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Scale issues in weathering studies

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Abstract

A review of the major scale issues in weathering studies reveals concerns over the fundamental spatio-temporal distributions of weathering phenomena, as well as issues of upscaling microscope-based observations, and linking different scales of observations in explanations of landform development. Various strategies are proposed which can be used to tackle these issues, many rooted in non-linear dynamical systems ideas. As an initial step, spatio-temporal scale distributions are estimated here for weathering processes, landforms and controls based on a range of empirical data. Two case studies, of phytokarst in Grand Cayman and blistering and scaling of building stones, are presented to illustrate the types of data that might be used to establish more convincing scale linkages in weathering investigations. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

> 'We believe that distinctions between cause and effect in the molding of landforms depend on the span of time involved and on the size of the geomorphic system under consideration. Indeed, as the dimensions of time and space change, cause–effect relationships may be obscured or even reversed, and the system itself may be described differently'.

(Schumm and Lichty, 1965, p. 110)

Questions of linking different scales of processes to the development of landforms are fundamental to the study of geomorphology and have long provoked debate (Schumm and Lichty, 1965; Kennedy, 1977; Phillips, 1988; De Boer, 1992). Weathering scientists have been less voluble about such issues, although Colman (1981) and Smith (1996) provide useful discussion of scale issues, while Goudie and Viles (1999) discuss magnitude and frequency issues in respect of weathering. Such questions are currently highly topical within weathering studies, as geomorphologists and scientists in cognate disciplines struggle to explain the genesis of weathering features. Many small-scale landforms produced by weathering remain tantalizingly difficult to explain. Tafoni, for example, still seem to be enigmatic features with a number of different hypotheses proposed for their formation (see review in Goudie and Viles, 1997, pp. 169–178), and similar gaps in our knowledge exist for karren (Goudie et al., 1989; Vincent, 1996; Crowther, 1997), weathering pits (Schipull, 1978; Goudie and Migon, 1997) and blistering and scaling (Viles, 1993; Smith et al., 1994). Questions of equifinality in the production of landforms and problems of identifying fossil vs. actively forming landforms

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are also highly pertinent to many weathering situations, but have not received much attention from weathering scientists. Increasingly, our search for explanations of weathering features and processes is becoming focused at smaller and smaller scales, making use of developments in microscope technology to give ever more detailed views (e.g. Pope, 1995; Rodriguez-Navarro and Doehne, 1999). This has led, however, to some debate over how to upscale the information provided. This paper identifies some current debates over scale in weathering studies, indicates some methods for tackling the issues, and provides a preliminary test of these methods.

2. Scale issues in weathering studies

Four major scale issues can be identified in the recent weathering literature. The first issue is a fundamental one, which should affect many of our explanations of the role of weathering in landform development, i.e. are there characteristic spatio-temporal scales of landforms and processes? Despite the fact that morphometric data have been collected for many years on a range of weathering features (notably karst forms such as rillenkarren), there have been no attempts to present such data in the form of Stommel diagrams (which plot the spatial and temporal distribution of processes and events on log-log scales, as explained in Malanson, 1999). Such diagrammatic presentation helps to identify any patterns in scale distributions, which might aid in understanding the determining factors.

The second issue is whether scales of process observation are the same as the scales of process operation and is a serious one for most geomorphological investigations, which covers problems of spatial and temporal sampling networks and also the difficulties of extrapolating results from the laboratory to the field. In weathering investigations, for example, weathering rate estimates have often been made over periods of 1 or 2 years and then extrapolated to explain landform development over hundreds or thousands of years (e.g. weight loss tablets as discussed by Moses, 2000). Spatial extrapolations have also often been made from small-scale Micro-Erosion Meter (MEM) plots to much larger areas, which may be problematical especially where variability in weathering rates is high over small distances (Williams et al., 2000). Extrapolating laboratory-derived weathering rates to field situations can also be difficult, as many laboratory rates are an order of magnitude larger than those measured in the field (Trudgill and Viles, 1998). Logistical and technical difficulties often preclude measurement at the same scale and under the same conditions as processes actually operate, but the possibility of a mismatch of observation and reality should be taken seriously by weathering scientists.

The third problem is how to upscale observations made at the microscope scale (i.e. less than 1 mm) to the weathering landform scale (i.e. centimetre to metre), and the linked problem of downscaling. This issue has been aired recently as criticisms have been made of the so-called ‘reductive science approach’ involved in making microscope observations and applying them to explanations of visible weathering features (i.e. upscaling). For example, Viles and Moses (1998) observed nanomorphologies experimentally developed on calcite crystals subjected to acid spray. They used the term ‘nanomorphology’ to represent features at the micrometre scale, to differentiate them from micromorphologies at the millimetre to centimetre scale, but other authors use different terms (see for example Brunsden’s (1993) ‘picomorphology’). The nanomorphologies produced by Viles and Moses (1998) look very like the dissolution features developed on limestone pavements, but two to three orders of magnitude smaller (i.e. micrometre rather than centimetre to metre). Are such nanomorphologies in any way related to larger scale features? If so, how? On the other hand, there is debate also over the problems and potentials of using ideas drawn from large-scale landscape evolutionary models and theories (which deal with thousands of year timespans and spatial scales of several kilometres) to explain the development of centimetre to metre scale weathering landforms (i.e. downscaling). Geomorphologists have spent several decades trying to explain large-scale/long-term landscape development, and the insights they have gained may be applicable (at least in the form of analogy) to smaller scale features. However, the question remains as to how realistic it is to explain small-scale features using models and theories developed at much larger scales.

The final question is the most important to geomorphologists, i.e. how do different scales of processes and events interact (and, indeed, which scales interact and which do not) to produce the geomorphology we see around us. In order to answer this question, we need to use evidence collected from studies of the other three issues articulated above, as well as fuller knowledge of how the earth surface systems under study operate (Phillips, 1999). Many of the weathering process–response systems that we are interested in may exhibit non-linear dynamical behaviour, and may be characterised by ordered behaviour at some scales and chaotic behaviour at others. Thus, linking processes and system behaviour at one scale to the outcome at another scale may be a hugely difficult task. As Phillips (1999) acknowledges, for many geomorphological systems, we do not have vast amounts of quantitative data with which to analyze for chaos, but he provides a number of examples of qualitative analysis which allow geomorphologists to identify whether systems are '...stable or unstable, potentially chaotic or non-chaotic, self-organizing or not...' (Phillips, 1999, p. 14). This qualitative analysis could be carried out on weathering process–response systems for which we have a clearly specified box-and-arrow diagram or interaction matrix showing whether components have positive, negative or negligible influences on each other. An attempt to provide such a diagram is shown in Fig. 1. Weathering systems are quite difficult to represent in this way, because they are often sluggish and highly constrained by structural and other controls, but it would be a valuable exercise to identify potentially chaotic behaviour.

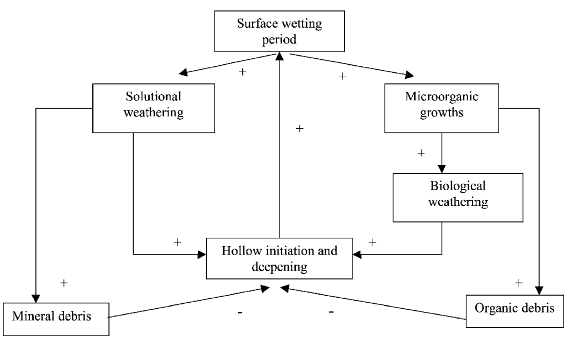

Fig. 1. An idealized diagram of a weathering system at the small scale on an impure limestone surface producing weathering hollows.

3. Approaches to scale linkage in geomorphology

Several approaches to linking scales in geomorphology have been proposed, including hierarchy theory (Haigh, 1987; De Boer, 1992), which provides a useful conceptual framework, but may be difficult to apply as an operational tool. Non-linear dynamical systems (NDS) approaches, as introduced, reviewed and tested by Phillips (1995, 1999, pp. 130–138) may provide a more practical approach. The details of Phillips' approach are set out in detail in his publications, and are merely summarized here. Phillips (1999) suggests that one approach is to extend the transient form ratio concept proposed by Brunsden and Thornes (1979) to investigate how sensitive landforms might be to events or processes operating at a range of scales.

Phillips (1995) uses this approach to discover whether vegetation has any important influence on geomorphology by computing ratios for both vegetation and landforms, using Eqs. (1) and (2).

$$TF_r = t_a / t_f \tag{1}$$

Where: TF_r = landforms transient form ratio, t_a = mean relaxation time, t_f = mean recurrence time

$$TF_{r,v} = t_{a,v} / t_{f,v} \tag{2}$$

Where: $TF_{r,v}$ = ecosystem or vegetation transient form ratio, $t_{a,v}$ = mean recovery time, $t_{f,v}$ = mean disturbance interval.

Where both ratios are less than or greater than unity, one can assume that the two are co-dependent, whereas when one ratio is < 1 and the other > 1, the two are largely independent. Phillips (1995, 1999) also proposes an alternative approach using abstracted earth surface systems, which gives the general result that components of the earth surface system operating at timescales an order of magnitude or more different are effectively independent of one another. Phillips (1988) uses similar abstracted systems arguments to show that factors differing by over an order of magnitude in spatial scale can also be effectively regarded as independent. Both arguments might fruitfully be adapted for use in weathering studies, assuming that we can quantify relaxation times and other important factors.

4. Identifying characteristic spatio-temporal scales of weathering processes and phenomena

Many processes and phenomena have characteristic time and spatial scale distributions (e.g. for hydrology as discussed and plotted by Blöschl and Sivapalan, 1995). As a precursor to investigating what is the preferred scale of analysis of weathering systems and which scales of processes and phenomena should be considered, it is useful to attempt to describe at which scales different processes and phenomena occur (see Table 1). This is a problematical exercise for two main reasons. Firstly, there are undoubtedly gaps in the empirical data on the size and timespan of many phenomena, thus some of the gaps found may simply be measurement gaps rather than fundamental 'spectral gaps' (Blöschl and Sivapalan, 1995). Secondly, because of terminological confusion and a lack of clear process-form knowledge it is hard to know whether features noted at widely differing scales are in fact of the same type. For example, it is difficult to determine whether micrometre-scale etch pits developed on mineral grains (Cremeens et al., 1992) are the same phenomena as weathering pits at centimetre to metre scale developed on granite outcrops (Goudie and Migon, 1997).

Table 1 indicates that most weathering features and processes occur over a wide range of scales from microns to metres at least. Some, however, have a much more restricted distribution with rillenkarren, for example, characteristically having widths in the order of centimetres, although fields of rillenkarren can occupy large areas. Fractures are found across a very large range of scales (in fact, Marrett et al. (1999) find that faults and extension fractures exhibit simple power-law scaling across 3.4–4.9 orders of magnitude with no evidence of 'spectral gaps'). To what extent fractures can be regarded as weathering features in a strict sense is debatable, but the study of Marrett et al. (1999) provides a good example of the sort of morphometric analysis that can be done on a disparate range of data. Examples of constant length/depth ratios across a wide range of scales do not necessarily imply that the processes producing such features are the same, although in some circumstances this might be the case. Characterizing the spatial scale of weathering processes is very difficult,

Table 1
Characteristic spatial scales of weathering processes and phenomena

Feature	μm	mm	cm	m	km
Fractures	✓	✓	✓	✓	✓
Rillenkarren			✓		
Alveoli		✓	✓		
Tafoni			✓	✓	
Weathering pits	✓	✓	✓	✓	
Scaling and blisters		✓	✓	✓	
Dissolution	✓	✓	✓	✓	✓
Salt weathering	?	✓	✓	?	
Biological weathering	✓	✓	✓		
Pressure release	✓	✓	✓	✓	✓
Deep weathering			✓	✓	✓

because at larger scale processes such as salt weathering, for example, may operate over a wide area but may also be concentrated in a shallow zone. The larger the scale, the more likely it is that other processes, such as fluvial erosion, are operating in conjunction with weathering. At smaller scales, weathering often dominates.

As noted by Pope et al. (1995), studies of weathering processes need to consider the controlling factors at the relevant scale. Controls such as geology, climate and vegetation operate in different ways at different scales. Pope et al. (1995) make the point that micro-climates are more significant than synoptic climates for understanding weathering, although many workers have found it impossible to monitor micro-climates and have been forced to make inferences from macro-climatic data. However, as Table 2 shows, a hierarchy of influences may in fact operate, and thus, macro- and micro-climates may be, at least partially, interlinked. In more general terms, the factors controlling weathering may operate within some spatial and temporal hierarchies. Does the 'One order of magnitude difference' rule apply to these sorts of controls? Or is it, perhaps, more complicated? One of the problems is that there appear to be important (and different) 'spectral gaps' in the distribution of each of these factors (apart, perhaps, from climate). For example, geological factors cluster into individual grains (which commonly range of microns to centimetres in scale), rock outcrops (which range from centimetre to kilometre), and large geological units (which may contain soil-covered and exposed components and occupies kilo-

Table 2
Geological, climatological and organic factors controlling weathering at different scales

Scale	Geological factors	Hydrological factors	Climatological factors	Organic factors
μm	Mineral grain size, crystallography, geochemistry	Pore water movements	Relative humidity, temperature	Presence of individual micro-organic cells
mm	Grain size and arrangement, geochemistry	Pore water movements	Relative humidity, temperature, wind flow	Presence of micro-organic colonies
cm	Bedding and other geological structures, geochemistry	Surface water flows, macropore flows	Relative humidity, temperature, wind flow, in boundary layer	Presence of lichens, cyanobacterial mats, biofilms
m	Stratigraphy, tectonics	Surface and channelled flows	Boundary layer climate	Presence of extensive microbial ecosystems
km	Geological structures, tectonism	River basins	Regional climate	Regional ecosystems or biomes

metre upwards). Similarly, organic factors cluster into individual cells, micro-organism colonies, biofilms, large microbially based ecosystems (such as metre-sized stromatolites), and soil-based ecosystems containing a mixture of micro-organisms, higher plants, and animals. Finally, hydrological factors are clumped spatially according to pore size distributions and the tendency to form channels (which occur at centimetre scale and upwards).

Overall, a consideration of the characteristic spatial scale of weathering features, processes and controls reveals considerable complexity. Weathering processes, although commonly thought of as micro-scale, can have cumulative impacts over a very large area, in which case large-scale controlling factors (such as groundwater hydrology and geological structure) will be important because they control when and where it happens, as well as micro-scale influences on the functioning of the process (which control how it happens). Looking at the temporal dimensions, we see a similar complex pattern emerging with possible overlapping life spans of landforms, processes and controlling factors (Table 3). As Table 3 shows, individual lichens, for example, have a similar life span to millimetre to centimetre scale weathering pits (which they are known to create in many circumstances—e.g. Wessels and Schoeman, 1988), but clearly are much shorter lived than metre-size weathering pits. On the other hand, cyanobacterial mats may well live for decades to hundreds of years (similar to some metre-sized landforms). As with spatial scale discussions in weathering, such assessments of the characteristic temporal scales of features, processes and controls are hard to make because of lack of data on life spans of landforms and other factors.

One way in which we can sharpen up our analysis of the characteristic spatial and temporal scales of weathering landforms is to consider general geomorphometry (i.e. measurements of relief) rather than specific geomorphometry (i.e. measurements of individual landforms) (Evans, 1972; Evans and McClean, 1995). There are now a whole host of techniques available that can produce Digital Elevation Models (DEMs) of weathering landscapes at different scales. For example, multi-photon microscopy can produce topographical profiles and maps at the micrometre to millimetre scale, while the laser scanner, the Micro-Erosion Meter (MEM) and close-range photogrammetry (Williams et al., 2000; Inkpen et al., 2000) can produce similar data for the millimetre to centimetre scale, and Light Detection and Ranging

Table 3
Characteristic timescales relevant to different spatial scales of controls on weathering and resultant landforms

Spatial scale	Landforms	Climate/hydrology	Organic factors
μm–mm	Days to years (nanomorphologies)	Seconds–hours (pore water)	Days–years (individual micro-organisms)
cm	Years–hundreds of years (e.g. rillenkarren)	Seconds–hours (surface storm runoff)	Years–decades (individual lichens)
m	Decades–thousands of years (e.g. kamenitzas)	Minutes–days (subsurface storm runoff)	Decades–hundreds of years (whole biofilm communities)
km	thousands of years–millennia	Days–years (tropospheric climate/groundwater)	hundreds–Thousands of years (whole ecosystems)

(LIDAR) and conventional remote sensing at scales from tens of centimetres to hundreds of kilometres. Analyzing such datasets, using techniques such as semi-variograms, would allow researchers to identify whether there are similar patterns of relief at different scales. Inkpen et al. (2000) illustrate the use of semi-variograms of DEMs derived from close-range photogrammetry of experimentally weathered blocks.

To summarize, the preceding discussion has shown how weathering processes, controlling factors and effects have characteristic spatio-temporal distributions. However, we are still some way from having a solid understanding of such distributions, and more empirical data is needed. The value of improving our knowledge of these distributions is that it should help us determine what are the appropriate scales of measurement, and which scales of processes and controlling factors may be most important in explaining landforms.

5. Case studies illustrating the challenges of linking scales in weathering studies

How we can best upscale microscope observations of weathering phenomena to the larger scale depends on the behaviour of the weathering system under study. If the systems behave in non-linear dynamical fashions, then at some scales ordered behaviour may be found, with chaotic behaviour at others. Furthermore, as the preceding discussion has shown, at larger scales a wider range of controlling factors may come into play, some of which do not operate at the microscopic scale. Some examples illustrate different situations likely to pertain to weathering systems, as discussed below.

Folk et al. (1973), in a seminar paper, described randomly sculpted limestone pinnacles at Hell, Grand Cayman Island and ascribed their development to cyanobacterial boring. As they put it:

> ‘Phytokarst is herein defined as a landform produced by rock solution in which boring plant filaments are the *major agent of destruction and the major morphological features are determined by the peculiar nature of this mode of attack*.’

(Folk et al., 1973, p. 2351, my italics)

This is a classic example of an attempt to link micrometre-scale weathering processes (in this case boring activity of cyanobacteria which were found to produce randomly oriented boreholes of around 10 μm in diameter) to metre-sized landforms (vertical pinnacles). Further work by Jones (1989) backed up this hypothesis, showing that boring activity was intense on limestone surfaces and present on dolomitic surfaces, in both cases effectively blanketing the surface and being the dominant form of weathering. Spencer (1981), however, identifies (from MEM data) that ‘solutional disintegration’ is the major process of weathering here, with more soluble calcitic cements being attacked preferentially by solutional weathering, causing more resistant grains to be loosened and producing millimetre-sized pitting. Neither process can be easily seen to produce a large-scale pinnacled landscape without the influence of other factors. Viles and Spencer (1986) suggest that structural control at the metre-scale influences where vertical surface lowering becomes concentrated—thus producing pinnacles. However, this argument does not help clarify how ‘solutional disintegration’ and/or micro-organic boring produces randomly orientated, spongey textures over the surface of the pinnacles.

In fact, all these studies seem to be addressing different scales of effects. Jones (1989), for example, finds micro-organic boreholes all over surfaces, with no apparent link to millimetre-size topography. Spencer (1981) observes evolution of millimetre- to centimetre-scale topographic roughness over the short term (ca. 1 year) and infers this to be a result of solutional disintegration, while Viles and Spencer (1986) indicate that both scales of topography are nested on pinnacles, which probably can be explained by metre-scale variations in hydrology related to groundwater levels and jointing patterns. The problem here seems to be that the landforms themselves are ‘multi-scale’ features. Fractal analysis of surface roughness at different scales here would help elucidate if there is scale-similarity or not (cf. Evans and McClean, 1995) in the resultant forms. Morphometric and process studies at a range of scales need to be combined in order to explain the genesis of such weathering landscapes, within a framework of a better understanding of the whole multi-scale weathering system (see Table 4). Such understanding would, for example, consider whether there was evidence of chaotic behaviour, and include detailed assessment of processes, features and controlling factors at different scales.

A contrasting example of scale-linkage issues comes from work on scaling and blistering of limestone and sandstone surfaces on buildings and monuments. Viles (1993, p. 313) presents a simple model of the production of blisters on Headington Freestone walls in Oxford which involves:

1. Growth of hard gypsum crust as a replacement product on the surface of the limestone, coupled with subsurface weakening of the stone.
2. Arching of this crust away from the surface, with continued weakening of the stone behind.
3. Breaching of the crust and removal of the weakened, weathered debris beneath to form an open blister.
4. Removal of the blister walls to produce a fresh, exfoliated surface.

Table 4
A multi-scale approach to studying phytokarst on Grand Cayman

Scale	Appearance	Questions to be asked	Techniques to be used
μm	Individual boreholes	What processes are at work?—e.g. micro-organism boring, and/or solutional disintegration	(1) SEM and multi-photon microscopy—to characterise relief and infer processes at work (2) SEM and thin sections to characterise geological variability.
mm–cm	‘Spongey’ textured surfaces	How do boreholes at micrometre scale and other processes lead to randomly oriented hollows?	(1) Sample on ridges and in hollows for SEM observations to identify different process regimes in different settings. (2) Quantify microtopography (using photogrammetry or laser scanning). (3) Characterise micro-environmental conditions in hollows and on ridges using micro-probes. (4) Use thin sections and hand specimens to investigate geological variability.
m	Pinnacles	How do pinnacles develop? Are the randomly oriented hollows a part of the development of the pinnacles? Or have they formed subsequently?	(1) Identify joint patterns, geological variability and groundwater characteristics. (2) Use LIDAR to characterise topography at this scale. (3) Investigate millimetre–centimetre scale topography on different faces and at different heights on pinnacles to aid inference of how their development relates to that of pinnacles.

Table 5
A multi-scale approach to studying scaling and blistering on stone walls

Scale	Appearance	Questions to be asked	Techniques to be used
μm	Surface crust	What processes are causing the surface hardening? What processes are causing the sub-surface softening?	(1) Use SEM and micro-geochemical analysis to identify transformations and reactions at the mineral scale. (2) Investigate geological variability using SEM/thin sections.
mm–cm	Blisters	What creates the stresses which cause the blisters/scales to initiate, grow and eventually fail?	(1) Take SEM samples from a range of locations on, in and under blisters to identify different process regimes. (2) Monitor micro-environmental conditions within blisters using micro-probes. (3) Take repeat photogrammetry/laser scans to examine rate of blister formation. (4) Use thin sections and hand specimens to examine geological variability.
m	Blocks affected by coalescing or individual blisters	How do whole blocks become scaled? Do individual blisters grow into one another or are large-scale processes at work?	Use photogrammetry/laser scanning to analyse topography and geological variability on individual stone blocks and across whole walls. Monitor microclimate across walls + investigate groundwater, capillary rise, and runoff patterns.

Stages 1 to 4 may be repeated several times over the lifetime of a building under polluted atmospheric conditions. Smith et al. (1994, p. 148) present a similar model for scaling of sandstone walls in Belfast involving the production of a stable case-hardened surface, accompanied by subsurface salt weathering producing a build-up of stress, which eventually breaches the case-hardened layer producing visible and often catastrophic scaling. In both cases a series of micro-scale process (salt weathering, gypsum crust development) is presumed to be operating in different parts of the surface zone, controlled by micro-scale environmental conditions, which leads to episodic and dramatic surface failure and the imposition of new environmental conditions. Table 5 illustrates the factors involved at different scales. The production of scaling and blisters is a good example of what Cooke (in BERG, 1989) calls 'the memory effect'. Phillips (1999, p. 121), discussing similar phenomena in soils, sees them as a manifestation of dynamical instability, chaos and self-organization within the soil system. Thus, blistering and scaling on stone surfaces may be a symptom of complex, self-organizing behaviour in sluggish weathering systems. This implies that upscaling the effects of individual processes (such as the transformation of calcite to gypsum producing cracking of individual calcite crystals as observed with Scanning Electron Microscopy (SEM)) needs consideration of other processes at different scales, within a self-organizing system.

6. Conclusions

Scale issues are fundamental to the study of the causes, nature and consequences of weathering, but are difficult to conceptualize and even more difficult to operationalize in real-world studies. A fundamental scale issue in weathering studies is how to best link very different scales of observations into an explanation of landform development. The ideas presented in this paper illustrate that to do this, we need to do the following:

1. Identify the fundamental spatio-temporal distributions of weathering processes, controls and landforms of the system under study. Geomorphometric analysis of topographic data at different scales should be a vital part of this.
2. Characterise the system behaviour at the scale(s) of interest (i.e. qualitative analysis for chaotic, self-organizing behaviour using box-and-arrow diagrams).

3. Decide which scales of observation are most vital for the study (considering transient form ratios, or the one order of magnitude difference rule of Phillips, 1999, as well as the fundamental spatio-temporal distributions identified in point (1) above).

The two examples presented above indicate the initial stages of this process for two contrasting weathering situations. In order to make more progress, we need to have more empirical data on processes, topography and controlling factors at different scales, as well as better-developed conceptual models of the systems under study.

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