Manual for Mapping Rock Glaciers in Google Earth

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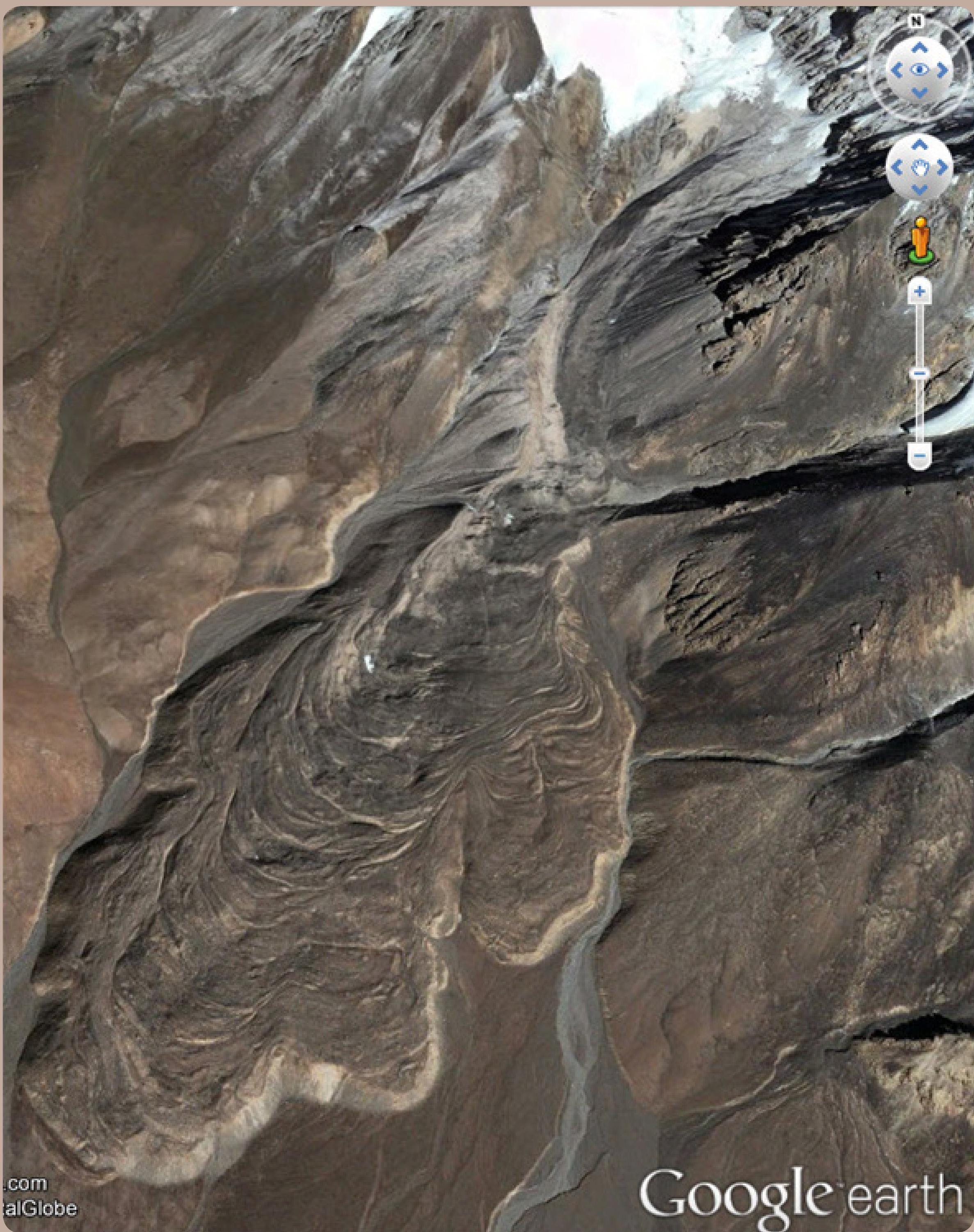

The manual was developed for the Hindu Kush Himalayan (HKH) region but can be used for rock glacier mapping in any area. The results of the application of the methodology in the Hindu Kush Himalayas have been published as a journal article:

Schmid, MO; Baral, P; Gruber, S; Shahi, S; Shrestha, T; Stumm, D; Wester P (2015) 'Assessment of permafrost distribution maps in the Hindu Kush Himalayan region using rock glaciers mapped in Google Earth.' The Cryosphere 9: 2089-2099. doi:10.5194/tc-9-2089-2015 available at http://www.the-cryosphere.net/9/2089/2015/tc-9-2089-2015.html with supplementary material (including the final draft of this manual) at

http://www.the-cryosphere.net/9/2089/2015/tc-9-2089-2015-supplement.zip

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Manual for Mapping Rock Glaciers in Google Earth

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Objectives

The manual aims to provide a detailed and comprehensive methodology for mapping rock glaciers in Google Earth. The method was developed to support an assessment of permafrost distribution in the Hindu Kush Himalayan (HKH) region and the examples are based on this study.

The objectives are

- to provide a step-by-step manual on how to map rock glaciers in Google Earth,
- to provide examples of the diversity of rock glaciers encountered, of permafrost related features, and of how to classify rock glaciers, and
- to provide a step-by-step guide on how to extract spatial attributes from the mapped rock glaciers.

1. Introduction

Permafrost is defined as lithospheric material that remains at or below zero degrees Celsius (0°C) for at least two consecutive years (William and Smith 1989). The near-surface layer above it thaws during the warm season and is termed the 'active layer'. The definition is thermal rather than visual, thus it is difficult to identify permafrost simply by looking. To directly measure permafrost, either a borehole or excavation is needed, which is expensive and laborious. Thus data on the occurrence and distribution of permafrost are scarce, especially in remote regions and developing countries. It is possible, however, to partly overcome the problems associated with direct measurement by measuring and mapping proxy components that are directly related to permafrost, such as ground surface temperature or geomorphologic features.

The term rock glacier is used to describe a creeping mass of ice-rich debris (i.e. permafrost material) on mountain slopes (e.g. Capps 1910; Haeberli 1985). Rock glaciers often have a lobed shape with longitudinal or transversal flow structures (ridges and furrows) and a characteristic frontal appearance, and the texture of the rock glacier surface frequently differs from the texture of surrounding slopes (Figures 1 and 2). The presence of ground ice at depth, usually inferred from signs of recent movement, is indicative of the presence of permafrost. In areas with a continental climate, like those commonly found in the Hindu Kush Himalayan (HKH) region, surface ice interacts with the permafrost and results in complex mixtures of buried snow or glacier ice and segregated ice formed in the ground. In such environments, a range of transitions can occur from debris-covered polythermal or cold glaciers to ice-cored moraines and deep-seated creep of perennially frozen sediments (e.g. Owen and England 1998; Shroder et al. 2000; Haeberli et al. 2006). In this manual, we use the term rock glacier to describe any landscape feature with the morphological appearance of creeping permafrost. The most likely origin of the ice is not used as an exclusion criterion for glacier-derived ice.

The occurrence of rock glaciers is governed both by the thermal regime of the ground and by the availability of subsurface ice either derived from snow avalanches or glaciers or formed directly in the ground. The other requirements are a sufficient supply of debris and topography steep enough to promote significant movement. The presence of intact (active and inactive) rock glaciers is an indicator of permafrost occurrence, but the absence of intact rock glaciers does not indicate the absence of permafrost. As intact rock glaciers contain ice (latent heat) and move (or have moved) downslope, their termini can be surrounded by permafrost-free ground. Rock glaciers are frequently covered with coarse clasts, which further retards the melting of the ice within the rock glacier. In steep terrain, the termini of rock glaciers can be taken as local-scale indicators for the presence of permafrost, and the elevation of the terminus can be taken as an indication of the lowermost occurrence of permafrost in that area (Haeberli et al. 2006). In more gentle terrain, such as parts of the Tibetan Plateau, the slope angle is often the limiting factor for formation of rock glaciers, even where permafrost is present. In these areas, rock glaciers may be absent over large areas of permafrost due to low slope angles, lack of debris, lack of avalanche snow, or high elevation of the valley floor.

The tendency for rock glaciers' termini to indicate the lowermost occurrence of permafrost in (steep) mountain areas is exploited in the mapping exercise described here.

Figure 1: **Schematic diagram of a rock glacier**

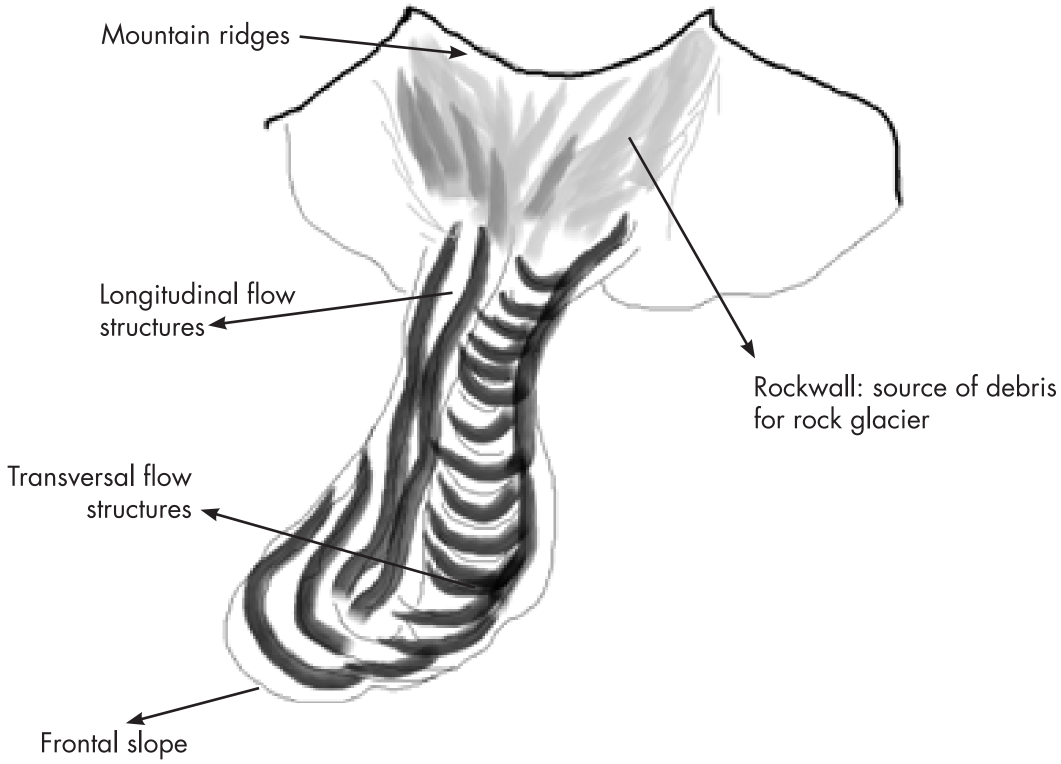
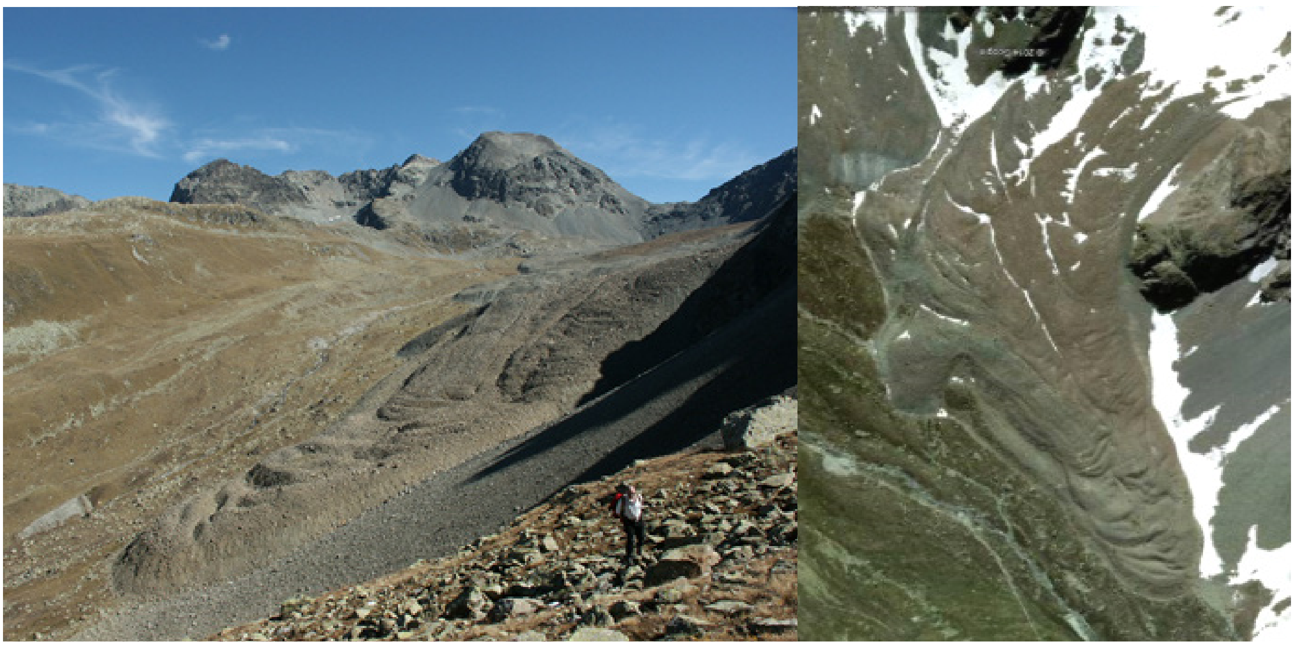


Figure 2: **Rock glacier (A) photo (D. Stumm), and (B) Google Earth image**



2. Methodology

The method presented here was specifically developed to support systematic analysis of rock glacier distribution in randomly distributed squares in the HKH region, but it can be applied in any geographical area.

2.1 Overall procedure and software

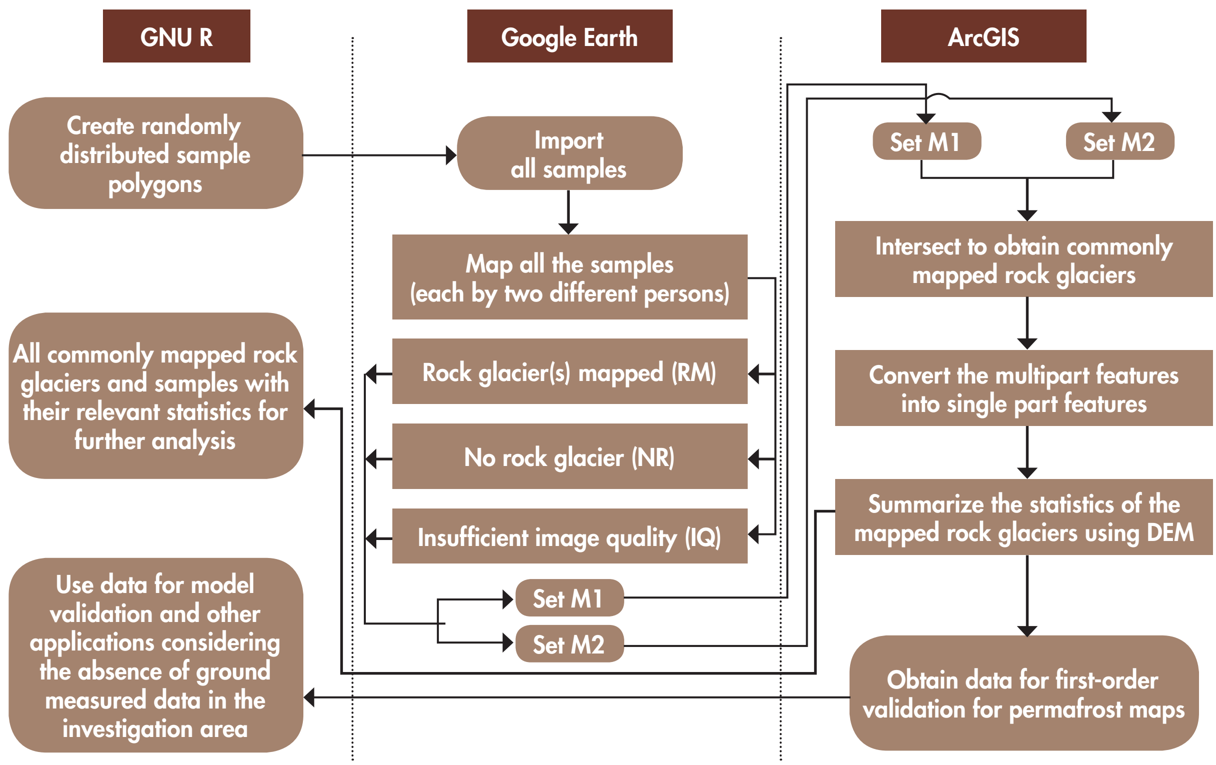
The following software is required:

- GNU R to create randomly distributed sample polygons.
- Google Earth to map rock glaciers within the sample polygons.
- ArcGIS 9.3 to extract spatial attributes for the sample polygons and the mapped rock glaciers. (Later versions of ArcGIS may show small differences in the commands, but the principle of the approach remains the same.)

GNU R, or simply 'R', is a scripting language for manipulation and analysis of statistical data and can be used to create randomly distributed samples. Specific packages are required to work with spatial data in R. The packages used in this study were 'maptools' (Bivand and Lewin-Koh 2014), 'sp' (Pebesma 2005; Bivand and Pebesma 2013), and 'ggplot2' (Wickham 2009). Once the random sample polygons have been created, rock glaciers found within the sample polygons are mapped by different observers using Google Earth. ArcGIS is then used to extract spatial information (mean minimum elevation) for the rock glaciers within the sample polygons.

Figure 3 shows the overall schematic mapping and analysis process and the use of the software.

Figure 3: **Flow chart illustrating the overall mapping and data analysis procedure. M1 and M2 are sets of KML files with the polygons mapped for rock glaciers by observer 1 and observer 2, respectively.**



2.2 Creation of randomly distributed sample polygons

Sample polygons for mapping should be randomly distributed in the investigation area in order to obtain an unbiased result. Thus the first step is to delineate the investigation area with a polygon and then use GNU R to continuously fill this area with randomly distributed square sample polygons as follows.

Use the user defined function **f.RandomPolygon()** to generate randomly distributed square sample polygons in the Keyhole Markup Language (KML) format, which is readable in Google Earth. The function can be downloaded from (http://www.the-cryosphere.net/9/2089/2015/tc-9-2089-2015-supplement.zip). Each sample polygon is given a unique name consisting of two capital letters and three numbers. The first sample polygon is named AA001. The function used to create the randomly distributed sample polygons is **f.RandomPolygon (in.file.shp, out.file.kml, sample.start, sample.end, sample.length)**

Define the following five arguments:

- **in.file.shp:** this is an input shapefile containing the investigation area delineated by a single polygon within which the randomly distributed sample polygons will be created.
- **out.file.kml:** this is the name and location of the KML output file with the randomly distributed sample polygons.
- **sample.start** and **sample.end:** These numbers specify the location and name of the sample to be used to start and end the creation of sample polygons. The number of polygons in the output file is equal to the difference between sample.start and sample.end, i.e.:
  1. **sample.start** = 1, **sample.end** = 50, creates 50 randomly distributed polygons starting at AA001
  2. **sample.start** = 50, **sample.end** = 100, creates 50 randomly distributed polygons starting at AA050
- **sample.length:** This is the latitudinal width of each sample polygon in decimal degrees (DD). An approximate adjustment is applied for longitudinal width (see below).

The steps integrated in the **f.RandomPolygon()** function to create the sample polygons in KML format are briefly as follows:

The **readShapePoly** function from the maptools package is used to read the data from the polygon shapefile (i.e. in.file.shp).

- The **fortify** function from the ggplot2 package is used to extract the coordinates from the shapefile.
- Each sample (i.e. one square sample polygon) needs to be created with a specified latitudinal length (LATL) and longitudinal length (LONL). The LATL is already specified for each sample (i.e. polygon side length in decimal degrees). An approximate adjustment is applied for LONL as follows, where LAT is the latitude for a specific sample.

$$LONL = \frac{LATL}{cos\left(\frac{\pi * LAT}{180}\right)}$$

- Five points with longitude, latitude coordinates are used to define a sample square polygon; four of the points represent the corners, while the fifth point is needed to close the square (and is identical to the first point). The output is a list with longitudinal coordinates in the first column and latitudinal coordinates in the second column forming a closed square (the first row equals the fifth row).
- The **sample** function is used to create random sample polygons with a defined sample size.
- Every sample polygon is assigned a unique name i.e. which includes letters (uppercase or lowercase), numbers, or a combination of both. The **LETTERS** function is used to assign uppercase letters and the **sprintf** function to create formatted combination of text and variable values which feed in the values that differ in each loop.
- Finally, the **kmlPolygons** function from the maptools package is used to export the samples into a KML file.

The output is a file with a total of n square-shaped sample polygons with a latitudinal length of sample. length in the KML format used for rock glacier mapping.

[NOTE: If you get the following message **Error in sample.int(length(x), size, replace, prob): cannot take a sample larger than the population when 'replace = FALSE'** then the number of output polygons exceeds the number of possible polygons within the boundary defined by in.file.shp. In this case either decrease the number of polygons (use a smaller difference between sample.start and sample.end) or decrease the sample.length (size of polygons).]

2.3 Rock glacier mapping in Google Earth by individual observers

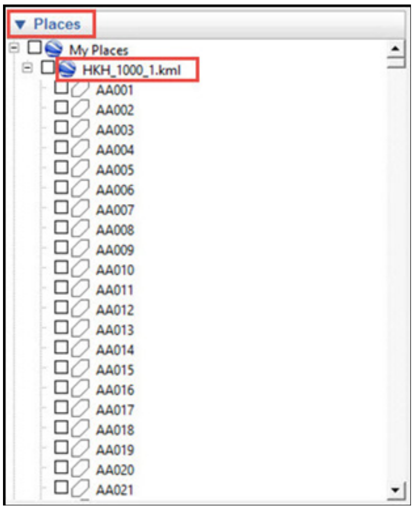
After the randomly distributed sample polygons have been created in KML format, they can be inspected for the presence of rock glaciers using Google Earth (Figure 4). There is considerable variation in the rock glacier outlines mapped manually by different people using high resolution Google Earth images. To reduce this subjectivity, each sample polygon should be mapped by at least two people independently (usually using different computers). This will lead to at least two separate layers of mapping (M1 and M2) for each set of KML files.

The following steps are conducted by each observer separately.

- Load the KML files with the randomly distributed sample polygons into Google Earth by double clicking on **KML files, or Google Earth > File > Open > Select KML files**, and uploading the files in the 'My Places' folder ready for further analysis (Figure 5).

Figure 4: **White dots represent the randomly distributed sample polygons defined in the study within the defined boundary (yellow) of the study area (HKH boundary) as displayed in Google Earth.**

Figure 5: **Example of a KML file uploaded into the 'My Places' folder in Google Earth**



2.3.1 Mapping the sample polygons

The mapping procedure involves the following steps:

- Assessment of entire sample polygon
- Assigning labels to sample polygons
- Delineation of rock glacier outlines
- Labelling rock glaciers

Assessment of sample polygons

Visually inspect all polygons for the presence of rock glaciers by checking each sample polygon in the Google Earth image (Figure 6A). Several Google Earth features can be used in the detailed inspection. You can navigate through the images using either the arrow keys, a mouse, or the navigation controls (Look joystick and Move joystick) in the top right corner of the 3D viewer (Figure 6B). The speed of navigation can be adjusted **(Google Earth > Tools > Options > Navigation)** to enable efficient inspection of every part of the sample polygon.

You can zoom in and out of the Google Earth image while searching inside a sample polygon using either a mouse, the keyboard **(Ctrl + Shift + Arrow Key)**, or the zoom slider in the middle right corner of the 3D viewer.

You can also tilt the view using shortcuts **(Shift + Arrow Key)** or the navigation slider (Move joystick). This Google Earth function is very useful for viewing mountainous terrain and for mapping rock glaciers as it helps to distinguish changes in elevation.

Figure 6: **Example of a sample polygon (A) and navigation tools available in Google Earth (B)**

(A) (B)

Use all image layers available in Google Earth to ensure comprehensive mapping of the sample polygons. If you suspect the presence of a rock glacier but it isn't clear, study earlier images to see if the same features are present. Activate the historical imagery in Google Earth **(Google Earth > View > Historical Imagery**, or **Click on Clock icon)** to see earlier images (Figure 7).

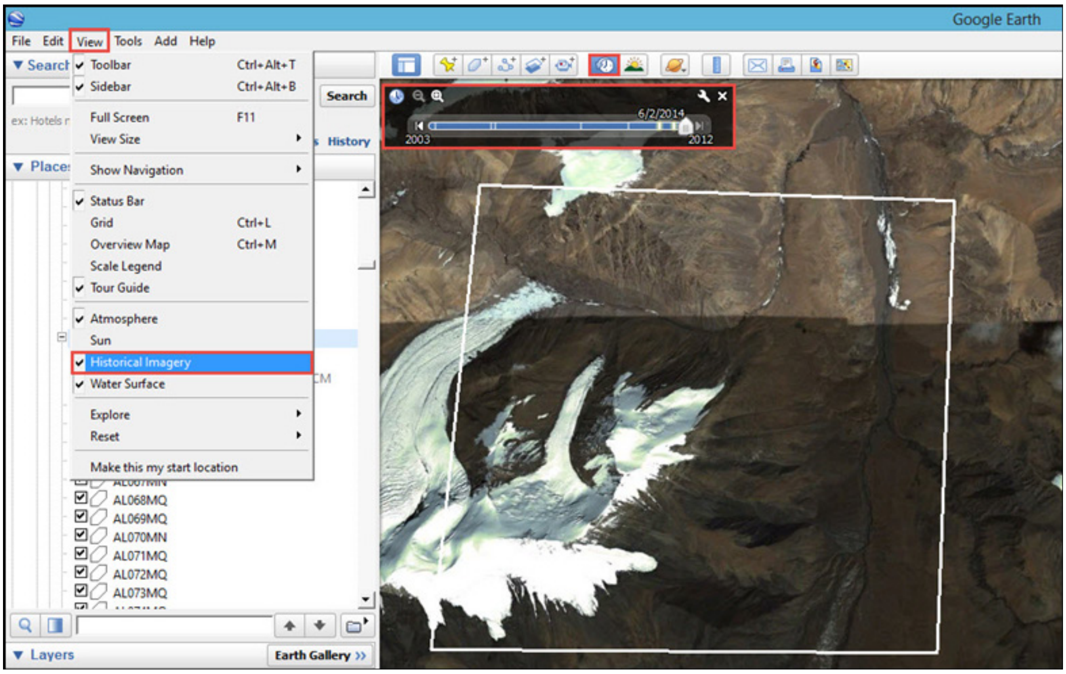


Figure 7: **Activated time slider in Google Earth to view historical images**

Assigning labels

Assign a label to every sample polygon as follows (Table 1). If no rock glacier is seen, add the label NR (no rock glacier) to the polygon name. If any rock glaciers are identified, add the label RM (rock glacier(s) mapped). If it is not possible to detect rock glaciers visually due to poor image quality, excessive snow, or cloud coverage over any part of the sample, add the label IQ (insufficient quality). Do not assign any label until the sample polygon has been thoroughly inspected. This will help you to ensure that all sample polygons in the KML files are inspected.

Table 1: **Labelling of sample polygons.**

Description	**Naming (e.g. here sample polygon AA001)**
Not yet mapped	AA001
Mapped – no rock glacier	AA001NR
Mapped – with rock glacier(s)	AA001RM
Mapping not possible due to poor image quality, snow cover or clouds (even if that applies just to parts of the sample).	AA001IQ

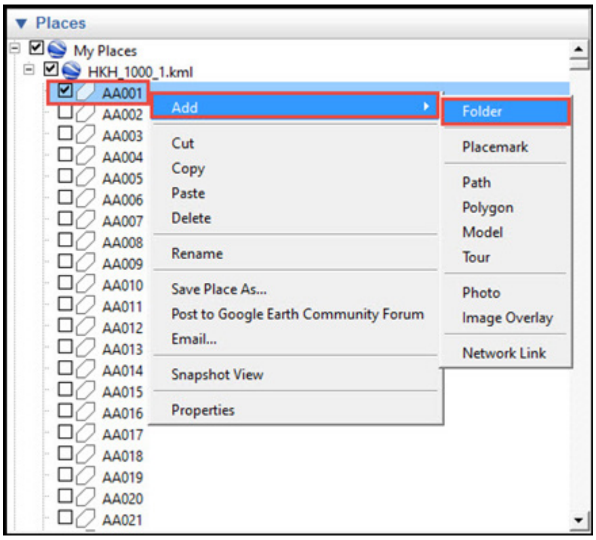
Delineation of rock glacier outlines

Map the individual rock glaciers using the Google Earth 'polygon' feature. Delineate the outlines as precisely as possible using visual interpretation. To enable subsequent processing, it is important that you create a separate folder for the mapped rock glaciers in each sample polygon (RG_MAPPING folders), and that you save each rock glacier as a uniquely labelled polygon within this mapping folder. Do not create RG_Mapping folders for sample polygons labelled as 'NR' or 'IQ'. Create and name the folders and rock glacier polygons as follows.

Open the KML files with the sample polygons.

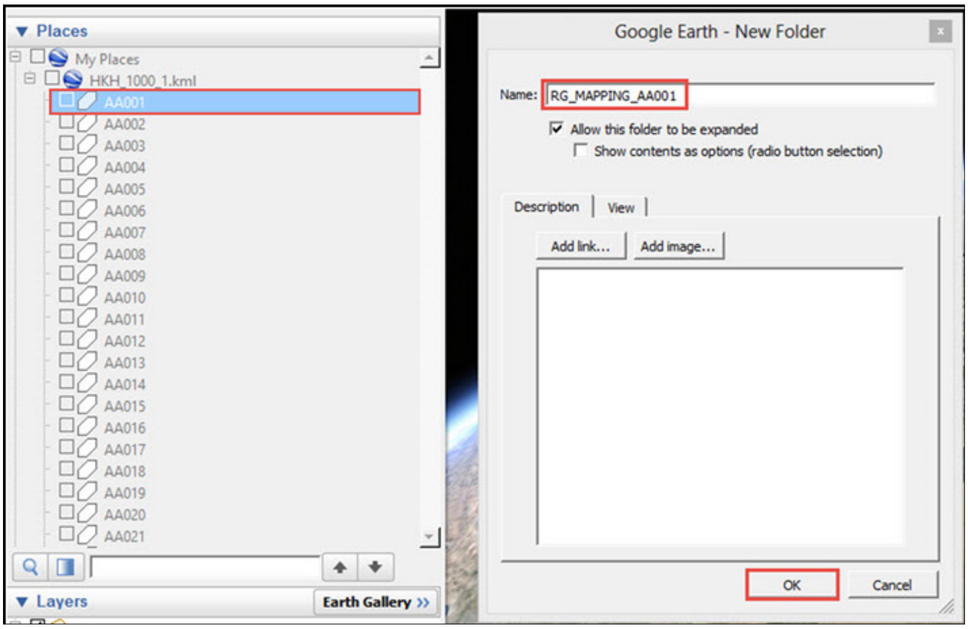
1. Right click on the sample polygon to be mapped
2. Click on 'Add' in the dropdown menu that appears.
3. Click on 'Folder' (Figure 8).

Figure 8: **Creating an RG_MAPPING folder inside a sample polygon**



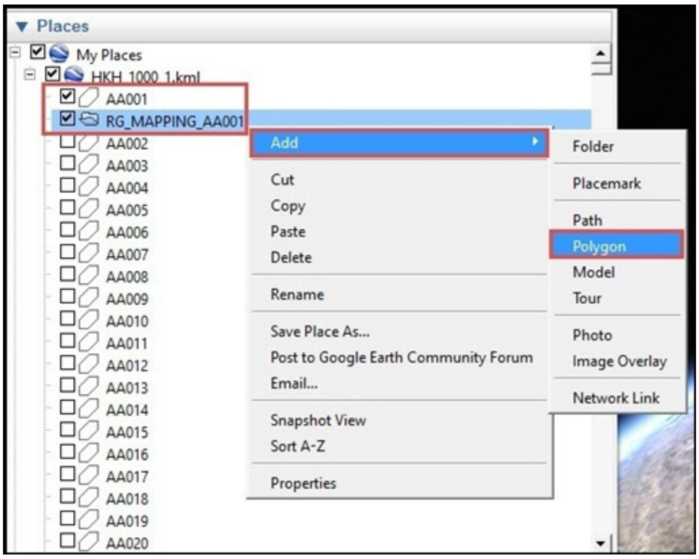
4. A new dialogue box 'Google Earth – New Folder' appears. Give a name to the folder 'RG_MAPPING_name of the sample polygon' (e.g., 'RG_MAPPING_AA001' for all rock glaciers mapped within the sample square 'AA001'), be sure you place the folder below the sample polygon AA001 in the KML fines and click 'OK' (Figure 9).

Figure 9: **Naming the RG_MAPPING folder**



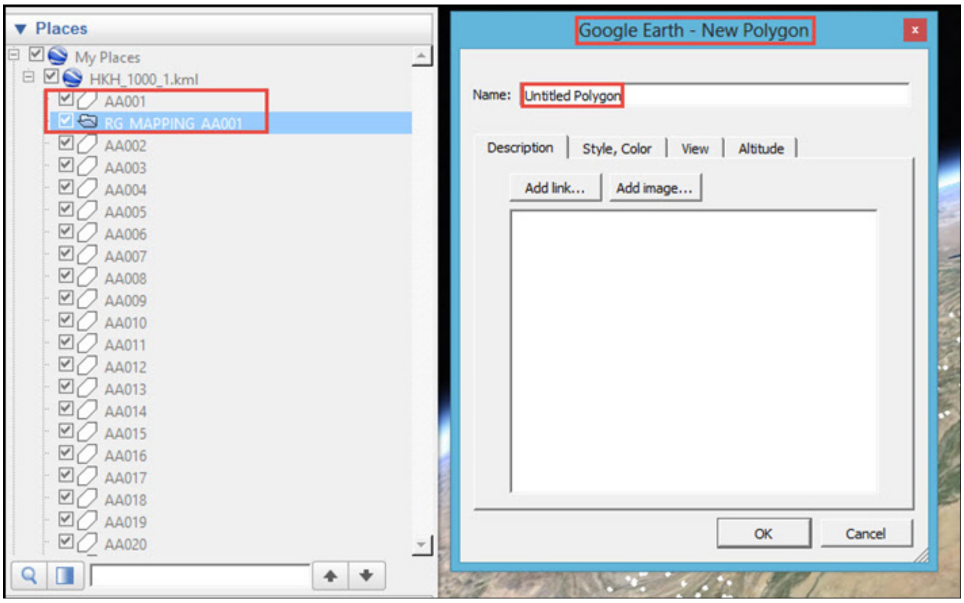
5. The folder will be placed at the end of the KML file. Either drag it to the top and place it below the sample polygon for which it is created OR right click on the folder, cut, and paste it below the sample polygon (Figure 10).
6. Right click on the 'RG_MAPPING' folder created for the sample polygon.
7. Click on 'Add' in the dropdown menu that appears.
8. Click on 'Polygon' (Figure 10).

Figure 10: **Creating a new polygon inside an RG_MAPPING folder**



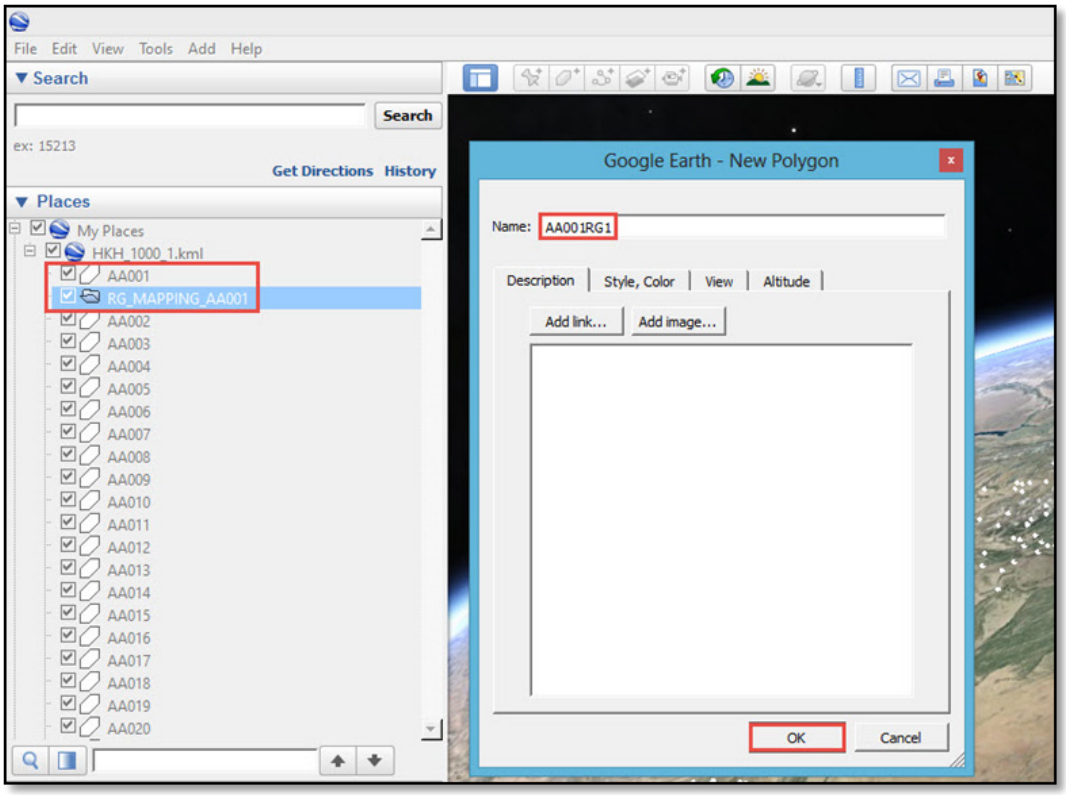
9. A new dialogue box 'Google Earth – New Polygon' appears with the name 'Untitled Polygon' in the name field (Figure 11).

Figure 11: **Dialogue that appears for the new polygon in the RG_MAPPING folder AA001**



10. Give a name to the polygon for the mapped rock glacier consisting of the name of the sample polygon plus the 'RG' extension and a number starting from 1. E.g. if a number of rock glaciers are encountered within sample polygon AA001, label the first mapped rock glacier as AA001RG1, the second as AA001RG2, the third as AA001RG3, and so on, to create a unique name (Figure 12). When you have finished inspecting the sample polygon relabel it to AA001RM.

Figure 12: **Creating a new polygon in the folder RG_MAPPING_AA001 and labelling it as AA001RG1**

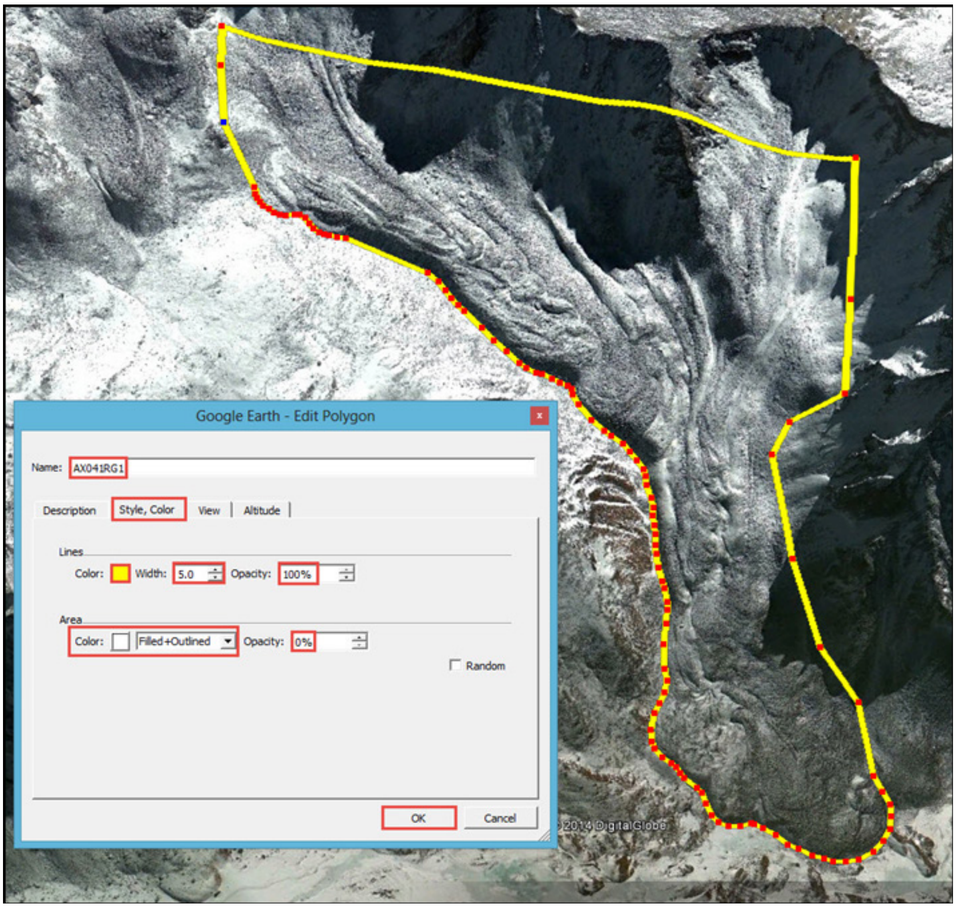


Each person involved in mapping should use a specific colour for the polygon outlines to allow easy visual identification of who has mapped a particular rock glacier outline. Click on the Style, Color tab (Figure 13), and choose a specific colour, width, and opacity for the boundary lines. Delineate the outline of the rock glacier using the mouse. Either click and drag the cursor to outline the shape, or click the cursor and release to add a single point to the polygon, and repeat to add more points. Try to map only the part of the rock glacier that lies within the sample polygon. Even if a mapped outline does cross the boundary of a sample polygon, it will be removed during the spatial analysis in ArcGIS so that only rock glacier features within the sample polygon are included in the final analysis. Figure 13 shows an example: the outline of a rock glacier mapped as 'AX041RG1'. The parts of the outline with many points were mapped by clicking and dragging the cursor, the parts with fewer points were mapped by clicking and releasing the cursor.

Labelling the rock glaciers

Details of the rock glacier attributes are recorded in the form of labels after the rock glacier polygon name. The labels are added in the order: image date, upslope boundary (i.e. origin), activity, longitudinal flow structures, transversal flow structures, frontal appearance, outline visualization, snow coverage, and overall confidence. Detailed descriptions of how to identify and label the various features are given in the following sections. The classification and abbreviations used are given in Table 2. If a rock glacier has multiple forms of one attribute, choose the most dominant form, for example, if the front slope of a rock glacier is gentle in some places and steep in others, label with the attribute type occupying the greatest area or length. The classification 'unclear' is used if none of the labels seem to match.

Figure 13: **Outline of a rock glacier created using the polygon feature in Google Earth**



Save an example set of features showing the different attribute labels in a single KML file called 'Labeling.KML' in Google Earth to use as a reference while labelling the rock glaciers. Write the abbreviations for the labels into the 'Description' tab of the polygon separated by a semicolon. A typical complete label might look like this (example is for rock glacier 1 in the random polygon AD043): AD043RG1_03112011;BS;AM;LN;TV;FG;OV;SP;CM

Image date

The first attribute is the image date and shows the image layer used for mapping. In default images the date is displayed on the screen, in images accessed

Table 2: **Labelling the rock glaciers**

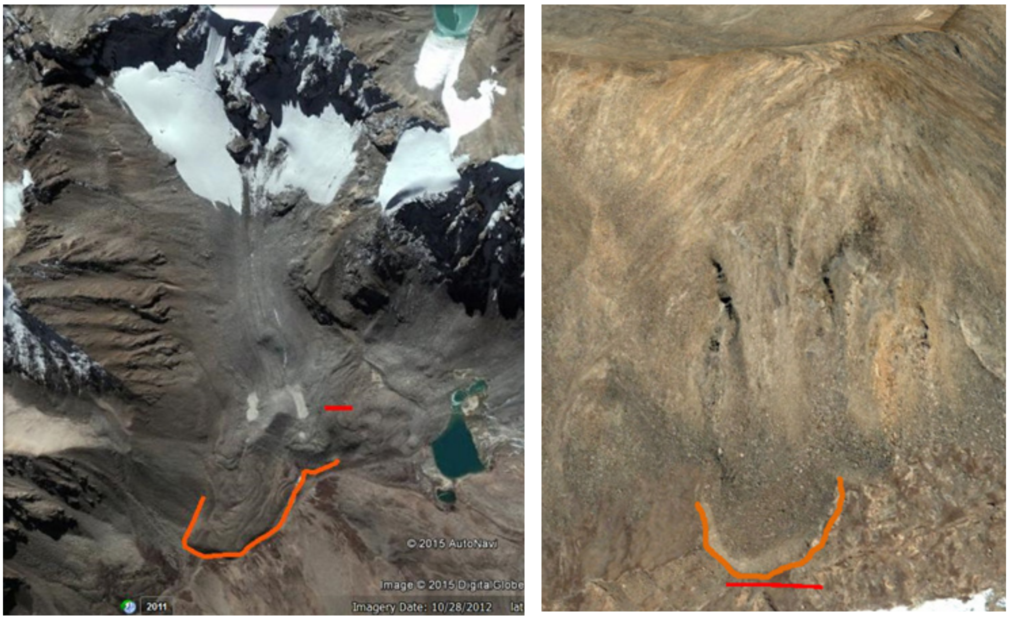
Attribute	Classification	Abbreviation
Image date	MMDDYYYY	
Upslope boundary	Glacial	BG
	Slope	BS
	Unclear	BU
Likelihood active	Virtually Certain	AVC
	High	AH
	Medium	AM
Longitudinal flow structure	Clear	LC
	Vague	LV
	None	LN
Transversal flow structure	Clear	TC
	Vague	TV
	None	TN
Front	Steep	FS
	Gentle	FG
	Unclear	FU
Outline	Clear	OC
	Fair	OF
	Vague	OV
Snow cover	Snow	SS
	Partial Snow	SP
	No Snow	SN
Overall confidence	Virtually Certain	CVC
	High	CH
	Medium	CM

through a time slider, the image date is shown in the time slider itself or is displayed when the cursor is placed on the 'new polygon' dialogue. Note the date in the format 'MMDDYYYY'.

Upslope boundary

The origin of a rock glacier is called the upslope boundary. Three types of boundary area are differentiated: 'Glacial' if the area is a glacier, abbreviated BG; 'Slope' if the area is sloping, abbreviated BS, and 'Unclear' if the area can't be defined, abbreviated BU (Figure 14).

Figure 14: **Examples for the attribute upslope boundary: A) glacial (BG); B) sloping (BS) (orange lines indicate the lower limits of the rock glaciers; red line = 100 m)**

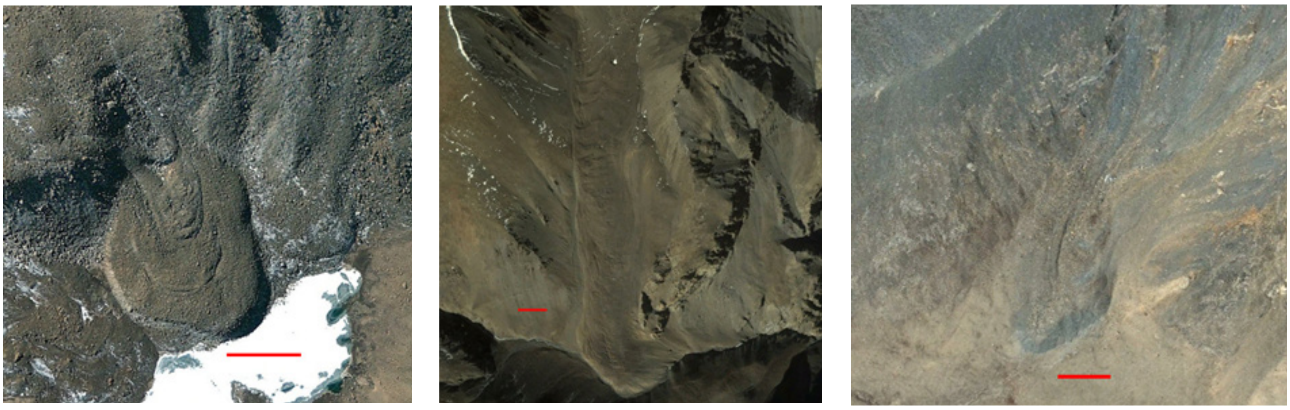


(A) **(B)**

Activity

It is important to add a label to show how clear the indication is that the rock glacier is active, i.e. moving. You can tell this by looking at a combination of the surface relief, the frontal slope, vegetation, and the composition of the material. An active rock glacier is characterized by well pronounced ridges and furrows (see section 'Flow structures'), a steep gradient along the frontal slope (see section 'Front'), absence of vegetation, and presence of fresh, unweathered material. Three categories are used to describe the likelihood that the rock glacier is active: 'Virtually Certain', 'High', and 'Medium', abbreviated as AVC, AH, and AM, respectively (Figure 15).

Figure 15: **Examples for the attribute Likelihood Active:**
A) **Virtually Certain (AVC);** B) **High (AH);** C) **Medium (AM) (red line = 100m).**
Less pronounced visible flow structures and outline and frontal appearance mean less certainty.

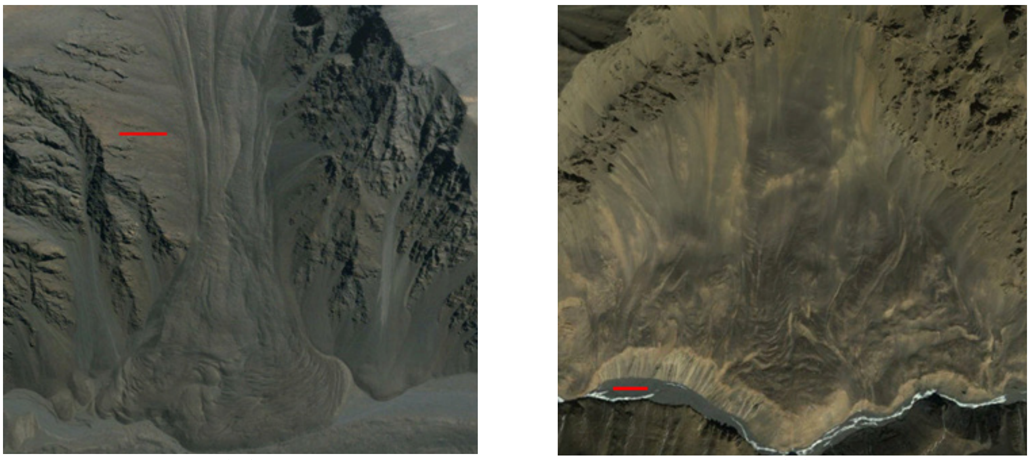


(A) (B) (C)

Flow structures

Rock glaciers can have both longitudinal and transversal flow structures (ridges and furrows). Longitudinal and transverse structures are labelled separately; both have three categories: 'Clear', 'Vague', and 'None', abbreviated for longitudinal structures as LC, LV, and LN (Figure 15), and for transverse structures as TC, TV, and TN (Figure 16).

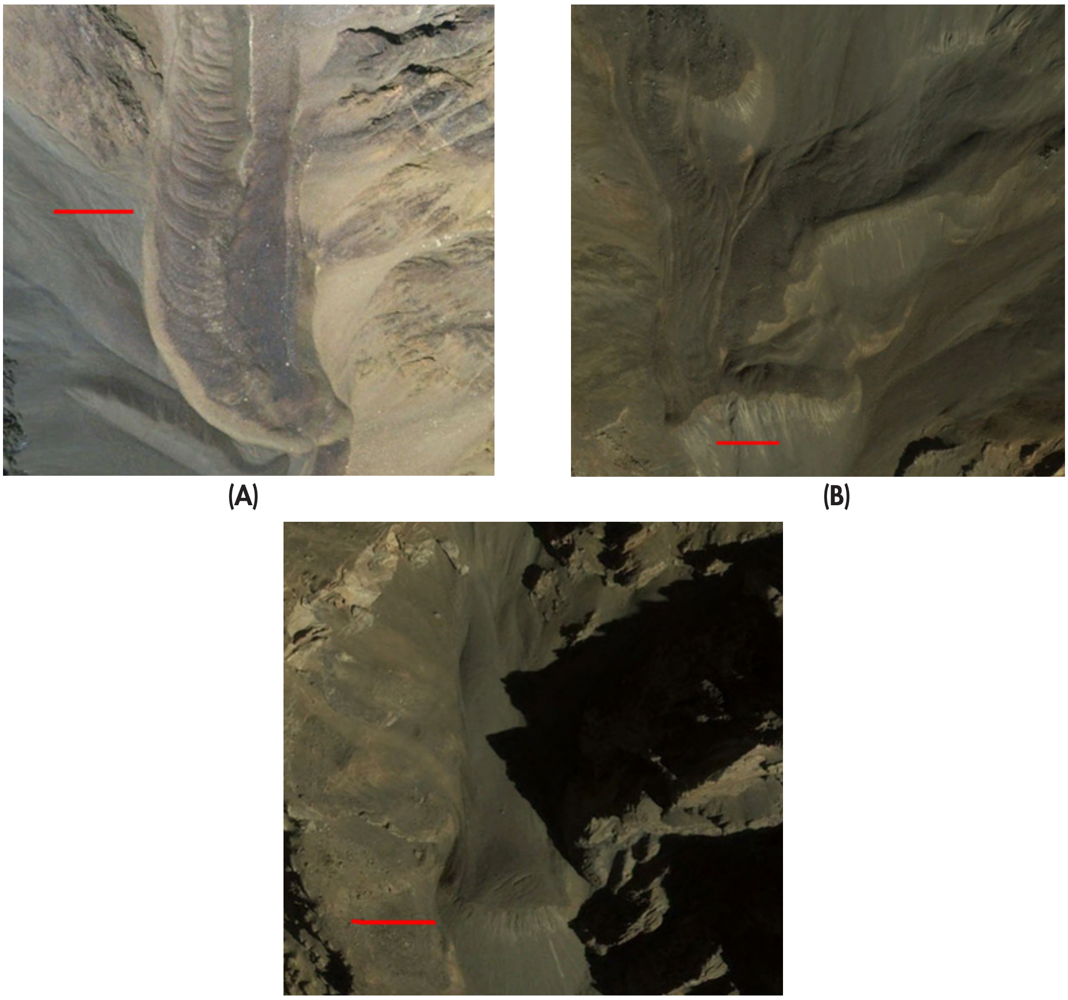
Figure 16: Examples for the attribute 'Longitudinal flow structure':
A) **Clear (LC);** B) **Vague (LV);** C) **None (LN) (red line = 100m)**



(A) (B)

(C)

Figure 17: **Examples for the attribute 'Transversal flow structure': A) Clear (TC); B) Vague (TV); C) None (TN) (red line = 100m)**

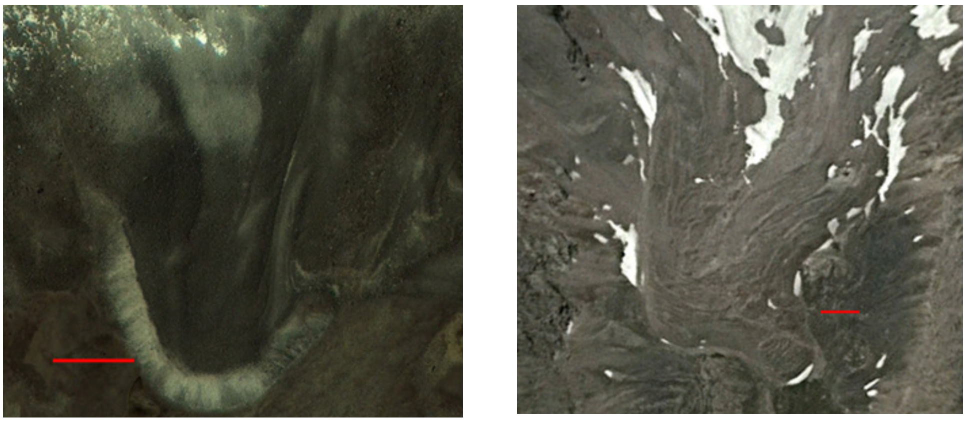


(A) **(B)** **(C)**

Front

Three categories are used to describe the slope of the attribute 'Front': 'Steep', 'Gentle', and 'Unclear', abbreviated as FS, FG, and FU, respectively (Figure 18). 'Steep' means that the front slope is at a steep angle relative to the horizontal plane and is indicated by the presence of loose material along the front slope which has a lighter colour than the material on the rock glacier surface. At this angle, the material on the slope face is on the verge of sliding.

Figure 18: **Examples for the attribute 'Front': A) Steep (FS); B) Gentle (FG) (red line = 100m)**



(A) **(B)**

Outline

Mapping of rock glacier outlines using Google Earth images is subjective. The attribute 'Outline' is used to indicate how clear the outline appears to the person doing the mapping. The attribute has three categories: 'Clear', 'Fair', and 'Vague', abbreviated as OC, OF, and OV, respectively (Figure 19).

Figure 19: **Examples for the attribute 'Outline': A) Clear (OC); B) Fair (OF); C) Vague (OV) (red line = 100m).**

(A)

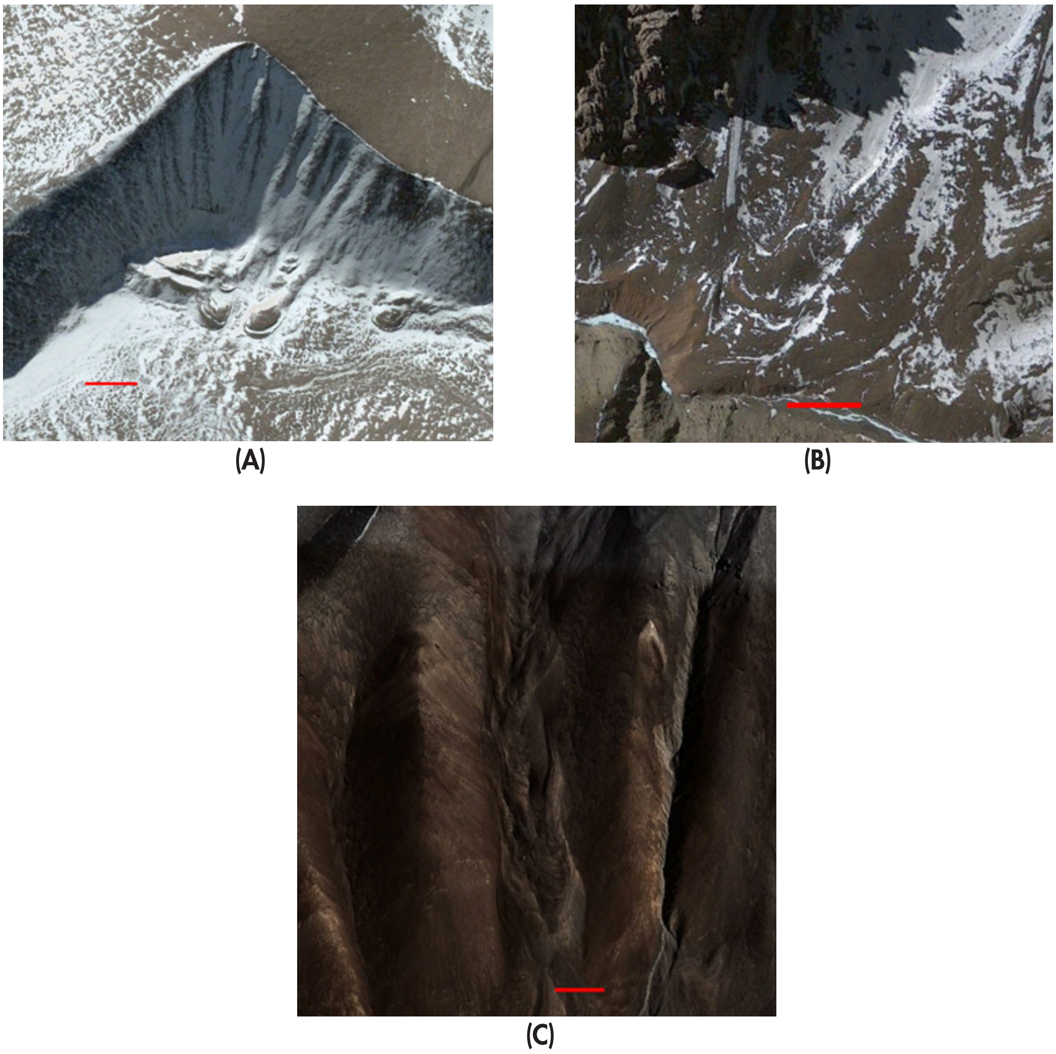
(B)

(C)

Snow cover

The presence of snow on the rock glacier is indicated by the attribute 'Snow Cover'. There are three categories: 'Snow', 'Partial Snow', and 'No Snow', abbreviated as SS, SP, and SN, respectively (Figure 20).

Figure 20: **Examples for the attribute 'Snow Cover': A) Snow (SS); B) Partial Snow (SP); C) No Snow (SN) (red line = 100m)**



Overall confidence

The final attribute 'Overall Confidence' summarizes the overall impression of the degree to which all the features together are consistent with the mapped feature being a rock glacier. There are three categories: 'Virtually Certain', 'High', and 'Medium', abbreviated as AVC, AH, and AM, respectively (Figure 21).

Figure 21: **Examples for the attribute 'Overall Confidence': A) Virtually Certain (CVC); B) High (CH); C) Medium (CM) (red line = 100m)**

(A)

(B)

(C)

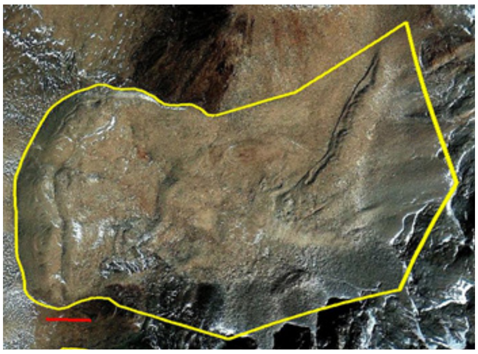
Figure 22: **Examples of rock glaciers with their full set of attribute labels:**

A) **(AD043RG1_03112011;BS;AM;LN;TV;FG;OV;SP;CM);**

B **(AS029RG1_07292008;BG;AVC;LC;TC;FG;OF;SP;CVC);**

C) **(AD005RG1_10142011;BS;AM;LV;TN;FS;OF;SN;CM);**

D) **(AC010RG2_12202006;BS;AH;LV;TN;FS;OF;SP;CH) (red line = 100m)**



(A)

(B)

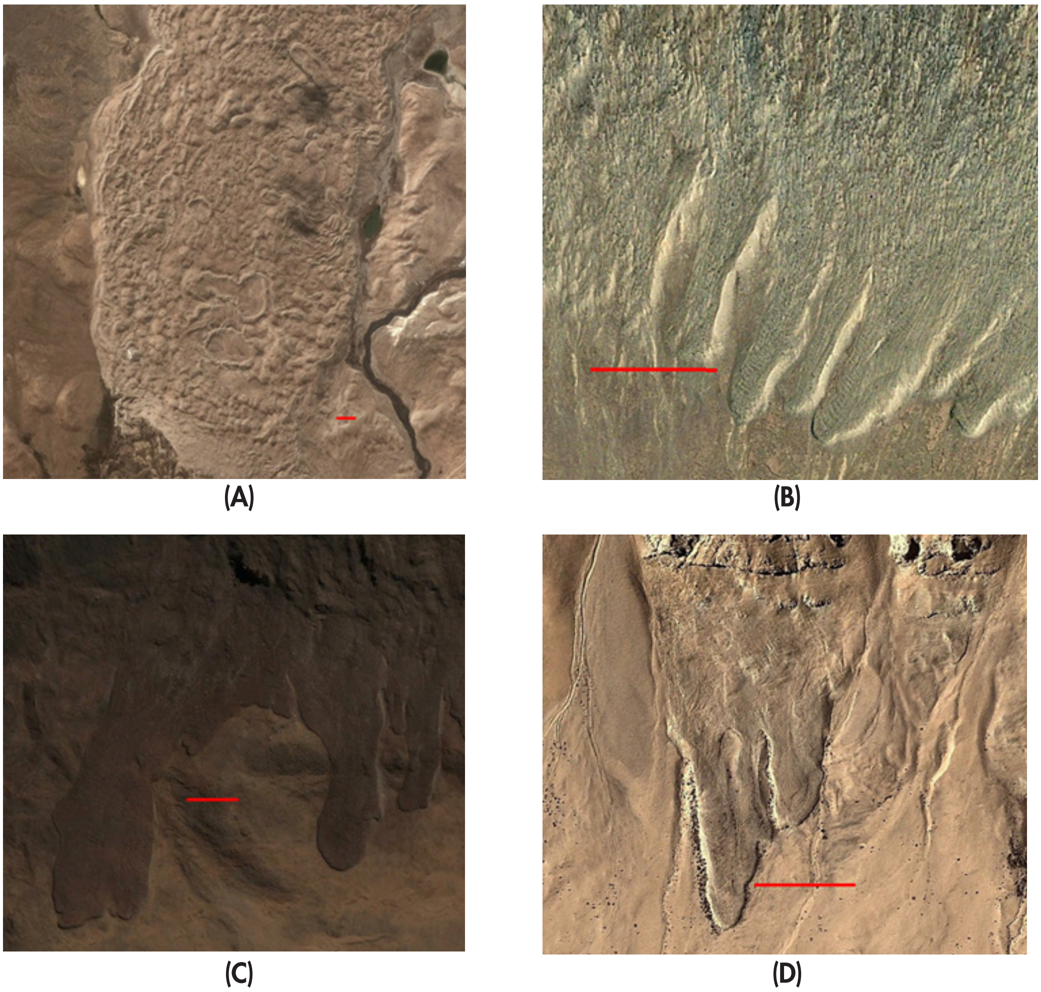
(C)

(D)

Other features

Adding attributes increases the confidence that the structures observed really are rock glaciers. During mapping we encountered other structures that indicate ground movement or creep, but which couldn't be linked to the presence of ice or permafrost with any certainty. These structures were not mapped as rock glaciers; some examples are shown in Figure 23. Further investigations will be needed to clarify whether permafrost plays a role in their existence.

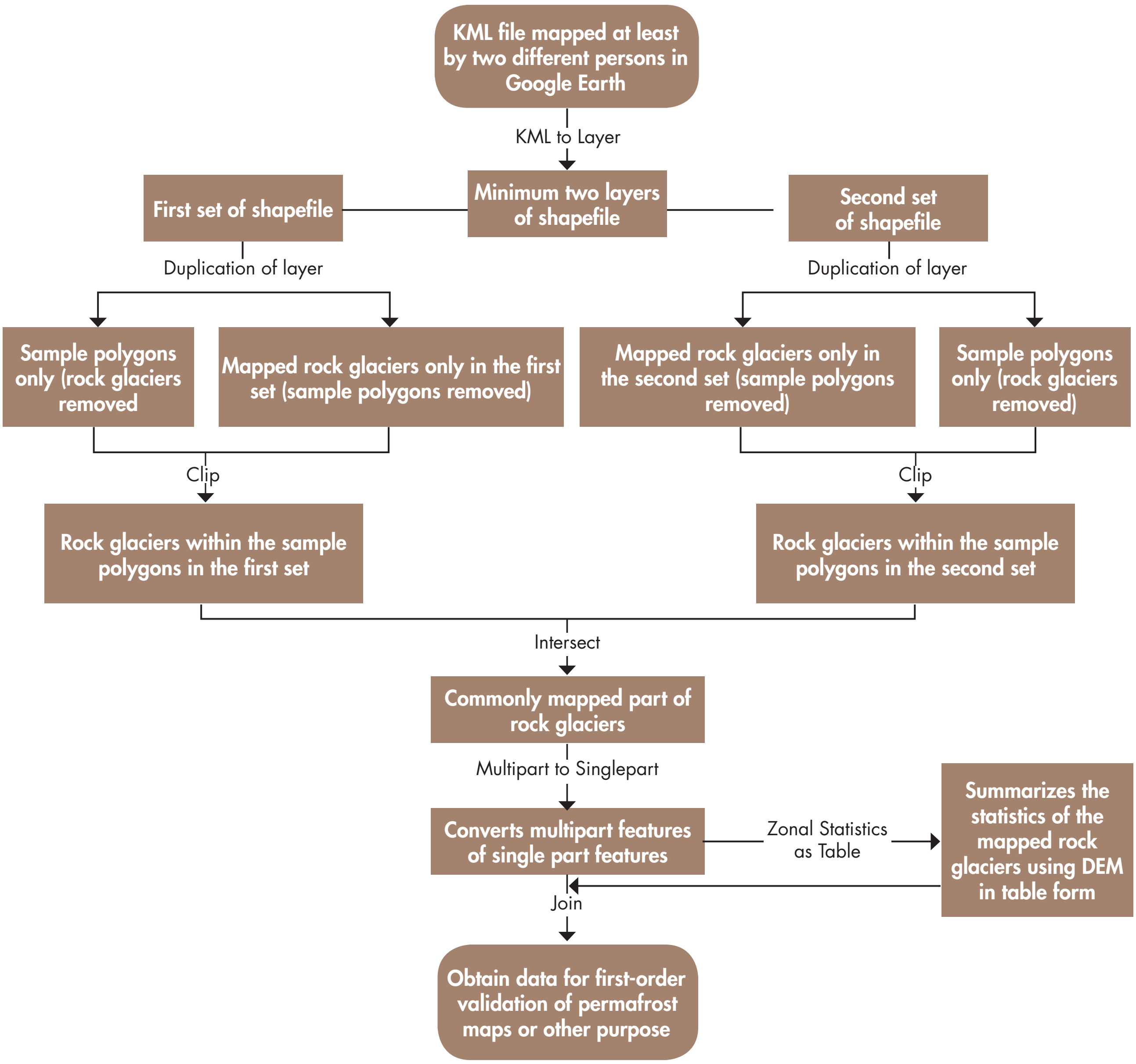
Figure 23: **Examples of creeping ground features without sufficient attributes to be classified as a rock glacier (red line = 100m)**



2.4 Spatial attributes of the mapped rock glaciers

Once mapping is complete, the KML files are imported from Google Earth to ArcGIS to determine which parts of the rock glaciers have been mapped by both observers and extract the spatial attributes. Figure 24 shows the procedure in the form of a flow chart. The individual steps are described in detail in the following sections.

Figure 24: **Flow chart illustrating the overall procedure to extract the spatial attributes from commonly mapped rock glaciers using ArcGIS**



2.4.1 Extracting statistical attributes for the mapped rock glacier polygons and sample polygons

The following steps are carried out separately for the KML files mapped by the different observers (M1 and M2 and so on).

1. Convert the KML file created in Google Earth into a layer file in ArcGIS using the Conversion Tools. This tool creates a file geodatabase containing a feature class (e.g. File_name.gdb or M1.gdb).

   ArcToolbox > Conversion Tools > From KML > KML To Layer

2. To view the converted file (polygons), navigate to the folder where geodatabase (File_name.gdb or M1.gdb) is stored. The polygon file will be placed within placemarks.

   Add Data > File_name.gdb > Placemarks > Polygons

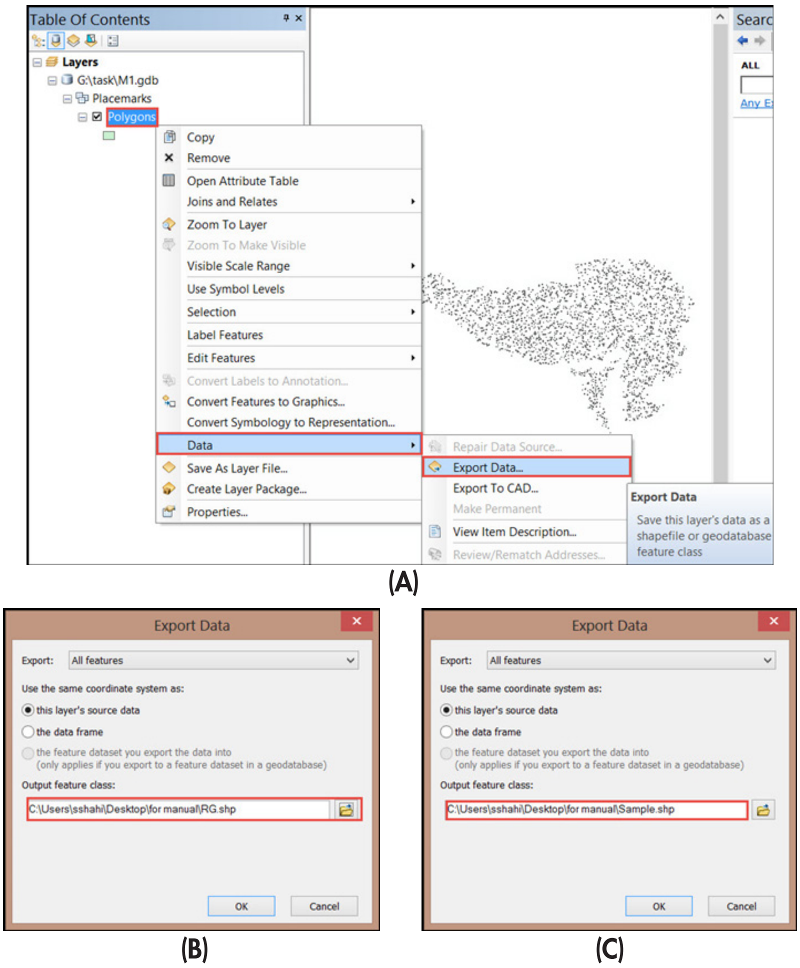
3. Duplicate the layers and create two separate polygon files, one with only rock glaciers and one with only sample polygons.

   Right click on the Polygons.shp and choose

   Data > Export Data

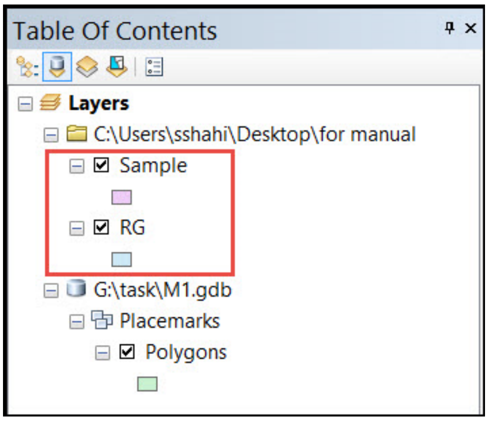
   to create a shape file with the file name 'RG.shp' (the file that will have only rock glaciers); repeat to make a second file named 'Sample.shp' (the file that will have only sample polygons) (Figure 25). The separate sets of files from the two observers will have different names, i.e. RG_M1.shp and RG_M2.shp, and Sample_M1.shp and Sample_M2.shp.

Figure 25: **Creation of two shp files: A) Duplication of the Polygon.shp layer using the 'Export Data' tool; B) creation of RG.shp; C) creation of Sample.shp**



- Right click on the shapefile 'RG.shp' and click Open Attribute Table.
- Sort the PopupInfo column by double clicking on the column header. The rock glaciers will be listed at one end of the column and the sample polygons at the other.
- Use the editor tool bar to remove the sample polygons. (If the editor tool bar is not activated, then use the 'Customize' root menu to show it as a dockable window on the menu bar. Customize > Toolbars > Editor). Click on 'Editor', select 'Start Editing', and delete all sample polygons (i.e. all rows with empty PopupInfo) leaving a file with all the rock glacier polygons. Save.
- Repeat for the shapefile 'Sample.shp' but delete all the rock glacier polygons (with PopupInfo containing information).
- Save the files. You should now have two shape files, one with only rock glaciers and other with only sample polygons (Figure 26). Keep a backup of both files.

Figure 26: **Two shapefiles: one with rock glacier polygons only (RG), the other with sample polygons only (Sample)**



4. Use the command Repair Geometry to RG.shp to fix any geometry problems in the rock glacier polygons.

   ArcToolbox > Data Management Tools > Features > Repair Geometry

5. Use the command Clip to remove any rock glacier parts lying outside the sample polygons.

   ArcToolbox > Analysis Tools > Extract > Clip

   Use the following input and output parameters:
   - 'Input Features' is RG.shp
   - 'Clip Features' is Sample.shp
   - Choose a suitable name and location in 'Output Feature Class', e.g. RG_clip
   - 'XY tolerance' is 0

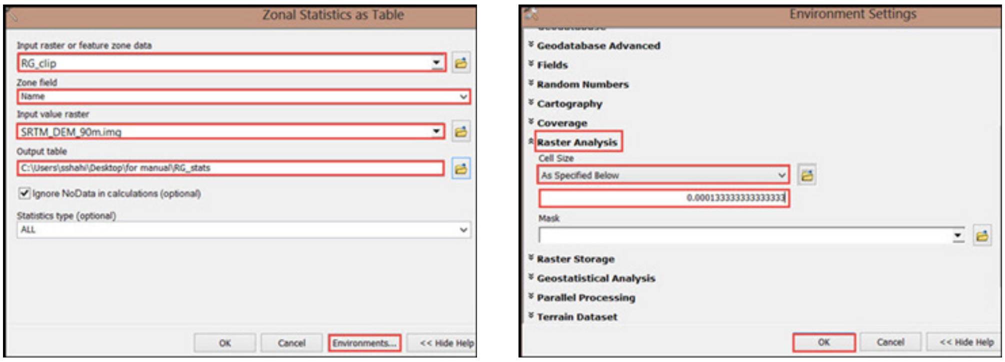
6. Use the command Zonal Statistics as Table for RG_clip.shp (RGM1_clip.shp and RGM2_clip.shp) and Sample.shp (RGM1_ Sample.shp and RGM2_ Sample.shp) to prepare a table with the values given in the DEM for the zones within each shapefile.

   ArcToolbox > Spatial Analyst Tools > Zonal > Zonal Statistics as Table

   Use the following input and output parameters (Figure 27A):

   - 'Input raster or feature zone data' is RG_clip.shp or Sample.shp
   - 'Zone field' is the field that holds the values that define each zone. In this case it is 'Name' of mapped rock glaciers.
   - 'Input value raster' is a DEM of the study area.
   - In 'Output table' give a suitable name, e.g. RG_stats or Sample.stats.
   - If any very small mapped rock glacier areas are not taken into account because they are too small (i.e. NULL values after clipping, see below), the Cell Size in Environments > Raster Analysis must be set to a smaller value, for example, half the size of the cells in the DEM. Don't use a value smaller than 0.000133333333333333 or the computation will be extremely slow (Figure 27B).

Figure 27: **Preparation of tables with the statistics from the DEM for the zones within the files: A) setting the parameters; and B) changing the environmental settings**



(A) **(B)**

7. Join the table with the zonal statistics with the corresponding layer as follows. Right click on layer (RG_clip or Sample) and choose

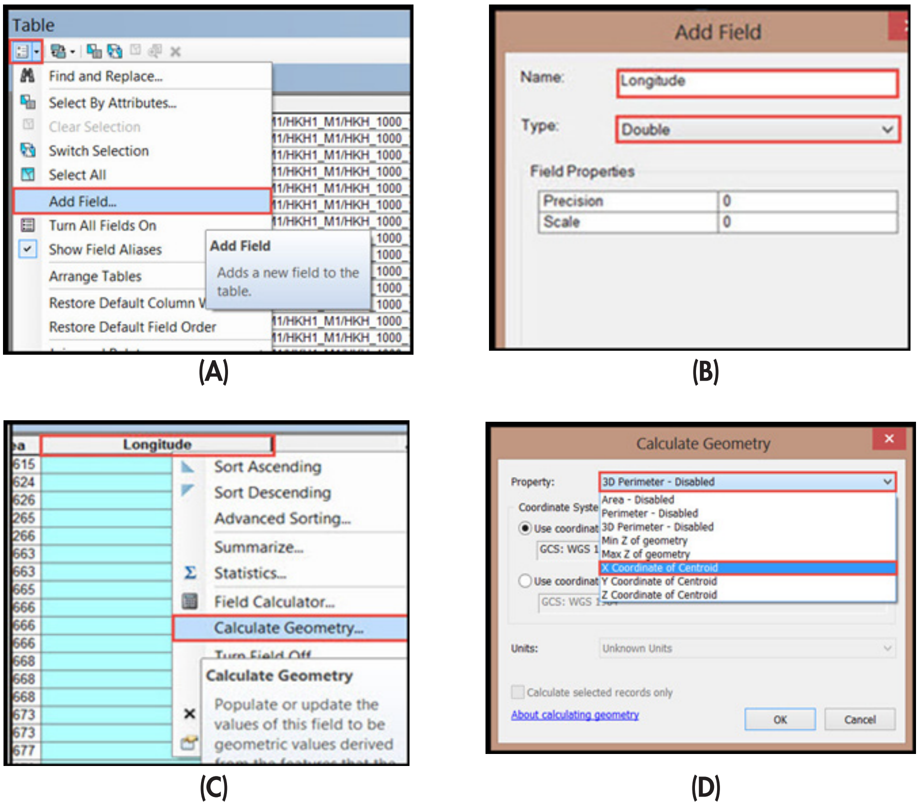
   Joins and Relates > Join

   Use the following input and output parameters:

   - Choose 'Name' from the drop down menu as the field on which the join will be based.
   - Choose previously created table (RG_stats or Sample.stats) from the dropdown menu to join to this layer.

8. Calculate the latitude/longitude for each sample polygon and rock glacier as follows (Figure 28).
   - Right click on the layer (e.g. Sample or RG) and choose Open Attribute Table. Click 'Add field' in the drop down menu of 'Table Options'. In 'Name' write Longitude or Latitude; in the drop down menu of 'Type' select 'Double'; and click OK. Edit the session using the Editor tool bar (as described above). Right click on the recently added field (Longitude or Latitude) and choose Calculate Geometry (under 'Property' choose 'Y Coordinate of Centroid' for latitude or 'X Coordinate of Centroid' for longitude).

Figure 28: **Procedure for calculating latitude and longitude of sample polygons or rock glaciers**



2.4.2 Extracting minimum elevation of the commonly mapped areas of rock glaciers

Each square sample polygon is mapped separately by at least two observers. Differences in delineating rock glaciers are inevitable, especially the upper limit of the glacier and the separation between individual rock glaciers. Usually the lower limit of rock glaciers can be more easily recognized than the upper limits. However, to ensure that the data sets are robust and that the final estimates of the elevation of the lower limit are conservative, only areas identified as rock glaciers by both observers are included in the assessment.

1. Use the Intersect tool to extract the commonly mapped areas.

   ArcToolbox > Analysis Tools > Overlay > Intersect

   Use the following input and output parameters:
   - 'Input Features' are RG_M1.shp and RG_M2.shp
   - Choose a suitable name for 'Output Feature Class', e.g. M1interM2.shp.

2. Use Multipart to Singlepart to separate the multipart features into single part features.

   ArcToolbox > Data Management Tool > Features > Multipart to SinglePart

   Use the following input and output parameters:

   - 'Input Features' is M1interM2.shp
   - Choose a suitable name for 'Output Feature Class' e.g. M1interM2_ms.shp
   - XY tolerance' is 0

3. Use the Zonal Statistic command as a Table for M1interM2_ms.shp to summarize all values and take the lowest value for each polygon from the DEM within the zones of the given shapefile in a table (Figure 27).

   ArcToolbox > Spatial Analyst Tools > Zonal > Zonal Statistics as Table

   Use the following input and output parameters:

   - 'Input raster or feature zone data' is M1interM2_ms.shp
   - 'Zone field' is the field that holds the values that define each zone. In this case it is Name.
   - 'Input value raster' is a DEM of the study area.
   - In 'Output table' give a suitable name, e.g. M1M2_RG_stats
   - If any very small mapped rock glacier areas are not taken into account because they are too small (i.e. NULL values after joining), the Cell Size in Environments > Raster Analysis must be set to a smaller value, for example, half the size of cells in the DEM. Don't use a value smaller than 0.000133333333333333 or the computation will be extremely slow.

4. Join the M1M2_RG_stats table with the corresponding layer as follows. Right click on layer (M1interM2_ms.shp) and choose

   Joins and Relates > Join

   Use the following input and output parameters:

   - Choose 'Name' from the drop down menu as the field on which the join will be based.
   - Choose previously created table (M1M2_RG_stats) from the dropdown menu to join to this layer.

The result is a table containing data showing the names of individual commonly mapped rock glaciers together with the minimum elevation of their termini, assigned attributes, and position coordinates.

3. Example of Application: Rock Glacier Mapping in the HKH Region using Google Earth

A total of 4000 randomly distributed sample squares were created in GNU R within the boundary coordinates of the HKH as defined by ICIMOD. The total area of the randomly distributed squares was close to 2% of the total HKH area. The 4000 squares were divided into four sets of 1000 sample polygons. These sets were stored in four separate Keyhole Markup Language (KML) files and referred to as 'HKH_1000_1.kml', 'HKH_1000_2.kml', 'HKH_1000_3.kml', and 'HKH_1000_4.kml'. Each sample polygon inside these KML files was given a unique name consisting of two capital letters and three digits between 001 and 100. Table 3 shows the alphabetical prefixes used for the four sets of KML files.

Table 3: **Assigning attributes to sample polygons**

KML FILES			
HKH_1000_1.kml	HKH_1000_2.kml	HKH_1000_3.kml	HKH_1000_4.kml
AA	AK	AU	BE
AB	AL	AV	BF
AC	AM	AW	BG
AD	AN	AX	BH
AE	AO	AY	BI
AF	AP	AZ	BJ
AG	AQ	BA	BK
AH	AR	BB	BL
AI	AS	BC	BM
AJ	AT	BD	BN

Each sample polygon was mapped independently by two of the three observers performing mapping (Table 4) to give two mapping layers (M1 and M2) for each set of KML files.

Table 4: **Mapping of sample polygons**

Set 1			**Set 2**			**Set 3**			**Set 4**		
Sample	**M1**	**M2**	**Sample**	**M1**	**M2**	**Sample**	**M1**	**M2**	**Sample**	**M1**	**M2**
AA	[yellow]	[blue]	AK	[yellow]	[orange]	AU	[yellow]	[blue]	BE	[yellow]	[blue]
AB	[yellow]	[blue]	AL	[yellow]	[orange]	AV	[yellow]	[blue]	BF	[yellow]	[blue]
AC	[yellow]	[blue]	AM	[yellow]	[orange]	AW	[yellow]	[blue]	BG	[yellow]	[blue]
AD	[yellow]	[blue]	AN001-AN033	[yellow]	[orange]	AX	[yellow]	[orange]	BH	[yellow]	[orange]
AE	[yellow]	[blue]	AN034-AN100	[yellow]	[blue]	AY	[yellow]	[orange]	BI	[yellow]	[orange]
AF	[yellow]	[orange]	AO	[yellow]	[blue]	AZ	[yellow]	[orange]	BJ	[yellow]	[orange]
AG	[yellow]	[orange]	AP	[yellow]	[blue]	BA	[blue]	[orange]	BK	[yellow]	[orange]
AH	[yellow]	[orange]	AQ001-AQ067	[yellow]	[blue]	BB	[blue]	[orange]	BL	[blue]	[orange]
AI	[blue]	[orange]	AQ068-AQ100	[orange]	[blue]	BC	[blue]	[orange]	BM	[blue]	[orange]
AJ	[blue]	[orange]	AR	[orange]	[blue]	BD	[blue]	[orange]	BN	[blue]	[orange]
			AS	[orange]	[blue]						
			AT	[orange]	[blue]						

Observer 1	[blue]
Observer 2	[yellow]
Observer 3	[orange]

The outlines were drawn using a line width of '5.0', Opacity '100%', Area Colour 'White', 'Filled + Outlined', and Opacity '0%' (Figure 13) using blue, yellow, or orange for Observers 1,2, and 3, respectively. The rock glaciers were mapped as described above. The results are given in (Schmid et al. 2015) and can be downloaded as supplementary material from http://www.the-cryosphere.net/9/2089/2015/tc-9-2089-2015-supplement.zip.

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About ICIMOD

The International Centre for Integrated Mountain Development, ICIMOD, is a regional knowledge development and learning centre serving the eight regional member countries of the Hindu Kush Himalayas – Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan – and based in Kathmandu, Nepal. Globalization and climate change have an increasing influence on the stability of fragile mountain ecosystems and the livelihoods of mountain people. ICIMOD aims to assist mountain people to understand these changes, adapt to them, and make the most of new opportunities, while addressing upstream-downstream issues. We support regional transboundary programmes through partnerships with regional partner institutions, facilitate the exchange of experience, and serve as a regional knowledge hub. We strengthen networking among regional and global centres of excellence. Overall, we are working to develop an economically and environmentally sound mountain ecosystem to improve the living standards of mountain populations and to sustain vital ecosystem services for the billions of people living downstream – now, and for the future.

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