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# 3.6.1. Karst Landform Classification Techniques

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ABSTRACT: Karst landform classification is fraught with problems because of a combination of synonymic terminology and the polygenetic nature of many karren features. The genetic classification of Bögli (1960) and morphogenetic classification proposed by Ford and Williams (1989; 2007) remain the most comprehensive and widely embraced by the academic community. A morphometric approach has predominated within karst studies in a bid to characterise and classify karst landforms at a variety of scales, as well as to understand and simulate their development. However, discrepancies between methods of measurement create difficulties in the global comparison of data between authors. Future morphometric techniques in karst studies are likely to evolve from the collection of data via complex and laborious field measurement methodologies, to the use of ergonomic, fast and sub-millimetre accurate LIDAR systems with associated GIS analysis.

KEYWORDS: Karst, Karren, Morphometry, Classification.

## Introduction

The objective of this paper is twofold. Firstly, this paper seeks to briefly explore how karst landforms have been classified, the inherent difficulties involved in their classification, and the benefits and shortfalls of the most common classification systems.

Secondly, common techniques employed in the mapping and morphometric analysis of karst landforms at a variety of scales are outlined. Research techniques to date are summarised with some potential research directions and promising research techniques identified. The methods and techniques used in karst studies vary greatly due to the range of scales of investigation within which karst studies may be undertaken. Scientists have investigated karstic morphologies from the larger landscape scale down to the individual mineral scale, with an increasingly reductionist approach in recent years. As such, this review of analytical techniques will adopt a scaled approach, within which relevant techniques are organised into the scale boundaries in which they are most applicable.

Due to their relevance to geomorphological studies, particular emphasis is placed on surface karst features, in particular karren landforms. In order to familiarise the reader with noteworthy research to date, reference is made to noteworthy literature throughout this paper. For wider reading, key texts by Ford and Williams (2007) and Ginés *et al*., (2009) review the process of karstification in detail.

## The classification of karst landforms

The nature of karst systems dictates that most dissolution is expended in the epikarst, i.e. at the interface between karst rocks and the atmosphere, the source of meteoric water. Geomorphologists, concerned with landforms and the earth surface processes that form them, seek to understand a range of karst landforms and landform assemblages at a variety of scales.

*Table 1. Simple classification of karren and karst surface landforms according to scale.*

| Scale Boundary | Karst Terminology | Examples in Karst |
|---|---|---|
| Macro (c.>10m) | Large Scale Karst Landforms | Polje (Gams, 1973; 1978; Bonacci, 2004), Uvala (Ćalić, 2011), Doline (Sauro, 2003; Ford and Williams, 2007). |
| | Karrenfield Landscapes and Karren Assemblages | Limestone pavements (Williams, 1966; Zseni *et al.*, 2003), Megaausgleichsfläche (Kunaver, 2009), Pinnacle karst (Knez *et al.*, 2003), Ruiniform karst (Perna and Sauro, 1978), Schichttreppenkarst (Bögli, 1980), Corridor / Labyrinth karst (Jennings and Sweeting, 1963; Brook and Ford; 1978), Tower karst (Sweeting, 1995), Cockpit / Cone karst (Xiong, 1992; Lyew-Ayee *et al.*, 2007; Fleurant *et al.*, 2008). |
| Meso (c.1cm-10m) | Karren | Rillenkarren (Glew and Ford, 1980; Lundberg and Ginés, 2009), Rinnenkarren (Bögli, 1976; Veress, 2009a), Kluftkarren (Williams, 1966; Goldie, 2009), Flachkarren (Williams, 1966; Goldie, 2009), Mäanderkarren (Veress, 2000; 2009b), Kamenitze (Bögli, 1960; Cucchi, 2009; Eren and Hatipoglu-Bagci, 2010), Ausgleichsfläche (Bögli, 1980), Trittkarren (Veress, 2009c), Grübchenkarren (White, 1988; Ginés and Lundberg, 2009), Rundkarren (Zseni, 2009), Tumuli (Calaforra and Pulido-Bosch, 1999). |
| Micro (c.1mm-1cm) | Microkarren | **Dissolutional**: Microrills (Ford and Lundberg, 1987; Gómez-Pujol and Fornós, 2009; Grimes, 2007), Rillensteine (Laudermilk and Woodford, 1932), Rainpits (Ginés and Lundberg, 2009).<br>**Biological**: Biotroughs (McIlroy de la Rosa *et al.*, 2011). |
| Nano (c.<1mm ) | Nanokarren | **Dissolutional**: V-in-V etching, Stepped etching, Crystal widening, Cleavage widening (Moses *et al.*, 1995; Viles and Moses, 1998).<br>**Biological**: Endolithic lichen biopits (McIlroy de la Rosa *et al.*, 2011), Filament-shaped trenches, Circular etch pits (Viles and Moses, 1998). |

*Table 2. Genetic classification of karren forms after Bögli (1960).*

| Free Karren | Half-Free Karren | Covered Karren |
|---|---|---|
| *Rillenkarren* (solution flutes)<br>*Trittkarren* (heelprint karren)<br>*Rinnenkarren* (solution runnels)<br>*Mäanderkarren* (meandering decantation runnels)<br>*Wandkarren* (decantation runnels)<br>*Kluftkarren* (grikes)<br>*Flachkarren* (clints)<br>*Grübchenkarren* (rainpits) | *Kamenitza* (solution basins / pans)<br>*Korrosionskehlen* (solution notches)<br>*Hohlkarren* (undercut solution runnels) | *Kavernösen* Karren (cavernous subsoil weathering)<br>*Rundkarren* (rounded solution runnels)<br>*Geologische Orgeln* (solution pipes, pits and shafts) |

*Table 3. Morphogenetic classification of karren forms after Ford and Williams (1989; 2007).*

| Circular plan forms |
|---|
| *Micropits and etched surfaces* – wide variety of pitting and differential etching forms commonly less than 1.0cm in characteristic dimension.<br>*Pits* – circular, oval, irregular plan forms with rounded or tapering floors, >1cm in diameter.<br>*Pans* – rounded, elliptical, to highly irregular plan forms: planar, usually horizontal floors in bedrock or fill, >1cm in diameter.<br>*Heelprints or trittkarren* – arcuate headwall, flat floor, open in downslope direction. Normally 10-30cm in diameter.<br>*Shafts or wells* – connected at bottom to proto caves / small caves draining into epikarst. Great range of form. |
| Linear forms (fracture controlled) |
| *Microfissures* – microjoint guided, normally tapering with depth. May be several centimetres long but rarely more than 1cm deep. Transitional to:<br>*Splitkarren* – joint-, styolite-, or vein-guided solution fissures. Taper with depth unless adapted for channel flow. From centimetres to several metres in length, centimetres deep. Closed type terminates on fracture at both ends. Open type terminates in other karren at one or both ends.<br>*Grikes or kluftkarren* – Major joint-, or fault-guided solutional clefts. Normally 1-10m in length. Master features in most karren assemblages, segregating clint blocks (*flachkarren*) between them. Scale up to karst bogaz, corridors, streets etc. Subsoil forms are termed cutters. |
| Linear forms (hydrodynamically controlled) |
| *Microrills* – as on *rillensteine*. Rill width is c.1mm. Flow is controlled by capillary forces and / or gravity and / or wind.<br>*Gravitomorphic solution channels*<br>*Rillenkarren* – packed channels commencing at crest of slope; 1-3cm wide. Extinguish downslope. Rainfall-generated, no decantation.<br>*Solution runnels* – Hortonian channels commencing below a belt of no channelled erosion. Sharp-rimmed on bare rock (*Rinnenkarren*), rounded if subsoil (*Rundkarren*). Channels enlarge downslope. Normally 3-30cm wide, 1-10m long. Linear, dendritic or centripetal channel patterns.<br>*Decantation runnels* – solvent is released from an upslope, point-located store. Channels reduce in size downslope. Many varieties and scales up to 100m in length, e.g. wall karren (*Wandkarren*), *Mäanderkarren*.<br>*Decantation flutings* – solvent is released from a diffuse source upslope. Channels are packed; may reduce downslope. 1-50cm wide.<br>*Scallop forms or solution ripples* – ripple-like flutes oriented normal to direction of flow. A variety of scallop. Prominent as a component of *cockling patterns* on steep, bare slopes. |
| Polygenetic forms |
| Mixtures of solution channels with pits, pans, wells and splitkarren. Subsequent development of *Hohlkarren*, *Spitzkarren* and subsoil *pinnacles*. Superimposition of small forms (microrills, rillenkarren, small pits) upon larger forms |
| Assemblages of karren |
| *Karrenfeld* – general term for exposed tracts of karren.<br>*Limestone pavement* – a type of karrenfeld dominated by regular clints (flachkarren) and grikes (kluftkarren). Stepped pavements (*Schichttreppenkarst*) when benched.<br>Pinnacle karst – pinnacle topography on karst rocks, sometimes exposed by soil erosion, Arête-and-pinnacle, stone forest ,etc. with pinnacles up to 45m high and 20 wide at base.<br>*Ruiniform karst* – wide grike and degrading clint assemblage exposed by soil erosion. Transitional to *tors*.<br>*Corridor karst* – (or *labyrinth karst*, *giant grikeland*): scaled-up clint-and-grike terrains with grikes several metres or more in width and up to 1km in length.<br>*Coastal karren* – distinctive coastal and lucustrine solutional topography on limestone or dolomite. Boring and grazing marine organisms may contribute. Includes intertidal and subtidal notches, and dense development of pits, pans and micropits. |

The term *karren* encompasses a complex group of small to medium-sized exokarstic (karst features developed on surfaces exposed to direct precipitation) and cryptokarstic (karst features developed beneath permeable sediments such as soil or till) landforms, showing a great variety of characteristic shapes and forms (Ginés, 2009). Many of these forms are believed to be polygenetic in nature. Consequently, like karst terminology, the classification of karren forms is complex.

A simple classification of karst forms may be devised according to scale. Table 1, compiled by the author, displays karst features of interest to the geomorphologist organised into the major scale boundaries. References to key texts dealing with specific landforms are also included. The proposed classification organises karst landforms into categories of decreasing size and complexity. Macroscale features include karrenfield landscapes and assemblages of karren after Ginés (2009), as well as large scale karst landforms (non-karren). Mesoscale forms encompass the elementary karren forms described by Ginés (2009), Bögli (1980) and Ford and Williams (2007). At the nano and microscales, surface features are differentiated into those which are dissolutional in origin and those which develop due to biological activity. At larger scales, this biotic / abiotic differentiation becomes blurred as many karren features are believed to be largely dissolution-induced but may sometimes develop with biological contribution, for example rillenkarren (Fiol *et al*., 1996) and kamenitze (McIlroy de la Rosa *et al*., 2012). A scaled approach to classification permits a useful organisation of landforms according to dimension, but cannot easily encompass landform morphology or genesis. An alternative classification of karstic forms according to scale, with some reference to landform genesis, is provided by Ginés (2009).

According to Bögli (1980), the multiplicity of possible karren landforms makes a morphological classification system endless, while a genetic one allows a meaningful grouping. Bögli (1960) produced the most comprehensive genetic classification system of karren forms. He distinguishes between features that form on bare, exposed rock (free karren), partly covered rock (half free karren), or rock completely covered by soil or dense vegetation (covered karren) (Table 2).

White (1988) also adopts a genetic approach to classification based on the angle of slope, rock structure, and whether the karst surface is covered or bare. He classifies karren features according to their relationship to water flow. However, only individual karren forms fit within his categories, with polygenetic and coalescing forms unable to be included. Whilst agreeing with the benefits of a genetic classification over a morphological one, Ford and Williams (1989; 2007) argue that the development of many karren features is not yet sufficiently understood to permit a purely genetic classification. Consequently, they propose a morphological classification with five primary classes broadly defined in terms of genetic criteria (Table 3). To conclude, the classification of karren landforms is inherently difficult due to the polygenetic origin and morphology of many forms. Ginés (2009) argues that a variety of criteria constitute a valid base for classification, and that one classification or another should be adopted depending on the problem being addressed.

## Methods in karst landform classification

The use of morphometric techniques in karst research has revealed karren features and karst landform assemblages to be highly organised systems, and not chaotic as was previously believed (Ford and Williams, 2007). As a simple classification of karst landforms may be drawn up according to scale (Table 1), scale divisions are also a useful way to categorise the methods and techniques used in karst landform classification. Figure 1, compiled by the author, shows the applicability of various analytical methods and techniques used in karst studies within the major scales of investigation. By their very nature, some methods may only be used at a defined scale, while others may traverse scale boundaries and be utilised at a variety of scales.

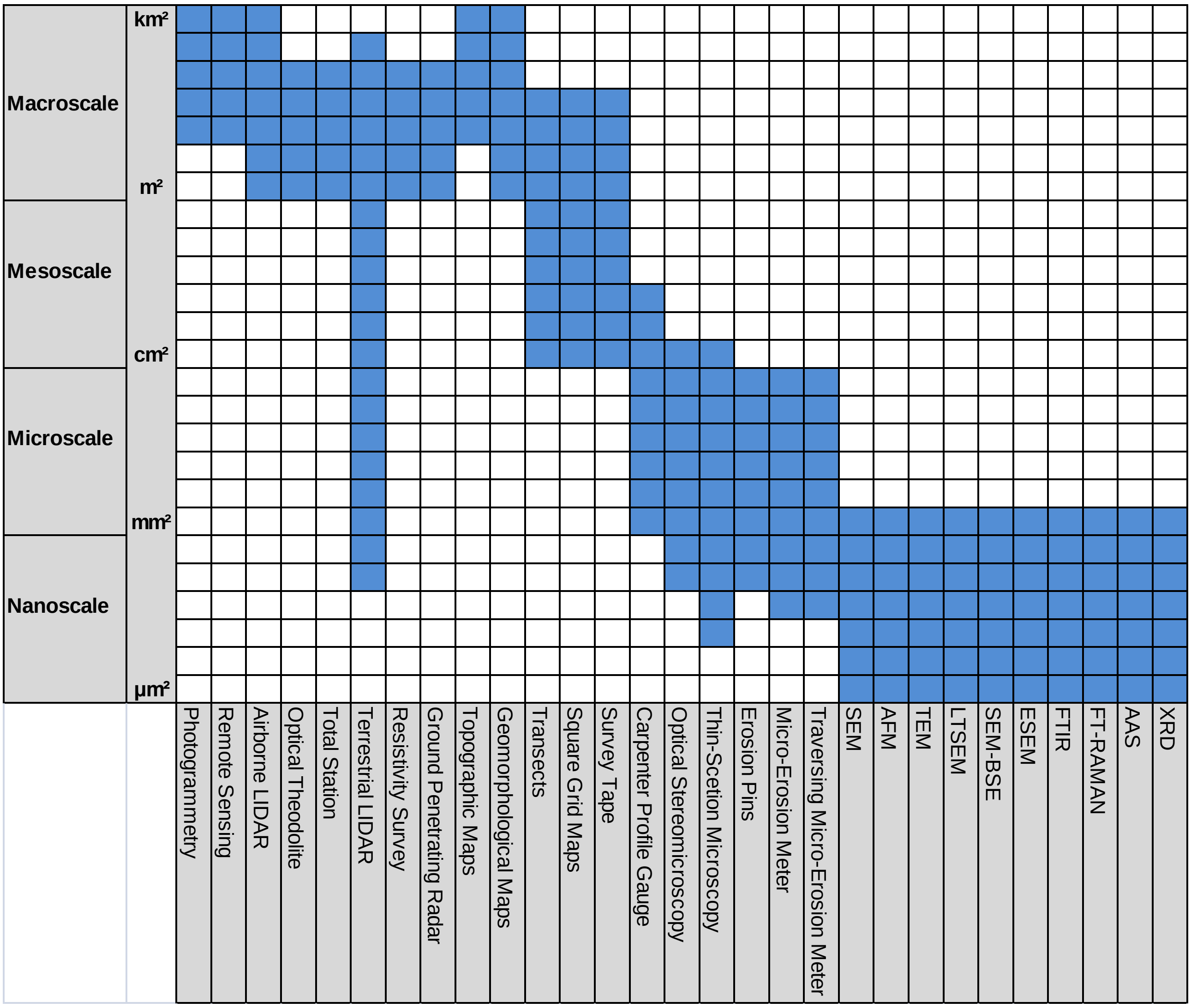

*Figure 1. Methods in karst landform classification organised within the major scale boundaries.*

## Macroscale (c.>10m)

At the macroscale, a combination of field measurement, topographical map analysis, photogrammetry and remote sensing are often used to derive morphometric data in karst studies (e.g. Xiong, 1992; Lyew-Ayee *et al.*, 2007; Ćalić, 2011). Traditionally, aerial photogrammetry has allowed the visualising and mapping of features such as grike networks on limestone pavements (Goldie, 2009). However, the two dimensional nature of simple photogrammetry meant that, in the past, digital elevation models could only be derived from the digitisation of contours on topographic maps, many of which were at too large a scale to accurately reflect karren landform assemblages and features such as small dolines. The scale of traditional geomorphological maps has also proved difficult in karst studies, with only larger forms such as poljes and dolines able to be plotted.

Today, airborne light detection and ranging (LIDAR) systems, such as NASA's Airborne Topographic Mapper, are able to produce digital elevation models of landscapes at a resolution of 20cm (Krabill *et al.*, 1995; Montané, 2001). Airborne LIDAR has revolutionised the remote sensing of karst, allowing the derivation of accurate morphometric data for dolines and poljes. The large-scale mapping of doline fields and other karrenfields by LIDAR and other remote sensing techniques has revealed that the distribution patterns of dolines are relatively uniform, with many karsts globally displaying similar spatial organisations (Ford and Williams, 2007). However, the potential of airborne LIDAR at this scale is under-explored as its resolution would allow the morphometric analysis, not only of dolines and other large scale landforms, but of mesokarren assemblages, such as clints and grikes on limestone pavements or assemblages of limestone pinnacles.

Ground surveys at the macroscale have traditionally involved field measurements in order to complement and verify cartographic sources and remotely sensed data. Today, manual field measurement and the use of optical theodolites have largely been replaced by the use of total stations and terrestrial LIDAR systems, with the latter having significant morphometric potential in karst studies. Terrestrial laser scanning is a portable, non-destructive, accurate and fast method of 3D data capture. Already employed in the scanning and 3D digital representation of karst cave systems and other subsurface cavities (Rüther *et al*., 2009; Canevese *et al*., 2011), terrestrial LIDAR has, as yet, under-explored possibilities in the digital documentation and derivation of high resolution morphometry of karren features, assemblages of karren features and karst landforms such as dolines, with few studies having applied the technology to this research area (Siart *et al*., 2011). High resolution digital elevation models derived from laser scanning allow the production of detailed topographical analyses, providing a detailed insight into macrokarren, mesokarren and microkarren morphometry. Crucially, the integration of laser-scanned data into Geographical Information Science (GIS) software allows the accurate derivation of topographical parameters such as slope gradient, volume, aspect or surface drainage patterns (Siart *et al*., 2011). Indeed, such a GIS based approach is applicable at a range of scales of investigation from the macroscale to the microscale.

Finally, at the macroscale, resistivity surveys and ground penetrating radar (GPR) may also be used to identify and map subsoil karren features. GPR has been successfully applied to the locating of hazardous buried collapse dolines prior to full subsidence (Montané, 2001; Kruse *et al*., 2006; Pueyo-Anchuela *et al*., 2009; Gutiérrez *et al*., 2011).

## Mesoscale (c.1cm-10m)

Mesokarren features in particular have been the subject of numerous morphometric analyses, not only in order to characterise and classify these landforms through diagnostic measurement parameters, but as a means to understand their formation and simulate how they develop. The selection of individual mesokarren forms for morphometric analysis often involves sampling strategies based along transects (Veress *et al*., 2001) or square-grid maps (Tóth, 2009) situated amongst mesokarren assemblages or on karren outcrops. Morphometric analyses of mesokarren forms have traditionally been performed with a carpenter profile gauge in the case of small measurements (c.1-15cm), and survey tapes for larger features (c.0.15-10m). The precise protocol for mesokarren morphometry varies for different landforms. Some features, such as rillenkarren, have been extensively studied and have an established and detailed morphometric protocol (Lundberg and Ginés, 2009), while other features, such as rainpits, have ill-defined morphological protocols.

Morphometric studies (Mottershead *et al*., 2000) and modelling (Glew and Ford, 1980) of rillenkarren typically encompass records of solution flute width, depth, slope angle and length, and are often recorded with a carpenter profile gauge whose pins conform to the shape and size of the rills (Lundberg and Ginés, 2009). Similar studies of kamenitze comprise solution basin depth, width, length and micro notch measurements (Cucchi, 2009; Tóth, 2009), while trittkarren analysis generally involves measurements of slope, riser height and width, tread angle and length, and foreground width (Vincent, 1983; Veress, 2009c). Mäanderkarren morphometric records include maximum width, horizontal width, horizontal middle and maximum depth, and large and small cross-sectional area (Hutchinson, 1996), which are similar to the parameters applied to river channels (Veress, 2009b).

Successful mesokarren morphometry involves the comparison of different parameters of the same form, allowing the researcher to deduce how the topographical and stratigraphical position of the karst terrain may influence the development of mesoscale forms. According to Tóth (2009), for any given karren form, characteristic parameters such as width, depth and length should be chosen and compared with measurements of the same karren form under different conditions of, for example, slope angle, exposure and precipitation. Adopting such an approach to research has led to the idea of karren forms as ecological indicators, since the precise morphology and morphometry of karren features indicates a particular series of ecological and environmental conditions. For example, Ginés (1990) found a negative correlation between altitude (precipitation) and rillenkarren length in the Sierra Tramuntana, Mallorca, while Glew and Ford (1980) identified a positive correlation between slope angle and rillenkarren length, and that wider rillenkarren evolve on karst limestones than on evaporitic karstic materials. Similarly, data comparison by Zeller (1967) identified the sinuosity of mäanderkarren to be greater than that of fluvial meanders and glaciers.

Apart from the slow and laborious nature of manually measuring and deducing mesokarren morphometry, discrepancies between methods of measurement often create difficulties in the accurate morphometrical description of mesokarren landforms and in the global comparison of data between authors (Lundberg and Ginés, 2009). As with macroscale investigations, the widespread application of terrestrial laser and optical scanning systems to mesoscale morphometric analysis in the near future is likely to significantly increase the accuracy and speed of data capture. In a recent study, Mottershead *et al*. (2008) successfully employ a scanning total station and resultant digital elevation models to examine morphological change and determine solutional surface lowering on rocksalt slopes over an eight month period. As highlighted by the authors, the study of highly soluble karstic substrates, such as saltrock, has the potential to shed light upon dissolutional processes and morphological development on less soluble karstic materials such as gypsum and limestone within a much shorter experimental time period.

Terrestrial LIDAR may have further applications in karst modelling to document the evolution and development of mesokarren forms such as rillenkarren under controlled settings by, for example, scanning gypsum plaster blocks subject to rainfall at intervals. Potentially, the technology could also be employed to provide accurate, three dimensional morphometric data of natural karren forms which could then be faithfully recreated at 1:1 scale in gypsum plaster, exposed to runoff and monitored for further morphological development. Crucially, laser scanning may also resolve issues of data comparability and consistency between authors, as raised by Lundberg and Ginés (2009), by stipulating a new protocol and allowing morphometric data to be directly comparable on a global scale.

## Microscale (c.1mm-1cm)

Descending a scale boundary, investigations into karstic surface morphologies at the microscale commonly require the use of optical microscopical techniques, such as stereomicroscopy or thin-section microscopy, although some authors continue to opt for traditional mesoscale morphometric techniques, albeit at a smaller scale.

Millimetre to centimetre-sized rainpits are commonly measured with a carpenter profile gauge, although no protocol has ever been established for their measurement (Ginés and Lundberg, 2009). A measure of surface roughness at the microscale may also be achieved through the use of a carpenter gauge placed vertically along the surface of a rock and photographed. Digitisation of the images allows the height difference between consecutive points to be determined and a measure of surface roughness to be calculated (Crowther, 1996).

Dealing with millimetre-sized microrills, Gómez-Pujol and Fornós (2009) adopt an optical stereomicroscopy approach to morphometric analysis. They derive microrill width and geometry from digital image processing software, allowing them to calculate the lateral distance between microrill crests. McIlroy de la Rosa *et al*. (2012) employ thin-section optical microscopy to measure the width and depth of biotroughs, microscale biokarstic features formed by the coalescing and enlarging of nanoscale endolithic lichen-induced biopits.

Investigations into microscale surface morphology inevitably enter the field of weathering studies, as surface micromorphologies are a product of a karstic substrates interaction with the weathering environment. As such, our understanding of karst surface micromorphologies is derived not only from geomorphological studies but also from studies of karst substrates utilised as dimension stone within buildings and monuments. Highly soluble saltrock and gypsum yield observable morphological change over short experimental periods. However, the slow rate of natural limestone denudation inevitably entails that human observation and quantification of limestone surface loss occurs at a small, millimetre to centimetre scale, over the course of an extremely short, in geological terms, data recording period. In order to estimate decadal, centennial and millennial rates of limestone surface loss, data are often extrapolated from recording periods usually lasting between one and six years (Cucchi *et al*., 1995; Urushibara-Yoshino *et al*., 1999), with some up to 30 years (Stephenson *et al*., 2010).

A variety of techniques may be employed in order to quantify dissolutional surface loss from karst substrates. Long-term studies from a defined base point may be undertaken using equipment such as the micro-erosion meter, which is fixed to the rock with studs and measures surface loss accurately with a dial gauge (Coward, 1975; Cucchi *et al*., 1995). A modified version, the traversing micro-erosion meter was developed by Trudgill *et al*. (1981) and allows multiple individual measurements per erosion meter bolt site (Stephenson and Finlayson, 2009; Stephenson *et al*., 2010). Micro-erosion metres have traditionally been employed on slowly-dissolving karst substrates such as limestone. The rate of surface lowering for more rapidly dissolving karst substrates, such as gypsum or saltrock, may be assessed using plastic (Bruthans *et al*., 2008) or brass (Mottershead *et al*., 2007) erosion pins (c.3mm in diameter and c.50mm long) inserted into the rock until the upper end is flush with the surface. As the surface dissolves, the pins emerge allowing a rate of dissolution to be quantified. Alternatively, surface loss may be quantified by chemical studies of runoff from karst surfaces (Dunkerley, 1983; Vleugels, 1992; Fiol *et al*., 1992; 1996), or by simulated laboratory experiments under accelerated weathering environments (Goudie, 1999; Thornbush and Viles, 2007). Another method, often applied to slowly-dissolving substrates such as limestone, involves the weighing of rock tablets before and after exposure in order to derive solutional losses (Gams, 1981; Urushibara-Yoshino *et al*., 1999; Viles *et al*., 2002). In nature, pedestals formed beneath glacial erratics on limestone pavements have also been used to calculate solution rates since the last glacial maxima of the Pleistocene, when the pavements were scoured by ice and the erratics deposited (Jennings, 1987). Finally, optical and laser scanning (LIDAR) technology allows the precise quantification of surface loss and its spatial variation on rock surfaces. High-resolution laser scanners are capable of detecting sub-millimetre changes in surface morphology, making them highly relevant to investigations into microtopographical changes on karst surfaces over time. Optical and laser scanning approaches have a number of advantages over other techniques as they are non-intrusive, requiring no direct contact with the karstic surface under investigation, unlike the micro-erosion meter (Spate *et al*., 1985). They may also be used *in situ* in the field, without the need to remove rock surfaces for laboratory analysis. At present, the use of laser and optical scanning in the assessment of microscale surface roughness and mineral loss over time from karst substrates has been largely restricted to the study of stone decay in a cultural setting (Birginie and Rivas, 2005; Gomez-Heras *et al*., 2008; Meneely *et al*., 2009). However, the techniques and methodologies employed on dimension stone are equally applicable to the study of stone surface micromorphologies and morphological change over time in the natural environment. Gómez-Pujol *et al*. (2006) adopt a similar laser scanning approach to Mottershead *et al*. (2008) in order to quantify surface roughness on coastal carbonate rocks, with a scanning resolution of 0.1mm (±0.05mm error). At its current level of development, the applicability of traditional optical and laser scanning to karst landform morphometric analysis and classification generally ends at the microscale. Descending a scale boundary to the nanoscale, where observations are often made in microns, surpasses the resolution and accuracy of current laser scanning devices.

## Nanoscale (c.<1mm)

In recent years, weathering studies have adopted an increasingly reductionist approach, with research evolving towards morphological investigation at increasingly smaller scales. The smallest scale of observation for weathering morphologies is the nanoscale. The classification of nanotopographical features on karstic surfaces is problematic in that features at this scale are often difficult to differentiate and are surrounded by a degree of equifinality or convergence, as similar nanomorphologies may develop as a result of different processes (Viles and Moses, 1998).

Inevitably, investigations at the nanoscale enter the realm of crystallography and petrography, requiring the use of microscopical and spectroscopical techniques. Thin-section light microscopy is still applicable at this scale and has been applied to both biotic and abiotic weathering studies (Del Monte and Sabbioni, 1987; Bolívar and Sánchez-Castillo, 1997; Garcia Vallès *et al*., 2000; Bungartz *et al*., 2004; Favero-Longo *et al*., 2009; McIlroy de la Rosa *et al*., 2012). However, detailed investigations of surface features smaller than c.0.5mm are often pursued through the use of electron microscopy.

Scanning electron microscopy (SEM) has been successfully used to identify and attempt to classify carbonate stone weathering nanomorphologies on both experimental blocks sprayed with dilute acid, natural surfaces and building materials. Nanomorphologies such as stepped etching, etch pits, cleavage widening and v-in-v etching among others, have been observed on calcite crystals and are associated with crystal dissolution (Gillott, 1978; Moses *et al*., 1995; Moses and Viles, 1996; Viles and Moses, 1998; Thornbush and Viles, 2007).

SEM has also been applied to the identification of biologically-induced nanomorphologies on calcite. Circular etch pits, etch tunnels and filament-shaped trenches are the most widely documented (Moses *et al*., 1995; Moses and Viles, 1996; Viles and Moses, 1998), although morphologies produced by the excretion of organic acids are often difficult to distinguish from those produced by simple dissolution. SEM has also been successfully applied to the identification of algae cells (Fiol *et al*., 1996; Smith *et al*., 2000), fungal hyphae (Thornbush and Viles, 2006; Concha Lozano *et al*., 2012) and salts, such as calcium oxalate (Wadsten and Moberg, 1985; Russ *et al*., 1996; Giordani *et al*., 2003; Edwards, 2007) and gypsum (Delalieux *et al*., 2001; De Graef *et al*., 2005), within the rock matrix or at the interface between lithobionts and calcareous karst substrates. Variants of SEM successfully applied to the investigations of nanoscale interactions between lithobionts and karst substrates include transmission electron microscopy (TEM), favoured for the observation of biological structures (De los Ríos *et al*., 2002; 2009), low temperature scanning electron microscopy (LTSEM) (Ascaso *et al*., 2002; De los Ríos *et al*., 2009), and scanning electron microscopy with backscattered electron imaging (SEM-BSE) (Sanders *et al*., 1994; Ascaso *et al*., 1998; 2002; Bolívar and Sánchez-Castillo, 1997; Bungartz *et al*., 2004). Atomic force microscopy (AFM), a three-dimensional imaging and measuring approach, has also been employed to quantify limestone surface roughness at the micron scale (Fornós *et al*., 2011).

The recent reconsideration of the role of biological agents in karst landform development (e.g. Fiol *et al*., 1996; Moses and Viles, 1996; Mottershead *et al*., 2000; McIlroy de la Rosa *et al*., 2012), has opened the way for geomicrobiological techniques in biokarstic studies. Increasingly, we are seeing contributions from, and interdisciplinary research between, geomorphologists, microbiologists, lichenologists and mycologists, with the innovation in methods and techniques that this brings.

Finally, in an attempt to characterise the geochemical and mineralogical characteristics of weathered surfaces, weathering studies of karst substrates frequently involve spectroscopical techniques such as Fourier Transform infrared and Raman spectroscopy (Edwards *et al*., 1997; Holder *et al*., 2000; Monte, 2003; Frost, 2004), x-ray diffraction (Goudie *et al*., 1997; Ascaso *et al*., 1998; Giordani *et al*., 2003) and atomic absorption spectrophotometry (Goudie *et al*., 1997) among others.

## Conclusion

The classification of karst landforms is a complex combination of synonymic terminology and polygenetic karren features. Classifications by Bögli (1960) and Ford and Williams (1989; 2007) remain the most comprehensive and widely embraced by the academic community.

Karst surface morphologies exist at a variety of scales. Inevitably then, a wide variety of geomorphological techniques and methods are employed in karst morphometric analysis. Some techniques are applicable only at a particular scale while others may traverse scale boundaries. Karst and karren studies are at a methodological crossroads, with future morphometric techniques likely to evolve from the collection of data via complex and laborious manual field measurement methodologies, to the use of ergonomic, fast, non-intrusive and high resolution airborne / terrestrial LIDAR systems, the production of accurate digital elevation models and associated GIS analysis. Such an integrated approach is applicable from the macro to the microscale and allows morphometric data to be globally comparable.

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