The cart ruts of Malta: an applied geomorphology approach

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The mysterious rock-cut cart ruts of Malta are here examined by geomorphologists. They find that the ruts could be caused by two-wheeled carts with a gauge of 1.40m carrying moderate loads. In wet weather the carts would gradually cut into the limestone and reach their ground clearance of 0.675m, causing the carriers to try another route – so there are plenty of them.

Keywords: Malta, uncertain age, cart ruts, transport, wheeled vehicles

Introduction

The Maltese cart ruts are found mainly on the west part of the island, on the uplands formed by coralline limestone (Figures 1 and 2). The earliest reference to them was by Gian Francesco Abela in 1647, and descriptions have since been provided by numerous authors over a considerable period (Zammit 1928; Evans 1934; Gracie 1954; Parker & Rubinstein 1984; Ventura & Tanti 1994), culminating in a meticulous and comprehensive review by Hughes (1999). Trump (1993; 2000) provides further good illustrations. Their age is uncertain: attributions have variously included the later Bronze Age (1500 BC), the Punic occupation (*c*. 600 BC) and the Roman period (post 218 BC), and ranged as widely as the Neolithic and the Arabic periods (*c*. 870). Traces of these features are also present in Gozo and elsewhere in the Mediterranean (Parker & Rubinstein 1984). A notable and pioneering venture in experimental archaeology was carried out by the BBC in 1955 (BBC 1955), in which various types of vehicle were run along the cart ruts, although without producing an unequivocal and commonly accepted conclusion.

The ruts were created in soft limestone that, as a soluble rock, is subject to solution under rainfall when directly exposed at the Earth's surface. Their morphological details thus necessarily become degraded through time, obscuring original features and rendering interpretation still more difficult. Erosional forms such as cart ruts must, of necessity, be interpreted on the basis of their geomorphology alone, but this has previously only been attempted by Drew (1996).

The ruts are essentially small-scale erosional landforms incised into surface bedrock outcrops. A major focus of the science of geomorphology is erosion, hence geomorphology is an especially appropriate perspective from which to approach the problem of their formation, and enables a distinctive contribution to the study of these intriguing landforms. Geomorphology deals with landforms at various scales, their spatial patterns

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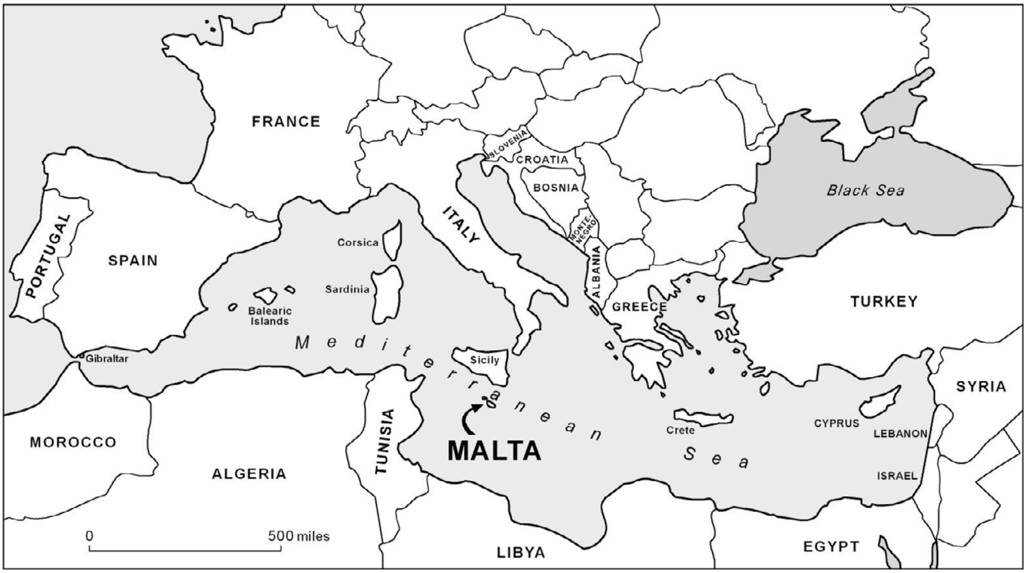

Figure 1. Location of Malta in the Mediterranean.

and distributions, material properties, surface processes and relationships between processes and forms. Many previous authors have described aspects of the form and distribution of the ruts, whereas material properties and erosion processes have been hitherto little considered. Here we present observations of properties and process, with a focus on the applied forces required to cause the erosion of the ruts.

Combining published descriptions with the authors' own field observations, the defining characteristics of the ruts can be identified as follows:

- They occur as paired parallel grooves incised into bedrock, and extending up to several hundred metres in length.
- Each rut pair possesses a constant gauge (distance apart) of *c*. 1.40m, although this may vary slightly between rut pairs.
- The width of a rut ranges from 0.04 to 0.10m, with depth variable up to a maximum of 0.675m (Gracie 1954).
- In cross-section they are commonly v-shaped channels with a rounded floor; the largest ruts tend to have a rectangular box cross-section.
- Some rut cross sections show multiple grooves, with two or three channel floors, and always replicated in both members of the rut pair.
- Locally they may divert in order to avoid obstacles.
- In the broader context, ruts are often clearly related to major landscape features, such as cols or scarp slopes.
- Concentrations may occur at regional route nodes, especially crossing points of high ground.

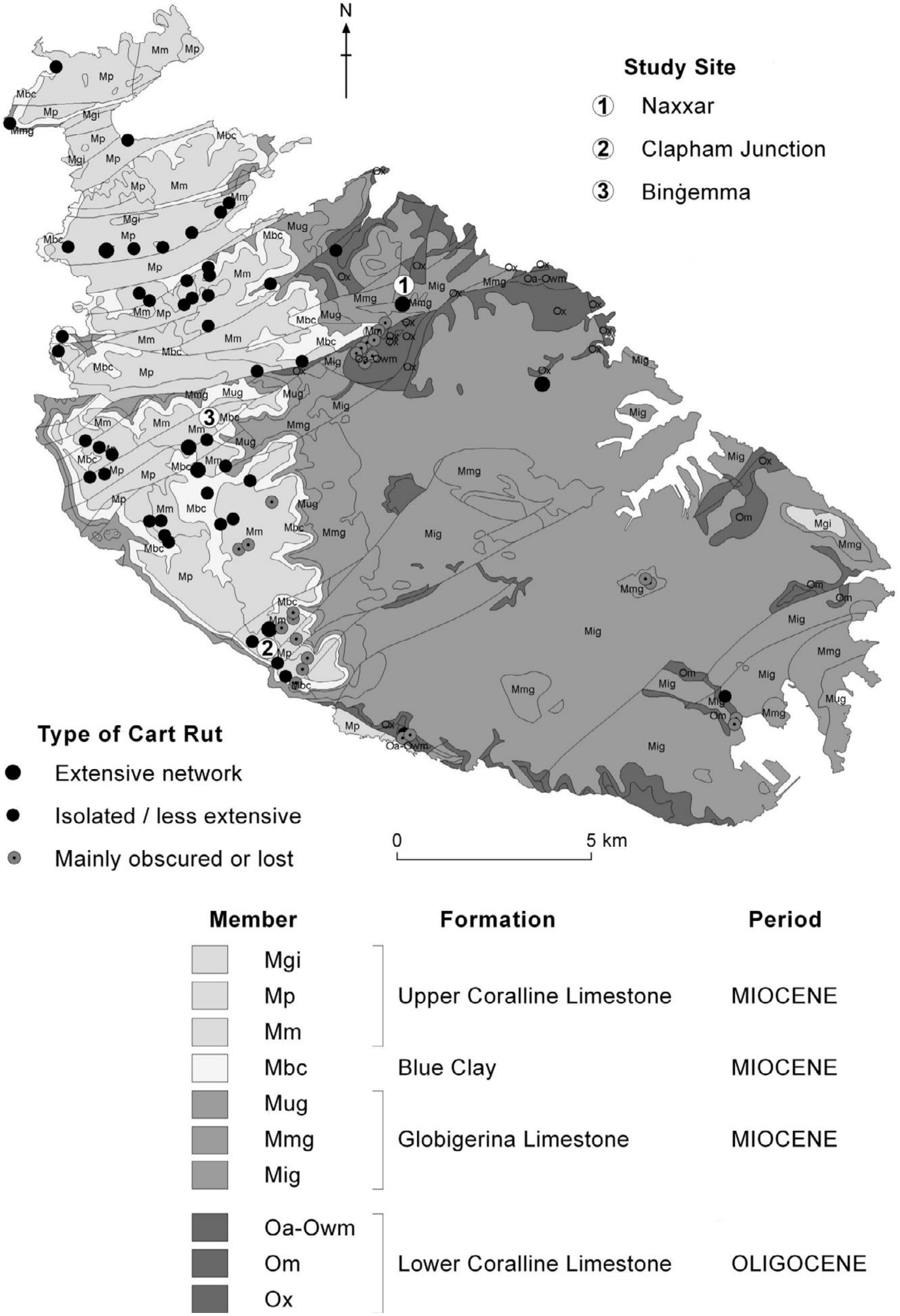

Figure 2. Surface geology and the sites referred to in this study (after Oil Exploration Directorate 1993; Hughes 1999).

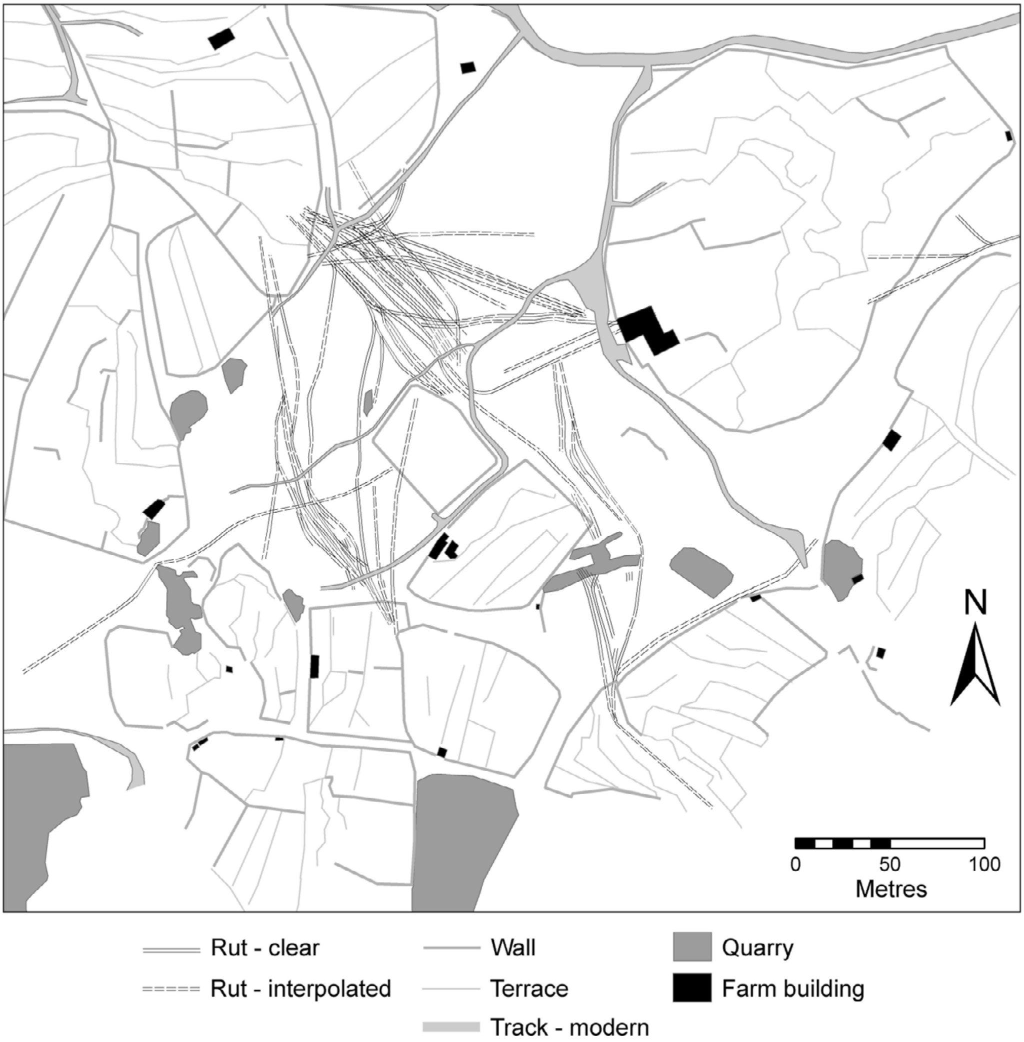

Figure 3. Rut patterns, Misrah Ghar il'Kbir (Clapham Junction), including convergent, anastomosing and quasi parallel forms. The parallel paired nature of the ruts is highlighted in this detailed original survey.

- They may be intermittent in plan, often oblique to contours, and exhibit convergent or crossing patterns (anastomosis), or in the case of ancient quarry sites, parallel patterns (Figure 3).

Whilst there is widespread agreement that the paired ruts are intimately related to the passage of vehicles, there are many unresolved questions concerning their origins. The principal questions are whether they were cut by manual labour to facilitate the passage of vehicles, or eroded by the passage of the vehicles themselves. If the latter, then the question arises as to whether the vehicles were wheeled or travelled on runners, or took the form of inclined shafts strapped to a draught animal (a *travois*).

Research objectives

The objectives of the present paper are to:

- investigate the material properties of the terrain materials in which the ruts are formed;
- determine the nature and magnitude of applied stresses, as a measure of the erosive forces, required to overcome the resistance of the rock materials; and
- reverse engineer a vehicle to fit the ruts and, with its load, generate sufficient stress to cause rock failure.

This study is based on field observations of ruts at three sites, San Pawl tat-Targa (near Naxxar), Binġemma and Misrah Ghar-il Kbir (popularly and locally known as Clapham Junction), in relation to the geotechnical properties of the local surface rocks.

Methods

In order to identify the resistance characteristics of the local rocks, standard geotechnical tests were applied. Rock density was determined from hand-sized samples by dry weighing the sample and determining the volume of fluid (normally water) that it displaces. *Uniaxial compressive strength* (UCS) measures the resistance of rock to imposed compressive stresses. It was determined directly in a uniaxial compression apparatus. The observed stress required to cause the rock to fail is defined as the compressive strength. Data were obtained under saturated (as is standard) conditions. Three replicate samples were investigated from three locations. Although a relatively small dataset, it is suitably indicative of the rock materials represented. A further indicator of rock resistance is that of *hardness,* a rock surface property. The instrument employed in this test was the Shore scleroscope, which measures resistance to penetration by a hard metal point under a controlled load, and yields a hardness number directly related to uniaxial compressive strength (more detailed information of these tests can be found in Winkler 1975, Gerrard 1988 and Attewell & Farmer 1976).

Reverse engineering was then undertaken in order to model the likely nature of vehicles involved in rut formation.

Material properties of the rocks bearing cart ruts

The properties of the rock materials in which the ruts are formed are crucial to understanding the processes responsible for their formation. The rocks outcropping at the three study sites are summarised in Table 1, and their petrographic details in Table 2.

The density and compressive strength as measured from samples taken at these sites are given in Table 3. The density is variable, with low values shown by the Binġemma samples, and very low densities by those from Clapham. Since these rocks are composed almost exclusively of the mineral calcite, with a density of 2.71 gm cm^{-2}, the values in the table are indicative of the high proportion of these samples occupied by voids. This indicates a relative lack of contact and bonding between the mineral components within the rock, and consequent low rock strength. The uniaxial compressive strength (UCS) values show that rock strength is low and very variable both within and between the sites represented. On a universal scale (Attewell & Farmer 1976) the rock strength of the samples is no higher

Table 1. Geological units at the study sites, summarised from Pedley *et al.* (1976; 2002) and Oil Exploration Directorate (1993). A stack of sedimentary rocks is composed of individual beds which are classified hierarchically into members embracing related beds; related members are then grouped into formations, as shown in this table. It is the characteristics of the rock at the bed or member level which determine the local response to erosional events.

Age	Formation	Site	Member
Miocene	Upper Coralline Limestone	Misrah Ghar il-Kbir	Tal-Pitkal
		Binġemma	Mtarfa
Oligocene	Lower Coralline Limestone	San Pawl tat-Targa, Naxxar	Xlendi

Table 2. Petrography of the rocks at the study sites, from microscope observations by Anthony Butcher, and descriptions in Pedley *et al.* (1976; 2002) and Oil Exploration Directorate (1993).

Member	Petrography
Tal-Pitkal	Coarse grained wackestones/packstones with coralline algae and corals.
Mtarfa	Thickly bedded carbonate mudstone/wackestone, crystalline with micritic matrix, algal biostrome with foraminifera and shell fragments.
Xlendi	Coarse grained crystalline limestone with micritic matrix, and abundant coralline fragments and foraminifera.

Table 3. Density and UCS for three sites, with strength classification after Attewell & Farmer (1976).

Sample	Member	Density (g cm^{-3})	Uniaxial compressive strength (MPa)	n	Strength Classification
Naxx 1	Xlendi	2.60	65.7	3	Medium
Bin	Mtarfa	2.40	12.3	3	Very weak
Clap 1	Tal-Pitkal	2.06	2.7	3	Extremely weak

than medium and as low as extremely weak, confirming the qualitative field observations of Parker and Rubinstein (1984). For comparison values for rocks of high strength, such as many granites, often exceed 200 MPa.

Shore scleroscope hardness values obtained from the sites in this study are listed in Table 4, in a test to investigate the extent to which rock strength of the rock mass varies between dry and saturated conditions. In all cases the rock is less resistant in the saturated condition, in 2 of 3 cases showing a strength reduction of at least 80 per cent. The implication of this finding is highly significant, for it shows the extent to which the rocks at the cart rut sites are weakened when saturated. Under field conditions, then, when surface rocks are wetted by rain, they become so reduced in strength that they are very susceptible to erosion by applied forces.

Table 5 compares Shore hardness values between the exposed field surface and the interior mass. The exposed surface may be affected by surface weathering, and generally carries a cover of lichens. These results show that the more resistant Naxxar rock has surface hardness reduced by lichen cover, whereas the extremely weak Clapham material is strengthened by

Table 4. Rock mass strength in dry and wet conditions, as determined by Shore scleroscope.

Sample	Member	UCS (MPa)	Dry interior	Wet interior	Difference (%)
Naxx 2	Xlendi	63.0	49.92	37.64	−24.6
Bin	Mtarfa	12.3	36.88	7.36	−80.0
Clap 1	Tal-Pitkal	2.7	20.48	3.24	−84.2

Table 5. Comparison of surface and interior scleroscope hardness under dry conditions.

Sample	Member	UCS (MPa)	Interior Shore hardness (dry)	Surface Shore hardness (dry)	Difference (%)
Naxx 2	Xlendi	63.0	49.92	13.40	−73.2
Bin	Mtarfa	12.3	36.88	31.32	−15.1
Clap 1	Tal-Pitkal	2.7	12.36	13.88	12.2

the lichen cover. In the latter case, the lichen cover increases rock resistance to erosion and thereby acts as a surface protector.

Resistance to erosion

Two failure modes are possible in eroding a surface by passage of traffic. The simple direct load of a weight on the surface, as in the case of a wheel (static or rolling), would create a crushing or compressive stress. A sliding object, such as a sled or *travois*, would create an abrading or shear stress. As a general rule, rocks are about six times more resistant to compression than to shear stresses.

The compressive strength values tabulated above were obtained in unconfined conditions. Rock in a confined state, that is, with a top surface exposed, whilst its body is surrounded by a confining rock mass as it would be in field conditions, is approximately 33 per cent more resistant to compressive stress. Accordingly, we can estimate compressive and shear strengths for the samples. Since the initial compressive strength observations were made on saturated samples, the estimates derived from those also represent the saturated condition. Since rock strength is significantly lower under saturated conditions (as demonstrated in Table 4), the values represent wet weather field conditions when the rocks are most susceptible to erosion.

With known values of resistance, we can now estimate the loadings in relation to both compression and shear stresses that would be required to cause the rocks to fail, and therefore erode, events which through repetition would inevitably lead to the development of the eroded troughs that are the ruts.

Force/resistance considerations

In creating the ruts, the forces applied to the rock surface would have been a function of the mass (weight) of the loaded vehicles. In this way it is possible to determine the forces required to erode the rock. By considering the stress requirements and the morphological field evidence, it becomes possible to design a vehicle capable of creating the ruts; this process is known as reverse engineering.

Figure 4. Rut cross section, San Pawl tat-Targa Naxxar, facing west. Note that the rut is tilted to the right, on account of the sloping ground surface above, and that the floor has a subsequent infill of tufa (crystalline calcite) which masks the original centre line of the floor.

The cross section form of the ruts is the footprint of the vehicle, and provides significant clues regarding the morphology of the vehicular component which carved them. Cross section form throughout the rut sites varies substantially, especially in respect of width. This should not be surprising, since lateral movement of loose wheels or lateral abrasion by linear runners rounding a curve would cause lateral enlargement of the ruts. The most precise evidence of wheel or runner form is provided by the most restricted cross sections, which most closely represent the form of the vehicular component which formed them. By their very nature, deep and tight ruts are difficult to measure accurately in cross section. At Naxxar, however, a rock-cut trench immediately east of an anti-aircraft post displays cart ruts in section (Figure 4).

Because these ruts run laterally across a slope of approximately 5°, the true base of the erosional rut form is offset slightly in the upslope direction. The cross section form of the eroded rut is that of a canyon narrowing downwards with linear sides which grade sharply into a slightly rounded floor, approximately 40mm in width. Evidence from several locations at Naxxar corroborates this value as a minimum rut basal width.

The strength of the surface materials governs their resistance to stresses and indicates the magnitude of the applied stresses required to cause them to fail. Consideration of material strength therefore permits calculations to be made regarding the mass of the vehicle and the form of traction (see Technical Appendix).

Reverse engineering of the rut-forming vehicles

It is now pertinent to consider the nature of the vehicular component which could have formed this cross section. Starting with the hypothesis of a *travois*, it seems inherently unlikely that a *travois* with bearers composed of timber alone would be sufficiently durable to withstand the abrasive forces caused by travel across the surface of the ground, including rock. An alternative suggestion is that the timber bearers could have been reinforced by having stones lashed to their bearing points. If this were the case, and the nature of the

Table 6. Timber material requirements to construct a vehicle of appropriate dimensions to fit the cart ruts.

Component	Dimensions (m)	Volume (m^3)	Mass (kg)
Deck	1 × 2 × 0.03	0.060	30.0
Sides (total)	6 × 0.6 × 0.02	0.072	36.0
Wheels (solid)	(2 π × 0.6 × 0.04) × 2	0.300	150.0
Axle	1.40 × 0.1 × 0.1	0.014	7.0
Shafts	(0.08 × 0.08) × 2	0.026	6.0
Stays	(8 + 2.4) × 0.06 × 0.06	0.037	18.5
Total		**0.509**	**254.5**

Table 7. Mass of loaded vehicle required under saturated and dry conditions to exceed the critical value for confined surface rock failure, including the effects of the stress concentration factor.

Sample	Member	Critical mass of loaded (vehicle tonnes)	Critical stress attained by
DRY CONDITIONS			
Naxx 2	Xlendi	1.21	Vehicle + 0.956 tonnes
Bin	Mtarfa	0.89	Vehicle + 0.636 tonnes
Clap 1	Tal-Pitkal	0.25	Vehicle alone
SATURATED CONDITIONS			
Naxx 2	Xlendi	0.91	Vehicle + 0.665 tonnes
Bin	Mtarfa	0.17	Vehicle alone
Clap 1	Tal-Pitkal	0.04	Vehicle alone

contact were stone on stone, then one would not expect the uniformity of width that the minimum rut sections apparently exhibit. There would be no incentive for uniformity in the size of such bearing stones. Furthermore, the relative hardness of the bearer stones and bedrock would make it inherently more likely that mutual abrasion would take place, and that more rounded rut basal cross sections would develop.

The relative tightness of the rut cross section floor suggests that erosion was concentrated in a restricted lateral section, which implies a narrowly concentrated force such as would be applied by a wheel. Such a component may have been formed of timber or, more effectively as an erosional agent, shod with an iron hoop (Fenton 1918; Parker & Rubinstein 1984), although no conclusive archaeological evidence has been found in support of this latter contention (Hughes 1999). These observations appear to imply that it is most likely that wheels were the agent of erosion, with the simplifying assumption that they were wooden wheels. The issue of whether wood can erode limestone rock by repeated compression can be addressed by considering the respective compressive strengths of the two materials. The maximum compressive strength of seasoned timber of a range of hardwood species is listed by Green *et al.* (1999) as ranging between 40 and 60 MPa. This considerably exceeds the compressive strength of the Clapham and Bingemma rocks (Table 4) and, given compressive contact between wood and rock at these sites, it is the rock which would preferentially fail.

At Naxxar the respective compressive strengths of wood and rock are more equally matched, and it is more likely that mutual erosion would take place, with wear of both rock and wheel. Wheels, of course, can be replaced when worn whereas the rutted rock surface remains exposed to continuing erosion.

The simplest form of wheeled vehicle is the two-wheeled cart, which was traditional in Malta in historic times and may have dated from much earlier times. The materials required to construct a vehicle with a gauge of 1.4m and an axle clearance (wheel radius) of 0.6m, in the simplest form of a two-wheeled cart can readily be estimated and quantified. It is assumed that such a vehicle would be constructed with timber, a substance with a density of approximately 500 kg m^{-3}.

The timber required for such a vehicle is estimated in Table 6. This yields a vehicular mass of 254.5 kg, or approximately a quarter of a tonne.

It now becomes possible to include both the estimated mass of the vehicle and the stress concentration factor (see Technical Appendix) in considerations of the vehicular erosion process. The stress concentration factor reduces the critical mass required to cause rock failure by a factor of 10. Part of this critical mass is now accounted for by the mass of the vehicle itself, and part by any load it is carrying. The values produced by these considerations are shown in Table 7.

Even under dry conditions, the mass of the unladen vehicle alone is sufficient to cause erosion of the Clapham rock surface. Failure of the rocks at Binġemma and Naxxar requires the vehicle to be loaded with 0.636 and 0.956 tonnes respectively. Under saturated conditions, the vehicle alone is sufficient to cause failure of both the Clapham and Binġemma rocks, whilst in the case of the more resistant Naxxar rock, a relatively modest load of 0.665 tonnes will cause rock failure. These calculations therefore demonstrate that these relatively weak rocks are readily eroded under vehicles of quite modest dimensions and loads.

Discussion

The calculations above strongly suggest that a two-wheeled cart is well capable of generating sufficient forces to damage the rock surfaces and, through repeated passages over time, causing the erosion of ruts of depths up to >0.5m. Furthermore, the passage of wheels would appear to account satisfactorily for all the morphological features of the ruts.

The sliding movement of a *travois* creates a shearing force on the ground surface, and a robust vehicle when loaded would be theoretically capable of generating sufficient shear stress to abrade the surface of the rocks considered here, especially if the bearing point of the wooden shaft were tipped with stone. Perhaps the strongest argument against this type of vehicle is presented by Pike (1967), in an extensive review, who found no evidence of transportation by *travois* anywhere in the Mediterranean region. It is also telling that no convincing evidence of stone reinforcement has been found in Malta (Hughes 1999).

In the case of a sled the critical load is applied through runners which, by virtue of their length (say, a metre or more), is applied across a much larger surface area than through the wheel. As a result of this large contact area, under any significant load a substantial frictional resistance would exist between runner and rock surface, and the amount of tractive force required for sliding motion would evidently be impracticable. It would also be very difficult to construct a load-bearing timber sledge with sufficient reinforcement of the runners to create a clearance of half a metre or more. A further difficulty would lie in the form of tracks created by sled runners on curves, which would necessarily be broader than on straights in order to accommodate the lateral rotation of the linear runners. Furthermore, tracks made by rigid runners tend to skate across and plane the summits of uneven terrain, thereby missing any hollows (Pike 1967). Neither of these features of rut morphology has been recognised in Malta. Several factors, therefore, appear to militate against sled transport in this case.

Observation by the authors has not produced evidence of any forms on the walls of the ruts other than those created by natural weathering and erosion processes in these locally variable rocks. Observation of rut walls during this study has produced no evidence, or even hint, of human activity in excavating ruts, such as might be provided by pick marks. Furthermore, given the geotechnical arguments presented in this paper, there is no need to invoke human excavation as a formative process. It is concluded, therefore, that the ruts were created simply by the repeated passage of vehicles, in the form of two-wheeled carts.

A feature of these results is the wide variation in threshold loads for failure between the different rock types. Whilst the strongest rock is capable of supporting a vehicular mass exceeding one tonne, at Clapham the rock would fail under the mass of an unladen vehicle alone. This raises the question of why rut depths do not show a similar range of variation between different rock types.

Explanation can be sought by considering possible material controls on rut depth. Maximum rut depths, however, are broadly equal on rocks whose material properties vary widely. This can be analysed by considering the ratios between maximum and minimum values of ruts depths and material properties between different rocks. Thus density varies between rock types by a factor of 1.73, uniaxial compressive strength by 24.3, Shore hardness by 11.62 (wet) and 2.43 (dry). Thus, because of the wide variation in the values of these properties between rock types, none of the properties examined individually acts as a control on rut depth. It is apparent, therefore, that rut depth is independent of these rock material properties.

It is surely not coincidental that maximum rut depths in both the strongest and the weakest rocks in this study are approximately equal. In the absence of any substantive evidence of differential usage, and any correlation between rut depth and material properties, explanation for the constancy of rut depth across different sites and materials must lie elsewhere. A single common factor may lie in the vehicles themselves. It would perhaps be surprising if the remarkable constancy of gauge were not mirrored by other design features, such as wheels. Thus, a ground clearance of 0.675m sufficient to enable passage of Gracie's (1954) deepest rut would, allowing for an axle diameter of 0.1m, imply a wheel diameter of 1.45m. In this way, vehicle design would impose a constraint on the development of rut depth on any type of substrate which, when attained, would then become unusable leading to duplication of routes by nearby alternatives.

There is no need to invoke climate change, as some authors have done, in deriving explanations of rut erosion. Geotechnical considerations have shown that a rainy day delivering a substantial rainfall would be sufficient to saturate and weaken surface rocks such that, given a vehicle mass of up to 0.25 tonnes, the rock surfaces other than Naxxar fail under the passage of the cart alone. Under dry conditions the rocks are somewhat more resistant but even the weakest one at Clapham would appear to be erodible by a single passage of an unloaded cart. With the data obtained in this study, and under the assumptions adopted, these rocks would erode under contemporary climatic conditions by the passage of moderately loaded carts and, in some cases, even unloaded carts.

Two lines of evidence, however, suggest that the current rock surface lay under a soil cover prior to the formation of the ruts. First, there are substantial discordances between the rutted routeways and the current bedrock topography. For example, rut tracks may climb through an abrupt 0.5m bedrock step, when an easy slope is readily available close by. Ruts tracks may also head directly toward a deep solution shaft exposed on the rock surface, and then develop a duplicate route which serves as a bypass to this obstacle. If the current bedrock topography were visible at the surface at the time, then surely more sensible and less energy consuming routes would initially have been chosen. Close by and visible from the area of cart ruts at the San Pawl tat-Targa site, Naxxar, quarrying has exposed a section in which a soil cover buries the bedrock topography (rockhead relief) and infills the solution pockets and shafts which form major irregularities in the general plane of the bedrock surface. This section is interpreted as an analogue of the former landscape of the rutted bedrock plain now exposed. Thus initial routes would have been selected at the soil surface, in ignorance of the irregularities in the buried rockhead relief. They would be determined by minor topographic variations in the land surface and, particularly perhaps, by stands of vegetation. Soil erosion by passing feet and wheels, particularly in wet conditions, would cause thinning of the soil cover, gradually exposing the bedrock surface beneath. Initially only the bedrock high points would be exposed, but increasingly the lows also, including the shafts which would eventually be revealed as impassable. Thus bypass routes would be developed. This combined evidence, then, strongly suggests the initial presence of a soil cover obscuring the true nature of the rockhead topography and its associated hazards, which only became visible as erosion by human and vehicular traffic eroded the soil, thereby superimposing existing vehicular trackways on to a gradually emergent rough and rocky surface.

Conclusion

The problem of the origin of the Maltese cart ruts is considered on a basis of geotechnical, morphological and archaeological evidence. Rut cross-section forms, as observed in the field, are treated as the locus of forces applied by the passage of vehicles. These forces are estimated in relation to rock strength properties. Under reasonable assumptions, it is demonstrated that the force applied through the contact of a wheel with the rock surface is sufficient to cause the local rocks to fail under quite moderate loads, and under wet conditions, a vehicle alone is sufficient to damage by erosion two of the three rock types tested. Under dry conditions the rocks are more resistant, and only at Clapham does the rock fail under the passage of a cart alone. The considerations set out in this paper show that a wheeled cart, of which the simplest version is one with two wheels, has the capacity to create sufficient applied force to cause rock failure.

The moderate loadings estimated above imply that local goods would have been sufficient to comprise the loads. There is no need to invoke transportation of giant stones such as megaliths as an explanation to create sufficient force for rut erosion. More likely is the transport of local materials, including produce for trading, and resources such as rock quarried from sites such as Misrah Ghar il-Kbir, soil and water around the landscape. Geomorphological evidence suggests that the trackways were formed during a period of soil erosion. It is precisely under such environmental conditions that soil becomes a scarce resource and the need arises to conserve it by transporting it to create artificially impounded fields (Zammit 1928).

Although limited occurrences of similar rutted trackways exist elsewhere in the Mediterranean region (Hughes 1999; Schneider 2001), nowhere do they occur in such abundance as the Maltese islands. It may be that the particularly low mechanical strength of the local rocks is a significant contributory factor in this local concentration. The uniqueness of this concentration may therefore be founded on an environmental factor rather than a cultural one. It is, however, this uniqueness that most strongly underpins Schneider's (2001) claim that these sites merit World Heritage Status.

This paper demonstrates the contribution that geomorphology and geotechnics can make to solving an environmental problem of this kind involving earth surface materials. Considered together with existing archaeological evidence, these specialisms are capable of providing a new perspective on a hitherto intractable problem.

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Technical Appendix

Equation 1 describes the relationship between a vehicle mass (including any load), whether static or moving, and the compressive stress it applies to the surface beneath it. This calculation assumes:

- plane surfaces of both wheel and rock;
- perfect clean contact;
- a two-wheeled vehicle;
- a contact area of 0.04m tread width (implied by the minimum rut basal width), and 0.02m length.

The mass of a vehicle required to cause failure by compression is given by:

$$M = \frac{4lt\sigma_{\max}}{3} \qquad \text{Equation 1}$$

where l, t = length, width of wheel/surface contact
M = mass of vehicle
$\sigma_{\max}$ = maximum compressive strength of surface material

By setting applied stress equal to rock compressive strength, the vehicle mass required to fail the underlying rock surface can readily be calculated. By setting $\sigma_{\max}$ equal to the compressive strength of the respective rock members, the value of vehicle mass (representing compressive stress) required to cause failure by compression of the rocks can be calculated.

The values above rest on the assumption of clean contact between smooth surfaces. In practice, however, this condition is unlikely to be met under field conditions for two reasons.

First, the rock surface is rarely perfectly smooth, and is characterised by microvariations in relief and rock composition. These irregularities increase the stress locally on asperities and, on their lateral gradients, translate the compressive stress into a shearing stress. Secondly, the presence of stones and other hard objects at the wheel/rock contact also serves to concentrate stress locally, and also translates into a tensile (splitting) stress tending to prise the rock apart. Since rock materials are substantially less resistant to shear and tensile stresses then compressive ones, these microscale failures will occur at significantly lower levels of applied force than that required to produce failure under simple compression in the ideal case. These microscale processes operating at the wheel/rock contact are the essence of rock breakdown in this case and enable the surface rock to fail at lower levels of applied stress. They are characterised by locally increased levels of applied stress, and the generation of types of stress, shear and tensile stresses, to which materials are substantially less resistant.

This combination of higher local stresses and lower resistance means that the values derived from the ideal case have to be revised. They cannot be precisely quantified, since they describe historical situations in which small surface irregularities, and small particles of unknown magnitude and composition take part, and are variables of unknown and unknowable magnitude. Nevertheless, in practice such micro effects are commonly accommodated by reducing the applied force required to cause failure by a factor of up to 10, termed the *stress concentration factor*. Equation 1 can now be modified to incorporate the stress concentration factor, as follows:

$$M = \frac{4lt\sigma_{\max}}{30} \qquad \text{Equation 2}$$