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The Application of Information Theory to Interpret Shore Platform Erosion Rates

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Abstract: Advancements in information physics have recently introduced the application of information theory to investigate physical systems. The behaviour of erosion at the granular scale is to date still a complex system to unpack, and therefore geomorphology research requires novel approaches to better inform the interpretation of temporal and spatial erosion patterns at different scales. This paper applies information theory concepts to re-evaluate erosional data that were measured on limestone surfaces of two shore platforms in Malta with a traversing micro-erosion meter (TMEM). By representing erosion rates through their information content using a Box-Cox style transformation of the raw data (application of an inverse normal distribution function to fractionally ranked data), it is possible to identify points and measurement periods that contribute to a disproportionately large share of unexpected erosion rates that could provide more insight into the causes of erosion rates. Despite the variations in the information content from erosion rates at individual measurement points, most points consistently contribute to a similar amount of information. These findings illuminate the importance of considering the informational value of erosion data to further understand the underlying physical processes and potentially improve predictive models.

Keywords: information theory; normal probability distribution; weathering; erosion patterns; shore platform; Malta

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1. Introduction

Recent developments in information physics have been used within the earth and life sciences. The potential of using mutual information flows to understand nonlinear feedbacks and multiple interactions and the production of complex structures in Earth systems has been explored [1]. Within the biological sciences, information theory has been used to develop a novel understanding of individuality [2], as well as of evolution itself [3]. Likewise, in genetics, information theory has been used to study genome mutation by calculating the information entropy spectrum of genomes using a relatively simple formula for quantifying information [4]. Similarly, this approach has also been used to identify the information entropy of genomes and their mutation dynamics [5]. Within physics itself, information theory has been used to suggest that there is an equivalence between mass, energy, and information [6]. Such a relationship would imply that a bit of information is physical, finite, and has a quantifiable mass.

Within the geosciences, the potential of information theory is largely untouched. The translation of concepts in geosciences to the lexicon of information theory requires some conceptual acrobats around the nature of collected data as well as its analysis. This paper is an initial step in exploring how the concepts of information theory might be translated into the use analysis of erosion rates and how the use of information might aid interpretation of erosion rates. Specifically, this paper uses concepts from information theory to re-examine erosional data from Maltese shore platforms in order to assess whether representing erosion rates for individual points at each site by their information content can aid in interpretation of temporal and spatial patterns of erosion.

Measuring the erosion of a point on a surface over time provides a lot of information, but the nature of this information is rarely considered in detail. The information contained in a single measurement of erosion rates at a point will integrate, within it, information about both the nature of the point and its response to the environment, as well as information about the environment itself. If the nature of the point, such as its geology or strength, tends to be a controlling factor in the erosion rate, then the information content of that single measurement will be reflected in a consistency in the quantity of information provided by that point through time. In other words, if the information content of the erosion rate at that point is 2 bits for the first measurement, it will remain at 2 bits for subsequent measurements. The characteristics of the point control the erosion rate totally; there is no flow of information from the environment that can alter the information content of the point erosion rate. In a sense, there is no reason to continue to measure erosion at that particular point, as there will be no additional information it can provide. It is completely isolated from any changes related to the environment of its erosion.

Where the erosion rates of a point change over measurement periods, this implies that there is a relationship between the point and its environment of erosion. If there is no persistency of information flow from one measurement period to another, this would imply that the environment controls the erosion rate at that point. The larger the information content of an erosion point, the more unexpected erosion rates may be, suggesting that that point in that time period is providing additional and surprising information about the erosion of that point. It is likely that the information content of erosion rates will contain both an element of persistency, the effect of the point itself and its history, as well as a more variable information content from the environment.

The value of the information in erosion rates measured at a single point is, however, dependent on the context of that measurement. The erosion rate of a point could be thought of as a message being communicated about the erosional nature of that point translated for the researcher, however well or poorly, by the instrument(s) that measures change. Assuming that the instrument can be trusted to produce a consistent translation, then the information content of the measurements will reflect information about the point itself as well as its environment of erosion. The potential of this information increases if the result is 'surprising', i.e., unexpected. A highly likely event carries little information about the point and the environment; it is unexpected values that carry more information about the erosion of a point and its environment. If erosion rates could be converted to information value for each point measured, then it would be possible to assess how the informational value of each erosion point changed with context and with time.

Calculation of the information content of an event requires that a number of assumptions are made concerning the event, some of which are difficult to justify for erosion of a point in a surface. Each event should be an independent event. Given that each point is situated within and likely to be influenced by the loss of points around it and, potentially, a collection of points will exhibit coordinated erosional behaviour. This assumption is difficult to apply to a point in an erosion surface, although if erosion is randomly distributed across a surface in any single measurement period, this would be a justifiable assumption. Similarly, it might be expected that the erosion at a point in one measurement period would impact the erosion of the same point at the next measurement period. In other words, the erosional history of a point will influence its future erosion. Although conceptually this seems a reasonable assumption, it is unclear from the literature if such historic impacts exist at individual points on a surface at the scale of this study.

2. Study Area

This study focuses on analysing the measured rates of surface change on two shore platforms on the island of Malta (Central Mediterranean). The archipelago of the Maltese Islands predominantly consists of late Oligocene to late Miocene marine sedimentary rocks [7]. The stratigraphic succession comprises five main formations of about 250 m in thickness, including horizontally stratified limestones, marls, and clays [8].

Shore platforms on the Maltese Islands mostly develop where the sub-horizontal formation of Globigerina Limestone (GL) outcrops at sea level due to differential erosion [9]. The geology of GL has been well documented for its abundance of planktonic foraminifera and biomicritic limestone with macrofossils [10–12]. The formation is further subdivided into three members—Lower; Middle; and Upper Globigerina Limestone Members—as a result of a depositional history influenced by tectonic controls; eustatic fluctuations; and erosional episodes and which also developed phosphorite conglomerates (known as C1 and C2) and hardgrounds as member boundaries [13–17].

Two shore platform sites have been selected for this study: Ponta tal-Qammieħ (Marfa Ridge) and Blata l-Bajda (Selmun). Ponta tal-Qammieħ is a relatively inaccessible platform in Lower Globigerina Limestone at the foot of the headland of Ras il-Qammieħ (Figure 1). The platform and its overlying headland are situated north of the ENE-WSW main fault system (known as Great Fault), which positions this study area on the western edge of Marfa Ridge in northern Malta [5]. Three parallel ENE-WSW faults, with an SSE downthrow, influenced the contact point between the limestone lithostratigraphy and sea level, bringing the Lower Globigerina Limestone close to sea level.

Figure 1. Location of Ponta tal-Qammieħ shore platform in the north of the main island of Malta. The six TMEM bolt sites are marked in white and coded MPQ1-6 in a cross-shore direction [18].

This shore platform is the largest one in Marfa Ridge and has a perimeter of 496.7 m and a surface area of 7327.9 m^2. Its longest cross-shore axis is 215.2 m, orientated WSW, and its longest parallel axis is 326.5 m wide. The platform gently dips to the northeast with a gradient of 5°, decreasing to 3° at the northern section (Figure 2a). The platform features a well-developed C1 conglomerate bed, which varies in thickness between 10 and 40 cm. Known as the Qammieħ Conglomerate Bed (Figure 2b), this bed is notable for its complex lithology, rich in fossils and composed of sub-rounded light brown phosphatic nodules, glauconite granules, and diverse fauna in a phosphatised state [12].

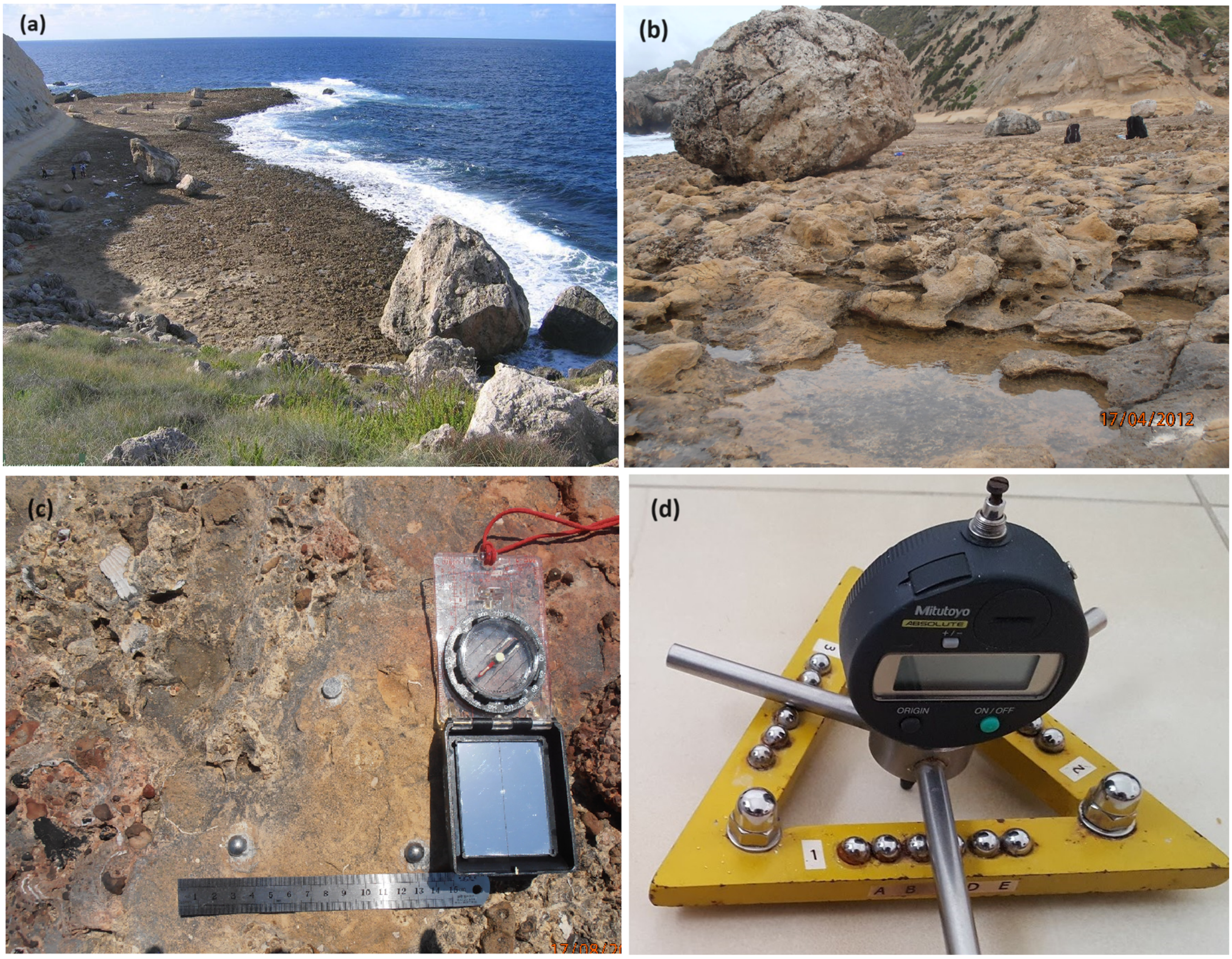


Figure 2. (**a**) Shore platform surface at Ponta tal-Qammieħ, Marfa Ridge; (**b**) Conglomerate Bed (C1) known as Qammieħ Bed; (**c**) MPQ1 TMEM bolt site; (**d**) Mitutoyo Traversing Micro-erosion Meter.

The shore platforms at Blata l-Bajda are formed from Upper Globigerina Limestone (UGL) stratigraphy and are considered the most extensive platform in the archipelago composed of UGL (Figure 3). The UGL is divided into four distinct beds, each with varying resistance to erosion, arranged from base to top as follows: (i) a relatively hard C2 phosphorite pebble bed, known as the Upper Conglomerate bed; (ii) a hard, compact limestone layer that is yellow to orange in colour (Figure 4); (iii) a middle layer consisting of calcareous mudstone within soft grey marl; and (iv) a hard, compact limestone at the top of the sequence, also yellow to orange. At Blata l-Bajda, the C2 pebble bed and the overlying compact yellow limestone are at sea level. They are relatively more resistant to erosion than the grey mudstone above, leading to the development of a shore platform at the base of the eroding grey mudstone [9]. The visible portion of the platform extends approximately 120 m in length and 30 m in width, covering an area of 5427 m^2. A vertical succession of three UGL beds can be observed at various points along the cliff-platform junction, with the grey marl beds rising as high as 17 m above sea level on the western side of the platform (Figure 4).

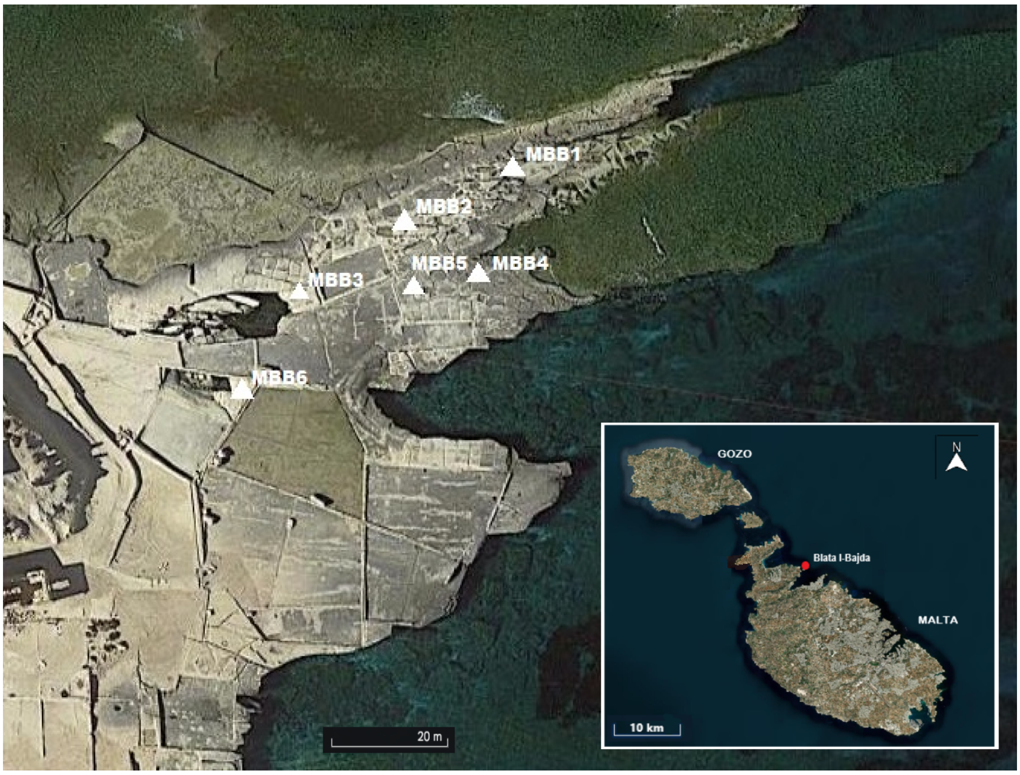


Figure 3. Location of Blata l-Bajda shore platform in the north of the main island of Malta. The six TMEM bolt sites are marked in white and coded MBB1-6 in a cross-shore direction [18].

Figure 4. Succession of lower yellow bed, grey marl middle bed, and upper yellow bed in Upper Globigerina Limestone at Blata l-Bajda, Selmun.

3. Materials and Methods

3.1. Traversing Micro-Erosion Meter (TMEM)

Micro-topographic changes on shore platform surfaces have long been studied using various field techniques, including the micro-erosion meter (MEM) and the traversing micro-erosion meter (TMEM) [19], and references within. Six TMEM bolt sites were installed on the shore platforms of Ponta tal-Qammieħ and that of Blata l-Bajda along a cross-shore profile (Figures 1 and 3). Each profile had three bolt sites positioned at seaward, middle, and landward locations at supratidal levels. Each TMEM bolt site included three titanium bolts: two round-headed bolts (Model L26 no. 50) and one flat-headed bolt (Model L24 no. 25) (Figure 2c). The TMEM bolt sites were coded MPQ1-6 and MBB1-6, with stations 1 and 4 corresponding to seaward sites, 2 and 5 to middle bolt sites, and 3 and 6 to landward bolt sites (Figures 1 and 3). This cross-shore sampling method, which has been employed in numerous studies [20–25], helps to identify spatial variation in surface erosion rates with increasing distance from the shoreline.

The TMEM features a digital dial indicator equipped with an electronic dial gauge with a resolution of 0.001 mm, a manufacturing accuracy of ±0.003 mm, and a range of 12.7 mm (Figure 2d). A total of 22 equidistant individual readings, approximately 15 mm apart, were collected within each bolt site every three months, forming a continuous measurement dataset for each site. Erosion rates are expressed in mm/year, with negative values indicating surface lowering and positive values indicating surface rising. Eight measurement sets were recorded from August 2014 to June 2016, resulting in 7 measurement periods and 96 datasets in total (see Table 1).

Table 1. TMEM Measurement periods at Ponta tal-Qammieħ and Blata l-Bajda, Malta.

Date	Measurement Period
13 August 2014–24 November 2014	1
24/11/14–19/3/15	2
19/3/15–12/6/15	3
12/6/15–4/9/15	4
4/9/15–26/12/15	5
26/12/15–29/3/16	6
29/3/16–29/6/16	7

Table 1 outlines the results from this analysis. The information content for each measurement point, measurement site, and measurement time period is expressed in terms of information content in bytes relative to the total information within a measurement site and across the shore platform as a whole.

3.2. Constructing a Probability Distribution for Erosion Rates

In calculating information content, the expression below is often used:

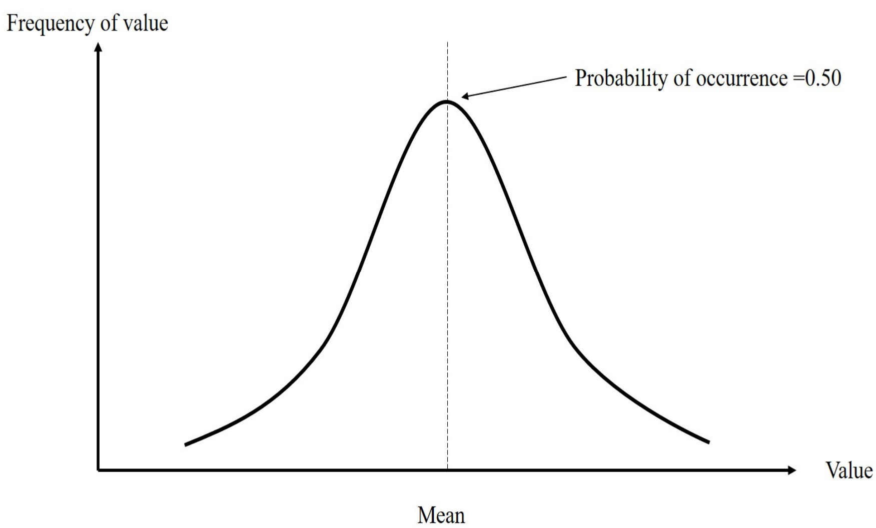
$$\text{Information (x)} = \log_b(1/p_x)$$

which is equitant to Information = $-\log_b(p_x)$ [26]. Where p_x is the probability of event x occurring. Log_b is Log_2 in this paper, as this represents information in bytes. Log_e could be used, in which case the resulting information is expressed in 'nats'. It is usually assumed that the events described by x come from a normally distributed population. Although this formula may seem to be a simple one, its application to erosion rate data is new. The original data were not collected with this form of analysis in mind, so this paper limits its analysis only to the potential of quantifying information content from such data. Further division of the information derived into that associated with point characteristics, historic erosion, and environmental factors would require a different research design for the initial research design.

For all the bolt sites and time period considered, Shapiro–Wilks normality tests suggested that all these data sets were statistically significantly different from normality. A Box-Cox transformation [27–29] was applied to the data at the level of each bolt site and at the level of each platform. A traditional Box-Cox transformation could not be applied to the data as this transformation cannot use negative values. The usual solution of increasing the value of data so that it is positive was not used. Instead, an approach used in business studies and genetics was employed [30,31]. The data were fractionally ranked in SPSS, after which an inverse normal distribution function was applied to the fractional ranked values using the average and standard deviation from the bolt site data as parameters in the distribution.

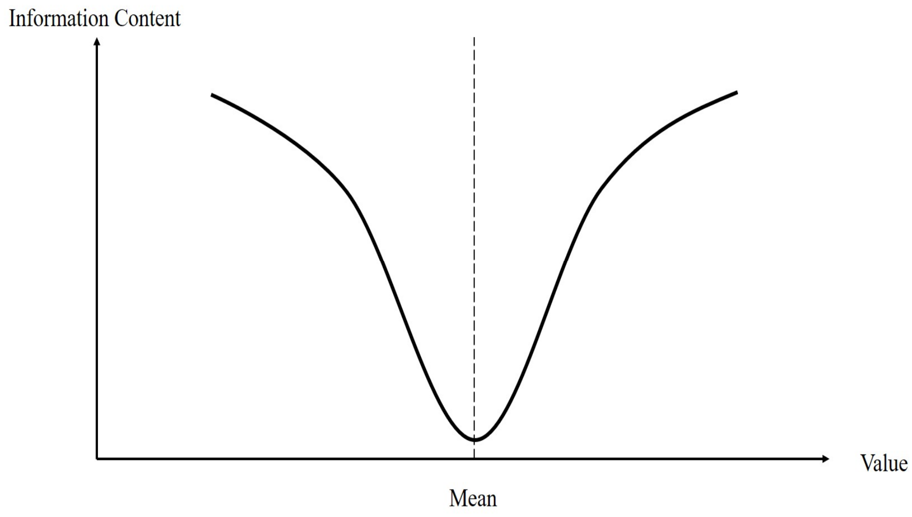
Shapiro–Wilk tests on the transformed datasets implied that they were now all normally distributed. Two sample T-tests of the average erosion rates for the original and transformed datasets for all bolt sites and platforms were carried out, and the data found to be similar statistically, implying that they were from the same population of erosion rates. It should be noted that, as with any transformation of this kind, some information contained within the raw data will be lost; however, the conversion to normally distributed data sets meant that deriving probabilities for individual values are much easier to calculate and explain as a normal distribution curve can be used. The use of transformed data was also felt to be justified in this paper, where we are concerned with initially assessing if erosion rate data can be used to meaningfully quantify information content.

Conceptually, deriving the probability of the occurrence of an erosion rate is as in Figure 5a. The erosion data for each bolt site can be represented by a normal distribution curve, where the average erosion rate is at the peak of the distribution. Most values will cluster around this peak; it is only more extreme and unusual values that will occur away from the peak, represented by the average value in the tails of the distribution. This means that the properties of a normal distribution can be used to calculate the distance each data point from the average value, which can be calculated as a z score. The data could, however, also be represented by a 'U' shaped curve as in Figure 5b, where the average value represents the most likely value and so contains the minimum information or 'surprise' for this particular set of data. Extremely low or high values are unexpected and so occupy the extreme ends of the 'U' shaped curve. As the 'U' shaped curve is the mirror image of the normal distribution, the properties of the normal distribution, such as the z-score, can be used to convert the value to a probability of occurrence on the 'U' shaped curve. From this probability, it is then possible to calculate the information content of each data point using the formula outlined above.



(**a**)

Figure 5. *Cont.*



(**b**)

Figure 5. (**a**) Normal distribution curve illustrating that the average value has a probability of occurrence of 0.5. (**b**) Inverse of normal curve illustrating how the information content of an erosion rate decreases from the low information content of the average value.

It is important to remember that the information content of a data point is not an absolute value. The value of each data point in a bolt site has been calculated in relation to the distribution of all data points at that bolt site. This means a distribution of 154 data values for each bolt site. This is so the relative information content of each time period can be compared as well as cross-platform comparisons made between bolt sites during the same time periods. Changing the reference data set will change the information content of each data point. This means that the purpose of any research analysis needs to be clear before data transformation and calculation of probabilities and information content. This means that the information content of an erosion rate at a point at a measurement site is not static. The information content of the point could also change as more data are gathered from sites. The information content changes, either increasing or decreasing depending on whether the new data are consistent with or unexpected given the existing data set. This means that the value of a point measurement for the interpretation of erosion on a bolt site or across the whole platform can change as more data are collected.

4. Research Questions

Given the above, five research questions were analysed using erosion rates and information content:

1. Is there variability in erosion rates and information content of different time periods at each bolt site?
2. If so, are these patterns consistent for both erosion rates and information content?
3. Is there variability in the erosion rates and information of the same time period across all bolt sites?
4. If so, are these patterns consistent for both erosion rates and information content?
5. Is there variability between the bolt sites on the same platform in information content?

The first two research questions use each bolt site as a reference data set for calculating the information content of a time period at a bolt site. The third research question uses the erosion rates across the whole platform as the reference data set for calculating the information content of a single bolt site. As the scale of the analysis expands, so does the nature of the reference data set.

5. Results and Discussion

Averages of erosion rates and information content for each measurement period at each bolt site are provided in Tables 2 and 3. Data from MBB6 could not be used due to the loss of bolts and subsequent replacement, which interrupted the continuity of the dataset. Analysis shows that there are individual points that contribute a relatively greater proportion of unexpected erosion rates, or rather, have contributed proportionately to more information about the nature of erosion rates. Indeed, despite variations in the information content from erosion rates at individual measurement points, most points are consistent in the amount of information they contribute, averaging about 2.3 bits of information per point per measurement period.

Table 2. (a) Average erosion rates (mm per year, to 2 decimal places) by bolt site and measurement period for Ponta tal-Qammieħ shore platform. (b) Average erosion rates (mm per year, to 2 decimal places) by bolt site and measurement period for Blata l-Bajda shore platform.

Measurement Period	**Bolt Site**					
			(a)			
	1	2	3	4	5	6
1	−0.36	−0.12	−0.19	−0.25	−0.40	−0.37
2	−0.18	−0.04	0.06	−0.76	−0.13	−0.17
3	0.05	−0.16	−0.07	−0.03	−0.09	−0.07
4	−0.04	−0.14	−0.01	−0.01	0.07	−0.01
5	0.74	0.18	0.95	0.83	0.92	0.90
6	−0.11	−0.25	−0.13	−0.03	−0.12	−0.13
7	−1.02	−1.42	−1.11	−1.14	−1.18	−1.11
			(b)			
1	−0.17	−0.07	−0.21	−0.25	−0.12	
2	0.03	−0.08	−0.12	−0.04	−0.08	
3	−0.07	−0.03	−0.13	−0.09	−0.13	
4	−0.15	−0.01	−0.01	−0.17	−0.15	
5	0.11	0.20	−0.07	0.07	0.12	
6	−0.21	−0.19	−0.24	−0.27	−0.24	
7	−0.12	−0.02	−0.11	−0.14	−0.01	

At each bolt site, measurement periods 5 and 7 tend to contribute the highest percentage of information content to the overall information content of the bolt site, as illustrated in Figure 6. This higher contribution suggests that these time periods are those with the greatest number of unexpected measurements within each bolt site. This suggests that the behaviour of measurement points in these measurement periods may be more dominated by environmental conditions than at other measurement periods. It does suggest that these measurement periods may hold some key information about the interactions between points and environmental conditions that contribute to higher and lower than expected erosion rates. This form of analysis cannot be carried out using erosion rates alone, as these may be both negative and positive at some bolt sites and so not be obvious in the average for the measuring period.

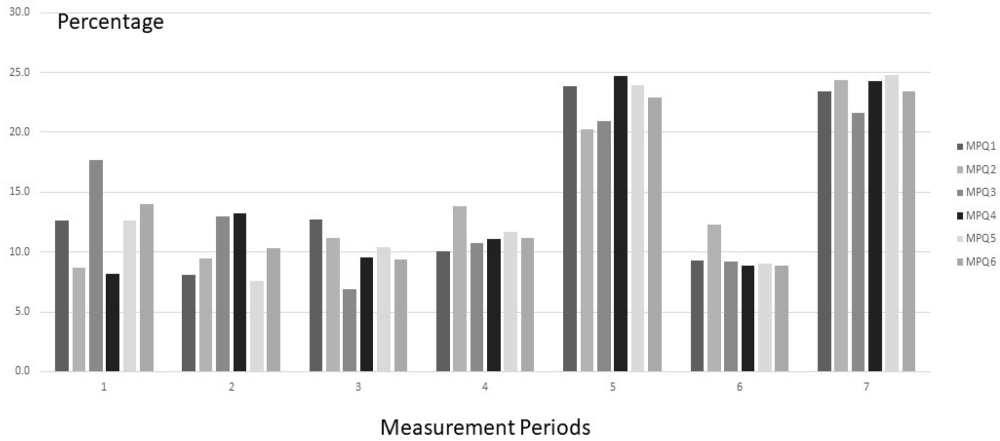
This observation was further explored using analysis of variance on both erosion rates and information content at each bolt site across all measurement periods as illustrated in Tables 4 and 5. The significant behaviour column, as in Tables 6 and 7, is derived from the post-hoc analysis of the comparison between measurement periods using the Tukey test. For erosion rates, measurement period 5 clearly stands out as being statistically significant from all other measurement periods at most bolts sites across the two platforms. For information content, measurement period 7 also tends to be statistically significantly different from the other measurement periods at each bolt site across both platforms. Measurement period 5 is dominated by surface rises that are clear in both measured erosion rates and in the high information content for points in this measurement period. Measurement period 7 shows an average surface loss that is not usually the greatest experienced at bolt sites across measurement periods. The high information content values for this measurement period seem to be related to the extreme, both losses and rises, during it.

Table 3. (a) Average information content (bits, to 2 decimal places) by bolt site and measurement period for Ponta tal-Qammieħ shore platform. (b) Average information content (bits, to 2 decimal places) by bolt site and measurement period for Blata l-Bajda shore platform.

Measurement Period				**Bolt Sites**		
			(a)			
	1	2	3	4	5	6
1	2.15	1.49	3.01	1.39	2.14	2.38
2	1.44	1.61	2.31	2.26	1.28	1.77
3	2.00	1.90	1.17	1.63	1.76	1.60
4	1.65	2.36	1.83	1.89	1.99	1.91
5	4.18	3.45	3.56	4.22	4.26	3.90
6	1.51	2.10	1.56	1.52	1.54	1.50
7	3.62	4.15	3.67	4.15	4.21	3.99
			(b)			
1	2.22	1.98	2.68	2.80	2.36	
2	2.30	2.71	1.75	2.28	1.77	
3	1.94	1.84	1.92	1.80	1.76	
4	2.34	1.64	2.63	2.31	2.34	
5	3.62	4.00	3.36	3.49	3.67	
6	2.60	3.42	2.52	2.24	2.98	
7	2.14	1.49	2.23	2.16	2.19	

Turning to the second research question, an analysis of variance was carried out on the erosion rates and information content for each measurement period across all bolt sites on each platform, as illustrated in Tables 6 and 7. There seem to be less statistically significant differences between bolt sites when compared together at each measurement period. For both platforms, there are a number of measurement periods where there are no statistically significant differences between bolt sites, whether in terms of erosion rates or information content.

In answer to the third research question, Figure 7 illustrates the percentage contribution of information at each bolt site to the total information content for each platform. Most platforms tend to contribute about the same percentage, except for a few bolt sites on each platform. At Ponta tal-Qammieħ, bolt sites MPQ3 and MPQ4 contribute slightly more than the other bolt sites to the total information content of the platform. The difference is slight but noteworthy. At Blata l-Bajda, bolt site MBB4 contributes over 4% more than any other bolt site to the overall information content of the platform. This is a relatively big difference and does suggest that the characteristics of this bolt site are worth exploring in further detail to identify any characteristic that might contribute to this production of more unexpected erosion rates.



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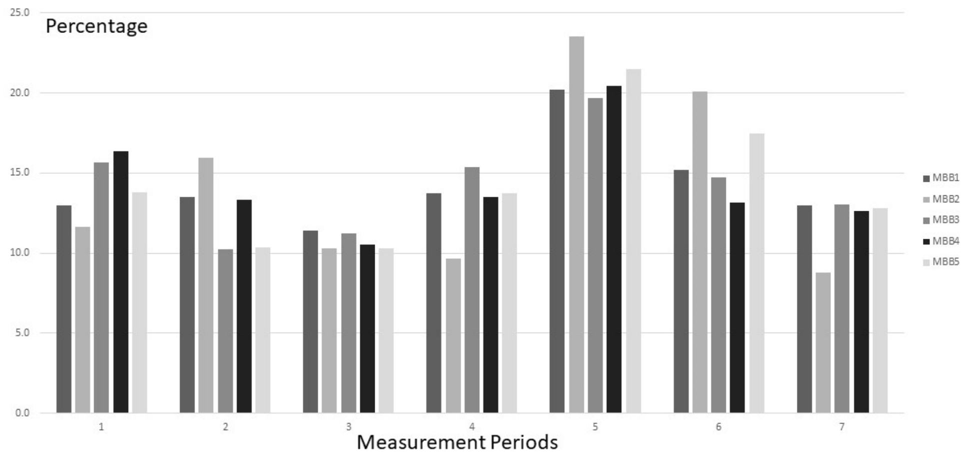

(**b**)

Figure 6. (**a**) Relative contribution of each measurement period to the overall information content of the platform by bolt site for Ponta tal-Qammieħ shore platform. (**b**) Relative contribution of each measurement period to the overall information content of the platform by bolt site for Blata l-Bajda shore platform.

The high information content is distributed across points and measurement periods rather than concentrated in a particular point on the measured surface. There seems to be a great deal of variability in information content by measurement period, with the last measurement period tending to be the one with the highest information content. This suggests that the 5th to 7th measurement periods contain more information spread across a number of points than the other measurement periods.

Linking TMEM data analysis to information theory may provide a novel perspective to examine the complex processes of rock surface changes driven by weathering and erosion at different scales. By applying empirical probability distributions, researchers may quantify the informational content of erosion data and, as a result, may uncover patterns that might be overlooked with traditional methods used for TMEM data analysis.

Recent scientific interest, for example, has focused on short-term temporal scales (hours and days) within extended periods (typically over two years). Current findings suggest that at short-term scales, observed micro-topographic changes are characterised by fluctuations in surface elevations (rises and falls) that do not significantly contribute to net surface lowering [32,33]. Short-term surface rises were detected by T/MEM studies on a number of lithologies, including limestone, with significant surface erosion (net lowering) primarily detected over longer annual time scales (>2 years) [25,34,35].

Table 4. F-values for comparison of erosion rates (mm/year) and information content (bits) across measurement periods at each bolt site on Ponta tal-Qammieħ shore platform.

Bolt Site	Data	F Value *	Significant Behaviour
MPQ1	Erosion Rates	**150.76**	Measurement period 5 rises or low losses
	Information Content	**34.34**	Measurement periods 5 and 7 high values
MPQ2	Erosion Rates	**54.23**	Measurement period 7 high losses
	Information Content	**20.91**	Measurement periods 5 and 7 high values
MPQ3	Erosion Rates	**24.37**	Measurement period 5 rises or low losses, measurement period 7 high losses
	Information Content	**20.40**	Measurement periods 5 and 7 high values
MPQ4	Erosion Rates	**159.05**	Measurement period 5 rises or low losses, measurement period 7 high losses
	Information Content	**56.28**	Measurement periods 5 and 7 high values
MPQ5	Erosion Rates	**181.61**	Measurement period 5 rises, or low losses measurement period 7 high losses
	Information Content	**62.42**	Measurement periods 5 and 7 high values
MPQ6	Erosion Rates	**112.63**	Measurement period 5 rises or low losses, measurement period 7 high losses
	Information Content	**27.40**	Measurement periods 5 and 7 high values

* Values in the table are in bold text depending on their statistical significance. **xxx** = statistically significant at $\alpha = 0.01$.

Table 5. F-values for comparison of erosion rates (mm/year) and information content (bits) across measurement periods at each bolt site on Blata l-Bajda shore platform.

Bolt Site	Data	F Value *	Significant Behaviour
MBB1	Erosion Rates	**13.32**	Measurement periods 2 and 5 rises or low losses
	Information Content	**3.83**	Measurement period 5 high values
MBB2	Erosion Rates	**10.08**	Measurement period 5 rises or low losses
	Information Content	**18.55**	Measurement periods 5 and 6 high values
MBB3	Erosion Rates	**6.71**	Measurement period 4 rises or low losses, measurement period 6 high losses
	Information Content	**3.81**	Measurement period 5 high values
MBB4	Erosion Rates	**5.44**	Measurement period 5 rises or low losses
	Information Content	**3.97**	Measurement period 5 high values
MBB5	Erosion Rates	**18.39**	Measurement period 5 rises or low losses, measurement period 6 high losses
	Information Content	**6.68**	Measurement period 5 high values

* Values in the table are in bold text depending on their statistical significance. **xxx** = statistically significant at $\alpha = 0.01$.

Table 6. F-values for comparison of erosion rates (mm/year) and information content (bits) across bolt sites at each measurement period on Ponta tal-Qammieħ shore platform.

Measurement Period	Data	F Value *	Significant Behaviour
1	Erosion Rate	1.24	
	Information Content	**12.85**	MPQ2 high values
2	Erosion Rate	**8.13**	MPQ4 high losses
	Information Content	**4.06**	MPQ3 and MPQ4 high values
3	Erosion Rate	0.85	
	Information Content	**3.97**	MPQ3 low values
4	Erosion Rate	**4.64**	MPQ2 rises or low losses
	Information Content	1.78	
5	Erosion Rate	**34.26**	MPQ2 low losses
	Information Content	1.81	
6	Erosion Rate	2.41	MPQ2 high losses
	Information Content	**4.09**	MPQ2 high values
7	Erosion Rate	2.41	MPQ2 high losses
	Information Content	0.66	

* Values in the table are in bold or normal text depending on their statistical significance. **xxx** = statistically significant at α = 0.01. xxx = not statistically significant.

Table 7. F-values for comparison of erosion rates (mm/year) and information content (bits) across bolt sites at each measurement period on Blata l-Bajda shore platform.

Measurement Period	Data	F Value	Significant Behaviour
1	Erosion Rate	2.97	MPQ2 rises or low losses
	Information Content	1.48	
2	Erosion Rate	1.83	
	Information Content	**3.09**	MPQ2 high values
3	Erosion Rate	1.70	
	Information Content	0.12	
4	Erosion Rate	**5.20**	MPQ2 and MPQ3 rises or low losses
	Information Content	1.57	
5	Erosion Rate	**7.16**	MPQ2 rises or low losses, MPQ3 high losses
	Information Content	0.55	
6	Erosion Rate	0.97	
	Information Content	**3.07**	MPQ2 high values
7	Erosion Rate	**3.19**	MPQ2 and MPQ5 rises or low losses
	Information Content	1.96	

* Values in the table are in bold or normal text depending on their statistical significance. **xxx** = statistically significant at α = 0.01. xxx = not statistically significant.

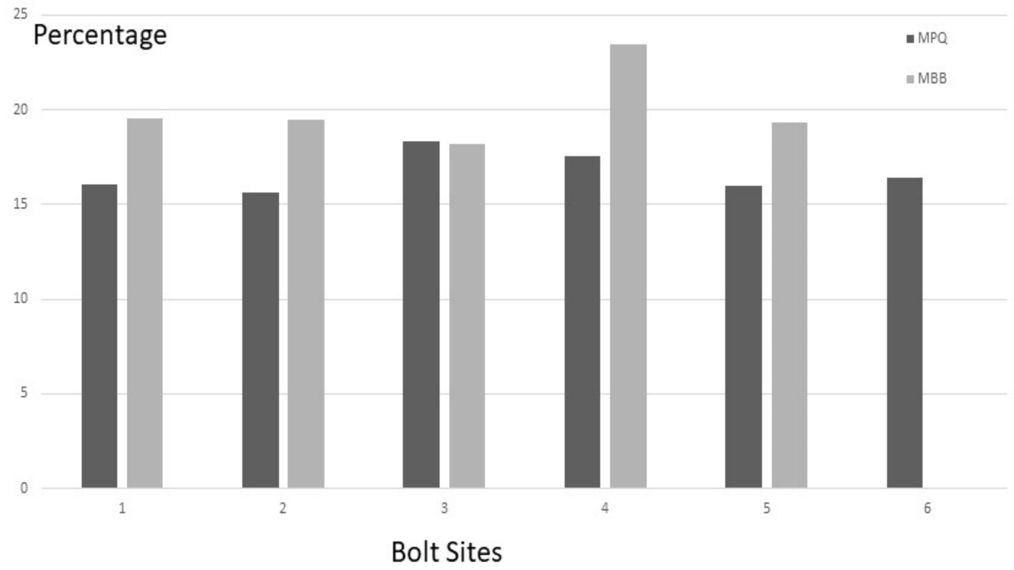

Figure 7. Relative contribution of each bolt site to the overall information content of the platform for platforms Ponta tal-Qammieħ (MPQ) and Blata l-Bajda (MBB).

The cause of surface fluctuations and their contribution to erosion remain elusive, however. Initial studies have proposed them as a precursor to erosion, i.e., creating weakened surfaces at granular level susceptible to wave-induced detachment [36,37]. The complexity of unpacking the effect of weathering processes of microtopographic surface change has led to a number of different experiments: wetting and drying by tidal inundations and salt weathering [23,24,35,38–40], frost weathering [41,42], and bioprotection [43]. These studies confirm to various degrees the synergistic interplay of different weathering processes in driving microtopographic changes in situ and, in some instances, the need to run controlled experiments to measure more accurate trends of surface change across various timescales. Using information content rather than erosional loss or rates may provide a common measure with which to analyse change over differing time scales as well as the links between information content at one scale and another.

The dynamics of spatial variability in erosion rates are also crucial for understanding the behaviour of rock surface changes. Comparing the erosion rate of a single measurement to those of increasingly distant readings can reveal whether or not the measured surface is behaving as a homogenous spatial unit and at what spatial scale. From a two-year dataset of TMEM readings, collected from two limestone shore platforms, Gauci et al. (2022) found consistent patterns in how erosion rate differences vary with distance between single-point measurements across both time periods and locations on a platform [25]. While these relationships are complex and not easily characterised, they suggest variations in how the same surface responds to erosional forces. Again, conversion of erosion rates to information content permits the development of informational surfaces to compare across spatial scales.

Gomez-Pujol and Fornos (2023) observed how the microtopography of rock surfaces on a limestone shore platform at supratidal level evolved more homogeneously from multi-annual to decadal scales [44]. Over longer monitoring periods, the impact of short-term surface elevation changes diminished due to higher magnitudes of erosion. Similarly, Yuan et al. (2024) identified a comparable spatial pattern over shorter time periods on sandstone. Initially, the rock surface changes exhibited a heterogeneous pattern at an hourly scale, driven by repeated short-term surface changes, which evolved into a more homogeneous pattern at a monthly scale over extended monitoring periods [39]. From an informational content point of view, this suggests that longer time periods result in a reduction of surprising values, potentially suggesting a threshold for how much additional information content prolonged periods of measurement provide.

6. Conclusions

Quantifying erosion rates in terms of their information content allows concepts from information theory to be used to analyse erosion. The new quantitative measure could be used to explore the relationships between different temporal and spatial scales of erosion on a surface. Through a Box-Cox style transformation, it is possible to transform erosion rate data into data with a normal distribution and so calculate probabilities and information content. derived from measured erosion rates within the context of both the bolt site and platform as a whole. Analysis suggests that certain points contribute a disproportionately large amount of information but that this contribution is not consistent across all measurement periods. Each bolt site contributes roughly a third of the information content on each platform through all measurement periods, while there are two specific measurement periods that make a disproportionately large contribution of information content. This suggests that specific measurement periods produce unexpected rates of erosion and that research should be concerned with the processes operating in these periods to gain a deeper understanding of the mechanism of erosion at this scale.

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References

1. Fan, J.; Meng, J.; Ludescher, J.; Chen, X.; Ashkenazy, Y.; Kurths, J.; Havlin, S.; Schellnhuber, H.J. Statistical physics approaches to the complex Earth system. *Phys. Rep.* **2021**, *896*, 1–84. [PubMed]
2. Krakauer, D.; Bertschinger, N.; Olbrich, E.; Flack, J.C.; Ay, N. The information theory of individuality. *Theory Biosci.* **2020**, *139*, 209–223. [CrossRef]
3. Avery, J.S. *Information Theory and Evolution*; World Scientific: Singapore, 2021.
4. Vopson, M.M.; Robson, S.C. A new method to study genome mutations using the information entropy. *Phys. A* **2021**, *584*, 12638. [CrossRef]
5. Vopson, M. A possible information entropic law of genetic mutations. *Appl. Sci.* **2022**, *12*, 6912. [CrossRef]
6. Vopson, M. The mass-energy-information equivalence principle. *AIP Adv.* **2019**, *9*, 095206. [CrossRef]
7. Carbone, S.; Grasso, M.; Lentini, F.; Pedley, H.M. The distribution and palaeoenvironment of Early Miocene phosphorites of southeast Sicily and their relationships with the Maltese phosphorites. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **1987**, *58*, 35–53. [CrossRef]
8. Gauci, R.; Scerri, S. A synthesis of different geomorphological landscapes on the Maltese islands. In *Landscapes and Landforms of the Maltese Islands*; Gauci, R., Schembri, J.A., Eds.; Springer International Publishing: Cham, Switzerland, 2019; pp. 49–65.
9. Gauci, R.; Inkpen, R. The physical characteristics of limestone shore platforms on the Maltese islands and their neglected contribution to coastal land use development. In *Landscapes and Landforms of the Maltese Islands*; Gauci, R., Schembri, J.A., Eds.; Springer International Publishing: Cham, Switzerland, 2019; pp. 343–356.
10. Pedley, H.M. Oligocene-Miocene Stratigraphy of the Maltese Islands. Ph.D. Dissertation, University of Hull, Hull, UK, 1975.
11. Pedley, H.M.; Bennett, S.M. Phosphorites hardgrounds and syndepositional solution subsidence: A palaeoenvironmental model from the Miocene of the Maltese Islands. *Sediment. Geol.* **1985**, *45*, 1–34. [CrossRef]
12. Baldassini, N.; Di Stefano, A. New insights on the Oligo-Miocene succession bearing phosphatic layers of the Maltese Archipelago. *Ital. J. Geosci.* **2015**, *134*, 355–366. [CrossRef]
13. Pedley, H.M.; House, M.R.; Waugh, B. The geology of Malta and Gozo. *Proc. Geol. Assoc.* **1976**, *87*, 325–341. [CrossRef]

14. Pedley, H.M.; House, M.R.; Waugh, B. The Geology of the Pelgian Block: The Maltese islands. In *The Ocean Basins and Margins: Of the Western Mediterranean*; Nairn, A.E.M., Greenough Stehli, F., Kanes, W.H., Eds.; Plenum Press: New York, NY, USA, 1978; Volume 4, pp. 417–433.
15. Rose, E.P.F.; Pratt, S.K.; Bennett, S.M. Evidence for sea-level changes in the Globigerina Limestone Formation (Miocene) of the Maltese Islands. *Paleontol. I Evol.* **1992**, *24*, 265–278.
16. Rehfeld, U.; Janssen, A.W. Development of phosphatized hardgrounds in the Miocene Globigerina Limestone of the Maltese Archipelago, including a description of Gamopleura melitensis sp. nov.(Gastropoda, Euthecosomata). *Facies* **1995**, *33*, 91–106. [CrossRef]
17. Baldassini, N.; Di Stefano, A. Stratigraphic features of the Maltese Archipelago: A synthesis. *Nat. Hazards* **2017**, *86*, 203–231. [CrossRef]
18. Open Topography. Available online: https://openotopgraphy.org (accessed on 22 June 2024).
19. Yuan, R.; Kennedy, D.M.; Stephenson, W.J.; Finlayson, B.L. The precision and accuracy of measuring micro-scale erosion on shore platforms. *Mar. Geol.* **2022**, *443*, 106691. [CrossRef]
20. Kirk, R.M. Rates and forms of erosion on intertidal platforms at Kaikoura Peninsula South Island New Zealand. *N. Z. J. Geol. Geophys.* **1977**, *20*, 571–613. [CrossRef]
21. Robinson, D.A. Erosive processes on the shore platform of northeast Yorkshire England. *Mar. Geol.* **1977**, *23*, 339–361. [CrossRef]
22. Gill, E.D.; Lang, J.G. Micro-erosion meter measurements of rock wear on the Otway coast of southeast Australia. *Mar. Geol.* **1983**, *52*, 141–156. [CrossRef]
23. Porter, N.J.; Trenhaile, A.S.; Prestanski, K.J.; Kanyaya, J.I. Shore platform downwearing in eastern Canada: Micro-tidal Gaspé Québec. *Geomorphology* **2010**, *116*, 77–86. [CrossRef]
24. Porter, N.J.; Trenhaile, A.S.; Prestanski, K.J.; Kanyaya, J.I. Patterns of surface downwearing on shore platforms in eastern Canada. *Earth Surf. Process. Landf.* **2010**, *35*, 1793–1810. [CrossRef]
25. Gauci, R.; Inkpen, R.; Soar, P.J. Spatial analysis of eroding surface micro-topographies. *Mar. Geol.* **2022**, *452*, 106880. [CrossRef]
26. Vopson, M.; Lepadatu, S. Second law of information dynamics. *AIP Adv.* **2022**, *12*, 075310. [CrossRef]
27. Sakiam, R.M. The Box-Cox Transformation technique: A review. *J. R. Stat. Soc. Ser. D Stat.* **1992**, *41*, 169–178.
28. Beasley, T.M.; Erickson, S.; Allison, D.B. Rank-based inverse normal transformation are increasingly used, but are they merited? *Behav. Genet.* **2009**, *39*, 580–595. [CrossRef]
29. Velez, J.I.; Correa, J.C.; Marmolejo-Ramos, F. A new approach to Box-Cox transformation. *Front. Appl. Math. Sci.* **2015**, *1*, 12. [CrossRef]
30. Malik, F.; Khan, A.W.; Shah, M.T.A. Box-Cox transformation for data normalization: A study of new product development in manufacturing sector of Pakistan. *IBT J. Bus. Stud.* **2018**, *14*, 110–119. [CrossRef]
31. McCaw, Z.R.; Lane, J.M.; Saxena, R.; Redline, S.; Lin, X. Operating characteristics of the rank-based inverse normal transformation for quantitative trait analysis in genome-wide association studies. *Biometrics* **2020**, *76*, 1262–1272. [CrossRef]
32. Yuan, R.; Kennedy, D.M.; Stephenson, W.J. Hourly to daily-scale microtopographic fluctuations of supratidal sandstone. *Earth Surf. Process. Landf.* **2018**, *43*, 3142–3151. [CrossRef]
33. Yuan, R.; Kennedy, D.M.; Stephenson, W.J.; Gómez-Pujol, L. Experimental investigations into the influence of biofilms and environmental factors on short-term microtopographic fluctuations of supratidal sandstone. *Earth Surf. Process. Landf.* **2019**, *44*, 1377–1389. [CrossRef]
34. Mayaud, J.R.; Viles, H.A.; Coombes, M.A. Exploring the influence of biofilm on short-term expansion and contraction of supratidal rock: An example from the Mediterranean. *Earth Surf. Process. Landf.* **2014**, *39*, 1404–1412. [CrossRef]
35. Gauci, R. The Identification and Quantification of Surface Change on Limestone Shore Platforms of the Maltese Islands. Ph.D. Thesis, University of Portsmouth, Portsmouth, UK, 2018.
36. Stephenson, W.J.; Finlayson, B.L. Measuring erosion with the micro-erosion meter-Contributions to understanding landform evolution. *Earth Sci. Rev.* **2009**, *95*, 53–62. [CrossRef]
37. Stephenson, W.J.; Kirk, R.M. Surface swelling of coastal bedrock on inter-tidal shore platforms Kaikoura Peninsula South Island New Zealand. *Geomorphology* **2001**, *41*, 5–21. [CrossRef]
38. Kanyaya, J.I.; Trenhaile, A.S. Tidal wetting and drying on shore platforms: An experimental assessment. *Geomorphology* **2005**, *70*, 129–146. [CrossRef]
39. Yuan, R.; Kennedy, D.M.; Stephenson, W.J.; Finlayson, B.L. The influence of weathering processes on microtopographic changes of sandstone under simulated upper intertidal conditions from hourly to weekly scales. *Geomorphology* **2024**, *446*, 108999. [CrossRef]
40. Yuan, R.; Kennedy, D.M.; Stephenson, W.J.; Finlayson, B.L. The influence of weathering processes on microtopographic changes of sandstone under simulated upper intertidal conditions from weekly to monthly scales. *Geomorphology* **2024**, *455*, 109209. [CrossRef]
41. Robinson, D.A.; Jerwood, L.C. Frost and salt weathering of chalk shore platforms near Brighton Sussex UK. *Trans. Inst. Br. Geogr.* **1987**, *12*, 217–226. [CrossRef]
42. Robinson, D.A.; Jerwood, L.C. Sub-aerial weathering of chalk shore platforms during harsh winters in Southeast England. *Mar. Geol.* **1987**, *77*, 1–14. [CrossRef]

43. Gowell, M.R.; Coombes, M.A.; Viles, H.A. Rock-protecting seaweed? Experimental evidence of bioprotection in the intertidal zone. *Earth Surf. Process. Landf.* **2015**, *40*, 1364–1370. [CrossRef]
44. Gomez-Pujol, L.; Fornós, J.J. Long-term vs. short-term subsite erosion rates on microtidal shore platforms (Southern Mallorca Balearic Islands Western Mediterranean). *Environ. Earth Sci.* **2023**, *82*, 570. [CrossRef]

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