Landform characterization using geophysics—Recent advances, applications, and emerging tools

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**Abstract**

This paper presents an overview of the strengths and limitations of existing and emerging geophysical tools for landform studies. The objectives are to discuss recent technical developments and to provide a review of relevant recent literature, with a focus on propagating field methods with terrestrial applications. For various methods in this category, including ground-penetrating radar (GPR), electrical resistivity (ER), seismics, and electromagnetic (EM) induction, the technical backgrounds are introduced, followed by section on novel developments relevant to landform characterization. For several decades, GPR has been popular for characterization of the shallow subsurface and in particular sedimentary systems. Novel developments in GPR include the use of multi-offset systems to improve signal-to-noise ratios and data collection efficiency, amongst others, and the increased use of 3D data. Multi-electrode ER systems have become popular in recent years as they allow for relatively fast and detailed mapping. Novel developments include time-lapse monitoring of dynamic processes as well as the use of capacitively-coupled systems for fast, non-invasive surveys. EM induction methods are especially popular for fast mapping of spatial variation, but can also be used to obtain information on the vertical variation in subsurface electrical conductivity. In recent years several examples of the use of plane wave EM for characterization of landforms have been published. Seismic methods for landform characterization include seismic reflection and refraction techniques and the use of surface waves. A recent development is the use of passive sensing approaches. The use of multiple geophysical methods, which can benefit from the sensitivity to different subsurface parameters, is becoming more common. Strategies for coupled and joint inversion of complementary datasets will, once more widely available, benefit the geophysical study of landforms.

Three cases studies are presented on the use of electrical and GPR methods for characterization of landforms in the range of meters to 100 s of meters in dimension. In a study of polygonal patterned ground in the Saginaw Lowlands, Michigan, USA, electrical resistivity tomography was used to characterize differences in subsurface texture and water content associated with polygon-swale topography. Also, a sand-filled thermokarst feature was identified using electrical resistivity data. The second example is on the use of constant spread traversing (CST) for characterization of large-scale glaciotectonic deformation in the Ludington Ridge, Michigan. Multiple CST surveys parallel to an ~60 m high cliff, where broad (~100 m) synclines and narrow clay-rich anticlines are visible, illustrated that at least one of the narrow structures extended inland. A third case study discusses internal structures of an eolian dune on a coastal spit in New Zealand. Both 35 and 200 MHz GPR data, which clearly identified a paleosol and internal sedimentary structures of the dune, were used to improve understanding of the development of the dune, which may shed light on paleo-wind directions.

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1. Introduction

To understand processes of development and evolution of landforms it is often critical to obtain information on the internal structures, composition, and below-ground dimensions. Outcrops and boreholes provide the opportunity to obtain such information with significant detail. Outcrops are usually limited, however, in spatial extent and coverage. Whereas boreholes can improve spatial coverage of subsurface characterization, cost and time constraints often impose limits. Geophysical methods, on the other hand, are uniquely positioned to non-invasively characterize the internal properties of a landform in multiple dimensions. The understanding of landform development can be even further improved by conducting time-lapse measurement to monitor ongoing processes and by combining geophysical imaging and characterization with historical records (e.g., aerial photography) and methods for age dating (e.g.,...
Recent developments in data acquisition, processing, and interpretation, have changed the use of geophysics in landform studies and geomorphology. Instead of simply providing complementary information to traditional methods of investigation, geophysical data are now more frequently used as the primary source of evidence.

Landforms can be classified according to different criteria, including size, genetic origin, geographic or climatic position, based on-landscape position, or whether they are accumulative or erosional. Geographic or climatic geomorphology is not specifically discussed in this paper, although two of the case studies address periglacial and subglacial landforms. Classes of landform sizes range from continental scale to features with dimensions of meters and smaller. Geophysical methods can play a role in the study of all landforms, including potential field methods for the study of continental scale morphology, and high-resolution imaging tools for the smallest of features. In this paper, the emphasis is on methods most applicable for characterization of landforms with spatial dimensions between meters and 10 s of kilometers. Several case studies presented in this paper are at the lower end of this range (meters to 100 s of meters).

Classifications based on-landscape position include landforms on slopes or in plains, whereas classifications based on environment include landforms in fluvial, coastal, eolian, glacial, and volcanic landscapes. In addition, landforms may be related to tectonic or other deformation processes. In any of these environments and landscape positions, landforms can form under the conditions of net accumulation or erosion, and under conditions that involve neither. Depending on the conditions and specific questions at hand, suitable geophysical methods may be available for the study of any of these landforms. Most of the examples presented in this paper address conditions of net accumulation or neither accumulation nor erosion. Geophysical methods can also play a role, however, in characterization of processes related to weathering, erosion, and denudation, as well as slope processes (e.g., Beylich et al., 2004; Leopold et al., 2008). Recent advances in remote and geophysical sensing of microbial and chemical processes in groundwater and at water-mineral interfaces (Snieder et al., 2007; Atekwana and Slater, 2009) may lead to new or improved strategies for geophysics-assisted characterization of biochemical processes in the regolith.

Geophysical tools use variations in physical properties of Earth material to characterize the subsurface (Knight and Endres, 2005); in the case of landforms the information obtained can include the type of material, the internal structures, and the dimensions. The range of geophysical methods is very broad and can be categorized based on the physical principles that govern a response, but also on whether the technique uses an active source or a passive one. No current overview exists of the state-of-the art or recent developments for a number of potential field methods and applications in the 1970s. From the 1980s, when the first commercial applications of GPR has steadily increased. Since the middle of the 1990s, the use of GPR in the 1940s but was first used for geotechnical applications in the 1970s. From the 1980s, when the first commercial systems became available (Atekwana and Slater, 2009; Casas-Sainza and de Vicente, 2009). A more thorough discussion of the technical aspects of these and other geophysical methods can be found in literature and text books (e.g., Butler, 2005; and references therein).

2. Methods

Traditionally, geophysical methods for subsurface characterization are classified as either potential field methods, including gravity and magnetics, or methods that use propagating fields, such as electromagnetic and seismic methods (National Research Council, 2000). For select methods, this section provides a brief technical background, discusses strengths and limitations, and gives examples from scientific literature of applications in landform characterization and geomorphology. Following a brief description of potential field approaches, methods that use propagating fields are addressed in more detail. Also, a brief discussion is given on the joint use of complimentary methods. This paper does not specifically discuss borehole geophysics, including single-well geophysical borehole logging (e.g., Danil and Goodman, 2007) or cross-borehole tomography (Paillet and Ellefson, 2005).

The emphasis of this paper is on terrestrial geophysical methods, although some examples given in the text use airborne and marine equipment platforms. Geophysical surveys from the air typically allow for much faster spatial coverage than most terrestrial equivalents, but the relatively high cost of data collection limits its widespread use. Nevertheless, this approach often yields results very useful for studies of landforms and (buried) landscapes (e.g., Worrall et al. 1999; Gabriel et al., 2003). Similarly, marine geophysical platforms for use in oceans and lakes are not addressed separately in this paper, but most tools available for terrestrial applications have offshore equivalents. Marine geophysical surveys are ideally suited to study drowned or buried paleo-landscapes and landforms (e.g., Amelio and Martorelli, 2008).

2.1. Potential field methods

The gravity method uses small variations in the gravitational field of Earth caused by a non-homogeneous subsurface mass distribution to obtain information on the density, depth, and geometry of subsurface features. The magnetic method measures variations in the magnetic field of Earth to obtain information on the depth and geometry of subsurface bodies with anomalous magnetic characteristics. In the context of landform characterization and landscape evolution, potential field measurements are useful for study of intrusive bodies, karst and tectonic features, and buried topography, amongst others (e.g., Wu and Bruhn, 1994; Almeida-Filhoa et al., 2009; Casas-Sainza and de Vicente, 2009). A more thorough discussion of the technical aspects of these and other geophysical methods can be found in literature and text books (e.g., Butler, 2005; and references therein).

2.2. Ground-penetrating radar

Ground-penetrating radar (GPR) has become widely used as a tool to study the shallow subsurface in a broad range of applications and settings. GPR measures changes in the electromagnetic properties of subsurface features that cause reflection of transmitted electromagnetic waves, typically in the frequency range of 0.025–1 GHz. The technique emerged in the 1940s but was first used for geotechnical applications in the 1970s. From the 1980s, when the first commercial systems became available (Annan, 2002), the use and variety of applications of GPR has steadily increased. Since the middle of the 1990s, the use of GPR in the field of Earth sciences has seen dramatic increases because of significant advances in equipment functionality and software for data processing and visualization. The use of GPR in geomorphology started with work on deltaic deposits and eolian
landforms (Jol and Smith, 1991; Schenk et al., 1993), but has spread to a much wider range of environments since then, including, amongst others, glacial landforms such as eskers, kames, and kettles (e.g., Busby and Merritt, 1999; Burke et al., 2008) and morphology associated with peat landscapes (e.g., Comas et al., 2004; Rosa et al., 2009).

The typical application of GPR involves a pair of transmitting and receiving dipole antennas in common-offset mode that are moved across the surface to generate 2D cross-sections of the subsurface (Fig. 1). Signal post processing is often limited to the removal of low and high frequency content, a static shift to correct for first arrival drift and surface topography, and the application of a gain function to correct for signal attenuation with depth. More advanced processing steps, however, can bring out additional data qualities (Cassidy, 2009).

Radar reflections result from contrasts in dielectric properties between adjacent layers, which can be induced by, amongst others, changes in textural characteristics, water content and state (i.e., liquid, frozen), and fluid conductivity. In unsaturated conditions of the near-surface, typical for many landform studies, the most prominent cause for GPR reflections is variations in water content, which can be attributed to differences in water-retention capacity. Such differences result from textural variations (e.g., porosity, grain-size distribution) or the presence of material that prevents interstitial water from draining (Van Dam and Schlager, 2000; Neal, 2004). In exceptional cases reflections can be caused by mineralogical changes (Moore et al., 2004; Buynevich et al., 2007; Girardi and Davis, 2010).

Among the most significant drawbacks of GPR is the usually poor performance in electrically conductive material, causing signal attenuation. An additional consideration is the tradeoff between penetration depth and resolution for different antenna frequencies. Although in many cases a change in frequency will not significantly alter the character of the imaged structures (Fig. 2), in situations with liquid, frozen, and fluid conductivity. In unsaturated conditions of the near-surface, typical for many landform studies, the most prominent cause for GPR reflections is variations in water content, which can be attributed to differences in water-retention capacity. Such differences result from textural variations (e.g., porosity, grain-size distribution) or the presence of material that prevents interstitial water from draining (Van Dam and Schlager, 2000; Neal, 2004). In exceptional cases reflections can be caused by mineralogical changes (Moore et al., 2004; Buynevich et al., 2007; Girardi and Davis, 2010).

Novel developments — in recent years, GPR has seen several developments and advances in equipment, novel surveying methods, and processing that have the potential to have an impact on how GPR is used for landform studies. Most major equipment manufacturers now offer multi-channel systems that can be used for a range of

![Fig. 1. GPR data collection using (A) traditional common-offset arrangement with one transmitter (Tx) and one receiver (Rx) antenna, (B) dual-channel configuration (e.g., Gerhards et al., 2008), and (C) multiple-receiver setup (e.g., Bradford, 2006). Both (B) and (C) allow for multi-offset or multi-fold data collection. The diagonal lines represent travel paths for energy from transmitter to receiver that reflects off a horizontal interface.](image)

![Fig. 2. GPR data of eolian sediment collected using (A) 100 and (B) 200 MHz antennae.](image)

Full-resolution data with un-aliased reflections in three dimensions can dramatically increase the resolution of complex stratigraphic information over conventional 2D and pseudo-3D data (Grasmueck et al., 2005). Such full-resolution 3D data acquisition requires quarter-wavelength (1/4λ) spatial sampling in both inline and crossline directions (Fig. 4). Using traditional approaches, 3D data are very time consuming to collect. In recent years, however, researchers have experimented with different approaches to increase positioning accuracy, including prism tracking (Heincke et al., 2005) and rotary laser systems (Grasmueck and Viggiano, 2007). To highlight the benefit of 3D GPR data for characterization of complex subsurface structures, a full-resolution dataset of a heterogeneous braided river deposit (Dogan et al., in review) was artificially downsampled. To represent typical pseudo-3D data (coarsely spaced parallel lines or grids), this full-resolution cube was resampled to include only lines spaced 50 cm and 1 m apart. The results illustrate that coarser sampling has relatively little effect on subhorizontal reflections (Fig. 4C, E), but strongly impacts the quality of angled reflections in vertical cuts (Fig. 4D, F) and time slices.
2.3. Electrical resistivity

Active electrical methods for subsurface characterization are numerous, but can generally be divided into those that induce currents into the ground through direct coupling or through capacitively-induced coupling. In the typically used direct coupling method, also called the galvanic source method, low-frequency alternating current is applied to the earth using a pair of electrodes that have been inserted into the ground. Two separate electrodes are used to measure the potential difference over the circuit. Using Ohm’s Law and the geometry of the used electrode configuration, the resistivity (or in the case of non-homogeneous material, apparent resistivity) can then be calculated. The electrical resistivity of a material is a measure of the difficulty of conducting electrical current, and is a complex function of textural properties, surface conductance effects of clays, water saturation, fluid conductance (–salinity), and temperature (Revil and Glover, 1998; Knight and Endres, 2005; Rey and Jongmans, 2007; Jayawickreme et al., 2010). Examples of the use of electrical methods in geomorphology can be found in the study of landslides (Naudet et al., 2008), sedimentary environments (Baines et al., 2002; Maillet et al., 2005), glacial landforms (Parke et al., 2009), and karst and caves (Roth et al., 2002; Zhou et al., 2002; Pánek et al., In press).

An alternative galvanic-source resistivity method is induced polarization (IP). The IP method uses frequency-domain phase shifts to estimate the chargeability of a medium. The capability to store energy is particularly present in certain metals, clay minerals, and fluids with high ionic content. The IP method is popular for study of, amongst others, geothermal areas. The IP chargeability can be characterized in sounding and mapping modes and provides complementary information to regular resistivity surveys; many modern instruments allow for collection of both types of data in conjunction. More details about both IP and passive methods using spontaneous potential (SP) effects and telluric currents can be found in Zonge et al. (2005).

Electrical methods have been used in Earth sciences for more than a century. Originally, the resistivity method was primarily used for depth sounding and lateral profiling, or so-called constant spread traversing (CST). Electrical resistivity electrodes can be deployed in a large number of ways, but data are often collected using standard configurations, such as Wenner and dipole–dipole (Fig. 5). Modern electrical resistivity tomography (ERT) equipment, which uses multiplexers or electronically switching (active) electrodes and sometimes multi-channel receivers, collects data for numerous electrode combinations along arrays of electrodes to generate tomographic images or maps of subsurface electrical properties (Dahlin and Zhou, 2004). ERT data collected along 2D transects are typically plotted in pseudosections, where image points correspond to the lateral position of the electrodes and to the approximate depth of investigation (Fig. 5). The depth of investigation of the various array types is related to electrode separation and configuration and also to the distribution of subsurface resistivity. Resolution decreases with increasing depth of exploration (Szalai et al., 2009).

Interpretation of ERT data requires inversion of the apparent resistivities, where through an iterative process a model is calculated that best fits the measurements (Pelton et al., 1978; Loke and Barker, 1996). Typical inversion procedures use a finite difference mesh with a starting model that can be based on the average apparent resistivity in the data set or use a-priori information, such as obtained from borehole or other geophysical data. To choose between multiple models that fit the data it is common to use smoothness constraints. Such constraints ensure that the resulting model explains the observed values to a level that is acceptable, while simultaneously avoiding large spikes in the modeled resistivity values.Constraints can also be placed on the ‘hardness’ of a-priori information. To interpret the final model in terms of the properties of interest, site-specific petrophysical relationships may need to be developed in the laboratory.

Novel developments — in recent years, capacitively-coupled resistivity (CCR) systems have seen increased use. A notable benefit of this inductive-source method is the elimination of electrodes, because currents are induced into the ground using coils that do not need to make physical contact with the ground (Christensen and
Sorensen, 2001). This can lead to a significant increase in survey flexibility and speed of data collection, although production increases can also be achieved by innovative electrode designs (Panissod et al., 1997). The CCR may be hindered by lower reproducibility than galvanic source methods. Also, CCR systems commonly use a relatively small number of electrode pairs, which limits the depth coverage. Examples of the use of CCR for geomorphology can be found in permafrost detection and mapping (Hauck and Kneisel, 2006; De Pascale et al., 2008) and characterization of fluviatile and coastal deposits and landforms (Hickin et al., 2009; Ziekur and Grelle, 2009).

A second novel development is the use of electrical methods for the monitoring of dynamic processes, which has become possible as a result in recent advances in equipment and software. Although successful examples exist of time-lapse data collection using various types of geophysical equipment, electrical resistivity methods are particularly suited for this task because permanent field installations can be achieved at relatively low cost and with minimal disturbance (e.g., Jayawickreme et al., 2010). Time-lapse monitoring of dynamic processes requires that the change in electrical properties over the time period of interest is sufficiently large, which is not always the case. Nevertheless, numerous potential applications exist for this approach. For example, time-lapse ERT was successfully used to monitor the dynamics of permafrost in rock walls (Krautblatter and Hauck, 2007; Krautblatter et al., 2010). Hilbich et al. (2008) included time-lapse ERT in a study of short- to long-term freeze-thaw processes in mountain permafrost. Time-lapse ERT has also been used to monitor resistivity distribution in landslides caused by changes in fluid saturation and hydrostatic pressure (Lebourg et al., 2010).

**Fig. 4.** (A) Full-resolution, un-interpolated GPR data cube with clearly visible sedimentary structures in the vertical cuts and in the depth slice. Time-to-depth conversion used a velocity of 0.058 m/ns. The data shown are part of a larger 3D dataset that was collected using a Sensors and Software pulseEkko100 system with 1000 V transmitter and 100 MHz antennas at the Columbus Air Force Base in Mississippi in water-saturated channel deposits (Dogan et al., in review). Data were processed using ReflexW and plotted using MATLAB. (B) Survey grid consisting of $31 \times 31 = 961$ measurement locations. The bin size of $10 \times 10$ cm ensures full-resolution ($\lambda/4$ wavelength in both inline and crossline directions) data collection for 100 MHz antennas in saturated sediment. Data were collected along inlines; arrows indicate the start of the first three survey lines. The full-resolution data in (A) were resampled to highlight the effect of lower data density on quality of imaged sedimentary structures. Data resampled to 50 cm distance for (C) crosslines and (D) inlines and to 100 cm separation for (E) crosslines and (F) inlines.
2.4. Electromagnetic induction

Electromagnetic (EM) methods for near-surface applications include several active and passive source methods that are very suitable for rapid mapping of electrical conductivity, magnetic susceptibility, or magnetic permeability variations, either in handheld, on-the-ground, or airborne modes (Tezkan, 1999; Auken et al., 2006). The measured quantity can be related to various properties of interest, including texture and fluid content. Because EM methods are especially sensitive to conductive bodies, variations in clay content, water saturation, and fluid salinity are good targets. The majority of applications of EM methods are in hydrology and mineral prospecting; its use in landform studies is still relatively rare. Electromagnetic methods can be categorized as controlled-source frequency-domain methods (FDEM) and transient or time-domain methods (TEM/TDEM). All EM data collection can be strongly impacted by nearby metal structures, such as underground cables, fences, and power lines.

Most controlled-source FDEM methods use a transmitter coil or loop to generate a continuous, sinusoidal field that interacts with the ground and with individual conductors. The secondary field, measured as a vectorial summation with the primary field in a receiving coil/loop, is used to obtain information about subsurface conductivity. The ability of FDEM systems to detect weak secondary responses requires removal of the primary field, which is difficult for systems with separate transmitter and receiver coils. Smaller systems with both coils in a rigid configuration do not have this limitation and are effective for near-surface investigations. FDEM methods are primarily used for lateral profiling, without quantitative interpretation of depth and true conductivity. The depth sensitivity and range of FDEM systems, however, can be varied in a number of ways, including by changing the spacing distance between transmitter and receiver coils, changing the signal frequency, and changing the coil orientation or instrument height. Inversion can then be used to infer vertical subsurface electrical conductivity structure (e.g., Hendrickx et al., 2003; Christensen et al., 2010).

Transient electromagnetic systems use a primary field that is pulsed instead of continuous as in FDEM systems. TEM is typically used for mapping of depth and spatial extent of conductive subsurface features. After the primary field in the transmitter coil has been turned off, a receiver coil or loop measures the time-decay of the secondary EM field. The measured response depends on the depth to and conductive properties of the target. TEM systems come in a variety of designs that all have tradeoffs between near-surface resolution and depth of investigation.

Typically, EM data are inverted with 1D models (Farquharson et al., 1999; Vallée and Smith, 2009), which benefits from a relatively small computational effort and has been demonstrated to work well when the subsurface is layered. Multi-dimensional approaches for the inversion of spatial data, which may be required in case of more complex subsurface structures, are only useful when the depth coverage is significant and station spacing sufficiently small. In recent years there has been a push for laterally constrained as well as full 2D and 3D inversion codes (e.g., Wisen and Christiansen, 2005), which will make EM methods more attractive for geomorphological research.

Examples of the use of FDEM methods for geomorphology include the study of frost wedges (Cockx et al., 2006) and sediment anisotropy (Sutinen et al., 2009). Based on the observation that a preferred orientation of (magnetic) particles and the clast fabric of tills can lead to electrical micro-anisotropy, Sutinen et al. (2009) used azimuthal measurements to determine the orientation of depositional features. Such measurements are easy to perform using most FDEM systems with fixed coil distance (as well as with electrical resistivity arrays) and can serve as complementary information to surface mapping. Airborne FDEM and TEM techniques have been used to reconstruct large-scale landscape evolution (Wilford, 2009) and to map buried onshore and offshore paleo-channels (Evans et al., 2000; Bosch et al., 2009; Steuer et al., 2009). For a 150 km² area in Denmark, Jorgensen et al. (2010) used airborne TEM data in combination with borehole data to develop a series of models of tunnel valleys.

In recent years, plane wave methods, which use signal propagation on a wave front without curvature, have been applied occasionally for near-surface and landform studies. The method, which in itself is new, requires an EM source located at a significant distance (at least 10 times longer than the wavelength) and measures orthogonal components of the magnetic field to locate anomalies (Auken et al., 2006). The EM source can be a dedicated antenna, but exists more commonly of existing transmitters in the frequency range of interest. Measurement equipment is sometimes augmented with galvanic or capacitive electrodes to measure electrical field components. Signal penetration is a function of the frequency and material conductivity. For the purpose of landform studies, anthropogenic sources that operate at radio frequencies (radio magnetotellurics, RMT) or only in the very low frequency (VLF) range of radio signals (Beamish, 2000), are most relevant. At these frequencies depths of penetration are typically on the order of meters to several 10s of meters.

Multi-frequency VLF and RMT equipment is relatively small and allows for rapid on-the-ground or airborne profiling. An additional advantage is the availability of inversion codes to obtain 2D subsurface models (Auken et al., 2006). Examples of recent studies using RMT have delineated structural features (Carvalho Dill et al., 2009) and subsurface stratigraphy (Seher and Tzekan, 2007). Beylich et al. (2004) used RMT in combination with water discharge and water chemistry data to characterize regolith thickness in a study of chemical denudation in an arctic-alpine drainage basin. VLF was used to characterize the internal structure of a mud volcano (Lin and Jeng, 2010) and for the study of faults (Gürrer et al., 2009).

2.5. Seismic

Seismic methods have long been used in Earth science research, but applications in geomorphology and landform studies have been somewhat limited. The most commonly used seismic methods are seismic reflection, seismic refraction and the seismic surface wave method. A useful summary of the theory and methods is found in Steeples (2000).

Seismic reflection — seismic reflection images of landforms have mostly been obtained from submarine and lacustrine features. For geomorphologists, such studies provide invaluable information on the
offshore extent of on-land features. The seismic imaging of sub-bottom sediments typically involves relatively high-frequency (low kHz range) acoustic sources, such as Sparker or Chirp systems. More traditional sources with frequencies in the range of 10 s to 100 s of Hz, however, can also be used (Larsen and Andersen, 2005). The depth of penetration and resolution depend on the signal frequency and vary with sediment type and characteristics (that govern velocity); in the case of the Sparker-type systems they are usually on the order of several 10s of meters and 1–2 m, respectively. Applications of marine and lacustrine seismic reflection include the study of drowned glacial (e.g., Praeg, 2003; Larsen and Andersen, 2005; Amelio and Martorelli, 2008), coastal (e.g., Akso et al., 2002), and deltaic (e.g., Baster et al., 2003; Lee et al., 2010) landforms and sediments. Also, tectonic features can be identified (e.g., Piper and Perissoratis, 2003; Larsen and Andersen, 2005).

In recent years, several new approaches have been introduced that expand the possibilities of the seismic method for terrestrial near-surface studies. Significant advances have been made in the collection and processing of near-surface 3D reflection data, adopting procedures developed in reservoir characterization (Pelton, 2005). For example, normal move out corrections on common-mid point gathers are used to determine layer velocities, layer dip, and to increase signal-to-noise ratios. Despite advances in data collection procedures (e.g., digital seismographs, cable-less geophones) and processing, however, seismic reflection will, at least in the near future, continue to require significant efforts and costs.

Seismic refraction — seismic refraction allows for the mapping of the geometry of geologic interfaces through the analysis of first arrival data recorded using an array of geophones. The primary requirement is the existence of an interface between two layers of different velocity; the lower one having a higher velocity. Seismic energy that strikes the interface at the so-called critical angle refracts in the higher velocity material at such an angle that it propagates parallel to the interface.

The seismic refraction method has been successfully applied to the investigation of glaciallandforms, including a moraine complex and a rock glacier (Otto and Sass, 2006). Seismic refraction techniques can also be used for relatively shallow studies. Hunt and Wu (2004) studied soil erosion and mass wasting on a hill in an arid climate whereas Bourne et al. (2002) analyzed the uniformity of alluvial material covering a pediment surface.

Surface waves — the surface wave method is most commonly employed in geotechnical engineering, where it is used to estimate material properties (Socco and Strobbia, 2004), usually expressed by means of a ‘stiffness’ model. This method also has applications in several non-engineering fields. The method is based on the estimation of phase-velocity dispersion curves from Raleigh wave signals that are recorded with paired vertical-component geophones. Assuming that a seismic source and receiver are spaced sufficiently far apart, lower frequency signals will arrive before higher frequency signals because the associated longer wavelengths travel deeper in the subsurface, where velocity is typically higher. Following a calculation of the phase difference for the signal recorded in two geophones (e.g., via Fourier transform), the velocity and wavelength of the seismic wave can be calculated and plotted in a dispersion curve. These dispersion curves, in turn, are used to estimate the change in the velocity of the seismic wave (–material type) with depth through inversion or comparison with forward modeling results (Steeples, 2000). The maximum depth range of the method depends on the source strength and frequency range as well as the geophone separations.

Since the 1980s, spectral analysis of surface waves (SASW) has been the primary method to estimate the vertical velocity profile. In SASW, seismic signals generated with a multi-frequency wave source are recorded with a single pair of vertical-component geophones. Alternatively, a single frequency source can be used where the spacing between both geophones is gradually increased about a central mid-point (Steeples, 2000). In modern acquisition systems, the single geophone pair is replaced with an array of geophones, which allows for multichannel analysis of surface waves (MASW). Laterally continuous data can be collected in combination with so-called land streamers. In MASW, spatial averaging results in higher signal-to-noise ratios than SASW, without significantly increasing data collection time (Park et al., 1999). Alternative approaches to obtain the dispersion curves are through multi-offset phase analysis and spatial autocorrelation methods.

Surface wave methods can be used to determine the textural properties of soils (Long and Donohue, 2007) and shallow subsurface stratigraphy (Watabe and Sassa, 2008). The method has also been employed for the study of karstic terrain and landforms (Thierry et al., 2004; Nasser-Moghaddam et al., 2007). Socco et al. (2010) use surface wave data in combination with other geophysical methods for the study of a recent rock fall. Vignoli and Cassiani (2010) discuss the use of multi-offset phase analysis for characterization of lateral subsurface discontinuities.

Novel developments — in recent years, passive sensing methods that use cross-correlation of noise records between geophones to extract information on the distribution of subsurface structures, has become more popular (Gouëdard et al., 2008). Among the prime advantages of this method is the limited weight of the required equipment, which facilitates field deployment. Although most published work deals with studies of crustal structure and volcanoes (e.g., Shapiro et al., 2005; Sens-Schoenfelder and Wegler, 2006), an increasing number of studies have considered near-surface applications. Examples include the study of depth to sliding surfaces of mass movements (Méric et al., 2007; Picozzi et al., 2008) and estimates of subsurface anisotropy and structural heterogeneities (Miyazawa et al., 2008; Picozzi et al., 2008). This field is still very much in development and significant advances are needed for this method to become widely accessible and used in geomorphologic and landform studies.

2.6. Multiple methods

In most cases geophysical data require complementary information before they can be fully interpreted. For example, in the case of GPR and seismic reflection, a time-depth conversion requires that either the velocity or the depth to specific reflectors is known. For other methods, such as ERT or EM, where inversions produce non-unique models of subsurface properties, a-priori information can limit the number of solutions and improve data interpretation. To obtain such complementary information, it is possible to use independent (non-geophysical) methods of investigation such as well and outcrop data or laboratory-developed petrophysical relationships. In other cases, the geophysical method at hand is used to obtain information needed to interpret the data. Examples of this approach include the use of normal moveout and common-mid-point measurements to determine the velocity of seismic and GPR waves, respectively.

In some cases, two or more complementary geophysical methods can enhance data interpretation. When multiple collocated geophysical data are available, it is common to use all data for a single interpretation of the subsurface. Most such approaches integrate the results of different complementary methods after independent analysis and interpretation. Independent inversion of multiple datasets can yield excellent results, and may lead to significantly better interpretations than when using a single method. Hickin et al. (2009) used a combination of ground-penetrating radar and electrical methods (as well as trenching) to simultaneously derive structural and textual information for fluvial deposits. Other examples are found in the study of, amongst others, karst features (Guérin et al., 2009), ephemeral stream sediments (Burrell et al., 2008), landslides (Jongmans and Garambois, 2007; Götürküler et al., 2008; Naudet et al., 2008; Sass et al., 2008; Jongmans et al., 2009), and buried paleo-landscapes and incised valleys (Gabriel et al., 2003; Ahmad et al., 2009; Burval Working Group, 2009; Barnaba et al., 2010).
Alternative approaches to combine geophysical data are constrained or coupled inversion and joint inversion. In joint inversion, a common objective function is minimized to obtain a single inverse model (Christiansen et al., 2007). Geophysical methods are governed, however, by different physical properties of Earth material, and the sensitivity to specific subsurface features is often different. Therefore, joint inversions can result in large data misfits. An alternative and simpler approach is the use of mutually constrained inversion of geophysical data (Wiesen and Christiansen, 2005), who discuss this approach for resistivity and surface wave seismic data. Examples of joint inversion of geophysical datasets is found in a paper by Schmutz et al. (2000), who used TEM and electrical resistivity sounding data to improve understanding of an earthflow in the French Alps (Schmutz et al., 2009). Gallardo and Meju (2003) use a cross-gradient criterion to jointly invert resistivity and seismic refraction data. It is likely that when joint and coupled inversion approaches become more widely accepted and available, they will provide benefits for high-resolution characterization of landforms.

3. Example applications

In this section three case studies are discussed that represent a small cross-section of the possible applications of geophysical tools for landform characterization and geomorphology. The emphasis of these case studies is on the use of electrical resistivity methods and ground-penetrating radar in the study of two types of (peri)glacial landforms and one sedimentary landform. These studies are all limited to landforms smaller than a few 100s of meters. The examples are placed in the context of relevant other research, including those that study a similar type of landform using a different geophysical method and vice versa. The first example discusses a study of ERT imaging of patterned ground, a feature common in permafrost landscapes. The second example is of the use of CST for characterization of large-scale glaciotectonic deformation structures. The third example covers GPR methods to study the development of an eolian dune on a coastal spit.

This section is not intended to cover all geophysical methods or all types of landforms covered earlier. For example, this section does not discuss several genetic classes of landforms, including volcanic, marine, and fluvial landforms and peat landscapes, as well as erosive and buried landscapes and regolith processes. As much as possible, the previous sections have identified published research on the use of geophysical methods for those types of landforms. Some of the approaches and methods discussed for the presented case studies may be applicable to other types of landforms.

3.1. ERT imaging of patterned ground

Non-sorted polygonal patterned ground is often an indicator of current or past permafrost conditions. The genesis of such features is not always clear, however, because different processes can result in similar forms of patterned ground and different forms of patterned ground can result from a single process. One of several genetic processes that have been proposed for the development of patterned ground is the thermal contraction-fissuring of seasonally frozen ground or permafrost. During thermal degradation of permafrost (or seasonally frozen ground), ice wedges that formed during contraction-fissuring will thaw, and can be replaced by allochthonous material (Murton and French, 1993). Patterned ground has been characterized by traditional approaches such as surface mapping and trenching, but also by geophysical methods, including GPR (Hinkel et al., 2001; Moorman et al., 2003; Munro et al., 2007; Doolittle and Nelson, 2009), EM induction (Cocks et al., 2006), electrical resistivity (Greenhouse and Morgan, 1977), or a combination of methods (Fortier and Allard, 2004; Godfrey, 2008).

In a recent study in the Saginaw Lowlands in Michigan, USA, polygonal patterned ground, attributed to paleo-permafrost, was characterized by mapping with aerial photographs, GIS and statistical methods, soils characterization, and geophysics (Lusch et al., 2009). Strongly patterned ground was found in approximately 5% (~1000 km²) of the total study area, bounded by paleo-shorelines of Glacial Lakes Elkton and Warren (Fig. 6). This constrains the formation to a period of approximately 500 years between 14.8 to 14.3 thousand calendar years before present. The majority of polygons in the study area are about 1 hectare in size, with a long axis that is, on average, double the short axis. Most polygons are oriented roughly north–south and are formed in loamy soil texture classes (Lusch et al., 2009). Sites for detailed field investigations were chosen based on aerial photographs and were located in forested areas to minimize disturbance from farming activities (Fig. 6). Soil-boring transects were completed between polygon centers, crossing at least one low-lying inter-polygon swale; the elevation differences between the polygon interiors and swales are up to 1.5 m. For each 1–2 m deep boring, soil texture, color, gravel content and sediment type was recorded. Along these transects, electrical resistivity was used to identify lateral and vertical variations in textural properties and water content, using the assumption of limited variation in the fluid conductivity of the pore water, which is reasonable for Michigan conditions (Jayawickreme et al., 2010).

ERT data collected at sites A–C showed higher resistivity in the polygon centers than in the polygon swale (Fig. 7). At sites A and B, this difference in resistivity is related to a sand cap (thin A, ~80 cm thick at B) that was located above dense till in the polygon centers. The thick sand cap at B resulted in substantially higher values of resistivity than at site A or C. Because no significant textural difference between polygon centers and swale was detected in soil borings at site C (silt-loam till extended to the surface), the difference in resistivity there is interpreted to result from a contrast in moisture content. At sites B and C, the values of resistivity are markedly different on opposite sides of the swale (for both, the values are highest on the left of the swale). This difference is likely a result of topography, with the driest conditions and, thus, highest values of resistivity for the highest elevation.

At site D, constant spread electrical resistivity profiling was successfully used to locate a high resistivity anomaly in a swale very near the location of an apparent sand-wedge cast (Lusch, 1982; Lusch et al., 2009). Fig. 8 shows the results of two parallel CST profiles; test borings prior to opening the soil pit confirmed that at a position of x = 0 m, where values of resistivity where highest, sand was present. This anomaly was excavated and confirmed to be a bowl-shaped, laterally continuous, body of sandy loam, interpreted as a thermokarst channel (Lusch et al., 2009). In this study, ERT and CST provided complementary information to mapping from aerial photos and traditional methods for characterizing soils. The data were collected in late fall, post harvest, to ensure access for fieldwork to agricultural plots. Better results could likely be achieved during the summer months, when the contrast in water content, and, thus, electrical resistivity, between polygons and swales would be larger.

3.2. CST characterization of large-scale glaciotectonic deformation

Traditional methods for characterizing glaciotectonic deformation include outcrop and aerial mapping (Boulton, 1999; Arnaud, 2008), as well as coring, borehole logging, and cone penetration tests (Bakker, 2004). Outcrop mapping can provide excellent two-dimensional information on the distribution of grain sizes, stratigraphy, and structural features, but is limited to available exposures. Remote sensing data, including satellite images, aerial photos, and derived products such as digital elevation models, have been extensively used to characterize glacial deformation structures (Smith et al., 2006). Whereas remotely sensed data allow for large spatial coverage, it does not provide direct subsurface information. Borehole methods are very useful for gathering high-vertical-resolution data on textural properties, and subsurface stratigraphy. Cone penetration tests (CPT) and direct-push measurements can be used to obtain geotechnical and
hydrological properties of the subsurface at a fairly rapid pace (Bakker and Van Der Meer, 2003; Liu et al., 2009). All borehole methods, however, are limited by the spatial distribution.

Geophysical methods that have been used for the study of glaciotectonic features include GPR (Lønne and Lauritsen, 1996; Busby and Merritt, 1999; Jakobsen and Overgaard, 2002; Bakker and Van Der Meer, 2003; Bennett et al., 2004; Sadura et al., 2006) and seismic methods (Williams et al., 2001; Larsen and Andersen, 2005). Of these, GPR may have a small penetration depth compared to the dimensions of the deformation, whereas seismic data collection can be cumbersome on-land and is, therefore, often limited to offshore transects. Electrical resistivity studies offer the opportunity to penetrate deeper than most GPR surveys, but are likely to have lower resolution. Because of its governing principles, electrical resistivity will be most useful to delineate glaciotectonic features that are associated with large textural or water content changes. Examples in the literature of the use of electrical resistivity for the imaging of glaciotectonic deformation are rare.

The work presented here focuses on an area known as the Ludington Ridge, south of the town of Ludington, Michigan, where Larson et al. (2003) described several large-scale deformation structures in a steep cliff bordering Lake Michigan. Throughout the Ludington ridge, and particularly in the cliff area, springs and gullies indicate a preferred pattern of groundwater drainage and past landslides related to this deformation. The Ludington Ridge is an elongated NW–SE extending landform of considerable height (Fig. 9). Stratigraphic units in the ridge include glaciolacustrine sediments as well as glacial re-advance tills and young eolian dune sand. The sediment below the area of interest is entirely comprised of the “lower stratified sand” unit, which reaches a thickness of over 35 m. The unit consist primarily of horizontally and cross-bedded sands, but is locally interbedded by finer units up to several meters thick. Evidence for a subaqueous origin of the unit includes drop stones and load structures, amongst others (Larson et al., 2003).

This study focuses on an area of deformation characterized by several broad synclines and narrow anticlines (Fig. 9C), which were likely formed as a result of differential loading during an ice readvance associated with the Port Huron moraine system. The anticlinal structures in the cliff face observed during this study (Fig. 9B) match those mapped previously (Fig. 9C), when lake levels where ~1 m higher and the cliff face was largely devoid of vegetation. Although primary sedimentary structures pre-dating the deformation are present in most of the folded units, they are largely absent in the center of the narrow anticlinal structures. Although Larson et al. (2003) observed that crests of the anticlines trend east-northeast and appear to form wall-like bodies that separate several broad structural depressions, it is currently unknown whether the deformation structures observed in the outcrop are isolated or continuous features, and if the latter, what is the length and orientation.

Electrical resistivity data were collected along several 2D profiles parallel to the cliff face, with the objective to exploit the large resistivity contrast between the two primary textural units in the deposit (Fig. 10). Field data were collected in electrical sounding, constant spread traverse (CST), and multi-electrode tomography modes (Aylsworth, 2008), all in Wenner configuration (Fig. 5B). The focus in this paper is on the CST data. CST data were collected using 25 and 75 m a-spacings on the beach (CST1) and 30 and 90 m a-spacings for the profiles on the top of the cliff (CST2-5); the larger a-spacings on top of the cliff were necessary to characterize deeper deformation structures. After each measurement, which consisted of reciprocal measurements (Fig. 5), the array was moved by 45 m increments (25 m on the beach); the station spacing was reduced to 15 m in areas of particular interest. The values of apparent resistivity were then plotted as a function of distance along the profile (Fig. 11). Despite high contact resistances, the collected resistivity data were of high overall quality, as indicated by generally small differences between reciprocal values and small repeat errors. An AGI Supersting Earth resistivity system (Advanced Geosciences, Inc., Austin, TX, USA) was used for data collection in the laboratory (Fig. 10) and field (Fig. 11).

The beach profile, CST1, has lowest overall apparent resistivity, reflecting the subsurface glaciolacustrine clays (Fig. 11). The small lateral variability indicates absence of any major textural differences. The profiles on top of the cliff (CST2-5) show much more spatial variation in apparent resistivity, related to the presence of deformed clay structures or other heterogeneities. The results indicate that at least one of the narrow anticlinal structures observed in the cliff has
an inland extent; for the structure at 600 m north of Chauvez Road, a WSW to ENE orientation of the deformation structure can be interpreted from the CST data by following the lowest apparent resistivity data from the cliff to inland (indicated with arrows in Fig. 11). The large-amplitude anomaly observed in CST2 coincides with the northernmost cliff structure, but its inland extent (profile CST5) is less evident. This suggests that the structure pinches out or changes in character or dimensions. Overall, the measurements of electrical resistivity contributed to a much improved understanding of the subsurface structures.

3.3. GPR imaging of an eolian dune

GPR is probably the most commonly used geophysical method to characterize near-surface sedimentary landforms, particularly in the absence of significant amounts of clayey material. The signal response depends on variations in water content or porosity. In combination with dating techniques, such as optically stimulated luminescence (OSL) or \(^{14}C\) dating, GPR imaging has been used to help unravel the depositional record of depositional systems. Examples include studies of, amongst others, eolian dunes (Bristow et al., 2010), coastal sediments (Van Heteren et al., 1998; Nielsen et al., 2009; Johnston et al., 2007), river deltas and fans (Pelpola and Hickin, 2004; Winsemann et al., 2009), fluvial deposits (Bridge et al., 1998; Vandenberghe and Van Overmeeren, 1999; Wooldridge and Hickin, 2005; Sambrook Smith et al., 2009) and glaciofluvial material (Fisher et al., 2003).

Here, the results of a GPR study into the stratigraphy and development of a large active solitary dune on a coastal sandspit in New Zealand are presented (Fig. 12). Interdune flats make up about 70% of the total area, which is characterized by outcrops of a Late Pleistocene paleosol that underlies the dunes and interdunal areas (Van Dam et al., 2003a). Organic material in the paleosol suggests that the spit was densely vegetated at the time of formation. The now semi-consolidated paleosol formed in a sequence of beach and dune
sediments. Subaerial exposure of the paleosol has led to an irregular weathered surface, which causes signal diffraction of the higher frequency GPR signals. A couple of hyperbolic reflections associated with this feature are identified in Fig. 13. The clastic sedimentary material on the spit consists primarily of fine sandy quartz. The dominant wind direction in the region is from the southwest with an important component of secondary winds from the northeast to southeast (Van Dam et al., 2003a). Detailed sediment transport dynamics on the spit, however, are not known. Unusually high quality (deep penetration, low noise) GPR data were collected using a GSSI SIR 2000 system with 200 MHz bistatic antennas triggered by an odometer wheel and a manually triggered 35 MHz monostatic antenna. The 200 MHz data were minimally processed in RADAN-NT (Geophysical Software Systems, Inc.) with a time-zero correction, horizontal stacking, distance normalization, and gain. The 35-MHz data were further processed using a high- and low-pass filter and migration.

The GPR images reveal three phases of dune development. The oldest part of the dune (the core) below the small plateau at ~90 m is characterized by cross-strata sets of maximum 1.5 m thickness (Fig. 13). These cross-strata sets are separated by gently dipping bounding surfaces with concave-upward shapes. The cross-bedding appears to be mostly eastward dipping at varying degrees of steepness. Foreset dip direction, however, could be oriented at an angle to the GPR survey line. Because of this uncertainty it is recommend that GPR data is collected in perpendicular lines or in a grid pattern (e.g., Van Dam, 2002). The sediment body between 0 and 70 m forms the main part of the dune. This section contains large cross-strata sets with thicknesses of up to 5 m. Cross-bedding is mostly westward dipping at or near the angle of repose. This apparent westward migration of the dune is still active (Fig. 14), while some reactivation has occurred near the small plateau at ~90 m. Lateral expansion to the north and south was observed in a perpendicular GPR survey line near the dune crest (Van Dam et al., 2003a), which indicates a possible change in dominant wind direction.

4. Conclusions

In this paper, an overview of the use of geophysics for landform characterization is given. This summary should benefit the
geomorphological research community because in recent years rapid developments in hardware and software have resulted in new and improved acquisition techniques, data processing strategies, and methods for visualization and interpretation of results. The paper presents an introduction to a range of different methods and includes basic theory and applications, literature examples on the use of these methods in geomorphological research, and novel developments. In addition to an introduction to the various methods, this paper presents three case studies. Geophysical methods are typically classified as either potential or propagating field methods. Potential field methods are not a focus of this paper, although several possible applications exist in landform studies for gravity and magnetics. Examples of this include, amongst others, the study of buried valleys, karst, and fault-related landforms. Geophysical tools that have been discussed in detail in this paper are GPR, electrical resistivity, electromagnetic induction, and seismic methods, which are all propagating field methods. The previous sections allow for some discussion of the possibilities and limitations of different geophysical methods for landform studies.

Ground-penetrating radar has become a popular method for study of the shallow subsurface in a wide range of areas, and is especially successful in resistive sediments. Advantages of GPR are the relative ease of use and the limited processing that is required for basic data interpretation. A potential drawback of GPR is the sometimes limited signal penetration, particularly in conductive sediments; a lower frequency can increase penetration but results in a lower resolution. Recent advances of GPR include the use of multi-offset systems to improve signal-to-noise ratios, collect continuous common-shot gathers, or increase data collection efficiency. Another recent development is the increased use of 3D data to image complex subsurface environments. A case study was presented that used GPR to image internal structures of an eolian dune on a coastal spit in New Zealand. The GPR data clearly identified a paleosol below more than 10 m of sediment at the dune base and found evidence for its subaerial weathering prior to the existence of the dune at that location. Internal sedimentary structures, including foresets and bounding surfaces that were imaged in great detail, were used to trace back the development of the dune.

Electrical resistivity methods have been part of the geophysical toolset for a long time. Recent advances, including the availability of multi-electrode systems and easy-access data processing software have made electrical resistivity tomography a popular tool for subsurface imaging studies. In the context of landforms, ER methods can provide important information when substantial variation in electrical conductivity exists in the subsurface related to, for example, deformation and transition from sediments to bedrock. A recent advance is the development of novel approaches (equipment, software) to monitor dynamic processes through time-lapse measurements. Although not in all dynamic systems sufficient change in electrical properties occurs in the time period of interest, numerous potential applications exist for this approach. Another recent advance is the use of capacitively-coupled resistivity systems that do not require electrodes to be planted in the ground, as in the more common galvanic source method. Although the method has a few drawbacks, including potentially poor reproducibility and a more limited depth of investigation than traditional ER, it allows for much faster spatial coverage. Two case studies from field sites in Michigan

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Fig. 11. Apparent resistivity data collected in constant spread traverse (CST) mode for five transects across the Ludington Ridge; the transect positions are given in meters north of Chauvez road (see Fig. 8 for locations). The resistivity values above 2000 Ωm in CST2 are likely influenced by the close proximity to the cliff face. Note the different vertical scale for CST1. Surface topography is given for all transects, except CST1, which was flat.
were presented. In a study of patterned ground, ER tomography was used to characterize subsurface textural and water content differences below polygons and the adjacent swales. At a site with large-scale glacio-tectonic deformation, constant spread traversing was successfully used to map the spatial extent and orientation of narrow clay-rich anticlines.

Whereas electromagnetic induction methods have been used for a long time for environmental studies, examples from landform studies are relatively sparse. Controlled-source EM methods are very well suited for fast spatial mapping of variation in subsurface electrical conductivity. Frequency and time-domain equipment can also be used, however, to obtain information on the vertical variation conductive properties. Vertical resolution and detail is typically less than with other geophysical methods. EM data collection is fast, but data quality can be hampered by the presence of power sources and nearby metal. Examples of the use of EM induction methods for landform-related research include the mapping of buried paleo-drainage, the characterization of sediment anisotropy, and the identification of subsurface discontinuities such as faults. In recent years, several novel uses of plane wave EM have been developed for the study of landforms and landform processes. To estimate variations in resistivity with depth, plane wave EM methods record signals from distant sources, such as military VLF transmitters or AM radio antennas, at different frequencies. Although this method has drawbacks, plane wave EM data collection is relatively cheap and equipment can be lightweight.

Seismic methods for landform characterization include seismic reflection and refraction techniques and the use of surface waves. A strong benefit of seismic methods over other geophysical methods is the penetration depth. As a ray-based method, similar to GPR, the reduction in resolution with depth is much smaller than compared to ER and EM methods. Because on-land data collection of high-resolution seismic data is time consuming and costly, the majority of landform studies using seismic reflection methods are found in offshore settings. Nevertheless, work is ongoing to make high-resolution seismic data more accessible. Seismic reflection is ideal for the spatial (horizontal and vertical) mapping of layer interfaces and has, for example, been used to study the sliding surface below mass movements. Seismic surface waves have traditionally been used as a tool to estimate subsurface engineering properties, which are related to the texture. Typically, seismic surface wave data collection is simpler than seismic reflection, and examples illustrate successful applications in landform-related studies. A recent development in seismics is the use of passive sensing approaches, which benefit from the limited equipment weight, facilitating field deployment. Near-surface applications are still sparse, but recent research indicates the applicability of the method for depth to-interface and subsurface anisotropy and heterogeneities studies.

Geophysical tools have proven to be of value over decades, for independent studies of the subsurface and in conjunction with complementary approaches and techniques. Despite all technical progress, however, geophysical methods will not be able to provide all desired information in all circumstances. Therefore, the search for new strategies that maximize the information from geophysical data needs to continue. One of these areas is use of multiple complementary geophysical methods, which can benefit from the sensitivity to different subsurface parameters. In addition to separate interpretation of multiple datasets, increased research into coupled and joint inversion strategies has shown promising results that, if more widely available, will be of benefit in the study of landforms.

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