



permafrost
cci

**CCI+ PHASE 2
PERMAFROST**

CCN4

**MOUNTAIN PERMAFROST: ROCK GLACIER INVENTORIES (RoGI)
AND ROCK GLACIER VELOCITY (RGV) PRODUCTS**

D2.2 Algorithm Theoretical Basis Document (ATBD)

VERSION 2.0

15 NOVEMBER 2024

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Document status sheet

Issue	Date	Details	Authors
1.0	31.05.2023	First version, based on CCN2 D2.2	L. Rouyet, T. Echelard, L. Schmid, C. Barboux, C. Pellet, R. Delaloye, A. Onaca, F. Sirbu, V. Poncos, F. Brardinoni, A. Kääh, T. Strozzi, N. Jones, A. Bartsch
2.0	15.11.2024	Phase 2, iteration 2, D2.2 update: minor corrections for RoGI, adjustment of RGV workflow, presentation of RGV intercomparison exercise.	L. Rouyet, C. Pellet, L. Schmid, T. Echelard, R. Delaloye, B. Brardinoni, F. Sirbu, A. Onaca, V. Poncos, L. Wendt, T.R. Lauknes, A. Kääh, T. Strozzi, P. Bernhard, A. Bartsch

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EUROPEAN SPACE AGENCY CONTRACT REPORT

The work described in this report was done under ESA contract. Responsibility for the contents resides in the authors or organizations that prepared it.

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Executive summary

The European Space Agency (ESA) Climate Change Initiative (CCI) is a global monitoring program, which aims to provide long-term satellite-based products to serve the climate modelling and climate user community. The objective of the ESA CCI Permafrost project (Permafrost_cci) is to develop and deliver the required Global Climate Observation System (GCOS) Essential Climate Variables (ECV) products, using primarily satellite imagery. The two main products associated to the ECV Permafrost, Ground Temperature (GT) and Active Layer Thickness (ALT), were the primary documented variables during Permafrost_cci Phase 1 (2018–2021). Following the ESA Statement of Work for Permafrost_cci Phase 2 (2022–2025) [AD-1], GT and ALT are complemented by a new ECV Permafrost product: Rock Glacier Velocity (RGV). This document focuses on the mountain permafrost component of the Permafrost_cci project and the dedicated rock glacier products.

In periglacial mountain environments, permafrost occurrence is patchy, and the preservation of permafrost is controlled by site-specific conditions, which require the development of dedicated products as a complement to GT and ALT measurements and permafrost models. Rock glaciers are the best visual expression of the creep of mountain permafrost and constitute an essential geomorphological heritage of the mountain periglacial landscape. Their dynamics are largely influenced by climatic factors. There is increasing evidence that the interannual variations of the rock glacier creep rates are influenced by changing permafrost temperature, making RGV a key parameter of cryosphere monitoring in mountain regions.

Two product types are therefore proposed by Permafrost_cci Phase 2: Rock Glacier Inventories (RoGIs) and Rock Glacier Velocity (RGV) time series. This agrees with the objectives of the International Permafrost Association (IPA) Standing Committee on Rock Glacier Inventories and Kinematics (RGIK) [RD-5] and concurs with the recent GCOS and GTN-P decisions to add RGV time series as a new product of the ECV Permafrost to monitor changing mountain permafrost conditions [AD-2 to AD-4]. RoGI is an equally valuable product to document past and present permafrost extent. It is a recommended first step to comprehensively characterise and select the landforms that can be used for RGV monitoring. RoGI and RGV products also form a unique validation dataset for climate models in mountain regions, where direct permafrost measurements are very scarce or lacking. Using satellite remote sensing, generating systemic RoGI at the regional scale and documenting RGV interannual changes over many landforms become feasible. Within Permafrost_cci, we mostly use Synthetic Aperture Radar Interferometry (InSAR) technology based on Sentinel-1 images that provide a global coverage, a large range of detection capability (mm–cm/yr to m/yr) and fine spatio-temporal resolutions (tens of m pixel size and 6–12 days of repeat-pass). InSAR is complemented at some locations by SAR offset tracking techniques and spaceborne/airborne optical photogrammetry.

This Algorithm Theoretical Basis Document (ATBD) specifies the theoretical background of the methods used to develop the RoGI and RGV products of the Permafrost_cci Phase 2. For RoGI, we describe the methodology recommended by RGIK to generate consensus-based inventories. In iteration 1, the procedure has been applied in subareas with the objective to identify discrepancies between operators and refine the outcomes of Permafrost_cci Phase 1. In iteration 2, the same procedure is applied in new regions. For RGV, the processing steps to generate multiple velocity time series based on InSAR and convert the results into annualized and spatially averaged RGV products are explained. The procedure is applied for pilot sites located in the Alps and in Norway. This is an updated version (version 2.0) including minor corrections and updates.

1 Introduction

1.1 Purpose of the document

The mountain permafrost component of Permafrost_cci Phase 2 focuses on the generation of two products: Rock Glacier Inventory (RoGI) and Rock Glacier Velocity (RGV). The Algorithm Theoretical Basis Document (ATBD) specifies the theoretical background of the methods used to develop the two products described in the PSD [RD-1], with respect to the user requirements described in the URD [RD-2].

1.2 Structure of the document

Section 1 provides information about the purpose and background of this document. Section 2 summarizes the scientific background related to the monitoring of mountain permafrost and explains the justification of the selected methods. Section 3 describes the processing lines. Sections 4 and 5 describe the required input data and the properties of the output products, respectively. Section 6 outlines some practical considerations for the implementation. A bibliography complementing the applicable and reference documents (Sections 1.3 and 1.4) is provided in Section 7.1. A list of acronyms is provided in Section 7.2. A glossary of the commonly accepted permafrost terminology can be found in [RD-18]. The ATBD also contains two Annexes describing the RoGI procedure in a generic GIS tool and the InSAR guidelines for documenting moving areas on rock glaciers and using them to assign kinematic attributes in RoGI [RD-8].

1.3 Applicable documents

[AD-1] ESA. 2022. Climate Change Initiative Extension (CCI+) Phase 2 – New Essential Climate Variables – Statement of Work. ESA-EOP-SC-AMT-2021-27.

[AD-2] GCOS. 2022. The 2022 GCOS Implementation Plan. GCOS – 244 / GOOS – 272. Global Observing Climate System (GCOS). World Meteorological Organization (WMO).

[AD-3] GCOS. 2022. The 2022 GCOS ECVs Requirements. GCOS – 245. Global Climate Observing System (GCOS). World Meteorological Organization (WMO).

[AD-4] GTN-P. 2021. Strategy and Implementation Plan 2021–2024 for the Global Terrestrial Network for Permafrost (GTN-P). Authors: Streletskiy, D., Noetzli, J., Smith, S.L., Vieira, G., Schoeneich, P., Hrbacek, F., Irrgang, A.M.

1.4 Reference Documents

[RD-1] Rouyet, L., Schmid, L., Pellet, C., Echelard, T., Delaloye, R., Brardinoni, F., Sirbu, F., Onaca, A., Poncos, V., Kääh, A., Strozzi, T., Bernhard, P., Bartsch, A. 2024. ESA CCI+ Permafrost Phase 2 – CCN4 Mountain Permafrost: Rock Glacier inventories (RoGI) and Rock glacier Velocity (RGV) Products. D1.2 Product Specification Document (PSD), v2.0. European Space Agency.

[RD-2] Rouyet, L., Pellet, C., Schmid, L., Echelard, T., Delaloye, R., Brardinoni, F., Sirbu, F., Onaca, A., Poncos, V., Kääh, A., Strozzi, T., Bartsch, A. 2024. ESA CCI+ Permafrost Phase 2 – CCN4 Mountain Permafrost: Rock Glacier inventories (RoGI) and Rock glacier Velocity (RGV) Products. D1.1 User Requirement Document (URD), v2.0. European Space Agency.

- [RD-3]** Delaloye, R., Barboux, C., Bodin, X., Brenning, A., Hartl, L., Hu, Y., Ikeda, A., Kaufmann, V., Kellerer-Pirklbauer, A., Lambiel, C., Liu, L., Marcer, M., Rick, B., Scotti, R., Takadema, H., Trombotto Liaudat, D., Vivero, S., Winterberger, M. 2018. Rock glacier inventories and kinematics: a new IPA Action Group. Proceedings of the 5th European Conference on Permafrost (EUCOP), Chamonix, 23 June – 1st July 2018.
- [RD-4]** RGIK. 2022. Towards standard guidelines for inventorying rock glaciers: baseline concepts (version 4.2.2). IPA Action Group Rock glacier inventories and kinematics, 13 pp.
- [RD-5]** RGIK. 2022. Towards standard guidelines for inventorying rock glaciers: practical concepts (version 2.0). IPA Action Group Rock glacier inventories and kinematics, 10 pp.
- [RD-6]** RGIK. 2022. Optional kinematic attribute in standardized rock glacier inventories (version 3.0.1). IPA Action Group Rock glacier inventories and kinematics, 8 pp.
- [RD-7]** RGIK. 2023. Guidelines for inventorying rock glaciers: baseline and practical concepts (version 1.0). IPA Action Group Rock Glacier Inventories and Kinematics, 25 pp. <https://doi.org/10.51363/unifr.srr.2023.002>.
- [RD-8]** RGIK. 2023. InSAR-based kinematic attribute in rock glacier inventories. Practical InSAR guidelines (version 4.0). IPA Action Group Rock glacier inventories and kinematics, 33 pp.
- [RD-9]** RGIK 2022. Rock Glacier Velocity as an associated parameter of ECV Permafrost: baseline concepts (version 3.1). IPA Action Group Rock glacier inventories and kinematics, 12 pp.
- [RD-10]** RGIK 2023. Rock Glacier Velocity as an associated parameter of ECV Permafrost: practical concepts (version 1.2). IPA Action Group Rock glacier inventories and kinematics, 17 pp.
- [RD-11]** RGIK 2023. Instructions of the RoGI exercise in the Goms Valley (Switzerland). IPA Action Group Rock glacier inventories and kinematics, 10 pp.
- [RD-12]** Bertone, A., Barboux, C., Delaloye, R., Rouyet, L., Lauknes, T. R., Käab, A., Christiansen, H. H., Onaca, A., Sirbu, F., Poncos, V., Strozzi, T., Caduff, R., Bartsch, A. 2020. ESA CCI+ Permafrost Phase 1 – CCN1 & CCN2 Rock Glacier Kinematics as New Associated Parameter of ECV Permafrost. D4.2 Climate Research Data Package Product Specification Document (CRDP), v1.0. European Space Agency.
- [RD-13]** Sirbu, F., Onaca, A., Poncos, V., Strozzi, T., Bartsch, A. 2022. ESA CCI+ Permafrost Phase 1 – CCN1 & CCN2. Rock Glacier Kinematics in the Carpathians (CCN1 Budget Extension). Climate Research Data Package Product Specification Document (CRDP), v1.0. European Space Agency.
- [RD-14]** Bertone, A., Barboux, C., Bodin, X., Bolch, T., Brardinoni, F., Caduff, R., Christiansen, H. H., Darrow, M. M., Delaloye, R., Etzelmüller, B., Humlum, O, Lambiel, C., Lilleøren, K. S., Mair, V., Pellegrinon, G., Rouyet, L., Ruiz, L., Strozzi, T. 2022. Incorporating InSAR kinematics into rock glacier inventories: insights from 11 regions worldwide. *The Cryosphere*. 16, 2769–2792. <https://doi.org/10.5194/tc-16-2769-2022>.
- [RD-15]** Rouyet, L., Echelard, T., Schmid, L., Pellet, C., Delaloye, R., Onaca, A., Sirbu, F., Poncos, V., Brardinoni, F., Käab, A, Strozzi, T., Jones, N., Bartsch, A. 2023. ESA CCI+ Permafrost Phase 2 – CCN4 Mountain Permafrost: Rock Glacier inventories (RoGI) and Rock glacier Velocity (RGV) Products. D3.2 Climate Research Data Package (CRDP), v1.0. European Space Agency.
- [RD-16]** Pellet, C., Bodin, X., Cusicanqui, D., Delaloye, R., Käab, A., Kaufmann, V., Thibert E., Vivero, S. and Kellerer-Pirklbauer, A. 2023. Rock Glacier Velocity. In *Bull. Amer. Soc. Vol. 105(8), State of the Climate in 2023*, pp. 44–45. <https://doi.org/10.1175/2024BAMSSStateoftheClimate.1>.

[RD-17] Adler, C., Wester, P., Bhatt, I., Huggel, C., Insarov, G.E., Morecroft, M.D., Muccione, V. and A. Prakash. 2022. Cross-Chapter Paper 5: Mountains. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 2273–2318. <https://doi.org/10.1017/9781009325844.022>.

[RD-18] van Everdingen, R. Ed. 1998, revised in May 2005. *Multi-language glossary of permafrost and related ground-ice terms*. Boulder, CO: National Snow and Ice Data Center/World Data Center for Glaciology. <http://nsidc.org/fgdc/glossary>.

2 Scientific background and selected algorithms

2.1 Rock glacier inventory (RoGI)

Although many regional rock glacier inventories (RoGIs) exist, they are not exhaustive worldwide. Existing RoGIs have various ages and have been compiled using different methodologies, which depend on the experience of the cartographer, the review process, the data availability, and the varying objectives that motivated each study. For these reasons, merging all existing inventories in a fully coherent way is presently not possible. Previous glacier-oriented initiatives, such as the World Glacier Inventory (WGI) or Global Land Ice Measurements from Space (GLIMS), tried to include rock glaciers but have not succeeded in being systematic and homogeneous. It has been particularly difficult to properly include rock glaciers due to the complexity of detecting them automatically by remote sensing (GLIMS methodology). Additionally, relict rock glaciers have been systematically excluded from these inventories, as they are not part of the current cryosphere.

The increasing availability of remote sensing data (e.g., optical and radar imagery) facilitates the development of new inventories and/or the update of existing ones. Systematically acquired and openly disseminated satellite images covering the entire globe (e.g. Sentinel-1 SAR images) also enable the detection of rock glacier surface movement at the large scale, and can be used to integrate kinematic information in standardized RoGIs. The development of widely accepted guidelines for inventorying rock glaciers, including kinematic information, serves the compilation of new regional inventories and the adaptation of existing ones, with the final objective to merge all RoGIs in an open-access worldwide database. Standard guidelines should avoid, or at least minimize, potential discrepancies between rock glacier datasets originally compiled for different purposes.

Inventorying rock glaciers is a manual (visual) procedure, which cannot be fully automatized yet and requires geomorphological expertise by the operators. Identifying and characterizing rock glaciers has often led to various and sometimes controversial mapping outcomes due to the complexity of morphologies (e.g., multiple generations, coalescent landforms, heterogeneous dynamics, interaction with glaciers) and the diversity of environments in which rock glaciers have developed. Subjectivity must be acknowledged as part of the rock glacier inventorying process. Establishing guidelines and a consensus-based inventorying procedure aims at minimizing the degree of variability of the final outcomes. In the future, we envision that an increasing number of manually identified rock glaciers based on widely accepted standards will support the development of automatic techniques (e.g. deep learning) as a complementary tool to compile inventories.

There are various **motivations for producing RoGI**:

- **Geomorphological mapping:** Rock glaciers are identified and mapped as functional or inherited (relict) landforms of the geomorphological landscape. They are part of the mountain sediment toposequence and as such contribute to control the pace of periglacial mountain landscape evolution. Enhancing the value of geomorphological heritage could also be the main motivation to compile a rock glacier inventory.
- **Proxy for permafrost occurrence:** Functional rock glaciers are geomorphological indicators of the occurrence of permafrost. Even if it is accepted that functional rock glaciers may export perennially frozen ground outside of a permafrost prone area and may be no longer reflect surface conditions favourable to permafrost occurrence, they can be used to approximate the regional lower limit of the mountain permafrost belt and to validate spatial models of permafrost extent.

Conversely, inherited (relict) rock glaciers are discriminative landforms of currently permafrost-free areas.

- **Paleo-permafrost studies:** Inherited (relict) rock glaciers can be used as proxies for various paleo-permafrost extents. Discrimination between inherited and functional state is often difficult, making the integration of inherited landforms in a global inventory indispensable.
- **Hydrological significance:** Functional rock glaciers are, by nature, ice (and water) storage features, which may play a prominent role in the hydrological regime of mountain catchments, especially in dry areas. RoGIs have been developed and/or used in particular for estimating their regional water-equivalent significance. In addition to being ice storage features, rock glaciers can affect water transit time and water chemistry in a catchment.
- **Geohazards:** Functional rock glaciers may be the source of direct or indirect geohazards (e.g. destabilization, conveyance of loose debris into a gully) that may pose a risk to human activities and/or facilities (e.g. transport infrastructures, buildings, livelihoods). RoGIs can be used to locate and assess potential geohazards at the local to regional scales. In the context of infrastructure construction/maintenance, the information from RoGIs is not sufficient to entirely understand the issues related to permafrost degradation. However, it may provide clues for assessing permafrost occurrence (or absence) in the study area.
- **Climate relevant variable:** Rock glacier movement is particularly sensitive to changing permafrost temperature. Updating and comparing inventories of functional rock glaciers, which include temporally well-constrained kinematic information, can be used to assess the impact of ongoing climate change on the mountain periglacial environment across regions.

In the framework of Permafrost_cci, the last motivation listed above is the most relevant. The objective is **to develop climate change indicators dedicated to mountain regions, as a complement to other global permafrost products**. In this regard, RoGI generation can be seen as a necessary first step to identify functional rock glaciers within a region, characterise their morpho-kinematic properties and then select rock glaciers to be monitored (RGV production). Independently to this goal, it is important to note that the original motivation for producing a RoGI may differ from the one of subsequent third-party users. Therefore, standardized guidelines should help in avoiding, or at least minimizing, potential discrepancies.

2.2 Rock glacier velocity (RGV)

Observing changes in rock glacier velocity provides information about the impact of climate change on mountain permafrost and has the potential to become a key parameter of cryosphere monitoring in mountain regions. In the last two decades, several studies conducted in particular in the European Alps have shown that there is a dependency between the rock glacier interannual behaviour and permafrost temperature, with the latter impacting in particular the rheological and hydrological properties of the frozen ground (Delaloye et al., 2010; Delaloye & Staub et al., 2016; Frauenfelder et al., 2003; Ikeda et al., 2008; Kääh et al., 2007; Kellerer-Pirklbauer & Kaufmann, 2012; Kenner & Magnusson, 2017; Roer et al., 2005). It has been observed that rock glaciers tend to accelerate on an interannual basis under warmer climatic conditions, as long as the permafrost degradation has not become too severe to prevent this response. The temporal evolution of rock glacier kinematics depends, among others, on the altering of the temperature profile between the permafrost table and the main shear horizon: the closer the temperature rises to 0°C, the faster the rock glacier tends to become. In addition, it has been shown that rock glaciers tend to display a similar regional kinematic behaviour at (pluri-)annual to (pluri-)decennial time scales (Delaloye et al., 2010; PERMOS, 2023). Relative interannual

acceleration and deceleration are occurring at almost the same time and in the same proportion in a given region, whatever the absolute velocity and the morphological characteristics of the rock glaciers (*Figure 1*). Continuous or periodic monitoring has shown that the observed rock glaciers develop a landform-specific repetitive intra-annual behaviour, but these variations are usually not altering the interannual and decadal trends in a significant manner. The similar regional behaviour of rock glaciers enables the development of regional indices, to be used as regional climate change indicators.

Based on these evidence, GCOS and GTN-P decided in 2022 to add RGV as a new product of the ECV Permafrost [AD-2] [AD-3] [AD-4]. RGV is becoming a variable that is systematically monitored worldwide [RD-14] (*Figure 2*), however the monitoring is currently still performed for a few unevenly distributed landforms due to variable national resources and strategies. The use of satellite remote sensing for producing RGV can be a turning point to set up a global dataset of RGV time series and document many landforms in several regions.

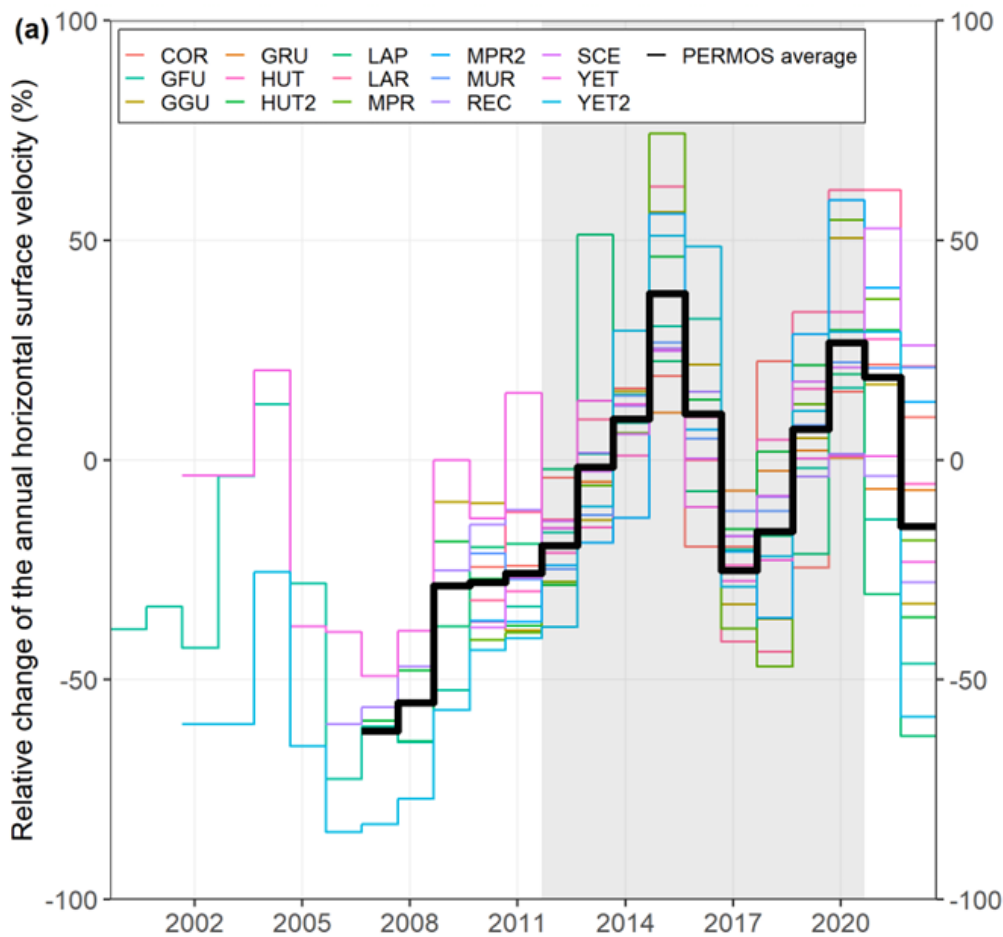


Figure 1. Mean annual horizontal surface velocity derived from terrestrial geodetic surveys relative to the reference period 2011–2020 (grey area). The black line represents the average of the Swiss Alps based on 15 monitored rock glacier lobes. (PERMOS, 2023)

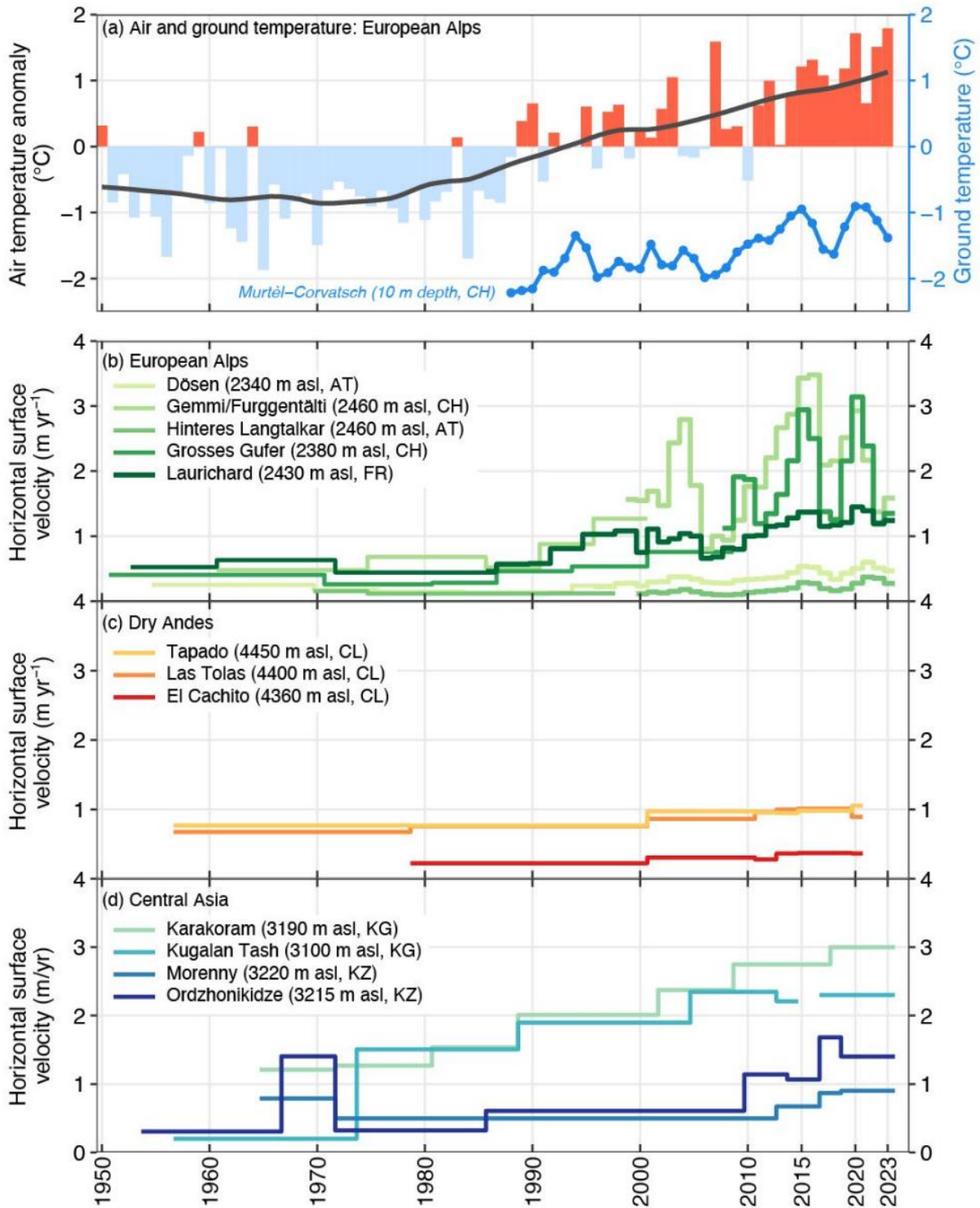


Figure 2. Rock glacier velocity and climate. (a) Air and ground temperature (°C) in the European Alps. Rock glacier velocities (m/yr) at selected sites in (b) the European Alps, (c) the Dry Andes (adapted from Vivero et al. 2021) and (d) central Asia (adapted from Kääb et al. 2021) [RD-16].

2.3 InSAR for rock glacier mapping and monitoring

To fulfil the criteria described in the PVASR, **Spaceborne Synthetic Aperture Radar (SAR) Interferometry (InSAR)** has been selected as the main Permafrost_cci technique to measure kinematics over rock glaciers. In this section, we therefore summarize the background of the technique. For a more theoretical background about InSAR, refer to Massonnet and Feigl (1998), Bamler and Hartl (1998), Rosen et al. (2000), Rocca et al. (2000), Hanssen (2001), Kampes (2006) and Ferretti (2014).

InSAR is a satellite remote sensing technique used to measure surface movement over large areas. The approach consists of analysing **the phase differences between two SAR images taken at different times**, after removal of unwanted phase components (e.g., associated with the topography or the atmosphere).

The resulting map of phase differences is referred to as an “interferogram”. It contains **one-dimensional information about the surface displacement**, corresponding to the **projection of the real displacement along the sensor view angle, i.e. the SAR line-of-sight (LOS)** (*Figure 3a*). A single SAR interferometric observation therefore does not allow to fully determine the magnitude and direction of a surface deformation. The three-dimensional displacement vector can only be computed if one assumes a certain displacement direction when focusing on a specific process, e.g. creep occurring along the steepest slope direction for the rock glaciers.

A Synthetic Aperture Radar (SAR) is not able to measure displacements that are fully perpendicular to its LOS and detects an underestimated displacement if the LOS deviates from the real displacement orientation. We therefore need **to know the measurement geometry of the available datasets to correctly interpret the interferograms**. SAR satellites are polar orbiting and imaging the Earth’s surface at specific azimuth and incidence angles. With a right-looking sensor, a satellite crossing the Equator from South to North (**ascending passes**) looks **towards East**. When crossing the Equator from North to South (**descending passes**), it looks **towards West** (*Figure 3a*).

The SAR geometry has an impact on the achieved spatial coverage in mountainous terrain. North- and South-facing slopes are difficult to analyse, because creeping landforms include a displacement component perpendicular to the LOS orientation. **Back-facing slopes** (*D-I, Figure 3b*), defined as the western slopes when viewing in descending mode (eastern slopes in ascending mode), **are the most appropriate configurations**. The local spatial resolution is less affected by geometric distortions and the displacement orientation is more or less aligned with the LOS. The slopes facing the radar (*A-D, Figure 3b*) are less favourable for an InSAR analysis. In addition, the difference between the slope steepness and the radar incidence angle has to be considered. A steep incidence angle reduces shadow effects observed in back-facing slopes (*F-H, Figure 3b*) but increases layover effects in slopes facing the SAR (*B-D, Figure 3b*). Consequently, it is important to **use a combination of interferograms with different view angles and geometries (ascending/descending) to investigate different slopes in a region**.

The displacement that occurs between the two image acquisitions can be estimated by **visually interpreting the interferograms**. The results are spatially relative to a reference area selected outside the studied moving area. The spatial change of colour in the interferogram expresses the surface displacement projected onto the LOS direction. **An entire colour cycle (fringe) is equivalent to a change of half the SAR wavelength ($\lambda/2$) along the LOS during the time interval between the two images**. One phase cycle represents half the wavelength as the radar signal travels to the ground and

back to the sensor. The direction of the change can be interpreted using the key in *Figure 4*. Considering back-facing slopes, clockwise colour changes mean that the radar beam has travelled further in the second acquisition and thus corresponds to a downslope process or subsidence. In the opposite case, it will be interpreted as an upslope displacement or uplift.

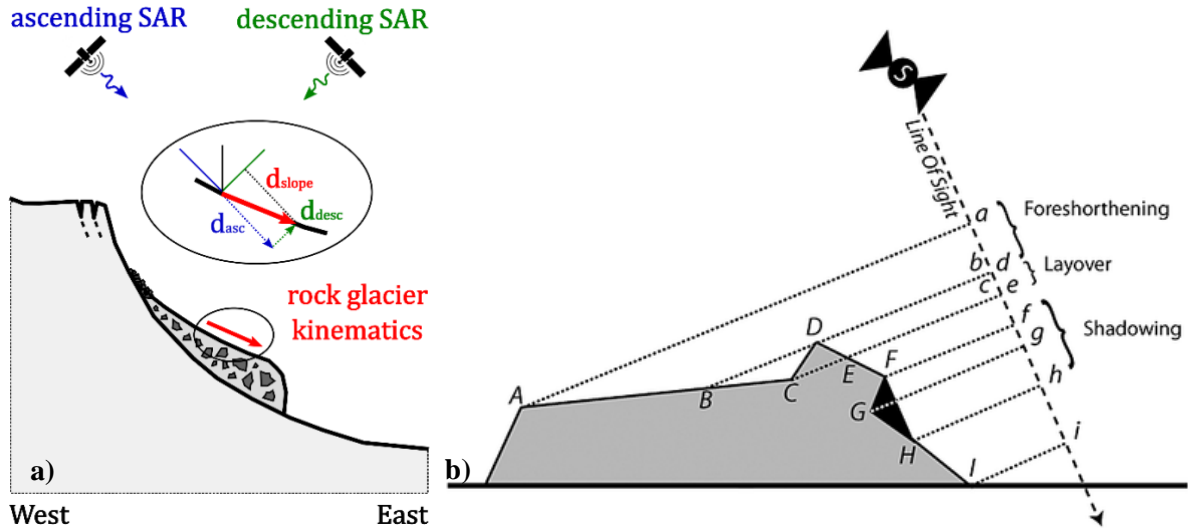


Figure 3. (a) A displacement (d) vector along the slope (d_{slope}) and the line of sight (LOS) components measured by InSAR when using SAR images from ascending (asc) and descending ($desc$) geometries: d_{asc} and d_{desc} . (b) Geometric distortions from SAR measurement geometry in mountainous regions.

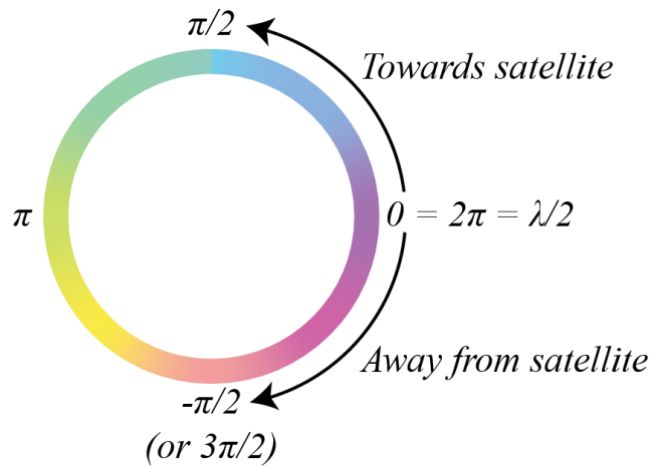


Figure 4. The difference in displacement rate between locations with the same colour is a multiple of $\lambda/2$. When the colour changes in clockwise direction, the ground has moved away from the satellite. In the opposite direction, the ground has moved towards the satellite.

The minimum and maximum displacement rates that can be detected depend on the time interval, the resolution and the SAR wavelength of the interferograms (Figure 5 and Table 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 changes occurring during the selected time interval are too large within the pixels. Temporal decorrelation can also occur due to changes in surface properties (e.g. vegetation, snow and wetness).

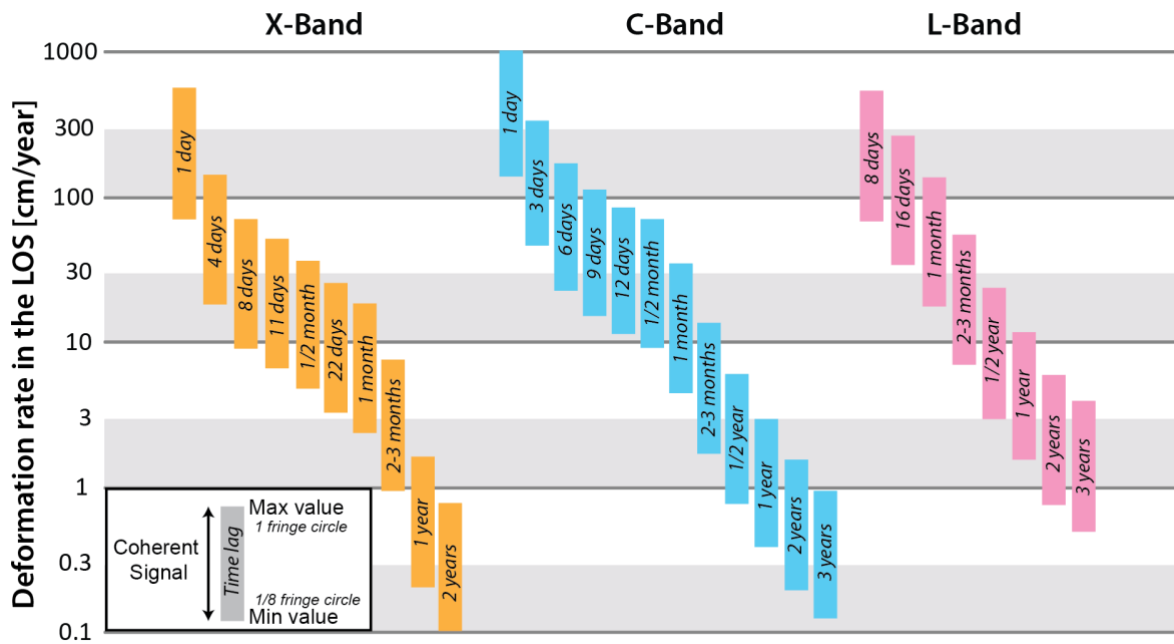


Figure 5. Deformation rate observed by SAR sensors for the most commonly used time intervals. A bar defines the interval of deformation rate in cm/yr for which a coherent signal can be identified and interpreted on an interferogram generated with a certain time interval. It shows the detection capability of different InSAR data. The lower limit corresponds to the minimal detectable velocity (1/8 of fringe cycle). The upper limit corresponds to the maximum velocity (one entire fringe). A movement lower than the minimum value of the bar is not detectable. A movement higher than the maximum value of a bar may decorrelate on the interferogram (adapted from Barboux et al., 2014).

Table 1. Radar characteristics of the main SAR systems used in the exercise.

Satellite	Terrasar-X	Cosmo-SkyMed	Sentinel-1	Radarsat-2	ALOS-2	SAOCOM
Date	from 2007	from 2007 ²	from 2014	from 2007	from 2014	from 2018
Agency	DLR	ASI	ESA	CSA	JAXA	CONAE
Wavelength (cm)	3.1	3.1	5.5	5.6	24.3	23.5
Band	X	X	C	C	L	L
Incidence angle (°)	20–45	25–40	20–45	35	30–40	18–50
Range resolution (m) ¹	1–16	1–100	5–25	3–100	3–60	5–10
Azimuth resolution (m) ¹	1–16	1–3–100	5–40	3–100	3–60	10–50
Scene width (km)	10–100	10–200	80–400	50–500	70	10–400
Repeat cycle (day)	11	1–4–8–16	(6)–12 ³	24	14	(8)–16 ³

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 two satellites operating, the repeat cycle is 6 days for Sentinel-1 and 8 days for SAOCOM.

To automatically obtain displacement maps (e.g. with units in cm), a processing step called **phase unwrapping** is required. This step allows to convert the cyclic phase differences (that range between $-\pi$ and $+\pi$) into the absolute phase values and subsequently into displacements.

An advantage of adding an automated unwrapping step is that it allows for including and combining the information from a large amount of interferograms. All interferograms (with a chosen time interval depending on the expected velocity, see *Figure 5*) can be generated, unwrapped and then averaged to provide **average velocity maps** that are easily interpretable. **This process is called InSAR Stacking.** Such maps are usually expressed in m/yr along the LOS, with negative values (typically in red) showing areas moving away from the satellite and positive values (typically in blue) showing areas moving towards the satellite.

To take advantage of the redundancy of temporally overlapping interferograms and improve the measurement accuracy (e.g. in areas affected by significant atmospheric noise), more advanced multi-temporal InSAR techniques can be applied. These are typically divided into two main groups:

- Methods based on locating Persistent Scatterers (PSs), referred to as **Persistent Scatterer Interferometry (PSI)** or **Interferometric Point Target Analysis (IPTA)**. A stack of interferograms is generated at full resolution using a single reference scene, i.e. including long (interannual) interferograms. PSI is typically designed for linear and slow-moving features, and thus does not allow for correctly quantifying velocities higher than a few dm/yr. PSI can be useful for slow-moving landforms, e.g. to discriminate transitional and relict rock glaciers. For most active rock glaciers, PSI must be complemented by single interferogram analysis and/or distributed scattering InSAR.
- Methods based on Distributed Scattering (DS), referred to as **Small BAseline Subset (SBAS)**. These methods incorporate a large number of interferograms (multiple reference scenes) below chosen spatial and temporal baseline thresholds to reduce geometric and temporal decorrelations. The maximum detection capability depends on the chosen threshold of temporal intervals used to build the interferograms, following the same logic as *Figure 5*.

Phase unwrapping and resulting averaged products based on a large amount of interferograms (InSAR stacking, PSI or SBAS maps) are widely used to produce one single output and automate the processing over large regions. However, this step may introduce **data gaps from decorrelation and potential errors over fast-moving areas, as well as in areas with snow or vegetation. Results from InSAR Stacking, PSI/IPTA or SBAS must therefore be interpreted carefully and in combination with single wrapped interferograms.**

3 Processing line

3.1 Rock glacier inventory (RoGI)

In Permafrost_cci Phase 1, several partners were involved in the production of standardized RoGIs including an InSAR-based kinematic attribute in selected regions of interest. Heterogeneities and discrepancies were identified when comparing the results from the different regions, due to different availability and quality of data (interferograms and auxiliary data) as well as varying initial knowledge in the region (past inventories, field measurements, use of redundant information from different techniques). Conclusions of this work are summarised in Permafrost_cci CCN1&2 CRDP [RD-12] [RD-13] and the related peer-review article [RD-14]. In the first iteration of ESA CCI+ Permafrost Phase 2, a **cross-validation exercise based on a multi-operator inventorying procedure** in 12 subareas of the initial regions has been designed to identify potential discrepancies between multiple operators, adjust the guidelines and evaluate the quality of the final products. In the second iteration, the same procedure is applied to new regions. The selected subareas and responsible partner institutions are described in the PSD [RD-1].

3.1.1 Multi-operator inventorying procedure and cross-validation exercise

For each subarea, a consensus-based inventorying procedure involving a team of multiple operators is applied to be able to cross-validate the results. The procedure follows the generic structure explained in the instructions of the newly released RGIK RoGI exercise in the Goms valley [RD-11]. It is inspired by two main publications dealing with the procedure to compile RoGIs, reduce discrepancies and achieve consensus-based inventories (Way et al., 2021; Brardinoni et al., 2019).

The RoGI is generated by **a team of several operators, led by a Principal Investigator (PI)**. The PI sets the intermediate deadlines, combines the outputs and takes responsibility for the final decision. The PI is also included as an operator of the inventory team. The results in the new regions will be sent to the project coordinator (Unifr) with a deadline on May 1st, 2025. The inventorying procedure includes two main phases summarized in *Figure 6*.

During the **first phase**, the team must:

- Detect and locate the rock glacier units by primary markers (only points, no outlines at this stage).
- Detect, delineate and classify the moving areas using InSAR data (iterative process with the first bullet point of rock glacier identification).

During the **second phase**, the team must:

- Document the rock glacier characteristics (attributes).
- Delineate the rock glacier outlines.

Each phase is divided into **three steps**:

- **Step 1:** Individual work by each team operator. At the end of this step, all the operators send their results to the PI.
- **Step 2:** Compilation and summary from the PI. At the end of this step, the PI has chosen a suggested solution to potential discrepancies between operators, to be discussed with the team.
- **Step 3:** Discussion and consensus-based final decision by the inventory team. At the end of this step, the team agrees to the intermediate (first phase) or the final outputs (second phase).

The exercise is performed in a generic QGIS-based tool with generic structure, files and a semi-automatic attribute filling system with dialog boxes. The procedure is detailed in *Annex 1*.

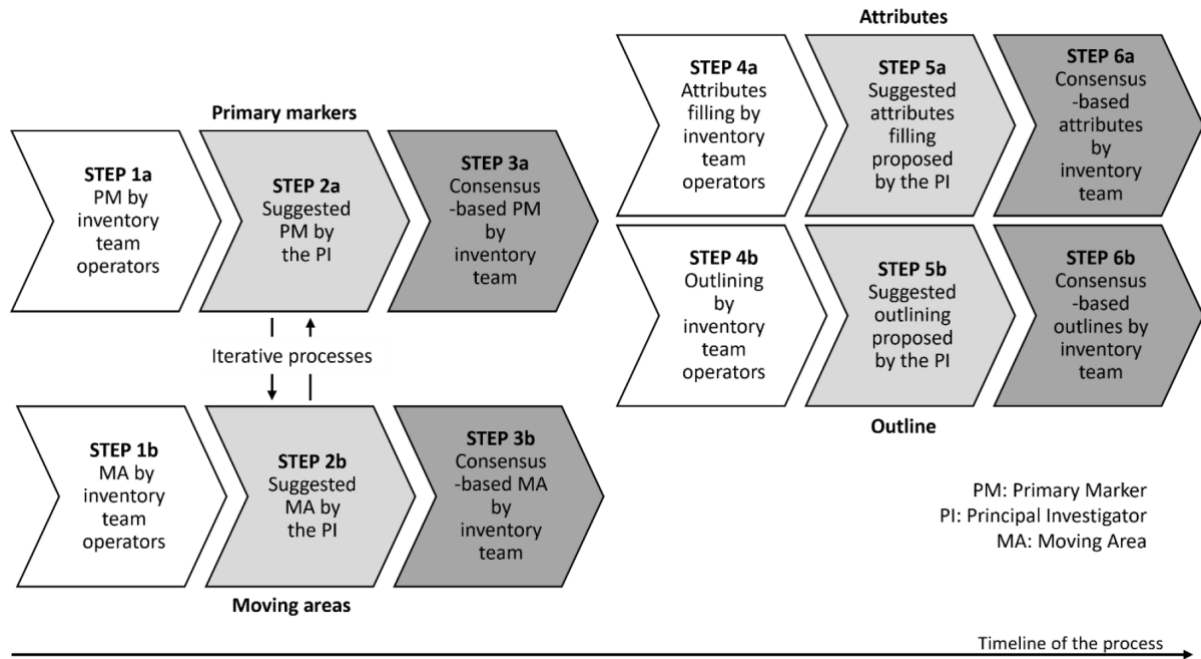


Figure 6. Summary of the main phases and steps of the consensus-based inventorying procedure.

3.1.2 Rock glacier identification

All recognized rock glacier units are identified with a point (primary marker, PM) in a vector layer named “*RGU_PrimaryMarkers_xxx**” (xxx being the number/name of the subarea). Relict rock glaciers are also included. Other landforms, such as debris-covered glaciers, moraines or landslides, are excluded. Orthoimages are the primary source of data used at this step, but additional available datasets can also be considered (e.g., topographic map, geological map, DEM). InSAR data can also be useful to detect or confirm the location of rock glaciers.

Based on the individual results of step 1a (*Figure 6*), the PI suggests a final solution and makes a suggested PM layer that will be discussed with the team (step 2a, *Figure 6*). The inventory team reviews the suggested PM layer, finds consensus if needed and approves the final PM locations (step 3a, *Figure 6*). The resulting layer will be used as a reference for next phase.

3.1.3 Moving area (MA) identification, delineation and characterization

The MA are identified, delineated and characterized based on InSAR data (see Section 4). The procedure is based on the updated version of the practical InSAR guidelines (v.4.0) “InSAR-based kinematic attribute in rock glacier inventories”, released in May 2023 on the RGIK website [RD-8] and available in *Annex 2* of the present document.

All recognized moving areas are identified with a polygon in a vector layer named “*MovingAreas_xxx**” (xxx being the number/name of the subarea). The attributes documenting the velocity class, the observation time window and validity time frame, the spatial representativeness and the reliability are filled using a semi-automatic dialog box. Based on the individual results of step 1b (*Figure 6*), the PI suggests a final solution and makes a suggested MA layer that will be discussed with the team (step 2b, *Figure 6*). The inventory team reviews the suggested MAs layer, finds

consensus if needed and approves the final MA outlines and velocity classes (step 3b, *Figure 6*). The resulting layer will be used as a reference for next phase.

3.1.4 Rock glacier characterization, incl. kinematic attribute (KA) assignment

The morpho-kinematic attributes characterizing the rock glacier units are filled using a semi-automatic dialog box in the final consensus-based PM layer from step 3a (see Section 3.1.2). The attributes are listed in Section 5. For the geomorphologic attributes, orthoimages are the primary source of data but additional available datasets can also be considered (e.g. topographic map, geological map, DEM). The kinematic attribute is based on the InSAR-based MA (see Section 3.1.3). The procedure to convert velocity information from the MA to a KA category is explained in the updated version of the practical InSAR guidelines (v.4.0) “InSAR-based kinematic attributed in rock glacier inventories”, released in May 2023 on the RGIK website [RD-8] and available in *Annex 2* of the present document.

Based on the individual results of step 4a (*Figure 6*), the PI suggests a final solution and makes a suggested PM layer with attributes that will be discussed with the team (step 5a, *Figure 6*). The inventory team reviews the suggested attributes, finds consensus if needed and approves the final results (step 6a, *Figure 6*). The resulting layer is the main final product of the inventorying process.

3.1.5 Optional rock glacier outlines

The extended and restricted rock glacier outlines are delineated with polygons in a vector layer named “*RGU_Outlines_xxx**” (xxx being the number/name of the subarea). For each polygon, attributes (outline type and reliability of the delineation) must be filled. The attributes are listed in Section 5.

Based on the individual results of step 4b (*Figure 6*), the PI suggests a final solution and makes a suggested Outlines layer with attributes that will be discussed with the team (step 5b, *Figure 6*). The inventory team reviews the suggested outlines, finds consensus if needed and approves the final rock glacier outlines (step 6c, *Figure 6*). The resulting layer is an additional (optional) product of the inventorying process.

3.2 Rock glacier velocity (RGV)

Permafrost_cci Phase 2 aims to generate standardized annualized RGV products, following the GCOS and user requirements [AD-3] [RD-2]. Based on InSAR technology, it requires to define a procedure to aggregate initial velocity data, both spatially (in a representative area of the rock glaciers) and temporally (in a consistent observation time window, during the snow-free season). The generic procedure recommended by RGIC is described in Section 3.2.1, while the InSAR-based method developed by the Permafrost_cci team is documented in Section 3.2.2–3.2.7. In the iteration 1 of Permafrost_cci Phase 2, the procedure was first tested on well-studied rock glaciers, with available in-situ measurements, to compare the relevance and reliability of the final RGV products using InSAR. In the iteration 2, we are updating the procedure accounting for the long-term objective of large-scale applicability and automation. The selected study sites are described in the PSD [RD-1]. In addition, in 2024, we designed an intercomparison exercise, during which a group of about 20 scientists is simultaneously processing RGV for three selected rock glaciers, using a set of three different techniques (in-situ, optical remote sensing, radar remote sensing). The exercise objectives and procedure are described in Section 3.2.8.

3.2.1 Generic procedure for RGV production

RGV is defined as a **time series of annualized surface velocity values expressed in m/yr and measured/computed on a rock glacier unit or a part of it** [RD-9]. RGV is computed for rock glacier units identified and located according to the inventorying guidelines [RD-7] and refers to observed surface velocities related to permafrost creep.

The annual surface velocity values that build up RGV are called **RGV values**. RGV values result from the spatial and/or temporal aggregation of measured/computed velocity data following a technique-dependent procedure. RGV values should be measured/computed as far as possible **each year**, following a **methodology that must be precisely documented and remains consistent over time**. The RGV monitoring strategy is proposed with respect to the [GCOS monitoring principles](#).

The production of RGV follows several steps from the design of the monitoring setup to the data acquisition and its transformation into the final RGV product. The term **initial data** refers to the surface velocity/displacement or positioning data obtained with the applied technique (here InSAR). Initial data are then converted into surface velocity values – the **velocity data** – and used for RGV processing.

To produce RGV, the following steps are required (*Figure 7*):

- **Design of the monitoring setup**, which controls initial data acquisition.
- **Initial data acquisition**, which yields initial data.
- **Initial data preparation**, which pre-processes and evaluates initial data, yielding quality-controlled initial data.
- **Velocity data processing**, which calculates and provides cleaned velocity data that can be used for RGV processing.
- **RGV processing**, which temporally and spatially sorts and aggregates the velocity data to produce RGV.
- **RGV consistency evaluation**, which evaluates the consistency of the RGV during the entire chain of RGV production and provides recommendations for long-term monitoring.

The generic requirements for RGV production are described in the RGV practical guidelines released by RGIC [RD-10]. In Sections 3.2.2–3.2.7, we focus on specific methodology designed for the InSAR technology for each step shown on *Figure 7*.

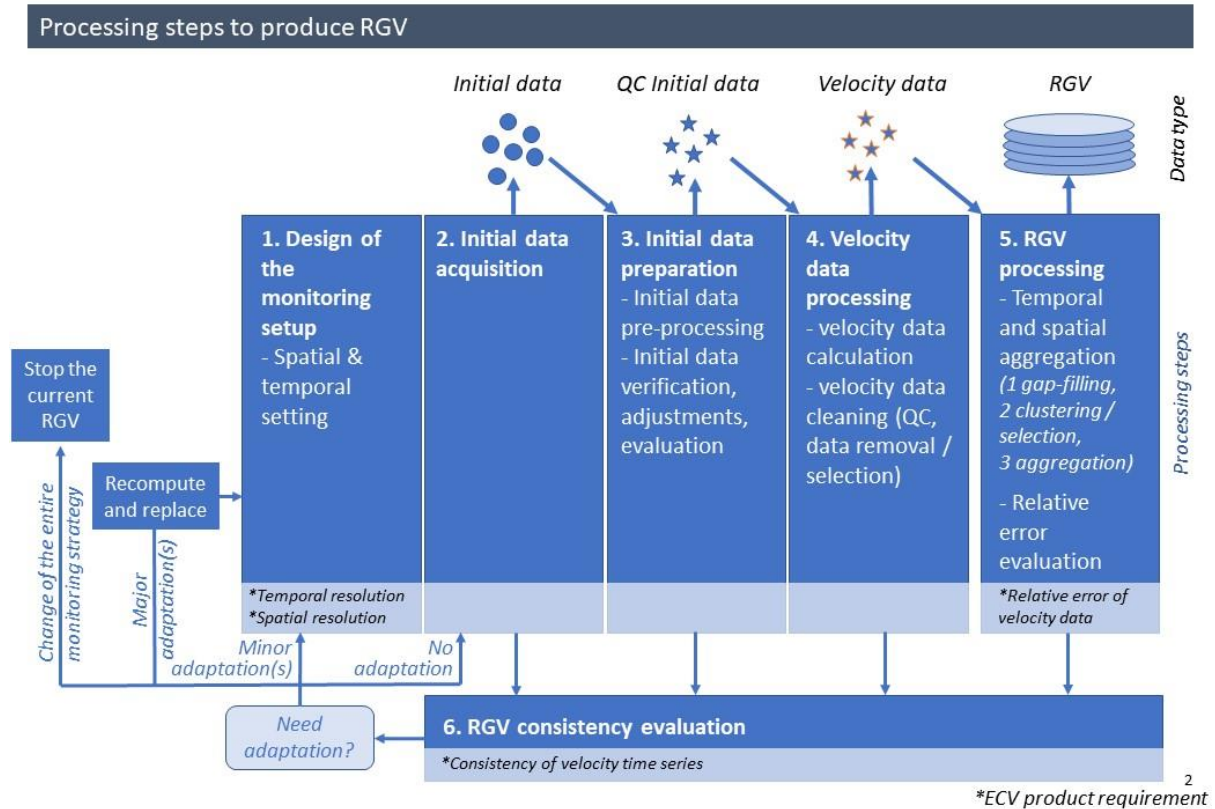


Figure 7. Summary of the processing steps required for RGV production [RD-10].

3.2.2 InSAR-based RGV production: Step 1 – Design of the monitoring setup

Verify the fulfilment of the RGV requirement for movement representing the rock glacier creep:

It is important to consider that the displacement phase term is measured in the satellite line-of-sight (LOS) direction. This means that only the movement component in the viewing direction is measured, and movement perpendicular to the LOS direction cannot be detected. The ideal viewing geometry must be selected based on the rock glacier orientation to ensure optimal measurement capabilities. To assess the suitability of InSAR for RGV generation, a layover-shadow mask must be generated, indicating regions that are not visible and thus not usable for InSAR analysis (see Section 2.3). For slope-parallel movement assessment, scale factors should be computed as a function of the slope orientation using a terrain model (recommended 2m DEM averaged over 200 m). A scale factor threshold of 4 is suggested, as larger values lead to increasingly unreliable velocity measurements. It is suggested to generate masks to identify the usable regions. The selected viewing geometry settings must be systematically documented in the RGV metadata and remain consistent over time.

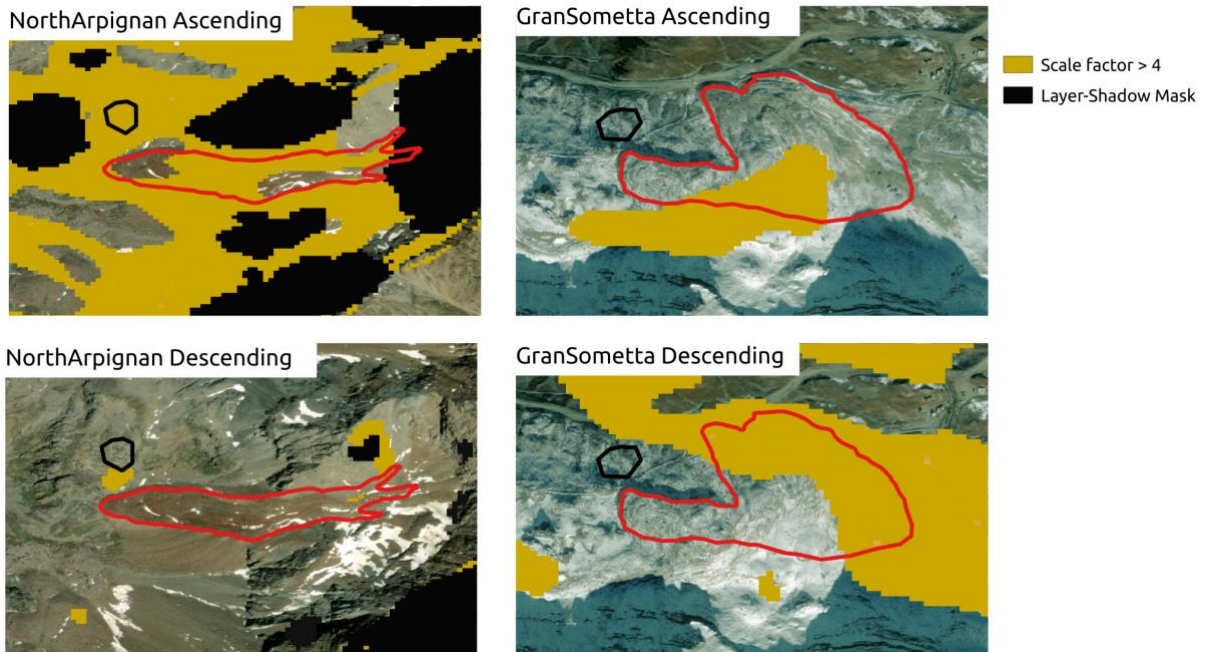


Figure 8. Layover-Shadow mask (black) and Scale factor (orange) greater than 4. Red polygons show the rock glacier outlines. Black polygons show the reference regions. The North Arpignan rock glacier is facing towards the West and the descending orbit provides favourable viewing conditions. The Gran Sometta rock glacier is facing towards the North and both orbits are favourable for different parts of the RG.

Verify the fulfilment of the RGV requirement for temporal resolution:

The ideal setup is to use a measurement frequency of once per year and an observation time window of 1 year with measurement dates/periods that remain approximately the same every year. However, using InSAR, this may not be possible due to data gaps in winter (snow cover) and velocity that is often too high to be able to connect the summer seasons with long interferograms (over the detection capability of half the wavelength of the sensor during the considered time period). A medium quality (breakthrough requirement, see *Table 8* in the PVSAR) can be achieved by aggregating velocity data during the summer seasons. The observation time window is < 1 year but the frequency is once per year. The observation time window must be at least 1 month and cover approximately the same period every year, with maximum +/- 15 days of difference. In case this requirement cannot be fulfilled due to environmental constraints associated with typical limitations of InSAR technology (e.g. near-perennial snow patches), the site must be discarded. The selected settings must be systematically documented in the RGV metadata and remain consistent over time.

Verify the fulfilment of the RGV requirement for spatial resolution:

The ideal spatial resolution is to use several spatially distributed measurement points or a continuously covered area allowing a complete understanding of the displacement field and the appropriate selection of the area to be considered in the RGV processing step. This is possible using InSAR technique, which theoretically allows for continuous coverage if the data is not affected by major limitations, such as layover/shadow, loss of coherence or unwrapping errors. In reality, however, as shown in *Figure 8*, part of the rock glacier is often discarded. The selected settings and area used for RGV generation must be systematically documented in the RGV metadata and remain consistent over time.

3.2.3 *InSAR-based RGV production: Step 2 – Initial data acquisition*

Download the SAR images:

All available Interferometric Wide (IW) swath mode Sentinel-1 SAR Single Look Complex (SLC) images are downloaded for at least one geometry. Ascending or descending geometries are chosen depending on the slope orientation of the site. The geometry providing the best LOS alignment with the considered slope is favoured (see Section 2.3 and *Figure 8*).

3.2.4 *InSAR-based RGV production: Step 3 – Initial data preparation*

Crop, coregister and multi-look the images:

The initial SLC are cropped around the selected rock glaciers. The SLC subsets are coregistered to a reference image. To reduce the speckle, improve the image quality and provide square pixels, multi-look is applied (e.g., 4x1 in range x azimuth, which results in pixels of approx. 15–20 m ground resolution).

Set the maximal temporal baseline:

All interferograms below a chosen temporal baseline (time interval between the pairs) are generated. The temporal baseline is chosen depending on the expected maximum velocity of the landform. Sentinel-1 had a 6-day repeat-pass between 2017 and 2021 and a 12-day repeat-pass in 2015–2016 and since 2022. The C-band wavelength (5.5 cm) enables the detection of LOS movement up to 1.7 m/yr with a 6-days interval and 0.8 m/yr with a 12-day interval. This can be determined by looking at the fringe and decorrelation patterns on wrapped interferograms. For rock glaciers moving close to or more than 1 m/yr, only 6-day interferograms are selected for the next steps. This will reduce the documented period to 2017–2021 (only one Sentinel-1 satellite available). If the landform is overall slower than 0.8 m/yr, 12-day interferograms can be used over the entire Sentinel-1 period (2015–). If the velocity is variable over the landform, the rock glacier can be divided into subareas and different temporal baselines can be applied.

Generate all interferograms:

Interferograms are generated for each pair equal or under the chosen maximum baseline. The topographic phase is removed using a digital elevation model (DEM). The noise level is reduced by applying a spatially adaptive coherence-dependent filter. The contribution from the stratified atmosphere is mitigated by fitting a linear relation between the residual phase and the topography. A reference point is selected close to the rock glacier in an area where the movement is assumed to be stable. The interferograms are unwrapped using a minimum cost flow algorithm. For each interferogram, coherence maps are generated. All subproducts (initial wrapped interferograms, atmosphere-filtered interferograms, unwrapped interferograms and coherence maps) can be geocoded. The quality of the interferograms is visualised to check the quality of the unwrapping and identify the location of the main moving area based on the displacement field.

Define a selection grid:

To select the velocity data that will be extracted, a grid following the extent of the moving area is defined. Ideally, at this stage, all pixels within the grid are selected but a lower density (e.g. every 40, 60, 80 m) can be chosen depending on the landform size and the processing resources. To map the extracted locations, the centre points of the pixels are extracted and converted to geographic coordinates. In the following, “points” refer to the centre points of the pixels.

3.2.5 InSAR-based RGV production: Step 4 – Velocity data processing

Compute velocity and coherence time series:

Using the unwrapped interferograms, LOS displacement time series relative to a reference point, along with coherence values, are extracted for each point on the grid. The LOS displacements during the interferogram time intervals are converted into LOS velocity in m/yr. Signal quality can degrade significantly during periods with snow cover or in regions where LOS velocities exceed half a phase cycle, resulting in low coherence values, increased uncertainties in LOS velocity measurements, and unwrapping errors. The degradation in signal quality becomes more pronounced with longer InSAR time intervals. To account for these error sources, valid time intervals and regions must be identified.

Define the Observation Time Window:

For choosing a valid observation time window, it is suggested to plot the time series of coherence values. To reduce noise, additional averaging windows (e.g., monthly averages) can be applied. A strong increase in coherence is typically visible when the area becomes snow-free. In fast-moving regions and for longer InSAR intervals, maximum coherence values may drop significantly (e.g., below 0.5), reducing the contrast between snow-covered and snow-free periods. However, these different conditions can generally still be distinguished. For rock glaciers in the Alps, a window between July and September often provides good data quality, but this varies by location and year. See *Figure 9* for an example. The chosen observation period should cover at least one month with approximately the same time each year (± 15 days). The chosen observation time window should be carefully documented to be able to similarly process future seasons.

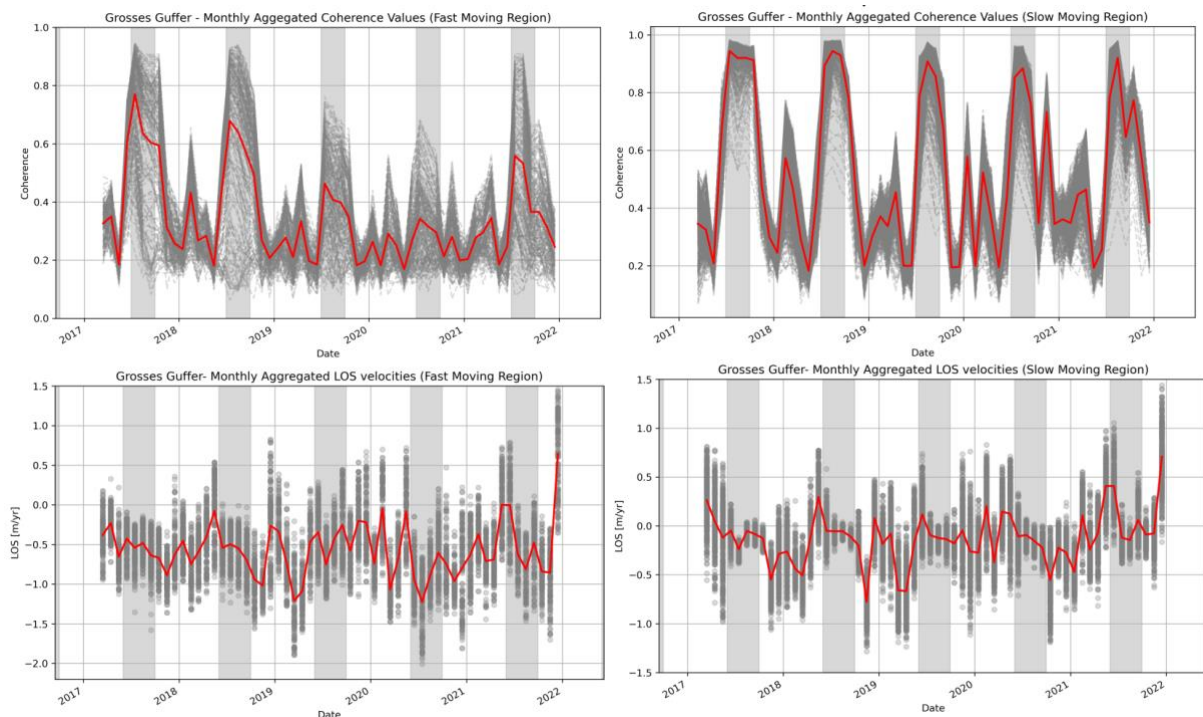


Figure 9. Example time-series of a fast moving (left) and slow moving (right) region on the Rock Glacier Grosses Gufer. The top row shows the coherence and the bottom row the LOS velocity aggregated by month. The faster moving regions shows a drop in coherence in 2019 and 2020 likely related to an acceleration. LOS velocities in these years should be checked carefully for potential unwrapping issues. The highlighted grey regions indicate the months from July to end of September.

Identify valid regions:

When identifying valid regions for velocity analysis, only observations within the chosen observation time window should be used. Regions with velocities exceeding half a phase cycle (~ 0.85 m/yr for a 6-day repeat cycle, ~ 0.42 m/yr for a 12-day repeat cycle) are prone to unwrapping errors. These errors are more likely to occur in areas with strong spatial velocity variations (abrupt transitions from slow to fast movement at the scale of the spatial resolution). To identify valid regions, several approaches can be used:

- Coherence-based thresholding:

Fast-moving regions tend to exhibit lower coherence. By setting a coherence threshold (e.g., 0.3) and counting the number of valid observations per point, regions with coherence drops can be identified. Regions with consistently low coherence or too few valid observations should be checked for unwrapping errors, and accordingly corrected or removed from the analysis. See *Figure 10* (top) for an example.

- Identification via time series visualisation of individual points:

Additionally, time series visualisation of LOS displacement for individual points can be used to filter remaining outliers. By plotting the LOS displacement over time, unwrapping errors – or sudden drops in coherence – can be visually detected. This approach allows for a more detailed identification of single remaining points or single problematic interferograms that can then be removed. See *Figure 10* (bottom) for an example.

- Identification via interferograms:

One option is to manually examine individual interferograms to identify fast-moving areas that experience unwrapping issues. Here also single erroneous observations can be identified and removed. However, this method is time-consuming and automated methods should be preferred with the objective of large-scale applicability. See *Figure 11* for an example.

Invalid regions should be masked in the further processing. The process of identifying valid regions should begin with the shortest available time interval (e.g., 6 days). Regions that have been identified as moving fast in the shorter interval (e.g., > 0.42 m/yr identified in the 6-day interval) can then be masked in longer intervals (e.g., 12 days). The removal of invalid regions can be revisited after the stacking/clustering steps if inconsistencies are found.

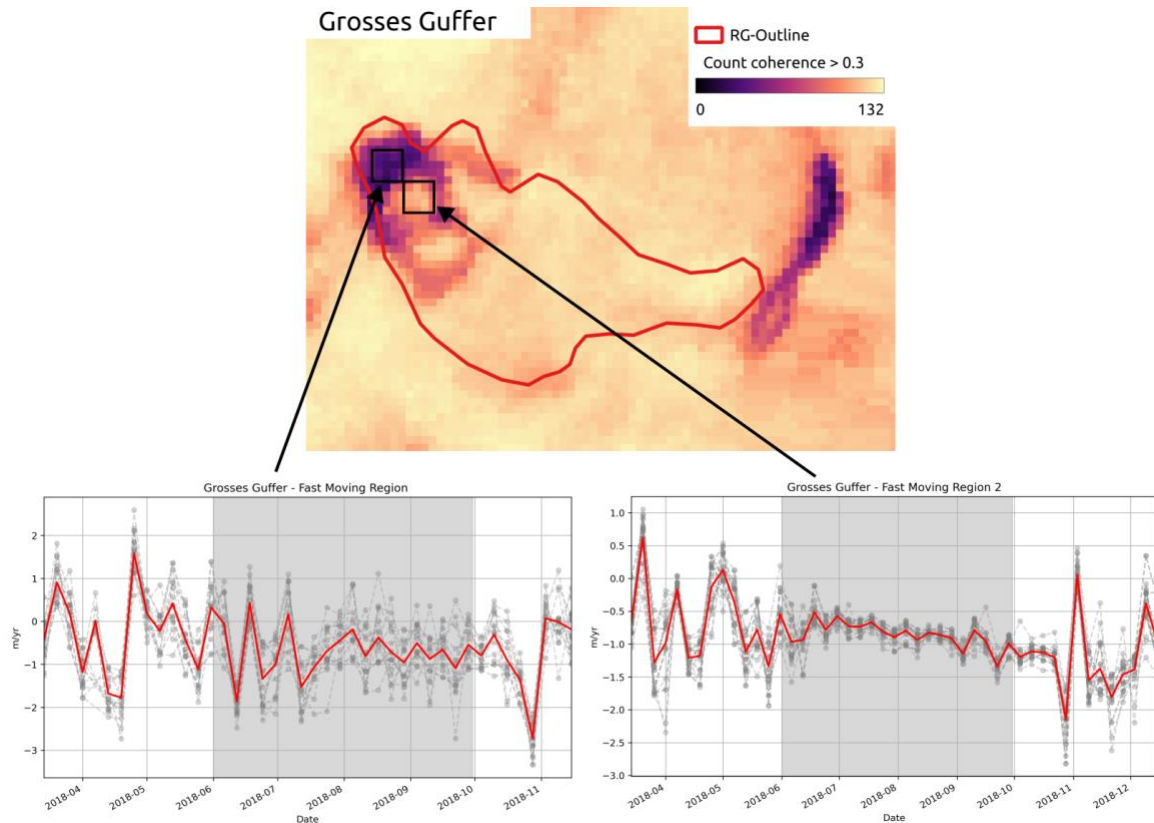


Figure 10: Rock Glacier Grosses Gufer. Top: Number of interferograms during the defined time-window with coherence values above a threshold of 0.3. Low coherence values indicate low InSAR data quality often related to fast movement. Bottom shows the time-series of measured InSAR displacements of two regions in 2018. The graph in the bottom-left shows large fluctuations of LOS velocities, indicating potential unwrapping issues. The graph in the bottom-right also shows high LOS velocities of about 1m/yr but the time-series shows only small variations indicating good data quality.

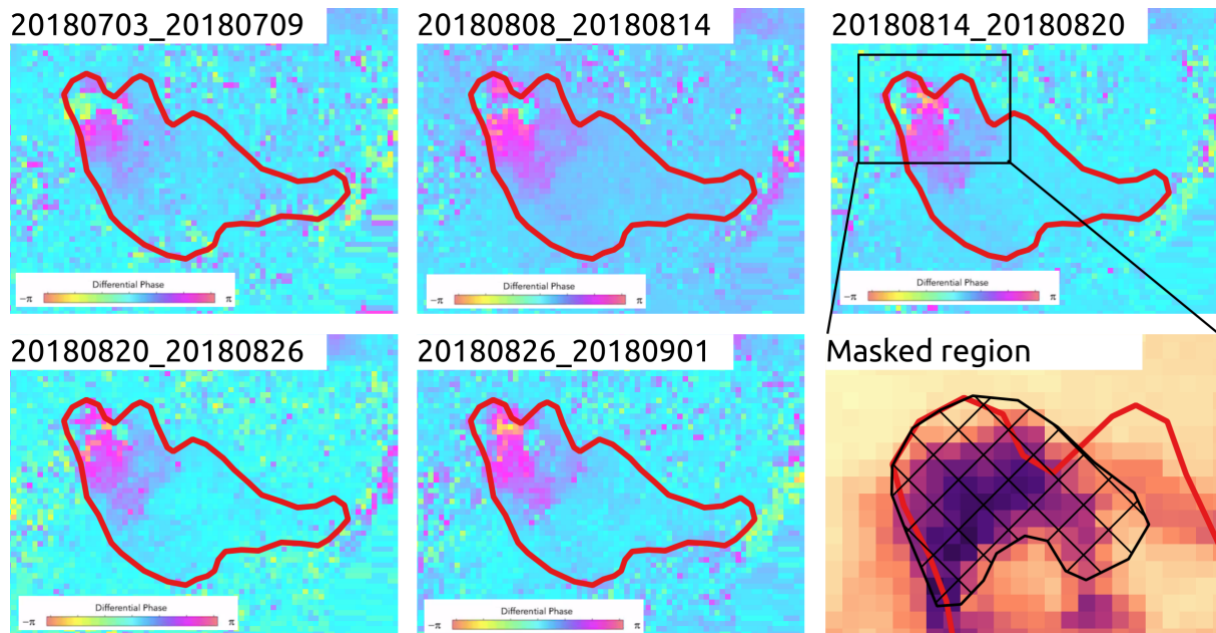


Figure 11. Examples of unwrapped phases of Grosses Gufer in 2018. The top left corner of the rock glacier shows unwrapping errors which need to be masked. An obtained masked based on this year is shown in the bottom right zoom in. The region is affected by low coherence values (purple background colour). For the final applied mask, all available years need to be checked.

Correct unwrapping errors:

In some cases, unwrapping errors can be corrected by limiting the range of allowed phase values within regions identified as problematic and repeating the phase unwrapping process (adding/subtracting a phase value of 2π in the unwrapped interferograms). This can recover valid regions by correcting unwrapping errors but requires careful monitoring and evaluation. Especially for small regions and if only few interferograms of the whole time series show errors, this approach is well suited (*Figure 12*).

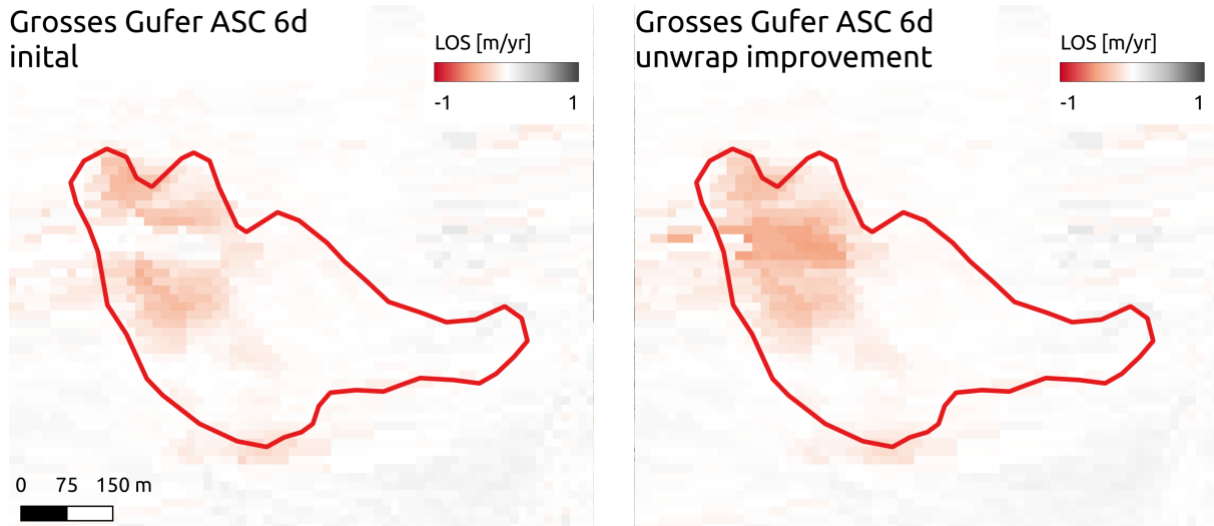


Figure 12. Multi-year average of LOS velocities of Grosses Gufer. By correcting the unwrapping error, a fast-moving region could be recovered. Nevertheless, a detailed analysis revealed that in the years 2019 and 2020 unwrapping errors are still present.

Average the results within the observation time window (stacking)

The quality of the estimated LOS velocities varies from InSAR pair to InSAR pair as well as in each interferogram from pixel to pixel. To use as many interferograms as possible but also exclude erroneous estimations, we employ two thresholding techniques. In a first step, the average coherence inside the rock glacier boundary is computed and a threshold is set for accepting an InSAR pair (e.g., 0.3). Secondly, a coherence threshold (e.g., 0.25) is used at the pixel level with an additional threshold on the minimum number of data points (e.g. 5). This results in regions of the rock glaciers that have a high number of valid velocity estimations, whereas other have a lower number. The averaging (stacking) is applied for each summer season. The used threshold values should be documented.

Normalize the velocity time series:

The yearly time series should then be normalized. For the normalization, we use the average over all available years and divide each yearly LOS velocity rate by this average. If this rate is below the noise level (approx. 0.2 m/yr for 6d and 0.1 m/yr for 12d), it leads to large fluctuations, and we remove these values from the analysis.

3.2.6 InSAR-based RGV production: Step 5 – RGV processing

Cluster the velocity time series:

Clustering algorithms can be used to relate regions with similar velocities or similar velocity changes together. Pixels of the rock glaciers can be grouped according to their behaviours. Agglomerative clustering can be used and is available in the python package scikit-learn (`sklearn.cluster.AgglomerativeClustering`). It is a hierarchical cluster method that starts with individual data points as clusters and iteratively merges them based on similarities. The silhouette score, ranging from -1 to 1, can be used to evaluate the clustering quality. Higher scores indicate better-defined clusters. This score also helps to determine the optimal number of clusters for our rock glacier velocity data, balancing between over-segmentation and over-simplification. Each cluster is plotted separately so that the locations of the corresponding points can be mapped. If spatial distribution and time series reveal uniform movement across the rock glacier, the cluster solution can be neglected, and all points are considered as one group. On the other hand, if the results are spatially clustered, this may indicate that the rock glacier is affected by contrasting behaviours. In such a case, the generation of two different RGV products may be required. Alternatively, areas affected by unrepresentative processes can be discarded. A high number of clusters also often indicates erroneous velocity estimations, and these regions should be checked again for errors and potentially be added to the mask. The clustering can be applied on the measured LOS velocities to identify fast- and slow-moving regions with a normalization afterwards, or directly on the normalized LOS velocities.

Generate the RGV product:

The final RGV product corresponds to the spatial aggregation of a certain number of points in a defined part of the rock glacier. Multiple RGVs are generated only if significant differences between different parts of the glacier are identified. The location of the selected points must be carefully documented to be able to process future seasons similarly. See an example of InSAR-RGV product for Gran Sometta rock glacier in *Figure 13*.Relative error estimation:

The relative error is estimated by calculating the ratio between the absolute error of a measurement and the absolute value measured/computed over the same observation time window. The estimated maximal measurement error is approx. 0.4 m/yr based on 6-days interferograms, 0.2 m/yr based on 12-days interferograms and decreasing accordingly using longer temporal baselines (Strozzi et al., 2020; Crosetto et al., 2009). The absolute velocity depends on the study site.

Gran Sometta Descending

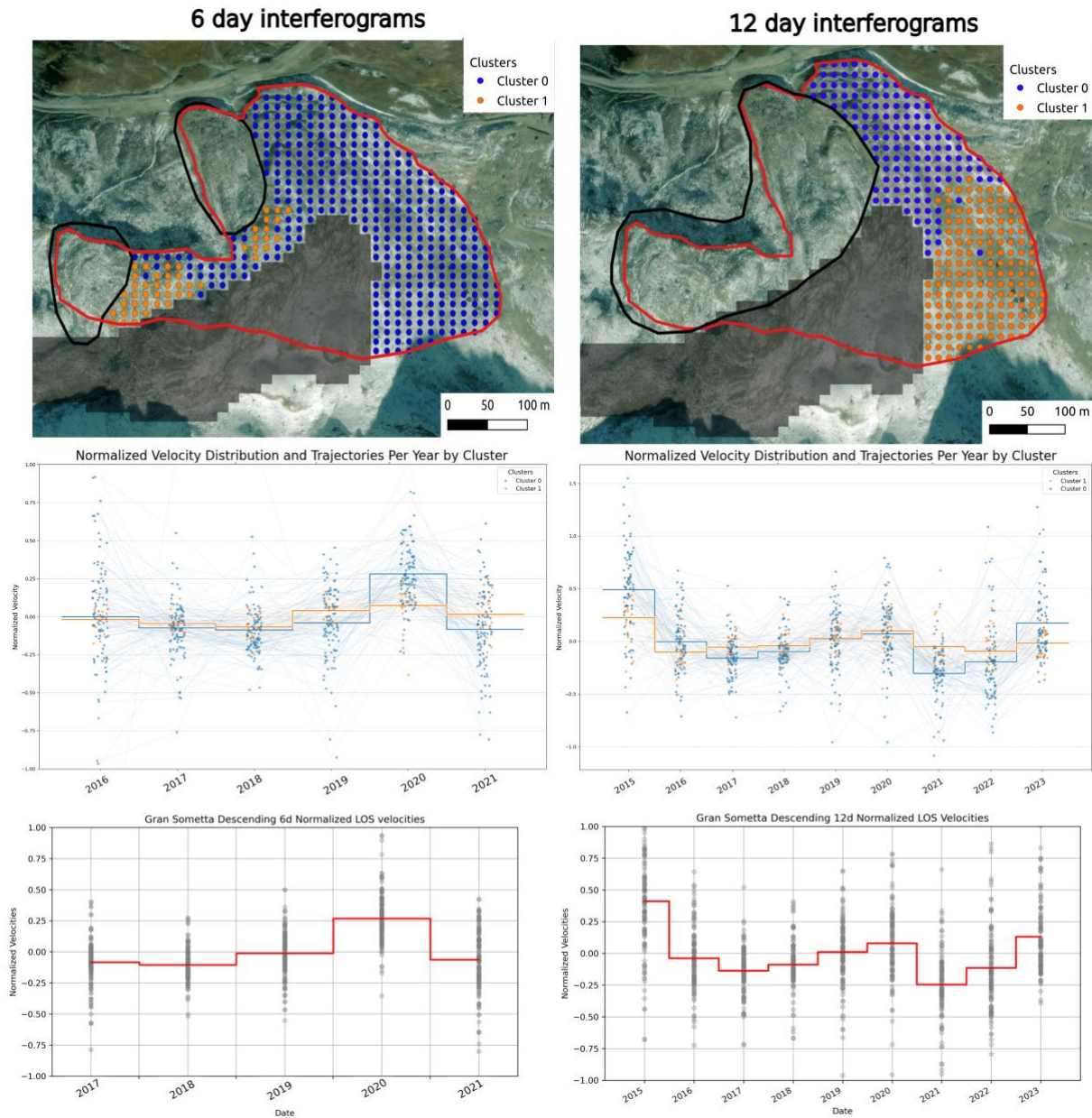


Figure 13. Example of final RGV product for Gran Sometta with observation from a descending orbit using either 6d or 12d interferograms. The top row shows the valid regions with clustering applied on the measured LOS velocities where the clusters indicate fast- and slow-moving regions. The black polygons have been identified as unreliable. The middle row shows the normalized change. The differences between the clusters are small. The bottom row shows the final RGV product with the changes over the years.

3.2.7 *InSAR-based RGV production: Step 6 – RGV consistency evaluation*

The consistency of the velocity time series is defined as the stability of the time series measurement procedure and quality over time. During Permafrost_cci Phase 2, the time series will be processed once. The monitoring technique and the monitoring surface will remain the same. As long as the procedure above is applied systematically, with a constant temporal baseline and observation time window, the consistency is expected to be high.

3.2.8 *RGV intercomparison exercise*

The current RGV guidelines are meant to be generic (technique-independent). However, it is still unclear if these requirements are suitable to all conditions and applicable measurement techniques or if adjustments/complements are needed. To answer this question, we brought together a group of scientists with good experience in the field, to simultaneously generate RGV on similar landforms, intercompare results using various methods and identify concrete issues occurring during the production. The RGV working group has been kicked-off in April 2024 and consists of approx. 20 people. The first task of the working group is to perform an intercomparison exercise for RGV production. In the future, the RGV working group is expected to be included in the RGIK activities, with the long-term mission to promote and foster the production, dissemination, and exploitation of RGV as climate change indicator.

Concretely, the objectives of the RGV intercomparison exercise are to:

- Bring together a group of people currently working with rock glacier velocity time series and/or linked to the related projects (CCI Permafrost and ORoDaPT).
- Apply the current guidelines to produce RGV on selected rock glaciers, using three sets of applicable techniques (in-situ measurements, optical remote sensing, radar remote sensing).
- Compare the results from different people within and between the three sets of techniques (in-situ, optical or radar).
- Identify differences, problems in the recommended workflow and/or lack of clarity in the guidelines. Refine the RGV procedure and improve the guidelines & ECV requirements.
- Elaborate strategies to interpret and exploit RGV as climate change indicator. In regions with extensive RGV collection, discuss how to produce regional indices describing (dis)similar velocity changes.

Timeline 2024:

- **Early July:** Work instructions and data folder sent to the participants.
- **15th of August:** Deadline for registration in one (or more) technical subgroup.
- **July to early September:** Individual work of the participants – read the guidelines, get known with the data collection, perform first processing tests.
- **Early September:** Digital meeting of each technical subgroup to remind the objectives, answer to questions and kick-off the actual work. Communication on the preliminary workshop programme and registration procedure.
- **Early September to early November:** Individual work of the participants – RGV production.
- **Early November:** Short summary reports on RGV results sent to each subgroup coordinator.
- **Early to end of November:** Finalisation of the workshop detailed programme.
- **20–22 November:** RGV workshop in Fribourg, Switzerland.

Technical groups:

- **In-situ group:** The group participants will use annual GNSS data to derive RGV. Two levels of data are provided: E-N-H positions for all measured points, and calculated velocity for all measured points.
- **Optical group:** The group participants will use aerial optical images acquired by manned or unmanned aircrafts to derive RGV. Two levels of data are provided: orthorectified images or DEM, and displacement fields (raster or vector format).
- **Radar group:** The group participants will use Sentinel-1 Synthetic Aperture Radar (SAR) images to derive RGV. Synthetic Aperture Radar Interferometry (InSAR) or SAR offset tracking can be used for this purpose. One level of data is provided by Gamma Remote Sensing AS: coregistered Single Look Complex (SLC) images.

Selected rock glaciers and data collection:

Rock glacier name/country	Lat/Long coordinates	In-situ data	Optical data	Radar data	Velocity range	Slope orientation
Gran Sommetta (IT)	45.921428 N 7.669550 E	Annual since 2012	Annual UAV from 2013	Sentinel-1 coregistered SLC images 2014-2024	0.2–2 m/yr	NNW
Grosses Gufer (CH)	46.425292 N 8.083018 E	Annual since 2007	Aerial images from the 50ties		0.2–5 m/yr	NW
Laurichard (FR)	45.018091 N 6.399865 E	Annual since 2000			About 1 m/yr	N

Workshop programme:Wednesday 20.11.2024:

- Morning: Introduction. Reminder on objectives. Past-current research in the field.
- Afternoon: Group discussion (in-situ / optical / radar). Comparison of RGV results on the selected sites and technical discussion.

Thursday 21.11.2024:

- Morning: Plenary discussion. Summary of Day 1 by the group coordinators. Discussion on discrepancies within the groups and technical recommendations.
- Afternoon: Plenary discussion. Discussion on discrepancies between the groups. Identified issues with the current guidelines/requirements.

Friday 22.11.2024:

- Morning: Wrap-up. Next steps. Regional indices as climate change indicators.

4 Required input data

Input data required for the generation of the two Permafrost_cci Phase 2 mountain permafrost products are summarized in *Table 2*. Validation data are described in the PVP.

Table 2. Required input data for the development of the Permafrost_cci mountain permafrost products.

Data class	Data type	Source	Spatial coverage	Temporal coverage	Repeat periodicity	Availability
Production RoGI/RGB (SAR data, required)	Sentinel-1 SAR SLC images	ESA	All subareas and pilot sites	2015–2022 Depending on the subarea	6/12 days Depending on the subarea	Freely available
Production RoGI (SAR data, required)	Sentinel-1 SAR interferograms	CCI+ Permafrost	All subareas	2015–2022 Depending on the subarea	6 days to one year	CCI+ Permafrost consortium
Production RoGI (SAR data, optional)	Interferograms from other SAR sensors (ALOS, SAOCOM, TSX, COSMO-SkyMed, ERS)	CCI+ Permafrost	ALOS1-2: All subareas except in Norway SAOCOM: Central Andes TSX: Western Swiss Alps, Brooks Range COSMO-SkyMed: Southern Venosta ERS1-2: Tien Shan, Brooks Range	ALOS1-2: 2006-2021 SAOCOM: 2021-2022 TSX: 2009-2014 COSMO-SkyMed: 2016-2019 ERS1-2: 1991-1999	1 days to several years	CCI+ Permafrost consortium
Production RoGI (SAR data, optional)	InSAR Stacking based on Sentinel-1 interferograms	CCI+ Permafrost	All subareas, except Disko, New Zealand, Brooks Range, Tien Shan	2015–2022 Depending on the subarea	6/12 days to one year Depending on the subarea	CCI+ Permafrost consortium
Production RoGI (SAR data, optional)	PSI based on Sentinel-1 interferograms	InSAR Norway	Finnmark (Norway) subarea	2015–2021	6 days to several years	Freely available
Production RoGI (SAR data, optional)	PSI based on Sentinel-1 interferograms	CCI+ Permafrost	Carpathians (Romania) subarea	2015–2021	6 days to several years	CCI+ Permafrost consortium
Production RoGI/RGB (optical, required)	DEM	mixed	All subareas and pilot sites	Irregular	Single dates	CCI+ Permafrost consortium

Production RoGI/RGB (optical, required)	Orthoimagery (satellite/aerial)	mixed	All subareas and pilot sites	Irregular	Single dates	CCI+ Permafrost consortium
Production RoGI/RGB (optical, required)	Google Earth™/ Bing imagery	Google Earth	All subareas and pilot sites	Irregular	Single dates	Freely available
Production RoGI Previous outputs (required)	RoGI from Phase 1	CCI+ Permafrost	All subareas	Irregular	Irregular	CCI+ Permafrost consortium

5 Output products

Two products are considered in Permafrost_cci Phase 2:

- Rock glacier inventories (RoGI)
- Rock glacier velocity time series (RGV)

Product specifications and formats are described in detail in the PSD [RD-1]. We present in *Table 3*, *Table 4* and *Table 5* the attributes associated with the three outputs of the RoGI procedure (see Section 3.1). *Table 6* shows the attributes of the RGV products (see Section 3.2).

Table 3. Attribute table of the RoGI output [RGU_PrimaryMarkers] (M: mandatory attribute; O: optional attribute). Output layers are identified with square brackets (e.g. [RGU_PrimaryMarkers]), attributes with double quotation marks (e.g. "PrimaryID") and values with single quotes (e.g. 'Talus-connected'). The last column refers to the sections of the RGIK guidelines documenting the recommendations to assign the values of each attribute.

Attribute	Description	Values	Related guidelines
Metadata			
Landform (M)	This attribute allows the operators to point out some landforms that look like rock glaciers but which are not. 'Uncertain rock glacier' is an option in case of suspected rock glacier but still uncertain based on the available data. 'Rock glacier' is the default value.	Rock glacier Not a rock glacier Uncertain rock glacier	RoGI guidelines chap. 3 (sections 3.1 and 3.7) RoGI guidelines chap. 5 (section 5.1)
Comment	Comments regarding the primary marker.	Text (250 characters maximum)	
fid (M)	Unique identifier of the primary marker.	Automatic filling	
PrimaryID (M)	RGU + 12 to 15 digits depending of "Lat.", "Long" values. Always 4 digits after the degrees. (e.g. RGU34567S123456E means 3,4567° South and 12,3456° East)	Automatic filling	RoGI guidelines chap. 5 (section 5.2)
Lat. (M)	Latitude of the Primary Marker in decimal degrees.	Automatic filling	
Long. (M)	Longitude of the Primary Marker in decimal degrees.	Automatic filling	
WorkingID (O)	Practical identifier chosen by the operator (e.g. TYR001, TYR002, ... for an inventory in Tyrol).	Text	
Alter.ID1 (O)	Alternative local or regional name	Text	
Alter.ID2 (O)	Identifier used in a previous inventory.	Text	
Polygon attributes			
Assoc.RGS (M)	Defines if the Primary Marker is part of a mono-unit system ('Mono-unit RGS') or a multi-unit system ('Multi-unit RGS').	Mono-unit RGS Multi-unit RGS	RoGI guidelines chap. 3 (section 3.2)
Morpho.	Defines if the rock glacier identified by the primary marker is a rock glacier with simple or complex morphology.	Simple Complex	RoGI guidelines chap. 3 (section 3.2) RoGI guidelines chap. 5 (section 5.3)
Upsl.Con.	Defines the geomorphological unit directly located upslope of a rock glacier unit or system (5 categories). When dealing with uncertain or intermediate situations, 4 additional categories are included: 'Poly-connected', 'Other', 'Uncertain' and	Talus-connected Debris-mantled slope-connected Landslide-	RoGI guidelines chap. 3 (section 3.3) RoGI guidelines chap. 5 (section 5.3)

	'Unknown'. See related documentation for further information.	connected Glacier-connected Glacier forefield-connected Poly-connected Other Uncertain Unknown	
Upsl.Cur.	Defines if the rock glacier is currently connected to the upslope unit or not.	Yes No Uncertain Unknown	RoGI guidelines chap. 3 (section 3.3) RoGI guidelines chap. 5 (section 5.3)
Upsl.Comment	Comment on possible poly-connection and uncertainty	Text	
Compleat.	Defines if the rock glacier identified by the primary marker is completely visible or not. 'No, Ups.Con' means that it is not complete due unclear upslope connection (e.g. overlapping of several rock glaciers generations). 'No, truncated front' means that it is not complete due to truncated front. 'Uncertain' when data or analysis do not allow to decide.	Yes No unclear connection to the upslope No, truncated front Uncertain	RoGI guidelines chap. 5 (section 5.3)
Acti.Ass.	Define how the activity assessment was performed: based on geomorphologic evidence only or with additional kinematic data.	Geomorphologic Kinematic	RoGI guidelines chap. 3 (section 3.4) RoGI guidelines chap. 5 (section 5.3)
Kin.Att.	Kinematic attribute assigned to the rock glacier. <u>Only if "Acti.Ass." is 'Kinematic'.</u>	Undefined < cm/a cm/a cm/y to dm/a dm/a dm/a to m/a m/a > m/a	RoGI guidelines chap. 6 (sections 6.1, 6.2 and 6.3)
Rel.Kin.	Reliability of the assignment of the KA <u>Only if "Acti.Ass." is 'Kinematic'</u>	Low Medium High	RoGI guidelines chap. 6 (sections 6.1, 6.2 and 6.3)
Kin.Period	Period of the data used to assign the kinematic attribute (e.g. 2018-2020). <u>Only if "Acti.Ass." is 'Kinematic'.</u>	yyyy-yyyy	RoGI guidelines chap. 6 (sections 6.1, 6.2 and 6.3)
TypeOfData	Type of data used for kinematic assessment. Use "Kin.Comment" if you want to add more details about the type of data used (e.g. InSAR or SAR offset tracking for 'Radar'). <u>Only if "Acti.Ass." is 'Kinematic'.</u> 'Other' can be used with there is a combination of methods (add comments in "Kin.Comment").	Optical Radar Lidar Geodetic Other	RoGI guidelines chap. 6 (sections 6.1, 6.2 and 6.3)
Kin.Comment	Comment regarding kinematic information, data type	Text	

	and quality, spatial representativeness, etc. Especially when the reliability is low-medium.		
Acti.Cl.	Activity class assigned to the rock glacier. See related documentation for further information. <u>Already pre-filled if “Kin.Att.” is filled.</u> However, it is also possible to change the value manually from the drop-down list. <i>e.g.</i> in case of low reliability of the kinematic attribute due to unideal slope orientation (N/S) compared to InSAR LOS measurements, the “Kin.Att.” may not be representative of the real activity of the rock glacier (based on geomorphologic evidences).	Active Active uncertain Transitional Relict uncertain Relict Uncertain	RoGI guidelines chap. 3 (section 3.4) RoGI guidelines chap. 5 (section 5.3) RoGI guidelines chap. 6 (sections 6.1, 6.2 and 6.3)
Destabili.	Describes if the rock glacier unit is (ongoing) or has been (completed) destabilized.	Yes, ongoing Yes, completed No Uncertain	RoGI guidelines chap. 3 (section 3.5) RoGI guidelines chap. 5 (section 5.3)

Table 4. Attribute table of the RoGI output [MovingAreas] (M: mandatory attribute; O: optional attribute). Output layers are identified with square brackets (e.g. [MovingAreas]), attributes with double quotation marks (e.g. “MA.ID”) and values with single quotes (e.g. ‘30-100 cm/yr’). The recommendations to assign the values of each attribute are documented in [RD-7] (also available in Annex 2).

Attribute	Description	Values
Metadata		
Fid (M)	Unique identifier of the polygon.	Automatic filling
MA.ID. (M)	MA + 12 to 15 digits depending of “Lat.”, “Long” values. Always 4 digits after the degrees. (<i>e.g.</i> MA34567S123456E means 3,4567° South and 12,3456° East)	Automatic filling
WorkingID (O)	Practical identifier chosen by the operator (e.g. MA_TYR001, TYR002, ... for a moving areas inventory in Tyrol).	Text
Ref.PrimaryID (O)	PrimaryID of the related rock glacier unit in the [RGU_PrimaryMarkers] table.	Text
Polygon attributes		
Vel.Class	Velocity class: variable characterizing the surface displacement rate. Using InSAR, it refers to velocity observed in the LOS during a specified observation time window (“Time.Obs”).	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)
Time.Obs.	Sensor type used to perform the characterization is documented here. Observation time window (period during which the detection and characterization is computed/measured, i.e. which months/seasons), and temporal frame (total duration during which the periodic measurements/computations are repeated and aggregated for defining the moving area, i.e.	Text containing: SENSOR(s)_OBSERVATION-TIME-WINDOW_TEMPORAL-FRAME e.g. with InSAR data: S1 Summer Y1–Y2 (velocity observed from Sentinel-1 with an observation time window in summer, each year between year Y1 to year Y2)

	which year(s)).	<p>TSX Summer Y1, Y2, ... (velocity observed from TerraSAR-X with an observation time window in summer, at year Y1, year Y2, etc.)</p> <p>CSK Annual Y1–Y2 (velocity observed from Cosmo-SkyMed with an observation time window of one year, each year in between year Y1 to year Y2)</p> <p>ALOS 08–10 Y1–Y2 (velocity observed from ALOS with an observation time window between August and October each year between year Y1 and year Y2)</p> <p>S1 Summer Y1–Y2 and TSX 10 Y3 (velocity observed from (i) Sentinel 1 with an observation time window in summer, each year between year Y1 to year Y2 + (ii) TerraSAR-X with an observation time window centred in October of the year Y3)</p> <p>Note: - “Summer” period must be described into the metadata, and it should be at least 2–3 months</p>
Rel.MA	Reliability of the detected moving areas.	<p>0. Low: signal interpretation (velocity estimation) <u>and</u> outline are uncertain but there is evidence of movement that needs to be considered.</p> <p>1. Medium: signal interpretation (velocity estimation) <u>or</u> outline is uncertain.</p> <p>2. High: obvious signal, best appropriate configuration (back-facing slope)</p>
Comment	Comments regarding the detection and characterization (if needed).	Text (250 characters maximum)

Table 5. Attribute table of the RoGI output “RGU_Outlines” (M: mandatory attribute; O: optional attribute). Output layers are identified with square brackets (e.g. [RGU_Outlines]), attributes with double quotation marks (e.g. “PrimaryID”) and values with single quotes (e.g. ‘Extended’). The last column refers to the sections of the RGIK guidelines documenting the recommendations to assign the values of each attribute.

Attribute	Description	Values	Related guidelines
<i>Metadata</i>			
Fid (M)	Unique identifier of the polygon.	Automatic filling	
PrimaryID (M)	Unique identifier of the rock glacier unit in the table [RGU_PrimaryMarkers]. The digitized polygon in this table is necessarily associated to the previously created Primary Marker (point geometry). The “PrimaryID” must, therefore, be the same as the associated Primary Marker.	Automatic filling	RoGI guidelines chap. 5 (section 5.2)
WorkingID (O)	Practical identifier chosen by the operator (e.g. TYR001, TYR002, ... for an inventory in Tyrol).	Text	
<i>Polygon attributes (optional)</i>			
Out.Type	Outline type.	Extended	RoGI guidelines chap. 3

		Restricted Other	(section 3.6) RoGI guidelines chap. 5 (section 5.4)
RelFr	Reliability of the front outline digitalization.	2 (High) 1 (Medium) 0 (Low)	RoGI guidelines chap. 5 (sections 5.4.1 and 5.4.4)
RelLeftLM	Reliability of the left lateral margin (i.e. orographic perspective) outline digitalization.	2 (High) 1 (Medium) 0 (Low)	RoGI guidelines chap. 5 (sections 5.4.2 and 5.4.4)
RelRightLM	Reliability of the right lateral margin (i.e. orographic perspective) outline digitalization.	2 (High) 1 (Medium) 0 (Low)	RoGI guidelines chap. 5 (sections 5.4.2 and 5.4.4)
RelUpsCon	Reliability of the upslope connection outline digitalization.	2 (High) 1 (Medium) 0 (Low)	RoGI guidelines chap. 5 (sections 5.4.3 and 5.4.4)
RelIndex	Outline reliability index summing the values assigned to the reliability attributes “RelFr”, “RelLeftLM”, “RelRightLM” and “RelUpsCon”.	Automatic filling From 0 (Low) to 8 (High)	RoGI guidelines chap. 5 (section 5.4.4)
Comment	Comments regarding the outline.	Text (250 characters maximum)	

Table 6. Structure and documented metadata of the RGV product.

<i>For each RGV time series</i>	
ID	Unique alpha-numerical identifier of the RGV time series)
Reference ID of the related rock glacier unit	When a RoGI is available
Data/technique	Description of the platform, sensor type and processing approach
Area considered for RGV processing	Area-based, several discrete points, three discrete points or single discrete point, and related specifications
Start date	Date of first observation
Velocity data	Computed RGV data in m/y
<i>For each annual increment of the RGV time series</i>	
ID	Unique alpha-numerical identifier of the RGV data
Reference ID of the entire RGV time series	Reference of the entire RGV time series
Start date	Start date of the observation time window
End date	End date of the observation time window
Base data	Data/platform/sensor used for the data acquisition
Velocity data	Computed RGV data in m/y
Relative error of the velocity data	Ideal: < 5% Medium: 5-15% Minimal: 15-20%
Consistency of the RGV time series	Ideal: no problem with newly added velocity data Medium: problems with newly added velocity data but no major change of procedure High: problems with newly added velocity data and major change of procedure
Comments	Documentation of any changes or specific aspect of the data production worth archiving and relevant for the data analysis and usage

6 Practical considerations for implementation

The main basic concept behind the development of the RoGI and RGV products, in line with the RGIK recommendations, is to propose a methodology that allows for upscaling of the systematic investigation of mountain permafrost and specifically the mapping and monitoring of rock glaciers by different research teams around the globe.

Despite the standards presented in the PSVAR and the processing lines described in the present document, several challenges are identified. These will be continuously assessed throughout the project duration. They can be summarized into three elements:

- **Risks of discrepancies regarding the geomorphological elements of RoGI products:**
The properties of the input data (e.g. DEM and orthophoto resolution) vary depending on the study areas and may affect the comparability of the results. In addition, despite the objectives to provide international standards that are similarly applicable in any mountain range, the variability of the environmental contexts and landform types may highlight a need for defining different RoGI practices. The results from Permafrost_cci RoGI processes are expected to contribute to further adjustments of the dedicated RGIK practical guidelines [RD-5].
- **Risks of discrepancies regarding the kinematic elements of RoGI products:**
The amount and availability of the InSAR data vary depending on the study areas (e.g. every 6 or 12 days for Sentinel-1 between 2018 and 2022, availability of SAR images from X- and L-band sensors). In addition, the different environmental contexts between the selected regions lead to various rock glacier kinematics and activities (e.g. low velocity in the Carpathians vs. high velocity in the Alps), which may require an adaption of the processing strategy to the specific regional needs. The results from Permafrost_cci RoGI processes are expected to contribute to further adjustments of the dedicated RGIK practical guidelines [RD-6] [RD-7].
- **Risks of discrepancies regarding the generation of RGV products:**
The definition of technique-independent standards for the generation of comparable RGV is recent [RD-9] [RD-10] and may evolve in the coming months and years. In Permafrost_cci, we aim to highlight that InSAR technique are able to generate similar RGV products (i.e. document similar interannual velocity trends) compared to available in-situ measurements at the same pilot sites (see PVP). Depending on the conclusions of the Permafrost_cci first iteration, the RGV procedure described in Section 3.2 may be adjusted to fulfill this objective. Currently, the workflow includes several steps for which subjective decisions have to be made (e.g. identify valid regions, threshold values for the stacking) which can result in discrepancies. These decisions are also challenging in regard to the implementation of an automated RGV processing chain. The results of the RGV intercomparison exercise and related discussions at the RGV workshop in November 2024 may help solving some open questions regarding the chosen processing criteria.

The identified challenges and risks of discrepancies in the final products will be assessed in the future deliverables, especially in the Product Inter-comparison and Validation Report (PVIR).

7 References

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7.2 Acronyms

AD	Applicable Document
AI	Artificial Intelligence
ALT	Active Layer Thickness
ADP	Algorithm Development Plan
ATBD	Algorithm Theoretical Basis Document
BR	Breakthrough Requirement
CAR	Climate Assessment Report
CCI	Climate Change Initiative
CCN	Contract Change Notice
CRDP	Climate Research Data Package
DEM	Digital Elevation Model
E3UB	End-to-End ECV Uncertainty Budget
ECV	Essential Climate Variable
EO	Earth Observation
ESA	European Space Agency
FT	Feature Tracking
GAMMA	Gamma Remote Sensing AG
GCOS	Global Climate Observing System

GNSS	Global Navigation Satellite System
GR	Goal Requirement
GT	Ground Temperature
GTN-P	Global Climate Observing System
GTOS	Global Terrestrial Observing System
IANIGLA	Instituto Argentino de Nivología, Glaciología y Ciencias Ambientale
InSAR	Interferometric Synthetic Aperture Radar
IPA	International Permafrost Association
KA	Kinematic Attribute
LOS	Line-of-sight
MA	Moving Area
MAGT	Mean Annual Ground Temperature
MAGT	Mean Annual Ground Surface Temperature
NORCE	Norwegian Research Centre AS
OT	Offset Tracking
PERMOS	Swiss Permafrost Monitoring Network
PI	Principal Investigator
PM	Primary Marker
PSD	Product Specification Document
PUG	Product User Guide
PVASR	Product Validation and Algorithm Selection Report
PVIR	Product Validation and Intercomparison Report
PVP	Product Validation Plan
RD	Reference Document
RG	Rock Glacier
RGIK	Rock Glacier Inventories and Kinematics
RGU	Rock Glacier Unit
RGV	Rock Glacier Velocity
RoGI	Rock Glacier Inventory
RMSE	Root Mean Square Error
SAR	Synthetic Aperture Radar
SfM	Surface from Motion
TR	Threshold Requirement
UAV	Unmanned Aerial Vehicle
UiO	University of Oslo
UniBo	University of Bologna
UNIFR	University of Fribourg
URD	Users Requirement Document
URq	User Requirement
UTM	Universal Transverse Mercator
WUT	West University of Timisoara
WMO	World Meteorological Organization

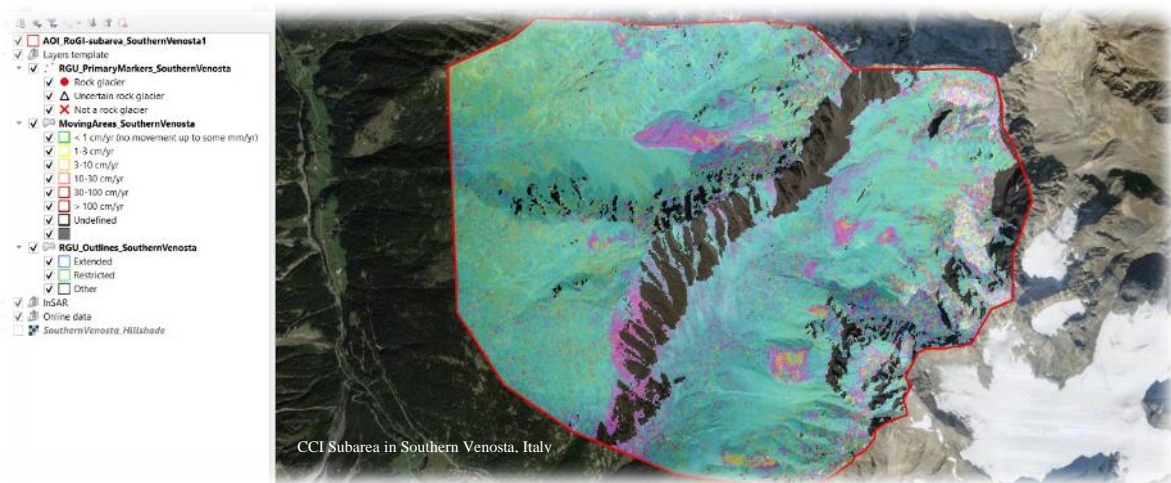
Annex 1:

RoGI procedure using a generic GIS tool



ESA CCI+ Permafrost

Consensus-based Rock Glacier Inventory (RoGI) procedure using a generic GIS tool



<https://climate.esa.int/en/projects/permafrost/>

<https://www.rgik.org>

19.09.2024

Preamble

This Rock Glacier Inventory (RoGI) tutorial has been designed within the framework of the CCI+ Phase 2 Permafrost project funded by the European Space Agency (ESA). The project is in synergy with the work of the IPA Action Group on Rock Glacier Inventories and Kinematics ([RGIK](#)) that developed international RoGI guidelines and a related GIS-based exercise. The following GIS-based tutorial describes the steps required in the mapping and characterization of rock glaciers. All data, instructions and notices describing the attributes of each vector layer can be found in the zip folder of each RoGI subarea (named “RoGI_AreaName”).

The inventorying procedure follows up on prior work aiming to reduce discrepancies between different operators and produce homogenous consensus-based RoGIs ([Brardinoni et al., 2019](#); [Way et al., 2021](#)).

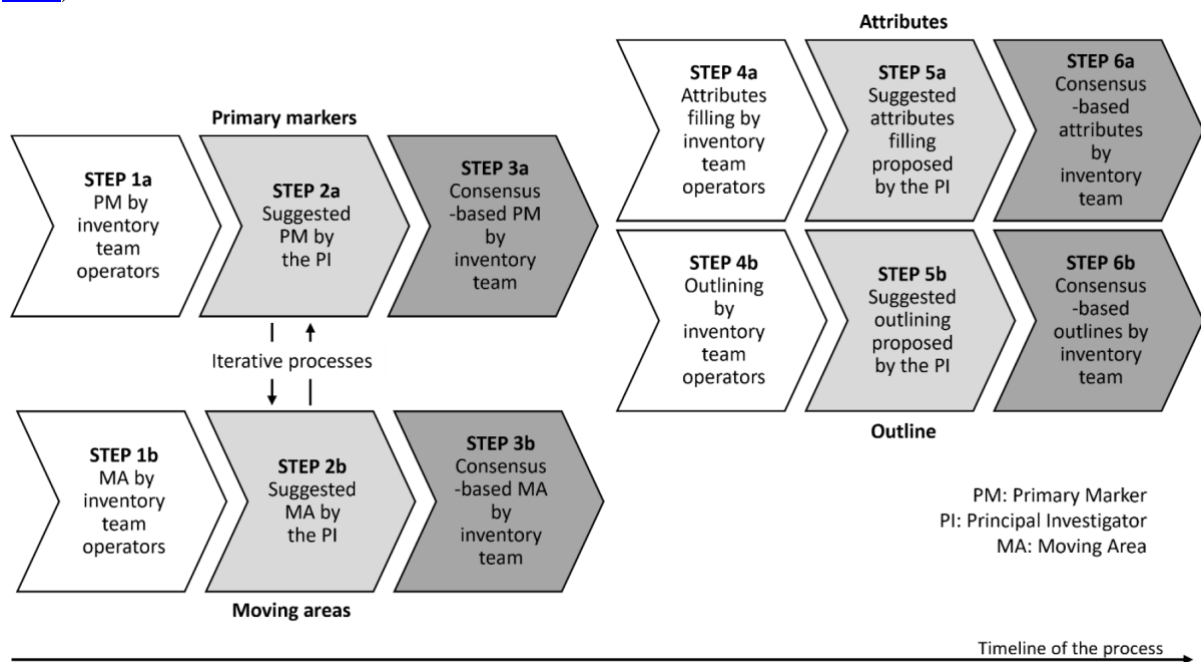


Figure 1. Consensus-based RoGI procedure

We recommend that the work is performed by an inventory team composed of several operators. A Principal Investigator (PI) in each region coordinates the work and is responsible for the final result. The PI is also included as an operator of the inventory team. The following instructions present all the detailed steps summarized in Figure 1.

Note that at this stage, rock glacier systems (RGS) are not included in the exercise. This exercise only focuses on the inventory of the rock glacier units (RGU).

For troubleshooting or technical support, please contact Thomas Echelard (thomas.echelard@unifr.ch) or use the [RGIK Slack Forum](#). For questions regarding the CCI RoGI procedure and InSAR guidelines, please contact Line Rouyet (line.rouyet@unifr.ch; liro@norceresearch.no).

GIS

- QGIS software - [Download QGIS](#) (version 3.22 or higher).
- Numbers in the text refer to the GIS tips, found at the end of this document.
- For more general information on QGIS software, refer to the [online manual](#).

GIS project data

The QGIS project comprises:

- Layer templates to be edited by the operator: *RGU_PrimaryMarkers_AreaName*, *RGU_Outlines_AreaName*, *MovingAreas_AreaName*.
- Polygon of your Area Of Interest (AOI).
- A set of InSAR data (interferograms) based on SENTINEL-1 and additional available SAR satellites depending on the CCI study area. The SAR images have been acquired in ascending mode (ASC) and descending mode (DESC). Relevant interferograms have been generated across a range of time intervals. For more information on the analysis of InSAR data, please refer to the [InSAR guidelines](#) (document 'InSAR_guidelines' in the project folder).
- Online open-access optical imagery (e.g. Google image, Bing). Note that it requires an Internet connection.

Depending on availability in the study area, each PI can add additional stream/online data (e.g. optical imagery, DEM and hillshade) before sending the GIS project to the inventory team. It is recommended to add this data in a dedicated group in the QGIS project (e.g. online data).

The zip folder of your subarea also contains the kml file of your AOI.

Other resources

In the folder INSTRUCTIONS you can find the information about each attribute table of the layers that you will edit (attributes, values, description, related documentation):

- Notice_RoGI_RGU_Primary_Markers.pdf
- Notice_MovingAreas.pdf.
- Notice_RoGI_RGU_Outlines.pdf

The 3D view in Google Earth can be very useful for geomorphological interpretation: <https://earth.google.com/>. When available, visual inspection of multi-temporal orthoimages can also be valuable.

Detecting and locating Rock Glacier Units (RGU)

Step 1a

Step 1a requires careful reading of the [Baseline Concepts](#) (especially Sections 3a-3d) and [Practical Concepts](#) (especially Sections 5a-5b) for inventorying rock glaciers.

→ Open the QGIS project *RoGI_AreaName.qgz*

→ In the study area, **mark each recognized rock glacier units with a point (primary marker, PM) in the layer *RGU_PrimaryMarkers_AreaName***. Relict rock glaciers must also be marked, but other landforms, such as debris-covered glaciers, moraines or landslides are excluded. InSAR analysis can be useful to detect/confirm and characterize the kinematics of the rock glacier units.

To edit the *RGU_PrimaryMarkers_AreaName* layer, start by selecting it and then click on the Edit icon (yellow pencil). The two icons to the right of the yellow pencil allow to add points and modify them ([GIS tip 1](#)).

Each new point is associated with an attribute table. In step 1a, fill only the “*Landform*” attribute (Rock glacier, Uncertain rock glacier, Not a rock glacier) and optionally the “*Comment*” attribute. Do not fill in the other attributes (this will be done later). Specify “*Rock glacier*” if you are confident to have detected a rock glacier unit, “*Uncertain rock glacier*” if you are not sure or if the landform may be too small to be considered as such. You may optionally use “*Not a rock glacier*” to indicate some landforms that look like rock glaciers but which are not. This is typically valuable for ambiguous cases that can be further discussed within the team and used as an educational example for potential future users. Add details in the “*Comment*” attribute if needed. Save your edits regularly (icon next to the yellow pen).

→ When step 1a is completed, save your project and close QGIS. Then rename the file VECTOR\LAYERS*RGU_PrimaryMarkers_AreaName.gpkg* by adding your name (or your initials) at the end (e.g. *RGU_PrimaryMarkers_AreaName_YourName.gpkg*).

→ Forward your layer *RGU_PrimaryMarkers_YourName.gpkg* to the PI. **The deadline to send the individual results is set by the PI** (potentially same deadline as step 1b).

Step 2a

Based on the individual results from step 1a, the PI suggests a final PM layer (*RGU_PrimaryMarkers_AreaName_PI*) that will be discussed with the team.

Step 3a

The inventory team reviews the suggested PM layer, finds consensus if needed and approves the final PM locations. The resulting layer will be used as a reference for the next steps. At the end of this step, the PI sends the final PM layer and the results of each individual operator to the CCI coordinators: line.rouyet@unifr.ch, lironorceresearch@unifr.ch and thomas.echelard@unifr.ch.

Detecting Moving Areas (MA)

Steps 1b

Steps 1b requires careful reading of the guidelines for [Optional kinematic attribute in standardized rock glacier inventories](#) and the [InSAR guidelines \(also available in the project folder: document 'InSAR guidelines'\)](#).

→ In the study area, **draw the Moving Areas (MA) polygons based on Synthetic Aperture Radar Interferometry (InSAR) data in the layer *MovingAreas_AreaName***. To edit the layer, start by selecting it and then click on the Edit icon (yellow pencil). The two icons to the right of the yellow pencil allow to add polygons and modify them ([GIS tip 5](#)).

→ Follow the instructions in the [InSAR guidelines \(also available in the project folder: document 'InSAR guidelines'\)](#) and identify all MAs in your study area.

→ Fill the attributes of each MA polygon. The descriptions of the attributes related to the MA polygons are described in the file *INSTRUCTIONS\Notice_MovingAreas.pdf*. The attribute table proposes a semi-automatic dialog box for filling out the velocity class (Vel.Class) and for defining the degree of reliability of the detected MA (Rel.MA) by selecting the value from the drop-down list ([GIS tip 3](#)). Save your edits regularly (icon next to the yellow pen).

→ When step 1b is completed, save your project and close QGIS. Then rename the file VECTOR\LAYERS*MovingAreas_AreaName.gpkg* by adding your name (or your initials) at the end (e.g. *MovingAreas_AreaName_YourName.gpkg*).

→ Forward your layer *MovingAreas_AreaName_YourName.gpkg* to the PI and wait for feedback from the PI before proceeding to the next steps. **The deadline to send the individual results is set by the PI** (potentially same deadline as step 1a).

Steps 2b

Based on the individual results from step 2b, the PI suggests a final MA layer (*MovingAreas_AreaName_PI*) that will be discussed with the team.

Steps 3b

After discussion/consensus and the final team agreement on MA location, outlines and attributes, the PI sends the final MA layer and the results of each individual operator to the CCI coordinators: line.rouyet@unifr.ch, lro@norceresearch.no and thomas.echelard@unifr.ch.

Documenting rock glacier attributes and drawing outlines

Step 4a: Documenting rock glacier attributes

Step 4a requires careful reading of the documents related to the attribute table (attributes, values, definitions, etc.) can be found in the file *INSTRUCTIONS\Notice_RoGI_RGU_Primary_Markers.pdf*. To access and fill out the attribute table form, refer to the [GIS tip 2](#) and [GIS tip 3](#).

→ In the study area, **specify the attributes of each rock glacier unit in the *RGU_PrimaryMarkers_AreaName_CB* layer** ([GIS tip 2](#)). The attribute table proposes a semi-automatic dialog box for filling in the attributes, by selecting the value from the drop-down list ([GIS tip 3](#)). Some attributes appear only if other attributes have been filled in before (e.g. *Kin.Att.* appears only when *Acti.Ass.* = 'Kinematic'; [GIS tip 4](#)). Values and definitions can be found in the layer documentation (*Notice_RoGI_RGU_Primary_Markers.pdf*). Save your edits regularly (icon next to the yellow pen).

→ When step 4a is completed, save your project and close QGIS. Then rename the file *VECTOR\LAYERS\ RGU_PrimaryMarkers_AreaName_CB.gpkg* by adding your name (or your initials) at the end (e.g. *RGU_PrimaryMarkers_AreaName_CB_YourName.gpkg*).

→ Forward your layer *RGU_PrimaryMarkers_AreaName_CB_YourName.gpkg* to the PI and proceed to the next step. **The deadline to send the individual results is set by the PI** (potentially same deadline as step 4b).

Step 4b: Drawing outlines (optional)

→ In your study area, **outline each rock glacier unit in the *RGU_Outlines_AreaName* layer**. To edit the *RGU_Outlines* layer, start by selecting it and then click on the Edit icon (yellow pencil). Use the two other icons on the right to add and modify polygons ([GIS tip 5](#)). If possible, draw both the *Restricted* and *Extended* footprints. Save your edits regularly (icon next to the yellow pen).

→ Fill the attribute table (Outline type and Reliability). The attribute table offers a semi-automatic dialog box for filling the attributes, by selecting the value from the drop-down list. Refer to the layer documentation (notices) for values and definitions. Do not import the Primary ID created in the PM table into the Outline table, as it will be done automatically at a later stage by the CCI coordinators (Unifr).

→ When step 4b is completed, save your project and close QGIS. Then rename the file *VECTOR\LAYERS\RGU_Outlines_AreaName.gpkg* by adding your name (or your initials) to the end (e.g. *RGU_Outlines_AreaName_YourName.gpkg*).

→ Forward your layer to the PI to move to the next step. **The deadline to send the individual results is set by the PI** (potentially same deadline as step 4a).

Step 5a/5b

Based on the individual results from steps 4a/4b, the PI suggests a final PM layer including attributes (*RoGI_AreaName_PI*) and makes a layer with the suggested RGU outlines (*RoGI_Outlines_AreaName_PI*).

Step 6a/6b

The inventory team reviews the suggested attributes and outlines, find a consensus (if needed) and approves the final results. The resulting layers will be the RoGI consensus-based results of your study area (*RoGI_AreaName* and *RoGI_Outlines_AreaName*).

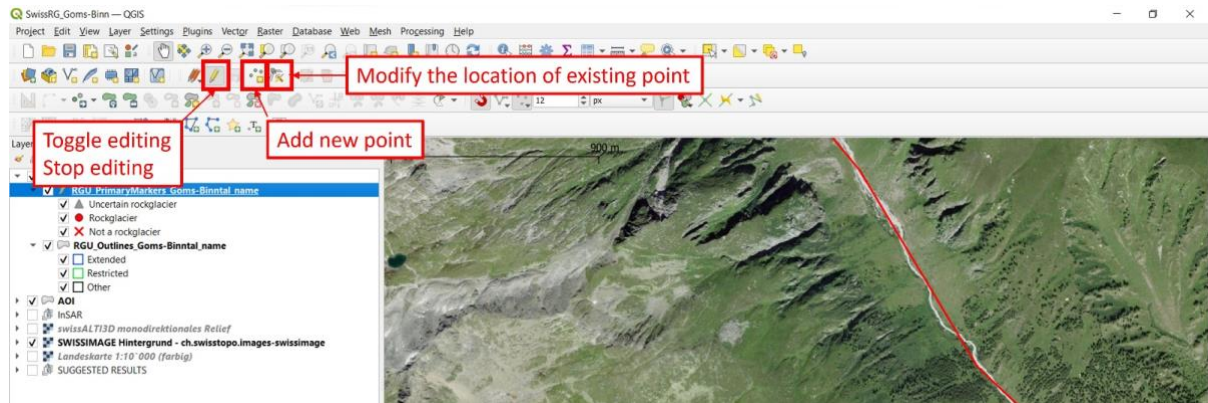
Congratulation, the whole inventory process is completed!

All files (from single operators and after the final team decision) are sent by the PI to the CCI coordinators: line.rouyet@unifr.ch, liro@norce-research.no and thomas.echelard@unifr.ch.

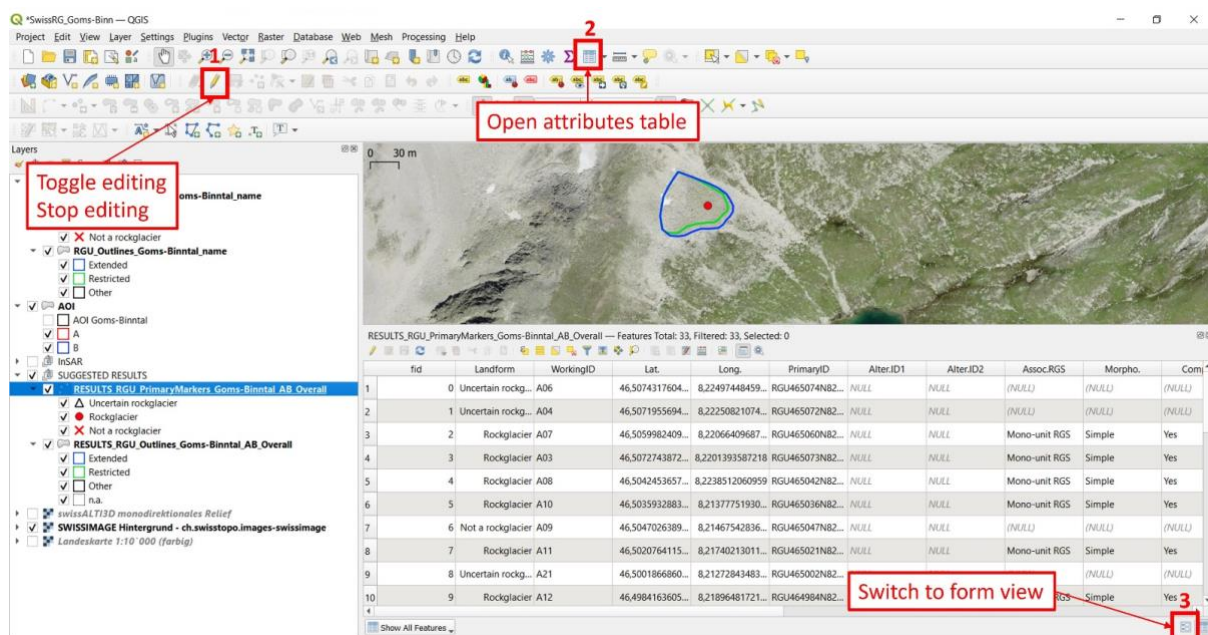
Deadline for final delivery to Unifr is May 1st 2025.

GIS TIPS

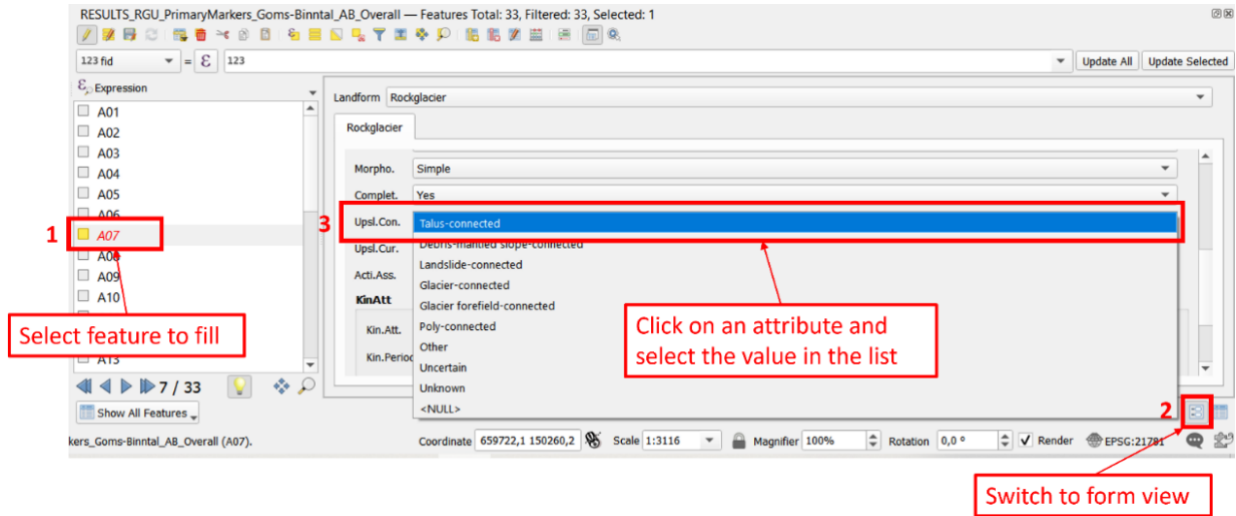
GIS tip 1



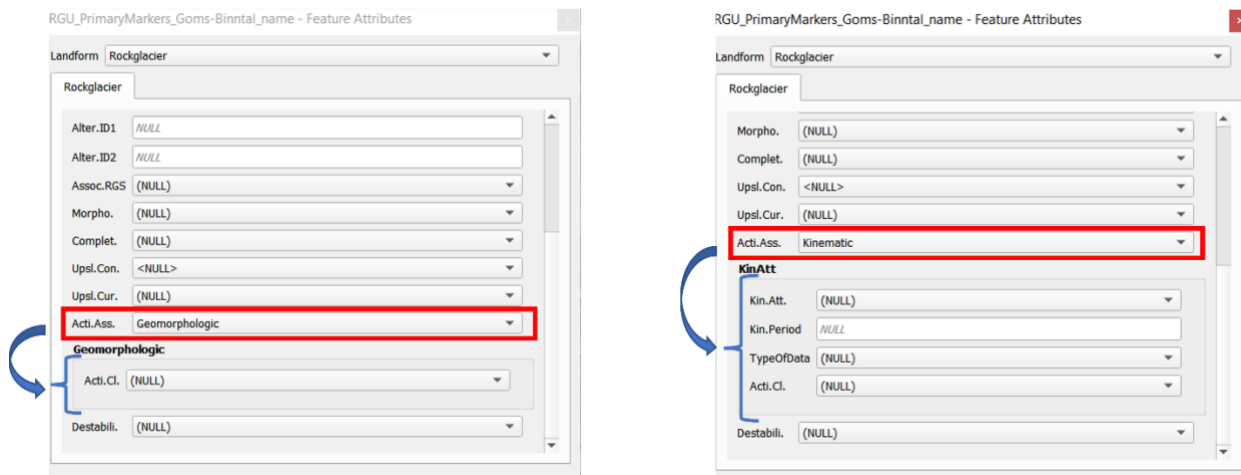
GIS tip 2



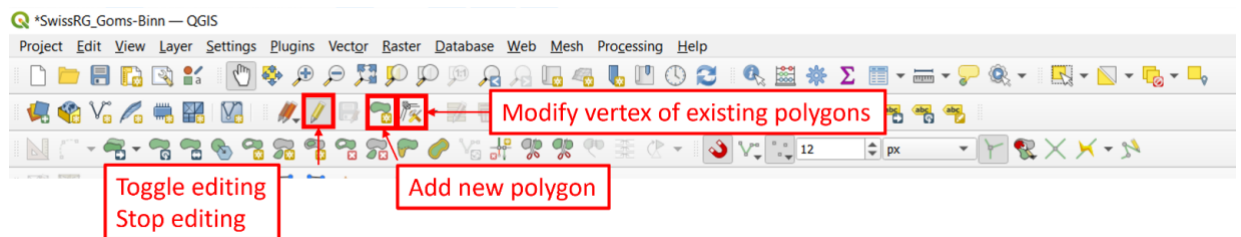
GIS tip 3



GIS tip 4



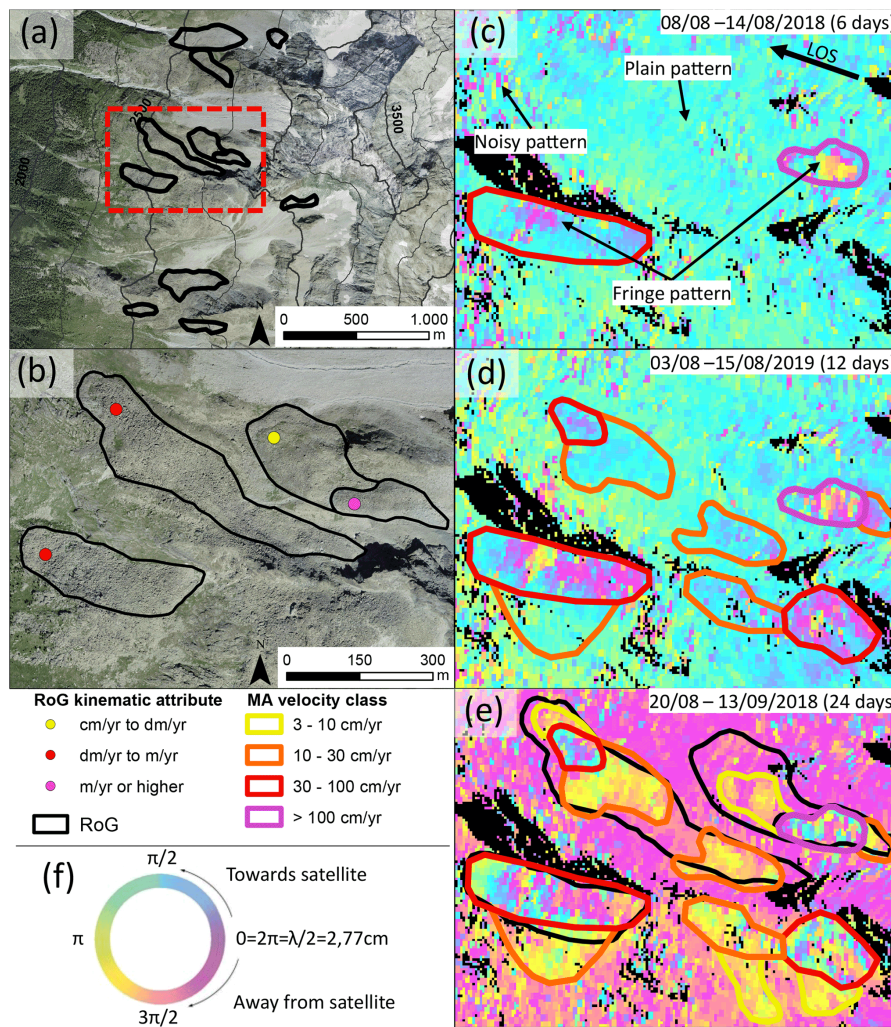
GIS tip 5



Annex 2: InSAR guidelines [RD-8]

InSAR-based kinematic attribute in rock glacier inventories

Practical InSAR Guidelines v.4.0



[Bertone et al., 2022](#) and [RGIK Action group](#)

31.05.2023

To the attention of RGIK community

The Practical InSAR Guidelines (InSAR-based kinematic attributes in rock glacier inventories) is a document describing the recommendations for using Synthetic Aperture Radar Interferometry (InSAR) to assign kinematic attributes in rock glacier inventories.

This is not a standalone document. It is a complement to the following reference documents of the IPA Action group on rock glacier inventories and kinematics (RGIK):

- [Baseline concepts: Towards standard guidelines for inventorying rock glaciers](#)
- [Practical guidelines: Towards standard guidelines for inventorying rock glaciers](#)
- [Baseline concepts: Kinematics as an optional attribute of standardized rock glacier inventories](#)

Useful methodological background information and additional examples on the interpretation of InSAR data can be found in [Bertone et al. \(2022\)](#). In the following document, we provide the basics necessary to use InSAR for the production of a rock glacier inventory (RoGI) (*Section 1. Basics*) and recommendations to perform the work in a standardized GIS-based tool (*Section 2. Practical guidelines*). We recommend reading this document as a complement of the tutorial of the [RoGI exercise in the Goms valley \(Switzerland\)](#).

To the attention of ESA CCI+ Permafrost external partners

In the framework of [the European Space Agency \(ESA\) Climate Change Initiative \(CCI+\) Permafrost Project](#) Phase 1 (2018–2021), several partners worked on assigning kinematic attributes in rock glacier inventories (RoGIs) produced in several regions worldwide. A past version of this document (v.3.0) was used to generate comparable RoGIs using a kinematic approach based on Synthetic Aperture Radar Interferometry (InSAR).

In ESA CCI+ Permafrost Phase 2 (2022–2025), a cross-validation exercise in subareas of the 12 initial regions has been designed to identify potential discrepancies between multiple operators, adjust the guidelines and evaluate the quality of the final products. The selected regions and involved partner institutions are shown in Annex C.

The present document is an updated version (v.4.0) of the Practical InSAR Guidelines. The objective is to define standard rules to assign an InSAR-based kinematic attribute to the rock glacier units and generate comparable RoGI products. This is not a standalone document. Consequently, we recommend that each operator read carefully the following documents before starting the inventorying process:

- [Baseline concepts: Towards standard guidelines for inventorying rock glaciers](#)
- [Practical guidelines: Towards standard guidelines for inventorying rock glaciers](#)
- [Baseline concepts: Kinematics as an optional attribute of standardized rock glacier inventories](#)

The inventorying process follows the procedure explained in the subfolder INSTRUCTION (*1_RoGI_practice_instructions.pdf*) of the project made for each Permafrost_cci subarea. The practical InSAR guidelines focus on delineating moving areas using InSAR and assigning InSAR-based kinematic attributes to inventoried rock glacier units.

Line Rouyet and Thomas Echelard, responsible for troubleshooting and technical support.

Contact: line.rouyet@unifr.ch / lir@norceresearch.no and thomas.echalard@unifr.ch.

1. InSAR basics

1.1 InSAR to map surface movement

Differential Synthetic Aperture Radar Interferometry (InSAR) is a satellite remote sensing technique used to measure surface movement over large areas. The approach consists of analysing **the phase differences between two SAR images taken at different times**, after removal of unwanted phase components (e.g. associated with the topography or the atmosphere).

The resulting map of phase differences is referred to as an “interferogram”. It contains **one-dimensional information about the surface displacement**, corresponding to the **projection of the real displacement along the sensor view angle, i.e. the SAR line of sight (LOS)** (*Figure 1a*). A single SAR interferometric observation therefore does not allow to fully determine the magnitude and direction of a surface deformation. The three-dimensional displacement vector can only be computed if one assumes a certain displacement direction when focusing on a specific process, e.g. creep occurring along the steepest slope direction for the rock glaciers.

A Synthetic Aperture Radar (SAR) is not able to measure displacements that are fully perpendicular to its LOS and detects an underestimated displacement if the LOS deviates from the real displacement orientation. We therefore need **to know the measurement geometry of the available datasets to correctly interpret the interferograms**. SAR satellites are polar orbiting and imaging the Earth’s surface at a specific incidence angle. With a right-looking sensor, a satellite crossing the Equator from South to North (**ascending passes**) looks **towards East**. When crossing the Equator from North to South (**descending passes**), it looks **towards West** (*Figure 1a*).

The SAR geometry has an impact on the achieved spatial coverage in mountainous terrain. North- and South-facing slopes are difficult to analyse, because creeping landforms include a displacement component perpendicular to the LOS orientation. **Back-facing slopes** (*D–I, Figure 1b*), defined as the western slopes when viewing in descending mode (eastern slopes in ascending mode), **are the most appropriate configurations**. The local spatial resolution is less affected by geometric distortions and the displacement orientation is more or less aligned with the LOS. The slopes facing the radar (*A–D, Figure 1b*) are less favourable for an InSAR analysis. In addition, the difference between the slope steepness and the radar incidence angle has to be considered. A steep incidence angle reduces shadow effects observed in back-facing slopes (*F–H, Figure 1b*) but increases layover effects in slopes facing the SAR (*B–D, Figure 1b*). Consequently, it is important to **use a combination of interferograms with different view angles and geometries (ascending/descending) to investigate different slopes in a region**.

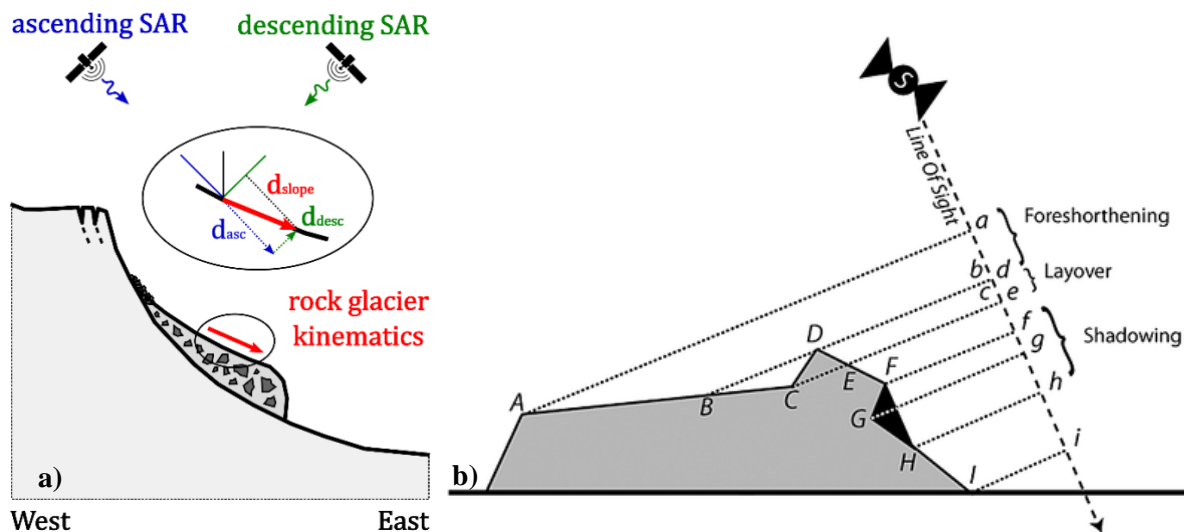


Figure 1. (a) A displacement (d) vector along the slope (d_{slope}) and the line of sight (LOS) components measured by InSAR when using SAR images from ascending (asc) and descending ($desc$) geometries: d_{asc} and d_{desc} . (b) Geometric distortions from the SAR measurement geometry in mountainous regions.

1.2 Visual interpretation of interferograms

The displacement that occurs between the two image acquisitions can be estimated by **visually interpreting the interferograms**. The results are spatially relative to a reference area selected outside the studied moving area. The spatial change of colour in the interferogram expresses the surface displacement projected onto the LOS direction. **An entire colour cycle (fringe) is equivalent to a change of half the SAR wavelength ($\lambda/2$) along the LOS during the time interval between the two images.** One phase cycle represents half the wavelength as the radar signal travels to the ground and back to the sensor. The direction of the change can be interpreted using the key in *Figure 2*. Considering back-facing slopes, clockwise colour changes mean that the radar beam has travelled further in the second acquisition and thus corresponds to a downslope process or subsidence. In the opposite case, it will be interpreted as an upslope displacement or uplift.

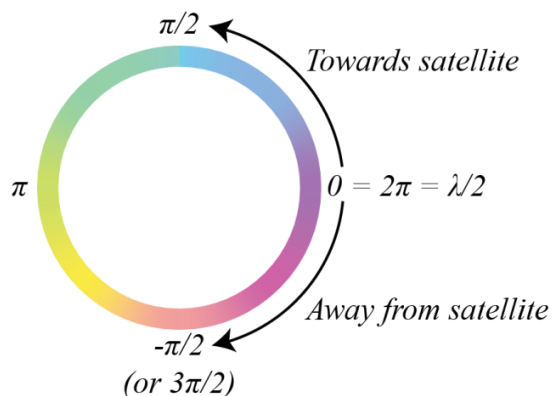


Figure 2. The difference in displacement rate between locations with the same colour is a multiple of $\lambda/2$. When the colour changes in clockwise direction, the ground has moved away from the satellite. In the opposite direction, the ground has moved towards the satellite.

The minimum and maximum displacement rates that can be detected depend on the time interval, the resolution and the SAR wavelength of the interferograms (Figure 3 and Table 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 changes occurring during the selected time interval are too large within the pixels. Temporal decorrelation can also occur due to changes in surface properties (e.g. vegetation, snow and wetness).

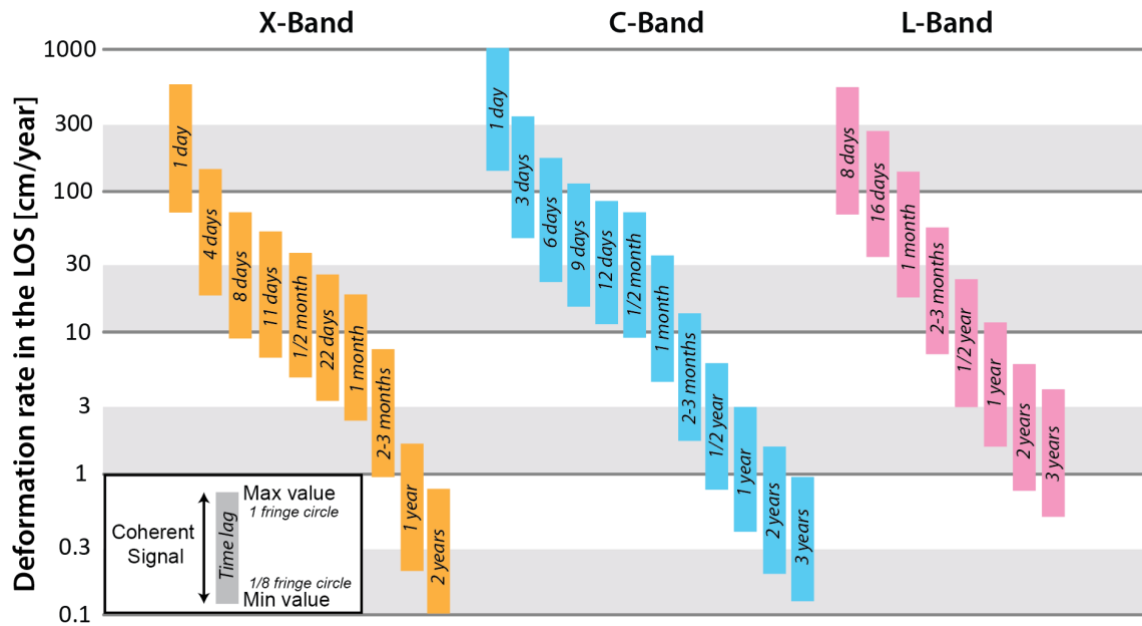


Figure 3. Deformation rate observed by SAR sensors for the most commonly used time intervals. A bar defines the interval of deformation rate in cm/yr for which a coherent signal can be identified and interpreted on an interferogram generated with a certain time interval. It shows the detection capability of different InSAR data. The lower limit corresponds to the minimal detectable velocity (1/8 of fringe cycle). The upper limit corresponds to the maximum velocity (one entire fringe). A movement lower than the minimum value of the bar is not detectable. A movement higher than the maximum value of a bar may decorrelate on the interferogram (adapted from [Barboux et al. 2014](#)).

Table 1. Radar characteristics of the main SAR systems used in the exercise.

Satellite	<i>TerraSAR-X</i>	<i>Cosmo-SkyMed</i>	<i>Sentinel-1</i>	<i>Radarsat-2</i>	<i>ALOS-2</i>	<i>SAOCOM</i>
Date	from 2007	from 2007 ²	from 2014	from 2007	from 2014	from 2018
Agency	DLR	ASI	ESA	CSA	JAXA	CONAE
Wavelength (cm)	3.1	3.1	5.5	5.6	24.3	23.5
Band	X	X	C	C	L	L
Incidence angle (°)	20–45	25–40	20–45	35	30–40	18–50
Range resolution (m)¹	1–16	1–100	5–25	3–100	3–60	5–10
Azimuth resolution (m)¹	1–16	1–3–100	5–40	3–100	3–60	10–50
Scene width (km)	10–100	10–200	80–400	50–500	70	10–400
Repeat cycle (day)	11	1–4–8–16	(6)–12 ³	24	14	(8)–16 ³

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 operating, the repeat cycle is 6 days for Sentinel-1 and 16 days for SAOCOM.

1.3 Interpretation of averaged velocity maps

To automatically obtain displacement maps (e.g. with units in cm), a processing step called **phase unwrapping** is required. This step allows to convert the cyclic phase differences (that range between $-\pi$ and $+\pi$) into the absolute phase values and subsequently into displacements.

An advantage of adding an automated unwrapping step is that it allows for including and combining the information from a large amount of interferograms. All interferograms (with a chosen time interval depending on the expected velocity, see *Figure 3*) can be generated, unwrapped and then averaged to provide **average velocity maps** that are easily interpretable. **This process is called InSAR Stacking.** Such maps are usually expressed in m/yr along the LOS, with negative values (typically in red) showing areas moving away from the satellite and positive values (typically in blue) showing areas moving towards the satellite.

To take advantage of the redundancy of temporally overlapping interferograms and improve the measurement accuracy (e.g. in areas affected by significant atmospheric noise), more advanced multi-temporal InSAR techniques can be applied. These are typically divided into two main groups:

- Methods based on locating Persistent Scatterers (PSs), referred to as **Persistent Scatterer Interferometry (PSI)** or **Interferometric Point Target Analysis (IPTA)**. A stack of interferograms is generated at full resolution using a single reference scene, i.e. including long (interannual) interferograms. PSI is typically designed for linear and slow-moving features, and thus does not allow for correctly quantifying velocities higher than a few dm/yr. PSI can be useful for slow-moving landforms, e.g. to discriminate transitional and relict rock glaciers. For most active rock glaciers, PSI must be complemented by single interferogram analysis and/or distributed scattering InSAR.

- Methods based on Distributed Scattering (DS), referred to as **Small Baseline Subset (SBAS)**. These methods incorporate a large number of interferograms (multiple reference scenes) below chosen spatial and temporal baseline thresholds to reduce geometric and temporal decorrelations. The maximum detection capability depends on the chosen threshold of temporal intervals used to build the interferograms, following the same logic as *Figure 3*.

Phase unwrapping and resulting averaged products based on a large amount of interferograms (InSAR stacking, PSI or SBAS maps) are widely used to produce one single output and automate the processing over large regions. However, this step may introduce **data gaps from decorrelation and potential errors over fast-moving areas, as well as in areas with snow or vegetation. Results from InSAR Stacking, PSI/IPTA or SBAS must therefore be interpreted carefully and in combination with single wrapped interferograms.**

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 **interpretation of wrapped interferograms from a large InSAR dataset in order to locate moving areas related to rock glaciers, and estimate their displacement rates**. Similar recommendations could be applied to other InSAR methods, such as unwrapped interferograms, InSAR stacking, PSI/IPTA or SBAS, but the results must be interpreted carefully (see Section 1.3).

The objective is to provide the following outputs:

- **The moving areas (MAs)**, a polygon vector layer containing the outlines of MAs identified on the available InSAR data.
- **The kinematic attributes (KAs)** associated with primary markers (and optionally the outlines) of the **rock glacier units (RGUs)**.

2.1 InSAR data and GIS structure

2.1.1 Interferograms, velocity maps and normalization factors

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 focusing on unrepresentative signals from one single interferogram, it is essential to **use 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 alpine mountain environments are the slope orientation/steepness and the presence of (wet) snow. **Selected SAR scenes must be mostly snow-free** (e.g. usually between June–July and September–October in the Northern Hemisphere). SAR scenes with a short (daily) time interval can also be used in wintertime, when the snow is still dry in periods without strong precipitation or wind. Estimating the extent of old or fresh snow and the weather conditions (rain events) occurring on or up to 2 days before each SAR acquisition on the basis of available meteorological data has proven to be a helpful step in evaluating the quality of an interferogram. Additionally, the influence of phase noise and residual unwanted phase components remaining after InSAR processing (e.g. atmospheric effects) must be considered when interpreting an interferogram.

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

- **Interferograms:** MAs have to be identified by analysing several interferograms and combining different time periods (start, middle and end of snow-free seasons), different sensors and wavelengths (e.g. Sentinel-1, TerraSAR-X and ALOS) and different time intervals (from day(s) to year(s)). Both ascending and descending modes are required to document areas with different slope orientations. Areas affected by geometrical distortions should be masked in the analysed interferograms.
- **Velocity maps, e.g. InSAR stacking** (when available): Velocity maps based on short time intervals (6–12 days for Sentinel-1) are used to provide the highest detection capability (up to 84 cm/yr for 6 days / 42 cm/yr for 12 days due to potential phase aliasing). After unwrapping and averaging, the maps are expressed in m/yr (+/- depending on the movement directions in respect to the LOS:

negative values show areas moving away from the satellite, positive values show areas moving towards the satellite. To enable a large range of detection capabilities, a multiple stacking procedure based on different time intervals can also be used. For a higher accuracy in areas with low velocity, PSI/IPTA can also be used. As for single interferograms, areas affected by geometrical distortions should be masked out.

- **Normalization factors or N-S slopes layer:** The normalization factor is an index to re-project the LOS displacement (i.e. displacement measured along the LOS) along the direction of the steepest slope. It ranges between 1 and ∞ . The value 1 means that the LOS and the slope are parallel (ideal case). By increasing the angle between the LOS direction and the steepest slope direction, the normal factor increases. In areas with a normalization factor greater than 5, LOS measurements from single interferograms or velocity maps are no longer reliable and should not be used. Normalization factors are used to identify the most appropriate geometry (ascending or descending) or exclude non-reliable pixels. When a MA is visible in InSAR data from both geometries, the data with the lowest normalization factor should be considered as more reliable. If the normalization factor is not available, west-facing slopes should be analysed in descending mode, while east-facing slopes should be analysed in ascending mode. As an alternative to normalization factors, a layer highlighting the North- or South-oriented slopes can be used with the similar objective to identify areas where InSAR data must be interpreted carefully.

Additional kinematic data (e.g. measurements from GNSS stations or airborne optical photogrammetry) can be used to complement the InSAR data and consolidate the assignment of a velocity class to the MAs.

The sources of InSAR data and the additional data used in the inventorying process (e.g. DEMs and orthophotos) should not have been acquired more than a decade apart, and the spatial resolutions of additional data sets should be comparable or higher than the spatial resolution of the InSAR data.

2.1.2 InSAR database in GIS

The InSAR data are organized in different groups and subgroups. **The first group level** discriminates between the sensors (e.g. Sentinel-1 and ALOS). **The second group level** discriminates between the geometries (ascending ASC and descending DESC). It may also include the layers documenting the normalization factors and the velocity maps (InSAR stacking, PSI/IPTA). **The third group level** discriminates between the time intervals used to generate the interferograms (e.g. 6D, 12D and 24D).

Example of GIS structure:

- INSAR
 - SENTINEL
 - ASC
 - 6D
 - 10_SENT1_ASC_20190903_20190909_0006_tflt.tif
 - ...
 - 12D
 - 10_SENT1_ASC_20160906_20160918_0012_tflt.tif
 - ...
 - 366D
 - 10_SENT1_ASC_20180902_20190903_0366_tflt.tif
 - ...
 - 10_SENT1_ASC_norm_factor.tif
 - 10_SENT1_ASC_stacking_2018_2019.tif
 - DESC
 - 12D
 - 10_SENT1_DES_20160910_20160922_0012_tflt.tif
 - ...
 - 24D
 - 10_SENT1_DES_20160910_20161004_0024_tflt.tif
 - ...
 - 366F
 - 10_SENT1_DES_20180918_20190919_0366_tflt.tif
 - ...
 - 10_SENT1_DES_norm_factor.tif
 - 10_SENT1_DES_stacking_2018_2019.tif

The file name of the interferograms has the following format:

Subarea-number_SARsensor_SARgeometry_AcquisitionDay1_AacquisitionDay2_TimeInterval_tflt.tif

Ex: *15_SENT1_ASC_20180212_20180320_036_tflt.tif*

The file name of a stacking map has the following format:

Subarea-number_SARsensor_SARgeometry_FirstYear_LastYear.tif

Ex: *10_SENT1_DES_stacking_2018_2019.tif*

2.2 Identify, delineate and characterize moving areas (MAs)

The MA identification is an initial step to assign a KA to each inventoried RGU (Section 2.3). All MAs related to rock glaciers should be compiled in the **polygon vector layer “MovingAreas_***”.

We recommend proceeding to **MA identification in parallel with the RGU identification with primary markers (iterative process)**. Firstly, InSAR-based MA identification may contribute to detect RGUs that may have been missed in a geomorphological assessment. Secondly, comparing InSAR with the location of the primary markers contributes to discard MAs that are related to processes other than rock glacier creep.

2.2.1 MA definition

A MA is defined as an **area at the surface of a rock glacier in which the observed direction and velocity of the flow field are spatially consistent and homogeneous during a documented time**. It must represent the downslope movement rate of the rock glacier (permafrost creep). Any confusion with movements related to other processes (e.g. melt-induced subsidence or subjacent landslide) should be avoided, based on geomorphological criteria. MA definition is described in detail in the [Baseline concepts document: Kinematics as an optional attribute of standardized rock glacier inventories](#).

Detecting and quantifying MAs is **technology dependent**. The present document provides **recommendations for deriving standardized MAs using InSAR**, that will then be used to assign a KA to the inventoried rock glaciers (Section 2.4).

2.2.2 MA identification

The MA detection is performed by looking at the textural features visible from wrapped interferometric phase differences (hereafter just named “interferograms”). **Three types of InSAR patterns can typically be identified: (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 (Figure 4 and Figure 5c). The texture is evaluated around the considered pixel depending on the size of the landform that has to be detected in the neighbouring environment. The minimal MA extent 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. We recommend delineating a MA only if at least 20–30 pixels show a clear InSAR pattern.

The MA detection is based on the combined visualization of **a set of wrapped interferograms of various time intervals**. The error sources (e.g. due to processing, snow cover or atmospheric artefacts) must be as low as possible to ensure that the resulting data is confidently exploitable for characterizing surface movement related to rock glacier creep. The combined visualisation of several wrapped interferograms avoids focusing on unrepresentative patterns and isolated artefacts. These effects are sometimes identifiable with a noisy pattern or with a fringe pattern extended over very large areas. Atmospheric or snow artefacts often occur only on a few interferograms, and therefore can be discriminated from movement by analysing a large dataset. Noise patterns related to vegetation or glaciated areas are persistent over all interferograms and can often be identified by comparing the interferograms with orthophotos. When available, **InSAR stacking, SBAS or PSI velocity maps** are also valuable to detect MAs, especially when the objective is to inventory large regions.

An estimation of the LOS velocity is possible when the MA is characterized by a fringe pattern (Section 2.3.3). When a MA is characterized by a noisy pattern, i.e. when the rate of surface movement is too fast for the selected time interval and the signal is decorrelated, the identification of the position, extent and outline of fast MAs is still possible. **Slow displacement rates (velocities below 3 cm/yr)** can be detected but are often difficult to delineate with enough precision based on single interferograms. Multi-temporal InSAR techniques including interferograms with long temporal intervals (e.g. PSI) are better suitable for detecting slow movements, as they exploit the redundancy of temporally overlapping interferograms and improve the measurement accuracy (e.g. in areas affected by significant atmospheric effects).

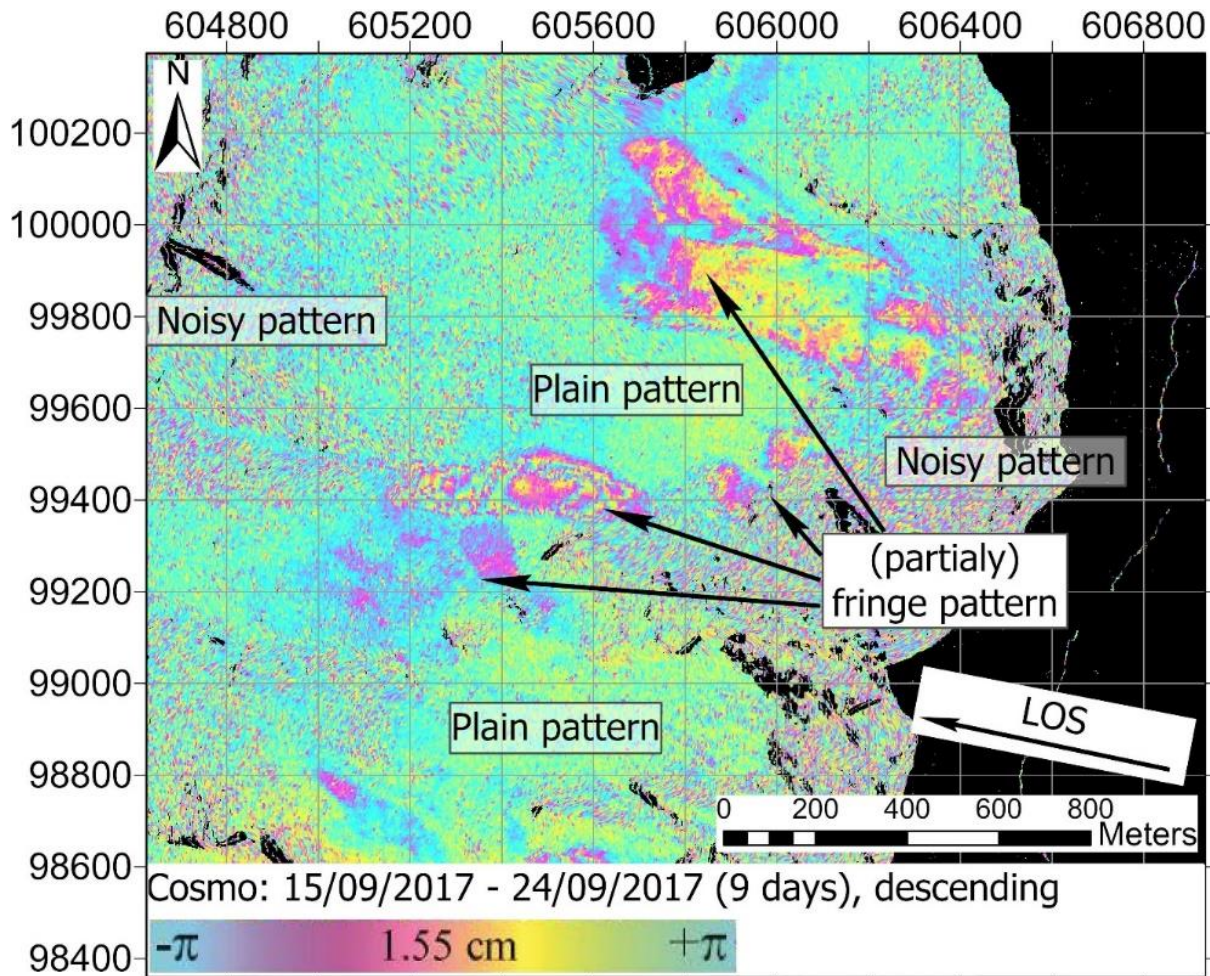


Figure 4. Example of InSAR signal patterns. Data where layover and shadowing are masked out and shown in black.

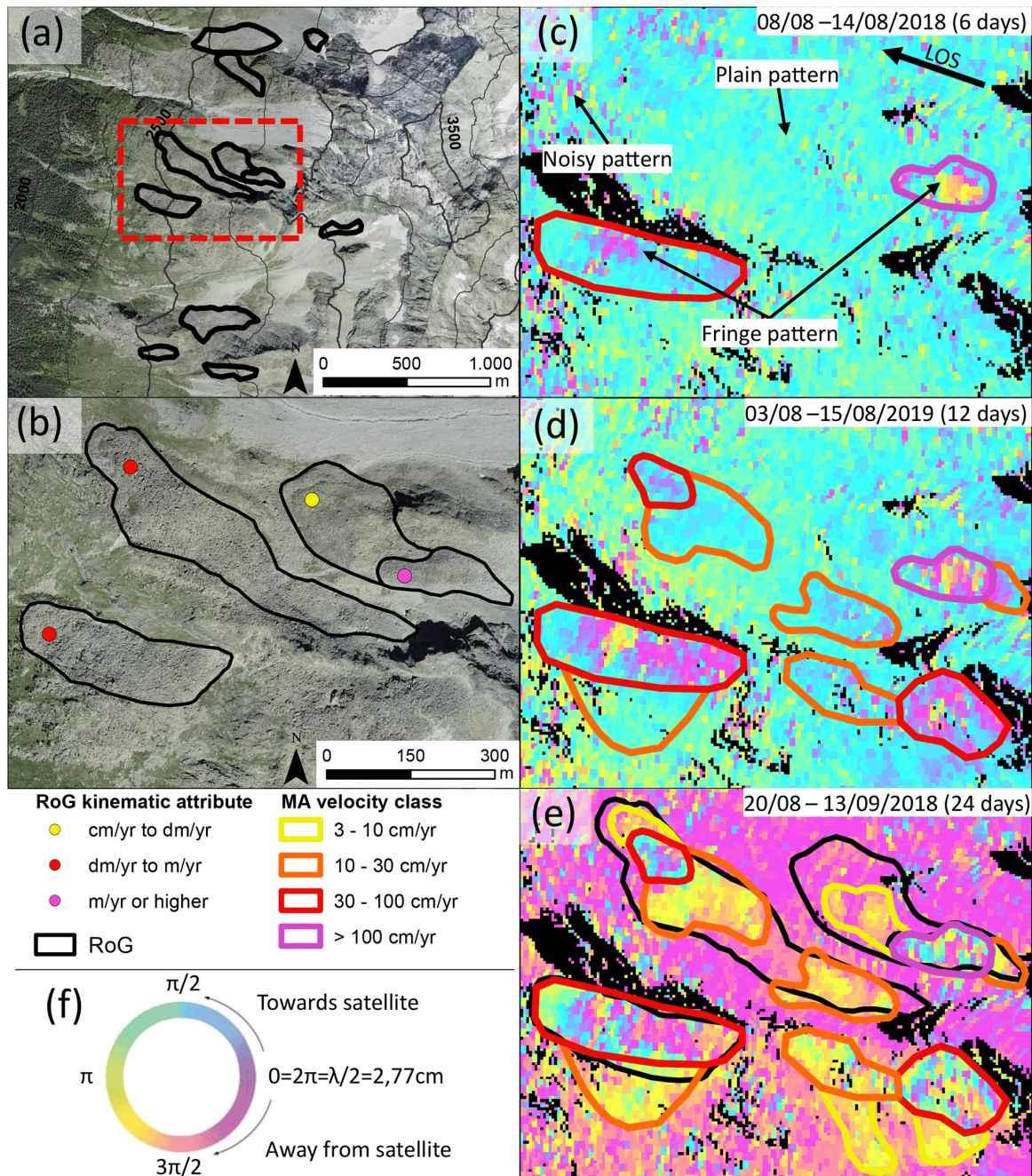


Figure 5. Example of RoGI in the Arolla region (location: $46^{\circ} 2' 24''$ N, $7^{\circ} 30' 36''$ E, 2750 m a.s.l.), Swiss Alps. **a)** outlines of the rock glaciers are in black, and the location of an investigated area is highlighted in red. Orthoimages from © Google Earth 2019. **c–e)** Sentinel-1 interferograms from the descending orbit, including examples of InSAR signal patterns; layover and shadow areas are masked out (black). **(c)** Two MAs are detected on the 6d interferogram. **d–e)** Using 12d and 24d, additional MAs are visible. This is an example where the MA outlines do not fully match the geomorphological outline of the rock glaciers. MAs (SE-border) not related to rock glaciers are visible and mapped. **b)** Based on MAs, the kinematic attributes are assigned to rock glaciers. **f)** Fringe cycle related to the change of colour: a complete fringe cycle is equivalent to a change of half a wavelength (2.77 cm for Sentinel-1) in the LOS direction (Bertone et al., 2022).

2.2.3 MA delineation

The detected MA is delineated using a polygon that is manually drawn around the relevant InSAR pattern. The polygon describes an area where a given InSAR signal is detected in most of the available interferograms.

MAAs have to be outlined according to the following requirements:

- **Outlines should be drawn starting from interferograms with small time intervals (and small wavelengths).** Subsequently, by increasing the time intervals, the outlines can be refined and additional outlines (landforms with lower velocities) can be identified and drawn. As the extent of a MA could partly vary depending on the observation time and the velocity patterns, the final outline should delineate a MA with homogeneous velocity, and the velocity range within a MA should fit the classes of velocity defined in Section 2.3.3.
- **The outline does not necessarily fit the geomorphological outline of the related RGU.** It has to match the limits of the detected InSAR pattern (*Figure 5e*).
- **A MA can override the geomorphological limits of the related RGU** (*Figure 5e*), e.g. when two overlapping landforms are moving at rates, that are not significantly different.
- **Several polygons can be related to the same landform and several MAs can be overlapping.** Slower MAs can embed faster ones (*Figure 5e*).
- **The minimum extent of a MA depends on the spatial resolution of the data inputs and the size of the landform.** 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. fitting 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 case of uncertainty, we recommend not to delineate the MA.

For the following steps, two important elements have to be considered:

- The border of a MA is often non-sharp, depending also on the detection capability of the used technique, making a precise delineation difficult. In this case, a low to medium reliability has to be noted (Section 2.3.4).
- Areas outside of any delineated MA refer either to the absence of movement, to a movement under the detection limit or to unreliable data. The lack of an identifiable MA does not mean necessarily mean that no movement occurs. With no additional information, the kinematic attribute must remain undefined (Section 2.4.2).

An example of the MA delineation procedure is showed in *Figure 6*.

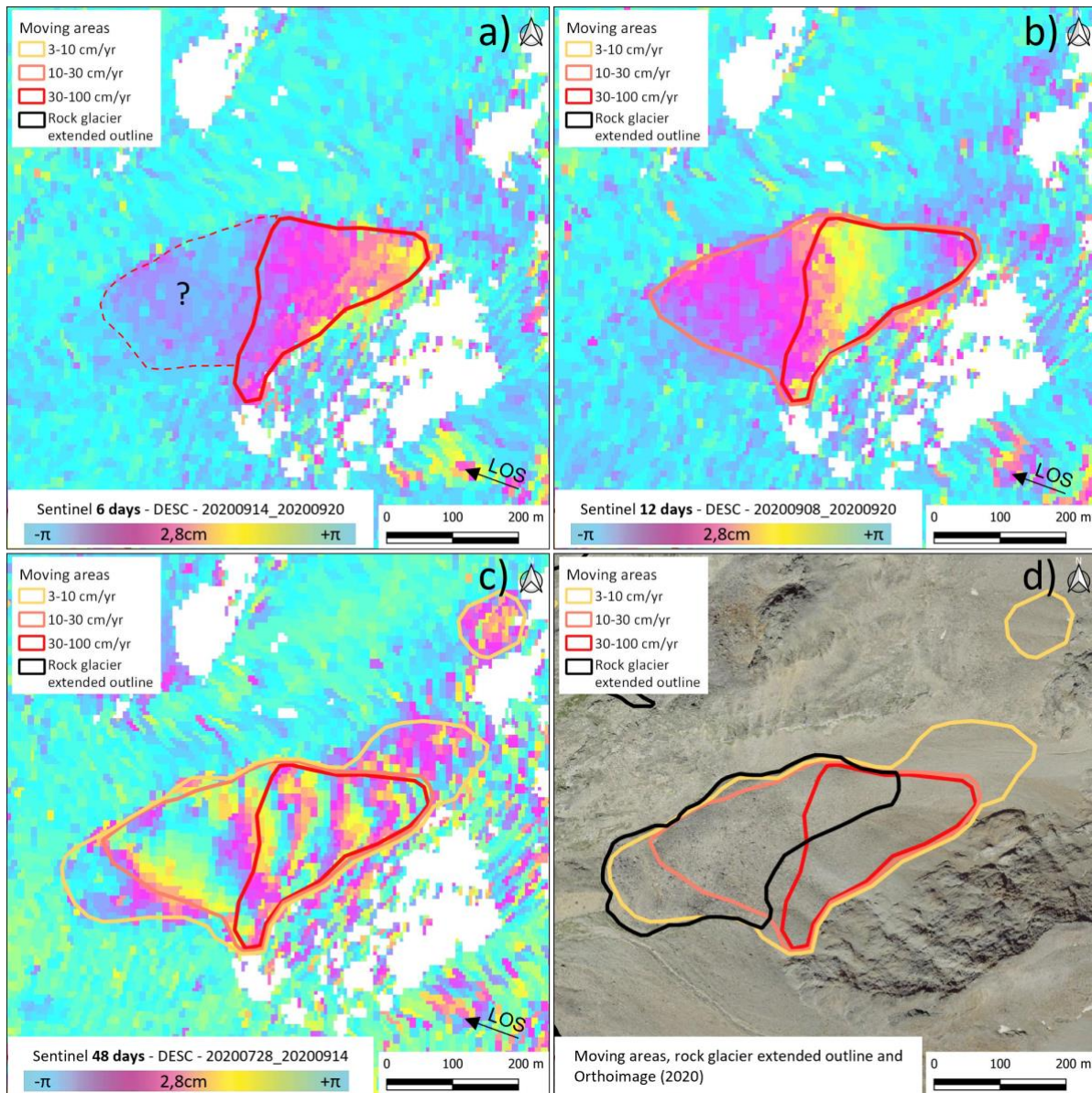


Figure 6. MA identification using Sentinel-1 interferograms. A large set of interferograms with different time intervals is required to confirm the delineation/characterization of the MAs. **a)** A signal is detected on a 6-day interferogram (red line) and a small signal could be detected on the left (dashed line). **b)** Using a 12-day interferogram, a signal could again be seen on the upper part and the small signal detected on the 6-days interferogram is now clearly visible. **c)** On a 48-day interferogram, the frontal and upper parts are well detected and confirm the delineation of the previous polygons. The upper part becomes partially decorrelated. **d)** Orthoimage with rock glacier outline and MAs. New MAs become visible (orange polygons). Three MAs have been drawn on the rock glacier (velocity: 30-100cm/yr in red, 10-30 cm/yr in orange and 3-10 cm/yr in yellow). Note that the MAs do not follow the delineation of the rock glacier (black polygon: extended footprint).

2.2.4 MA velocity classification

The MA velocity classification is recommended to determine the KA of each inventoried RGU (Section 2.3). The use of velocity classes intends to facilitate the assignment of a homogeneous simplified velocity information to the rock glaciers.

The velocity class of InSAR-derived MAs (“Vel.class” attribute of the MovingAreas_* layer) refers to the **1D LOS InSAR displacement rate on back-facing slopes**. It is **strictly stamped by time characteristics** (“Time.Obs” attribute of the MovingAreas_* layer):

- The **observation time window**, i.e. the period during which the detection and characterization is computed/measured (e.g. multi-annual, annual, intra-annual). The minimum required duration is **one month** (several months are preferable) **in snow-free periods**.
- The **temporal frame**, i.e. the duration during which the periodic computations/measurements are repeated and aggregated for defining the MA (i.e. during which year(s)).

The velocity class should reflect the spatio-temporal averaged displacement rate of the landform and neither a brief intra-annual variation nor an extreme. When MAs are detected/characterized using time intervals shorter than one month (e.g. 6 days for Sentinel-1), several pairs should be used in order to cover the minimal observation time window of one month (e.g. at least two 6-day interferograms within a month). 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 categorization of the velocity is performed exploiting two main approaches:

- a) **Classification using the InSAR colour scheme** by comparing the phase signal inside and outside a detected MA at different time intervals (*Figure 2*). This is done in two steps: first, by counting the entire fringe cycles from a point assumed to be stable relative to the detected MA (using *Figure 2*); second, by converting the fringe cycle into velocity per year (use Annex A for conversion).
- b) **Classification based on the detection limits according to the time intervals between images**, i.e. identifying the time intervals at which a moving feature is coherent or decorrelated. This is done by comparing the signal of each interferogram with the detection capability of each sensor and time interval (bars on *Figure 3*). Decorrelated patterns indicate that the displacement rate is greater than the maximum detectable limit within that interferogram (i.e. more than the upper limit of the bar). No visible fringe patterns indicate that the displacement rate is less than the minimum detectable limit with that interferogram (i.e. less than the lower limit of the bar). Visible fringe patterns indicate that displacement is detectable within that interferogram and can be used to categorize the MA velocity.

In areas where additional datasets are available, **a third approach can be used, ideally in combination with the two previous ones:**

- c) **Averaged velocity maps based on unwrapped interferograms and multi-temporal InSAR techniques (when available)**. InSAR stacking, SBAS or PSI maps are valuable to spot areas with movement when mapping large regions. In areas with very low velocity (typically over transition/relict landforms with mm/yr to a few cm/yr) and in areas with major atmospheric effects, these products are also more robust than single interferogram analyses. However, data gaps can

occur on fast-moving landforms, especially on datasets based on interferograms with long time intervals (such as PSI). No data does not mean that there is no movement, but can mean indicate the exact opposite. In areas where the velocity is high with a large gradient of velocity between neighbouring pixels, the results can also be affected by major errors. These are generally often easy to identify: the area is covered by a random combination of decorrelated areas (no data) and patches with various colours: blue (movement towards the sensor) and red (movement away from the sensor).

1D LOS velocity classes:

- Undefined
- < 1 cm/yr (no movement up to some mm/yr)
- 1–3 cm/yr
- 3–10 cm/yr
- 10–30 cm/yr
- 30–100 cm/yr
- > 100 cm/yr

The additional attribute named “Comment” can be used to give more detail to the classification (e.g. heterogeneity inside the MA, etc.). More detailed information about very fast landforms (> 100 cm/yr), e.g. from GNSS, optical photogrammetry or very high temporal resolution interferograms) can also be explained in this field.

An example of velocity classification is showed on *Figure 7* for seven MAs delineated based on different SAR sensors and time intervals. Looking at Sentinel-1 6-day interferograms (*Figure 7b*), two MAs can be identified with fringe pattern (labels 1 and 3 on *Figure 7a*). When increasing the time interval (i.e. 12-day interferogram, *Figure 7c*), additional MAs become visible (label 2, 4 and 6 on *Figure 7a*). More details can be observed with Cosmo-SkyMed (*Figure 7d, 7e and 7f*), due to the higher spatial resolution. By observing the 9-day interferogram (*Figure 7d*), two MAs characterized by many fringes can be identified (labels 1 and 3 on *Figure 7a*), while others have a partial fringe pattern (labels 2, 4 and 6 on *Figure 7a*). When increasing the time interval (i.e. to 16 days), MA 3 becomes completely decorrelated (noisy pattern), and the MA 1 become partially decorrelated. Fringe patterns can be well identified in MA 4, and two additional MAs can be detected (labels 5 and 7 on *Figure 7a*). When further increasing the time interval (i.e. 32 days), MA 1 also becomes completely decorrelated (noisy pattern) and fringe patterns become well visible in MAs 4, 5 and 7.

Based on this example, the two following main velocity classification methods can be applied:

a) Classification using the InSAR color scheme:

According to the color cycle shown in *Figure 2*, MA 3 is classified as > 100 cm/yr because a complete fringe cycle is visible on the Sentinel-1 6-day interferogram (i.e. 2.8 cm in 6 days). In the Cosmo-SkyMed 9-day interferogram, at least two complete fringe cycles are visible, referring to a full wavelength (3.1 cm) occurring in 9 days. MAs 1, 2 and 6 are classified as 30–100 cm/yr, as a complete fringe cycle (2.8 cm) is measured in the Sentinel-1 12-day interferogram. In the Cosmo-SkyMed 9-day interferogram, a complete fringe cycle is equally visible, indicating movement of 1.55 cm in 9 days. MAs 4, 5 and 7 are classified as 10–30 cm/yr, as a complete fringe cycle is not visible in the Sentinel-1 6-day and 12-day interferograms. In the Cosmo-SkyMed 32-day interferogram, a complete fringe cycle is visible, which indicated movement of 1.55 cm in 32 days.

b) Classification based on the detection limits according to the time intervals between images:

Based on *Figure 3*, MA 3 is classified as > 100 cm/yr, as the fringe pattern is visible only in the 6-day (Sentinel-1) and 9-day (Cosmo-SkyMed) interferograms, i.e. the interferograms with time intervals of more than 15 days become decorrelated. MAs 1, 2 and 6 are classified as 30–100 cm/yr, as the fringe pattern is visible in the 6-day and 12-day Sentinel-1 interferograms, as well as in the 9-day and 16-day Cosmo-SkyMed interferograms. It becomes decorrelated in the 32-day Cosmo-SkyMed interferogram. MAs 4, 5 and 7 are classified as 10–30 cm/yr, as the fringe pattern is not visible in the 6-day Sentinel-1 interferogram, but becomes visible in the 9-day Cosmo-SkyMed interferogram.

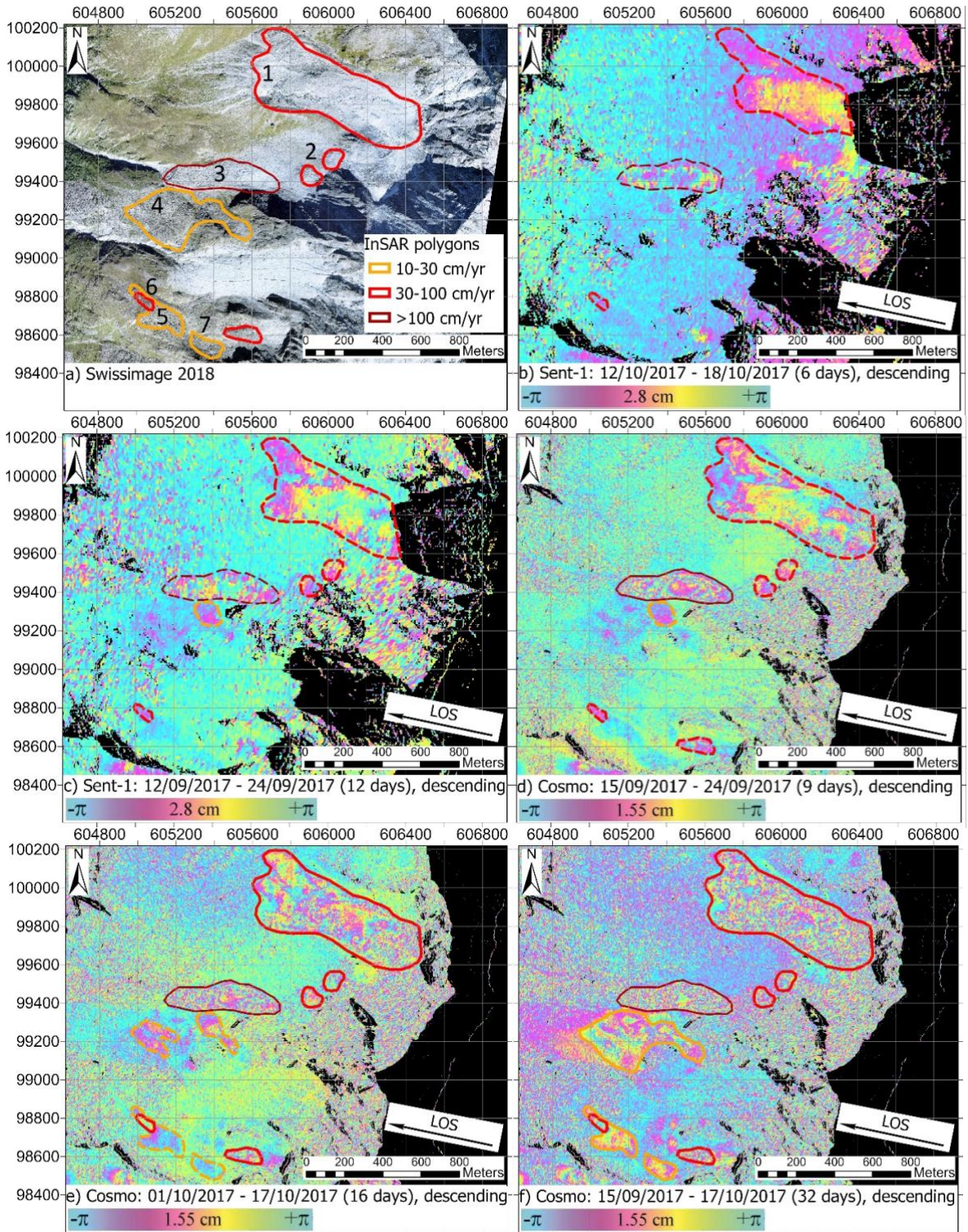


Figure 7. Example of MA outlining and classification (Arolla area, Western Swiss Alps). **a)** Orthoimage. **b-f)** Sentinel-1 (b-c) and Cosmo-SkyMed (d-f) interferograms. Areas affected by layover and shadow have been masked out (black). Dashed lines are the temporary outlines of MAs detected on an interferogram. Solid lines are the final outlines of MAs based on all interferograms.

When available, **averaged velocity maps based on unwrapped interferograms** can also be used. The averaged results are expressed in mm/yr, cm/yr or m/yr and can therefore be categorized using the standard velocity classes as shown in *Figure 8* and *Figure 9*. The KA attribute is then based on the criteria described in Section 2.3. Note that depending on the maximum time interval used to build the interferograms exploited to generate such averaged products, the detection capability is highly variable. When using PSI/IPTA techniques based on several years of SAR images, areas moving more than a couple of dm/yr are likely to become decorrelated (*Figure 10a*). To document areas moving up to dm–m/yr, averaged products based on short temporal baseline interferograms (only 6- and 12-day intervals using Sentinel-1) must be used (*Figure 10b*). It is recommended to use these maps **in combination with the single interferogram approaches** described previously.

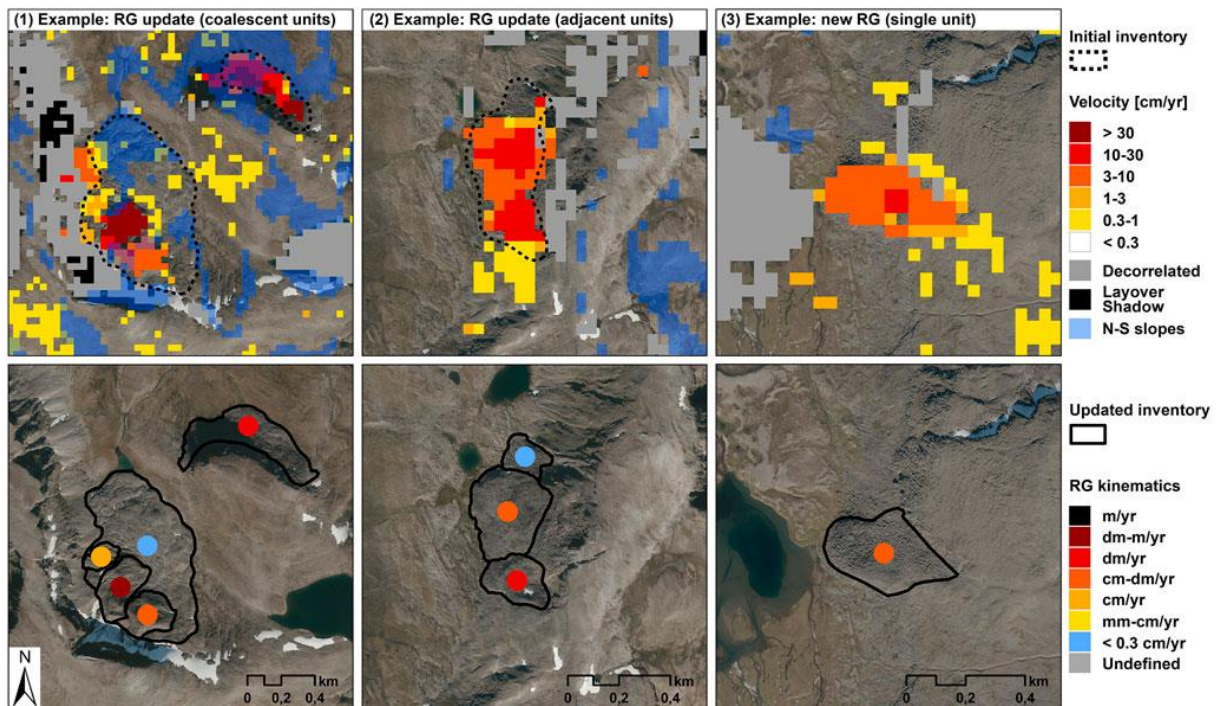


Figure 8. Example of categorized InSAR stacking based on unwrapped interferograms with variables time intervals (short intervals for high velocity, long intervals for low velocity) (Rouyet et al., 2021).

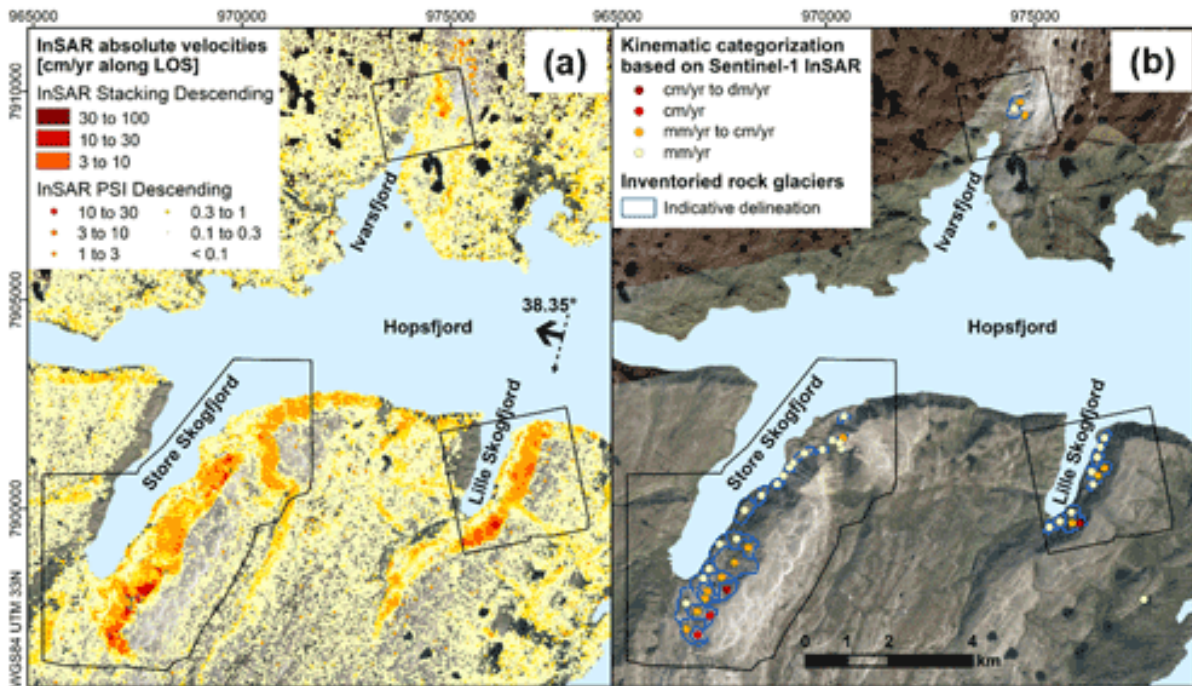


Figure 9. Example of categorized InSAR stacking and PSI results based on unwrapped interferograms with variables time intervals (short intervals for high velocity, long intervals for low velocity) ([Lilleøren et al., 2022](#)).

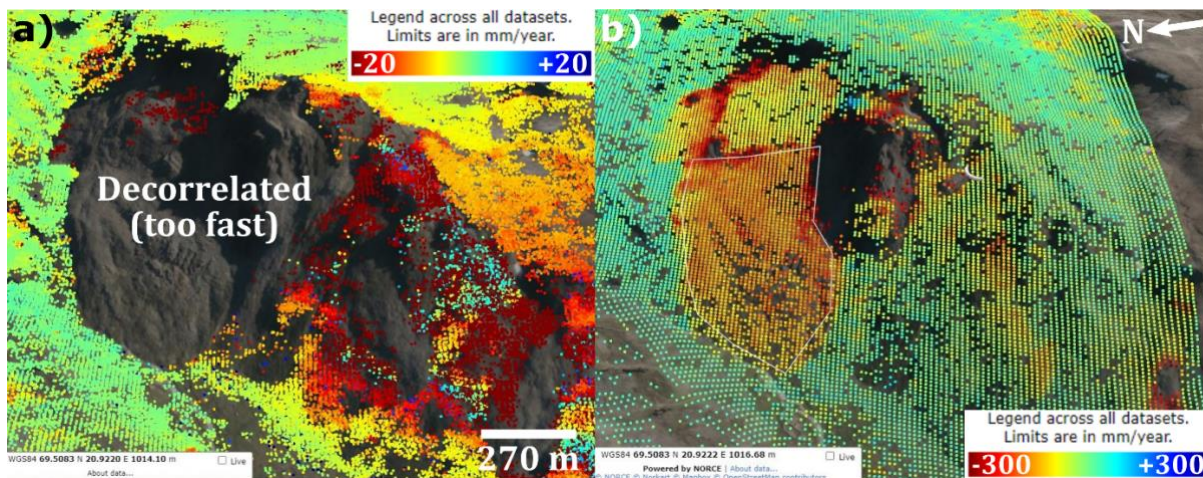


Figure 10. Comparison between two types of averaged velocity maps based on unwrapped interferograms. **a)** PSI averaged velocity maps over a fast-moving rock glacier showing that the technique fails to document the fastest part of the lobe. Areas moving more than a couple of dm/yr are decorrelated (no data). **b)** Averaged velocity map (InSAR stacking) based on 6-days and 12-days Sentinel-1 interferograms over the same rock glacier. Velocity up to several dm/yr is detected.

2.2.5 MA reliability

The reliability (or the degree of confidence) of the detected MA has to be qualitatively assessed (low, medium, high) according to the quality of both the outline detection and the velocity class assignment (“Rel.MA” attribute of the MovingAreas_* layer).

Reliability categories:

- **Low:** A MA can be identified but both the outline and the signal interpretation (velocity categorization) are uncertain.
- **Medium:** A MA can be identified but either the signal interpretation (velocity categorization) or the outline is uncertain.
- **High:** A MA can be identified and characterized based on a clear signal. The geometry is well appropriate (back-facing slope) and the data has high quality, allowing for reliable outlining and signal interpretation (velocity categorization).

When analysing North- and South-facing slopes, or when the number of interferograms is low, the reliability of the detection decreases. When the reliability in classifying velocity is too low due to specific technical limitations, the velocity class must be set as “undefined”.

When available, the comparison can be performed using other kinematic data (e.g. in-situ measurements). This approach allows for consolidating the assignment of the velocity class of the InSAR-based MA and improving the KA reliability (Section 2.4.2).

2.3 Assign a kinematic attribute (KA) to a rock glacier unit (RGU)

2.3.1 KA definition and categories

The KA documents the overall kinematic state of the rock glacier unit (RGU) at the time of the inventory. It is defined in detail in the [Baseline concepts document: Kinematics as an optional attribute of standardized rock glacier inventories](#).

The KA consists of **semi-quantitative categories expressing the multi-annual downslope velocity of an entire RGU**, defined as followed:

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

The default category is 0 “Undefined”. The RGU falls into this category when:

- No (reliable) kinematic information is available,
- The rock glacier is mainly characterized by an identified MA of undefined or unreliable velocity,
- The kinematic information is too heterogeneous.

When InSAR-based MA have been delineated and characterized, the activity assessment (“Acti.Ass” attribute in RGU_PrimaryMarker_* or RGU_Outlines_* layers) can follow a kinematic approach. In this case, the KA (“Kin.Att”) can in that case be filled.

Three others elements associated with the KA must be documented:

- The KA reliability (“Rel.Kin”):
 - NULL: if the KA is undefined.
 - Low: low reliability of the MAs and/or heterogenous coverage.
 - Medium: medium or high reliability of the MAs and/or heterogenous coverage.
 - High: clear KA assignment based on high MAs reliability quality and unambiguous distribution over the rock glacier.
- Multi-year validity time period (“Kin.Period” attribute) used to assign the KA.
- The type of data (“TypeOfData” attribute) used to assign the KA (“Radar” category in this case).
- Additional information regarding the datasets and the quality of the attribution (spatial representativeness: percentage of surface documented by MA) are documented in the field “Kin.Comment”.

2.3.2 Translation rules: from MA to KA

The MA velocity should be transferred to the proper KA category in order to indicate the overall multi-annual rate of movement observed on a dominant part of the rock glacier surface. **Manual transfer from a velocity class of an InSAR-derived MA to the rock glacier KA is recommended** instead of applying an automated way to extract the value.

The two following **cases a) and b)** present recommendations based on two different observation time windows. They are applicable if the following conditions are fulfilled:

- 1D LOS InSAR measurements are performed on back-facing slopes.
- A dominant part of the RGU is covered by one single MA.

In the case of several variable MAs:

- The assigned category should represent **the dominant velocity class of the RGU**.
- If two equally dominant, but directly adjoining KA categories (e.g. 4 and 5) are present on a RGU, **the category of the area closer to the front is favoured for the attribution**.
- In case of a larger spread of equally dominant categories on the same RGU (e.g. 4 and 6), **the median category** (e.g. 5) **should be used, with a comment about the heterogeneity and a medium to low reliability**.
- If MAs show a large heterogeneity over the unit (e.g. more than three MAs with velocity classes falling into various categories), **the category “0. Undefined”** should be chosen. A large heterogeneity can also indicate the need to refine/redefine the delineation of the initial units (if confirmed by geomorphological evidences).

An additional field named “Kin.Comments” can be used to provide more detail about the categorization, e.g. additional information about the data properties and the quality of the attribution (spatial representativeness: percentage of surface documented by MA, information about where the movement is faster/slower, etc.)

Case a: Annual or multi-annual observation time window

A dominant part of the RGU is depicted by a single MA, whose associated velocity class is reliably characterized at an annual or multi-annual observation time window (i.e. annual interferograms). This typically concerns MAs with the following velocity classes:

1. < 1 cm/yr
2. 1–3 cm/yr

(Note that larger movement is decorrelated using annual interferograms)

The KA of the considered RGU can be assigned as following (only for back-facing slope in 1D LOS InSAR measurements):

Velocity classes (annual)

1. < 1 cm/yr
2. 1–3 cm/yr

Kinematic attribute

1. < cm/yr
2. cm/yr

Case b: Observation time window shorter than 1 year

A dominant part of the RGU is covered by a single MA, whose associated velocity class is reliably characterized at an observation time window shorter than 1 year (at least one month in snow-free periods). This typically concerns MAs with the following velocity classes:

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

(Note that smaller movement remains undetected using short time intervals)

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

<u>Velocity classes (summer)</u>	<u>Velocity classes (annual)</u>	<u>Kinematic attribute</u>
3. 3–10 cm/yr	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	6. or 7. m/yr or > m/yr *

* the category “m/yr” or “> m/yr” should be selected and a note “m/yr or higher” should be indicated in the field “Kin.Comment”.

If additional kinematic information is available (GNSS, aerial photogrammetry, very high temporal resolution interferograms) and allows for detailing velocities that exceeds m/yr, this must be specified in the field “Kin.Comment”):

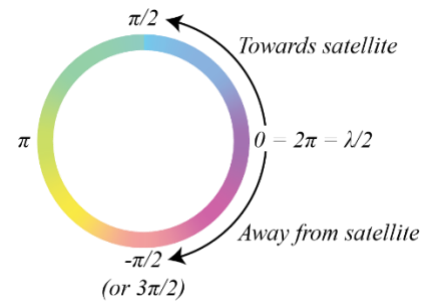
<u>Velocity classes (summer)</u>	<u>Velocity classes (annual)</u>	<u>Kinematic attribute</u>
6. 100–300 cm/yr	80–240 cm/yr	6. m/yr
7. > 300 cm/yr	>240 cm/yr	7. > m/yr

ANNEX A: Converting fringe patterns (colour cycle) to velocity (cm/yr)

Annual velocity (cm/yr) is calculated as $disp / time * 365$, where $disp$ is the displacement shown on the interferogram and $time$ is the interval used to generate the interferogram. A displacement for an entire fringe cycle is half the wavelength of the SAR sensor.

For example, with one entire fringe cycle on a Sentinel-1 12 days interferogram, we calculate the corresponding annual velocity as:

$$\frac{\lambda/2}{12} * 365 = \frac{2.75}{12} * 365 = 84 \text{ cm/yr.}$$



C-band SAR: SENTINEL-1/RADARSAT-2. Wavelength $\lambda = 5.5 \text{ cm}$

Fringe pattern (fraction of half a wavelength)	Velocity (cm/yr) based on 6 days interferograms	Velocity (cm/yr) based on 12 days interferograms	Velocity (cm/yr) based on 18 days interferograms	Velocity (cm/yr) based on 24 days interferograms
1/5	33	17	11	8
1/4	42	21	14	10
1/3	56	28	19	14
1/2 (half)	84	42	28	21
2/3	112	56	37	28
3/4	125	63	42	31
4/5	134	67	45	33
1 (entire)	167	84	56	42

L-band SAR: ALOS-2/SAOCOM Wavelength $\lambda = 23.6 \text{ cm}$

Fringe pattern	8 days	16 days	70 days	364 days
1/5	108	54	12	2
1/4	135	67	15	3
1/3	179	90	21	4
1/2	269	135	31	6
2/3	359	179	41	8
3/4	404	202	46	9
4/5	431	215	49	9
1	538	269	62	12

X-band SAR: TerraSAR-X/Cosmo-SkyMed. Wavelength $\lambda = 3.1 \text{ cm}$

Fringe pattern	9 days	11 days	16 days	22 days
1/5	13	10	7	5
1/4	16	13	9	6
1/3	21	17	12	9
1/2	31	26	18	13
2/3	42	34	24	17
3/4	47	39	27	19
4/5	50	41	28	21
1	63	51	35	26

ANNEX B: Technical advice

This annex shows some examples of discrepancies between operators that have been identified in the results of an exercise performed during a RGIK workshop in February 2020.

Note that this is based on a past version of the InSAR guidelines, resulting in different colours of the MA and RGU outlines, compared to the other figures of this document.

Case 1) Two or more MA outlines (related to the same RGU) with different velocity classes

Case 2) Two or more MA outlines (related to the same RGU) with different velocity classes observed in very different time observation windows.

Case 3) Two or more MAs superimposed with different velocity classes

Case 4) RGU not covered by MA(s)

Case 5) Two adjacent MAs cover the same RGU

Case 6) RGU partly covered by MA(s)

Case 7) MA velocity class > 100 cm/yr

Case 8) Complex RGU with diverse InSAR signal

For each case, 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 RGU) with different velocity classes

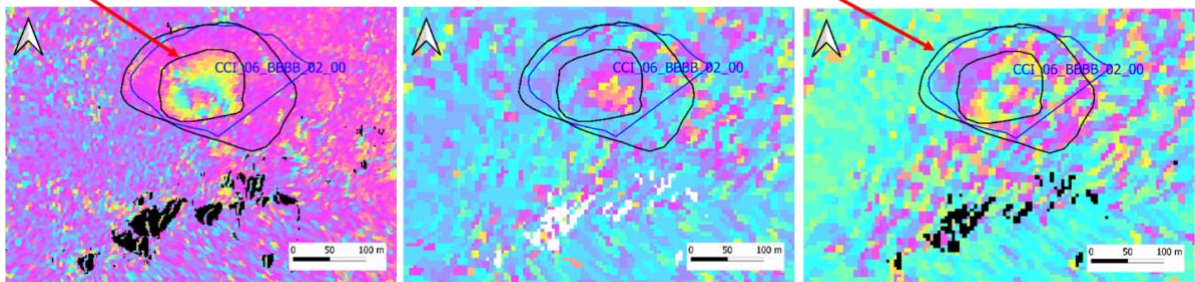
>> Rules:

- MAs related to the same RGU should be detected and outlined using all 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

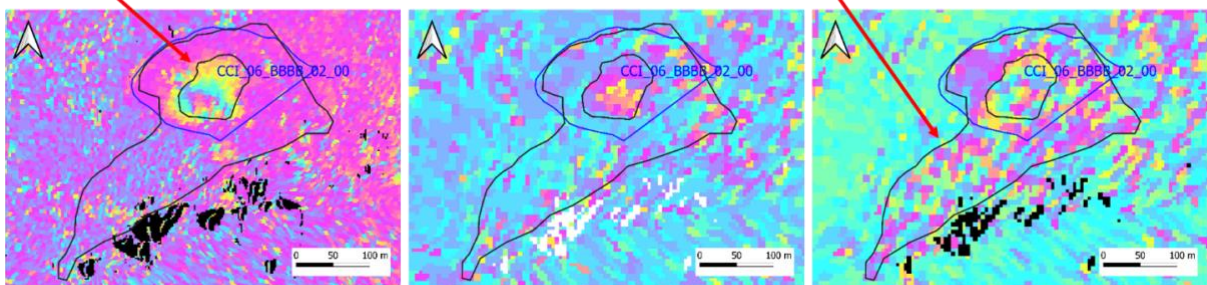


TERRA_20140723_20140814_22d_desc_diff ALOS2_20160712_20160920_70d_desc_diff ALOS2_20160712_20170808_392d_desc_diff

>> 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:

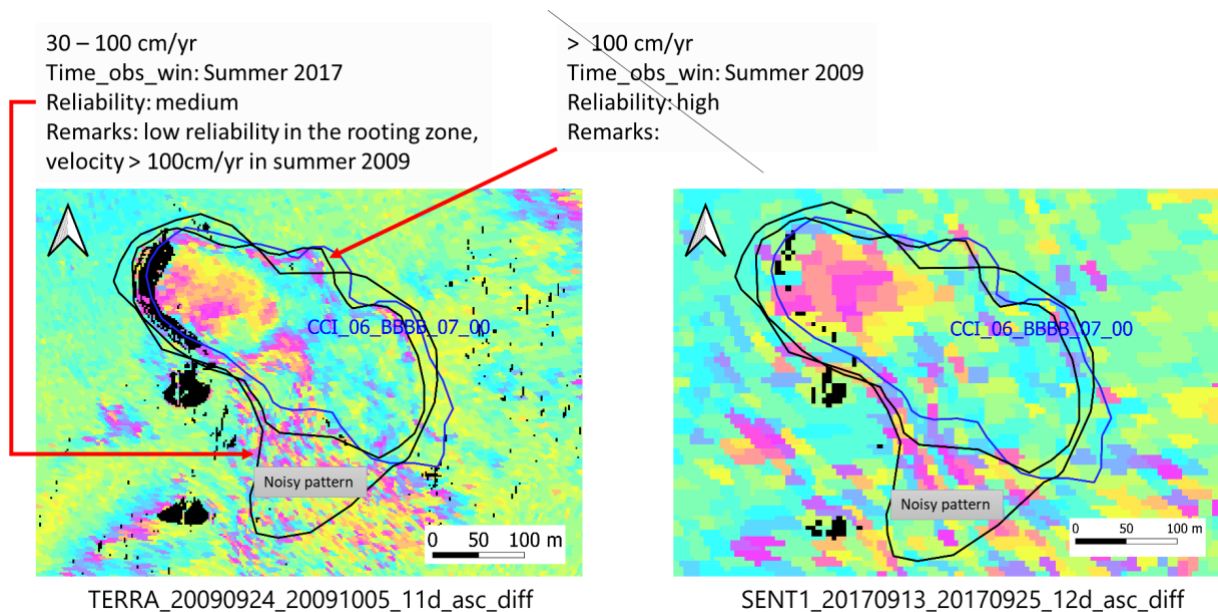
- As the faster MA is visible on summer 2016 and 2017 interferograms, it should also be visible on an annual 2016 – 2017 interferogram (e.g. with decorrelation).
- Faster MA is visible in all summer interferograms. Reliability should be set to “high”.
- Slower MA is visible only in one annual interferogram.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

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

>> Rules:

- If a long period separates the time observation windows of two analysed interferograms (e.g. summer 2009 and summer 2017), only the MA detected in the latest period should be outlined and classified. In the field “Comment”, information 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 2017), only one MA should be mapped and classified, according to the mean velocity observed in both summers. Indicate in the field “Comment” that there is variability between the years and document which summer was the fastest.

>> Example:



>> Notes:

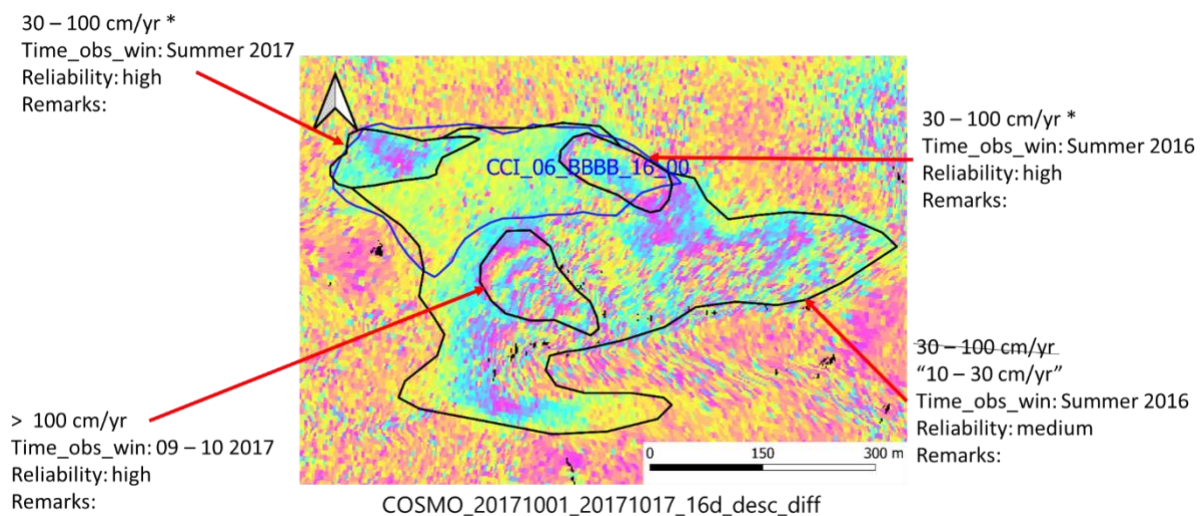
- MA with velocity class 30–100 cm/yr includes a part with noisy pattern in the rooting zone (southern part) detectable in all interferograms. It is certainly related to artefacts, and should be excluded.
- A long period separates the two time observation windows (i.e. summer 2009 and summer 2017), then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

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

>> Rules:

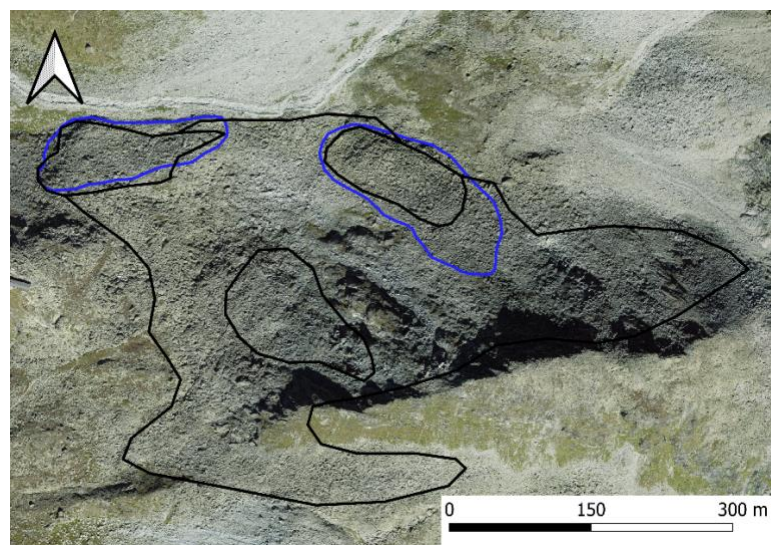
- Different outlines should be drawn when faster MA(s) are included in slower MA. If smaller MA(s) included in larger MA(s) have the same velocity classes, the smaller MA(s) should be removed or the velocity classes should be redefined.
- Note that a large heterogeneity can also indicate the need to refine/redefine the delineation of the initial geomorphological units (iterative process combining geomorphological and kinematic approaches).

>> Example:



>> Notes:

- *The velocity classes should be verified. Either the velocity classification is correct and the small MAs (*) should be removed (included in the largest MA), or the velocity classes should be redefined (e.g. here change the velocity class of the largest MA)*
- *The RGU(s) may need to be refined. An example is shown below:*



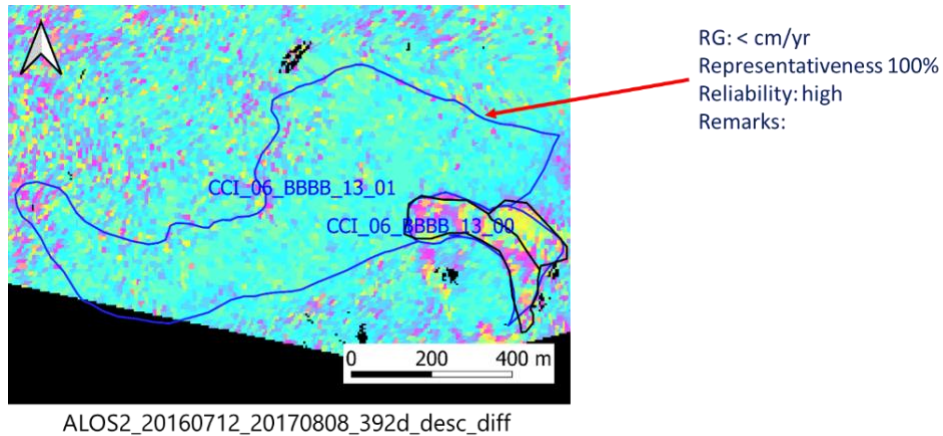
Case 4) RGU not covered by MA(s)

>> Rules: Check the available annual InSAR interferograms:

- If a similar plain pattern is visible both inside and outside the RGU, it means that no movement occurs. Therefore, the KA can be set to “< cm/yr”, and the reliability is “high”.
- If a decorrelation (noisy pattern) is visible on the RGU, it means that an estimation of a reliable velocity is not possible. The KA has to be set to “undefined”. Comments about the decorrelation patterns can be added in the field “Comment”.

When a plain or noisy pattern is visible on the entire RGU, the spatial representativeness is 100%.

>> Example for CCI_06_BBBB_13_01 RGU:

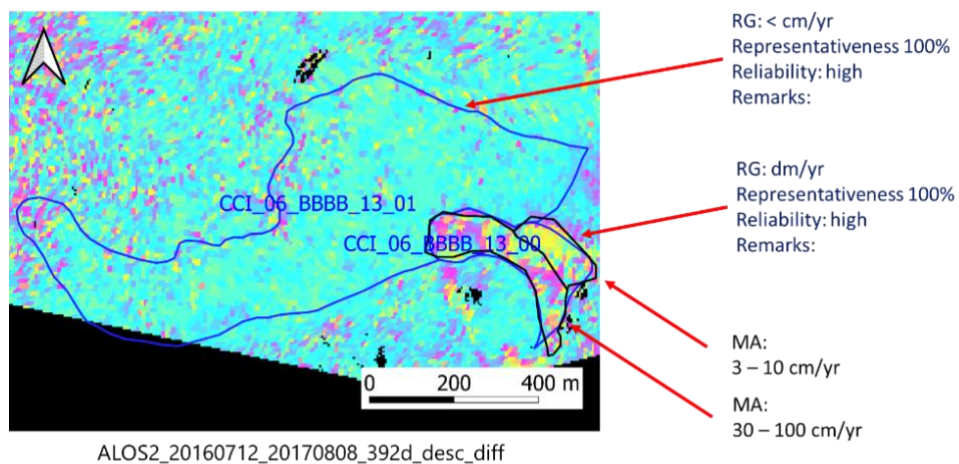


>> Notes: A plain pattern on the CCI_06_BBBB_13_01 RGU is visible in an annual interferogram, it indicating that no movement is detected. Therefore, the KA can be set to “< cm/yr” and the reliability to “high”.

Case 5) Two adjacent MAs cover the same RGU

>> Rule: The KA can be assigned using a mean value between the MAs.

>> Example for CCI_06_BBBB_13_00 RGU:



>> Note: CCI_06_BBBB_13_00 is covered by two MAs. For the KA, a mean value of dm/yr is chosen.

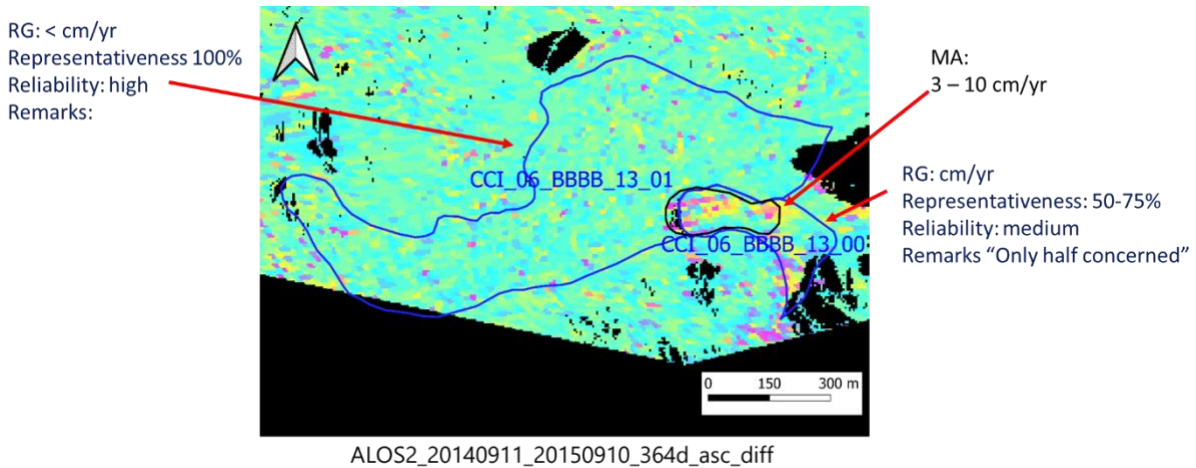
Case 6) RGU partially covered by MA.

>> Rules:

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

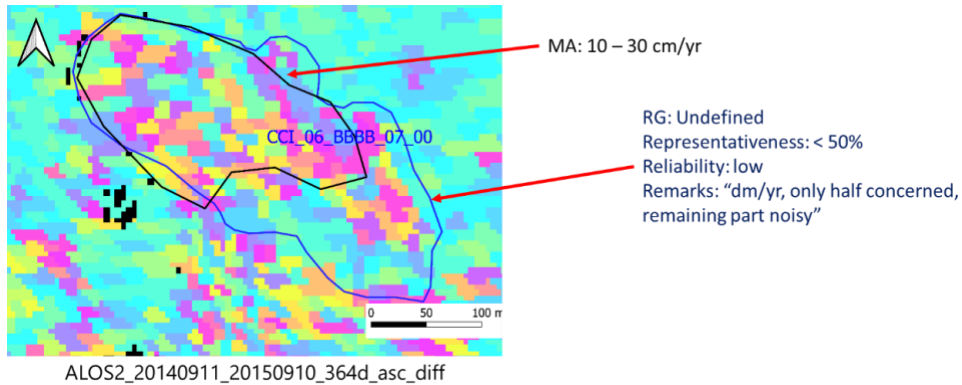
- If a plain pattern on the RGU not covered by MA(s) is visible, no movement is detected and velocity is “< cm/yr”. The KA can be assigned using a mean value between the detected MA(s) and the area with velocity “< cm/yr”. The spatial representativeness can be documented considering the MA(s) extension and the area with velocity “< cm/yr” (i.e. area with plain pattern). Information about the limited MA(s) extension can be added in the field “Comment” (e.g. “only half concerned”). A large heterogeneity can also indicate the need to refine/redefine the delineation of the initial geomorphological units.
- If a decorrelation (noisy pattern) on the RGU not covered by MA(s) is visible, it is not possible to estimate a reliable velocity. The KA has to be set to “Undefined” if the spatial representativeness is < 100. Additional information about the detected decorrelation and an estimated KA can be added into the field Comments. If the spatial representativeness is between 50–75% the KA can be assigned depending on the detected velocities of MA(s), but the reliability should be set to “low”.

>> Example for CCI_06_BBBB_13_00 RGU:



>> Notes: if a plain pattern is partially visible on the annual interferogram, in a part of the RGU that is not covered by an initially delineated MA, the KA must be attributed accordingly. CCI_06_BBBB_13_00 RGU can be classified as “cm/yr” considering the MA velocity class of 3–10 cm/yr and the velocity < cm/yr visible on the RGU not covered by MA.

>> Example for CCI_06_BBBB_07_00 RGU:



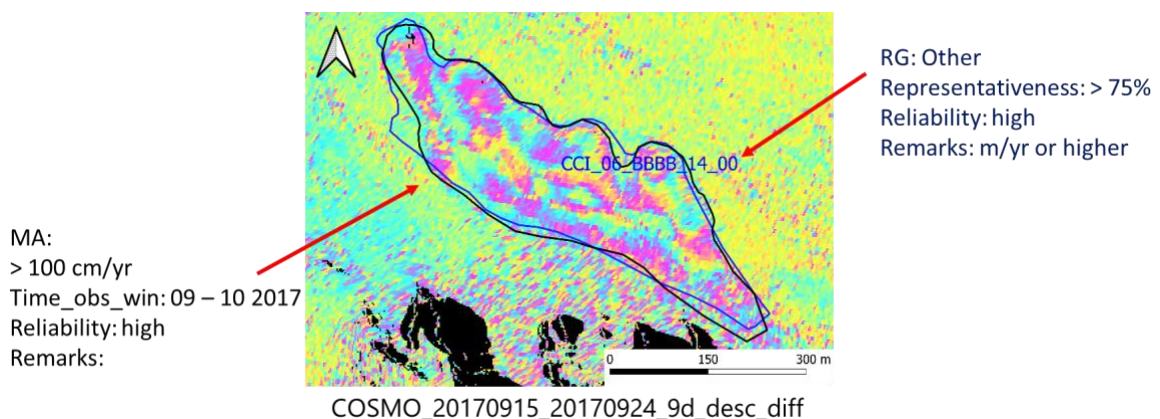
>> Notes: on annual interferograms, a noisy pattern is visible on the RGU not covered by a MA. In this example, the representativeness is near 50%: CCI_06_BBBB_07_00 should be classified as “undefined”. The detected noisy pattern and the estimated KA can be added in the field “Comment”.

Case 7) MA velocity class > 100 cm/yr

>> Rules:

- MA velocity class assignment: when it is possible to distinguish between the additional velocity classes 100–300 cm/yr and > 300 cm/yr, the velocity class is set to > 100 cm/yr but additional information can be added in the field “Comments”. This distinction is only possible very high temporal resolution (1–4 days) InSAR data or other kinematic data (e.g. GNSS) is available.
- KA assignment:
 - If the MA velocity class is “> 100 cm/yr”, with a comment “100–300 cm/yr” or “> 300 cm/yr”, the KA should be set to “m/yr” or “> m/yr” respectively. A description of how the velocity has been assessed (e.g. “validated by GNSS”, “optical photogrammetry”, “high temporal InSAR data”, etc.) can be added in “Comments”.

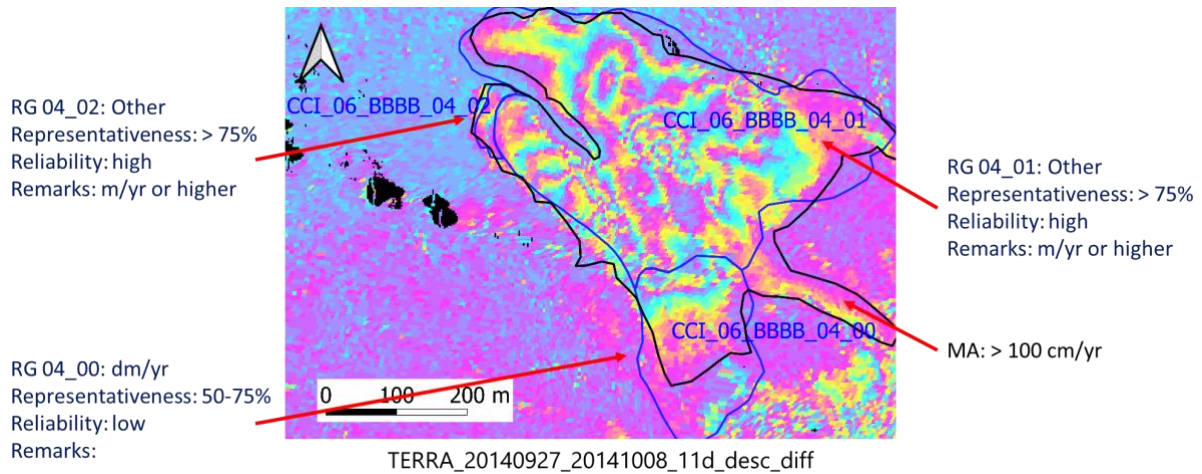
>> Example:



>> Note: If the MA velocity class is > 100 cm/yr, the KA is “m/yr” or “> m/yr”. Write a comment in “Kin.Comment”: m/yr or higher.

Case 8) Complex RGU with diverse InSAR signal

>> *Example:*



>> *Notes:*

- *RGU CCI_06_BBBB_04_00: a decorrelation (noisy pattern) on the RGU not covered by MA(s) is visible on annual interferograms. The RGU is classified as dm/yr with spatial representativeness between 50–75%, but the reliability is low (see Case 6).*
- *RGU CCI_06_BBBB_04_01: MA with velocity class > 100 cm/yr (see Case 7).*
- *RGU CCI_06_BBBB_04_02: MA with velocity class > 100 cm/yr (see Case 7). However, the small RGU (not related to a specific MA) suggests the need to renew the InSAR analysis to possibly detect specific movement. If a movement separated from the other MA is visible, re-outline the MA(s) at this location (see the example below).*

