Geomorphology and the Law of Unintended Consequences (Locke 1691): Lessons from coastal weathering and erosion at Prawle (UK) and Kaikoura (NZ).

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Abstract

The sites of two field experiments based on micro-erosion metering, one in UK the other in New Zealand, were independently revisited respectively 33 and 17 years after installation. At both sites natural weathering and erosion processes had been inadvertently interrupted by the experimental works, leading to the development of new landforms. These are interpreted in the context of modifications of the controls on weathering processes, leading to enhanced understanding of the processes themselves. This has lessons for the geomorphologist in maintaining a long term watching brief over former experimental sites, lest some unintended and potentially beneficial outcome has ensued. This theme is embraced by the Law of Unintended Consequences (after Locke 1691).

Highlights:

Application to Geomorphology of the Law of Unintended Consequences.

The value of long term monitoring in Geomorphology.

Unintended consequences of field experiments may generate new and instructive landforms.

Keywords: MEM, coastal weathering, unintended consequences, long term observations, experiment design.

1 Introduction

The concept unpinning the Law of Unintended Consequences, though not initially termed as such, has a long and distinguished history. It was apparently first articulated in the field of economic policy by John Locke (1691), who expounded the notion in the context of proposed legislation to restrict interest rates. The concept was subsequently discussed by Adam Smith (1759), and further developed in the twentieth century in particular by R.K. Merton in the context of social science (Merton 1936). The concept states that deliberate (purposive) action may have unanticipated outcomes that may include benefits, drawbacks, or perverse outcomes in which the outcome is the opposite of that intended. Merton explores the ‘unanticipated consequences of purposive action’, and identifies the causes of unanticipated consequence as ignorance, error, ‘imperious immediacy of interest’, basic values, and self-defeating prediction, the first four of which are potentially relevant in a scientific context. He also observes that they can be found in a wide range of contexts ‘from theology to technology’, noting that ‘no systematic or scientific analysis of it has as yet been effected’. The underlying concept thus has a venerable tradition, and is popularly described by the term Law.

In this paper we report the application and relevance of the Law to field observations in coastal geomorphology. At two contrasting locations, Prawle, South Devon, UK and Kaikoura, South Island, New Zealand, micro-erosion metering (MEM) installations and associated fieldwork disturbed geomorphic processes in the immediate vicinity. During the years and decades subsequent to the initial or intended experimental period, these intrusions have inadvertently created unexpected long term consequences including the development of new landforms. These unanticipated and unintended effects have, serendipitously, had beneficial consequences in permitting further insights into weathering and erosion processes at the two instrumented sites. We are pleased here to report the beneficial outcomes from two sites, each of which has independently led to increased understanding of the subject of study.

2 Prawle

2.1 Site details

At the coast near East Prawle, South Devon, UK (Figure 1), the sites of interest lie between Horseley Cove and Langerstone Point. Here a supratidal platform is formed in greenschist bedrock. At 1-2 m above mean high water, it lies in the spray zone of the rocky shore and is occasionally washed by storm surges. Two lithological variants are present (Floyd et al

1993). One variant is an initial assemblage of actinolite-epidote-albite schist, the second a retrograde assemblage of chlorite-epidote-albite schist in which the chlorite replaces the actinolite to varying degrees. The former is finely laminated in character, whilst the latter includes larger prismatic subhedral crystals of up to 500-1500 μm which create a more granular texture.

It is not known when the oil became stranded, but close examination showed that by 1979 it was breached in places on the top surfaces and had begun to recede from the shoulders of the pedestals.

The general freshness of the pedestal forms suggested that that had grown by emergence from a rapidly lowering rock surface. Accordingly, MEM sites were established in 1980 (designated t_0) on the rock platform to investigate weathering and erosion involved in their development. The MEM (Figure 3) consists of a dial gauge mounted on a triangular plate metal platform which was supported on three legs whose feet were machined into a cone, wedge and flat respectively to form a Kelvin's clamp when paced upon a triangular array of studs. This created a repeatable datum level from which measurement of rock platform height could be made at intervals of time to a notional precision of 0.001 mm.

Figure 2: A rock pedestal some 11 mm high, and capped by a protective cover of stranded oil, has grown by emergence from the rapidly lowering (0.68 mm a^{-1}) rock platform. Note the depth of the pedestal shadow. The penknife is 90 mm long. Incipient wearing back of the oil cover from the shoulders of the pedestal is visible; pale areas atop the pedestal indicate breaches of the oil cover.

At three sites arrays of six studs were installed (Figure 4), such that they formed four triangles. With an off-centre probe and three potential orientations for each triangle of studs, the MEM yielded provided twelve different point values per visit. A key feature of the installation was that the countersunk holes which housed the MEM studs were sealed with grease in order to protect them from exposure to weathering agents (Mottershead 1982a, 1989). The initial hope was that they would be sufficiently durable to permit a full year of observation; in the event, they facilitated effective continuous monitoring over a period of seven years.

Figure 4. An array of six MEM stud emplacements (Site 3). The six studs are arranged such that they define four contiguous triangles, on each of which the MEM can be seated; with an off-central probe, three different observations can be made on each triangle. The countersunk shafts which house the MEM studs are sealed by grease which has seeped laterally into the rock inhibiting weathering and erosion and creating emergent incipient pedestals 2-3 mm in height. Image dates from 1986 (t_6).

2.2 Unintended consequences

In the period of regular monitoring it was observed that, during the above average summer temperatures of the mid 1980s, the grease had seeped into the bedrock surrounding the countersunk holes. It became apparent that a small plateau had developed around each stud site, initially observed in September 1986 (Figure 4).

This implies that the grease-affected areas were resisting weathering and erosion, in contrast to the surrounds which continued to lower around them to create emergent pedestals akin to those described by Mottershead (1981, 1982a, 2013) where small stranded oil spills had provided a protective cap (Figure 2).

By 2012 some of these pedestals had assumed considerable height (W. J. Stephenson *pers. comm.*) and merited further investigation. Accordingly, in June 2012 (t_{32}) the site was revisited and new observations made (Figure 5). Orthogonal cross section profiles were taken with a profile gauge of the relief features present at the 18 stud sites, to yield four height readings per pedestal, the mean values of which then formed the basis of further analyses.

Figure 5: Pedestal development in 2012 (t_{32}). A. Site 3 shows sharply defined plateau forms with countersunk studs; B. Site 1 shows severely degraded forms, with formerly countersunk studs now protuberant.

By 2012 there were clear visual differences between the relief forms developed on chlorite schist (Sites 2, 3) and those on actinolite schist (Site 1). The former all still possess a well-defined plateau-like form surrounding the central shaft containing the stud emplacement. Where the latter is still in place, the surface of the plateau remains higher than the top of the stud. In contrast is the muted form of the irregular low rounded knolls at Site 1, several of

which no longer completely encircle the central shaft. The original (reference) surface is now completely destroyed and all remaining relief is reduced in height to below the top of the studs which it formerly protected.

Details of the sites and 2012 field observations are presented in Table 1. The morphometrics immediately reveal the close similarity between all the complete and robustly defined chlorite schist features (Sites 2, 3), which are both broader and higher than those on the actinolite schist. In addition to their dimensional similarities, the length/width ratio of the chlorite plateaux is both tightly constrained and similar at the two sites, the larger dimension being aligned approximately NW/SE, reflecting the orientation of the anisotropy of the schist.

Table 1: Site data and morphometric characteristics of the relief features at the three study sites at Prawle.

Variable	Unit	Site 1	Site 2	Site 3
Location		50° 12' 28.42''N 3° 42' 15.99''W	50° 12' 34.85''N 3° 42' 12.76''W	50° 12' 34.89''N 3° 42' 12.28''W
Mineralogy		Actinolite-epidote- albite schist	Chlorite-epidote- albite schist	Chlorite-epidote- albite schist
n		5	6	6
Mean L ₁	mm	76.2	117.8	126.2
Mean L ₂	mm	44.0	70.5	77.5
Mean L ₁ /L ₂ ratio		1.76	1.67	1.63
Mean Area	mm ²	2652.4	6570.1	7689.4
Mean Height	mm	9.35	15.84	15.46

The arrays were emplaced contemporaneously, and by 1986 all three sites had developed incipient pedestal forms (Figure 4); it is a reasonable expectation that they would develop further through time (Table 2). It is therefore instructive to extrapolate the 7 year mean erosion rates for the 3 arrays of studs to 2012, the year of the revisit. Although Viles & Trudgill (1984) urge caution in extrapolating short term MEM rates over longer periods, Stephenson et al (2012) show that a two-year record may suffice. In respect of the Prawle sites, Mottershead (1989) shows that for this site 30 point years of data (one point-year = one annual value per MEM point) are sufficient to identify a reliable measure of annual surface

lowering. The observed aggregate point rate over 7 years is therefore used to estimate values for total depth of erosion at each of the three sites. (Equation 1).

$$D_{32} = 32/7(Eros_7) \quad \text{Equation 1.}$$

Where D_{32} = Mean pedestal depth at year 32; $Eros_7$ = Mean erosion rate at year 7.

This yields values in Table 2 for each of the three arrays (Sites 1, 2, 3) of six MEM points each.

Table 2: Observed surface lowering rates 1980-1987 with projected and actual plateau heights of 2012.

	Units	Site 1	Site 2	Site 3
7 yr observed erosion rate ($Eros_7$)	mm a ⁻¹	0.682	0.486	0.408
32 yr projected height 2012 (D_{32})	mm	21.82	15.87	13.06
Actual mean height 2012 (t_{32})	mm	9.37	15.83	15.47

The chlorite schist (Sites 2, 3) in 2012 shows one array of exactly the height predicted by extrapolation, and the other within 15% of the predicted value. In contrast the actinolite schist (site 1) with the highest observed lowering rate shows a mean observed relief height of 9.35 mm, little over 40% of the predicted mean of 21.82 mm. The features observed in 2012 were, therefore, mere vestigial remnants of the well defined pedestals that had formed by 1987, the date of the last experimental observation.

2.3 Discussion (Prawle)

The 2012 revisit complements earlier studies of weathering-limited erosion of coastal greenschist in South Devon, which span the range from short term (one month and one year) instrumental monitoring data (Mottershead (1982a, 1989) to long-term data derived from historic structures at timescales of centuries (Mottershead 1997). Data from all three timescales confirm the maximum weathering-limited erosion rate of greenschist in this environment at ~ 0.68 mm a⁻¹, implying a weathering rate of the same magnitude.

In respect of weathering and erosion, the inadvertently created landforms yield helpful information regarding the mechanisms involved. It is inferred that the lateral permeation by grease through the rock from countersunk stud sockets led to the blocking of pores and in

consequence inhibited weathering and erosion. The uniform planform asymmetry of the permeation suggests that its lateral extent is controlled by the anisotropic mineralogical structure of the rock itself, with preferential permeation parallel to the foliation. This pore blockage leads to a significant diminution of weathering within the rock pores, in contrast to rock beyond the permeated zone which continues to be lowered, leading to the increasing emergence of the plateau forms.

The evidence from Site 1 suggests that the protective effect of the grease is of finite duration, and that weathering and erosion subsequently resume, leading to diminution and destruction of these relief features. It may reasonably be inferred that since 1987 pedestal heights around the MEM installations there increased up to some maximum value before, at some critical point, weathering and erosion initiated attack on their exposed top and shoulder surfaces leading to the degradation of the original forms. Comparison with the oil-capped pedestals suggests that thinning and recession of the protective agent thus permitted access of weathering agents to the subjacent bedrock forming the pedestals themselves, enabling weathering mechanisms to renew attack on the formerly protected rock fabric. The pattern of the oil diminution shows that the attacks occur both within the pedestal mass and on its shoulders, implying top surface lowering, subdivision of the upstanding masses, and lateral shrinkage.

The blockage of the pores also enables inference concerning the weathering mechanisms in play, as follows. It: -

- prevents ingress by seawater – thus nullifying salt-related mechanisms, such as crystallisation and solution
- eliminates slaking effects
- permits thermal weathering effects
- increases mechanical strength (coherence) thus inhibiting disintegration
- confirms the observed 7-year erosion rate as representative of the longer term.

Additionally, the inadvertent exclusion of salt and water from the rock interior has evidently nullified the effects of those agents in rock breakdown within the pedestals, providing a field confirmation of earlier experimental studies, (Mottershead (1982a, b) that those mechanisms were the predominant cause of rock breakdown in this environment. The contrast between the

actinolite schist and chlorite schist sites suggests also that their duration depends to a considerable extent on the petrographic properties of the local rock.

2.3.1 Development and decay of unintended perturbation forms

The forms present in 2012 provide evidence of the development and decay pathway of these inadvertent landforms. The well-defined plateau forms on the chlorite schist (Sites 1, 2) are evidently still developing, for they exhibit a crisp outline with a significant lack of evidence of erosion, sitting atop a broad exposed rock platform, quasi-planar at the microscale, which is still evidently undergoing surface lowering. It can reasonably be inferred that pedestal height is still increasing after 32 years of existence. In contrast the forms developed on actinolite schist (Site 3) are much reduced in height, of predominantly rounded form and clearly represent fragments of their former whole (Figure 5b). These provide evidence of the nature and duration of both the growth and the decay phases of their evolution.

The general lowering rate (R) at this latter site, monitored by MEM over seven years, is 0.68 mm a^{-1} . Although limited to just six point sources, the volume of data accumulated over five years of thrice yearly observations, and one year each of monthly and annual observations, provides a solid and representative long term dataset. Mottershead & Inkpen (2006) show that inheritance of both topography and erosion rates at individual points declines over a period of 7-12 years. In this way, the longer term lowering tends to become evenly distributed across the entire surface. It is thus appropriate to regard the overall mean lowering rate as a blanket mean representing the ambient rate of lowering at Site 1 equal to 0.68 mm a^{-1} , for the surrounding rock surface.

This ambient rate can be used to reconstruct change in the rock surface landscape during the derelict phase of the experimental site, simply by restoring the depth of rock removed by the

weathering-limited erosion (Figure 6).

Figure 6: Definition of variables relating to the baseline 1980 reference surface.

Over a period of 32 years from 1980 (t_0) to 2012 (t_{32}) it is estimated that a mean cumulative depth of 21.82 mm of rock was removed. This permits the reconstruction of the initial surface at t_0 to form a reference plane for the interpretation of the pedestal remnants (Table 3). The depth of erosion represented by each pedestal remnant is therefore given by: -

$$Eros_{32} = 21.8 - h_{(t_{32})} \text{ mm.} \quad \text{Equation 2.}$$

Table 3. Observed height and calculated erosion depth for the five viable pedestal remnants at Site 1.

Stud	$h_{(t_{32})}$	Erosion (t_0 - t_{32})
1	8.27	13.55
2	13.37	8.45
3	6.80	15.02

4	7.64	14.18
5	9.30	12.52

Since the aims of the initial experiment were more than satisfied by 1986, no erosion further erosion data were observed, and there is a data hiatus between 1986 and 2012 on for the pedestal surfaces themselves. Pedestal height at t_{32} , however, together with the known ambient erosion rate provide information from which pedestal growth and decay can be inferred by modelling. The creation of the pedestals themselves is instigated by the cessation of weathering and erosion at the pedestal top surface, hence the surface lowering rate can be assumed as zero during the period of pedestal emergence and growth.

Pedestal growth then continues until the point when its surface is breached, and weathering and erosion can begin again, thus initiating lowering of the top surface. This could have occurred though breaches in the grease cover, or the development of fissures along lines of weakness. This is the point in time when the pedestal height is at a maximum ($H_{\max}$), and this point in pedestal evolution is designated as $T_{(h\max)}$. Reduction of pedestal height necessarily requires the rate of modelled pedestal top surface lowering to be greater than the ambient rate.

Various scenarios can be estimated according to modelled accelerations of the observed blanket rate. These conservatively assume a linear rate of surface lowering, though it is more likely to be an exponentially declining rate through time (Brunsden 1990). If the ambient rate is nominated as 1, then values of 1.01, 1.02, 1.03, et seq. up to an intuitively reasonable value of 2.0 can be used to evaluate the effects of an accelerated top surface lowering rate. In this way, the time required under each scenario to erode the missing material can be estimated by back calculating from the fixed point provided by the 2012 observations to determine the initiation date of erosion $T_{(h\max)}$ for each postulated rate:

$$T_{(h\max)} = 2012 - \{Eros_{32}/(0.68 * 1.x)\} \quad \text{Equation 3.}$$

where x = centile increment (0.01, 0.02 et seq.)

The application of the ambient lowering rate then enables the determination of the time elapsed between initiation and their maximum height ($H_{\max}$) at that same time:

$$H_{(max)} = (T_{(H\max)} - t_0) * 0.68 \quad \text{Equation 4.}$$

The future lifetime of the pedestal remnants ($Eros_{(f)}$) is given by:

$$Eros_{(f)} = H_{32} / (0.68 * 1.x), \quad \text{Equation 5.}$$

The overall duration of the pedestal forms from initiation to obliteration $t_{(trans)}$ is then given by:

$$T_{(trans)} = T_{32} + Eros_{(f)} \quad \text{Equation 6.}$$

These equations are applied to height and time values for the five individual stud emplacements at Site 1, with iterations for each of 100 accelerated lowering rates, to provide 500 values for each variable estimated. The results for the three key characteristics of the pedestal evolution and decay pathway - maximum pedestal height, time to peak height, and overall duration - are shown as probability density histograms in Figure 7, and summarised in Table 4.

Table 4: Summary descriptive statistics of modelled values of key variables of development and duration of the inadvertent landforms at Site 1, Prawle.

Variable	Mean	S.D.	2σ Range (95%)	I/q range (50%)
T_(hmax)	1992.9	+/- 3.53	1986-2000	1991-1996
H_(max)	8.80	+/- 2.40	4.0-12.8	7.2-10.5
T_(trans)	41.2	+/- 3.02	35-47	39-43

Figure 7. Probability density histograms of transient pedestal development parameters.

A more rapid lowering rate in the decay phase implies a later initiation of pedestal erosion and a correspondingly longer preceding growth period. It then follows that the later the initiation of erosion, the longer the pedestal will have survived, deepening continuously through its growth phase to a greater maximum height. These show that at a probability level of 95%, the simulated peak years lie in the range 1986-2000, maximum pedestal heights lie in the range 4.0-12.8 mm and overall durations lie between 35 and 47 years. Since the distributions are moderately skewed the nonparametric alternative interquartile range is used to identify the 50% probability range for each characteristic.

2.3.2 Transience and Duration of forms

The development and decay pathway of the pedestals developed on the actinolite schist can be interpreted in relation to the concept of landscape sensitivity and change (Brunsden & Thornes 1979). The existing characteristic landscape of the rock surface is initially modified

by the perturbation of weathering processes caused by the experimental intervention; the newly created forms then appear in the landscape as transient forms, representing a transition between the initial characteristic state and a subsequent final characteristic state following the passage of the perturbation through the landscape (Figure 8). The information available from Site 1 at Prawle permits the modelling of the transient period, and predicts its duration of 35-47 years, returning to the new characteristic form by (at the latest) t_{47} or AD 2027 in calendar years.

Figure 8: Schematic representation of the pathway of pedestal development and decay at site 1, East Prawle, interpreted in relation to landscape states of equilibrium and transience and based on a quantified temporal scale.

It is important to note that this analysis is applicable only to the actinolite schist, since neither of the chlorite schist sites has yet undergone any significant decay and therefore neither presents sufficient information for such analysis. This also underlines the significance of lithological control on the rates weathering and erosion processes concerned.

3 Kaikoura

3.1 Site details

The extensive shore platforms of the Kaikoura Peninsula are located at 42°25`S; 173°42`E on the east coast of South Island, New Zealand (Figure 9). Under a temperate climate regime, they are exposed to an unlimited fetch of both storm and swell waves. Large waves break before reaching the intertidal platforms, which are interpreted as contemporary forms. The platforms span an altitudinal range of circa -2 to +2 m above MSL and are washed by semidiurnal tides with a microtidal regime. A mean tidal range of 1.36 m and a 2.57 m maximum were recorded over a 5-year period.

The platforms are developed on the Waima Formation mudstone, a massive or poorly bedded calcareous silty mudstone of early to middle Miocene age (Campbell et al 2005; Rattenbury et al. 2006). These rocks are characterised by networks of vertical joints, with major joints forming a quasi-orthogonal pattern with decimetric metric spacing, and minor joints at centimetric spacing.

As part of a project to investigate intertidal shore platform erosion processes MEM bolt stations were established at Kaikoura during December 1993 and April 1994, complementing an earlier study by Kirk (1977). Monitoring of the MEM sites undertaken by Stephenson (1997), Stephenson and Kirk (1998) and later by Stephenson et al. (2010) provides erosion rates over 10 years. The installation of these sites was accompanied by the drilling in 1995 of 68 mm diameter cylindrical holes in order to obtain rock cores for laboratory analysis. These coreholes were cut into flat rock platform surfaces adjacent to MEM sites, and extended to depths of circa 500 mm.

An important factor relevant to this study is the weathering environment of the platforms, in particular the wetting and drying (slaking) regime. Wetting and drying cycles vary across the shore platforms in the upper intertidal zone (0.7-1.3 m >MSL) and range in frequency from 100 to ~400 per annum over the two-year span 1995-96 (Stephenson & Kirk 2000).

Figure 9. Location map of the Kaikoura sites.

3.2 Unintended consequences

At Kaikoura the unintended consequences lie in the development of distinct raised rims around some boltholes and, in particular, two of the seven coreholes. These features are spatially concentrated in the upper intertidal zone, and are absent from holes drilled into platforms in the middle and lower intertidal zones. For analytical purposes we focus here on the 68 mm diameter cylindrical holes, where rims were clearly visible by 2012 and are now (2015) particularly well developed (Figure 10). It is apparent that they have grown by emergence from the more rapidly lowering platform surface which surrounds them, to form a hollow tower in which a central cylindrical well is surrounded by a shallow vertically developing tube at the platform surface. Similar features have been termed fonts (Twidale et al 1998, 2005; Netoff & Shroba 2001; Kennedy 2014, and citations therein).

The rims have not developed around all the coreholes, but are notably concentrated in the upper intertidal zone through an altitudinal range of 0.6-0.9 m above MSL. The two holes examined here are adjacent to MEM bolt Sites KM1AA and KM2 respectively (Stephenson

et al. 2010), where cores were extracted from platform surfaces that were completely flat, thus providing both a baseline date and a level for the evaluation of subsequent platform morphology.

Figure 10: A. Raised rim surrounding core hole. Internal diameter of core hole approximately 68 mm. B. 75 mm square post-it note for scale in B, shadows indicate relative heights of corehole rim and natural rims flanking bedrock joints.

Profiling of the core holes and newly developed rims was undertaken with a profile gauge in 2012 to capture their cross sections. Two profiles were taken across each hole, oriented N/S and E/W. The mean height of the annular rim above the surrounding rock surface is 26.2 mm; its width at the top is ~25 mm, thickening downwards towards its merge into the rock platform. It is evident that the presence of the coreholes is affecting the balance of weathering and erosion processes around their upper margins.

Rim growth represents a retardation of the rates of weathering and erosion at the rims relative to the surrounding surface. Rim height data for the two coreholes permit the evaluation of the lowering rate, and hence the growth rates of the rims themselves relative to the platform (derived from Equations 1, 2). MEM observations adjacent to each corehole after 10 years showed a mean lowering rate of 0.78 mm a^{-1} at Hole One (KM1A) and 5.1 mm a^{-1} at Hole Two (KM2A) (Stephenson et al. 2010).

After 17.4 years the average difference in elevation between the top of the rims and the surrounding surface was 9.7 mm at Hole One and 26.2 mm at Hole Two. These values represent a retardation of surface lowering of the rims subsequent to the baseline date by 29% and 70% respectively (Table 5) demonstrating the variability of both platform erosion ($0.78\text{--}5.10 \text{ mm a}^{-1}$) and rim height increase ($0.55\text{--}1.50 \text{ mm a}^{-1}$) rates.

Table 5 Core hole rim elevations above surrounding platform surface, and respective lowering rates of both rims and surrounding surface based on adjacent MEM rates and an elapse of 17.4 years since corehole creation.

Corehole/MEM Profile and Bolt Site	Rim Height Mean of 4 points (mm)	Rim Lowering Rate (mm a⁻¹)	Platform Lowering Rate (mm a⁻¹)	Rim lowering as % of platform lowering	Rim growth rate (mm a⁻¹)
Core 1 KM 1A	9.70	0.23	0.78	29	0.55
Core 2 KM 2A	26.20	3.60	5.10	70	1.50

The preceding section shows that the rock surface at the corehole margins experiences a lower erosion rate than the surrounding platform. In a weathering-limited situation it is therefore implied that the underlying cause is retarded weathering. We now consider the ways in which the weathering environment may have been modified under the new circumstances created by the perturbation initiated by the corehole.

A major effect of a newly created corehole is the formation of a well commonly 50 mm deep which retains trapped seawater during low tidal phases, thus diminishing the opportunity for drying to take place and thereby modifying the nature of the local weathering environment. The dimensions of the pool of water, 68 mm in diameter and ~500 mm deep, are not efficient for surface evaporation and will tend both to retain water and maintain its form. The water can be expected to infiltrate laterally into the surrounding rock walls and also follow an evaporation path by capillarity up through the rock toward the surface marginal to the corehole. Saline water evaporating to the atmosphere from that surface can be expected yield crystalline salts at the point of evaporation. These are observed to be present during dry conditions. Crystallisation may also occur below the rock surface, blocking pores and inhibiting capillary flows of fluids. In these various ways is the weathering environment modified and the retardation of surface erosion may be explained by the capillary flow of water initiated by the presence of the well, the retention of a supply of water in the well, and the increases in mechanical strength of the rock by salt impregnation.

3.3 Discussion (Kaikoura)

3.3.1 Natural analogues

The development of the corehole rims, an inadvertent landform, offers a comparator for similar naturally formed rims flanking the margins of rock joints outcropping on the shore platform surface (Figure 11). These natural rims are abundant within the altitudinal zone of the corehole rims, suggesting a commonality of process in their formation.

Figure 11. Water layer weathering morphology developed on platform surface in mudstone at Kaikoura. Lighter grey surfaces have dried while the darker surfaces are still wet. Raised rims are evident along the joints. Note that the pan surfaces dry more readily than the upstanding rims at L and R margins of image (Pen length = 150 mm). See also Figure 13.

These natural rims can be classified into two types, according to their relationship with local joint topography. Some simply bound a tight joint, which is marked topographically by a narrow groove. Others, however, are adjacent to hollows formed by clast removal at a joint boundary or junction, thereby creating a capacity for water storage and consequently acting as reservoirs following each tidal withdrawal. Figure 11 illustrates both types.

Adjacent to the KM2A MEM bolt hole we measured the heights of 52 rims obtained by random selection including both rim types within an area of approximately 20 m². A builder's level was laid across the rim and rim height above the adjacent platform surface was observed with callipers on opposite sides of each joint to produce 104 values. Summary statistics are presented in Table 6.

Table 6. Summary statistics of rim height measurements (mm) for rims with a reservoir and without.

Reservoir	Absent	Present
Mean	14.62	16.06
Median	13.25	15.78
Minimum	7.10	5.98
Maximum	27.60	29.10
Range	20.50	23.12

The frequency distribution of the 104 rim heights measured is shown in Figure 12 to be slightly negatively skewed. There is a steady increase in height frequency to a modal cluster at 10-16 mm around a modal class of 13.0 - 13.5 mm, and thereafter a decelerating frequency decline to the maximum value of 29.10 mm.

On the basis of observations of Corehole 2, it appears that the availability and retention of water may be a major control on rim development. The volume of the well ensures that a substantial reservoir of water is present at the beginning of each intertidal period, which will retard the completion of drying and, consequently, the frequency of slaking and salt crystallisation. In the case of joints, the availability of water may be expected to depend on the magnitude of the reservoir, which will be limited along the narrow linear joints but rather greater at joint junctions where they open out (Figures 11, 13).

A Levene's test for normality of the data returned an insignificant F score of 0.353 at $\alpha = 0.554$. Consequently, the non-parametric Mann-Whitney U Test was used to test for difference in rim height between samples with or without adjacent reservoirs. Results for this

test indicate that the difference is significant at the 0.084 probability level.

Figure 12: Frequency distribution of Kaikoura natural rim heights.

Although the statistical difference between the two rim subsets does not reach the commonly used 0.05 level (Mann/Whitney), the level attained at 0.084 may be regarded as indicative of some difference in elevation between lower rims adjacent to tight joints, and higher ones adjacent to reservoirs (Table 6). This in turn suggests that rim growth may be related at least in part to reservoir presence/absence, implying that other factors also are involved in influencing rim height.

3.3.2 Process implications

The corehole rims suggest a mechanism of rim creation by inhibition of weathering and erosion caused by the presence of an adjacent water source. Similar arguments can now be used to explain the presence of natural rims and the disposition of water on the platform surface, both in the orthogonal joint pattern grooving the platform surface and the associated rock pans which the rims impound.

The apparent association between the relationship between rim heights and the presence/absence of a significant adjacent reservoir is noted in Section 3.3.1. Figure 12 shows the disposition of rims adjacent to such a reservoir and also the presence of a salt

efflorescence on the rim itself, suggesting that the corehole mimics the natural rim in these respects, and that there may be a commonality of process between coreholes and natural rims.

Figure 13: Close view of salt accumulation along the rims marginal to major rock joints at the platform surface. At the joint intersection the removal of a clast has created a reservoir which contains still moist sediment at its base.

Once initiated the natural rims then form an impounding wall around the margins of the rock pan on the surface of the rock mass which they bound. They form a pan which during a receding tide retains a body of saline water of shallow depth and broad surface. It becomes a very efficient evaporating dish during daytime low tidal levels, especially when they coincide with strong solar radiation. In contrast to the rims, the pans fully exposed to the atmosphere across a surface broad relative to water depth become efficient evaporating pans, and will form salts crystallised from water at and around the rock surface. Complete drying will lead to maximum crystallisation of dissolved salts and maximum slaking effect, both very effective mechanisms of rock breakdown.

As the highest point in the local topography the rim will have the earliest exposure to the atmosphere as tidal level falls. The photo of pans with rims (Figure 11) shows a partially dried platform surface with dry pans and wet rims. The rims are shown to be last to dry out. Thus, over a single tidal cycle the rims are the first topographic component exposed to drying, and the last to be still wet. They therefore experience the longest period of evaporation and it is entirely possible under atmospheric conditions less favourable to

evaporation that complete drying may fail to take place before the next tidal inundation. The pans and the rims thus have quite different regimes of water supply, reservoir geometry and evaporation potential. Thus it is likely that the rims experience a lower frequency of complete slaking and crystallisation cycles than the pans, and hence lower rates of rock breakdown. These factors are likely to cause retardation of erosion and account to a significant extent for the observed difference in lowering rates between pans and rims.

The significance of differential drying patterns between rims and pans, especially in respect of incomplete drying cycles, is emphasised by the restriction of these forms to the upper intertidal zone at 0.6-0.9 m above MSL. It thus appears that in this zone is the drying part of the cycle long enough to achieve complete drying on a frequent basis and thereby maximise the effects of mechanisms such as slaking and salt crystallisation; the more limited drying time available in the lower intertidal zone inhibits complete drying and its associated weathering mechanisms.

We therefore interpret rim development as resulting from the presence of reservoirs retaining water, which cause the adjacent rock to experience fewer wetting and drying cycles than more distant rock. The reduction in the number of wetting and drying cycles in this manner and development of a rim is similar to those observed around flat surfaces that display the classic water layer weathering morphology (Bartrum and Turner, 1928; Bartrum, 1935; Wentworth, 1938; Hills, 1949). Bartrum (1935) explained this morphology as resulting from the repeated wetting and drying of the shallow pools in the wide flat surfaces. The ridges that form around the flat areas at Kaikoura typically occur along joints whose depth and limited exposure to the atmosphere enable them to retain a reservoir of water for longer than the shallow pans. Within the constraints of the tidal cycle there is a lower probability of completed drying of the rock adjacent to joints, thus diminishing the total of slaking cycles there (Figures 11, 13).

The coreholes may also be indicative of the same processes; where they hold water and reduce the number of wetting and drying cycles around the edge of the hole. The pan surface distant from the supply of water has been able to dry more frequently, creating more slaking cycles. The more distant rock has consequently weathered more rapidly leaving it more vulnerable to erosion. It has consequently eroded more quickly to create emergent rims around the core holes. The elevation to which platforms develop has been debated with one argument that the level of permanent saturation is a control (Bartrum, 1916). Others have

argued that the level is determined by wave energy (Trenhaile, 1980). Rim development certainly suggests that the reduction in the number of wetting and drying cycles reduced the efficiency of weathering processes and their upstanding presence would suggest that wave erosion is not effective in lowering the rims. Stephenson and Kirk (1998; 2000) argued for the dominance of weathering processes over marine erosion at Kaikoura, if their assertion is correct then the level of the platforms could in part be controlled by the level of permanent saturation.

3.3.3 Development and decay of unintended perturbation forms

Degradation of the Kaikoura rims has not yet been directly observed. In the case of coreholes it is clear, however, that because of limited weathering and erosion potential at their bases, the reservoirs in the corehole must become shallower through time as the platform surface and rim crests are eroded. Although the depth of coreholes was not measured at the time of installation, a fair order of magnitude operating assumption of initial depth would be ~500 mm, approximating to the length of the corer tube. Assuming the rim lowering rates in Table 5, the time of rim lowering to the point of extinction of the wells would be 2174 years for Corehole 1 and 139 years for Corehole 2. The font towers, now lacking summit basins, would have become solid rock pillars and achieved heights respectively of 1.19 m and 0.21 m respectively, assuming that no catastrophic event had intervened. From this point onwards, the solid rock pillars would be subject to further summit lowering at a rate equal to ambient rock platform lowering, thus preserving that form indefinitely.

It is more likely, however, that the increasingly taller structures would become less stable and more vulnerable to the shearing forces applied by waves and any large entrained clasts, in addition to the abrasion effects of finer sediments, and would at some stage suffer catastrophic failure by block detachment or toppling. Nevertheless, it is apparent that they have the potential to remain as transient forms in the landscape for many decades at least.

Estimated Natural Rim Ages (KM2)

Figure 14: Frequency distribution of estimated rim ages. The maximum frequency of 8-10 years, implies that rim destruction progressively exceeds rim creation at greater ages up to a maximum survival age of 20 years.

In the case of natural rims, it would appear that the survival of rims to heights above the modal value is a stochastic function of their ability to survive and develop to higher elevations. The rate of increase in rim height is both driven by and equal to the ambient rate of platform lowering represented by the adjacent KM2 site. Here the relative rate of rim growth is equal to the difference of 1.5 mm a^{-1} between platform lowering and rim lowering. This value can then be used to estimate the age of local natural rims. These are plotted in Figure 14, and show that the age at which growth development starts to become inhibited is around 8-10 years. Thereafter, on the basis of such calculations individual rims may continue to survive up to a maximum approaching ~20 years. It is unfortunate that, unlike the Prawle case, no measures have yet been identified which could help parameterise the nature of rim destruction; it is therefore not currently possible to validate the speculations made here.

3.3.4 Transience and Duration of Kaikoura forms

MEM observations at Kaikoura yield information both on rates of ambient surface change and on inadvertently created landforms, the latter directly applicable to naturally formed elevated rims. The development pathways of both the inadvertent pedestals and the rims, as argued here, include phases of formation, growth and degradation in parallel to those presented from Prawle.

4 Implications and Conclusions

4.1 Evolution of new landforms over time

The commonality in these two studies lies in experimental work in which each has independently and inadvertently disrupted natural weathering and erosion processes. In both cases unexpected long term changes in process and morphology were created, which offer insights into natural weathering and erosion processes uncompromised by human activity/intrusion at the respective field sites.

These commonalities occur despite some clear differences between the sites. First, the nature of the initial perturbation differs. Secondly, the lithological materials are very different in composition, mechanical properties and fracture characteristics. And thirdly, each is subject to a different erosional environment. The Prawle site lies in a subaerial location, washed only by seawater during exceptional events. The Kaikoura site is in the intertidal zone, directly washed by waves distributed by semidiurnal tides.

Nonetheless, both sites in common present new landforms which increase in height as a result of their gradual emergence from a continually lowering surface. Analysis of the enhancement or suppression of weathering mechanisms in the different circumstances permits inference regarding the respective ways in which the perturbation has modified the weathering and erosional environment at the respective sites. The consequences in each case are the creation of new landforms, representing a transient phase on a pathway of development and decay towards a new stable landscape. At only one location, Prawle Site 1, has it yet been possible to make direct observation of the decay phase. It appears that the remaining forms there, and those at Kaikoura, are still in a development (growth) phase. The timescale of change is such that decay and or destruction of the new forms will occur over the coming decades, and perhaps into the next century. This will provide the opportunity for the

geomorphologists of the future to observe to completion the landscape transitions at both Prawle and Kaikoura.

4.2 Broader perspectives

A yet wider perspective enables conclusions of broader significance to be drawn from this analysis. We have shown how a concept of historic and distinguished pedigree is applicable to modern scientific field experimentation in geomorphology. In the Prawle case, the initial hope (though not necessarily expectation) was that the monitoring experiment would survive for a complete year. In the event it persisted in serviceable form for seven years, considerably exceeding initial expectations, and leading to a well cited further paper. Completely unanticipated was that over a period of 33 years a set of new landforms would develop *ab initio* as a result of the experiment. In the Kaikoura case, new landforms developed which were not anticipated and yet helpfully mimicked similar naturally formed features nearby. Both examples yielded, in their different ways, serendipitous outcomes which led to new scientific insights into the processes at the core of the experiments.

There is a lesson in this also for experiment design. Merton (1935, page 901) identifies the third general type of factor as “imperious immediacy of interest” and the actors’ concern with foreseen immediate consequences. This impacts on experiment design and method and how researchers may tend not to think beyond getting the result they are aiming for within the timeframe available, constrained perhaps by the demands of the research grant or studentship. Experiments of the kind described here are generally intended to get an “immediate” (relatively speaking) short term measure of erosion rates. Unforeseen, and maybe unconsidered, was that this may modify the weathering environment, the associated processes and consequent erosion rates in a way that later illuminates how the natural processes work. In the two cases presented here it is also possible that the required level of understanding of process was not obvious at the time the experiments were designed.

If thought were given in a systematic manner at the outset, during the experiment design stage, to broader potential consequences beyond the specific experimental aims, then that may be more conducive to the anticipation of unintended outcomes, leading to a more complete experiment in consequence. Alternatively, if such foresight were routinely and comprehensively exercised, the serendipity associated with unexpected scientific gains would perhaps be diminished, thus depriving practising field scientists of the surprises which are a significant delight in our work. The Law of Unintended Consequences may therefore be a

significant contributor to achieving the re-enchantment of geomorphology as described by Baker & Twidale (1991).

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Figure 2

Figure 4

Figure 5A

Figure 5B

Figure 8

Figure 10A

Figure 10 B

Figure 11

Figure 13