

Feature

Airborne LiDAR reveals a spectacular landform record

Long-term preservation of landforms produces a geological record that can be used to unravel past Earth surface processes in space and time. Identification and analysis of landforms has been revolutionized by the availability of high-resolution (metre-scale) topographic survey data covering extensive areas, using Light Detection and Ranging (LiDAR). Airborne LiDAR has been in widespread use for over two decades; but due to increasing availability of data, some regions are only just beginning to be 'explored' in this way. In this article, we showcase high-resolution topography derived from airborne LiDAR survey data across South Island, New Zealand. We evidence a variety of tectonic, glacial, fluvial, hillslope and other landforms hitherto undetected within mountainous areas and beneath forests. We discuss how the characteristics of shape, size, position and association can differentiate landforms from one another, and how combinations of landforms enable landsystems to be identified that are diagnostic of past environmental conditions.

Landforms are the product of both contemporary Earth surface processes and those of the past. The preservation of landforms provides a geological record of those processes in space and in time. Glacial landforms in particular can be grouped into 'landsystems', or ground models, which are diagnostic of past glacial extent and behaviour. However, these landsystems often occupy very extensive areas across inaccessible terrain. Therefore, high-resolution remote sensing of topography has revolutionized our ability to identify landforms for landsystems analysis. The identification and classification of landforms depend on expert judgement of how a landform can be defined in terms of its shape, size, position and association, which can be gained remotely, and its surficial texture and internal composition where field surveys are possible.

Airborne LiDAR

High-resolution topographic survey data can be acquired using: (1) optical wavelength laser scanners that are either mounted on tripods or on airborne platforms, usually light aircraft (Fig. 1); or (2) a Structure

from Motion with Multi view Stereo (SfM-MVS) workflow that uses multiple overlapping images from a camera that can either be handheld and moved around or mounted on an airborne platform such as a drone. A Light Detection and Ranging (LiDAR) instrument comprises a laser, a scanner and a specialized GPS receiver (Fig. 1). LiDAR is a remote sensing method that measures the time taken for a pulse of light to hit a remote object and to reflect and (partially) return to the sensor. Because a laser travels at the speed of light, which is a constant, and because a laser is a very narrow beam, hence with a very small target area even at distances ~1 km, the time for a signal return can be considered along with the horizontal and vertical angles to compute distances to the object and, therefore, the remote 3D position of that object. The pulses are sent thousands of times per second as the instrument scans across a field of view; thus, a 3D point cloud is built up of the remote object. The intensity of the returning signal is largely dependent upon the material properties, but the utility of these data is not considered further in this article. Rather, we focus on the precise 3D information that can be gained by filtering a point cloud because

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Fig. 1. Terrestrial laser scanner (TLS), airborne laser scanner (ALS) and the gridded derivatives from the point clouds (from Carrivick *et al.*, 2013).



some laser returns come from the ‘first’ targets, such as on a forest canopy, and others come from the ‘last’ targets, which will be the bare ground. Raw point clouds have 3D points (a type of geospatial data based on X, Y, Z coordinates known as vectors) that are distributed unevenly in space. However, many types of spatial analyses are more easily achieved and are more efficiently performed on regular elevation grids (i.e. a raster format) called a digital elevation model (DEM). DEMs can be displayed using a standard technique called ‘hill-shade’ which uses a grayscale to represent the terrain as if it were illuminated from the north-west, which visually aids interpretation of the shape of the land surface (Fig. 1).

National survey campaigns

Owing to the expense of aircraft, airborne LiDAR is typically gained via national survey campaigns. The utility of airborne LiDAR for the whole range of geoscience disciplines and applications has promoted national survey campaigns in many countries. The timing and location of these surveys depend on national strategy; for example, in the UK, the [Environment Agency](#) prioritized surveys over riv-

ers and coasts between 2017 and 2023 so as to use the precise elevation datasets for flood risk analysis. Some countries, such as Switzerland, have already started to repeat surveys ([SwissTopo](#) plans between 2024 and 2029) first made between 2017 and 2022 to enable elevation changes to be detected in unprecedented spatial detail across whole landscapes. [Land Information New Zealand](#) (LINZ) is presently mid-way through gaining near-national coverage airborne LiDAR data. That progress is especially exciting because the New Zealand landscape, especially the Southern Alps, has a spectacularly rich landform record reflecting the interplay of climate, tectonics and geology on topography and hence the control of Earth surface processes spanning predominantly glacial, fluvial and hillslope terrain.

Exemplar landforms across the Southern Alps, New Zealand

Here we showcase some of the landforms that have been recently revealed using airborne LiDAR data from the Southern Alps. We include hyperlinks for some directly related, easily-accessible online resources and more information.

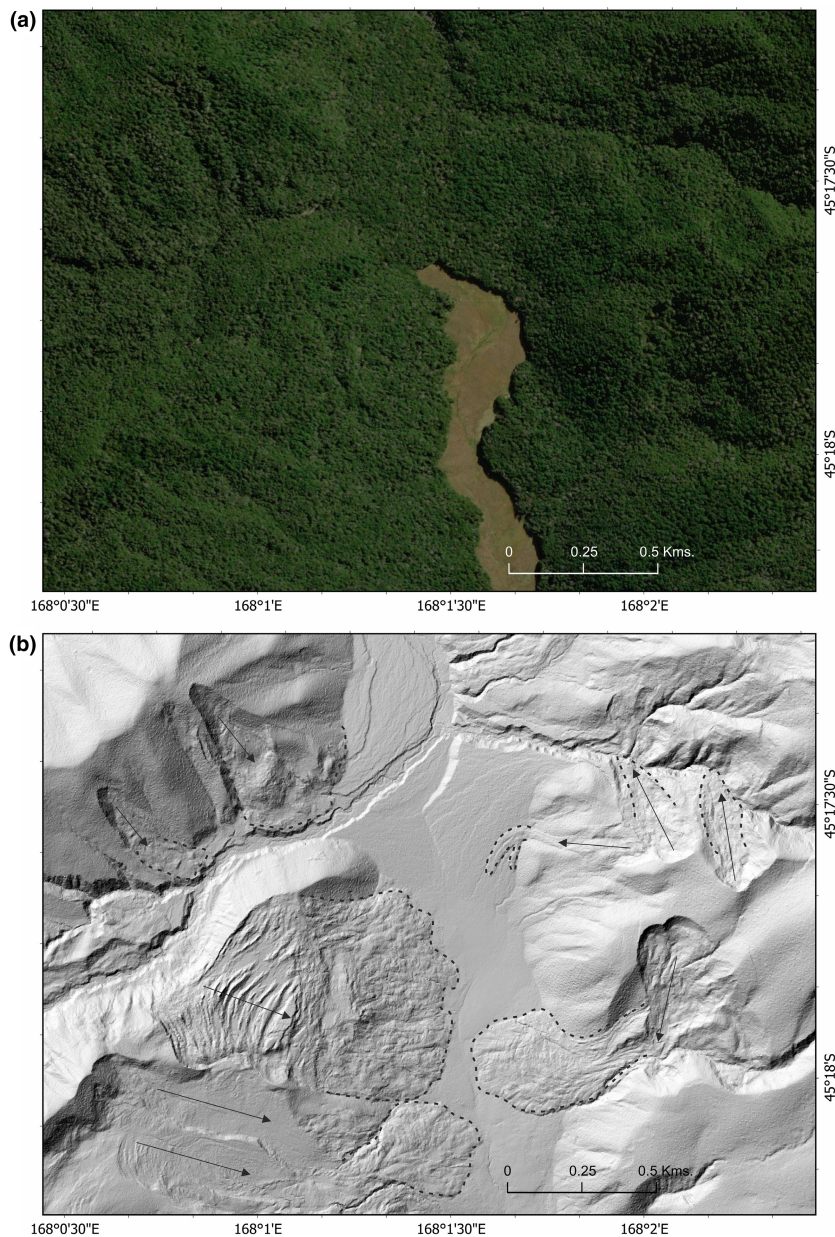


Fig. 2. Landslides in a valley immediately west of the mountain Snowdon, about 25 km east of Te Anau. These landslides, which are mostly hidden by trees (a), are demarcated by pronounced head scarps, slide surfaces (arrows) and a convex bulge of hummocky deposits (dashed outline, b).

Landslides

A canopy of pristine native forest between Te Anau and Queenstown (Fig. 2a) hides surprising and impressive landslides. Indeed, whether these particular landslides have been detected at all, let alone studied in such spatial detail before, seems unlikely without the recently available LiDAR coverage. Each landslide has the following: 1, a head scarp, where material has pulled away from a hillside creating a tension crack several tens of metres across; 2, a main body slide that has slope-parallel minor ridges reflecting a fluid type motion; 3, hummocks caused by material piling up as it decelerates; and 4, lobate arcs each relating to a major flow event. The surface patterns of these landslides suggest that they

are composites of material that has moved both during several different sudden and short-lived episodes, perhaps associated with an earthquake or with an intense precipitation event, for example, as well as with continuous creep type movement. Some of the landslides depicted in Fig. 2 have partially blocked valleys, causing rivers to re-route slightly and/or cut through the deposits. The landslide runout distance is determined by the drop, the height from which the landslide started, the type of material that has moved and the fluidity of motion, which depends on the water content. If the failing debris is dry, it forms a debris fall. Increasing water content in failing debris results in slumps and slides, and ultimately, with the highest water contents, debris flows. An example of a rockfall, and one that has produced impressively distinct hummocks composed of very large boulders that fell, bounced and rolled away from the hillside, is depicted in Fig. 3. The various types of movement that have been responsible for each of the landslides in Fig. 2 are clearly demonstrated by their morphology. Landslides have killed over 1,800 people in New Zealand within the last 200 years, which emphasizes the importance of analysing datasets such as LiDAR-derived DEMs of where and how landslides occur. Government research institute mapping of landslides across New Zealand can be viewed online at <https://data.gns.cri.nz/landslides/wms.html>; see if you can find the landslides in Fig. 2!

Tectonic fault scarps

The Alpine Fault that runs along the length of South Island, New Zealand marks a major and complex transform plate boundary. However, the vertical and horizontal movement along this boundary occurs across a swathe of mountains tens of kilometres wide, producing major faults that criss-cross the terrain. While some indication of the large-scale movement is now well constrained by a network of continuous differential Global Positioning System receivers, the native forest tree cover on the west coast (Fig. 4a) hides details of the fault structures. It is not until the acquisition and processing of airborne LiDAR data that the structural detail (Fig. 4b) and, hence, a visual impression of the precise nature of the movement can be obtained. In terms of crustal geology, the 100-m high hill in Fig. 4 is on the boundary between the Zealandia Western Province Median Batholith and the Zealandia Eastern Province terranes. In terms of surface geology, it is composed of massive to cross-bedded, weathered, greywacke conglomerate with sandstone interbeds and mudstone units, largely derived from the Caples Formation. The surficial hillsides are composed of a series of v-shaped dendritic planform fluvially-incised valleys, but the skyline/ridgeline is split by multiple parallel scarps, predominantly on the western side (Fig. 4b), which are a result of ancient (no longer active) slips

Fig. 3. A huge rockfall in Upper Matakītiki River has left sharp-crested hummocks radiating out from a debris fan and a deep-seated scar high up on the hillside above.

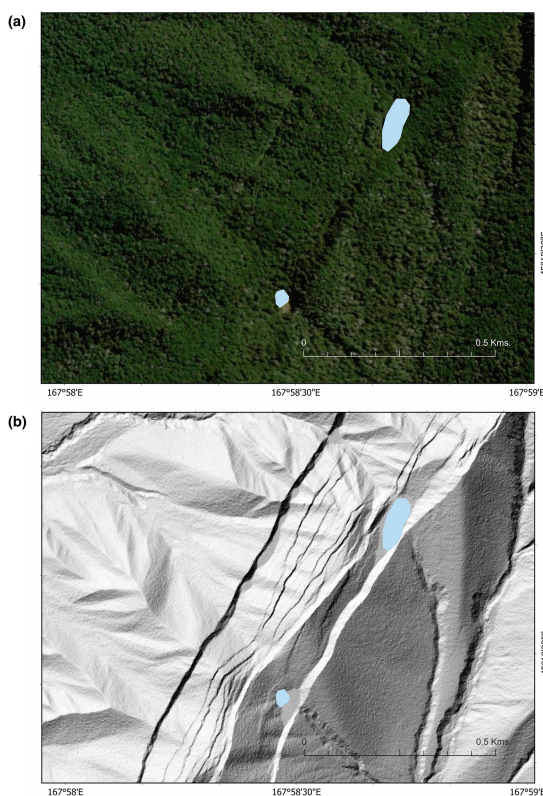
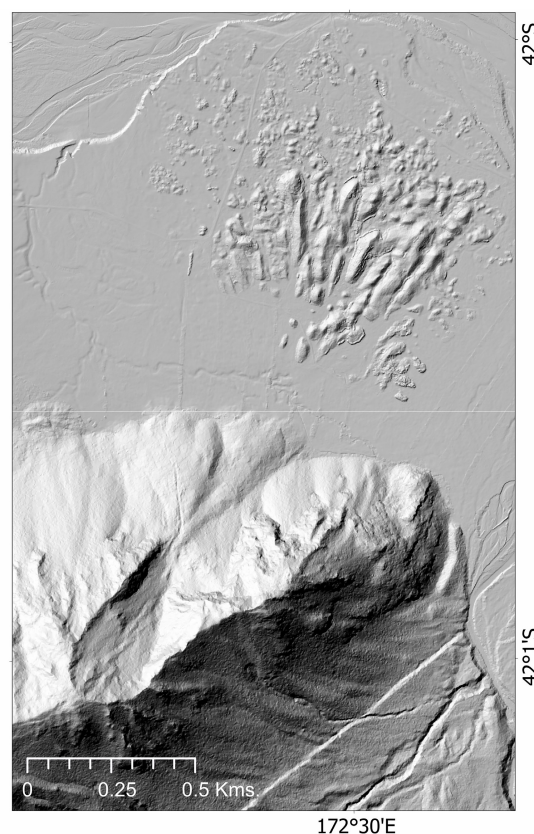


Fig. 4. Tectonic activity mostly hidden by ancient forest (a) and manifest in fault scarps along a ridgeline, 20 km east of Te Anau (b).

along the geological planes between the greywacke and the interbeds. On the eastern side of the ridge, the association of two stream gulleys each with a scarp-dammed lake at their head is notable (Fig. 4b).

Glacier moraine ridges

The Last Glacial Maximum (LGM), which was between 28,000 and 19,000 years ago, featured outlet glaciers draining from an icefield that stretched across most of the Southern Alps. Many of those outlet glaciers on the west coast terminated in the sea, but some, such as at the present-day Lake Kaniere (Fig. 5a), terminated on land. The major outlet glacier widened, straightened and deepened its valley, leaving a basin that is now filled by the lake water as well as by voluminous glaciifluvial sediments that were transported by meltwater from the retreating glacier. As the glacier retreated, it episodically held its terminus position (a stillstand), possibly in response to climate perturbations and sediment being transported both upon and beneath the glacier eventually formed a pile of material called a moraine ridge along the glacier margin. Moraine ridges are often mapped and correlated between valleys to reconstruct glacier extent and responses to climate. The size (volume) of a moraine ridge depends on the amount of time that the glacier

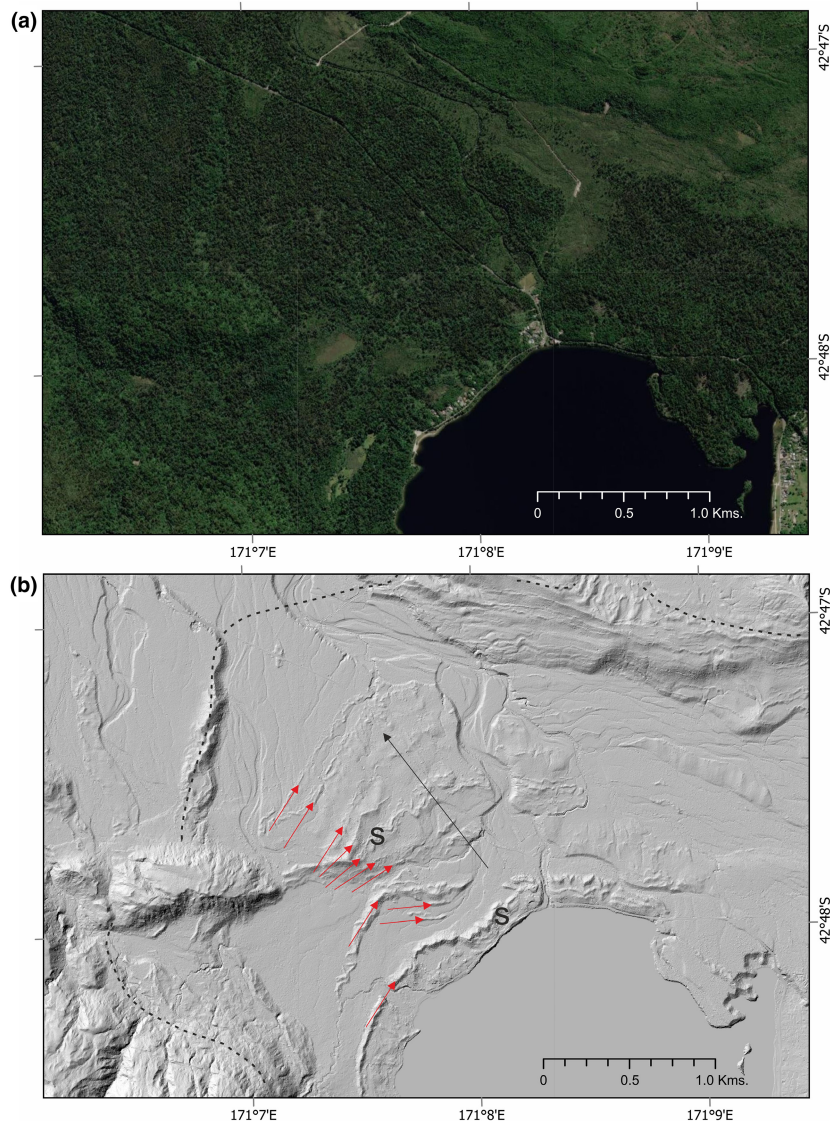


Fig. 5. Lake Kaniere, located about 20 km southeast of Hokitika and surrounded by native forest (a) is fronted by multiple, sub-parallel ridges of glacial sediment or sawtooth moraines (b). Major moraine ridges produced by an outlet glacier (flow direction towards the north-west indicated by black arrow) during the Last Glacial Maximum are indicated by a dashed black line, and a series of recessional moraines by red arrows.

margin is stationary, the transfer of mass through the glacier to its margin and the concentration of debris in the ice. The shape of a ridge crest, or its planform pattern, is determined by the shape of the glacier margin. If the glacier snout is heavily crevassed and hence possesses a crenulate margin, then the ridge is often sawtoothed (labelled 's' in Fig. 5b). The character of the sediment in the moraine is indicative of the transport pathway through the ice; rounded rocks tend to be produced by abrasion at the bed of the glacier, whereas rocks transported on the surface of the ice remain angular. This latter issue is somewhat complicated in tectonically active mountains, such as the Southern Alps, for rockfall or landslide material can get delivered onto glaciers, subsumed within them and arrive at the terminus as a short-travelled slug of material. A moraine composed entirely of such material can often represent merely the arrival of rockslope failure debris at the glacier snout rather than the construction of

a moraine ridge due to a climatically induced glacier stillstand.

Glacifluvial landforms

On the eastern side of the Alpine Fault and of the Main Divide of South Island, some glaciers draining from the Southern Alps onto the Canterbury Plains (Fig. 6a) during the LGM have left a rather different glacifluvial signature. This constitutes subglacial meltwater deposition rather than that usually associated with ice-marginal moraines. It is still extremely difficult to see these landforms in an aerial photograph, despite there being no forest cover, as the area appears as channels of gravel deposits, grass and tussocks (Fig. 6a). The low-lying, lobate and relatively thin glacier that occupied this area during the LGM was transporting vast amounts of sediment, most of which was carried by abundant meltwater. The subglacial meltwater at the base of the glacier enabled it to flow relatively quickly, moulding and streamlining sediment as it passed over and around it to form streamlined landforms called 'flutings' (Fig. 6b). Where meltwater was concentrated in subglacial tunnels, the sediment piled up into sinuous ridges called 'eskers' (Fig. 6b). The numerous small hummocks that are chaotically distributed and often conical in morphology (Fig. 6b) are composed of fine-grained material and hence are classified as kame and kettle topography produced by ponded meltwater in and around the increasingly stagnant and downwasting glacier snout. Other evidence of ice stagnation comes from the numerous pits or circular depressions called 'kettles' or 'kettle holes' that are distributed across parts of the braided river outwash surfaces, known scientifically by their Icelandic name 'sandur'. Kettle holes on the sandur were formed by the *in situ* melting of blocks of glacier ice that became isolated as the outwash gravels built up or 'aggraded' around and over them.

Fluvial terraces

Tectonic uplift of the order of several centimetres per year on the Alpine Fault serves to gradually but persistently steepen mountainsides. As the Southern Alps geology tends to be friable rock, the steep hillslopes are continuously liable to collapse due to a combination of frost-shattering and intense rainstorms. These hillslopes and thus valley gradients also dictate the energy of rivers and thus of fluvial sediment transport. Aggradation of valley-fill sediments occurs as fluvial energy diminishes through time or downstream. Furthermore, sea level rise of ~120 metres as the LGM has raised the South Island coastline elevation and base level of rivers, causing a reduction in overall long-profile gradient and, therefore, a

Fig. 6. Lake Emma and its environs, located immediately southeast of Lake Clearwater. This is an inter-montane basin located 40 km from the Main Divide, perched ~100 m above the Rangitata River, and is superficially composed of gravels, grass and tussock plains (a). The gravels are glaci-fluvially derived and include outwash plains, kames, eskers and kettles (b). Where the former glacier bed has not been reworked into glaci-fluvial deposits, it appears streamlined due to the occurrence of flutings.

loss of energy and subsequent sediment deposition. Superimposed on those effects is deglaciation, which supplies meltwater and sediment to a fluvial system. Glacier-fed rivers tend to be powerful and sediment-full in summer during the melt season, but far less so in winter. The fluctuations in meltwater discharge and sediment transport energy can be exceeded many times by episodic glacier floods, some of which probably routed along the Rakaia (Fig. 7a). Fluvial terraces can reflect these long-term and short-term river discharge regimes. It is possible to recognize at least six sets of terraces in the Rakaia Gorge on Fig. 7b.

Perspective and outlook

Overall, it is truly remarkable that such spectacular clarity and rich variety of landforms have been preserved across South Island, New Zealand, for so long. High-resolution topographic information obtained over very large areas is revolutionizing the identification of such landforms and our understanding of earth surface processes, both past and present. While the examples in this article are single survey datasets, many further opportunities are presented by surveys that are repeated and thereby enable the detection of

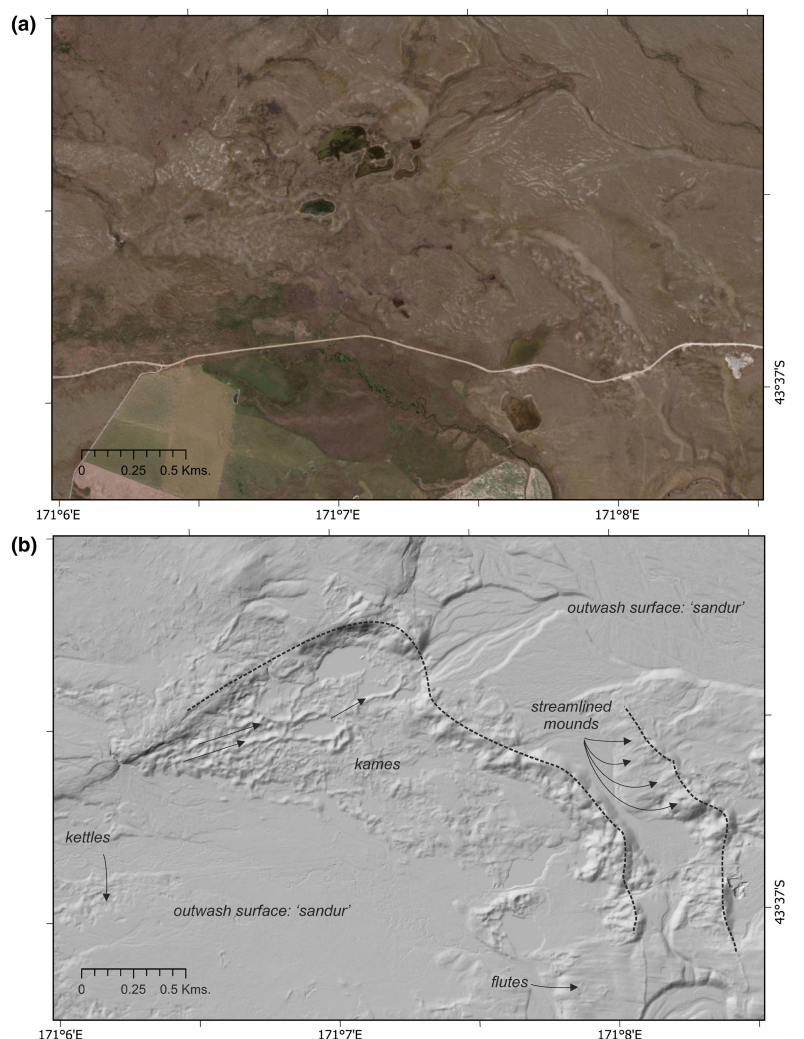
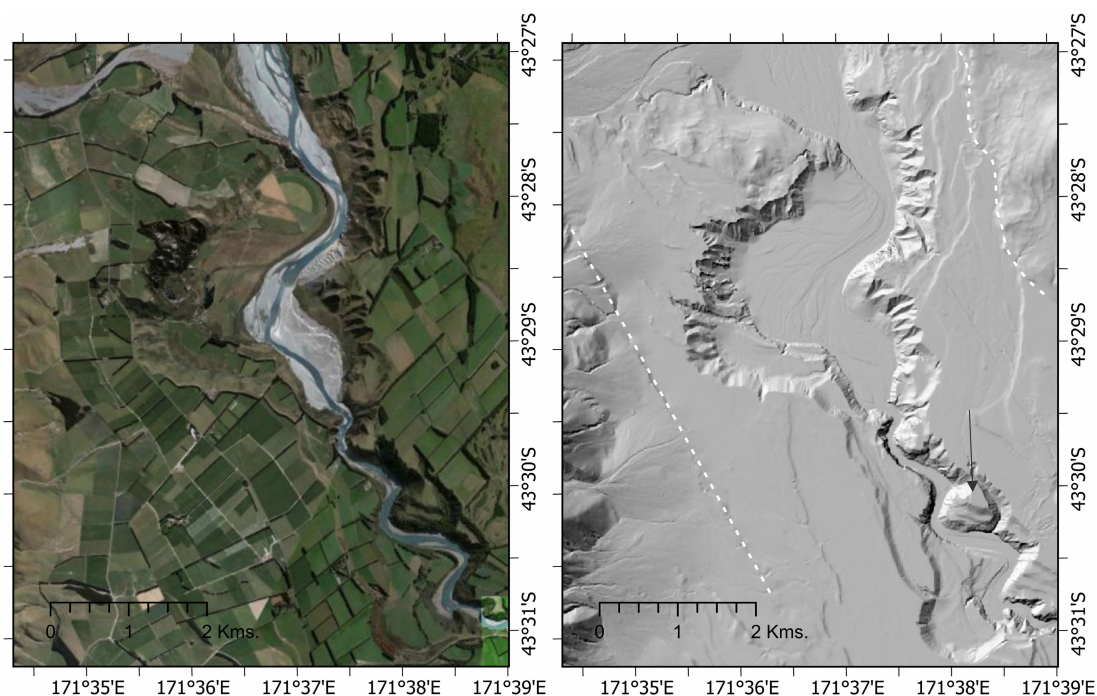


Fig. 7. Fluvial terraces in the Rakaia Gorge. Each terrace represents a phase of fluvial sediment aggradation, caused by a combination of long-term sea-level rise as the LGM and deglaciation characterized by glaciers retreating farther up valley. Incision of the terraces is due also in part to long-term tectonic uplift and episodic high-magnitude floods. The dashed white line in panel b marks the boundary between alluvial hillslope and fluvial valley-fill sediments. The black arrow indicates an 'island' or a remnant of a channel avulsion caused by the river abandoning the east side of the channel.



changes over space and time. The accuracy and precision of airborne LiDAR are good enough to detect changes at sub-metre scales in elevation, perhaps even to just 0.1 m. This means that landslides are not just identified and characterized, but the deformation, both horizontal and vertical, can be quantified for every point in a cloud or every grid cell in a DEM. Tectonic faults that are active can be assessed for displacement direction and rates. Riverbank failures, river channel avulsions, and hence channel stability can also be quantified.

With additional processing, moraine ridges can be quantified in an objective and repeatable manner, rather than being mapped entirely by hand (Fig. 8). This quantitative analysis can refine classifications of moraines, semi-automate the mapping process and enable inter-site comparisons more efficiently and robustly. The resulting classifications can then be used for interrogation of the original point cloud for texture analysis; for example, local roughness, which is a proxy for grain/clast/boulder size.

The utility of these datasets and processing of them is not restricted to scientific enquiry concerning landscape and landform evolution. Geologists have an applied interest in the Earth's surface, especially where it is rapidly changing, for mitigating and living with natural hazards, for resource management and for co-concerns of environmental, industrial and tourism activities. For example, New Zealand's multiple agencies and authorities must deal with earthquakes, landslides and floods annually, and understanding and responding to those events demands up-to-date high-quality topographic data.

Acknowledgements

The background satellite imagery is provided by Maxar and was obtained via Esri ArcGIS Pro base imagery. The hillshaded DEMs were created from LiDAR data made available by Land Information New Zealand (LINZ). Information on the tectonics and geology of South Island was obtained from GNS science.

Suggestions for further reading

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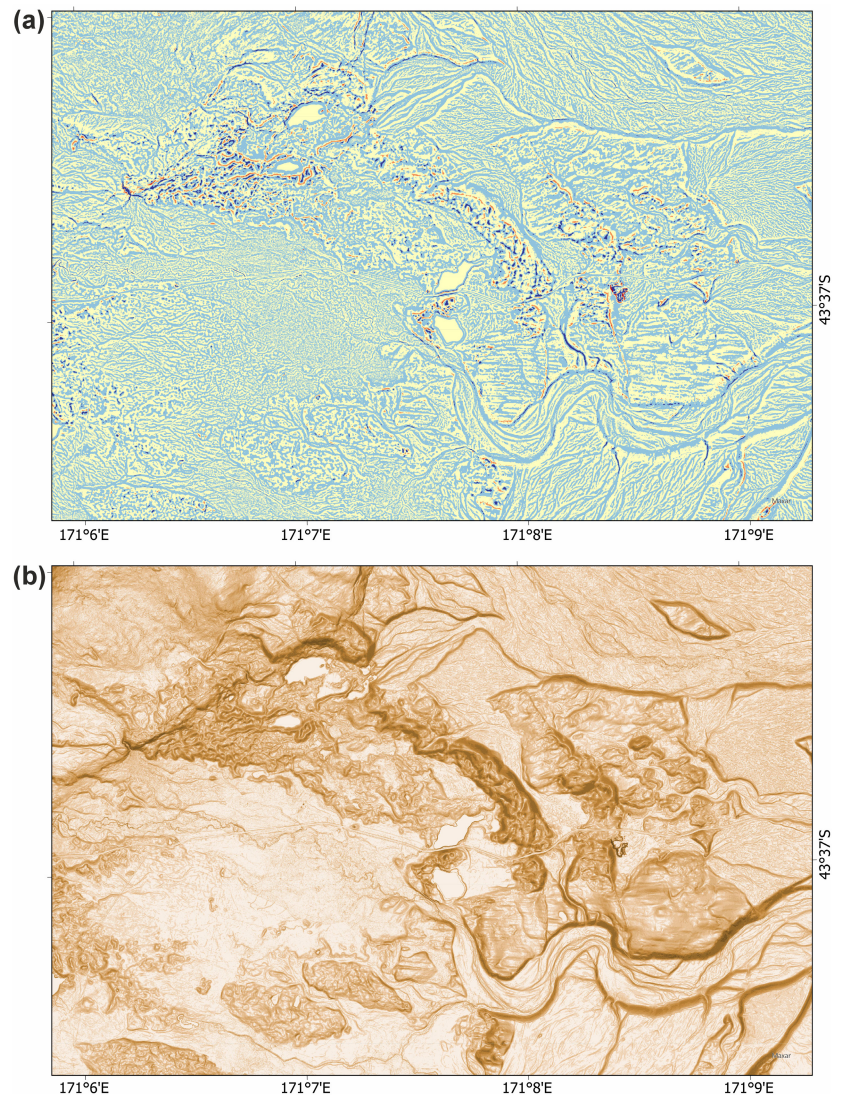


Fig. 8. The difference between the LiDAR-derived DEM and a detrended surface of that DEM, for the same area as in Fig. 6 (a). This processing removes the regional slope and reveals minor terrain deviations; 1 m over in red and 1 m under in blue (i.e. breaks of slope that are minor troughs and ridges, respectively). Slope is a derivative of elevation, and when classified reveals texture such as smooth versus rough areas, and streamlining, as well as edges of landform units (b). It is interesting to check here which landforms we can identify and measure geometrically using these two datasets.

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