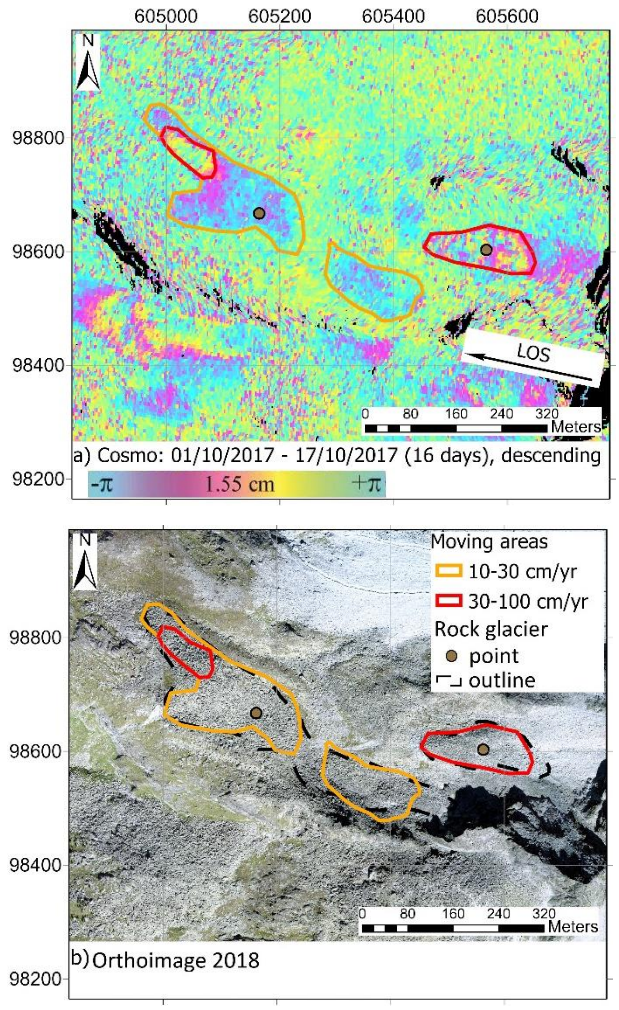
Rock glacier inventory using InSAR (kinematic approach)

Practical Guidelines v3.0.2



https://www3.unifr.ch/geo/geomorphology/en/research/ipa-action-group-rock-glacier (Action Group website)

11.06.2020

To the attention of ESA CCI+ Permafrost External Partners

In the framework of the ESA CCI+ Permafrost Project (2018-2021), External Partners are involved in the production of standardized rock glacier inventories including a kinematic attribute for selected regions of interest. Each inventory will be produced using a **kinematic approach based from SAR Interferometry (InSAR) data**. The present document is providing the necessary basics for the achievement of this inventory (*1. Basics*), suggestions about the GIS project organization and products requirements (*2. Practical guidelines*), as well as a practical exercise for a) training the identification and characterization of moving areas on the basis of InSAR data and for b) training the assignment of a kinematic attribute to selected rock glacier units (*3. Practical example*).

The guidelines outlined here are designed to help in the efficient homogenization of regional rock glacier inventories, including kinematics, with the use of InSAR data. The aim is to **provide standardized regional rock glacier inventories based on previously existing inventories** (InSAR polygons from GlobPermafrost and/or existing geomorphological rock glacier inventories). The update/upgrade has to rigorously follow the defined guidelines in order to ensure the homogeneity. These guidelines are compiled according to the technical definition provided by the IPA Action Group Rock glacier inventories and kinematics (Baseline concepts document: Kinematics as an optional attribute of standardized rock glacier inventories).

The importance of such compilations is growing in response to the need for regional to global assessments of climate change impacts, for the geohazard phenomena that may be a risk for human activities and/or facilities, for the indicators of the occurrence of permafrost conditions, and for the hydrological significance of the ice store inside rock glaciers. In this context, and according the technical definition provided by the IPA Action Group Rock glacier inventories and kinematics (Baseline concepts document: Towards standard guidelines for inventorying rock glaciers) the term "rock glacier" refers to debris landform generated by a former or current creep of frozen ground (permafrost), detectable in the landscape with the following morphology: front, lateral margins and optionally ridge-and-furrow surface topography. Any rock glacier landform is a system, which can be composed of either a single or multiple rock glacier units that are spatially connected, either in a topo-sequence or through coalescence. Rock glacier units are single landform that can be unambiguously discerned according to the technical definition of rock glacier and, in case of a spatial connection, can be differentiated from other (adjacent or overlapping) rock glacier units according to distinct generation of formation, connection to the upslope unit or activity.

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1. Basics

1.1 Moving area

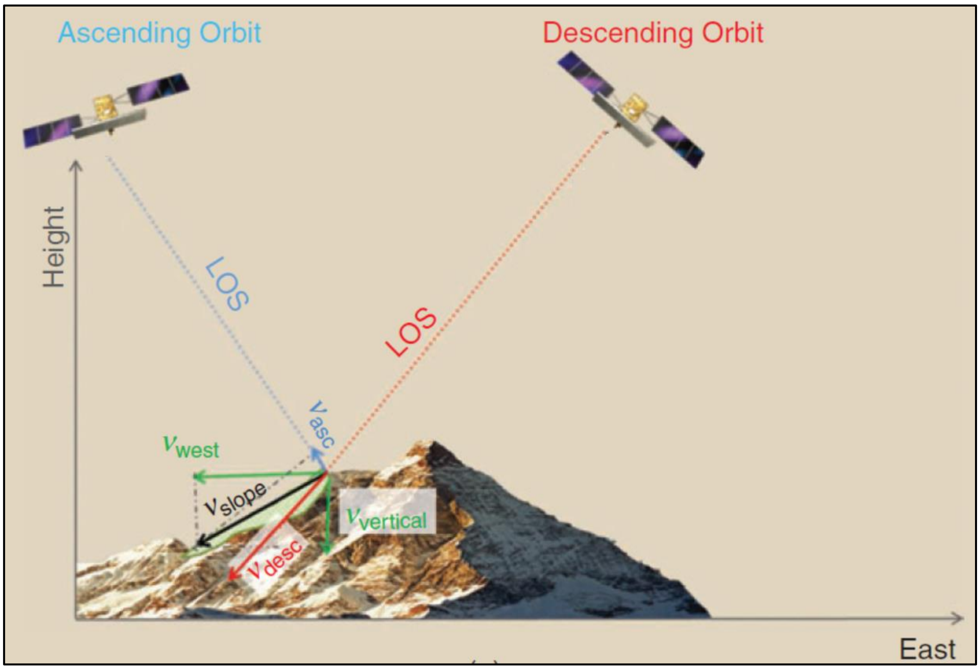
A moving area is defined as an **area at the surface of a rock glacier unit in which the observed flow field (direction and velocity) is uniform (spatially consistent/homogenous)** during a documented time. It has to represent the downslope movement rate of the rock glacier (permafrost creep) in the area of concern. The confusion with movement related to other processes (e.g. thaw subsidence) has – as far as possible – to be avoided. The identification of moving areas could be performed on the basis of any technique or combination of techniques providing areal (surface) displacement information.

Detecting and quantify moving areas is technology dependent. The present document gives **recommendations for deriving standardized moving areas using InSAR**, that will be used for characterizing the kinematic attribute associated to a rock glacier unit.

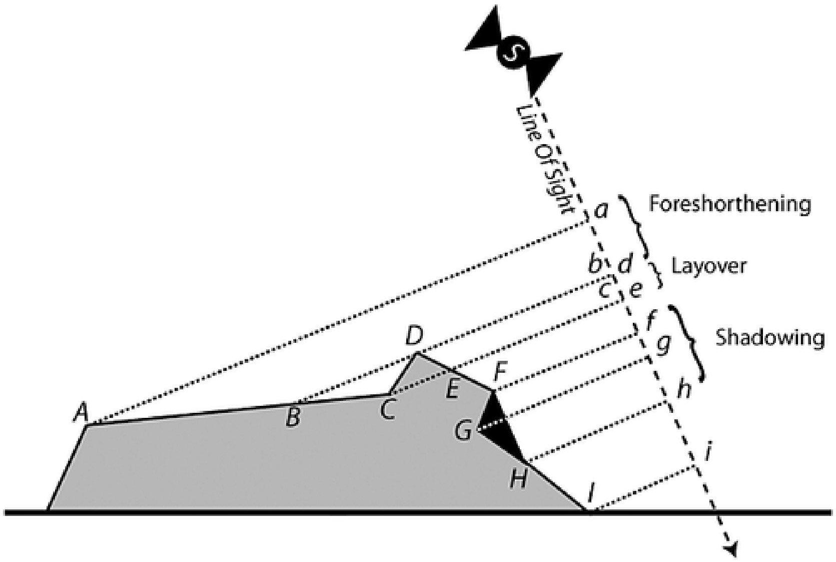
1.2 Characteristics of the surface changes with InSAR data

Two-pass differential interferometry (InSAR) is one of the most common methods in differential satellite-based interferometry and provides data with extensive spatial coverage allowing the simultaneous investigation of many phenomena at the regional scale. This approach consists of co-analyzing the phase difference between two SAR images from two separate flight tracks and removing the topographic contribution using a digital elevation model (DEM). The resulting interferogram provides the observation of the 3D surface deformation component projected along the radar look direction (i.e. the Line Of Sight, LOS). A single SAR interferometric observation does therefore not allow to fully determine the magnitude and direction of a surface deformation. The 3-dimensional displacement vector can be only computed if a displacement or "flow" direction is known, e.g. flowing along the steepest slope direction. Notice that the SAR measurement is not sensitive to the displacement if the flow and look directions are perpendicular to each other.

Current SAR satellites are polar orbiting and looking obliquely down, perpendicularly to the track direction. So the LOS is roughly East or West and has an impact on which slopes are suited in mountainous terrain (Fig.1a). North- and South-facing slopes, where deformations are often directed in the plane perpendicular to the LOS, can be difficult to analyze. **Back-facing slopes** (D-I, Fig.1b), defined as the western slope when viewing in descending mode or the eastern slope in ascending mode, **are the most appropriate configuration**: the local spatial resolution is less affected by geometric distortions and deformation orientation is more or less aligned with the LOS. The facing slopes (A-D, Fig.1b) are the opposite and are less favorable for an InSAR analysis. In addition, the slope steepness, along with the SAR incidence angle, has to be considered. A steep incidence angle (for instance 23° of ERS) reduces shadow effects observed in back-facing slopes but increases layover effect in facing slopes**.** Consequently, **a good compromise has to be chosen to observe correctly the two sides of the valley in mountainous terrain**.



(a)



(b)

Figure 1. (a) The projections of the sloped ground deformation (v_{slope}) in the two viewing geometries of the SAR sensor, ascending and descending, are reported as v_{asc} and v_{desc}, respectively (from IEEE Geoscience and Remote Sensing Magazine, March 2020, volume 8, number1). (b) SAR acquisition mode in the plane perpendicular to the orbit.

The displacement can be visually evaluated through interferograms. The change of color in the resulting interferogram expresses the ground deformation projected into the LOS direction and **the resulting fringe is equivalent to a change of half a wavelength in the LOS direction between two SAR images acquired at different times**. The direction of the change can be interpreted using the key in Fig. 2. Looking back-facing slopes, clockwise color changes mean that the radar beam has travelled further in the second acquisition and thus corresponds to a subsidence. In the opposite case, it will be interpreted as uplift.

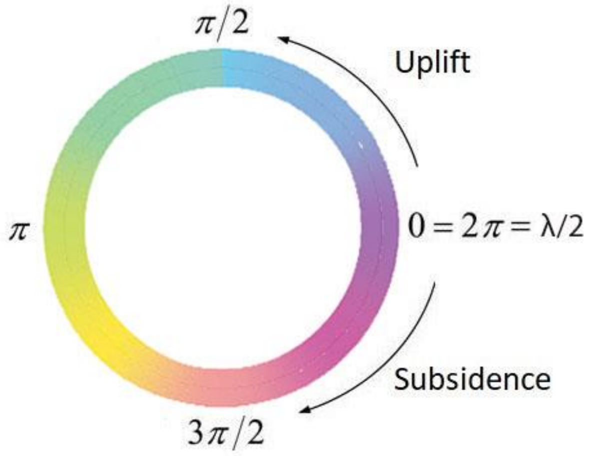


Figure 2: The difference in deformation rate between places having the same color is a multiple of λ/2. When the color turns in clockwise direction, the ground moves away from the satellite. In the opposite direction, the ground moves towards the satellite

The rate of terrain movement that can be detected depends among others on the time interval, **the spatial resolution, and on the wavelength** (Fig. 3 and Tab.1). The interferometric SAR signal will become ambiguous when the displacement gradient between adjacent pixels is higher than half of the wavelength during the selected time interval. It will decorrelate when the variability within neighboring pixels will become random during the selected time interval. Temporal decorrelation can also be due to changes of surface properties (e.g. due to vegetation, snow, wetness).

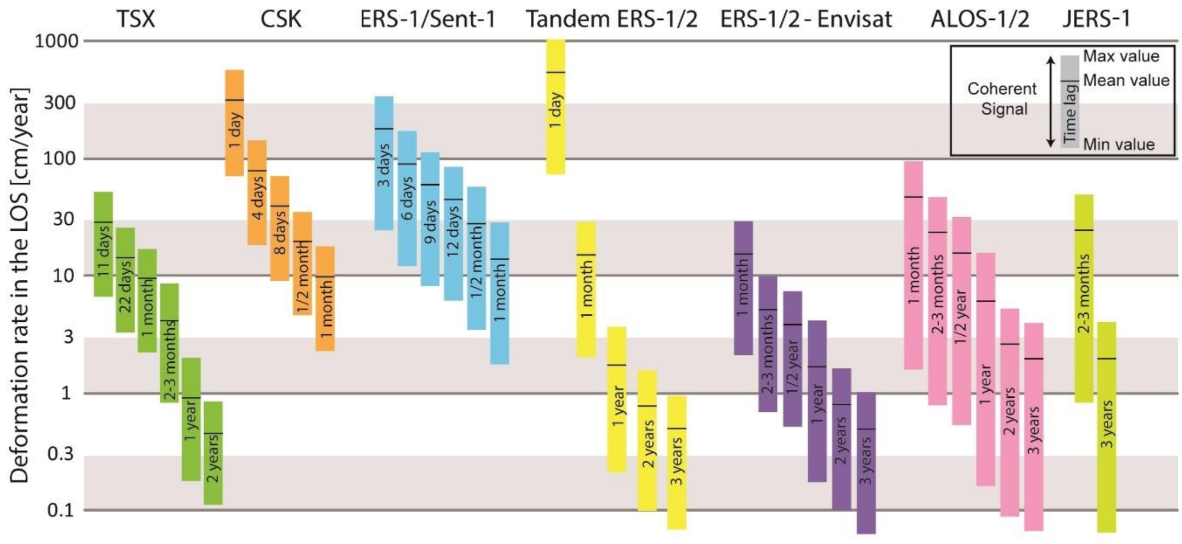


Figure 3: Deformation rate observed by SAR sensors for the most commonly used time interval. A bar defines the interval of deformation rate detected with a coherent signal on the interferogram of the selected time interval. For a specific time interval: a movement higher than the maximal value of deformation rate will be decorrelated on the interferogram, a movement lower than the minimal value is not detectable. The line in each bar defines the mean value of observable deformation rate (modified from Barboux et al. 2014).

To obtain an automatically quantitative displacement information (e.g. cm), a particular step called phase unwrapping is required. This step allows to convert the periodic trend of the phase (that ranges between -π and +π), computing the absolute phase values, and then converting the phase into displacement according to the wavelength of the sensor. However, this step is often complicated at large scale, and introduces large errors especially over fast moving areas and in mountainous regions, therefore results from this step should be interpreted carefully.

1.3 Data selection and processing

Different SAR sensors can be selected according to their availability and accessibility. To obtain a comprehensive overview of slope movements in a given region and to prevent misinterpretation of an InSAR signal, it is essential to have a **large set of valid interferograms** produced with time intervals from days to years in both orbit modes (ascending and descending). The major obstacles limiting the successful use of InSAR in a mountain environment are the slope orientation and presence of (wet) snow. Selected **SAR scenes must be snow free as much as possible** (e.g. usually between July and October in the European Alps). SAR scenes with a short (daily) time interval can also be used in the wintertime, when the snow is still cold. Estimating the occurrence of old or fresh snow and the weather conditions (rainy event) at or up to 2 days before each SAR image date on the basis of available meteorological data has proven to be a helpful step in evaluating the quality of an interferogram. Finally, **phase noise and residual phase error terms remaining after InSAR processing (e.g. from atmospheric artifacts) must not be neglected when interpreting the interferogram**.

Table 1. Radar characteristics of the SAR systems used in the practice

Satellite	*Terrasar-X*	*Cosmo-SkyMed*	*Sentinel-1*	*Radarsat-2*	*ALOS-2*
Date	from 2007	from 2007[2]	from 2014	from 2007	from 2014
Agency	DLR	ASI	ESA	CSA	JAXA
Wavelength (cm)	3.1	3.1	5.5	5.6	24.3
Band	X	X	C	C	L
Incidence angle (°)	20-45	25-40	20-45	35	30-40
Range resolution (m)[1]	1-16	1-100	5-25	3-100	3-60
Azimuth resolution (m)[1]	1-16	1-3-100	5-40	3-100	3-60
Scene width (km)	10-100	10-200	80-400	50-500	70
Repeat cycle (day)	11	1-4-8-16	(6)-12[3]	24	14

[1] The resolution in range and azimuth depends on the image acquisition mode. Common modes are the spotlight mode (extra precise), stripmap/standard mode and Wide/ScanSAR mode (extended).

[2] Constellation of small Satellites for Mediterranean basin Observation (1st and 2nd satellites launched in 2007, 3rd in 2008 and 4th in 2010)

[3] With both satellites Sentinel-1A and Sentinel-1B operating, the repeat cycle is 6 days.

2. Practical guidelines

InSAR data can be used to characterize rock glacier kinematics. The following recommendations are stated for a systematic procedure based on the accurate **interpretation of wrapped interferometric signals from a large InSAR dataset in order to locate moving areas related to rock glaciers and estimate their displacement rate**. These recommendations could be applied to other InSAR methods (unwrapped interferograms, multiple stacking, Persistent Scatter (PS), displacement time series (IPTA), etc.) but they require an initial evaluation regarding the need for any specific adaptations.

2.1 Data input and output

2.1.1 Inputs

Different types of InSAR data and associated files are useful to investigate the region(s) of interest:

- **Interferograms:** several interferograms generated with different sensors (e.g. ALOS, ERS, TerraSAR-X, and Sentinel-1) and with different time intervals (from day(s) to year(s)) are required for different periods of time. Both ascending and descending modes are suggested in order to select the most appropriate mode depending on the slope orientation. Areas affected by geometrical distortions should be masked in each respective provided InSAR results. Moving areas have to be identified using these interferograms, combining different time intervals and wavelengths to assign the respective kinematic attribute.
- **Normal factor:** for each sensor this map is useful to identify the most appropriate mode. This provide the normalization factor, i.e. an index to reproject the LOS displacement (i.e. displacement measured along the LOS) along the direction on maximum slope. It ranges between 1 and +∞. 1 means that LOS direction and maximum slope direction are parallel. By increasing the angle between the LOS direction and the maximum slope direction, the normal factor increases. Therefore, for pixels with a normal factor greater than 5, LOS measurements (e.g. interferograms and displacement maps) are no longer reliable and should not be used. Normal factor can be used to identify the best mode (i.e. ascending or descending) or exclude non-reliable pixels. However, the velocity class has to be estimated in the LOS and no conversion using this Normal factor is needed. When a moving area is visible from two modes, the most reliable will be that one with the lower Normal factor; the values of Normal factor on the moving area can be checked with the GIS. If the Normal factor is not available, western slope should be analyzed with the descending mode, while eastern slope should be analyzed with the ascending mode.

Additional data required to investigate the region(s) of interest:

- **Existing inventories**: geomorphological rock glacier inventories, slope movement inventories, etc. When available, the delivered standardized regional rock glaciers inventory consists of a homogenization of existing ones, the update/upgrade has to rigorously follow the defined guidelines in order to ensure the homogeneity.
- **Orthoimages** and **hillshade** for any geomorphological interpretations.
- **External kinematic** data (e.g. terrestrial slope motion measurements) for consolidating the assignment of the velocity class of the moving areas and later the reliability of the rock glacier kinematics characterization.
- **Any other georeferenced data** that could help in the interpretation of InSAR signals or in the visualization of the results (e.g. background maps, topographic maps, etc.)

While the sources of InSAR data and additional data are not prescribed, both should have been acquired no more than a decade apart, and the spatial resolutions of additional data sets should be comparable or higher than InSAR data.

2.1.2 Outputs

- **Moving areas**: polygon vector layer containing the outlines of moving areas related to rock glacier units and their required associated attributes (see 2.2.2a)
- **Rock glacier units:** point vector layer containing rock glacier units and their required associated attributes (see 2.2.2b)

2.2 Data organization

2.2.1 GIS project

It is necessary to first build a GIS project (e.g. ArcGIS pro, ArcGIS classic or QGIS) in which the analysis will be performed, including all available data (Fig. 4).

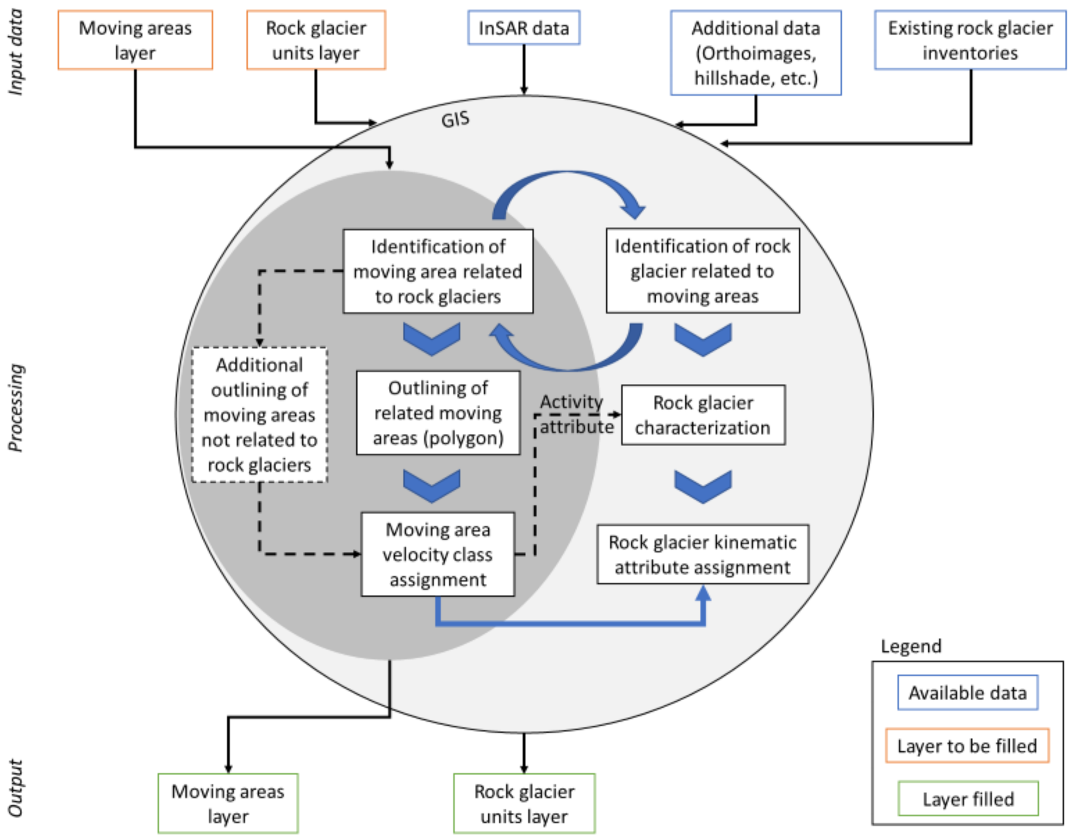


Figure 4: Procedure for the proposed standardization of rock glacier inventory using InSAR data. The analysis is performed in GIS software

For an easier data management, the InSAR data should be organized in different groups and subgroups. Two groups should contain data from the ascending and descending modes, respectively. Within each group, the data should be organized into several subgroups containing the data divided according to their type (i.e. interferograms, Normal factor etc.).

An example of the GIS data organization below.

- Existing geomorphological rock glacier inventories
- Existing slope movement inventories (e.g. GlobPermafrost)
- Moving areas outlines (polygons)
- Rock glacier units (points)
- Hillshade, DTM, topographic maps, etc. (e.g. shading can be used to visualize InSAR data at the same time)
- Ascending InSAR data
    - Interferograms
        - Interferogram 1
        - Interferogram 2
        - …
    - Normal factors
        - Normal Factor SAR sensor A
        - Normal Factor SAR sensor B
        - …
- Descending InSAR data
    - Interferograms
        - Interferogram 1
        - Interferogram 2
        - …
    - Normal factors
        - Normal Factor SAR sensor A
        - Normal Factor SAR sensor B
        - …
- Orthoimages

2.2.2 Files preparation

In order to get a global rock glacier inventory accomplished quickly, the restriction to a minimum set of rock glacier unit attributes and related moving areas attributes is required. This minimum set should be included in each compilation and consists of the following elements.

a) Moving areas file preparation

A polygon vector layer named, for example, "moving_areas_RG" has to be created in the GIS project. Depending on the project used, a polygon shapefile (for QGIS project) or a polygon file into a geodatabase (for ArcGIS projects) are recommended, in order to create multiple-choice rules for the attributes (see "How to create a multiple-choice attribute" Annex B). The detected moving areas related to rock glacier units will be added to this layer. A particular attribute table associated to the moving_areas_RG layer should be created according to the following description:

Name	***Definition***	***Values***
ID_CCI	A unique alpha-numerical identifier of the moving area	CCI_*CodeRG_N* *CodeRG*: ID_CCI of the related rock glacier unit *N*: numerical code allowing the differentiation of each moving area related to a single rock glacier unit (defined by the user)
Vel_class	Velocity class: variable characterizing the surface displacement rate observed in the LOS during the specified observation time window	0. Undefined 1. < 1 cm/yr (no movement up to some mm/yr) 2. 1-3 cm/yr (some cm/yr) 3. 3-10 cm/yr 4. 10-30 cm/yr (some dm/yr) 5. 30-100 cm/yr

		6. > 100 cm/yr (m/yr and higher) 7. Other (velocity can be then expressed in a field "Remarks") *Note:* - *when it is possible to distinguish in between the additional velocity classes 100-300 cm/yr and > 300 cm/yr, class 6 is chosen and the specific class can be indicated in the field "Remark".* - *When the reliability of the detected moving area is low due to specific technical limitation, the moving area has to be outlined and the velocity class has to be set as "undefined".*
Time	*Observation time window* (period during which the detection and characterization is computed/measured), and *temporal frame* (duration during which the periodic measurements/computations are repeated and aggregated for defining the moving area, i.e. during which year(s)). Sensor type used to perform the characterization is included here	Text containing: SENSOR(s)_ OBSERVATION-TIME-WINDOW_TEMPORAL-FRAME e.g: S1 Summer Y1-Y2 (velocity observed from Sentinel-1 with a summer length observation time window each year in between year Y1 to year Y2) TSX Summer Y1, Y2, … (velocity observed from TerraSAR-X with a summer length observation time window at year Y1, year Y2, etc.) CSK Annual Y1-Y2 (velocity observed from Cosmo-SkyMed with an annual length observation time window each year in between year Y1 to year Y2) ALOS 08-10 Y1-Y2 (velocity observed from ALOS with an observation time window centered in between August and October each year in between year Y1 and year Y2) S1 Summer Y1-Y2 and TSX 10 Y3 (velocity observed from (i) Sentinel 1 with a summer length observation time window each year in between year Y1 to year Y2 + (ii) TerraSAR-X with an observation time window centered in October year Y3) Note: - "Summer" length must be described into the metadata, and it should be at least 2-3 months
Reliability	Reliability of the detected moving areas	0. Low: signal interpretation (velocity estimation) and outline are uncertain but there is something to consider. 1. Medium: signal interpretation (velocity estimation) or outline is uncertain 2. High: obvious signal, best appropriate configuration (back-facing slope) *Notes:* - *When looking N-S facing slope or the number of InSAR data allowing detection*

		is low, the reliability of the detection decreases.
REF_ID	ID_CCI of the related rock glacier unit	
Remarks	Notes related to the detection and characterization (if needed)	Text e.g.: N-S facing slopes, few data, noisy signal, faster velocity in the rooting zone, etc.

The **moving areas related to rock glacier units have to be outlined** and the **fields in the attribute table have to be filled** for each detected polygon, according to the section 2.3.

b) Rock glacier units file preparation

A point vector layer named, for example, "RG_points" has to be created. Depending on the project used, a point shapefile (for QGIS project) or a point file into a geodatabase (for ArcGIS projects) are recommended. The rock glacier units location (see part 2.4.1 for the positioning) will be added to this layer. A particular attribute table associated to the RG_points layer should be created according to the following description:

Name	***Definition***	***Values***
ID_CCI	A unique alpha-numerical identifier of the rock glacier unit	CCI-*ZZ-XXXX-UU* *ZZ*: Area number 05: Romania 06: Switzerland, Western Swiss Alps 07: Norway, Troms 08: Norway, Finnmark 09: Svalbard, Nordenskiöld 10: France, Vanoise 11: Italy, Ultental 12-Greenland, Disko Island 13-Tien Shan 14-Alaska, Brookes Range 15-Argentina, Central Andes 16-New Zealand, Central part of the Southern Alps *XXXX:* numerical code of the rock glacier (defined by the user) *UU*: numerical code of the rock glacier unit (defined by the user)
Coord_X	X coordinate of the point	WGS 84 coordinate system
Coord_Y	Y coordinate of the point	WGS 84 coordinate system
Morph_Type	Unit morphology (see standards in the Baseline concepts document from the IPA Action Group)	0. Undefined 1. Simple 2. Complex
Spatia_Con	Spatial connection to the upslope unit (see standards the in Baseline concepts document from the IPA Action Group)	0. Undefined 1. Talus 2. Debris mantle 3. Landslide 4. Glacier 5. Glacier forefield

		6. Poly
Activity	Efficiency of the sediment conveying (expressed by the surface movement) at the time of observation (see standards in the Baseline concepts document from the IPA Action Group)	0. Undefined 1. Active 2. Transitional 3. Relict
Destabiliz (optional)	Signals of abnormally fast behavior, which can be expressed geomorphologically by the opening of large cracks and/or scarps (see standards in the Baseline concepts document from the IPA Action Group)	0. Undefined 1. Yes 2. No
Kin_attrib	Kinematic attribute assigned to a rock glacier unit, based on the previously delineated moving areas. It indicates the overall multi-annual downslope movement rate of an inventoried rock glacier unit	0. Undefined 1. < cm/yr 2. cm/yr* 3. cm/yr to dm/yr 4. dm/yr* 5. dm/yr to m/yr 6. m/yr* 7. > m/yr 8. Other (velocity can be then expressed in a field “Remarks”)
Val_time_frame	Multi-year *validity time frame* of the assigned Kin_attrib	Ya-Yb: between year Ya to year Yb (snapshot)
Data_used	Data type, observation time window, temporal frame and dimensionality of the data used (e.g. related to the moving area) to assign the Kin_attrib	Text containing: DIMENSIONALITY-DATA-TYPE_ TIME-OBSERVATION-WINDOW_TEMPORAL-FRAME e.g: 1D InSAR S1 Summer Y1-Y2 (velocity observed with Sentinel1 InSAR in the LOS using a summer length observation time window each year in between year Y1 to year Y2) 1D InSAR TSX Summer Y1, Y2, … (velocity observed with TerraSAR-X InSAR in the LOS using a summer length observation time window at year Y1, year Y2, etc.) 3D permanent GNSS Y1-Y10 (velocity observed with permanent GNSS between year Y1 to year Y10) Note: - “Summer” length must be described into the metadata, and it should be at least 2-3 months - If different data is used, it should be described here (e.g. 1D InSAR TSX Summer Y1, Y2 and 3D permanent GNSS Y1-Y10)
Spatial_rep	Spatial representativeness: percentage of surface that is documented by supporting kinematic data	0. Undefined 1. < 50% 2. 50-75% 3. > 75%

Reliab	Reliability of the kinematic attribute	0. Undefined 1. Low 2. Medium 3. High
Remarks	If needed	Text

For each rock glacier unit, the attribute table of the “RG_points” layer has to be filled according to the section 2.4.

2.2.3 Metadata

All meta-information that is required for a clear identification of the data set is submitted with the two mandatory outputs. These data files include, among others, information about the satellite scenes used (date, path, row, sensor, processing), the additional kinematic data used (used techniques, date acquisitions, points/areas measured, accuracy, precision), the date / source / spatial resolution of the available DTM and orthoimages, the available slope movement inventory and/or geomorphological rock glacier inventory as well as the names of the operators and the date / region of the analysis. The length of the “Summer” contained into the attribute tables (Time field for the moving_areas_RG layer and Data_used for the RG_points layer) must be reported here (e.g. start from the month xx and end at the month yy) and should be at least 2 - 3 months. Of course, references to be cited, acknowledgments and any other important metainformation can be submitted as well. In the case of a multitemporal composite for a specific region, the acquisition dates for each rock glacier units are particularly important.

2.3 Identification and characterization of moving areas

The identification of moving areas is an initial step, which is recommended to assign subsequently a kinematic attribute to a rock glacier unit. In principle, all moving areas related to rock glacier unit should be compiled in the polygon vector layer “moving_areas_RG”. However, a level 0 layer containing the whole identified moving areas irrespective of size, type or other factors could be useful. This one is not mandatory, it is under the responsibility and must fit the needs of the operator.

2.3.1 Visual identification of moving areas using InSAR

The detection is performed by looking the textural image features from wrapped interferometric phase image (called hereafter interferogram) according to three InSAR signal patterns: (1) no change defined by a plain pattern, (2) smooth change characterized by a (partly) fringe pattern and (3) decorrelated signal expressed by a noisy pattern (Fig. 5). The texture is evaluated around the considered pixel related to the size of the landforms that have to be detected. The minimal extent of a moving area is based on the operator’s judgment and depends on the spatial resolution of the interferogram, the filtering applied to reduce noise as well as the effective size of the landform. However, a moving area can be identified if at least 20-30 pixels show a fringe pattern.

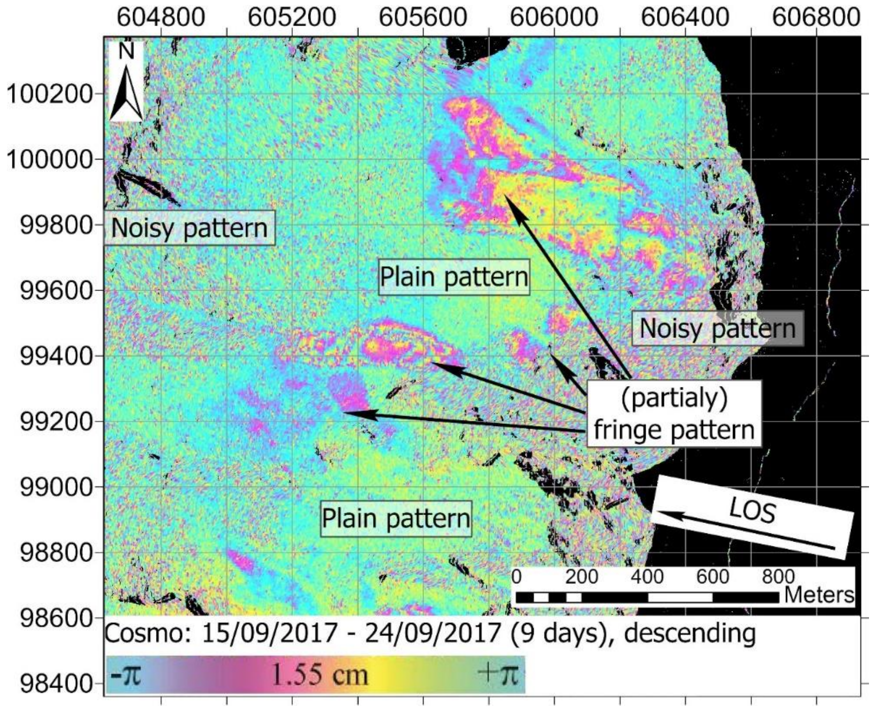


Figure 5: example of InSAR signal patterns. Data where layover and shadowing are masked (black)

The procedure to detect a moving area using InSAR is based on the combined visualization of a set of valid wrapped interferograms of various time intervals. Valid means that the error sources (e.g. due to processing, atmospheric artefacts, etc.) are as low as possible to ensure that the resulting data is confidently exploitable. This procedure allows for the systematical detection and characterization of moving areas related to mass wasting processes, rock glaciers in particular. The combined visualization of wrapped interferograms allow to prevent the presence of single artifacts due e.g. to atmosphere or snow, identifiable with a noisy pattern or, sometime, with a fringe pattern extended over very large areas. In fact, atmosphere or snow artifacts occur only on few (or single) interferograms, and therefore can be discriminated from moving areas. Noise pattern related to vegetation or glaciated area, persistent over all interferograms, has to be interpreted correctly.

An estimation (order of magnitude) of the related displacement rate (velocity) in the LOS will be possible when the moving area is characterized by a (partly) fringe pattern (see part 2.3.3). When moving area is characterized by noise pattern (i.e. the rate of terrain movement is too fast for the selected time interval and the signal became decorrelated), the identification of the position, the extent and the contour of rapid displacements is still possible. Slow movement rates (velocities slower than 3 cm/yr) are detectable but often difficult to be assessed with enough precision.

The detected InSAR-derived moving areas can be compared to their related geomorphological landforms with the help of topographical maps, orthophotos and/or existing rock glacier inventories. This step permits on the one hand to evaluate the reliability (or the degree of confidence) of the detected moving areas, and on the other hand allows to discriminate between moving areas related to rock glaciers.

2.3.2 Moving area outlining

The **detected moving area is indicated using a polygon that is manually drawn** around the detected InSAR pattern. A polygon describes an area where a given InSAR signal is detected for most of available interferograms.

Moving areas have to be outlined according to the following requirements:

- Outlines should be drawn starting from interferograms with lower time intervals (and lower wavelength). After which, by increasing the time intervals, the drawn outlines can be refined, and additional outlines (with lower speeds) can be identified and drawn. As the extent of a moving area could partly vary depending on the observation time and the velocity behavior, the final outline should delineate a moving area with homogeneous velocity inside, and the velocity range within a moving area should fit the class of velocity defined in part 2.3.3.
- **The outline does not necessarily fit the geomorphological outline of the rock glacier unit but has to fit the detected InSAR pattern** (Fig. 6).
- A moving area can override the geomorphological limits of a rock glacier unit (Fig. 7) (e.g. when two overlying rock glacier units are moving at rates, which are not significantly different).
- Several polygons can be related to the same landform, and several moving areas can be overlying, a slower moving area always embedding a faster one (then an area where only little movement is identified must be differentiated to parts where a movement rate is higher, Fig. 8).
- The minimum extent of a moving area depends on the spatial resolution of the data inputs and the size of the landform, based on operator's judgment. However, interferograms with high spatial resolution allow for higher detail when drawing outlines. It is recommended that a fixed precision of the drawn outline is applied (e.g. the drawn line should fit the size of one or two image pixels of the highest resolution InSAR data available).
- Isolated movements, unreliable areas and unrepresentative parts have to be avoided.

In addition, one has to note that:

- The border of a moving area is often non-sharp, depending also on the detection capability of the used technique, making a precise delineation difficult to obtain.
- Areas outside of any delineated moving area refer either to the absence of movement, or to a movement which may be under the detection limit, or to unreliable data.

An example of moving area outlining is showed in Fig. 8.

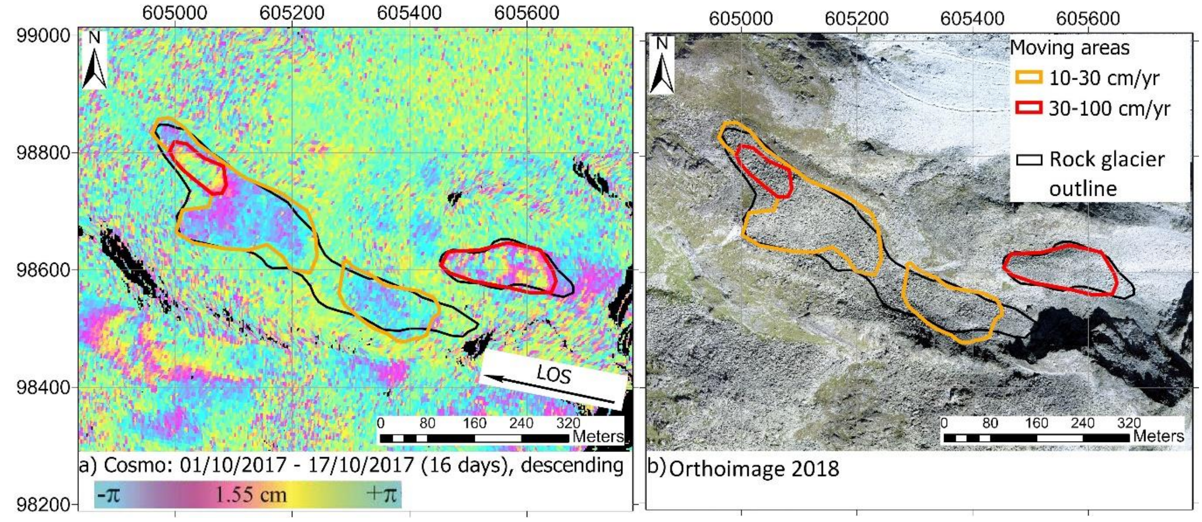


Figure 6: Example of moving areas outlines that do not fit with the geomorphological outlines (restricted footprint) of the rock glacier units but fit the detected InSAR pattern (a); (b) orthoimage.

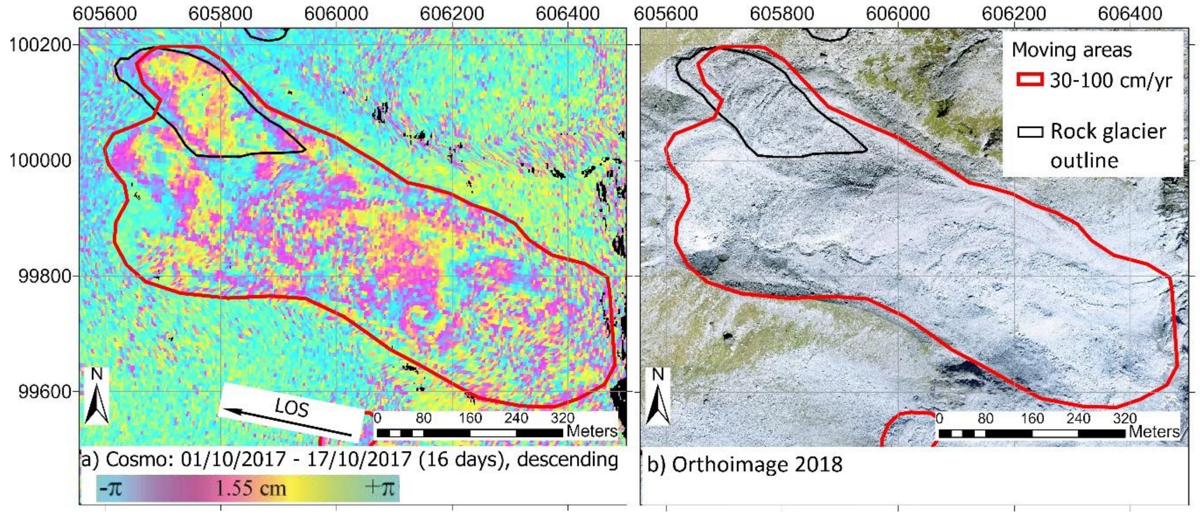


Figure 7: Example of moving areas (red line) that override the geomorphological limits of a rock glacier unit outlines (black line: restricted footprint): (a) InSAR pattern; (b) orthoimage. Most of the area depicted by the moving area is a debris-covered glacier. The upslope boundary of the rock glacier unit is uncertain.

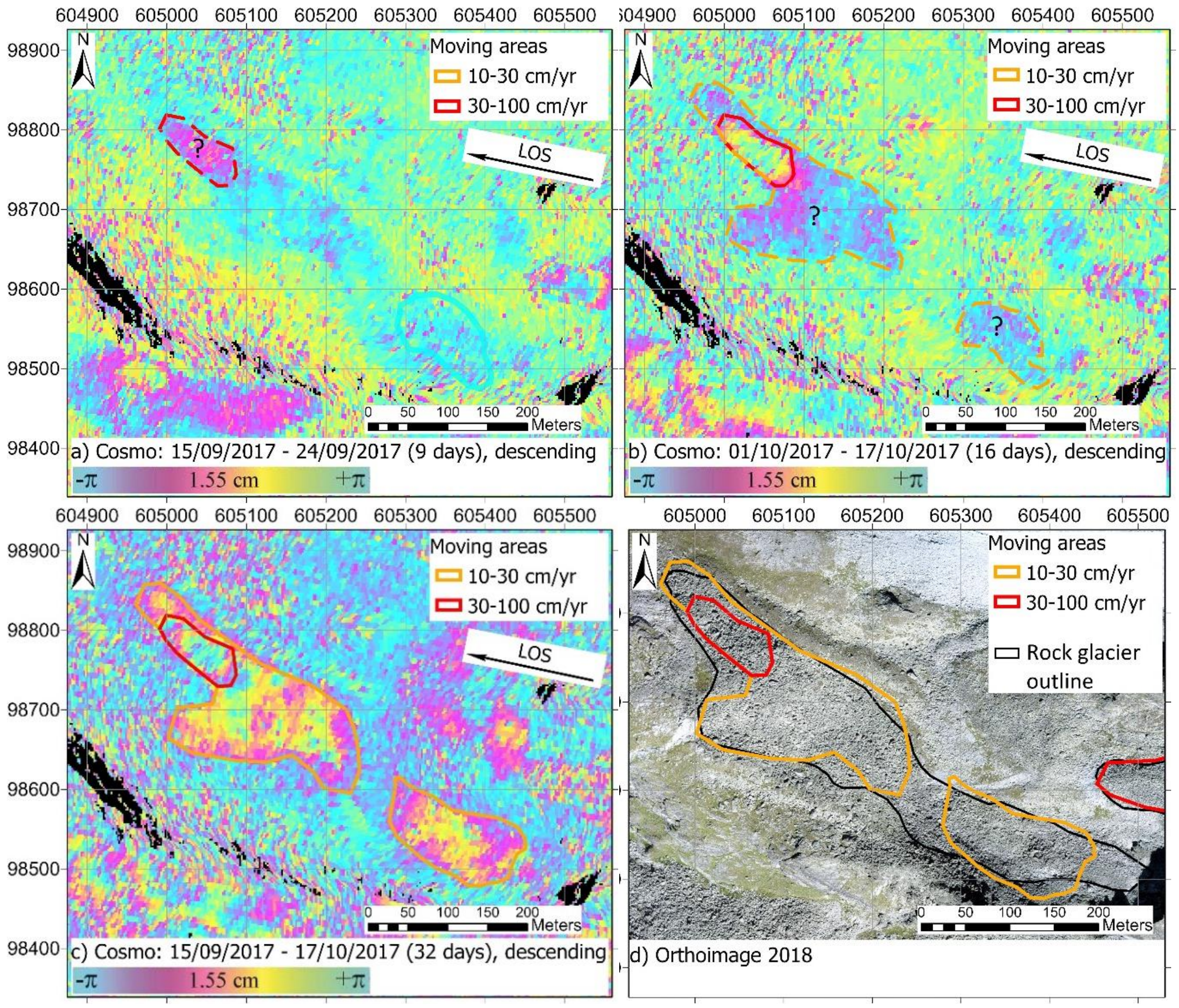


Figure 8: Rock glacier detection using Cosmo data. A large set of valid combinations of interferograms with different time intervals is required to increase the relevance of detected polygons. (a) A small red signal could be detected on the 9-day interferogram. (b) Using a 16-day time interval, a signal could again be seen on the frontal part and around two parts of the whole landform. (c) The frontal and upper parts are now well detected on the 32-day interferogram whereas a signal appears around two parts of the rock glacier. The frontal part becomes partially decorrelated. (d) The entire rock glacier is visible on the orthoimage (black line: restricted footprint). Three moving areas have been drawn and classified in terms of the deformation rate as moving in the order of 30-100cm/yr in red and of 10-30 cm/yr in orange. However, other not outlined moving areas are visible in these figures.

2.3.3 Velocity class of a moving area

A velocity-dependent classification of moving areas is also recommended to be able to determine subsequently the kinematic attribute of a rock glacier unit. The use of velocity classes is intending to facilitate the assignment of a more homogeneous, but simplified velocity information to moving areas. It also permits an assignment, which is based on operator's judgment.

The velocity class of InSAR-derived moving areas ("Vel_class" attribute) refers, as far as possible, to the **1D LOS InSAR measurement performed on back facing slopes** (the local spatial resolution is less affected by geometric distortions and deformation orientation is more or less aligned with the LOS). It is **strictly stamped by time characteristics** ("Time" attribute):

- The ***observation time window***, i.e. period during which the detection and characterization is computed/measured (e.g. multi-annual, annual, intra-annual). The minimal required duration is **one month** (several months are preferable) **in snow free period**.

- The ***temporal frame***, i.e. the duration during which the periodic computations/measurements are repeated and aggregated for defining the moving area (i.e. during which year(s)).

The velocity class should reflect somehow the spatio-temporal mean movement rate, but neither a single intra annual variation nor an extreme. Thus, when moving areas are detected/characterized using time intervals shorter than 1 month (e.g. 6 days for Sentinel InSAR data), several pairs should be used in order to cover the minimal observation time window of one month (e.g. at least two 6-day pairs spaced by 18 days). When periodic measurements are available during a temporal frame of several years (consecutive years are preferable), the same observation time window must be applied (e.g. always August-September in 2018 and 2019).

The following classification of 1D LOS velocity is recommended:

0. Undefined
1. < 1 cm/yr
2. 1-3 cm/yr
3. 3-10 cm/yr
4. 10-30 cm/yr
5. 30-100 cm/yr
6. > 100 cm/yr *
7. Other (velocity can be then expressed in a field "Remarks")

* Optional. If high temporal resolution kinematic data (e.g. GNSS, 1-4 days InSAR data, etc.) are available, the velocity class should be set at *7. Other* and the following classes can be indicated in a field "Remarks":

- 100-300 cm/yr
- > 300 cm/yr

The additional attribute named "Remarks" can be used to give more detail to the classification (e.g. heterogeneity inside the moving area, etc.)

The categorization of the velocity is performed exploiting two different approaches:

- Either by estimating the velocity value by comparing the phase signal inside and outside a detected moving area at different time intervals (Fig. 2). This is done by two steps: first, by counting the entire fringe cycles from a point assumed to be stable to the detected moving area (exploiting Fig. 2); second, by converting the fringe cycle into velocity per year (use Annex A for conversion).
- Or by the categorization related to the time intervals at which a moving feature is detected by a coherent, respectively a decorrelated, signal (Fig. 3). This is done by comparing the signal of each interferogram with the respective bar of Fig. 3 (i.e. the bar with the same sensor and time interval): decorrelated pattern means that the displacement is greater than the maximum detectable limit with that interferogram (i.e. the displacement exceed the upper limit of the bar); no visible fringe pattern means that the displacement is less than the minimum detectable limit with that interferogram (i.e. displacement lower than the lower limit of the bar); visible fringe pattern means that the displacement is detectable with that interferogram and the bar provides a velocity value.

One has also to be aware that the class assignment is difficult when the dominant velocity is close to the category border. An example of classification is showed below, where seven examples of moving areas can be observed in Fig. 9 from different SAR sensors and time intervals. Looking at Sentinel-1 6-day interferogram (Fig. 9b) two moving areas can be identified with fringe pattern (labels 1 and 3);

increasing the time interval (i.e. 12-day interferogram, Fig. 9c) additional moving areas are visible (label 2, 4 and 6). More details can be observed with Cosmo (Fig 9d, 9e and 9f), thanks to the higher spatial resolution. By observing Cosmo 9-day interferogram (Fig. 9d) two moving areas characterized by many fringes can be identified (labels 1 and 3); further moving areas can be identified with slight fringe pattern (labels 2, 4 and 6). Increasing the time interval (i.e. 16 days), the moving area labelled 3 become completely decorrelated (noisy pattern), and the moving area labelled 1 become partially decorrelated. Fringe pattern can be well identified in the moving area labelled 4, and two additional moving areas can be detected (label 5 and 7). Further increasing the time interval (i.e. 32 days), the moving area labelled 1 also become completely decorrelated (noisy pattern), and fringe pattern of the moving areas labelled 4, 5 and 7 become well visible. The two different classification methods are shown below.

a) Example of classification observing InSAR color scheme:

According to the table proposed in Fig. 2, the moving area labelled 3 is classified as > 100 cm/yr because with the Sentinel-1 6-day interferogram a complete fringe cycle is visible, then 2.8 cm in 6 days are measured; with Cosmo 9-day interferogram at least two complete fringe cycles are visible, then two half wavelengths (2 * 1.55 cm) in 9 days are measured. The moving areas labelled 1, 2 and 6 are classified as 30-100 cm/yr because with the Sentinel-1 12-day interferogram a complete fringe cycle is visible, then 2.8 cm in 12 days are measured; with Cosmo 9-day interferogram a complete fringe cycle is visible, then 1.55 cm in 9 days are measured. The moving areas labelled 4, 5 and 7 are classified as 10-30 cm/yr because with the Sentinel-1 6-day and 12-day interferograms a complete fringe cycle is not visible; with Cosmo 32-day interferogram at least a complete fringe cycle is visible, then 1.55 cm in 32 days are measured.

b) Example of classification analyzing InSAR signal according to time interval:

According to the table proposed in Fig. 3, the moving area labelled 3 is classified as > 100 cm/yr because the fringe pattern is visible only with the 6-day (Sentinel-1) and 9-day (Cosmo) interferograms; interferograms with time intervals of more than 15 days become decorrelated. The moving areas labelled 1, 2 and 6 are classified as 30-100 cm/yr because the fringe pattern is visible with the 6-day, 12-day (Sentinel-1), 9-day and 16-day (Cosmo) interferograms, and become decorrelated with the 32-day (Cosmo) interferogram. The moving areas labelled 4, 5 and 7 are classified as 10-30 cm/yr because the fringe pattern is not visible with the 6-day (Sentinel-1) interferogram, and becomes visible from the 9-day interferogram.

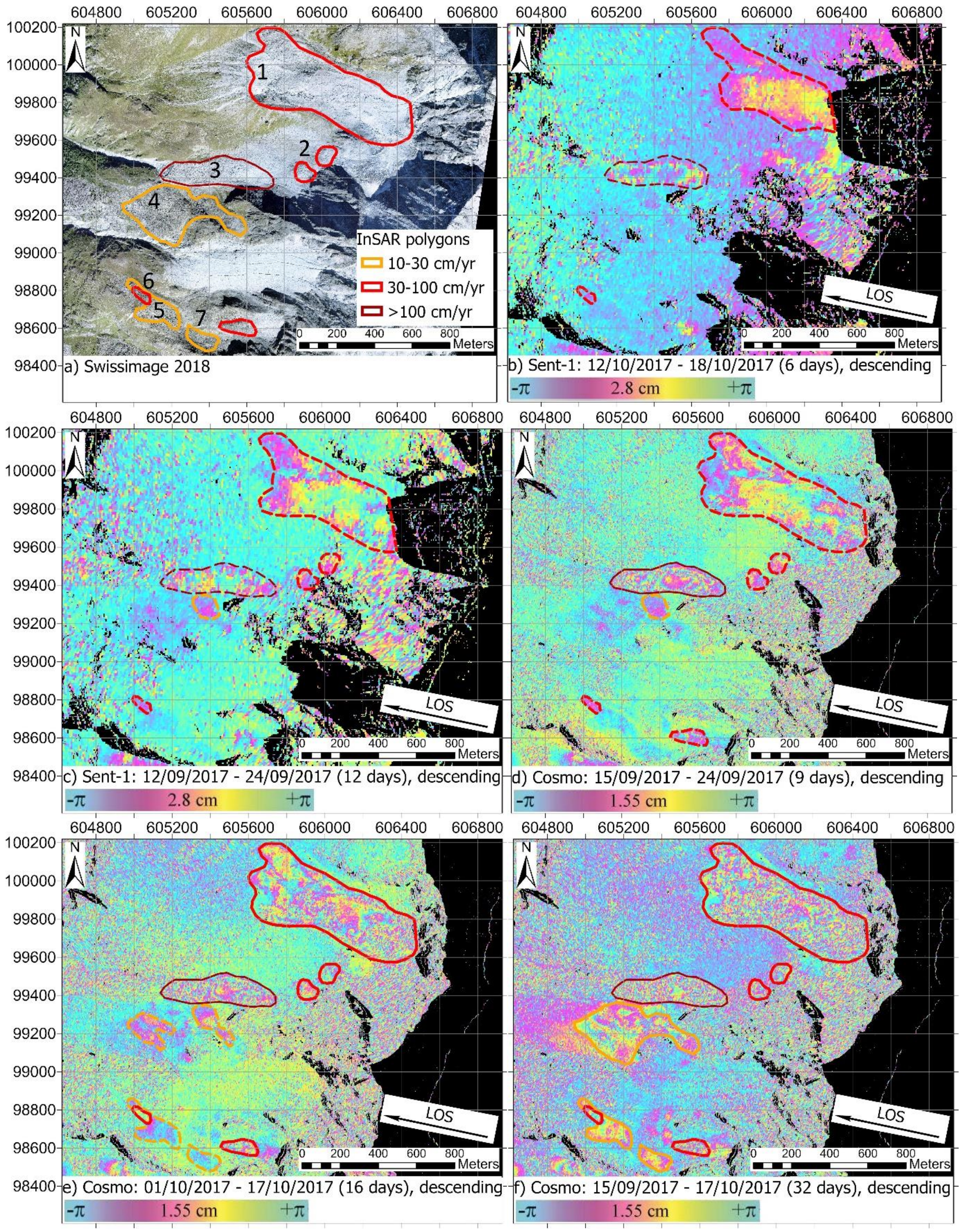


Figure 9: Example of moving area outlining and classification (Arolla area, Western Swiss Alps). (a) Orthoimage. Interferograms of the area using Sentinel-1 (b) and (c) and Cosmo (d)–(f) data where layover and shadowing are masked (black). Dotted lines are the temporary outlines of moving areas detected on an interferogram; plain lines are the final outlines of moving areas according to all interferograms. Depending on the operator, some other delineation or additional polygons are possible.

2.3.4 Reliability of moving area identification and characterization

The *reliability* (or the degree of confidence) *of the detected moving area* has to be qualitatively assessed (low, medium, high) according to the quality of both the outline detection and the velocity class assignment ("Reliability" attribute).

<u>Value</u>

0. Low: signal interpretation (velocity estimation) and outline are uncertain but there is something to consider.
1. Medium: signal interpretation (velocity estimation) or outline is uncertain.
2. High: obvious signal, best appropriate configuration (back-facing slope).

When looking N-S facing slope, or the number of interferograms is low, the reliability of the detection decreases. Moreover, when the reliability in classifying velocity is low due to specific technical limitations, the velocity class has to be set as "undefined".

When available, the comparison can be performed with other available kinematic data (e.g. in-situ measurements). This analysis allows for consolidating the assignment of the velocity class of the moving areas and later the reliability of the rock glacier kinematics characterization.

2.4 Rock glacier units

In principle, all rock glacier units should be compiled in the point vector layer "RG_units" irrespective of size, type or other factors.

2.4.1 Rock glacier identification

According to the IPA Action Group, a rock glacier unit (i.e. a single rock glacier landform that can be unambiguously discerned from other rock glacier units) is differentiated from a rock glacier system (i.e. landform identified as rock glacier, which is composed of either a single or multiple rock glacier units that are spatially connected either in a toposequence or in coalescence).

The recommendation is to use **a dot** manually positioned on the landform, **able to identify the rock glacier units location, and discriminate it clearly from other rock glacier units without ambiguity**; the positioning of the point on the rock glacier unit should avoid, as far as possible, any (frequent) temporal updating. It is recommended that 0.01 km2 be used as the minimum size of a rock glacier unit to be registered when conditions permit.

When rock glacier inventories are not previously available over the region of interest, the typology of the landform (geomorphologic process) related to each moving area must be evaluated on satellite or air-borne optical images or by field visits. Rock glaciers units can be discriminated using the technical definition proposed by the IPA Action Group and compiled in the point vector layer "RG_points".

When rock glacier inventories are available over the region of interest, they can be used to discriminate rock glacier units. However, it is recommended to evaluate remaining detected moving areas that can be related to missed rock glaciers.

Basic attributes recommended by the IPA Action Group have to be documented (Morph_Type, Spatia_Con and Destabiliz attributes). As kinematic data are available from moving areas previously inventoried, they must be considered in order to assign the category of activity (Activity attribute).

For further details regarding the technical definition and standardized attributes of rock glacier, see current baseline concepts proposed by the IPA Action Group.

2.4.2 Kinematic attribute definition

A kinematic attribute is a semi-quantitative (order of magnitude) information, which must be representative of the overall multi-annual downslope movement rate of an inventoried rock glacier unit. It is technology independent. A kinematic attribute must reflect the mean kinematic behavior of a rock glacier unit, then it can be assigned only when the rock glacier unit is documented by consistent kinematic information on a significant part of its surface. It gives the order of magnitude of the multi-annual rock glacier creep rate and must be spatially representative of the rock glacier unit for a given multi-annual validity **time frame** (snapshot) **of at least 2 years**. This allow to minimize the potentially large inter-annual variations of rock glacier movement rate. The exploited data, the applied method and their related time characteristics (observation time window and time frame) of all supporting kinematic data must imperatively be documented.

The kinematic attribute is basically determined by the exploitation of the characteristics (extent, velocity class, time specificities) of the moving area(s), which have been identified at the surface of the rock glacier unit. However, as dominant moving area(s) are only rarely covering a rock glacier unit in its whole and may be not reflecting a multi-annual displacement rate, a systematical translation of a (moving area) velocity class to a (rock glacier unit) kinematic attribute is not always possible and has to be performed carefully. It must also be taken into consideration that the documented surface velocities may be faster than the effective rock glacier displacement rate at depth and that intra-annual (usually summer) velocities may be faster the annual ones.

The categorization of the kinematic attribute consists of semi-quantitative classes of the **multi-annual downslope displacement rate** of the entire rock glacier body:

Category	Label	Comment	Related activity
0.	Undefined	(default category)	
1.	< cm/yr	(no up to very few movement)	relict
2.	cm/yr	(order of magnitude ≈ 0.01 m/yr)	transitional
3.	cm/yr to dm/yr	(order of magnitude ≈ 0.05 m/yr)	transitional
4.	dm/yr	(order of magnitude ≈ 0.1 m/yr)	active
5.	dm/yr to m/yr	(order of magnitude ≈ 0.5 m/yr)	active
6.	m/yr	(order of magnitude ≈ 1 m/yr)	active
7.	> m/yr	(more than ≈ 3 m/yr per year)	active
8.	Other	Velocity can be then expressed in a field “Remarks”	

There is only one assigned category per rock glacier unit. If two equally dominant, but directly adjoining categories (e.g. 5-6) occur on a rock glacier unit, the category of the area closer to the front is favored for the attribution. In case of a larger spread of equally dominant categories on the same rock glacier unit (e.g. 4, 6), the median category (e.g. 5) should be retained, with a specific additional indication of heterogeneity. A large heterogeneity can also indicate the need to affine/redefine the delineation of the initial geomorphological units (iterative process combining geomorphological and kinematic approaches). The default category is *0. Undefined*. The rock glacier unit falls into this category when (i) no (reliable) kinematic information is available (e.g. North/South-facing slopes), (ii) the rock glacier unit is mainly characterized by a moving area of undefined velocity, (iii) the kinematic attribute could not be defined reliably.

For each rock glacier unit with assigned kinematic attribute, the following additional information has to be documented into the attribute table associated to the "RG_units" layer:

- Multi-year *validity time frame* ("Val_time_frame" attribute) of the kinematic attribute,
- *Data/techniques used* and related characteristics of all the supporting kinematic data ("Data_used" attribute) including: sensor (e.g. Sent1), method (e.g. InSAR), observation time window (e.g. multi-annual, annual, intra-annual), temporal frame (e.g. which year(s)) and dimensionality (e.g. 1D).
- *Approximated spatial representativeness* ("Spatial_rep" attribute): percentage of surface that is documented by supporting kinematic data (e.g. < 50%, 50-75%, > 75%). This is qualitatively estimated by comparing the total area of the moving areas inside the rock glacier unit and the total area of the rock glacier unit. The restricted geomorphological footprint method is recommended to delineate the rock glacier unit.

2.4.3 Rules for the kinematic attribute assignment

The velocity information from moving areas should be transferred to the proper category of kinematic attribute in order to indicates the overall multi-annual rate of movement observed/estimated on a dominant part of the rock glacier surface. The assignment of a kinematic attribute is based on the operator's judgment. **Manual transfer from a velocity class of an InSAR-derived moving area to its kinematic attribute is recommended** instead of automated transfer (e.g. automatic transfer using GIS software). Additionally, a manual iterative interpretation of the InSAR signal may be helpful to confirm the correct categorization.

The two following cases a) and b) present recommendations based on two different observation time windows. They are proposed on the conditions that:

- 1D LOS InSAR measurements are performed on back facing slopes (the local spatial resolution is less affected by geometric distortions and the deformation orientation is more or less aligned with the LOS),
- a dominant part of the rock glacier unit is depicted by a single moving area.

In the case of several variably moving areas, the assigned category should represent the dominant velocity class of the rock glacier unit. For example, the median category should be used, with a specific additional indication of heterogeneity. However, if moving areas show a large heterogeneity over the unit (e.g. more than three moving areas with velocity classes falling into various categories), the category *0. Undefined* should be chosen.

An additional field named "remark" can be used to give more detail to the categorization (e.g.: half of the RG at class X, only upper part of the RG is moving, maybe faster, maybe slower, etc.)

<u>Case a: Annual or multi-annual observation time window</u>

A dominant part of the rock glacier unit is depicted by a single moving area, whose associated velocity class is reliably characterized at an annual or multi-annual observation time window (i.e. annual interferograms). Of concern are moving areas typically with a velocity class of:

1. < 1 cm/yr
2. 1-3 cm/yr

(nb: larger movements are decorrelated using annual interferograms)

The kinematic attribute of the considered rock glacier unit can be assigned as following (only for back-facing slope in 1D LOS InSAR measurements):

Velocity classes (annual)	Kinematic attribute
1. < 1 cm/yr	1. < cm/yr
2. 1-3 cm/yr	2. cm/yr

Case b: Observation time window shorter than 1 year

A dominant part of the rock glacier unit is depicted by a single moving area, whose associated velocity class is reliably characterized at an observation time window shorter than 1 year (at least one month in snow free period). Of concern are moving areas typically with a velocity class of:

3. 3-10 cm/yr
4. 10-30 cm/yr
5. 30-100 cm/yr
6. > 100 cm/yr

(nb: smaller movements are undetected using these time interval interferograms)

The order of magnitude of the rock glacier creep rate is estimated per default as 20% lower than the summer time velocity. The kinematic attribute of the considered rock glacier unit can be assigned as following (only for back-facing slope in 1D LOS InSAR measurements):

Velocity classes (summer time)	Velocity classes (annual)	Kinematic attribute
3. 3-10 cm/yr	2.4-8 cm/yr	3. cm/yr to dm/yr
4. 10-30 cm/yr	8-24 cm/yr	4. dm/yr
5. 30-100 cm/yr	24-80 cm/yr	5. dm/yr to m/yr
6. > 100 cm/yr	> 80 cm/yr	8. Other*
7. Other		
Remarks: 100-300 cm/yr	80-240 cm/yr	6. m/yr
Remarks: > 300 cm/yr	>240 cm/yr	7. > m/yr

* the category "8. Other" should be selected and the note "m/yr or higher" should be indicated in a field "Remarks".

2.4.4 Reliability of the assigned kinematic attribute

The *reliability* (or the degree of confidence) *of the assigned kinematic attribute* ("Reliab" attribute) has to be qualitatively assessed (low, medium, high) according to the quality of the moving areas related to the rock glacier unit, and the certainty of the assigned kinematic attribute.

Value

0. Undefined: if the kinematic attribute is undefined
1. Low: low quality of the moving area(s).
2. Medium: medium or high quality of the moving area(s) but uncertain kinematic attribute assignment.
3. High: high quality of the moving area(s) and clear kinematic attribute assignment.

When available, the comparison can be performed with other available kinematic data (e.g. in-situ measurements). This analysis permits to consolidate the assignment of the kinematic attribute of the rock glacier unit.

2.5 Validation and consolidation with second operator

2.5.1 Consolidation of the results

The geomorphological elements of the inventories, i.e. the identification of the rock glaciers, the definition of the units/systems, the delineations of the landforms, the attributes “spatial connection of the rock glacier to the upslope unit” and the attribute “activity”, as well as the kinematic elements of the inventories, i.e. the velocity classes of the identified moving areas and the order of magnitude of the kinematic attribute have to follow the recommended methodology and guidelines, developed by the IPA action group. During production/update of the inventory, it is recommended that at least two persons perform the work to reduce operator’s subjectivity and ensure the quality of the results.

Following this approach, moving areas and kinematic attributes are assigned by the first operator, that provides also the reliability degrees. Then the second operator checks the results of the first operator, confirming the results or modifying them. In addition, the first operator can also suggest supplementary checks at the second operator for specific cases. The uncertainties are reduced by taking advantage of the knowledge of two different operators.

2.5.2 Assessment of the results

When possible, inventoried moving areas must be compared with available in-situ or complementary remote sensing measurements recorded at (or around) the same temporal frame. Terrestrial geodetic survey data (DGNSS, Total station, Lidar, etc.), as well as air-borne photogrammetry data are, for instance, precious sources of validation and can be used to assess the quality of the results. Comparison may be performed to verify that the kinematic attribute of the rock glacier unit falls into the correct category. In the absence of terrestrial data, only the analysis of several interferograms and a good knowledge of the corresponding geomorphology allow for a good interpretation of the results. The presence of a clear signal on a long-time interval, which confirms the activity of the landform, is an absolute prerequisite for attributing the signal to a change in the topography rather to noise. In any case, the interpretation of the dataset by a second operator is highly recommended in order to improve the validity of the inventory (see part 2.5.1 Consolidation of the results).

3. Practical example

In this section an exercise is explained for a) training the identification and characterization of moving areas on the basis of InSAR data (3.1 *Part 1*) and for b) training the assignment of a kinematic attribute to selected rock glacier units (*3.2 Part 2*). During the workshop II of the IPA Action Group Rock glacier inventories and kinematics, participants have proceeded to this exercise. External partners can use this example to get ideas (e.g. about organizing the GIS project, compiling files etc.) or even to train.

3.1 Part 1: Identification and characterization of moving areas

3.1.1 Data provided

The provided GIS projects (i.e. ArcGIS pro, ArcGIS classic and QGIS) contain several SAR data here described, organized in different groups depending on the geographic location. In detail, two geographic regions are provided: “Rechy” and “Arolla”. Rechy contains both ascending and descending modes, Arolla only contains descending mode due to the main westward slope of this area. Each ascending and descending subgroup contains different types of SAR data:

- **Interferograms:** several interferograms generated with different sensors (e.g. ALOS2, Cosmo, TerraSAR-X, and Sentinel-1) and with different time intervals are provided for different periods of time. The nomenclature is: “SENSOR-NAME_MASTER-IMAGE-DATE_SLAVE-IMAGE-DATE_TIME-INTERVAL_MODE_diff”. Areas affected by geometrical distortions are masked in each respective provided InSAR results. Moving areas have to be identified using these interferograms, combining different time intervals and wavelengths to assign the respective kinematic attribute.
- **Normal factor**
- **Reference_points**: depending on the project used, this is a point shapefile (QGIS project) located into the shp folder, or a point file contained into the geodatabase (ArcGIS projects). The location of the points will be used to identify the areas of interest.
- **Polygons_moving_areas**: depending on the project used, this is a polygon shapefile (QGIS project) located into the shp folder, or a polygon file contained into the geodatabase (ArcGIS projects). This (empty) file will contain the outlines of moving areas.
- **Orthoimages** and **hillshade** are also provided for any geomorphological interpretations.

The detection of moving area should be performed using the data explained above. Additional data is provided for information only:

- **Displacement maps:** these maps contain the displacement rates measured along the LOS in meters per year (m/yr). The nomenclature is: “SENSOR-NAME_FIRST-DATE_LAST-DATE_MODE_disp”. The displacement, expressed in the LOS, is obtained by stacking all the consecutive interferograms acquired between the first and the last date. The phase periodicity of each interferogram is first resolved by performing the phase unwrapping and converting the phase into displacement.
- **Persistent scatters:** these shapefiles contain the displacement rates measured along the LOS in milliliters per year (mm/yr) for particular points called “persistent scatter”. The nomenclature is: “SENSOR-NAME_FIRST-DATE_LAST-DATE_MODE_PSdisp”. The displacement rates, expressed in the LOS, are computed through a particular multi-interferometric technique, that allow to identify points with particular phase and intensity of the SAR signal (i.e. permanent scatters) and calculate their displacements over time. Because only snow-free acquisitions from late spring to early autumn of every year are considered, there are gaps in the interferogram time-series that limit the intervals over which reliable

phase unwrapping can be performed. As a consequence, only rates of motion of less than a few cm's per year can be determined with persistent scatters.

3.1.2 Formulation of the practice Part 1

The aim of this practice is to identify and characterize moving areas (polygons, Fig. 8). A dedicated layer named “Polygons_moving_areas” has to be filled according to the detected polygons over the Arolla and Réchy regions. That means that the **moving areas have to be outlined** and the **fields in the attribute table associated to the file have to be filled** for each detected polygon. The detection has to be restricted around the reference points contained in the layer “Reference_points”. The priority has to be given to the area located around reference points OBJECTID: 1, 3, 4, 10, 13, 14, 15, 17 and 18.

An example of moving areas delineation is proposed in Fig. 8. Two examples of velocity classes assignment are proposed Fig. 9.

3.2 Part 2: Rock glacier kinematics

3.2.1 Data provided

- Geomorphological_outline_RG: this layer contains the geomorphological outlines of rock glaciers units. Depending on the project used, this is a polygon shapefile (QGIS project) located in the shp folder, or a polygon file contained into the geodatabase folder (ArcGIS projects).
  Note: in this exercise the rock glacier location is provided within this layer, and rock glaciers are identified by outlines (polygons). In the practical guidelines (Section 2.4) rock glaciers will be identified by points (instead of polygons).

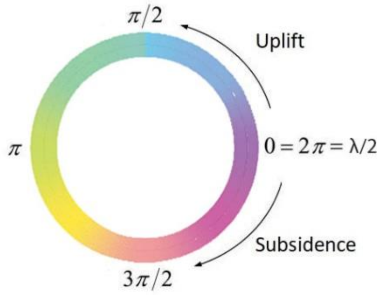
3.2.2 Formulation of the practice Part 2

The aim of this second part of the practice is to characterize the kinematics of a rock glacier unit according to the previously detected moving areas. A dedicated layer named “Geomorphological_outline_RG” is provided and gives the geomorphological outlines of a selection of rock glacier units located over Arolla and Réchy regions. This layer is not exhaustive and other rock glaciers can be found in the regions of interest. In this layer, **the fields “Kin_attrib” and “Activity” have to be filled** for each of the proposed unit.

ANNEX A: Visual interpretation - Converting the fringe cycle into velocity per year

SENTINEL 1 (cm/yr) lambda = 5.5 cm

Fringe / Days	***6***	***12***
1/5	33	17
1/4	42	21
1/3	56	28
1/2	84	42
2/3	112	56
3/4	125	63
4/5	134	67
1	167	84



ALOS2 (cm/yr) lambda = 23.6 cm

Fringe / Days	***70***	***364***	***392***
1/5	12	2	2
1/4	15	3	3
1/3	21	4	4
1/2	31	6	5
2/3	41	8	7
3/4	46	9	8
4/5	49	9	9
1	62	12	11

CosmoSkymed (cm/yr) lambda = 3,1 cm

Fringe / Days	***9***	***16***
1/5	13	7
1/4	16	9
1/3	21	12
1/2	31	18
2/3	42	24
3/4	47	27
4/5	50	28
1	63	35

Terrasar-X (cm/yr) lambda = 3,1 cm

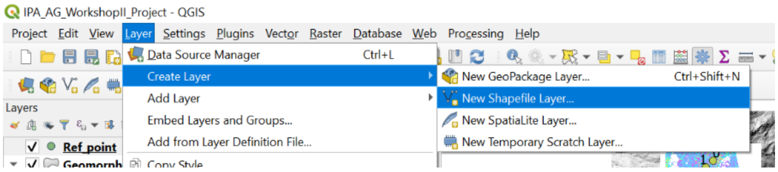
Fringe / Days	***11***	***22***
1/5	10	5
1/4	13	6
1/3	17	9
1/2	26	13
2/3	34	17
3/4	39	19
4/5	41	21
1	51	26

ANNEX B How to create multiple-choice attribute in GIS software

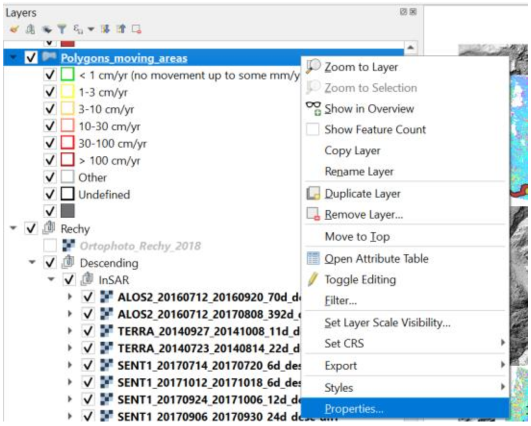
Some indication about "How to create" a multiple-choice attribute into shapefile (with Qgis) or feature class into geodatabase (with ArcGIS classic and ArcGIS pro) are here provided.

QGIS (version 3.1 or later)

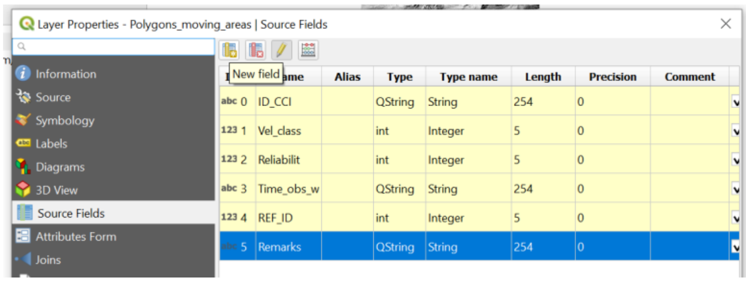
1. Create a new shapefile



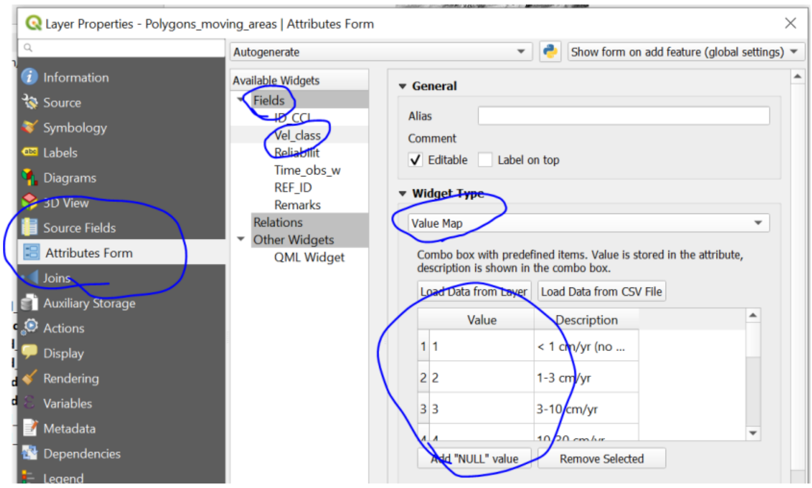
2. Go into the shp properties



3. Add the required fields (in Source Fields)



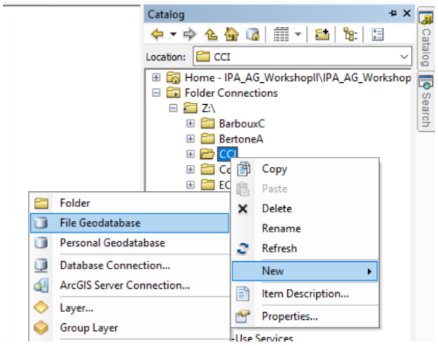
4. Go in Attributes Form >> Fields, and for each field where a multiple choice is required select Value Map. Then in the table insert the Value (0, 1, 2 etc.) and the Description. Then Ok

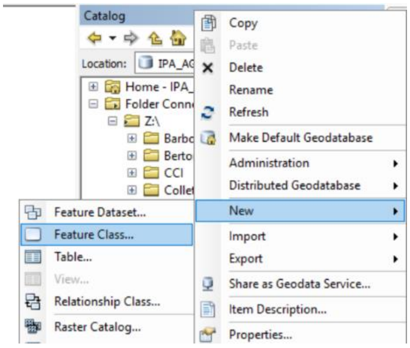


Now when you draw a feature, you can choice a description from a list for the attribute

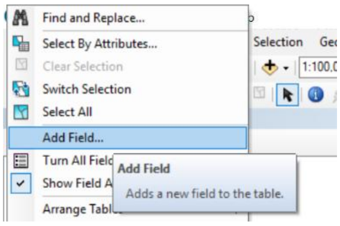
ArcGIS classic

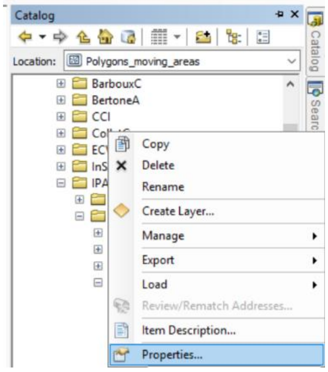
1. Create a new geodatabase: Catalog >> go into the folder >> right click >> New >> File Geodatabase. Then create a new feature: Catalog >> Go into the geodatabase >> Right Click >> New >> Feature Class



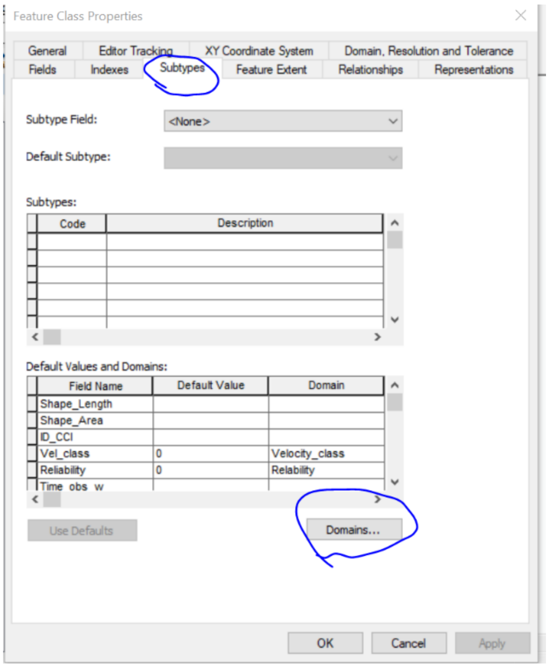


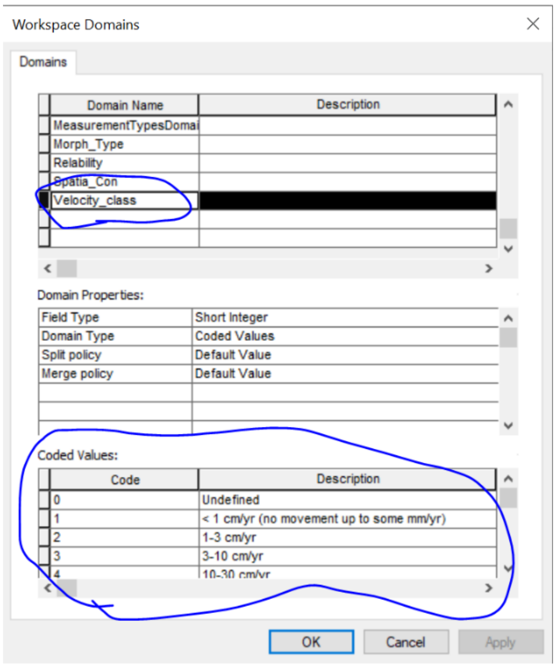
2. From the attribute table (Layer >> right click >> Attribute Table), add the required fields. Then go into the feature class properties form the Catalog (right click on the feature class into the Catalog >> Properties)



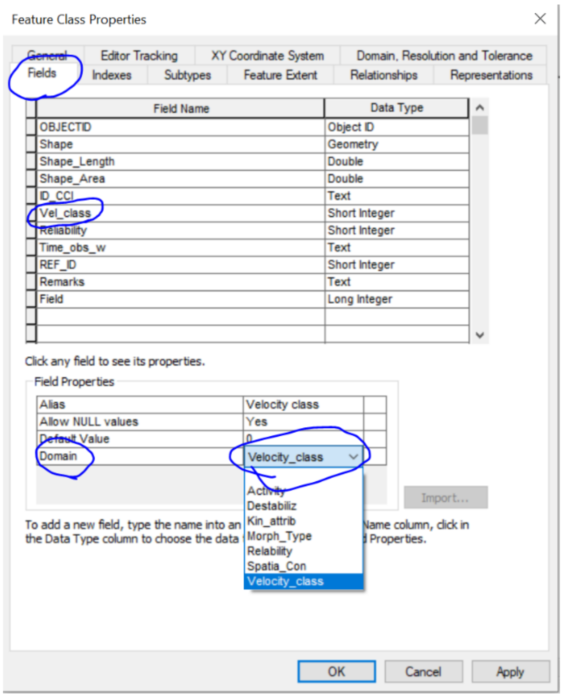


3. Go into Subtypes >> Domains. Then insert a Domain Name (into the upper table) and in the table Coded Values (lower table) insert the Code value (0, 1, 2 etc.) and the Description. Make a Domain Name and respective Coded Values for each field where a multiple-choice is required.





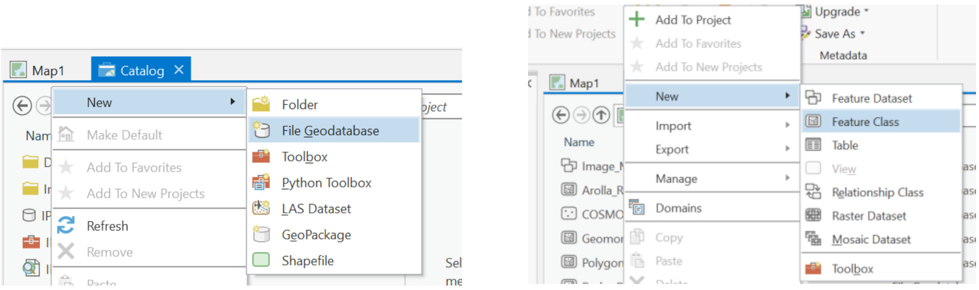
4. Go in Fields and for each field where a multiple-choice is required: select the field (into the upper table) and in Domain (lower table) select the respective domain name (compiled before). Then ok.



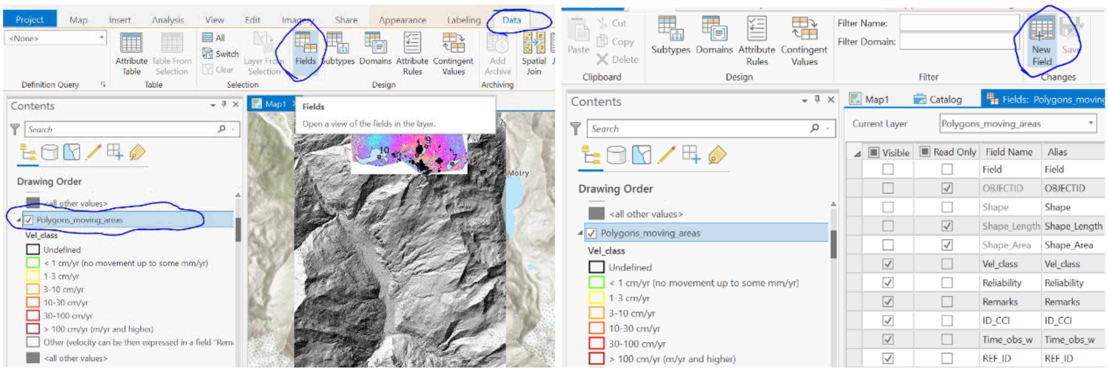
Now when you draw a feature, you can choice a description from a list for the attribute

ArcGIS Pro

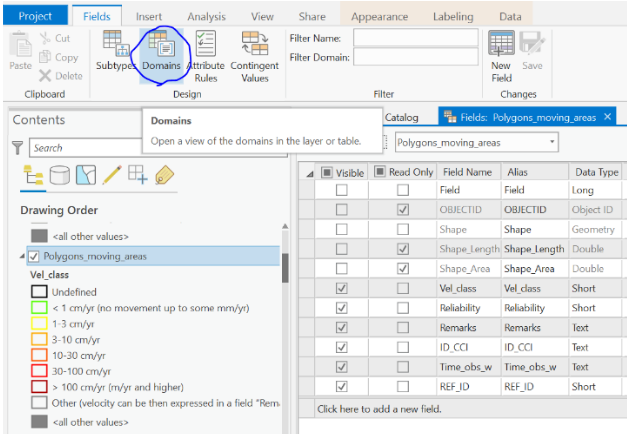
1. Create a new geodatabase: Catalog >> go into the folder >> right click >> New >> File Geodatabase. Then create a new feature: Catalog >> Go into the geodatabase >> Right Click >> New >> Feature Class



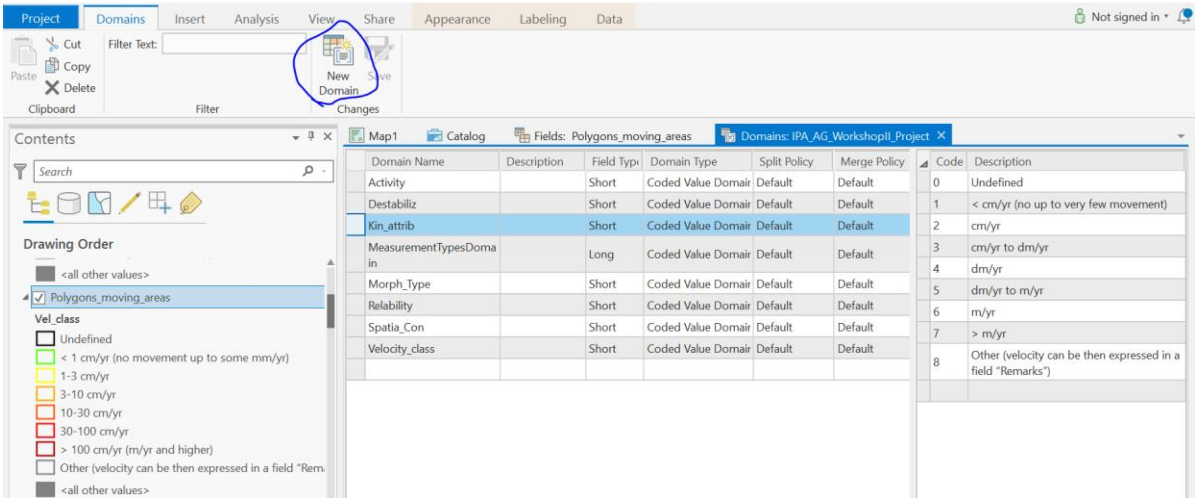
2. Add the required fields: select the layer >> Data >> Fields. Then add the new fields



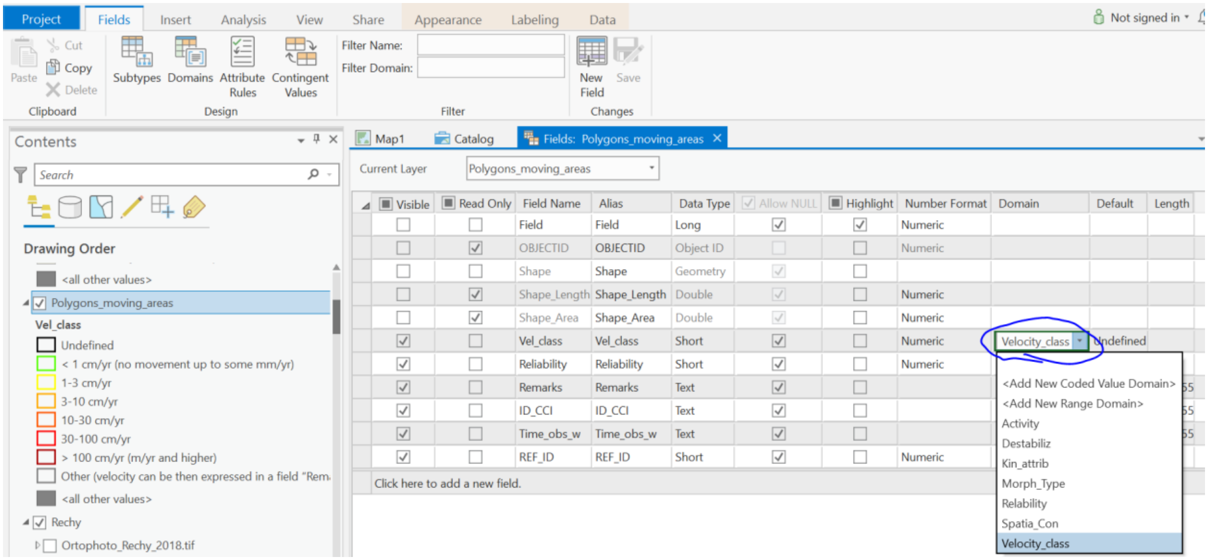
3. Go into Domains



4. Then insert a New Domain, assign it a Domain Name and in the table at the right insert the Code (0, 1, 2 etc.) and the Description. Make a Domain Name and respective Coded Values for each field where a multiple-choice is required. Then Save.



5. Return in Fields and for each field where a multiple-choice is required select the respective Domain into the table. Then Save.



Now when you draw a feature, you can choice a description from a list for the attribute

ANNEX C Technical notes

External partners were involved in a training exercise on the areas of Rechy and Arolla (Swiss Alps) and the results were analyzed. The homogeneity is very good and results are quite confident. However, some discrepancies related to particular cases were detected. This annex shows some examples of these particular cases, providing all the necessary basics and possible solutions to fill these problems. For each case described here, a brief description and a possible solution is provided, followed by one or more practical examples with explanations.

Case 1) Two or more outlines of MAs (related to the same RG unit) with different velocity classes

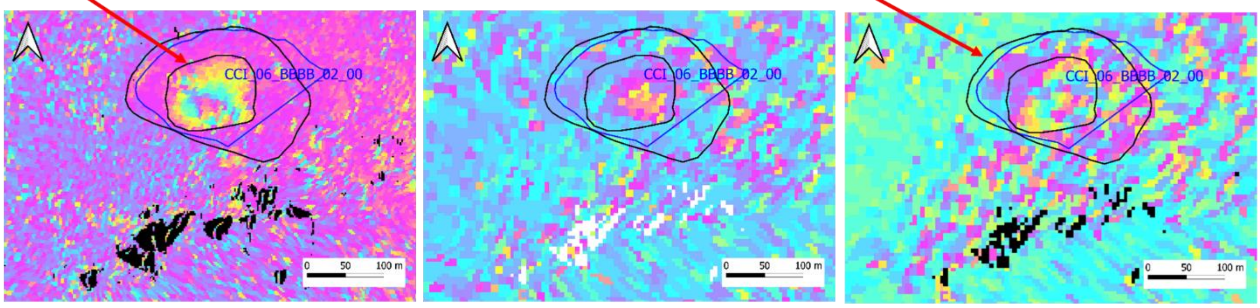
>> Rules:

- MAs related to the same RG unit should be detected and outlined using all the available InSAR data.
- The faster MA visible on summer interferograms should also be visible on the annual interferograms that include the summer periods.

>> Example from operator A:

30 – 100 cm/yr
Time_obs_win: Summer 2014, 2016 and 2017
Reliability: high
Remarks:

3 – 10 cm/yr
Time_obs_win: Annual 2016 – 2017
Reliability: low
Remarks: low reliability especially into the rooting zone

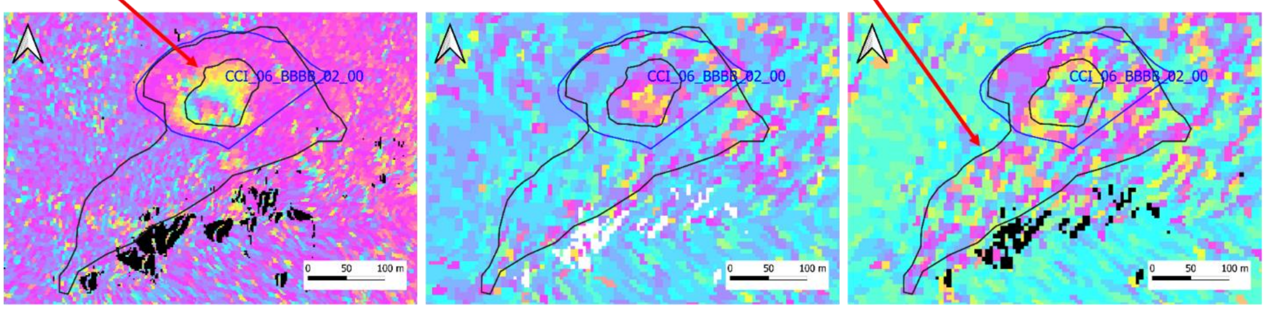


TERRA_20140723_20140814_22d_desc_diff ALOS2_20160712_20160920_70d_desc_diff ALOS2_20160712_20170808_392d_desc_diff

>> Example from operator B:

10 – 30 cm/yr
Time_obs_win: Summer 2014, 2016 and 2017
Reliability: high
Remarks:

3 – 10 cm/yr
Time_obs_win: Annual 2016 – 2017
Reliability: low
Remarks: low reliability especially into the rooting zone



TERRA_20140723_20140814_22d_desc_diff ALOS2_20160712_20160920_70d_desc_diff ALOS2_20160712_20170808_392d_desc_diff

>> Notes for both operators A and B:

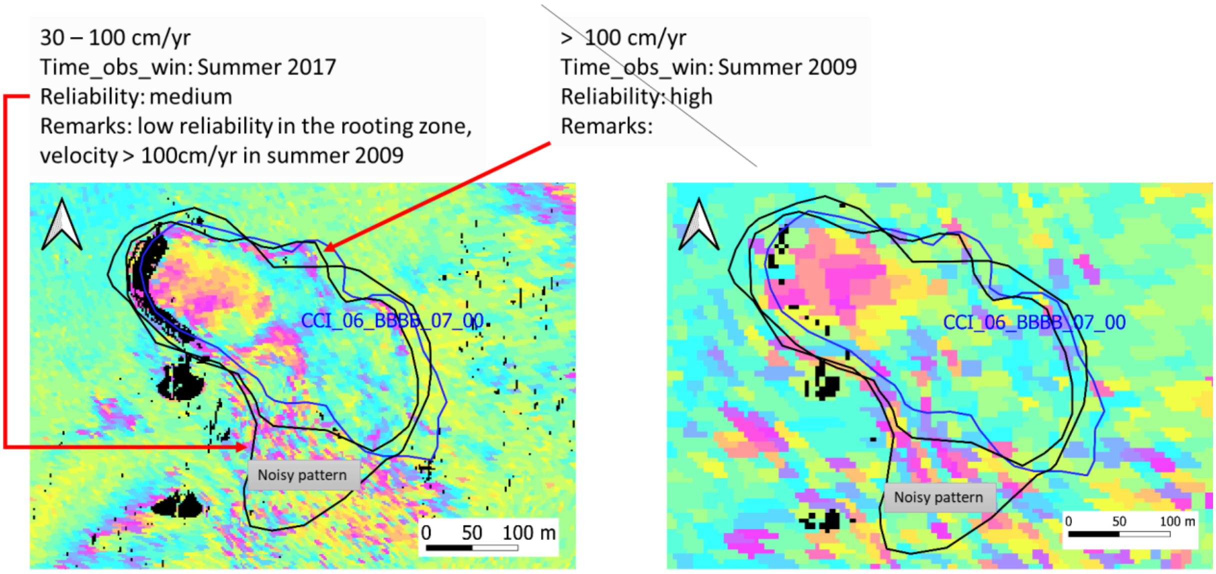
- *The faster MA is visible on summers 2016 and 2017 interferograms, then it should also be visible on annual 2016 – 2017 interferogram (e.g. with decorrelation).*
- *Faster MA is visible in all summer interferograms. Reliability should be set to “high”*
- *Slower MA is visible only in one annual interferogram. Reliability should be set to “low”, with additional Remarks: “low reliability especially into the rooting zone”.*

Case 2) Two or more outlines of MAs (related to the same RG unit) with different velocity classes observed in very different time observation windows.

>> Rules:

- If a long period separates the two time observation windows (e.g. Summer 2009 and summer 2017): only MA detected in the latest period should be outlined and classified. Remarks about the previous detected velocity (e.g. in 2009) can be added.
- If the two time observation windows are very close (e.g. summers 2016 and summer 2017): map only one MA and classify the velocity using the mean velocity observed in both summers. Indicate in Remark the fastest summer.

>> Example:



TERRA_20090924_20091005_11d_asc_diff

SENT1_20170913_20170925_12d_asc_diff

>> Notes:

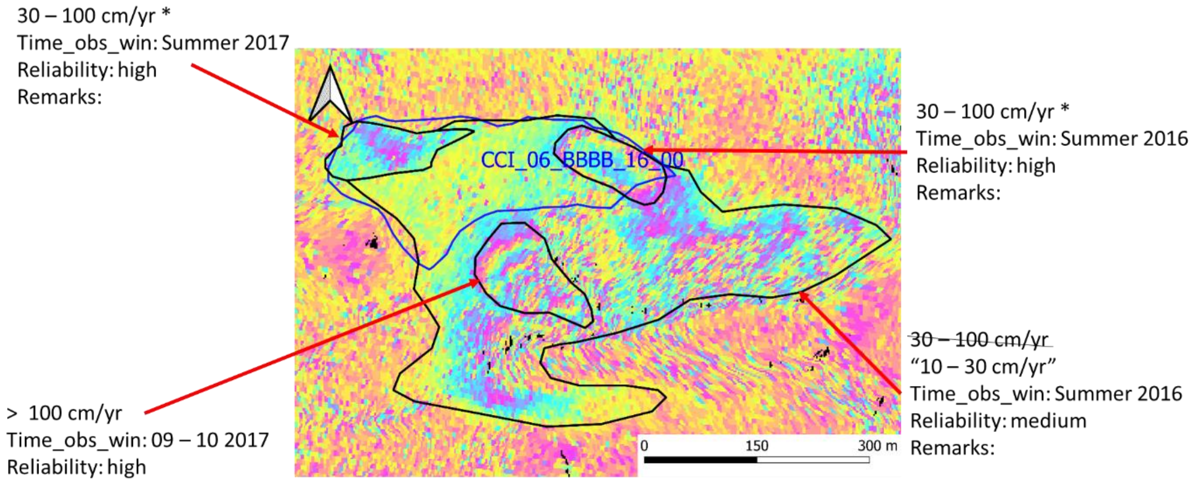
- *MA with velocity class 30 – 100 cm/yr includes a part with noisy pattern in the rooting zone (Southern part) detectable in all interferograms. It is certainly related to artefacts, and should be excluded.*
- *A long period separates the two time observation windows (i.e. Summer 2009 and summer 2017), then only MA detected in summer 2017 should be outlined and classified. Remarks about the previous detected velocity in summer 2009 can be added.*

Case 3) Two or more MAs superimposed with the same velocity classes.

>> Rules:

- Different outlines should be outlined when faster MA(s) are included in slower MA. If the small MA(s) included in big MA have the same velocity classes, the small MA(s) should be removed, or the velocity classes should be redefined.
- If you are sure about the MA(s), you should refine the RG unit(s). "A large heterogeneity can also indicate the need to refine/redefine the delineation of the initial geomorphological units (iterative process combining geomorphological and kinematic approaches)" (from Guidelines).

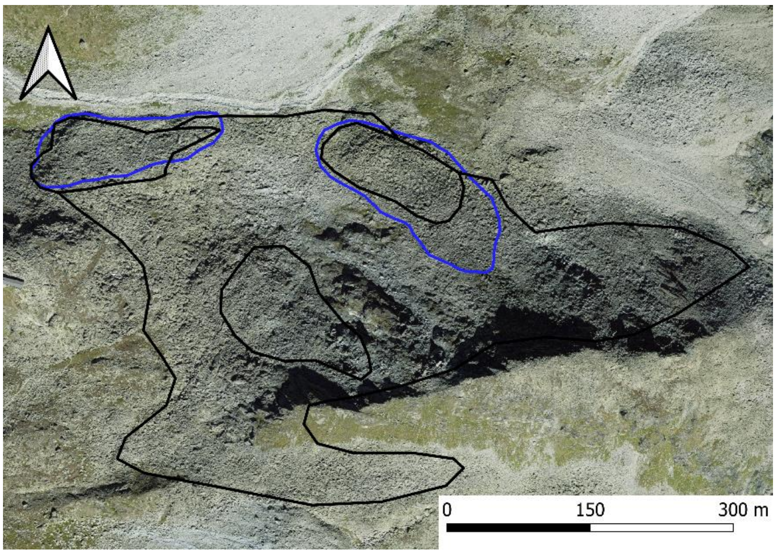
>> Example:



COSMO_20171001_20171017_16d_desc_diff

>> Notes:

- *The velocity classes should be verified. Either the velocity classification is correct and the small MAs (*) should be removed (included in the biggest one), or the velocity classes should be redefined (e.g. here change the velocity class of the bigger MA)*
- *If you are sure about the MA(s), you should refine the RG unit(s). An example below.*



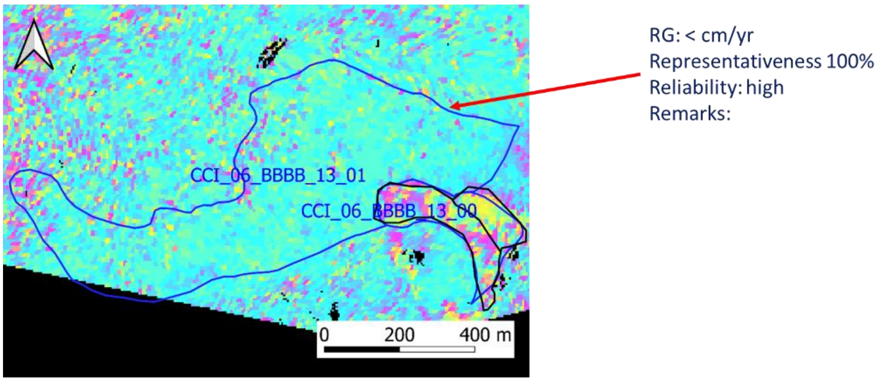
Case 4) RG unit not covered by MA(s)

>> Rules: Check the available annual InSAR interferograms:

- if a plain pattern on the RG unit is visible, it means that no movement is detected. Therefore, the RG kinematic attribute can be set to "< cm/yr", and reliability "high".
- if a decorrelation (noisy pattern) on the RG unit is visible, it means that it is not possible to estimate a reliable velocity. The RG kinematic attribute has to be set to "Undefined", adding into Remarks the detected decorrelation, and reliability "high".

When a plain or noisy pattern is visible on the entire RG unit, the Representativeness has to be set at 100%.

>> Example for CCI_06_BBBB_13_01 RG unit:



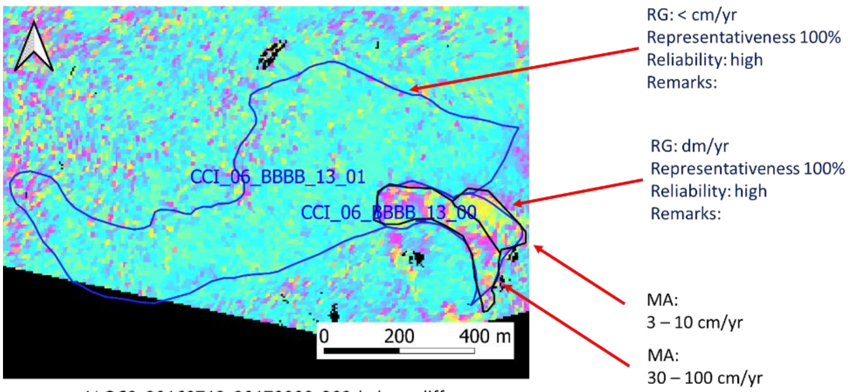
ALOS2_20160712_20170808_392d_desc_diff

>> Notes: A plain pattern on the CCI_06_BBBB_13_01 RG unit is visible with an annual interferogram, it means that no movement are detected. Therefore, the RG kinematic attribute can be set to "< cm/yr", and reliability "high".

Case 5) Two adjacent MAs cover the same RG unit

>> Rule: The RG kinematic attribute can be assigned using a mean value between the MAs.

>> Example for CCI_06_BBBB_13_00 RG unit:



ALOS2_20160712_20170808_392d_desc_diff

>> Note: CCI_06_BBBB_13_00 is covered by two MAs, whose mean value of RG kinematic attribute is dm/yr.

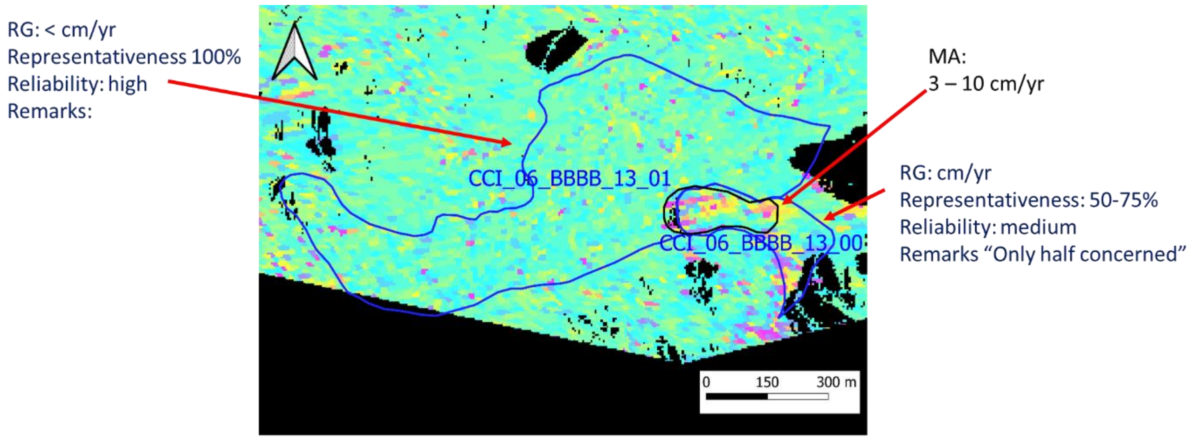
Case 6) RG unit is partially covered by MA.

>> Rules:

Check the available annual InSAR interferograms on the remaining part of RG unit not covered by MA, in order to understand if a plain or noisy pattern is visible (as case 4):

- If a plain pattern on the RG unit not covered by MA(s) is visible, it means that no movement is detected and velocity is "< cm/yr". The RG kinematic attribute can be assigned using a mean value between the detected MA(s) and the area with velocity "< cm/yr". Representativeness has to be set considering the MA(s) extension and the area with velocity "< cm/yr" (i.e. area with plain pattern). Information about the restricted MA(s) extension can be added into Remarks (e.g. "Only half concerned"). However, if MA(s) has a velocity greater than 10-30 cm/yr, this high velocity difference suggests the need to refine the RG unit(s) ("A large heterogeneity can also indicate the need to refine/redefine the delineation of the initial geomorphological units", from Guidelines).
- If a decorrelation (noisy pattern) on the RG unit not covered by MA(s) is visible, it means that it is not possible to estimate a reliable velocity. The RG kinematic attribute has to be set to "Undefined" if the Representativeness is < 50%; additional information about the detected decorrelation and an estimated RG kinematic attribute can be added into Remarks. If the Representativeness is 50-75% the RG kinematic attribute can be assigned depending on the detected velocities of MA(s), but reliability should be set to "low".

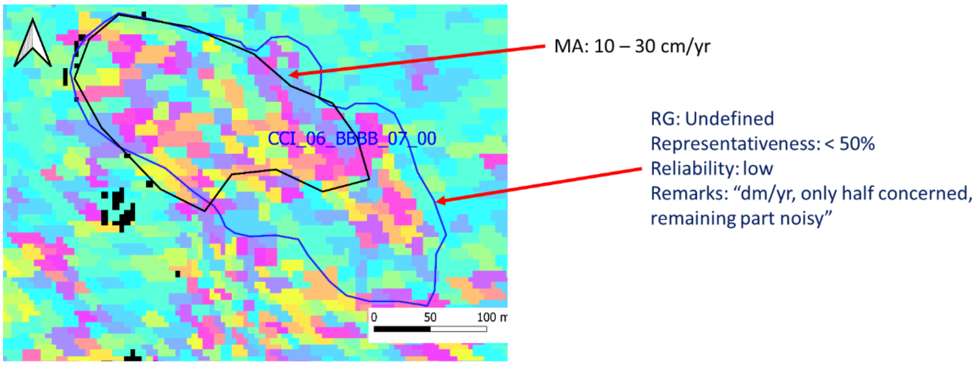
>> Example for CCI_06_BBBB_13_00 RG unit:



ALOS2_20140911_20150910_364d_asc_diff

>> Notes: on annual interferogram a plain pattern is partially visible on the RG unit not covered by MA. CCI_06_BBBB_13_00 can be classified as "cm/yr" considering the MA velocity class of 3 – 10 cm/yr and the velocity < cm/yr visible on the RG unit not covered by MA.

>> Example for CCI_06_BBBB_07_00 RG unit:



ALOS2_20140911_20150910_364d_asc_diff

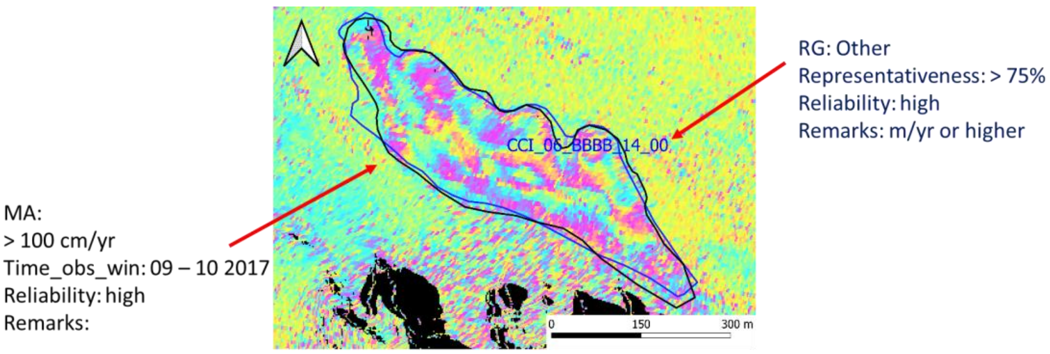
>> Notes: on annual interferogram a noisy pattern is visible on the RG unit not covered by MA. In this example the Representativeness is really near 50%, and CCI_06_BBBB_07_00 can be classified as “Undefined”. The detected noisy pattern and the estimated RG kinematic attribute can be added into Remarks.

Case 7) MA velocity class > 100 cm/yr

>> Rules:

- MA velocity class assignment: when it is possible to distinguish in between the additional velocity classes 100-300 cm/yr and > 300 cm/yr, the velocity class can be set at “Other” and the note “100-300 cm/yr” or “> 300 cm/yr” should be indicated in the field Remarks. This distinction is possible if high temporal resolution kinematic data (e.g. GNSS, 1-4 days InSAR data, etc.) are available.
- RG kinematic attribute assignment:
    - If MA velocity class is “> 100 cm/yr”, the RG kinematic attribute should be set to “Other”, adding into Remarks “m/yr or higher”.
    - If MA velocity class is “Other” with Remarks “100-300 cm/yr” or “> 300 cm/yr”, the RG kinematic attribute should be set to “m/yr” or “> m/yr” respectively, adding into Remarks how was assessed this velocity (e.g. “Validated by GNSS”, “high temporal InSAR data”, …).

>> Example:

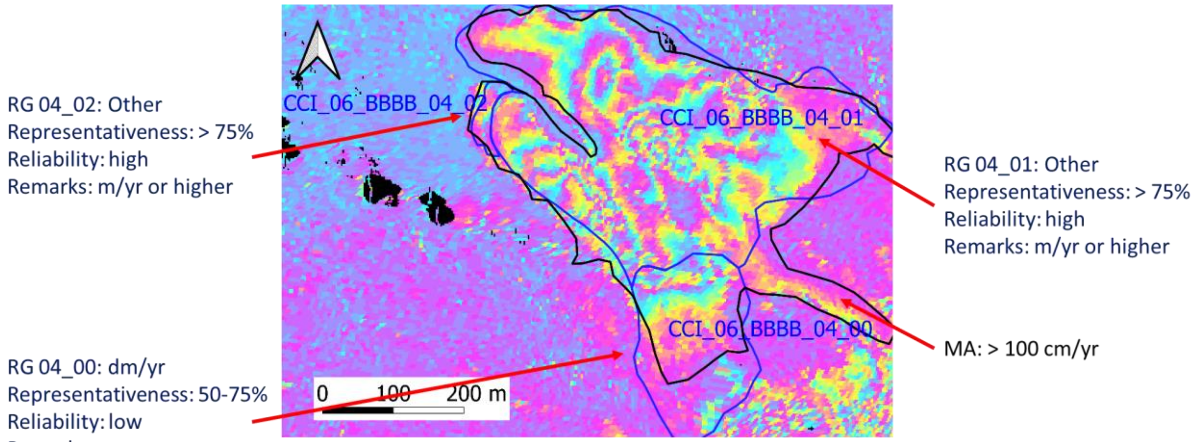


COSMO_20170915_20170924_9d_desc_diff

>> Note: MA velocity class is > 100 cm/yr, then RG kinematic attribute is “Other”, Remarks “m/yr or higher”.

Case 8) Complex RG unit (includes some of the previous cases)

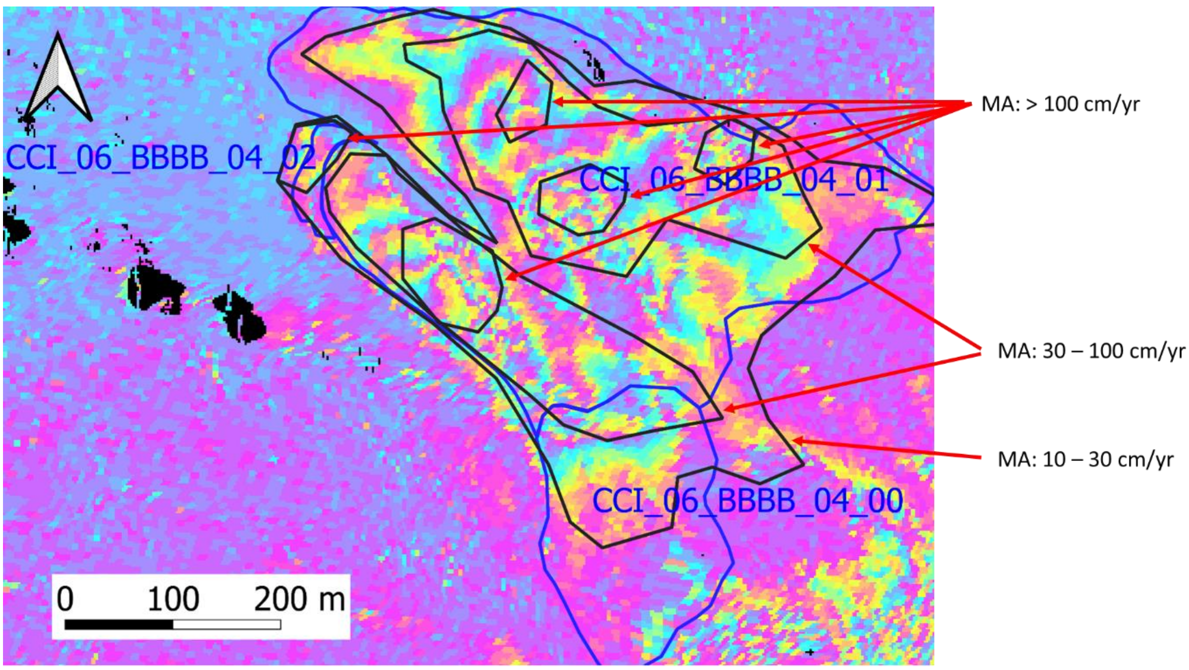
>> Example:



TERRA_20140927_20141008_11d_desc_diff

>> Notes:

- *RG unit CCI_06_BBBB_04_00: a decorrelation (noisy pattern) on the RG unit not covered by MA(s) is visible on annual interferograms. RG unit is classified as dm/yr with Representativeness 50 – 75%, but reliability is low (see case 6).*
- *RG unit CCI_06_BBBB_04_01: MA with velocity class >100 cm/yr (see case 7).*
- *RG unit CCI_06_BBBB_04_02: MA with velocity class >100 cm/yr (see case 7). However, the small RG unit (not related to a specific MA) suggests returning to the InSAR data to see if there is specific movement there. If a movement separated from the other MA is visible, re-outline MA(s) at this place (see the example below).*



TERRA_20140927_20141008_11d_desc_diff