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W. BRIAN WHALLEY [1*]

MAPPING SMALL GLACIERS, ROCK GLACIERS AND RELATED FEATURES IN AN AGE OF RETREATING GLACIERS: USING DECIMAL LATITUDE-LONGITUDE LOCATIONS AND 'GEOMORPHIC INFORMATION TENSORS'

ABSTRACT: WHALLEY W.B., *Mapping small glaciers, rock glaciers and related features in an age of retreating glaciers: using decimal latitude-longitude locations and 'Geomorphic Information Tensors'.* (IT ISSN 0391-9838, 2021).

The need to study and record small, vanishing or vanished glaciers, moraines and rock glaciers, is examined with respect to climate changes since the Little Ice Age maximum. Geo-location, rather than just naming a location or inventory entry, should be used to allow comparisons with earlier records (in papers, as maps, images and inventories) and in subsequent research. Geo-locations can be given as metadata in texts, tables and figures with a decimal Latitude-Longitude (dLL) specified as a comma separated string. Linking a dLL to a topographic feature allows identification of and searching for landscape elements in a landsystem with a precision given by the decimal places used. Google Earth^{TM} provides a convenient way to find a dLL as well as examine landform elements and relationships between those elements. A dLL defined location can also act as an origin for a transect, with a bearing incorporated as a three-element csv string. Locations and bearings can be derived from Google Earth^{TM} as well as displayed on images. Information, such as slope elements, can be added to a transect to give a geo-referenced 'geomorphic information tensor'. Examples show how these devices can be used to explore connectivity relationships between rock glaciers, debris-charged small glaciers and ice patches. This has implications for future mapping and inventories such as the Randolph Glacier Inventory as well as mapping sites of potential hazards.

KEY WORDS: Vanishing glaciers, Rock glaciers, Little Ice Age, Landform connectivity, Geomorphic information, Decimal degree geolocation.

RIASSUNTO: WHALLEY W.B., *Rappresentazione cartografica di piccoli ghiacciai, di* rock glaciers *e degli elementi correlati, in un'epoca di ritiro glaciale: l'utilizzo di coordinate decimali e di "tensori di informazioni geomorfologiche".* (IT ISSN 0391-9838, 2021).

La necessità di studiare e catalogare i piccoli ghiacciai in via di estinzione o scomparsi, le morene e i *rock glaciers*, viene esaminata in relazione ai cambiamenti climatici a partire dalla massima espansione raggiunta nella Piccola Età Glaciale. La geolocalizzazione, piuttosto che il semplice toponimo o la sigla di un catasto, dovrebbe essere usata per permettere confronti con i dati precedenti (da documenti storici, carte topografiche, immagini storiche e catasti glaciologici) e con le successive ricerche. Le geo-localizzazioni possono essere fornite come metadati in testi, tabelle e figure con coordinate (Latitudine e Longitudine) in forma decimale (dLL), specificate come una stringa separata da virgola. Il collegamento di un dLL a un elemento topografico permette l'identificazione e la ricerca di specifici morfotipi con una precisione data dal numero di decimali utilizzati. Google Earth^{TM} fornisce un modo conveniente per trovare un dLL e per esaminare gli elementi che caratterizzano le forme del rilievo e le loro relazioni. Una posizione definita da dLL può anche fungere da origine per un transetto geomorfologico, che incorpora una stringa di dati in forma di 'csv' a tre elementi. Le coordinate per ubicare i siti e le stringhe di dati possono essere ottenuti da Google Earth^{TM} così come sono visualizzati sulle immagini. Le informazioni, quali ad esempio la pendenza, possono essere aggiunte a un transetto per fornire un "tensore di informazioni geomorfiche" georeferenziato. Alcuni esempi mostrano come questi dispositivi possano essere usati per esplorare le relazioni di connettività tra *rock glaciers*, piccoli ghiacciai coperti di detrito e glacionevati. Questo approccio ha implicazioni per la rappresentazione cartografica dei ghiacciai attuali e la costruzione di catasti glaciologici come il "*Randolph Glacier Inventory*", ma è anche utile per la localizzazione di siti potenzialmente esposti a pericolosità geomorfologica.

TERMINI CHIAVE: Ghiacciai in estinzione, *Rock Glaciers*, Piccola Età Glaciale, Connettività geomorfologica, informazioni geomorfiche, geolocalizzazione.

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This paper is dedicated to the late Prof. Walther Schwarzacher, mathematical sedimentologist and earlier glaciologist, of Queen's University, Belfast and Graz and the late Jean Grove, Girton College, Cambridge, for her pioneering work on Little Ice Age glaciers.

INTRODUCTION

The world at large is becoming aware of the importance of the recession of small glaciers and their ephemeral existence; for example, the recent 'funerals' for Ok in Iceland and Clark Glacier in Oregon (Milman, 2021). In the Italian Alps, glacier recession can be seen in the Ortles-Cevedale, Adamello-Presanella, and Marmolada groups as pointed out in recent annual glaciological surveys (Baroni & *alii*, 2020) and environmental change is also revealed in the way traces of the fighting on the Stelvio pass in the Italian Alps during WW1 are being exhumed that have reached the general European newspapers (Giuffrida, 2021). Such changes, investigated from images of the time (for example Carturan & *alii*, 2020) indicating glacier recession are culturally significant elsewhere (Carey, 2010). Popularizations bring home what has been known in the glaciological world for many years, that glacier 'recession' since has been particularly significant since the Little Ice Age (LIA) maximum recorded in most parts of the world (Grove, 2012) since about 1900 CE. Although satellite observations can reveal changes in glacier extents, these are usually related to high albedo ice and on a relatively large scale. Distinguishing between debris-covered glaciers and rock glaciers (Herreid & Pellicciotti, 2020) also presents technical and operator variance challenges (Schmid & *alii*, 2015). In the guidelines for preparing satellite-mapped glacier outlines for the GLIMS (Global Land Ice Measurements from Space) database, Raup & Khalsa (2010) note that defining mountain glaciers and rock glaciers may be difficult, 'Rock glaciers and heavily debriscovered glaciers tend to look similar, but their geneses are different. GLIMS does not currently deal with the former but does include the latter'.

Thus, some form of ground truth is necessary for mapping, model building, large-scale interpretations and downscaling tasks. This is also helpful for predicting and evaluating changes and in hazard/risk evaluation as well as providing public awareness about 'climate change'. Various inventories of 'glacial' features now exist, some of which give data on past extents. Notably the world-wide GLIMS and the Rudolph Glacier Inventory (RGI) and additional observations on debris-covered glaciers (Herreid & Pellicciotti, 2020) as well as data for rock glaciers (e.g. Guglielmin & Smiraglia, 1997) are to be commended. Google Earth^{TM} (GE) and OpenStreetMap can give useful data, via recent high-resolution images, when compared to old records and provide important topographic, geomorphic and glaciological information. If images can be digitized and geo-referenced, then information about landscape features and changes over time can be stored, evaluated and perhaps added to existing spatial databases. For this to be effective a scheme of geo-referencing that can be applied to old images and maps is required. These locations can then be compared with other, older, or younger, images of the same location.

Very small glaciers, those about to disappear, have been discussed by Leigh & *alii* (2019) and related to examples in Norway. Leigh & *alii* (2021) have also produced a geomorphological map of glacial features in north Norway related to the Norwegian Glacier Inventory (Andreassen & *alii*, 2012). However, the locations of glaciers are given on a map and not supplied with geo-coordinates (unlike the *Atlas over breer i Nord-Skandinavia*, Østrem & *alii*, 1973) where latitude-longitude are given for each location). Locating where a glacier is, or has been, becomes difficult unless some unique geo-location is given. The method described here allows identification of any terrestrial point for scrutiny, whether glaciers, moraines and associated features or associated data points in texts. Readers of papers or reports should also benefit from inline text location citations for viewing on Google Earth^{TM} and the GLIMS Glacier Viewer. Descriptions of the methodology and method of citation are now given with four subsequent illustrations of its use.

This paper develops simple geo-location methods that can be used to investigate features in mountain landscapes as visible in recent detailed satellite images (e.g. Google Earth^{TM}) and to allow comparison with earlier observations and records. Some illustrative examples of the method are also given.

METHODOLOGY AND METHODS

Many papers provide locational information of features by reference to an in-text map, perhaps with latitude/longitude values noted on the perimeter. Alternatively, a location might be mentioned in the text. However, the format of latitude/longitude used is variable according to local journal, book or inventory practice. This may make it difficult for the reader or other researcher to find a location. The procedures used here provide standardisation of format by using decimal degree specifications for areas or points as appropriate. A method for designating transects is also presented. Geolocation is particularly important for small glaciers not in inventories as well as in the development of geomorphic landsystems. Landsystems are increasingly used as means of co-ordinating studies of landforms, sediments, glaciers, plants and fauna together with climate and social systems (Dearing & *alii*, 2010).

Although latitude-longitude have been used as locational devices on maps (see above) they tend to be in the traditional, degree, minute, second (° ' ") format but there may be considerable diversity in typographic representation. Location in decimal degree notation provides a neater format but which can still be used in OpenStreetMap, Google Earth^{TM} and GPS devices. Locations in decimal latitude-longitude (dLL) values can also be found via Google Maps or smartphone apps. Here, a simple comma separated, dLL identification of locations is used. This is notified in the text by a character string, for example [46.833,11.013]. These values can be pasted directly into the Google Earth^{TM} search bar (including the square brackets) to locate the point. Locations west of the Prime Meridian are preceded by - (negative) and similarly for southern hemisphere locations. The number of decimal places helps to specify the location; a 4 decimal place location can unambiguously locate a large building to about 8 m precision (at 45°N or S; 4.4 m at 67°N/S) and 6 decimal place values can identify locations better than 100 mm (at 45°N or S) and see also Munroe (n/d). Thus, the reader can ascertain the topographic location without map searching and where locations without names may be difficult to find. Conversely, if a dLL location is required, for example, a snowpatch or WW1 military emplacement (as above), then it may be located in Google Earth and the dLL string taken directly from the results bar in GE. Imagery and dLL data may be used together as in the examples below.

Locating a topographic feature by co-ordinates depends on the dLL precision stated but if searching for a location in GE the image quality/resolution may be too poor for the dLL precision required. Recent GE images can be of very high resolution, although shadows and snow cover may inhibit clarity. Some locations have (via the 'historical imagery' tool) several possibilities. OpenStreetMap can also use dLL and the visualisation (map layer) options may be of sufficient resolution to provide the location required although there is no dLL readout as with GE.

It may be useful to designate a traverse, transect or view direction that can be located in GE. A bearing from an origin, identified on GE by its dLL, can be obtained (and shown on an image) using the 'Ruler' tool. The bearing value, in degrees from N, is placed after the dLL values as a csv string; {46.8271,11.0186,326}. This incorporates the previous location near the Langtalereckhütte, Obergurgl [46.8287,10.9919], which can be found on a GE search. The three-element string dLL plus bearing can also be used to examine landsystem elements more precisely via the 'geomorphic information tensor', described more fully below.

It may be necessary to include an observation date for a located point, transect. This could be done by adding year after the position and bearing, as for example [46.8287,10.9919,@2019]. This may provide useful extra information although literature search tools have yet to be developed. Google Earth for visualisation and dLL location techniques can be developed to aid to research and data preservation as in the next sections.

THE OBSERVATIONAL BASIS

We know from observations over the last hundred years or so, since the Little Ice Age (LIA) maximum, that glaciers have been receding and down-wasting (Grove, 2012). Past glacier limits and moraines are often recorded in published papers and reports (although in some cases these may not be easily accessible or referred to) and in maps and photographs. GLIMS data and the Rudolph Glacier Inventory (RGI) provide some past as well as present-day mapping so comparisons of ice extents can be made. This is especially important for very small glaciers that may soon vanish. Some (although not all) RGI maps (via 'Glacier View') may show relationships between glaciers and rock glaciers; an example is the Hochebenkar system in Austria [46.833,11.013]. In GLIMS, Hochebenferner, ID: G011018E46822N shows AD1850: area = 0.77 km^2 and 1969: area = 0.21 km^2. This paper illustrates how, using Google Earth images and a simple mapping technique, links between glaciers, moraines, rock glaciers and associated features (such as protalus ramparts) can be examined and recorded for future reference. The paper also shows a means of encoding geomorphological (landform) elements and materials (debris, ice) that allow comparisons over time and that can incorporate past observations. Examples, mainly from Europe, are presented showing potentially 'climatically sensitive' landforms and relationships between glaciers and rock glaciers.

MAPPING TOPOGRAPHIC ATTRIBUTES VIA DIGITAL GEO-LOCATION

Rapid glacier recession is particularly significant for small glaciers in the circum-Mediterranean area such as the Pyrenees (Campos & *alii*, 2021) and the Calderone glacier in the Apennines (Pecci & *alii*, 2008, Baroni & *alii*, 2020)) although there are indications that some meteorological events may provide a 'stay of execution' (Colucci & *alii*, 2021). Indeed, Vincent & *alii* (2005) show that for several glaciers across the Alps, 'this [glacier] recession clearly results from winter precipitation decrease'. However, here I am interested in identifying locations for site comparisons rather than a wider consideration of environmental gradients, although it may also be useful for comparing glaciers to benchmarks (Carturan, & *alii*, 2013).

Large scale mapping interest with satellite imagery has led to GLIMS (Global Land Ice Measurements from Space) and the Randolph Glacier Inventory (RGI 6.0) glacier outlines and locations. The latter can be accessed with the GLIMS 'Glacier Viewer' (which uses OpenStreetMap as a base) together with some basic data about areas and data acquisition dates. Along with an interest in 'debris covered glaciers' there has also been increased activity in mapping and the behaviour of rock glaciers. The resolutions now achievable with Google Earth^{TM} (GE) can be used to investigate rock glaciers as well as small glaciers. The GLIMS manual differentiates between rock glaciers and debris covered glaciers, but examination by GE can show variance between features mapped via a landsystem approach. Some rock glaciers are excluded from the RGI although they have distinct 'glacial' origins. More usually, the GLIMS glacier viewer shows changes in glacier extent over time, as with the Hochebenkar system noted above. What is not evident from these mappings are the various 'early' observations and conclusions about the status of rock glaciers. For example, Pillewizer (1957) includes the 1922 mapping by Sebastian Finsterwalder and photographs from 1938 are in Vietoris (1972) and Hartl & *alii* (2016), none of which have geolocated data.

Glacio-geomorphological maps in the literature can be re-examined by GE. Historic maps show many rock glaciers having Little Ice Age glacier origins that can be examined by GE and in the RGI. European examples from the Pyrenees (Whalley, 2021a) and Swiss Alps (Whalley, 2020) show that rock glaciers have glacial rather than permafrost origins. Google Earth^{TM} provides a good way of looking at small glaciers that were previously, say 50 years ago, only recorded in aerial photographs and about 100 years ago by photographs and maps and diagrams by field workers. Frequently, perhaps because rock glaciers were not a 'main line' research area, these early observations have been published in local and regional journals and neglected in trying to estimate environmental changes in the last 100 years. GE can be used to provide information about changes in the 'rapid disappearance' of small glaciers and associated features when linked to some past records. The paper also starts to develop a scheme to enable the digitization of previous records of features in areas of interest. This allows integration into a database along with other 'landsystem' features together with, where available, recording in the Randolph Glacier Inventory (RGI) as mentioned previously. As well as Pillewizer (1957), several other authors have 'historic' images in their publications which contain, perhaps after 30+ years, information about changes in the intervening years as warming takes place. Examples are by Gerhold (1967, 1969, 1971), Vietoris (1972) and Kerschner (1983).

MAPPING SMALL GLACIERS AND ROCK GLACIERS AND METHODS

Google Earth™ (GE) images are now of sufficiently high resolution that large boulders can be identified. Changes can even be monitored by comparison (using the date slider) with earlier imagery if of sufficiently high resolution, although snow cover, cloud and shadow may be problematic. However, imagery may now be obtainable for which there has never been good (or even any) aerial photography and resolution will improve in GE. Sometimes better image resolution can be achieved in OpenStreetMap (as used as a base for the RGI/GLIMS) and DEMs, such as ArcticDEM provide topographic information, but GE provides a suitable basis for compilation, analysis and integration (Whalley, 2021b).

Some investigation with GE can link imagery to inventory locations. GE can also be used in an interpretative mode by identifying a point on a mountain top or ridge and recording its latitude/longitude location. From this origin a line downslope can be drawn; usually the fall-line across the slope elements (geomorphological features). GE can be used to draw this line and its bearing determined, located and referred to uniquely as part of the site description. Onto this line transect, the slope elements can be encoded for a particular time snapshot. A repeat in GE can show changes in these elements, for example, the reduction in size of a glacier, the occurrence of a moraine or identification of a potential hazard. As well as GE, locations in the Randolph Glacier Inventory (RGI) have been used to track glacier location and size. Various examples are identified to show the utility of Google Earth™ for 'ground truth' investigations.

GEOMORPHIC INFORMATION TENSORS

The transect defined by the starting point specified by WGS84 dLL, plus a bearing provides a unique reference for locations on the transect that can be viewed on Google Earth. An outline of the technique for developing 'geomorphological information tensors' (GIT) is presented here (see also Whalley, 2021a, b).

A tensor is an array of mathematical 'objects', usually numbers or functions. A scalar, such as a data point of information like a temperature value, is a rank-0 tensor. A vector, such as force, is rank-1 with 3^1 (3 components) for 1 dimension and stress is a rank-2 tensor with $3^2 = 9$ components for dimension (d) = 2. Thus, information is contained in the tensor. While tensor calculus is well-defined mathematically, its extension into 'geomorphic information tensors' (GIT) is more complex and very ill-defined. The concept depends not only on the frame(s) of reference but also the dimensionality (d) and the variability of geomorphic process 'operators' such as glacier flow or movement of materials. This can be considered as a conceptual way of mapping geomorphic information via a transect and storing it digitally rather than as a static geomorphological map. The concept makes a GIT amenable to searching and for comparing information on a GIS.

Information on a GIT, from existing knowledge or as published papers on specific glaciers, can be incorporated into a digital, searchable database together with the GLIMS/RGI inventory. Fig. 5, as the image itself, contains area change data for specified years. This also exists in for example, the paper by Villa & *alii* (2007) on Rutor glacier where the paper's information could be incorporated on a GIT via its DOI (or other digital locator) and the location of the glacier can be included as a searchable digital location [45.636,7.011] that can be related to other references, for example Pelto (2015).

EXAMPLES

I now explore various ways of using 'lost' or 'hidden' data to examine relationships between small glaciers, rock glaciers and related features. Using GE, it is now possible to explore areas and associated features as part of a landsystems approach that can be tracked back through available images. Although inventories of rock glaciers have been used increasingly to show their importance world-wide, it is not easy to access individual data points to examine specific features and their characteristics. Conversely, there are many small glaciers and rock glaciers that have been examined but are now 'buried' in the literature as papers not in English or in local journals. This is especially true for old surveys and books that contain information about glacier extents before accurate mapping. This paper is not an immediate solution to finding such 'lost' data! However, it does suggest a way of coding and recording historic data such that it can be compared with present day results. The examples which follow are indicative of the use of GE and other points of information:

1. Identified rock glacier from database (Sierra Nevada, USA) by Millar & Westfall (2008)
2. Rock glaciers identified from a database (Guglielmin & Smiraglia, 1997) linked to:
   i. Map of Val Pisella (Gruppo Nazionale Geografia fisica e Geomorfologia, 1987)
   ii. Images and data, permafrost in rock glacier via geophysics (Ribolini & Fabre, 2006)

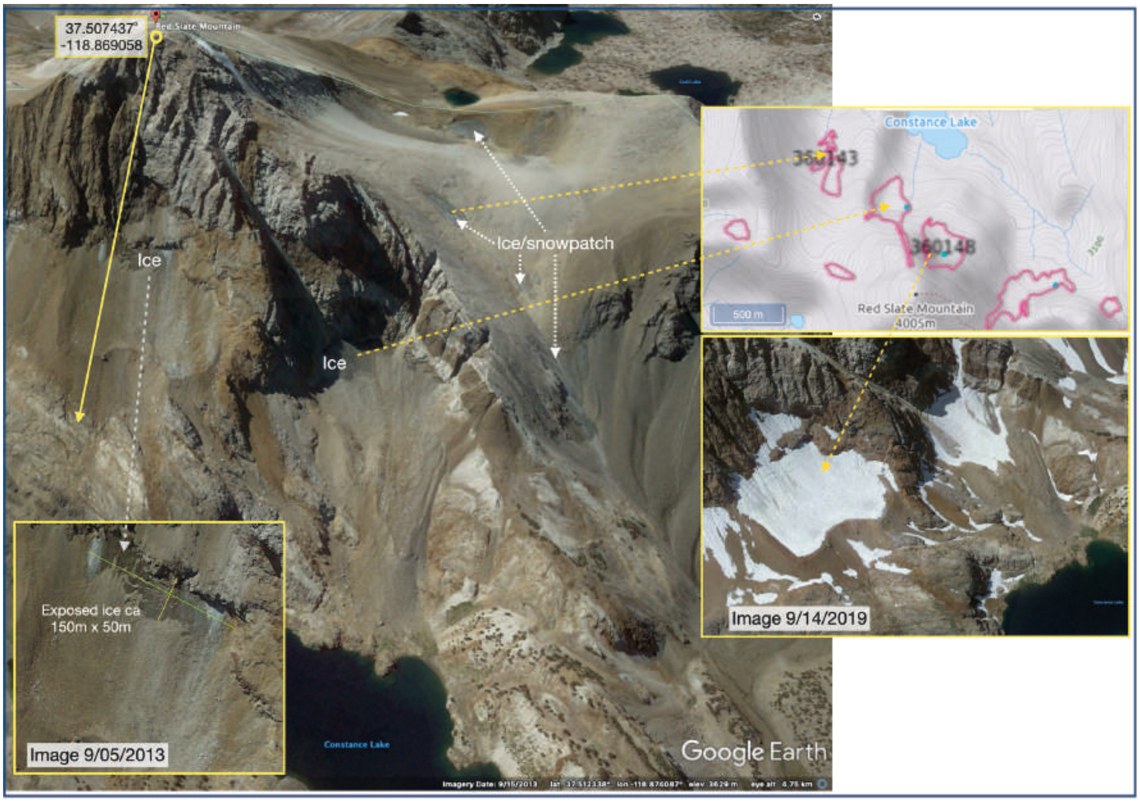


FIG. 1 - Oblique and near vertical images of glacier and rock glacier features around Red Slate Mountain, Sierra Nevada, CA, USA, [37.5076,-118.8693]. Main image looking southwest, see text and table 1. for further information. Main image ©Google Earth^{TM}. Top inset from GLIMS Glacier Viewer.

3. An 'inactive' rock glacier and geomorphological map in the Pyrenees (Angély, 1967)
4. Glacier and rock glacier description and analysis, Fissladferner, Austria (Gerhold, 1967)
5. Changing glacier-rock glacier relationships, Glockturmferner, Austria (Kerschner, 1983)

Glaciers and rock glaciers in the Sierra Nevada via digital inventory

Francois Matthes (1948) examined some of the small glaciers in the Californian Sierra Nevada (Trent, 1983; Guyton, 1998) that preserve climatic signals. Millar & Westfall (2008) mapped some 421 'rock-ice features' (rock glaciers) in the eastern Sierra Nevada. Some of these features are mentioned and described by Kesseli (1941) and Guyton (1998). Millar & Westfall (2008) provide accessible online latitude/longitude supplementary data (National Snow and Ice Data Center, http://nsidc.org/data/ggd652.html) and it is possible to locate these on Google Earth. Kesseli's (1941) paper provides some very clear photographs of rock glaciers and related features. For example, his fig. 12, 'Rock stream protruding from moraines of a small body of ice on Red Slate Mountain, Convict Creek' can be located on Google Earth with locating co-ordinates [37.516149,-118.870375,@2019] at elevation 3360m. This can be tracked back to Millar and Westfall's data and designation (RGC-Mo = Cirque rock glacier, moraine). This feature and its neighbour [37.5114,-118.8664] show traces of glacier ice grading into ice covered by debris vertically above the moraine crest/rock glacier snout (fig 1). The 2013 image is snow free although others, e.g. 2005, show snow cover behind the moraine but provide good geomorphic evidence of how far rock-debris/slush avalanches may reach across of the snowpack. This is important information concerning debris inputs protecting small decaying ice bodies as seen in other examples.

By linking Millar and Westfall inventory data, Kesseli's fig. 5 (1941) and the RGI as summarized in fig. 1, we see that not only have the mapped glaciers vanished to less than 0.05 km^2, the exposed ice on RGI60-02.15386, being about 0.006 km^2, it is barely visible except at the end of the summer with no late-lying snow. However, the ice can be identified with the RGI and earlier (1967) mapping (although this might be snow filling behind the moraines as in the 2019 image). Ice covered with debris and associated snowpatches can be observed in the high basin, although there is no RGI identification (indicated by a cyan dot) even though ice/snow was mapped previously. Further, a suite of landforms associated with glacier ice decay and debris input can be observed. As Kesseli noted (1941, p. 227), «the prevalent location of rock streams close to the foot of cliffs shows that they develop best when the amount of debris is large in comparison with the volume of the body of ice. […] The volume of ice was sufficient to transport the material a short distance from the cliffs but was too small to hold the mass of debris into

TABLE 1 - Examples of geo-located data for Red Slate Mountain, California [37.5076,-118.8693]. A: Data extracted from Millar and Westfall's (2008) database. B: Information derived from inspection of Google Earth as a transect (shown in fig. 1). C: Recorded basic transect data to which could be added further information, such as in B, and which could be searched for in a GIS system. The amalgamation of the slope element information (B) and the transect data (C) produces the concept of a 'geomorphic information tensor'.

A

Watershed	No.	Latitude	Longitude	Position Type	Activity	Age	Mean Elev.	Elev. High	Elev. Low	Aspect	Shape	Size	Water	Lat / Long
ConvictCyn	2A	37.5114	-118.8664	RGC-Mo	M	H	3490	3566	3414	0	0	2	1	37.5114, -118.8664

B

Transect	Origin: lat. / long.° (to 6 places)	Elevation (m)	Bearing °	Randolph Glacier Inventory (RGI)
(Sierra Nevada)	[37.516149, -118.870375]	3360	036	RGI60-02.15386
Slope element type information	FF : GL : UD/GLd : MT : BR			

C

GPS-formal	{37.516149,-118.870375,036 + data}	Topographic informal	Red Slate Mountain, east
GPS-formal	{37.507356,-118.869754,257 + data}	Topographic informal	Red Slate Mountain, west

the form of a true glacial basin held by voluminous lateral moraines. The debris was thus spread more evenly over the limited area of deposition, a process that accounts for the voluminous appearance of many streams».

The latitude/longitude given above and used by Millar and Westfall [37.5114,-118.8664] gives the ridge of the rock glacier. However, if we take a position, the origin, of a transect downslope from near the peak (Red Slate Mountain) on a bearing of 036° (the default image at the time of writing is 2019 but rather covered with snow on 27 June, 2016). This transect covers a free face of rock [*FF*], a very small patch of remnant glacier ice [*GL*], undifferentiated rock debris [*UD*], although this might be debris covered buried glacier ice [*GLd*] a terminal moraine [*MT*] and a bare rock slope [*BR*]. Although this feature may be interpreted as a rock glacier (as did Millar and Westfall), inspection of the RGI (inset fig. 1) shows mapped glacier limits of RGI60-02.15386. This suggests that the small remnant glacier was covered with debris from the free face. The very small exposure of ice can be seen in the 2013 image, although it is covered with snow in most others.

Other rock glacier and buried ice features can be seen in this vicinity and related to the RGI. The advantages of using GE, the ability to zoom, view features obliquely and change direction are immediately obvious. The ability to use the historical image slider and pick the most useful for interpretation and examine other features is clear as is recording decimal degree co-ordinates. The Millar and Westfall database ('Rock-Ice Feature Inventory for the Sierra Nevada, California, USA, version 1') opens in a spreadsheet as in table 1A, with a final column combining latitude/longitude and used this to locate the feature, of 430 in total. A further row in B: the trajectory, is defined by a five-figure dLL and a bearing/direction together with a cell for the RGI number and geomorphic mapping information as mentioned above. This analysis of one of the locations for a rock glacier in Millar and Westfall's inventory shows the validity of Kesseli's interpretation from about 70 years previously and the extra information that can be added to that from the RGI and GlacierViewer. We now turn to various other examples from the European Alps.

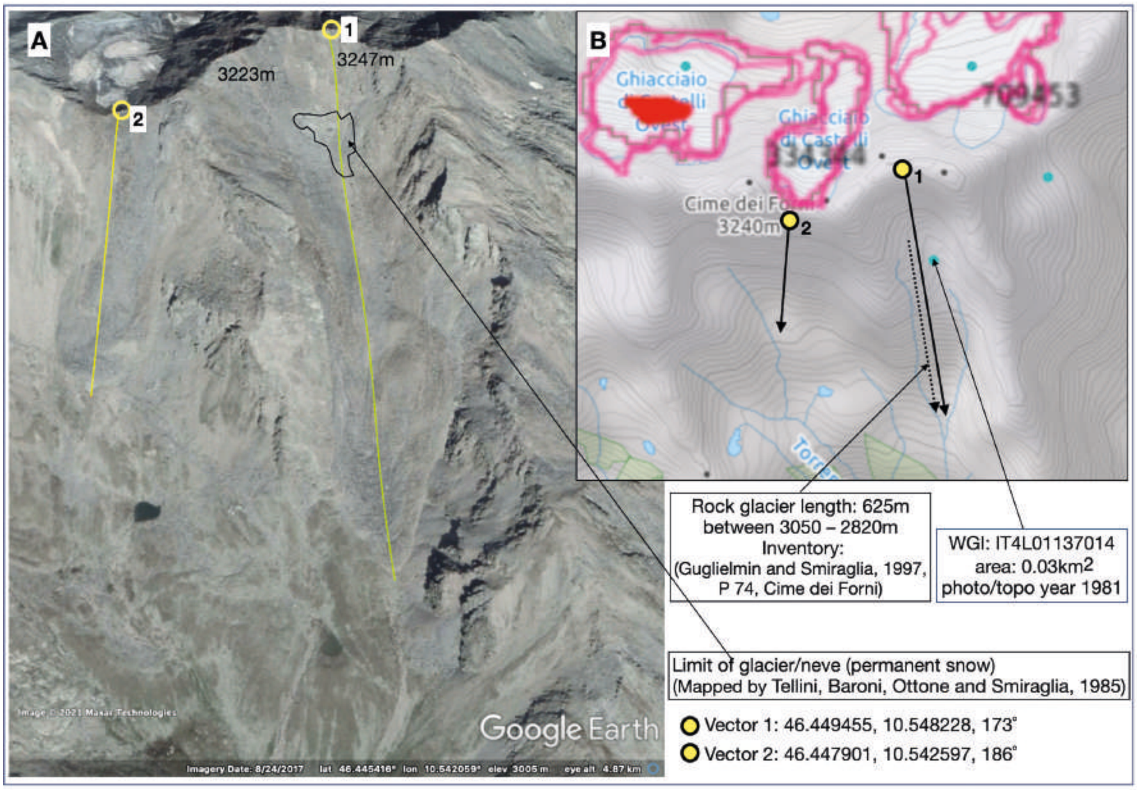
Rock Glaciers from Italian Rock Glacier Inventory

Before the present trend to work on particular rock glaciers and create inventories and generalise from these data, there existed many descriptions and images which provide useful data concerning the development of features and the recession of glaciers. Some are now examined using the techniques mentioned above. Locating a feature on a transect from a dLL location can identify the feature and its flow (or the 'fall line') of ice and debris and the geomorphological features on this line. As above, the start point is generally at the highest and although may not be accurate topographically it will be sufficient for identification purposes and approximate calculations. Associated Randolph Glacier Inventory locations are noted as RGI. As with the Californian example, the GE image date used may not be the most recent because of cloud, shadow or, more usually, snow cover, nevertheless it provides the most useful link to past observations.

Glaciers and rock glaciers in Ortles-Cevedale and a geomorphological map

The Italian Glaciological Committee published a 'Rock glacier inventory of the Italian Alps' listing nearly 1600 features, 'active' and 'inactive' (Guglielmin & Smiraglia, 1998). It records information such as aspect, maximum and minimum altitudes, slope, surface area, lithology and 'relationship with glacial landforms'. This important compilation provides information that can be checked against current characteristics seen in Google Earth™ and other authors' work. Two examples from this (paper-based) inventory (Guglielmin & Smiraglia, 1997) are considered and related to RGI information.

Fig. 2 shows a 2017 GE image with two rock glaciers shown by slope vectors/trajectories. {46.44945,10.54828,173} and {46.44790,10.54259,186}. This figure and caption provide a summary of glacier and geomorphological changes, including the formation of two rock glaciers mapped by Claudio Tellini (in Gruppo Nazionale Geografia Fisica e Geomorfologia, 1987).



Rock glacier length: 625m between 3050 – 2820m Inventory: (Guglielmin and Smiraglia, 1997, P 74, Cime dei Forni)

WGI: IT4L01137014 area: 0.03km2 photo/topo year 1981

Limit of glacier/neve (permanent snow) (Mapped by Tellini, Baroni, Ottone and Smiraglia, 1985)

Vector 1: 46.449455, 10.548228, 173°

Vector 2: 46.447901, 10.542597, 186°

FIG. 2 - A: Two south-directed transects marked on a Google Earth image from the Cime dei Forni [46.4494,10.5466] (Alta Valfurva-Sondrio) covering the 1985 geomorphological map of Tellini (Gruppo Nazionale Geografia Fisica e Geomorfologia, 1987). The mapped rock glacier length is shown dashed in B together with the glacier/neve/permanent snow area. Image: ©Maxar Technologies/Google Earth^{TM} 2021. B: Map covering part of A from GLIMS base map (OpenStreetMap) with locations of Transects 1 and 2. The three large glaciers north of the ridge are relatively free of debris but south of the ridge debris covers the once larger glacier body mapped in the World Glacier Inventory (WGI) and by Tellini & *alii* (1985) as marked in A.

Fig. 2 can be compared with the Val Pisella rock glacier descending south from the Cime dei Forni as mapped in the Rhaetia Alps by Tellini, Baroni, Ottone and Smiraglia (1985) (in Gruppo Nazionale Geografia Fisica e Geomorfologia, 1987). The Val Pisella rock glacier: ID No 668, Cime dei Forni (p. 74, Guglielmin & Smiraglia, 1997). The geomorphological map shows geomorphic landsystems including two glaciers and indicates a substantial glacier/neve area upstream of the mapped rock glacier linking with the inventory relationship of 'snowbank'. Also shown on fig. 2 B is mapping from the GLIMS with a World Glacier Inventory (WGI) number. Unlike the substantial glaciers to the north of the ridge, shown in red for various mappings in Figure 2B, no RGI data are given. The mapping for 1981 (with an estimated area of 0.03 km^2) is no longer a glacier and is confirmed by the 2017 GE image. The transport of rock debris downslope will have covered the glacier, resulting in a rock glacier but the glacier ice exposed at the surface no longer exists.

For useful glaciological or geomorphological work Google Earth^{TM} transects do not show differences in surface relief accurately or precisely enough without information added from a DEM. Nevertheless, a transect could be covered with LiDAR/InSAR scans or flown with a UAV and topographic information derived from structure-from-motion analyses. Such data could be used to build up a GIT and changes monitored over time.

Rock glaciers in the Maritime Alps

Fig. 3 shows another rock glacier in the Italian Rock Glacier Inventory ('Baissa Margot', identification no 49 of the Maritime Alps section [44.1501,7.3419]) (p. 54 of Guglielmin & Smiraglia, 1997). This is given as 'uncertain activity' and is also noted as a rock glacier by Ribolini & Fabre (2006).

Fig. 3 presents a detail of a rock glacier included in the inventory also studied by (Ribolini & Fabre, 2006) with geophysical DC resistivity. Although no glacier ice can be seen, it seems clear that the feature is a moraine formed at the foot of the small cliff, covered with rock debris from the free face which protected the (down-wasting) glacier ice. Lateral moraines [*ML*] are present, merging into a distinct terminal moraine [*MT*]. The inset oblique shows clearly that this is a moraine sequence from which the glacier ice has melted, and the surface has lowered behind the moraine ridges. As with the example from the Sierra Nevada in fig. 1, there is a close relationship between mapped 'rock glacier' and 'moraine'.

Measure the distance between two points on the ground

Map Length: 447.97 Meters
Ground Length: 530.78
Heading: 359.35 degrees

FIG. 3 - North facing transect {44.15043,7.33896,360} from a spur of Cima dell'Agnel [44.1461,7.3410]. The 'pin' co-ordinates are those given in the rock glacier inventory. The inset box shows the Google Earth^{TM} 'Ruler' information for the transect on a 2014 image. Labels are geomorphological features on the transect (*FF* free face, *SP* Snow patch, *MT* terminal moraine). *ML* is a lateral moraine arrowed to the oblique image (inset) from 2017 showing the differences in snow cover. Images: ©Copernicus, Data SIO, US Navy, NGA, GEBCO/Google Earth^{TM}.

Recent work by Carturan & *alii* (2020) on using First World War images from the Italian/Austro-Hungarian front promises to be useful for extending debris-glacier relations and rock glaciers by linking to the inventory of Seppi & *alii* (2012).

'Old' rock glaciers in the Pyrenees

Angély (1967) examined three rock glaciers in the French Pyrenees. One, the Glacier Rocheux de Guerreys {42.71070,0.34532,325} is a northeast facing tongue and sequence of moraines which he mapped (fig. 4 with an insert of a GE image). The implication of Angély (1967) calling this 'ancien', is that is 'inactive'. No movement data seem available and, although the snout appears steep, it is not near the scree resting angle. However, close examination with GE shows a very small patch of ice appearing under the scree just below the ridge crest near snow patches. Some 100 m to the west is a distinct protalus rampart [*PR*], again with late-lying snow.

The transect not only indicates the slope/geomorphological elements but their location on the transect and

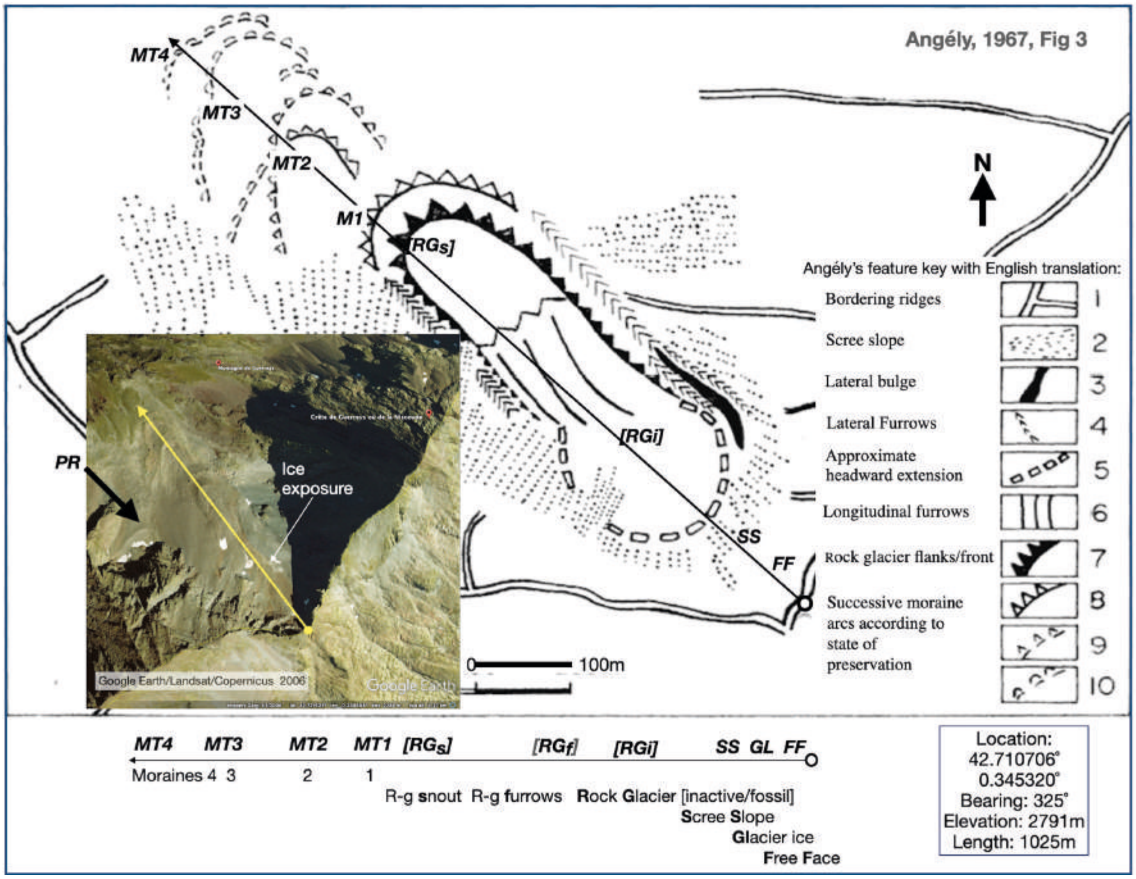


FIG. - 4. Geomorphological map of Angély (1967) with his (translated) key. Added to this is a longitudinal transect, also shown is the Google Earth image with the transect marked and the location of the ice exposure identified on the 2006 Google Earth image [42.7124,0.3444]. At the base is summary diagram of the geomorphological elements mapped symbolically down the transect as a simple GIT; [*RGi*] means no apparent movement with [*SS*] as indicating an active feature, [*RGs*] indicates rock glacier snout and [*PR*] (on the inset image) a protalus rampart on {42.7123,0.3386,006}. The summary transect is {42.71070,0.34532,325}. Image ©Google Earth™/Landsat/Copernicus.

with distances downslope (although not shown here). The presence of a small patch of ice is assumed to be remnant glacier which has melted from the rest of the rock glacier and which has earlier deposited terminal moraines [*MT4*] to [*MT1*], earliest to latest.

A feature from Gerhold's rock glacier classification

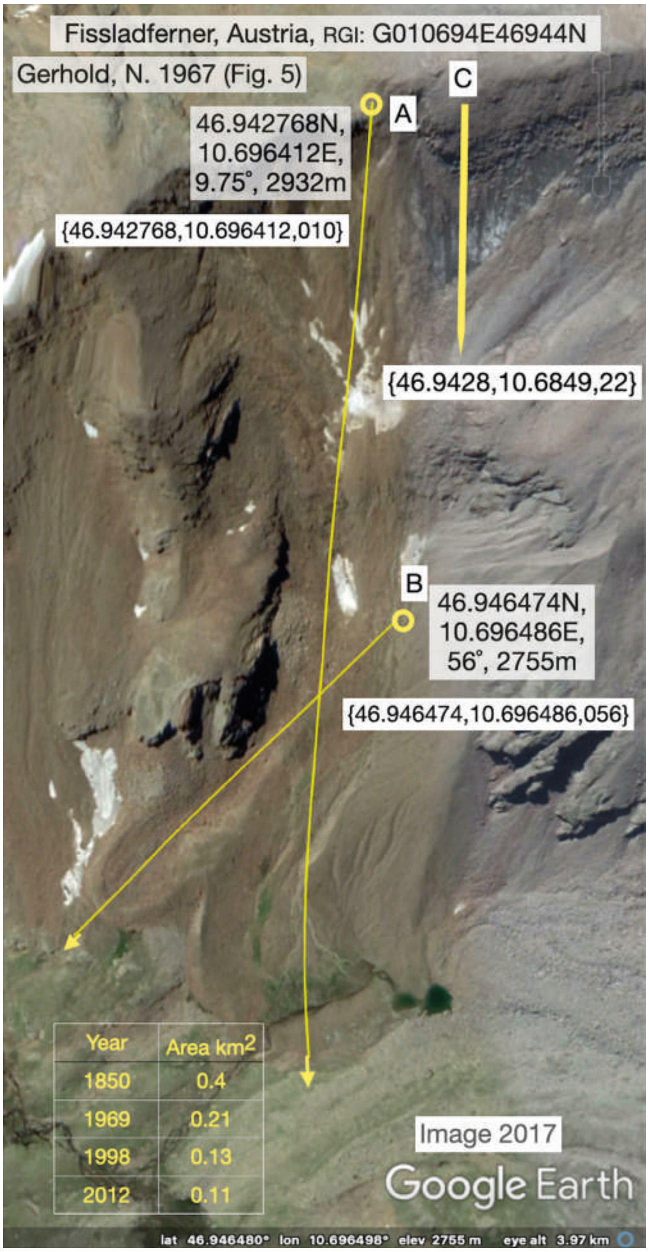
Nobert Gerhold (1967) produced a rock glacier classification, one of which is the type 'Fissladferner' (Gerhold, 1967, fig 5) shown here in GE as fig. 5. Gerhold suggested that this type was a modified glacier.

Fig. 5 shows a small glacier system that can be identified from Gerhold (1967) on a current (2017) GE image. Additional digital material can be added by three transects. A and B summarise information about the 'Fissladtyp' but also other changes over time on C. This shows slope characteristics (as in fig. 4) that can be summarised, downslope as a simple GIT:

SS : FF-BR : GL : GLd : MT/PR

That is; weathered material from a scree slope [*SS*] is moved over a free face [*FF*] with bare rock [*BR*] leading to bare glacier ice patch remnant (*GL*) to ice with a debris cover [*GLd*] ending in a small terminal moraine [*MT*] or protalus rampart [*PR*]. The difference between profiles C and A is that the latter has had more debris input over a larger glacier remnant. Ultimately, we would expect the ice patch on transect C to vanish (see fig. 1) whereas the debris-buried ice in transects A and B would have a much longer existence.

Changes in glacier-rock glacier systems can also be seen with data from Pillewizer (1957) in the vicinity of the Gepatschhaus [46.901,10.737] for the Innere Ölgrube that has been continued more recently by Berger & *alii* (2004 fig. 2). They show the 1850 moraine system, with the 'Karsee' melt pool, between the glacier system of the Hinterer Ölgrubenferner and the rock glacier. A transect {46.8959,10.7792,270} shows not only the downstream debris/ice relationships of this glacier ice-cored system but the changes size of the lakes over the years, 2000 to 2019. The Karsee [46.89600,10.76612,@2016] is sometimes two lakes [46.89541,10.76731,@2015] and shows slumping around the sides. Although no bare glacier ice is shown, this is typical of down-wasting debris-covered glacier ice. This effect of warming of glaciers (as opposed to permafrost) is that glacier ice is melting, and we shall see an 'epidemic' of surface melt pools on many rock glaciers (Whalley, 2021c). If rock glaciers consist of an ice-rock mixture, as supposed in the permafrost model, then we would expect nearly iso-volumetric ice melting with little surface lowering. This does not appear to be the case and melting of glacier ice below surface debris is now revealed by melt pools. A transect from the ridge above the Ölgrubenjoch {46.89399,10.77829,325} shows, on recent GE imagery, that there is a large lake below the glacier [46.8954,10.7768]. This lake may be impounded by the rock glacier or that it will increase in size until is escapes over the Ölgrubenjoch. The possibilities of this potential hazard can be recognised from GE surveys of glacier-rock glacier systems.



Year	Area km^2
1850	0.4
1969	0.21
1998	0.13
2012	0.11

FIG. 5 - Google Earth^{TM} image of Fissladferner, type rock glacier (Gerhold, 1967) with Randolph Glacier Inventory (RGI and GLIMS) designation. The three transects are discussed in the text.

Glockturm glacier-rock glacier system Ötztal Alps, Austria

The final example showing changes in a rock glacier system is illustrated in fig. 6. Kerschner (1983) provided a geomorphological map of the Glockturmferner flowing N from [46.893,10.665] in the Hütterkar. The long-term development of the rock glacier is clearly visible with debris added from the exposed western slopes of the Glockturm as the Glockturmferner decreased in size. Further information can be defined on two transects A and B (given in the caption). The first clear GE image is 2000 (fig 6.B) and a supraglacial stream is clearly seen, including an ice-cliffed section [46.8979,10.6567]. This system is also seen in images from 2007, 2015, 2016, 2017 and 2019. Between 2017 and 2019 there is not only a development of the stream system across to the snout, but a section of the snout front has collapsed (fig. 6C). To date (2021), here are no further images but it will be interesting to monitor subsequent changes in GE or by fieldwork. The utility of Google Earth^{TM} to record change is clearly shown in this example and suggests that the site should be monitored for future slope failure as a result of ice core melting.

DISCUSSION

By geo-referencing locations and transects, features and their development in mountain landsystems can be investigated and made available by digital geolocation. Considerable changes have occurred in mountain landsystems since the LIA. In 1900 alpine glaciers were still around their maximum extents. Subsequent recession has not only resulted in substantial water equivalent loss but has produced retreat from moraine walls and cliff faces. Consequently, ice dammed lakes have formed and their discharges (GLOFs) produced local high magnitude events. Rockfall and landsliding activity have similarly been enhanced. Both glacier melt and permafrost degradation have been considered as causes for these geomorphological landsystem changes. Past changes, such as moraines sequences, can be dated with various techniques and past images and maps related to these changes such as fluctuations of the La Mare glacier (Carturan & *alii*, 2014). It would be useful to record information items such as moraine positions with soil pits and dated surfaces. This could be done with geolocated points. In particular, landscape connectivity and ecological changes need to be recognised, explained and predicted (Brighenti & *alii*, 2019). Geomorphic information tensors, that is geo-referenced transects containing additional data, can potentially be used to explore changes in alpine systems and their connectivity. For example, identifying locations that may require closer inspection and monitoring (Marcer & *alii*, 2019) and fig. 6 can easily be identified and monitored by, for example, time-lapse cameras (Giordan

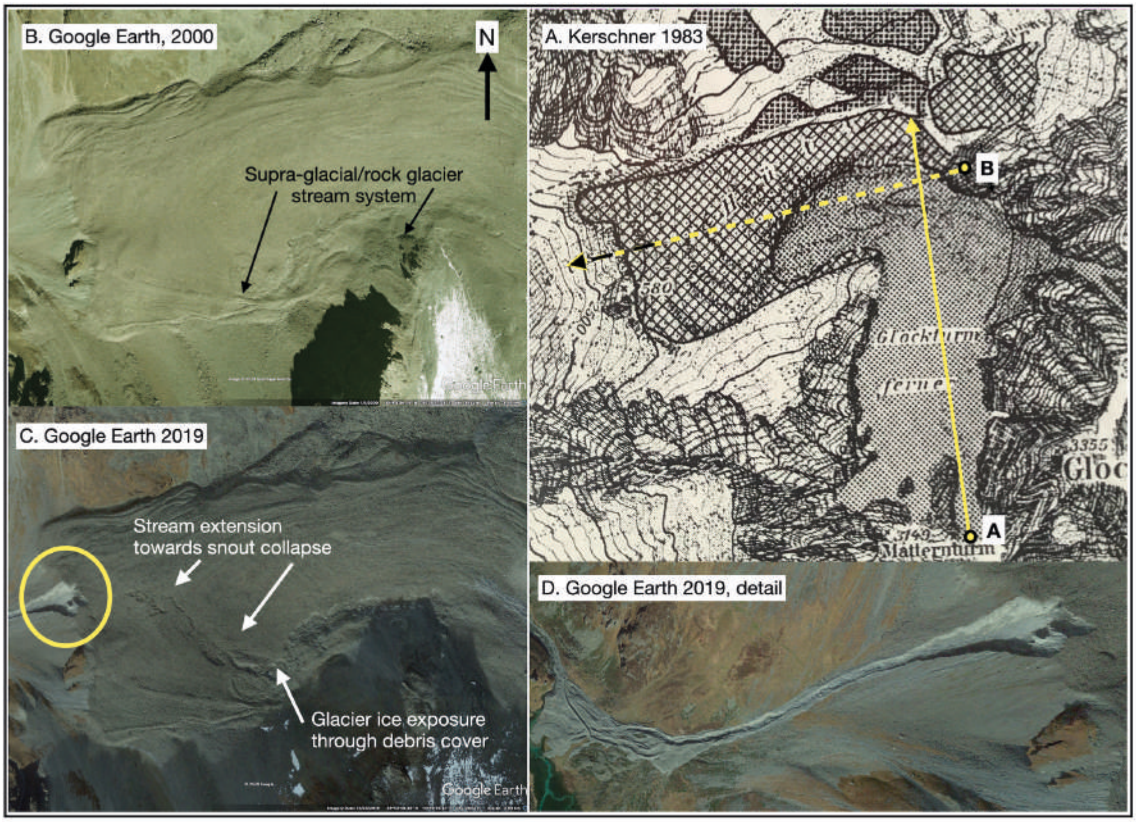


FIG. 6 - Composite images of Glockturmferner-Glockturm rock glacier [46.893,10.665]. A) Part of a map by Hanns Kerschner (1983) of the system with the glacier (Glockturmferner) turning west at the base of the steep slope. This mirrors the main rock glacier extending downstream to the west. Transects A: {46.8906,10.6635,350}, B: {46.9000,10.6636,260}. B) Google Earth^{TM} image, 2000, where the rock glacier smoothly continues from the exposed glacier ice upstream. A supraglacial stream system can be seen developed in the southern area. C) Google Earth^{TM} image of 2019 showing recent changes, most notably that since 2000 where the supraglacial stream system (in B) has developed further, and the snout area appears to have collapsed. This is best interpreted as melting of a glacier ice core of the rock glacier. D) Is a detail of C showing the downstream development of a fluvial sediment system removing the near frontal debris.

& *alii*, 2020). Localities and features remote from named places can be identified by locations and transects specified via dLL designations to aid observations and discussion (Whalley, 2021c).

There is a tendency to consider glaciers as being distinct from the 'periglacial' (as with the original definition, see Warburton, 1992)) and 'permafrost' domains but vanishing glaciers make these terms of diminished value. Snow and glacier melting will increase water availability for, sometimes catastrophic, activity and the release of debris downhill (fig. 6). Rock glaciers have been considered as increasingly important components of such instabilities (Deline & *alii*, 2015). Glaciers and rock glaciers are sometimes considered as distinct with the former having no role to play in the formation of the latter. However, the profiles and instances outlined in this paper suggest that this is not the case. Even if an area might be in a permafrost zone, according to altitude and aspect for example, a rock glacier can be formed on a small glacier by high debris inputs at the start or early in the LIA. This debris protects the glacier (or perhaps perennial snowbank) from melting. This has been shown from recent work in the Swiss Alps (Whalley, 2020), the Pyrenees (Whalley, 2021a) and Iceland (Whalley, 2021b). Further observations on rock glaciers, especially those that have long histories of observation as mentioned here, are likely to show degradation at snouts or on their surfaces with the formation of melt pools (Whalley, 2021c). Repeat observations by Google Earth^{TM} and in the field was well as structure-from-motion (SfM) from UAVs and InSAR measurements of surface topography and displacements will add more detail to this picture at an individual glacier and rock glacier level. Such data would benefir from being georeferenced using a dLL.

DATA RECORDING, PRESERVATION AND USE

This paper has shown some of the advantages of recording decimal Latitude-Longitude (dLL) strings, as for example [42.47114,13.56695] to identify small glaciers, landform features and data points. Few papers give the latitude and longitude of data or sample points let alone in decimal form. One exception is the mapping of last glacial maximum extents in Baroni & *alii* (2018), although this is not the condensed, csv string form, as used here. With increasing awareness of the linkages between biota, mountain landforms and climate/meteorology and ecosystem shifts (Brighenti & *alii*, 2019) collaboration between disciplines is important. This would be enhanced with data procurement and sharing and by identifying data as well as topography and sampling sites specified by dLLs. Work is currently underway about specifying and searching for dLLs and using the ideas of geomorphic information tensors. Sharing and interoperability of data would also be very much aided if data/location points in inventories (whether of glaciers, rock glaciers or events like rockfalls and glacier lake outburst floods – GLOFS) could be recorded using dLLs and be publicly accessed for the future.

CONCLUSIONS

Linking the present positions of glacier ice, snow collecting areas and features such as rock glaciers, moraines and protalus ramparts in a time of rapid climate warming requires not only present-day data but observations from the past. The identification of geomorphological features (and their changing dimensions) can be best accomplished using locations that are searchable on a database (as well as GE) and transects, as geomorphological information tensors as outlined here. There is now the potential for digital (or digitized) information to be collected and compared. This paper has shown how earlier mapping, photography, compiling inventories etc can be related to present day (post 2020) conditions with Google Earth^{TM}. With a suitable database, local observations could be compared worldwide. I hope this paper will be a first step towards this and will promote investigations of 'papers in the past', those perhaps buried in 'the literature' (English as well as French, German and Italian for the examples given here) to treat those observations as worthy of their originators for future generations.

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