architectural characteristics, expressed as a percentage of their new value.

For buildings founded on softer material than limestone, the MDR is taken as the progressively corresponding higher value on the scale: e.g. if a type C building, founded on clay, is subjected to MSK VI, its MDR is to be taken at 10%. Further, if it is founded on a poorly backfilled, disused quarry, a MDR of 25% is to be taken.

During the past 25 years, building construction in Malta has been subjected to changes brought about by the economic expectations of landed property. The commercialisation of buildings has opened up the layout, especially at groundfloor level, obtaining a flexible, soft structure, whilst on the upper levels, rigid masonry structures are still being constructed because of the economical availability of good building stone. Another recent innovation is the availability of precast, prestressed slabs, which are ideal for obtaining the large, open spans necessary for the carparking facilities required by our society. These slabs normally sit freely on the supporting structure, with no tying provided to the rest of the structural system. In earthquake design, the tying of the various structural systems is a requisite for obtaining a rigid diaphragm that ties the whole building together.

An enhanced factor, F_r, must be obtained for a highly irregular building, with abrupt change of stiffness between floors. The MDRs in Table 4 are worked for a weighting factor, F_{r1}, of 1.3 for irregularity and asymmetry in relation to a recessed elevation of building (shape A1 in Table 5A), a similar value for F_{r2} (shape B1 in Table 5B) of 1.3 in relation to a L-shaped floorplan, and a value F_{r3} of 1.5 in relation to internal irregular spans and layout of walls of buildings (shape C1in Table 5C), giving a global factor of:

$$F_{rA} = 1.3 \times 1.3 \times 1.5 = 2.5$$

Soft designs encountered locally could incorporate a partial soft groundfloor, yielding a F_{r1} factor of 4 (shape A2 in Table 5A). A T-shaped floorplan, with increased damage probability at both sides of intersection, yields a F_{r2} factor of 1.5 (shape B2 in Table 5B). For the continuous window bands at upper level, a F_{r3} factor of 2. 5(shape C2 in Table 5C) is yielded, giving a global factor of: .

$$F_{rB} = 4 \times 1.5 \times 2.5 = 15$$

The effects of asymmetry lead to an amplification of MDR given by:

$$F_{rB}/F_{rA} = 15/2.5 = 6 \text{ times}$$

The local buildings that fall into this category are type C and D1, and an amended damage ratio matrix (Table 6) is proposed to cater for higher asymmetry and irregularity.

The DPM[1] (Table 7) for buildings now follows. This shows the effects of MDRs, differing substantially from that assumed; it could well be that the loss is much higher than that given by the MDR.

The highest damage class (G) in Table 7, covering damage between 50% and 100%, is of particular importance, as most casualities and severe indirect losses due to business interruption are associated with these severely damaged buildings.

Table 8 is more useful than Table 7 in showing the approximate percentage of the homogeneous buildings in the 80–100% damage class, depending on the MDR of the sample.

As an example, let us assume a moderately asymmetrical and irregular type-C building, founded on rock, subjected to an earthquake of intensity MSK VII. From Table 4, MDR is taken as 10%.

From Table 7, for a MDR of 10%, the following respective sample class damage is obtained: A: 36%, B: 23%, C: 18%, D: 12%, E: 8%, F: 3%, and G: 1%.

From Table 8 for a MDR of 10%, the percentage of buildings subjected to damage varying between 80–100% given as 0.25%.

This exercise could be carried further to see how much of the damage is non-structural. For a type C building (Table 2), 70% of the above-mentioned MDR is for non-structural components, whilst for a type D1 building this value increases to 80%, 90% for D2, 98% for D3, and 99.9% for D4. In Malta, the proportion of shell cost to finishes varies in the ratio of 1:2, whilst for a more sophisticated building type, such as a hotel, this increases to 1:4. The amount of non-structural damage affects the number of people injured and the degree of business interruption..

Buildings that incorporate a high or very high collapse probability will kill many people as they collapse and leave few to be injured. As a rule-of-thumb, it may be assumed that about 1/4–1/8 of the population in the 80–100% (Table 8) damage class buildings will be killed.

As the quality of buildings improves, the importance of structural failure diminishes, while the contribution of non-structural damage increases; buildings with failure-prone non-structural parts will have a higher number of injuries in and around them.

The death-rate (Table 9[1]) is also influenced by the hour of the day, the day of the week, and the season, when the earthquake strikes. People are not distributed uniformly between buildings and throughout each individual building. During shopping hours, many will be in buildings that have a soft groundfloor and other features that increase failure probability. A further correction is required to allow for fire and explosion, as well as for the consequences of tsunami.

A medium-sized earthquake occurring today could cause losses amounting to many thousands of Maltese lira/inhabitant, with the situation even worst than in other localities, as the economy is concentrated in a small region, with all eggs (buildings, labour, stock, etc.) being in one basket, a situation that cannot be remedied by help from other parts of the country.

The reduction of losses due to earthquake can be obtained by improving and tying together the building fabric. Even though unreinforced masonry is unsuitable for use in seismic areas, its performance may be enhanced if recommendations highlighted previously are followed. If future workmanship and detailing achieves a D1 type of building, then, from Table 4, MDR is reduced from 10% to 3% at MSK VII.

Vulcanism

There are 13 active volcanoes in the central Mediterranean area, with a chain density of 68km. The general rate of activity is related to the chain density, being the average distance between alternate volcanoes in a particular region. Eruptions in central America, with an average chain density of 37km, and Japan (42km) are somewhat higher than in the central Mediterranean (68km), but higher than in the northern island of New Zealand (88km).

The volcanic explosivity index (VEI), based on the volume of products, eruptive cloud height, descriptive terms, and other measures, produces a simple 0–8 index of increasing explosivity, defined in Table 10.

For the central Mediterranean the return periods in years for various VEIs approximate to the following, as given in Table 11[1]:

Mount Etna, situated 220km due north of Malta, is the largest active volcano in Europe and erupts fairly regularly. It does not seem to have exceeded VEI 3 over the last 3500 years, but its two caledras and its rather viscous lava are a warning that this is not an absolute rule. Its extensive magna chamber amounts approximately to 550km^2 with a volume estimated at 1600km^3 on an ellipsoid structure extending horizontally 22 × 31km and vertically 4km. Etnean eruptions tend to be less explosive and therefore produce less fine-grained fragmental debris and ash. Etna erupted a total of 37 times during the 18th and 19th centuries and has erupted six times so far during the 20th century. In 1669 (VEI 2–3) the volume of lava discharged from Etna was estimated at 1km^3, while in 1971–1981 it was estimated at 0.1km^3. The greatest distance of lava flows measures 240km in Kenya.

TABLE 7 – Damage probability matrix for buildings

Damage class % of value			Mean damage ratio (MDR) (%)									
			1.5	3	5	10	25	37.5	50	60	70	85
0	–1.5	(A)	83	73	60	36	9	2				
1.5	–3	(B)	17	25	26	23	9	3				
3	–6	(C)		2	10	18	11	5	2			
6	–12.5	(D)			3	12	18	12	6	2	1	
12.5	–25	(E)			1	8	24	24	15	7	3	
25	–50	(F)				3	19	28	29	23	18	10
50	–100	(G)				1	10	29	48	68	78	90

TABLE 8 – Percentage of buildings with 80–100% damage, depending on MDR

MDR	10	20	30	40	50	60	70	80	90
%	0.25	3.5	10	20	30	45	56	70	85

Other volcanic areas include Pantelleria and Limosa, roughly in line with Malta. Further north are Ustica, the Aeolian Islands (340km away), together with Vesuvius (570km away) further up.

In 1906, the height of column reached by steam ejected from Vesuvius was 13km. A height of 50km, with fine ash, was recorded in Krakatoa (1883). During AD 79 the volume of solid material ejected from Vesuvius during an explosive eruption was estimated at 4km^3 (max. recorded 1000km^3). Vesuvius has a span of 5.27 years between each eruption, with a standard deviation of 4.8 years. The last eruption dates back to 1944, which could be an indication that a relatively violent event is probable now. The timespan exceeds the 38 years of repose separating the eruptions of 1906 and 1944, which were both VEI 3.

In 1930, the distance reached by a 30t projectile from Stromboli was 3km. The greatest distance measured in 1883 was 80km for pumice stones from Krakatoa. Stromboli tsunami in 1930 experienced a VEI 3 eruption which produced a 2.2m tsunami generated by the shaking of the flanks of Stromboli, which extend far out under the sea. It has erupted, on average, every 3.25 years, but somewhat irregularly, as shown by the standard deviation of 5.35 years.

Damage from volcanoes

The damage caused by a volcanic eruption depends primarily on the type and magnitude of the eruption, the distance between the risk and the source, and the wind direction and meteorological conditions.

On the basis of old observations and extrapolations, damage from lava flows is generally restricted to nearby terrain. Glowing avalanches or pyro-

TABLE 9 – The percentage deathrate for earthquake intensity against moderately irregular building type founded on rock

Building type	B	C	D_1	D_3	D_4
Earthquake intensity					
VII	0.03	–	–		
VIII	1	0.4	0.05		
IX	12	6	2	0.07	0.01
X	35	18	10	2	0.2
XI	75	45	25	18	1

TABLE 10 – Index of increasing volcanic explosivity

Volcanic explosivity index	Classification	Description	Eruptions
VEI 0	Hawaiian	Gentle and diffusive	443 records
VEI 1	Strombolian	Gentle	361 records
VEI 2	Vulcanian	Explosive	3,108 records
VEI 3	Pinian	Severe	720 records
VEI 4		Terrific	131 records
VEI 5	Ultra-Pinian	Cataclysmic	35 records
VEI 6		Colossal	16 records
VEI 7		Super-colossal	1 record
VEI 8		Mega-colossal	0 record

TABLE 11 – Volcanic explosivity index (VEI) v. return periods R *(in years)*

VEI	2	3	4	5	6	7	8
R(yrs)	80	750	5000	45 000	650 000	16M	8.10^{10}

clastic flows can bring total destruction to places 10–20km from source. Heavy tephra and ashfall is problematic today for both agriculture and horticulture and as a potential cause of damage to sensitive technical equipment. Corrosive and noxious gases can cause colossal damage in a modern technological society.

In the light of the above and the preceding section, the damage that may affect the Maltese Islands appears to be limited to that which, in turn, could be the cause of a reduction in visibility, temperature, ashfall, and build-up of corrosive and noxious gases, together with the effects of pressure disturbance in the air and electrical phenomena.

Ashfall

By considering the areas of ashfall of Tambora (VEI 7) (placed in such a way as to show the hypothetical distribution if one of the south Italian volcanoes suffered a similar fate), together with assumed meteorological conditions, the Maltese Islands could be covered with a distribution of ash and tephra of a thickness of more than 25cm. The eruption of Katmai in 1912 (VEI 6) produced a 10cm layer of ash, 200km from the vents.

According to R.J. Blong, at 25cm thickness of tephra falls on plants, a rice paddy is destroyed, whilst at 10 cm, some branches break under tephra load and palm fronds are broken.

Human beings are mostly endangered because of the exposure of the respiratory tract and eyes.

Quarry works tolerate a lot of ash, and low maintenance would be required before resuming operation. Electronic and electrical equipment can sustain damage because of the damaging fine particles, their abrasive effects ,and the electrical conductivity.

The danger to flying aircraft should also be mentioned, with the near crash of a jumbo jet cited.

With ash dispersal, the reduction of visibility may amount to total darkness. From an eruption (VEI 5)in 1932 at Quizapu Volcano, Chile, 10mm of ash fell at Buenos Aires, about 1200km to the east of the volcano, and 50mm of ash fell at a distance of 950km. 10–20mm of ash reduces visibility to such an extent that a World Cup soccer match is out of the question, apart from the danger to the players of exposure to pneumoconiosis or even silicosis During the eruption of Mt Pinatubo in 1991, a typhoon carried ash in a southward direction towards Manila 100km away. An ashfall of 10mm caused the international airport to close for 5 days.

Temperature effects

Temperature exposure depends on many parameters, such as the type of eruption, its time-history, the topography between the vent and area affected, the channelling of the products of eruption, and meteorological conditions; these are outlined in Table 12, with the 200km distance approximating to the distance of Etna from Malta and similarly the 550km from Vesuvius.

Gases and acids

Chemicals that can be said to be harmful and abundant in volcanic eruptions include compounds of sulphur, chlorine, and fluorine, all of which are corrosive.

The Mediterranean lavas are of the andesites type, contaminated by the limestone of the earth's crust. Andesites representing the majority of lavas contain about 59% SiO2, 16% Al203, 7% iron oxides, 6% CaO, 4% Na20, 3% Mg0, and 2%K20.

The Katmai (andesitic cone) eruption (VEI 6: 1912) caused sore throats at Kodiak, 160km from the volcano, eating became almost impossible, and every object made of bronze, brass or copper was tarnished black, even if in a drawer inside a sealed house. Washing on the line was reduced to shreds. The rain had so much acid that it caused blisters on the lips, and at Latouche, nearly 500km to the NE, the rain contained so much sulphuric acid that it caused burns on exposed skin.

TABLE 12 – Parameters affecting temperature exposure

Volcanic explositive index	Distance	Temperature elevation	Remarks
VEI 4	200km	50°C	Sensitive equipment will cease to work properly
VEI 5	550km	50°C	
VEI 5	200km	200°C	Plastic melts at 170°C
VIE 6	550km	200°C	
VEI 6	200km	800°C	At 600°C annihilation of all human life would occur
VEI 7	550km	550°C	

Pressure disturbance in the air

The distance of perception of volcanic explosion at Krakatoa (VEI 6: 1883) approximates to 4653km. At the Batavia Gasworks, 160km from Krakatoa, some windowpanes were broken, some walls were allegedly cracked and some lamps broken. More serious was the throwing down of lamps, the extinguishing of gas jets, and the escape of gas from a gasometer. The effects were similar at Buitenzorg, also 160km from Krakatoa.

Asama produced strong shockwaves (VEI 2: 1911). In Tokyo, at a distance of 300km, windows were rattled and allegedly even stone weights fell from roofs.

During the eruption in Lipari (VEI 2–3: 1890) windowpanes were broken in a 10km vicinity.

Electrical phenomena

During explosive volcanic eruptions even of a small magnitude, an extremely high incidence of lightning exists: the only prerequisite is the presence of dry particles of ash in the air.

The exposure of factories, plant and installations containing material that is explosive, easily inflammable or noxious must be viewed with concern. When Katmar erupted (VEI 6: 1912), the Woody Island naval station 150km away was struck by lightning and burned down.

The growing presence of electronic equipment in commerce and industry poses problems, as lightning can damage not only hardware, but also software, leading to loss of data.

Inherent risks of a volcanic eruption

As an example, consider Mount Etna, 200km away, subjected to a VEI 4–5 explosion. From enclosed data, one would expect an ashfall of 10mm thickness, temperatures rising from 50°–200°C. Ash dispersal would cause a reduction in visibility for about 3 days. The international airport would have to close for 5 days, with various damage caused to equipment and deterioration of building materials owing to heat build-up.

Tsunamis

'Tsunami', of Japanese origin, is the internationally accepted term for radially spreading, long-period gravity waves caused by large-scale disturbance of an impulsive nature. Such disturbances may be caused not only by earthquakes, but also by landslides, by the collapse of a caldera of a volcano in the sea, by the fall of large meteorites, and by the impact of asteroids. Earthquake-generated tsunamis have caused very grave losses during the second half of this century, although the incidence of the great earthquakes that generate severe tsunamis was rather nominal. There is a general correlation between earthquake magnitude and size of tsunami: it may be said that only events above intensity MSK7 cause damaging tsunamis. The accumulation of very substantial developments along shorelines during recent decades has greatly aggravated exposure to the possibility of tsunami damage. It has been estimated that some 100 000 people have lost their lives owing to tsunamis over the last 100 years.

Present risk assessment is hampered not only because of difficulties in translating the losses of the past into today's conditions, but also by the relative dearth of large earthquakes, in particular during the period when industrialisation and coastal development were progressing rapidly along most shores.

As the principal wavelength is substantially longer than the average ocean depth, tsunamis are considered to be shallow-water waves, where their speed of propagation approximates to

$$V \approx \sqrt{gd}$$

where g is the gravitation of the earth ($9.81 m/s^2$) and d is the water depth (m).

The waves generated by tsunami are not comparable to ordinary water waves, as considerable draw-down and run-up occurs. Owing to this, the action of tsunami waves is far more forceful and damaging than that of storm-generated waves. There is generally a succession of waves, possibly over a 2h period, with the first wave not being the worst.

In the Nihonkai Chubu Earthquake, Japan (M7.7: 1983), 3m-high tsunami waves carried inland very heavy tetrapods installed for the purpose of protecting the coast against waves; these tetrapods would have resisted much larger ordinary waves.

The run-up height depends on many factors, being higher for places in a

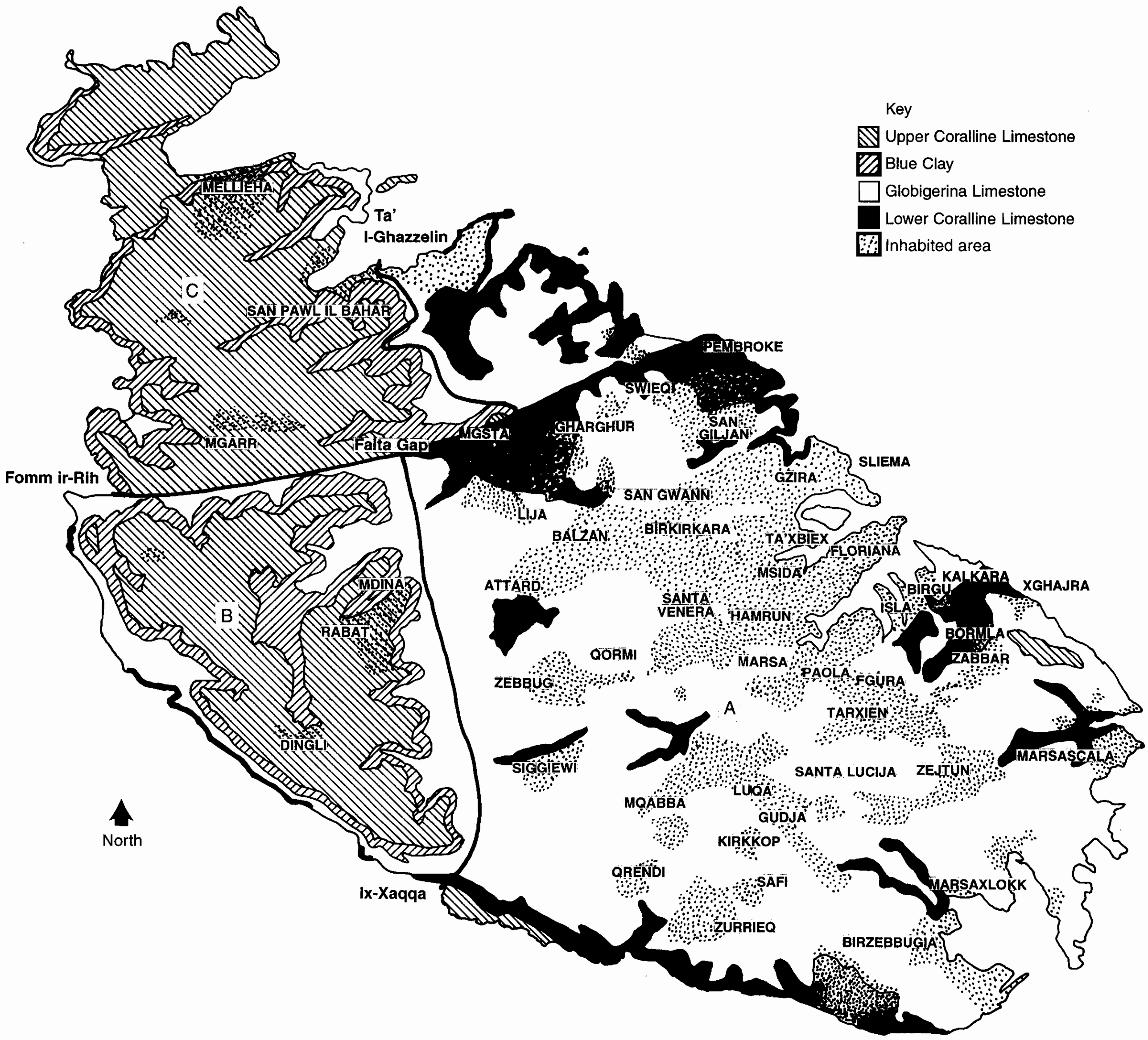

Fig 1(a). Malta: a simplified geological map

V-shaped (such as Xlendi bay) or U-shaped (such as Marsaxlokk bay). Reefs, or a large expanse of shallow water, tend to protect the coast; offshore submarine ridges, however, may increase the wave height.

20% of the recorded Mediterranean tsunamis have been damaging. In AD 365, following a M7.7 earthquake in Crete, a tsunami caused extensive damage in Libya, Egypt, Calabria, and as far as Spain. This tsunami is unique in the historical record, in that it is the only event of its kind known to have propagated across the entire Mediterranean without major attenuation of the sea waves.

Recorded tsunami heights exceeding 20m have reportedly been reached in the eastern Mediterranean, and the Messina Earthquake (M7.5: 1908) caused waves of 8.5m on the Sicilian and more than 10m on the Calabrian coast, with the maximum height of 11.7m at S. Alessio washing up 200m inland. The Messina Straits and the eastern coastline of Sicily, especially around Catania, have an average of up to 10 tsunamis/100 years. The last tsunami recorded in this region was in 1954, and a high probability exists for another tsunami disaster.

In the more exposed parts of the Mediterranean, for long coastlines, the return periods for approximate run-up height of tsunami waves have been given as[1]:

100 years: 1.5m high
500 years: 4.0m high
1000 years: 7.0m high

In 1960 a M8.5 earthquake in Queule, Chile, produced tsunami 15m–20m in height, with the debris extending 2km into the interior. It must be noted that low-lying areas exist to the foot of the mountain. The event damaged residential quarters, flattened a village 1.5km inland with 4.5m-high waves, destroyed factories, and sank ships.

In 1944 a M7.4 earthquake in Hawaii deposited large coral blocks of up to 1.3m across, which had been torn loose in the sea, up to 5m above sea level. Many steel framed structures were damaged, the boilerhouse and powerhouse of a sugarmill collapsed, machinery, tanks and pipes were swept out of the building, and a large tank was carried nearly 300m inland. One of the spans of a railway bridge in Hilo fared no better: it was carried 230m upstream.

In 1964, at Crescent City, California, the third wave ran 0.5km inland, and the debris carried along smashed into structures at velocities of up to nearly 40km/h.

In the Mediterranean, after the Algerian Earthquake M6.8 of 1954, turbidity currents travelled at 50– (nearly)100km/h on a slope of 1:150.

Overall, large tsunamis are less frequent in the Mediterranean than in the Pacific Ocean. Most Mediterranean tsunami sources lie along mainland and island coastal regions, with tsunamis reaching local coasts soon after they have been generated, giving little time for warning. The strongest tsunamis are excited in the Aegean Sea and the Hellenic and Calabrian areas.

Conclusion: subdividing the Maltese Islands for earthquake perils exposure

Fig 1(a) splits Malta into three regions (A, B and C (author's subdivision)); Fig 1(b) focuses on Gozo, corresponding with region B, with Comino corresponding to region C.

There is a striking contrast between eastern and western Malta, with a complete absence of clays from the eastern two-thirds of Malta (region A).

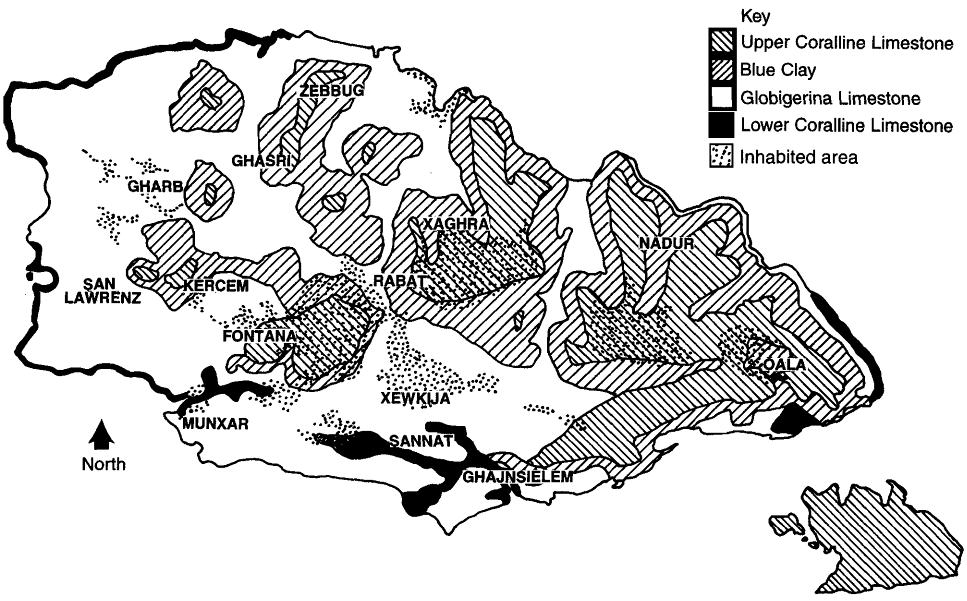

Fig 1(b). Gozo: a simplified geological map

Malta's dormant fault system is predominantly ENE–WSW. The islands' tilt to NE results in most valleys draining NE; a coastline of submergence on NE, with deep inlets and bays; and high cliffs on SW. Compared with Malta, Gozo shows a more varied geology, greater relief contrast, and a more extensive outcrops of clays.

The major difference between region A and other regions is that, in the latter, the rock is generally bare, except for the valleys, slopes and basins, whereas in region A, it is rare to see bare rock, because of the soft globigerina rock, which forms more quickly into soil. Another difference is the low altitude, most of it being below 90m, and lowlands dominate over the hills. The coastline is rather indented, with many headlands and bays, the principal one being the headland containing the capital, Valletta, and forming the Grand Harbour. The next important port is Marsaxlokk, in the southernmost part of region A.

A large part of region A is built on, since the greater part of Malta's population is concentrated here, as noted in Table 13.

It should be noted, also, that buildings in the inner harbour region, with a population density of 5258, consists mainly of old building stock, with building age exceeding 200 years not being uncommon. In Valletta, eight-storey masonry buildings exist. Although the outer harbour region contains buildings of more recent construction, building ages exceeding 80 years are not uncommon. In the outlying villages around the village core, an old building stock (of two- to three-storey height) exists, with ages varying up to 80 years and buildings constructed 200 years ago being also encountered. In the other regions (mainly B,C, and Gozo), where a reduced population density exists, the geology and relief have been noted already as being totally different from region A. The existence of clay slopes is to be noted, although most construction is away from the clay slopes. In Gozo, settlements occur on plateau tops founded on upper coralline limestone. Care must be taken of perched settlements on plateau edges, as minor rockfalls occur in the earthquake intensity range of MSK V–VIII, with massive rock falls occurring from the MSK VII upward range.

The long 136.7km shoreline of the Maltese Islands makes it susceptible to tsunami damage. From the islands' tilt to the NE, the most exposed areas are the sides facing Sicily, although deep valleys on the opposite face, such as at Wied iz-Zurrieq and Xlendi, may also suffer damage. Damage occurs mostly to beach concessions and port works at sea level, since where an escarpment of over 4m height exists, the risk is reduced.

TABLE 13 – Population density by region (1995 census)

	Locality	Population/km^2
A	Inner harbour	5258
	Outer harbour	3389
	Outlying areas	1146
B	Rabat-Dingli Uplands	475
C	–	298
Gozo	–	422

The causes of volcanism would again affect the shoreline facing Sicily, with greater damage in region A, as it consists of the most exposed site with little relief features breaking up the topography. The extent of damage is dependent on the type of wind blowing during the eruption. As Malta lies NE from Sicily, this direction corresponds to the second most frequent grigal wind, which blows violently for 10% of the year for about 3 days at a time, mostly during March and September.

Each region presents its own perils. Region A may be more stable towards earthquake loading, but then more susceptible to volcanic or tsunami damage.

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