

Technology and geomorphology: Are improvements in data collection techniques transforming geomorphic science?

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Abstract

In recent years technological developments have revolutionized our ability to collect data in geomorphology. Enhanced data collection not only enables us to provide deeper answers to a wider range of fundamental questions about the Earth's surface, but also encourages us to pose new questions. This paper considers in more detail the relationships between science, technology and the development of geomorphological tools and techniques, reviews the spectrum of tools and techniques now available to geomorphologists, and critically assesses what impact 'new technologies' are having on geomorphology. It focuses on the role of technology in biogeomorphology and weathering research, and how it is advancing theoretical, empirical and applied dimensions of these growing sub-fields of geomorphology. Five areas of important technological development are reviewed: remote sensing, dating, geophysical techniques, field and laboratory based analysis and sensing of physical and chemical characteristics, and field and laboratory based analysis of biological properties. There is good evidence that, taken together, technological developments are revolutionizing geomorphology through opening the doors to better cross-scalar investigations, blurring the boundaries between laboratory, field and computer model, and facilitating cross-disciplinary and democratized research.

Keywords: remote sensing, UAV, geophysics, field methods, sensors, molecular taxonomy, geogenomics.

Highlights:

- Technological developments have had a recent significant impact on data collection in geomorphology
- New techniques in geomorphology offer many new insights, but also have challenges
- A revolution in the questions that geomorphologists can answer is likely to be occurring because of technological change.

1. Introduction

In a recent paper on the role of fieldwork in today's geomorphology, Mike Church proposed that 'What has happened most recently ... – so recently in fact that it is not possible to see what the end may be – is that further technological development has furnished geomorphologists with the tools to return to the grand question, what is the history of the surface of the Earth?' (Church, 2013, p. 192). A recent, more quantitative survey by Piegay et al. (2015) poses the question of whether fluvial geomorphology has entered a new era because of recent technological revolution. Piegay et al. (2015) focus in particular on the plethora of new sources of remotely sensed data, terrestrial laser scanning and new radiometric dating techniques which are being increasingly deployed to tackle long-standing research questions. They report that, alongside such technological developments, fluvial geomorphology has also been marked in recent years by increasingly internationalized and interdisciplinary approaches to knowledge production. Both Church (2013) and Piegay et al. (2015) go some way towards answering Steven Wainwright's call for a more 'sociologically-aware' history of geomorphology in which developing technology, ideas and professional structures all intertwine to shape the subject (Wainwright, 2012).

Technology and geomorphology have long been intertwined. A recent review by Wohl et al. (2016) highlights the importance of developments in remote sensing technology, as well as geochronologic and isotopic methods to the progress of geomorphology over the last 50 years. An earlier paper on the trajectory of geomorphology (Church, 2010) illustrated the importance of improvements in technologies in remote sensing and survey, revolutions in computing facilities, and developments in absolute dating techniques in shaping geomorphology at the end of the 20th century. This paper builds on and updates

Church's observations and argument, while providing more detail on the varied uses of improved data collection techniques and how they are re-shaping geomorphology.

The three aims of this paper are: a) to consider in more detail the relationships between science, technology and the development of geomorphological tools and techniques, b) to review the spectrum of tools and techniques now available to geomorphologists, and c) to critically assess what impact 'new technologies' are having on geomorphology. Instead of tackling the issues, as other reviews have done, from the perspective of fluvial geomorphology, I focus here on a 'view from the margins' of geomorphology, through exploring the applications of technological developments to biogeomorphology and weathering. These components of geomorphology are marginal in the sense that they have very close links to other disciplines such as ecology, ecohydrology, engineering and heritage science. They are also marginal in the sense that they have often been neglected in mainstream accounts of geomorphology (Stine and Butler, 2011). But they are also important contributors to the overall status and nature of geomorphology, providing valuable insights into the workings of Earth surface systems. As sub-fields of geomorphology they are also representative of the field as a whole. This paper also focuses on technological developments as applied to data collection and generation in field and laboratory settings, rather than in terms of numerical modeling. In recent years the boundaries between these three core components of geomorphic practice have become blurred, largely as a result of technological innovation. Whilst modeling has been the focus of many papers on geomorphological practice in recent years, field and laboratory practices have been relatively neglected. However, the importance of fieldwork in weathering research has recently been reiterated by Dorn et al. (2013), and the importance of laboratory experimentation to geomorphology in general has been stressed by Bennett et al. (2015).

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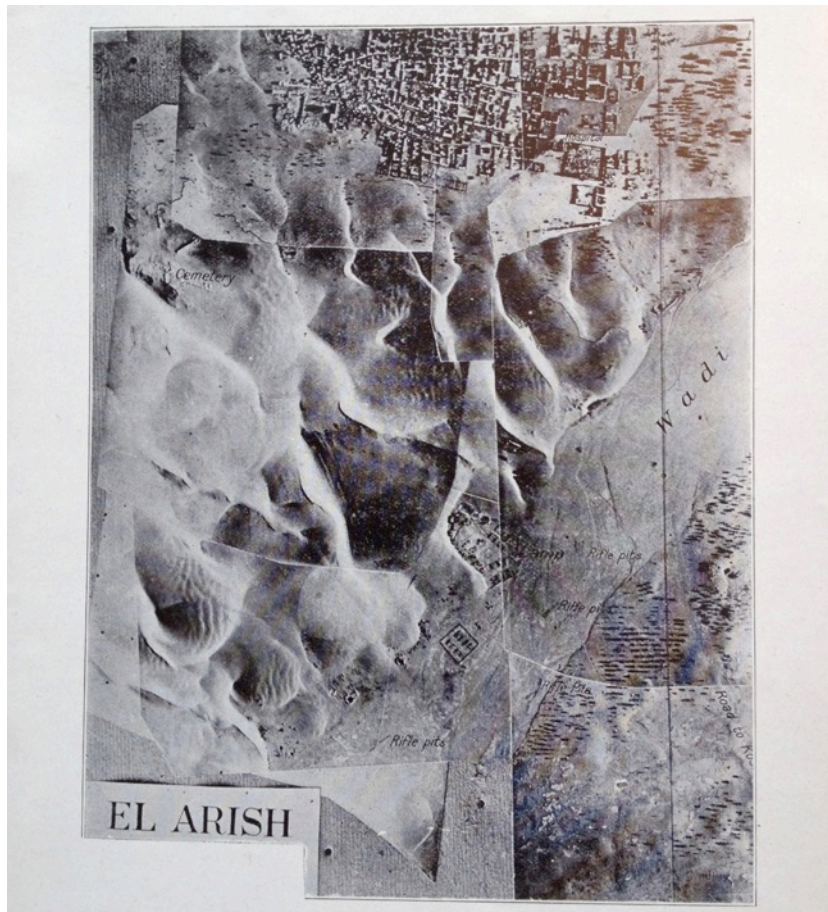
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84 **2. Technology, techniques science and geomorphology: Underpinning concepts and issues**

85 What do we mean by technology? The European Space Agency (ESA website accessed 10/9/2015)
86 defines it neatly as ‘...the practical application of knowledge so that something entirely new can be
87 done, or so that something can be done in an entirely new way’. The distinction between technology
88 and science is encapsulated by Andy Lane (Open University website, accessed 10/9/2015) as that:
89 ‘Technology is about taking action to meet a human need rather than merely understanding the
90 workings of the natural world, which is the goal of science.’ Science and technology are complexly
91 related, and different types of science interface with technology in different ways. Geomorphology is
92 largely seen as a secondary or derivative science and thus its relationship with technology is likely to be
93 very different to that of, for example, theoretical physics. Insights from theoretical physics may, often
94 indirectly, spawn technological innovations; but it is more likely that geomorphology will be a
95 downstream user of such technological advances. Techniques can be defined as the individual tools that
96 utilize technology, and are the entities that geomorphologists engage with. In many cases
97 geomorphology adopts and adapts techniques developed for other uses – leading to many challenges
98 for best practice use and for understanding the meaning of results. A science such as geomorphology
99 may, indeed, be shaped by technological change and development because new research questions may
100 be able to be answered with the advent of new techniques.

101 Despite the clear distinctions between science and technology made above, technology and science are
102 both complexly related to innovation, and these relationships change over time (Brooks, 1994). The
103 need for innovation in industry and society provides a key driver of development in technology and
104 science. Such external drivers of both science and technology have been noted in many historical

105 studies (Jacob, 1997). For example, Merton (1938) points out how in 17th century England rising
106 population and the concentration of people into towns and cities led to many problems such as poor
107 sanitation and the need to provide and transport sufficient food, coal and building materials. As Merton
108 (1938, p.572) notes these challenges 'serve to direct technologic and scientific research into fields
109 appropriate for the solution of these problems.' A similar situation may be identified more recently, with
110 environmental problems such as soil erosion and flooding influencing both technology and science. In
111 today's world, however, the drivers for developments in science and technology are often medical and
112 military, and many of the techniques geomorphologists now use originated in these fields (including
113 space exploration). Aerial photography, for example, developed as a surveillance technique in the first
114 world war, with early imagery now of great use in tracking geomorphological change (Fig. 1). Whilst
115 geomorphology is often a relatively late user of technologies developed as a response to medical,
116 military or space exploration needs, geomorphological problems can contribute to the further
117 development of technological solutions where these problems relate to societal challenges large enough
118 to stimulate innovation.



119

120 Figure 1: 1916 aerial photo montage of coastal dunes near El Arish, Egypt. (Source: Hume, 1925).

121 Technological innovations in late 19th and 20th century which influenced geomorphological fieldwork and
 122 laboratory experimentation have been effectively reviewed by Church (2013) and Bennett et al. (2015).
 123 Bennett et al. (2015), for example, note increasingly sophisticated equipment for experimentation (such
 124 as flumes and environmental cabinets) contributing to ‘transformative research’ over this period.
 125 Transformative research is where research is driven by ideas that have the potential to radically change
 126 interpretations or understanding. For example, Ralph Bagnold’s pioneering work on aeolian processes
 127 from the 1930s onward which greatly enhanced understanding in this area was assisted by his
 128 engineering skills in building wind tunnels and the multiple portable manometer (Fig. 2). The examples
 129 of transformative research that Bennett et al. (2015) give show the need for visionary leadership,

scientific and/or societal need, involvement of a federal agency or institution, new or repurposed facilities, and straddling disciplines. Technological developments are thus a necessary but not sufficient basis for transformative research.



Figure 2: Ralph Bagnold in the field with his portable multiple manometer.

So what are the main technological developments in the last few decades likely to be having an influence on the nature and practice of geomorphology? Underpinning most of the techniques discussed later in this paper is the move from analogue to digital, and in particular developments in image capture devices (such as cameras) to allow rapid collection of imagery over many different wavelengths. From military and surveillance fields there are a whole raft of new platforms on which to mount such image capture devices – from new satellites in Earth orbit, to unmanned aerial vehicles (UAVs or drones), time lapse and surveillance camera set-ups, and microscopes. Comparable data can now be collected at widely differing spatial scales and at high temporal resolution. Miniaturization, automation (both of data collection and data storage), field portability and robustness, and ever decreasing costs are all

making a huge difference to the ability of geomorphologists to make use of a growing range of techniques. Techniques that were once thought of as requiring large and complex laboratory facilities can now be used (to some degree of accuracy at least) in the field. Field portability is a major attraction to many geomorphologists as it removes the need for collection of samples for subsequent laboratory analysis, and allows in situ measurements of geomorphic processes and landform properties. The portable OSL reader (Stone et al., 2015; Portenga and Bishop, 2016), portable XRF (Shuttleworth et al., 2014), portable Raman spectroscopy (Malherbe et al., 2015) are all examples of such advances. Many devices are now becoming so small and robust that they can easily be used in the field in a hand-held way or mounted on platforms such as UAVs (e.g. hand-held terrestrial laser scanners (James and Quinton, 2014), and hand-held hyperspectral imaging cameras (Wu et al., 2014)). Many of these developments have flowed from technological innovations aimed at space exploration challenges, such as the need to equip the rover vehicles on Mars. They also flow from the video gaming and communications industries, with geomorphological applications of the Kinect™ device (Mankoff and Russo, 2013) and smartphone cameras (e.g. Micheletti et al., 2015) starting to multiply.

Whilst these technological developments have led to increasing sophistication in geomorphological techniques (as clearly seen by comparing the entries to the new on-line edition of the British Society for Geomorphology's 'Geomorphological Techniques' with those in the previous, hard copy version of Goudie et al., 1994) they also bring challenges. One such challenge is that most of these techniques require expertise in operating them as well as skill in interpreting the data produced and its meaning for geomorphology. For example, Mol and Viles (2012) follow Sass (2003) in using electrical resistance tomography (or ERT) in short arrays (c. 2 m) to investigate rock moisture distributions in tafoni developed on sandstone. Such adaptation (spatial downscaling) of a geophysical technique usually used to examine larger scale variations in subsurface conditions requires care – both in terms of developing ways to collect the data (for example using medical electrodes) and in terms of understanding what it

169 reveals (as resistance is a proxy for moisture in porous bodies, but is also influenced by other
170 confounding factors which need to be taken into account). A further challenge for most new techniques
171 is the sheer volume of data that they produce, with concomitant need for data processing, sampling and
172 storage. The challenge of comparability is also a key issue for many new techniques – how do they
173 compare with previously used techniques? How accurate are they? Or how do different variants of the
174 same technique compare one with another? Key examples are the various ways to measure grain size in
175 sediments, such as the classic methods of sieving and hydrometers, through to laser-based
176 granulometers. Many geomorphological papers now tackle such questions, which are important to
177 establishing confidence in the reliability and meaning of data.

178 In the light of the role of technological developments alongside the other drivers of change in
179 geomorphology and the benefits and challenges that they bring, we can identify a clear pattern of
180 technological uptake. Starting with the bold claim of novelty and extra insight of a new, or newly
181 borrowed technique (often given in a conference paper), there often follows a review of potential
182 applications raising awareness and exciting interest. Early adopters use the technique and publish
183 preliminary results from a case study. Later adopters follow, whilst others publish more critical reviews
184 showing how the technique performs in comparison with other alternative methods. Sometimes
185 techniques are found wanting and disappear from the literature; more often they are widely taken up,
186 resulting in compilations of comparable datasets from different areas. In many cases, further innovative
187 uses of the techniques are found within geomorphology, occasionally leading to industrial interest in
188 refining the product. An example of this is the Schmidt Hammer (Goudie, 2006) which was adopted in
189 geomorphology in the 1980s from the concrete testing field. This rebound device for measuring surface
190 hardness has been adapted by geomorphologists for use as a relative dating technique, as well as a way
191 of quantifying the degree of weathering and case hardening. Proceq have recently brought out a
192 ‘RockSchmidt’ hammer tailor-made for geomorphologists and geologists rather than aimed at the

concrete testing market. Thus, geomorphological appropriations of a technique have led to product innovation.

3. Recent technological developments in geomorphology

Whilst it is relatively simple to track the use of different techniques in geomorphology, it is much harder to elucidate the impact that these techniques are having on the subject itself. In this review, I have approached the problem by focusing on a close qualitative examination of a large range of papers in biogeomorphology and weathering fields published in Earth Surface Processes and Landforms (ESPL), Geomorphology and other major geomorphological journals from mid 2010 to mid 2016. This provides a six-year snapshot of the prevalence of different techniques. This approach has allowed me to investigate the range and nature of techniques being used, as well as how they are being used to tackle geomorphological problems.

The techniques used in biogeomorphological and weathering papers can be divided into 5 broad categories: remote sensing, geophysical, dating, field and laboratory based analysis and sensing of physical and chemical characteristics, and field- and laboratory-based investigation of biological properties. The boundaries between these categories are often hard to define and permeable. For example, how close does the platform have to be to the 'field' to fit into a 'field-based' rather than 'remote sensing' category? UAVs may be clearly seen as remote sensing platforms, but what about cameras on wires running over a field site? Importantly, many techniques which were only formerly available in the laboratory have now been developed to allow field and laboratory use of the same equipment. This further blurs the boundaries. Each of the categories is very different in terms of the number and diversity of techniques available, and their uptake by biogeomorphological and weathering

research. The six-year survey indicates, as Piegay et al. (2015) found in their much larger survey of fluvial geomorphological papers, the dominance of remote sensing methods (especially airborne and terrestrial LIDAR). In contrast, novel biological techniques (such as molecular taxonomy) have only been used in very few biogeomorphological and weathering studies to date. Some technologies have not yet been taken up widely by geomorphologists, but may be very helpful in future such as rapid prototyping or 3D printing (Bourke et al., 2008) and thermal imaging cameras (Schepfleitner et al., 2016). One of the key findings of the six-year survey is the innovative geomorphological use of many techniques – showing how geomorphologists often modify and develop existing techniques, and use them in combination with radically different techniques to provide additional insights. Another key finding is the growth of hand-held, field-portable devices which allow rapid ground-truthing of, and adjunct data to, remote sensing data at relatively small spatial scales.

3.1 Remote sensing – new platforms, new methods

Whilst remote sensing data has been available to, and utilized by, geomorphologists for many years the advent of new platforms (UAVs etc.), new methods (LIDAR etc.) and free availability of data (via Google Earth etc.) has had a strong, more recent impact on geomorphology. UAVs, for example, allow data to be collected at much closer range than more conventional remote sensing platforms, which is a boon for many areas of geomorphology for which high resolution data is required. As documented below, many geomorphological studies compare data collected from innovative platforms with more classic remote sensing methods. Furthermore, several new remote sensing techniques have been suggested as being of geomorphological utility but have not, as yet, been used extensively. As many other authors have noted, recent years have seen an abundance of geomorphological studies making use of freely or relatively cheaply available satellite data, as well as data collected from a range of airborne surveys

(using platforms such as planes, helicopters, balloons, UAVs). In biogeomorphological research, the use of collections of imagery in virtual globes such as Google Earth has proved particularly fruitful (fig. 3). Butler (2012), for example, uses imagery from Google Earth to investigate the occurrence of beaver ponds, whilst Phillips (2012) uses 1 m resolution aerial photo imagery from Google Earth alongside other data sources and field work to investigate the causes of river avulsions and their impacts on log jams, and Alice Goudie (2013) provides a quantitative assessment of creek and pan morphometry from salt marshes around the UK using imagery from Google Earth. For many weathering investigations, such large scale data is of less obvious use.



Figure 3: The mysterious 'fairy circles' in the Hartmann Valley, NW Namibia viewed from imagery available in Google Earth. Scale bar = 100 m.

251 Temporal sequences of Landsat and other satellite imagery are now available, allowing multi-decadal
252 observations of biogeomorphological change (e.g. Alatorre et al. 2011; Klaar et al. 2014; Hamdan and
253 Myint 2015). Whilst the timespans involved are not long enough to capture grand changes in the Earth's
254 surface, they are allowing geomorphologists to capture high-resolution change in many environments
255 for the first time. Klaar et al. (2014), for example, use Landsat imagery to document 22 years of change
256 in vegetation types and sediment availability in a rapidly changing paraglacial environment in Alaska.
257 High resolution remotely sensed imagery, such as ASTER data is also of great use to
258 biogeomorphological studies (see, for example, Bertoldi et al. (2011) who used it to investigate river
259 flow and vegetation interactions in a braided river system). Some remotely sensed data has yet to be
260 fully explored by biogeomorphological or weathering studies but has been shown to have
261 geomorphological use. For example, Jones et al. (2012) used a digital surface model derived from InSAR
262 (airborne interferometric synthetic aperture radar) with 5 m horizontal and 0.1 m vertical resolution to
263 map pingos in northern Alaska. Kruse (2012) reviews the potential for wider use of hyperspectral
264 imaging in identifying mineralogy across wide swathes of the Earth's surface in association with LIDAR
265 and InSAR. He suggests that such methods could drastically improve geomorphological mapping and
266 visualization in many areas.

267 Airborne LIDAR has been eagerly taken up in biogeomorphological research (and to a lesser degree in
268 weathering studies) in combination with aerial photography. Milodowski et al. (2015), for example,
269 report on the use of airborne LIDAR to investigate above ground biomass in the Sierra Nevada, northern
270 California, and its relationship with erosion rates (quantified using the proxy of mean basin slope).
271 Mapping vegetation structure through data collected from aeroplanes and UAVs is another growth area
272 in remote sensing for biogeomorphological research, as exemplified by the study of Hortobagyi et al.
273 (2015) who performed a methodological study on the comparative value of photogrammetric analyses
274 of data from the two platforms. They find the two datasets to be complementary, with both producing

accurate models of canopy height at different scales. Imagery using a wider range of wavelengths can now easily be captured from UAV-mounted cameras, and IR imagery from UAVs in particular may be of great help to biogeomorphological and weathering-based research in future (Fig. 4).

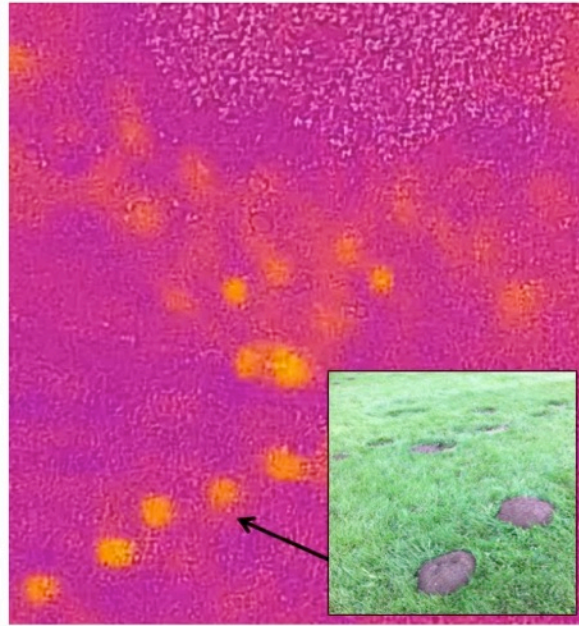


Figure 4: IR image of molehills near Oxford, taken from a UAV (source: Jerome Mayaud).

More bespoke methods of data capture are also now being used fruitfully in biogeomorphological research with, for example, Genchi et al. (2015) using ‘structure from motion’ (SfM) analyses of UAV imagery to investigate bioerosion by burrowing parrots on a cliff. This study exemplifies one of the key advantages of low-level, flexible platforms such as UAVs for biogeomorphological and weathering research, i.e. that close-range imagery can be collected at many different angles of otherwise inaccessible or hard to reach topographies. Tonkin et al. (2014) provide a useful test of the accuracy of a digital surface model of hummocky moraine produced using SfM methods from UAV imagery. They find the technique to work well (in comparison with total station survey), providing there are enough ground

control points. Such technological developments in remote sensing are allowing new data to be collected on biogeomorphological and weathering phenomena which could not otherwise be mapped or quantified. These novel datasets could be used to generate process rate information which can, in turn, be used to test hypotheses of how biotic processes contribute to landscape development.

The expansion of different remote sensing platforms and data capture devices allows us now to produce imagery at different resolutions, scales and wavelengths which can be combined with 3D topographic data. The fact that 3D topographic data can now be routinely collected allows an unparalleled insight into the changing nature of the land surface and its biological cover from centimetres to kilometres in scale. Now that comparable datasets of topography and vegetation cover are available, biological and ecological processes are becoming much easier to combine with mainstream geomorphological modeling. This is a key point about today's technology and its impact on geomorphology – it has helped move biogeomorphology (and other marginal areas of the subject) from 'fun to fundamental' to borrow the expression of Nick Cox who noted in a book review that '...while much of biogeomorphology is obviously fun, it is not so obviously fundamental' (Cox, 1989, p. 623). But, importantly, it has also preserved the 'fun' by allowing geomorphologists to engage with the latest gizmos and widgets and make innovative use of them in the field.

3.2 Geophysical techniques – new applications, new combinations of techniques

Geophysical techniques share many characteristics with the remote sensing techniques reviewed above, in that they allow non-contact and non-invasive data collection – in this case into the subsurface rather than the surface. As Church (2010) points out, geophysical techniques have been used for many years by geomorphologists. What has changed in recent years, however, is their much wider uptake across

geomorphology and the use of combined rather than individual techniques. Both of these changes have been driven by reductions in price, increased portability, and developing skills amongst geomorphologists. Van Dam (2012) provides a very helpful review of the application of geophysical techniques in geomorphology, covering key techniques such as ground penetrating radar (GPR), electrical resistance tomography (ERT), seismics and electromagnetic induction. These techniques can provide 3D information on subsurface structure and moisture variations across large areas. Geophysical survey techniques have long been used in karst geomorphological studies, to locate and characterize cave systems and other underground features. Technological advances mean that such techniques are now quicker and easier to apply in the field, and that 3D data can be captured relatively easily. Carbonel et al. (2015) illustrate the combined use of GPR, ERT and DinSAR (Differential Interferometric Synthetic Aperture Radar) to explore the nature of buried sinkholes in a karst terrain. Akiyama et al. (2015) provide a neat example of combining geophysical techniques with standard geomorphological field techniques, using ERT in combination with a field experimental study using limestone tablets to investigate subsurface dissolution rates. Combinations of geophysical (GPR), remote sensing techniques, and field observations are also used by Parsekian et al. (2011) in their biogeomorphological study of vegetation mats in thermokarst thaw lakes.

The use of geophysical techniques has also blossomed recently in weathering and critical zone studies. Sass (2003) was one of the early pioneers to use ERT in combination with temperature sensors to investigate moisture distributions in Alpine rock walls and its implications for freeze-thaw weathering. Siewert et al. (2012) report on an investigation of rock wall retreat rates in Svalbard using ERT to quantify the amount of talus produced by rock walls of known age. Mol (2014) uses multi-temporal ERT profiles, in association with field-based monitoring of surface microclimates (iButtons) and changing rock surface hardness values (Equotip) to investigate weathering rates and processes in tafoni in South

Africa. ERT has been used in combination with iButtons located within drillholes and IR thermography to investigate weathering regimes within granite tafoni in Morocco by Schnepfleiter et al. (2016) - fig. 5. Many intensive studies are now being made of weathering processes within the critical zone at a range of observatory sites, and here geophysical techniques are also of immense value in providing non-invasive rapid surveying of the nature of the critical zone. Leopold et al. (2013), for example, illustrate the use of ERT to map the critical zone depths at the Boulder Creek Critical Zone Observatory. Geophysical techniques are likely to be of increasing importance to both biogeomorphology and weathering research, because of the insights they can give into the subsurface at varying depths and scales without invasive disruption. They could, for example, be more widely used to map subterranean burrow structures and thus aid interpretation of the geomorphological roles of the animals that create them.



Figure 5: Setting up ERT electrode transects in tafoni, Tafraoute, Morocco ready to collect subsurface moisture data.

3.3 Dating – innovative uses for existing techniques

There has been long-standing interaction between biogeomorphological and geochronological research with, for example, tree-ring dating used to calibrate the recent end of the radiocarbon timescale to calendar years. Recent investigations have focused on improving dendro methods and applying combinations of cosmogenic and other radiometric techniques to a wider range of geomorphological problems (including biogeomorphic and weathering questions). Several papers in recent years discuss and apply improved dendrogeomorphological methods to date Earth surface events such as rockfalls. In most cases these improvements do not involve any great technological advances (indeed, some of the methods rely on extremely simple visual observations of scars on tree stems, as for example Trappman and Stoffel (2015) illustrate). Relatively few biogeomorphological studies have made use of radiometric dating techniques, although Persico and Meyer (2013) use a range of isotopic and geochemical analyses with ^{14}C dating to investigate beaver activity in the Greater Yellowstone ecosystem.

A good example of novel use of dating techniques in biogeomorphological research is the work of Johnson et al. (2014) who used a combination of Optically Stimulated Luminescence (OSL) and cosmogenic (^{10}Be) methods to explore the depth of bioturbation in a basaltic soil profile in NE Queensland, Australia. In a similar vein, Swales et al. (2015) utilize a variety of dating techniques (^{210}Pb , ^{137}Cs and ^7Be) to answer the classic question of whether mangrove trees actively promote sedimentation, or respond passively to changing sedimentation regimes. In their study area, the Firth of Thames coast, New Zealand, the latter was found to be the case. Weathering studies also have been relatively late to utilize radiometric techniques, but Brandmeier et al. (2011) provide a useful example of the combined use of microclimatic monitoring (temperature and relative humidity sensors) with cosmogenic dating (^{10}Be) to evaluate the development of granitic tafoni in Corsica. Furthermore, Wilson et al. (2012) illustrate the use of cosmogenic ^{36}Cl to quantify the rate of surface lowering of limestone pavements at sites in NW England – another good example of a new technique being deployed to tackle

a very old geomorphological question. Combining more classic methods (such as geochemical mass balance calculations) to measure weathering rates with cosmogenic methods to quantify long term denudation rates has been the focus of several recent papers (e.g. Schoonejans et al., 2016). There is undoubtedly much more scope to use cosmogenic nuclides innovatively to tackle many geomorphological questions about the rates of weathering and biogeomorphological processes.

3.4 Field and laboratory techniques to sense and monitor physical and chemical characteristics – an explosion of diverse applications of various technologies.

The choice of techniques now available to geomorphologists to collect data in the field and laboratory on physical and chemical characteristics of sediments, rocks and water is huge and bewildering. Whilst most of these techniques are not necessarily based on innovative technologies, they have benefitted hugely from recent developments in miniaturization and automation which has revolutionized their use in geomorphology. Such techniques are of particular importance to many weathering studies. It is in this area that the benefits of automation, miniaturization and fall in price have been most keenly felt. For example, in terms of field survey (i.e. capturing x,y,z coordinates across topographic surfaces to produce 2D or 3D datasets) dGPS and terrestrial laser scanning (TLS), as well as SfM from photosets taken in the field, can all generate rapid and accurate profiles. From being prohibitively expensive 15-20 years ago, such equipment is now affordable and it is also much more easily field-portable than previously. Stromsoe and Callow (2012), for example, use dGPS to map river cross sections in their study of the impacts of clearing riparian vegetation on channel characteristics in dryland rivers in Western Australia. Soulard et al. (2013) use TLS as part of their study to investigate the influence of fire on soils and surface roughness. They produce high resolution models of ground surface and vegetation structure from burned vs unburned plots using TLS. Several papers investigate the accuracy and comparability of

different, ground-based ways of creating DEMs in comparison with airborne LIDAR and total station methods, and provide detailed assessments of the performance of techniques for different purposes (e.g. Eltner and Baumgat, 2015 investigate the accuracy of TLS in quantifying soil erosion).

At a smaller scale Dabski (2014) reports on the first recorded use in geomorphological fieldwork of the Handysurf electronic profilometer alongside the Schmidt Hammer to investigate rock surface roughness and weathering in rapidly deglaciating environments in Iceland. This tool uses a diamond-tipped stylus to quantify the micron-scale topography of survey short profiles. Together, the suite of available surveying devices allows quantification of surface topography at scales from kilometers down to sub-millimeter level. For weathering studies in particular, high resolution TLS (often using object scanners) and SfM-based analyses of digital imagery provide rock surface DEMs of unparalleled quality, which can be used to investigate the interaction between process and form at a small scale (cf. Ehlmann et al., 2008).

Ground-based imagery to record changes in the field and within laboratory experiments can also now easily and cheaply be collected using new technologies, such as time-lapse cameras and digital videography. Such methods have proved fertile for many biogeomorphological studies. For example, Kramer and Wohl (2014) used a time-lapse camera to monitor changes in large woody debris in Slave River, Canada, and MacVicar and Piegay (2012) used video surveillance techniques as part of a study on wood budgets in rivers. Pledger et al. (2014) used videography to capture fish behavior in a flume study of Barbel grazing and erosion, and Tal and Paola (2010) used similar methods in their flume-based study of vegetation/channel morphology interactions using alfalfa seedlings. One issue with collecting long sequences of images using these techniques is the need for sampling and interpretation in order to pick out the major events.

419 Monitoring temperature and other microclimatic variables using small automatic weather stations and,
420 increasingly, miniaturized, robust sensors is another boon to geomorphologists investigating weathering
421 and biogeomorphology. For example, many papers use iButtons which are small (camera battery sized),
422 versatile loggers which can be used in many different environments (soil, rock surface and subsurface,
423 water). André et al. (2012) used iButtons in a study of weathering and forest clearance at Angkor Wat,
424 and Coombes and Naylor (2012) used them in an integrated laboratory and field study of rocky coastal
425 bioerosion and bioprotection. In a rather different environment, Ericksson and Eldridge (2014) used
426 iButtons as part of a study of the impacts of burrowing mice on sub-Antarctic Marion Island. Because
427 they are cheap and can be deployed for long periods without the need for downloading, iButtons can be
428 used in large arrays or networks to collect data in areas that cannot be visited frequently.

429 A range of other Earth surface processes can also be monitored using similar miniaturized sensors,
430 which record location amongst other attributes. RFID (Radio Frequency Identification) tags are
431 becoming a popular method of monitoring the movement over time and space of clasts and organisms.
432 For example, Schenk et al. (2014) use a combination of RFID tags and aluminium tags to monitor
433 movements of large woody debris within a river, Chapuis et al. (2015) use them to monitor gravel
434 movements in a gravel-bed river, and Arnaud et al. (2015) provide a detailed assessment of different
435 RFID tags and antennae and their performance in fluvial systems research. This type of technology, in
436 which small, cheap sensors can be embedded in geomorphic materials and/or attached to animals to
437 monitor location and perhaps other attributes such as temperature over time, could be immensely
438 valuable for future biogeomorphological research.

439

440 Much has recently been written about different methods to measure movements of fluids (air, water)
441 and the particles entrained within them in both field and laboratory settings. There are now many

different techniques with which to carry out such measurements. For example, saltating particles can be monitored with impact sensors (e.g. SENSIT) which have become increasingly miniaturized, ruggedized and automated, and there are many developments of pressure sensors to monitor bedload movement (Beylich and Laute, 2014). Often, multiple methods are used together. For example, Zhang et al. (2015) utilize particle tracking velocimetry (PTV) and high-speed photography to capture saltating particle tracks behind sand fences. Useful inter-comparison exercises have been undertaken, such as the study of Barchyn and Hugenholtz (2010) comparing the performance of four different piezoelectric sensors for aeolian sediment transport. Flow velocities can now be measured in natural channels and flumes using ADV (Acoustic Doppler Velocimetry) – see, for example, Chen et al. (2011), and in airflow using hotwire anemometry and other techniques.

There have also been many recent developments in the techniques available to measure soil moisture which is a highly important influence on many geomorphological processes, but one which has been frustratingly difficult to monitor in the past. Many different probes are now available operating on a whole range of principles (e.g. capacitance, resistance, microwave, neutron probes, IR, as well as non-invasive methods such as ERT). Even TLS can be used to monitor surface moisture trends in beach sediments (Nield et al., 2011). One key issue surrounding many of these techniques is that they are usually measuring a proxy for moisture, rather than directly measuring moisture, and care needs to be taken to ensure that other influences on the variable measured are taken into account (Eklund et al., 2013). For weathering studies, in which rock moisture contents are of great significance, other techniques have recently been applied. For example, probe permeametry (developed for engineering applications) has proved to be very useful in mapping permeability variations across rock surfaces in the lab and field (e.g Buj et al., 2011). In laboratory settings, micro X-Ray Computed Tomography (CT) is a very insightful technique, capable of providing highly detailed 2D and 3D monitoring movement of water

and other fluids within porous bodies. Bazilevskaya et al. (2013) provide one example of this technique applied to the study of weathering rates and regolith depths on granite and diabase; whilst Buss et al. (2013) used synchrotron micro X-Ray CT to investigate porosity variations along a drill core extracted from the deep critical zone. CT scanning has also been used to investigate freeze thaw weathering (de Kock et al., 2015).

Surface hardness and strength of rock and sediments are parameters of interest for many weathering and biogeomorphological studies. The family of Equotip rebound hardness testing devices, based on a similar principle to the Schmidt Hammer, but with much lower impact energies, have been shown to have much potential in weathering and relative dating studies (Fig. 6). These devices were designed for testing metals, and so their use in geomorphological applications is non-standard, and they may be affected by the rougher surfaces encountered on rocks in comparison with metals. Alberti et al. (2013) used the Equotip successfully to assess clast hardness as part of a relative age dating study. Viles et al. (2011) provide an assessment of the performance of the Equotip in comparison with the Schmidt Hammer for geomorphological applications. Developments in technology can have implications for comparability. For example, the new Digi-Schmidt Hammer (electronic data storage) has been shown to produce different values to the 'classic', analogue, Schmidt Hammer (Winkler and Matthews 2014).



Figure 6: Using the Equotip Piccolo in the field to collect rock hardness data on a sandstone outcrop.

Chemical sensing in the laboratory and field is also undergoing rapid development, with portable versions of X-Ray Fluorescence (PXRF) being used in both biogeomorphological and weathering research. Shuttleworth et al. (2014), for example, used PXRF to examine lead pollution in upland peat, whilst Goodfellow et al. (2014) used the technique in a study of Hawaiian regolith deep weathering, based on road cutting exposures. Other techniques such as portable Raman spectroscopy (Aulinas et al., 2015), UV-VIS spectroscopy and hand-held hyperspectral imaging cameras also have great potential for biogeomorphological and especially weathering research. Many of these techniques were originally developed for planetary exploration, and were deployed initially as part of the equipment on the Mars rovers.

One interesting aspect of the use by geomorphologists of the array of techniques to monitor chemical and physical attributes of landscapes in the field and lab has been innovation and adaptation of existing techniques to answer specifically geomorphological questions. Thus, for example, Ridge et al. (2011)

498 have devised a new field instrument - the Gauged Sediment Trap (GaST) - which is constructed using a
499 HoBo water level logger.

500

501 **3.5 Techniques to characterize and identify biological characteristics in the laboratory and field – an**
502 **emerging frontier for geomorphology?**

503 Currently, there are relatively few geomorphological studies making use of novel techniques to
504 investigate the structure and function of key biogeomorphic agents (e.g. root systems, riparian forest
505 architecture), nor of biotechnologies, such as molecular taxonomy to identify what species are present.
506 In the case of the former, many techniques deployed in geomorphology to investigate inorganic
507 materials and the land surface can also be applied to characterize the biotic dimension. For example, TLS
508 is being increasingly used by ecologists to provide highly accurate, high-resolution models of above-
509 ground biomass. Geophysical techniques can be used in a similar fashion to visualize sub-surface root
510 networks.

511 Molecular taxonomical methods have huge potential for biogeomorphological and weathering studies,
512 but again have only been used to a relatively modest degree so far. Whilst the techniques are now
513 standard in ecology and biogeography, they are quite alien to most geomorphologists - as are the
514 bioinformatic tools needed to process and interpret the data. For characterizing the structure and
515 function of rock surface and soil surface microbial communities, however, molecular methods provide
516 culture-independent methods which give an unparalleled picture of the diversity and nature of life
517 forms present. Once prohibitively expensive, and/or highly specialized, such techniques are now
518 becoming cheaper, faster and more easily available. Cutler et al. (2013), for example, use TRFLP and 454
519 pyrosequencing to identify eukaryotic microorganism communities (mainly fungi and green algae) on
520 sandstone walls; whilst Marnocha and Dixon (2014) use similar techniques to elucidate rock surface

microorganism communities at Karkevagge. Huang et al. (2014) use DNA-based methods (PCR-DGGE) to investigate biological soil crusts and their response to wetting, whilst Sanchez-Moral et al. (2012) use RNA/DNA ratios and stable isotopes to explore the role of microorganisms in the formation of cave moonmilk deposits. Other allied techniques, such as FISH (Fluorescent in situ Hybridization), offer huge potential for geomorphologists to investigate microbial communities and their functions, for example in relation to weathering.

Much larger scale applications of molecular taxonomy to geomorphological and Earth science problems are also now possible, as recently eloquently summed up in the name ‘geogenomics’ (Baker et al., 2014). As Baker et al. (2014) define it, geogenomics is the use of large-scale genetic data to test or constrain geological hypotheses (Fig. 7). They illustrate, through a number of examples, how geogenomics research can be useful through providing independent chronologies for past geological events, as well as providing constraint and nuance to palaeo-environmental interpretations. Two specific examples where geogenomics data can help decipher problems of geomorphological importance are the timing of the Andean uplift and the late Cenozoic history of the Amazon River (Baker et al., 2014). In terms of molecular taxonomy and geogenomics the relationship between geomorphologists and the cutting-edge techniques is likely to be quite different to those discussed in earlier sections of this paper. It is unlikely that geomorphologists are going to be major users of the techniques themselves, rather that they will work in close collaboration with ecologists and microbiologists. Baker et al. (2014) use the term ‘reciprocal illumination’ to describe this relationship and note that a certain degree of independence is healthy in order to avoid circular reasoning when using biological chronometers to constrain geological hypotheses. Surely geogenomics, supported by cutting edge molecular taxonomic techniques, offers some prospect of providing geomorphologists with new tools to return to Mike Church’s grand question – ‘what is the history of the surface of the Earth?’ (Church, 2013).

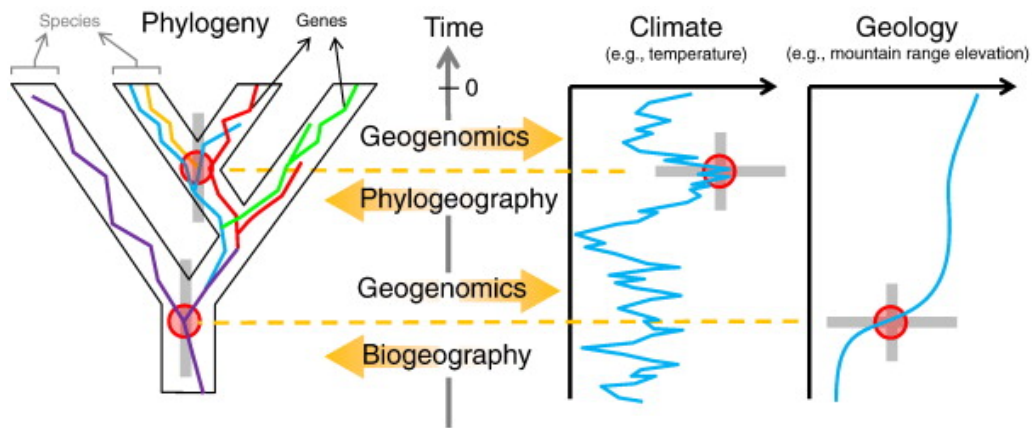


Figure 7: Conceptual illustration of how geogenomics can constrain geologic or climatic scenarios. In the phylogenetic tree (left), black ‘tubes’ represent species (i.e. the **species tree**), whose individuals are characterized by genes with different mutational histories (color lines within tubes; i.e. the **gene tree**). On the right, a climatic time series and temporal variation of a geologic feature are represented. Red circles and orange dashed lines highlight the correspondence between evolutionary and climatic/geologic events; gray bars represent confidence intervals for the timing of divergence (left) or the geologic/climatic events (right). Note also that the **nodes** in the phylogenetic tree on the left have uncertainty associated with them (i.e. the equivalent error depicted by horizontal error bars in the graphs to the right). (Source: Baker et al., 2014).

4. What impacts are new technologies having upon geomorphology?

Technological development is not a panacea for any science, including geomorphology. Whilst technological development leads to new or improved techniques, novelty is not without its challenges. Handling and evaluating data produced by new methods, and comparing it with that gained from older techniques can be challenging. Some exciting new techniques promise more than they can deliver. Classic methods still have their place in many geomorphological studies. Geomorphologists should always remain critical and carry out inter-comparisons of techniques, but continue to explore and

innovate. New techniques available in the early years of the 21st century have already radically improved dating of landscape changes, allowed geomorphologists to see that which was formerly invisible (e.g. active processes hidden by tree canopies), and permitted them to quantify topography at a much improved range of spatial scales (from microns to kilometers). New techniques have also allowed better measurement in the field of rock hardness, soil moisture and many other parameters from which new insights into geomorphic processes and landscape change can be gained.

Different communities within geomorphology will undoubtedly engage with new techniques in different ways, and the view that I have presented in this paper is of necessity selective. As this paper has demonstrated, different areas of technological development have been taken up by biogeomorphological vs. weathering studies, with the latter particularly benefitting from the new, flexible remote sensing platforms such as UAVs, geophysical techniques and new field based techniques for identifying physical and chemical characteristics. Such differential uptake of the range of novel techniques on offer is mirrored across other areas of geomorphology, depending on the temporal and spatial scales on which they focus, and the nature of the major problems they are concerned with.

That new technologies have provided a vast array of new or improved techniques for geomorphological applications is not disputed, and there is clear evidence that the early 21st century is a particularly fertile period in terms of technological diversification in geomorphology. But the question remains as to whether geomorphological practice and theory is being influenced in any significant way. Is it a technological revolution as Peigay et al. (2015) have suggested? In this author's opinion, the answer is yes, and geomorphology is undergoing a technological revolution that involves a lot more than simply being able to capture high-resolution topographic data rapidly. Three aspects are of particular importance. First, the availability of comparable data at many different scales about the Earth's surface covering four dimensions (i.e. x,y,z and one or more attributes of each point - fig. 8) now opens the door to serious geomorphological attention to scale issues. As fig. 8 demonstrates a wide range of non-

contact, non-invasive as well as contact, invasive techniques are available to monitor surface and subsurface conditions and changes at scales from microns to kilometers. Whilst not all scales of technique are yet being deployed by geomorphologists to the same extent, there is certainly the possibility now, for example, to investigate 3D patterns of rock surface hardness from the nanometer to meter scales. Similarly, the fact that hyperspectral imaging can now be used to map many different characteristics (moisture, mineralogy etc.) from kilometer scale down to sub-millimeter scale permits a whole series of novel questions to be asked. As several of the studies reviewed here have shown, using geophysical techniques in combination with surface remote sensing opens the way for a much deeper appreciation of how landscapes function.

Spatial scale of coverage	Non-contact, non-invasive						Contact, invasive					
	Surface				Subsurface		Surface				Subsurface	
	Topography	Visual images	Other surface properties	Topographic change	Subsurface structure	Subsurface moisture	Topography	Surface climate	Topographic change	Sediment movement	Weathering / erosion	Subsurface moisture
km	SAR	Landsat etc	Multi-spectral and hyperspectral imaging cameras	Interferometry	Synthetic aperture radar							
m	LIDAR	Airplane/ UAV-mounted camera			Ground penetrating radar	ERT		iButtons and other small dataloggers and probes		RFID tags	Micro-erosion meters	Moisture probes
cm	TLS	Handheld camera			XRay CT	Microwave	Digital roughness meter		LVDT and strain gauges			
mm	TLS/ object scanner										Profilometers	
um	Electron microscopy-derived DEM	USB microscopy					Electronic profilometry					

Figure 8: Summary of techniques available in geomorphology organised by scale, type (contact or non-contact), application (surface or subsurface) and variables investigated. Grey boxes mark where techniques are available but not yet utilised by geomorphologists.

The second way in which geomorphology is being changed by this technological revolution is the collapsing of boundaries between the different 'spaces of science' that geomorphologists use. Given the overlapping use of techniques in the laboratory and field, and the way in which data from both can now be combined with remotely sensed data and modeled on computer, the old differences between the different modes of enquiry are becoming lost. Third, geomorphology today is part of a much wider technological revolution in science meaning that we are now using similar techniques to scientists in other branches of environmental and earth science, enhancing the potential for new insights and a more holistic viewpoint. The fact that many of these techniques can be used with smart phones, are cheap and easy to deploy, and result in freely available data also means that geomorphology, like other sciences, is becoming increasingly open and democratized. Geomorphologists have perhaps been slow to take up the challenge of 'citizen science', but there are huge opportunities now to involve non-specialists in the collection and analysis of geomorphological data.

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I'd like to thank my late father, John Viles, for his long term support and encouragement. As an electronics engineer he had an irrepressible enthusiasm for technology which inspired my interest in gadgetry of all kinds.

Figure captions

Figure 1: 1916 aerial photo montage of coastal dunes near El Arish, Egypt. (Source: Hume, 1925).

Figure 2: Ralph Bagnold in the field with his portable multiple manometer.

Figure 3: The mysterious ‘fairy circles’ in the Hartmann Valley, NW Namibia viewed from imagery available in Google Earth. Scale bar = 100 m.

Figure 4: IR image of molehills near Oxford, taken from a UAV (source: Jerome Mayaud).

Figure 5: Setting up ERT electrode transects in tafoni, Tafraoute, Morocco ready to collect subsurface moisture data.

Figure 6: Using the Equotip Piccolo in the field to collect rock hardness data on a sandstone outcrop.

Figure 7: Conceptual illustration of how geogenomics can constrain geologic or climatic scenarios. In the phylogenetic tree (left), black ‘tubes’ represent species (i.e. the **species tree**), whose individuals are characterized by genes with different mutational histories (color lines within tubes; i.e. the **gene tree**). On the right, a climatic time series and temporal variation of a geologic feature are represented. Red circles and orange dashed lines highlight the correspondence between evolutionary and climatic/geologic events; gray bars represent confidence intervals for the timing of divergence (left) or the geologic/climatic events (right). Note also that the **nodes** in the phylogenetic tree on the left have uncertainty associated with them (i.e. the equivalent error depicted by horizontal error bars in the graphs to the right). (Source: Baker et al., 2014).

Figure 8: Summary of techniques available in geomorphology organised by scale, type (contact or non-contact), application (surface or subsurface) and variables investigated. Grey boxes mark where techniques are available but not yet utilised by geomorphologists.

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