CCI+ PERMAFROST

MOUNTAIN PERMAFROST: ROCK GLACIER INVENTORY (ROGI) AND ROCK GLACIER VELOCITY (RGV) PRODUCTS

D1.2 Product Specification Document (PSD)

VERSION 3.0

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PREPARED BY

b·geos
GAMMA REMOTE SENSING
UNIVERSITÉ DE FRIBOURG
UNIVERSITÄT FREIBURG
ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA
West University of Timisoara
TERRASIGNA
NORCE
UiO : University of Oslo

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Author team

Line Rouyet, Cécile Pellet, Alina Milceva, Reynald Delaloye, UNIFR

Francesco Brardinoni, Thomas Echelard, UNIBO

Flavius Sirbu, Alexandru Onaca, WUT

Valentin Poncos, TERRASIGNA

Line Rouyet, Tom Rune Lauknes, NORCE

Andreas M. Kääb, UiO

Tazio Strozzi, Philipp Bernhard, Nina Jones, GAMMA

Annett Bartsch, B.GEOS

ESA Technical Officer

Simon Pinnock

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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) Quantities, using primarily satellite imagery. The two traditional Quantities associated to the ECV Permafrost, Ground Temperature (GT) and Active Layer Thickness (ALT), were the primary documented products during Permafrost_cci Phase 1 (2018–2021). In Permafrost_cci Phase 2 (2022–2025), GT and ALT were complemented by the third ECV Permafrost Quantity: Rock Glacier Velocity (RGV). Permafrost_cci Legacy (2026–2027) is a 14-month extension to foster and extend the production of the ECV Permafrost Quantities initiated in the previous phases [AD-1] [AD-2].

This document focuses on the mountain permafrost component of the Permafrost_cci project and the dedicated rock glacier products. In periglacial mountain environments, the 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. The interannual variations of the rock glacier creep rates are influenced by changing permafrost temperature, making RGV a key parameter for cryosphere monitoring in mountains.

Two mountain permafrost products are included in Permafrost_cci: Rock Glacier Inventory (RoGI) and Rock Glacier Velocity (RGV). RoGI is a valuable product to document past and present permafrost extent. It is a recommended first step to comprehensively characterise and select the rock glacier units (RGUs) to be used for RGV monitoring. RGV has been added by GCOS and Global Terrestrial Network for Permafrost (GTN-P) as ECV Permafrost Quantity [AD-3 to AD-5], following the recommendations suggested by the International Permafrost Association (IPA) Standing Committee on Rock Glacier Inventories and Kinematics (RGIK) (www.rgik.org). It is a valuable product to monitor changing mountain permafrost conditions. Together, RoGI and RGV products form a unique validation dataset for modelling in mountains, where direct permafrost measurements are scarce or even lacking. Using remote sensing, the generation of systematic RoGI at the regional scale and the documentation of 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, which 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 by SAR offset tracking and spaceborne/airborne optical photogrammetry.

This Product Specification Document (PSD) describes the specifications of the RoGI and RGV products, in agreement with the content of the User Requirement Document (URD) [RD-1]. The PSD version 3.0 presents the regions selected for RoGI production, as well as the rock glaciers selected for applying the RGV procedure, in the continuity of the PSD version 2.1 from Permafrost_cci Phase 2 [RD-2]. Product resolutions, accuracies, documented attributes, required metadata, file formats and naming conventions are also specified.

1 Introduction

1.1 Purpose of the document

The Product Specification Document (PSD) details the characteristics and properties of the Permafrost_cci mountain permafrost products: Rock Glacier Inventory (RoGI) and Rock Glacier Velocity (RGV). We focus here on the final products of Permafrost_cci Legacy. The specifications are defined to obtain mountain permafrost products that are consistent, robust and error-characterised. The structure, syntax and file naming conventions used to describe the final RoGI and RGV are also specified.

1.2 Structure of the document

Section 2 introduces the expected outcomes of the Permafrost_cci project, describes the regions selected for RoGI generation in the second iteration of the project, as well as the sites selected for RGV production. Section 3 details the product specifications and format. A bibliography complementing the applicable and reference documents (Sections 1.3 and 1.4) is provided in Section 4.1. A list of acronyms is provided in Section 4.2. A glossary of the commonly accepted permafrost terminology can be found in RD-13.

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] ESA. 2025. CCN 6 – CCI PERMAFROST – Legacy. Change Request. ESA-EOP-SG-CCN-6.

[AD-3] GCOS. 2022. The 2022 GCOS Implementation Plan. GCOS – 244 / GOOS – 272. Global Observing Climate System (GCOS). World Meteorological Organization (WMO).

[AD-4] GCOS. 2022. The 2022 GCOS ECVs Requirements. GCOS – 245. Global Climate Observing System (GCOS). World Meteorological Organization (WMO).

[AD-5] 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., Pellet, C., Delaloye, R., Brardinoni, F., Echelard, T., Sirbu, F., Onaca, A., Poncos, V., Lauknes, T. R., Kääb, A., Strozzi, T., Bernhard, P., Jones, N., Bartsch, A. 2026. ESA CCI+ Permafrost Phase 2 – CCN4 Mountain Permafrost: Rock Glacier Inventory (RoGI) and Rock Glacier Velocity Products (RGV). D1.1 User Requirement Document (URD), v3.0. European Space Agency.

[RD-2] Rouyet, L., Pellet, C., Delaloye, R., Brardinoni, F., Echelard, T., Sirbu, F., Onaca, A., Poncos, V., Lauknes, T. R., Kääb, A., Strozzi, T., Bernhard, P., Jones, N., Bartsch, A. 2026. ESA CCI+ Permafrost Phase 2 – CCN4 Mountain Permafrost: Rock Glacier Inventories (RoGI) and Rock Glacier Velocity Products (RGV). D2.1 Product Specification Document (PSD), v3.0. 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. 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-5] RGIK. 2023. InSAR-based kinematic attribute in rock glacier inventories (version 4.0). IPA Action Group Rock Glacier Inventories and Kinematics, 33 pp.

[RD-6] RGIK 2023. Rock Glacier Velocity as an associated parameter of ECV Permafrost: baseline concepts (version 3.2). IPA Action Group Rock glacier inventories and kinematics, 13 pp.

[RD-7] 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-8] Bertone, A., Barboux, C., Delaloye, R., Rouyet, L., Lauknes, T. R., Kääb, 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-9] 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-10] Rouyet, L., Echelard, T., Schmid, L., Pellet, C., Delaloye, R., Onaca, A., Sirbu, F., Poncos, V., Brardinoni, F., Kääb, 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-11] Rouyet, L., Pellet, C., Echelard, T., Schmid, L., Delaloye, R., Brardinoni, F., Sirbu, F., Onaca, A., Poncos, V., Lauknes, T. R., Wendt, L., Kääb, A, Strozzi, T., Bernhard, P., Bartsch, A. 2025. 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), v2.0. European Space Agency.

[RD-12] Adler, C., P. Wester, I. Bhatt, C. Huggel, G.E. Insarov, M.D. Morecroft, V. Muccione, 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-13] 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 Study areas and sites

2.1 Conclusions from Phase 1

The Permafrost_cci Phase 1 applied the RGIK guidelines to develop pilot RoGI and RGV results, primarily based on satellite remote sensing products. This led to the generation of 12 RoGIs in different regions worldwide. The RoGI identified a total of more than 5000 InSAR-based moving areas (MAs) and more than 3600 rock glaciers (RGs). In addition, preliminary velocity time series based on radar and optical remote sensing methods (InSAR, SAR offset tracking and aerial/satellite photogrammetry) were generated on selected rock glaciers in the Swiss, Norwegian, Argentinian, Tien Shan and Disko Island regions. The results are presented in the Permafrost_cci Phase I CRDP and an associated peer-reviewed publication [RD-8] [RD-9] (Bertone et al., 2022).

The results of the Permafrost_cci Phase 1 work led to the following conclusions:

- **For the RoGI products**, the project contributed to establishing a common inventorying procedure following a kinematic approach [RD-4] [RD-5]. In a very short period, a large group of operators from nine institutions worked in parallel to generate comparable RoGIs in several mountain ranges worldwide. It was the first international attempt to coordinate the work on RoGI generation using InSAR and a first example of concrete application of the RGIK guidelines in many regions in parallel. However, 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). In addition, due to the simultaneous RGIK work, updated basic concepts and new practical guidelines approved these past years were not fully implemented in the Permafrost_cci Phase 1 products. The applied procedure was therefore partly outdated compared to the international recommendations. **We concluded that we need to take a step back to consolidate the initial RoGIs before going further with new regions. A cross-check exercise involving multiple operators in small subareas was designed to identify the causes of the discrepancies and improve the product quality.**
- **For the RGV products**, different groups from Swiss and Norwegian institutions have generated comparable surface velocity time series on several rock glaciers. The proposed methodology proved feasible and promises a large step forward in global monitoring of rock glacier velocity. The examples covered the full range of low to high absolute velocities, small to large velocity variations with rather stable velocities or increasing interannual trends. However, we only generated preliminary time series for one or a couple of selected points for each landform. We also used the initial temporal resolution of the applied technique (e.g. 6–12 days in all snow-free periods using InSAR), highlighting both the seasonal and interannual variations of the velocity. The next step was to provide standardised and annualised RGV products, following the new GCOS and user requirements [AD-4] [RD-1]. For InSAR data, this required defining a procedure to aggregate the results, both spatially (in a representative area of the rock glaciers) and temporally (in a consistent observation time window during the snow-free season). **We concluded that this procedure needed first to be developed on well-studied rock glaciers, with available in-situ measurements, to compare the relevance and reliability of the final RGV products using InSAR.**

2.2 Phase 2 and Legacy objectives

These conclusions served as basis for defining the workplan of Permafrost_cci Phase 2. **In the Permafrost_cci Phase 2 first iteration** (15.11.2022–15.05.2024), the main objectives were to:

- **For RoGI:** perform a multi-operator exercise following a consensus-based RoGI procedure to identify discrepancies, agree on common solutions and improve the quality of the products in 12 areas (*Table 1*, upper part; *Figure 1*, red squares), and refine the RoGI instructions and GIS tools.
- **For RGV:** define the procedure to convert initial InSAR time series into RGV, and generate pilot RGV products for selected rock glaciers.

In Permafrost_cci Phase 2 second iteration (15.05.2024–15.11.2025), the main objectives were to:

- **For RoGI:** publish the results of the multi-operator exercise from the first iteration (Rouyet et al., 2025a; 2025b), support RoGI compilation in eight new regions (*Table 1*, middle part; *Figure 1*, blue circles), and explore possibilities to use the generated RoGI products as training data for machine learning.
- **For RGV:** evaluate and refine the InSAR-RGV procedure developed during the first iteration with a multi-operator and multi-technique intercomparison exercise, implement the adjusted procedure, and extend the production to more landforms.

The last phase of Permafrost_cci consists of finalising the work initiated in the past years, by fulfilling all Phase 2 objectives and disseminating our outcomes. **In Permafrost_cci Legacy** (15.04.2026–15.06.2027), our priorities are to:

- **For RoGI:** finalise the work in the eight new regions of Permafrost_cci Phase 2 (*Table 1*, middle part; *Figure 1*, blue circles), release the data in an open-access database, publish main findings in scientific articles, update the kinematic attributes in Italy and Romania, and initiate RoGI work in six new regions (*Table 1*, lower part; *Figure 1*, purple pentagons).
- **For RGV:** release the recommended InSAR-RGV procedure as part of the merged RGV international guidelines from RGIK, finalise and publish the InSAR-RGV results covering alpine landforms (*Figure 2*), and extend the production to other regions.

Table 1: *Permafrost_cci RoGI regions and responsible institutions*

RoGI – Permafrost_cci Phase 2 first iteration		
RoGI region	**Responsible institution**	**CCI affiliation**
Western Alps (Switzerland)	University of Fribourg (Switzerland)	CCN4 Baseline
Disko Island (Greenland)	Gamma Remote Sensing (Switzerland)	CCN4 Baseline
Troms (Norway)	NORCE Norwegian Research Centre (Norway)	CCN5 Option 8
Finnmark (Norway)	NORCE Norwegian Research Centre (Norway)	CCN5 Option 8
Nordenskiöld Land (Svalbard)	NORCE Norwegian Research Centre (Norway)	CCN5 Option 8
Southern Venosta (Italy)	University of Bologna (Italy)	CCN4 Option 9
Carpathians (Romania)	West University of Timisoara and Terrasigna (Romania)	CCN4 Option 9
Vanoise Massif (France)	University Grenoble Alpes and Université Savoie Mont-Blanc (France)	External partner
Brooks Range (Alaska)	University of Alaska Fairbanks (U.S.A)	External partner
Central Andes (Argentina)	Instituto Argentino de Nivología, Glaciología y Ciencias Ambientales IANIGLA (Argentina)	External partner
Tien Shan (Kazakhstan)	Graz University of Technology (Austria)	External partner
Southern Alps (New Zealand)	University of Lausanne (Switzerland)	External partner
RoGI – Permafrost_cci Phase 2 second iteration		
RoGI region	**Responsible institution**	**CCI affiliation**
Goms–Binntal (Switzerland)	University of Fribourg (Switzerland)	CCN4 Baseline
Northern Venosta (Italy)	University of Bologna (Italy)	CCN4 Option 9
Rila and Pirin Mts (Bulgaria)	West University of Timisoara and Terrasigna (Romania)	CCN4 Option 9
Manaslu (Nepal)	Université Grenoble Alpes (France) and The Chinese University of Hong Kong (China)	External partner
Sajama (Bolivia–Chile)	Université Grenoble Alpes and Université Savoie Mont-Blanc (France)	External partner
Tsengel Khairkhan (Mongolia)	Mongolian Academy of Sciences (Mongolia)	External partner
Baralacha La (India)	University of Bologna (Italy)	Side-project
Thana (Bhutan)	University of Fribourg (Switzerland)	Side-project
RoGI – Permafrost_cci Legacy		
Northwest Antarctic Peninsula (Antarctica)	University of Lisbon (Portugal)	External partner
Hazelton Mountains (Canada)	University of Ottawa (Canada)	External partner
North Cascades (USA)	University of Ottawa (Canada)	External partner
Făgăraș (Romania)	West University of Timisoara (Romania)	Side-project
Karakoram (Greater Kashmir)	University of Bologna (Italy)	Side-project
Ampato–Coropuna (Peru)	Université Grenoble Alpes (France)	Side-project

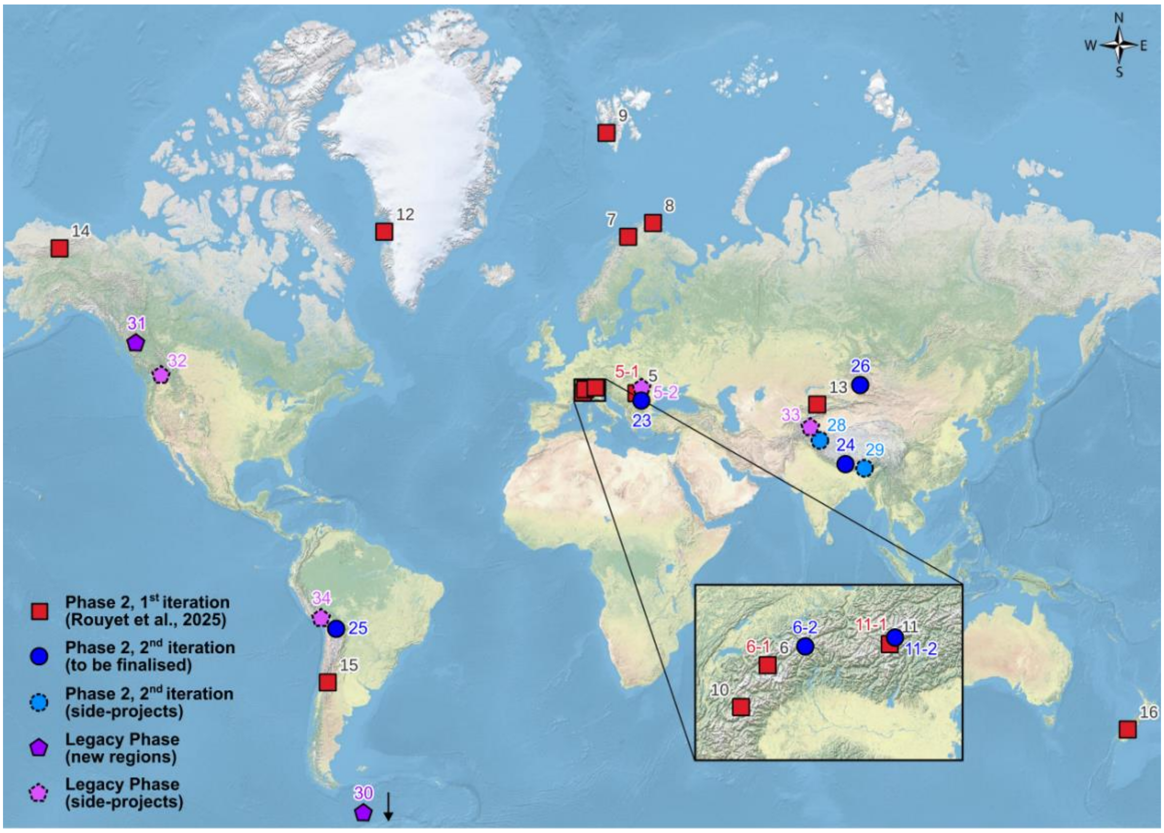

***Figure 1**: Locations of all Permafrost_cci RoGIs from the different phases. Numbering according to Permafrost_cci naming convention (Section 3.1.13).*

2.3 Phase 2 and Legacy RoGI areas

The 12 areas of Phase 2 first iteration are described in Rouyet et al. (2025). In the following, we describe the areas from Phase 2 second iteration: three RoGI areas led by Permafrost_cci partners (Sections 2.2.1–2.2.3), three RoGI areas led by external partners (Sections 2.2.4–2.2.6) and two additional areas associated with partners' side-projects (Sections 2.2.7–2.2.8). The two main regions of Permafrost_cci Legacy and four additional side-project are also introduced (Sections 2.2.9–2.2.14).

2.3.1 Goms–Binntal (Switzerland)

PI: Reynald Delaloye (University of Fribourg)

The Goms–Binntal area is located in the easternmost part of the Valais Alps in Switzerland and also comprises a part of the southeasternmost Bernese Alps. The area covers about 400 km^2 with elevations ranging from 1300 m a.s.l. to more than 3500 m a.s.l. for the highest peaks.

A previous version of the RoGI covers two small areas within the Goms–Binntal region and serves as training tool within the framework of RGIK. The GIS exercise is available in the "Resources" menu of the RGIK website, under "QGIS Tools" (https://www.rgik.org).

An extended version of the Goms–Binntal RoGI was compiled in the RoDynAlpS project "Rock glacier dynamics at multiple spatio-temporal scales in Switzerland" (2023–2027) funded by the Swiss National Foundation (SNF). A multi-operator RoGI procedure has been applied to cover the whole of Switzerland. The nationwide product is now finalised and about to be published.

2.3.2 Northern Venosta (Italy)

PI: Francesco Brardinoni (University of Bologna)

The northern Venosta area is located in western South Tyrol, Italy. The area covers 770 km^2, with elevations ranging from 620 m a.s.l. (Parcines/Partschins) to 3738 m a.s.l (Palla Bianca/Weisskugel). The lithology is metamorphic and dominated by paragneiss, micaschist and lesser orthogneiss.

The inventory relies on a regional geomorphological inventory completed in 2019 across South Tyrol (Scotti et al., 2024). The inventory has been adjusted to fit the RGIK recommendations. The kinematic attributes were documented using the combined use of Sentinel-1 and CosmoSky-Med InSAR data. The inventory is completed and a scientific publication is planned.

2.3.3 Balkan Mountains (Bulgaria)

PI: Flavius Sirbu (West University of Timisoara)

The Pirin and Rila Mountains are located in the Rhodope Massif of the Balkan Mountains in southwestern Bulgaria. The area covers about 700 km^2 with elevations ranging from 1100 m a.s.l. to 2914 m a.s.l.

The RoGI work in Bulgaria is related to the ChronoCaRP project (https://www.chronocarp.unibuc.ro). ChronoCaRP aims to date various glacial and periglacial features, including rock glaciers, for a “better understanding of past responses of geological and environmental systems to climate oscillations in SE Europe, with a main emphasis on global warming after the Last Glacial Maximum (LGM) in high mountain environments”.

The work on RoGI in the Pirin Mountains is finished. Similar RoGI process in Rila is still ongoing. A publication is under review for the Pirin Mountains.

2.3.4 Manaslu (Nepal)

PI: Adina Racoviteanu (Université Grenoble Alpes) and Lin Liu (Chinese University of Hong Kong)

The Manaslu area is located in the central Himalaya range in Nepal. The initial region covered ~1970 km^2 with elevation ranging from ~858 m a.s.l. to 8054 m a.s.l. Given the large size of the domain, the RoGI process focuses on a chosen subset of the AOI with an area of 188.5 km^2, which contains a high density of rock glaciers based on previous estimates (Harrison et al., 2024). For this smaller area, elevations range from 3710 m a.s.l. to 6462 m a.s.l.

The work was conducted in line with a PROCORE France–Hong Kong project. The main steps of the inventorying process have been performed. The consolidation and integration of the different components toward a comprehensive characterisation of all inventoried units is ongoing.

2.3.5 Sajama (Bolivia–Chile)

PI: Diego Cusicanqui (Université Grenoble Alpes and Université Savoie Mont-Blanc).

The Sajama volcano area is located in Cordillera Occidental in Bolivia. The area covers 383 km^2 with elevations ranging from 4200 m a.s.l. to 6542 m a.s.l. Sajama is an inactive volcano, with eruptive activity dated to the Pleistocene. Its morphology is composed of dacitic and andesitic lava flows, indicating an explosive eruptive behaviour in the past. The surrounding region features geothermal manifestations, such as hot springs and geysers, suggesting the presence of a still-hot magmatic system at depth. Its elevation places it among the snow-covered Andean peaks, with the summit permanently covered in ice and snow.

The work on the Bolivian side of the study area is completed. Further RoGI work on the Chilean part of the AOI is still ongoing. A combined publication is planned.

2.3.6 Tsengel Khairkhan (Mongolia)

PI: Avirmed Dashtseren (Mongolian Academy of Science).

The Tsengel Khairkhan area is located in the Altai range, in western Mongolia. The area covers approximately 208 km^2, with elevations ranging from approximately 2610 m a.s.l. to 3943 m a.s.l. The Tsengel Khairkhan mountain is covered by a small ice cap in the north and valley glaciers in the eastern and southern parts (total area: 8.2 km^2). This inventory contributes to the broader effort of documenting periglacial landforms in the Mongolian Altai and supports a better understanding of mountain permafrost dynamics in the region.

The work in the study area is completed. The partners are working on a scientific publication. The Mongolian partners are extending the RoGI work to other regions of the country.

2.3.7 Baralacha La (India)

PI: Francesco Brardinoni (University of Bologna).

The Baralacha La area is located in western Himalayas, India, along the border between Himachal-Pradesh and Ladakh states. The area covers about 530 km^2 with elevations ranging from 3752 m a.s.l. (Bhaga River floodplain) to 6111 m a.s.l. (Mount Yunam). Glaciers occupy about 20% of the terrain. The area is strategic, as it hosts key transportation corridors linking the regional centres of Leh and Zanskar with Manali and includes the proposed Leh-Manali Railway line.

The work was performed as part of a PhD project at UNIBO and included several iterations of validation, revisions and confirmatory fieldwork. The inventory is completed and a publication is planned.

2.3.8 Thana (Bhutan)

PI: Cécile Pellet (University of Fribourg).

The Thana area is located in the Bhutanese Himalayas. The area covers ~775 km^2 with elevations ranging from around 3000 m a.s.l. to 7500 m a.s.l. The study area is in the headwater of the Chamkar Chhu river.

The RoGI process is linked to the SNSF-funded Cryo-SPIRIT project (2024–2027), which aims at improving our understanding of rapidly changing high-mountain cryosphere and its impacts in Bhutan focusing on permafrost and snow. The last steps of the inventorying process are still ongoing. A publication is planned as part of a PhD project.

2.3.9 Northwest Antarctic Peninsula (Antarctica)

PI: Gonçalo Vieira (University of Lisbon).

The inventorying process will focus on the ice-free areas of the South Shetland archipelago, north of the Antarctic Peninsula, but will also be extended to the Antarctic Peninsula, for which cloud-free and very high-resolution satellite imagery is available. The work builds on long-term permafrost research performed by the University of Lisbon in this region.

2.3.10 Hazelton Mountains (Canada)

PI: Mishelle Wehbe (University of Ottawa).

The Hazelton Mountains are located in western British Columbia, Canada. The initiative builds on Wehbe's current work to compile a comprehensive RoGI in this region as part of a wider inventorying process at the national scale (CanRoGI). The geomorphological part is already well advanced. Permafrost_cci will support the integration of InSAR-based kinematic information.

2.3.11 North Cascades (USA)

PI: Mishelle Wehbe (University of Ottawa).

The North Cascades RoGI area is located between the northern part of Washington State (USA) and the southern part of British Columbia (Canada). The work has been planned as part of a North American initiative aiming to collaborate on RoGI production in transnational mountain ranges. Permafrost_cci InSAR data will contribute to integrate kinematic information in the inventory.

2.3.12 Făgăraș (Romania)

PI: Flavius Sirbu (West University of Timisoara).

The Făgăraș Mountains are located in the central part of the southern Carpathians, which hosts the highest peaks of Romania (Moldoveanu: 2544 m a.s.l.). The work in this region aims to complement the existing inventory from Phase 1 in the Retezat Mountains and contribute to the compilation of a comprehensive RoGI in the Carpathians.

2.3.13 Karakoram (Greater Kashmir)

PI: Francesco Brardinoni (University of Bologna).

The Karakoram area is located in the northwestern Himalayas, in the Great Kashmir region, geographically situated between India, Pakistan, and China. The initiative is a follow-up of the inventorying work performed by UNIBO further south (Baralacha La, Section 2.3.7). The work is also in synergy with the ESA CCI Karakoram Anomaly cross-ECV project (https://climate.esa.int/en/Cross_ECV_Projects/karakoram-anomaly) for the production of the SAR interferograms.

2.3.14 Ampato–Coropuna (Peru)

PI: Diego Cusicanqui (Université Grenoble Alpes).

The Ampato–Coropuna area is located in an arid region between Arequipa and the Catahuasi Reserve, in the Peruvian Andes. The area covers approximately 430 km^2 with elevations ranging from about 1000 m a.s.l. to 6100 m a.s.l. and hosts a high density of rock glaciers. The inventorying work is a partnership between France (Université Grenoble Alpes) and Peru (Universidad Nacional Santiago Antúnez de Mayolo UNASAM, Huaraz). The work builds on an existing geomorphological inventory (Medina et al., 2026) that will be updated using InSAR-based kinematic data.

2.4 Phase 2 and Legacy RGV sites

2.4.1 *Swiss sites (UNIFR/GAMMA)*

In the Permafrost_cci Phase 2 first iteration, the InSAR-RGV procedure was tested on four pilot sites: Distelhorn, Réchy (Becs-de-Bosson), Steintälli and Bru [RD-11] (Schmid, 2024). In the Phase 2 second iteration, the results were updated at the initial pilot sites and one rock glacier was added: Grosses Gufer. In Permafrost_cci Legacy, we will update and complement the production for a total of **16 sites**. The locations are shown in *Figure 2* (blue and black dots) and their properties are listed in *Table 3*. As for Phase 2, the results will compare with GNSS-RGV products from periodic and permanent GNSS monitoring (PERMOS, 2023; UNIFR, 2026).

2.4.2 *Italian sites (UNIBO/GAMMA)*

As part of the Phase 2 Option 9, the InSAR-RGV procedure was conducted in the Italian Alps, both in Aosta and Venosta. In Aosta, InSAR-RGV was processed for 13 rock glaciers: Gran Sometta, La Thile, Luseney, Moline, Monte Emilius Range 1 & 2, North Arpignan, Rhemes, Val Grisenche 2 & 3, Valnontey and Valsavarenche 1 & 3. In Venosta, we included two rock glaciers: Lazaun and Similaun. In Permafrost_cci Legacy, we will update and complement the production for a total of **24 sites**. The locations are shown in *Figure 2* (red triangles and green squares), and their properties are listed in *Table 3*.

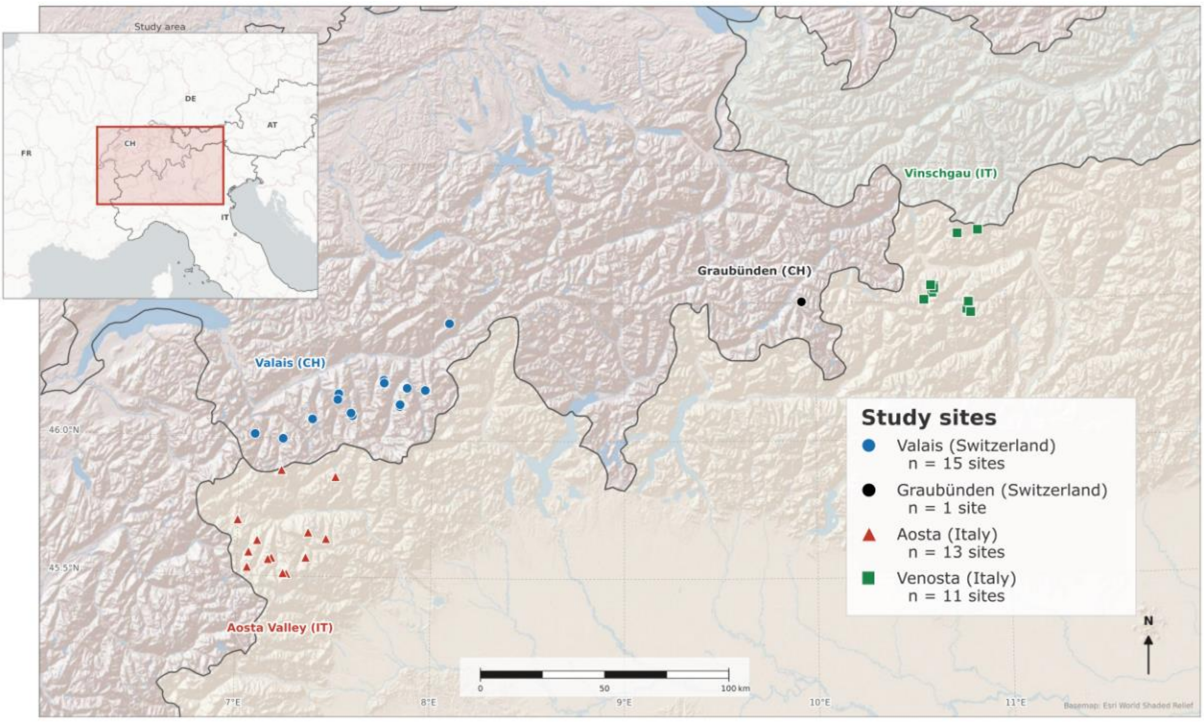

***Figure 2**: Locations of the rock glaciers selected for Permafrost_cci InSAR-RGV production in the European Alps (Switzerland and Italy).*

2.4.3 Norwegian sites (NORCE/UIO)

As part of the Phase 2 Option 8, NORCE and UIO provided preliminary results on rock glaciers located in the Troms country in northern Norway. In Permafrost_cci Legacy, we aim to complete the work in this area. The objective is to apply a combination of radar and optical remote sensing techniques: InSAR, SAR offset tracking and optical feature tracking. For some landforms, this combination allows cross-validation. In other cases, where velocity is too low or too high for one or another specific technique, we will take advantage of the complementarity of the techniques to document all velocity ranges. The Ádjet ridge in northern Norway was selected for this purpose as it includes many RGUs with a wide range of velocity, over short distances. The **9 RGUs** shown in *Figure 4* are included.

In addition, we will produce InSAR-RGV for selected Svalbard rock glaciers. In five regions on Spitsbergen Island, 2016–2023 InSAR time series have been processed by NORCE for the recent release of the InSAR Svalbard Ground Motion Service (https://svalbard.insar.no; Bredal et al., 2026) (*Figure 5*, left). For two of these regions (Longyearbyen and Kapp Linné), RoGI products developed in Permafrost_cci Phase 1 are available [RD-8] (Bertone et al., 2022) (*Figure 5*, right). These results will be used to select **10–15 landforms in both regions.** RGUs with ideal slope orientations (SW–NW or SE–NE) and with mean velocities within the detection range of the InSAR Svalbard products (cm–dm/yr to dm/yr–m/yr based on the RoGI kinematic attributes) will be favoured. The outlines will be used to select relevant pixels to be averaged before annualising the time series following the InSAR-RGV procedure.

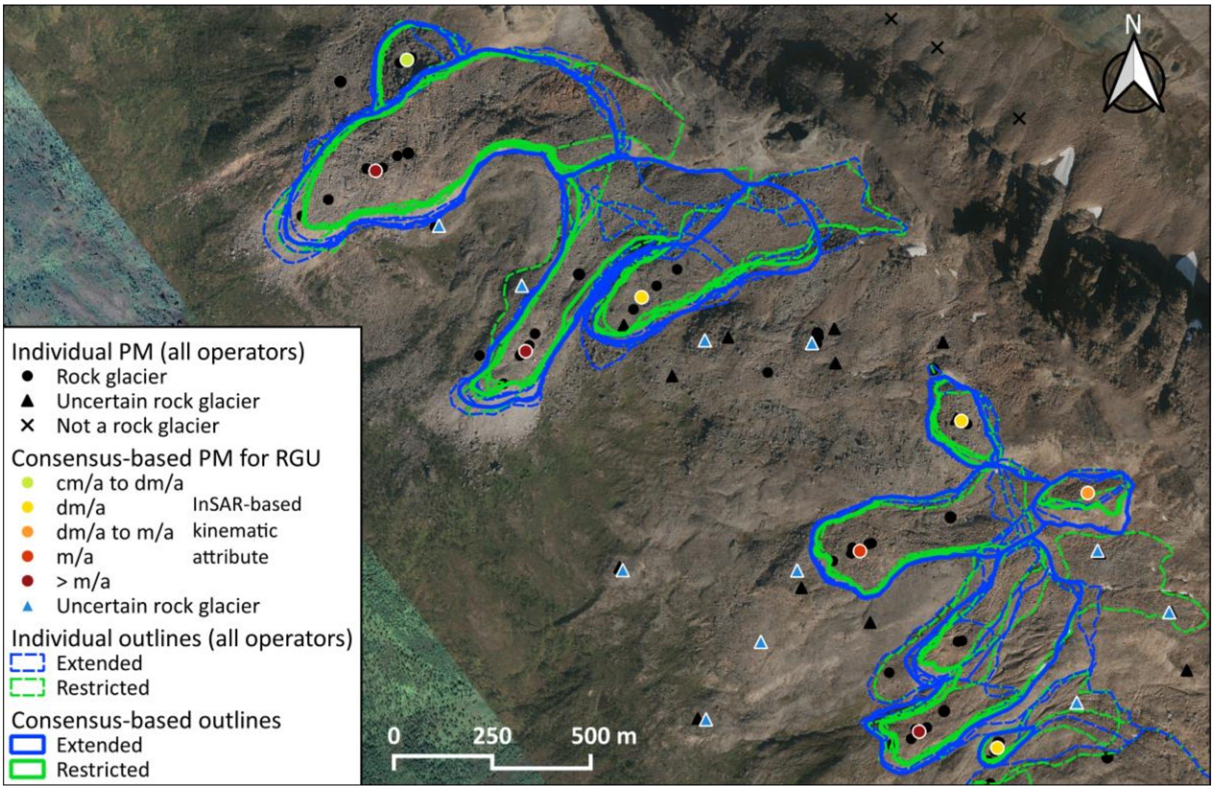

Figure 4. *Location map of the RGV sites in Troms, Northern Norway, along the Adjet ridge, previously studied during the RoGI multi-operator exercise (Phase 2 iteration 1).*

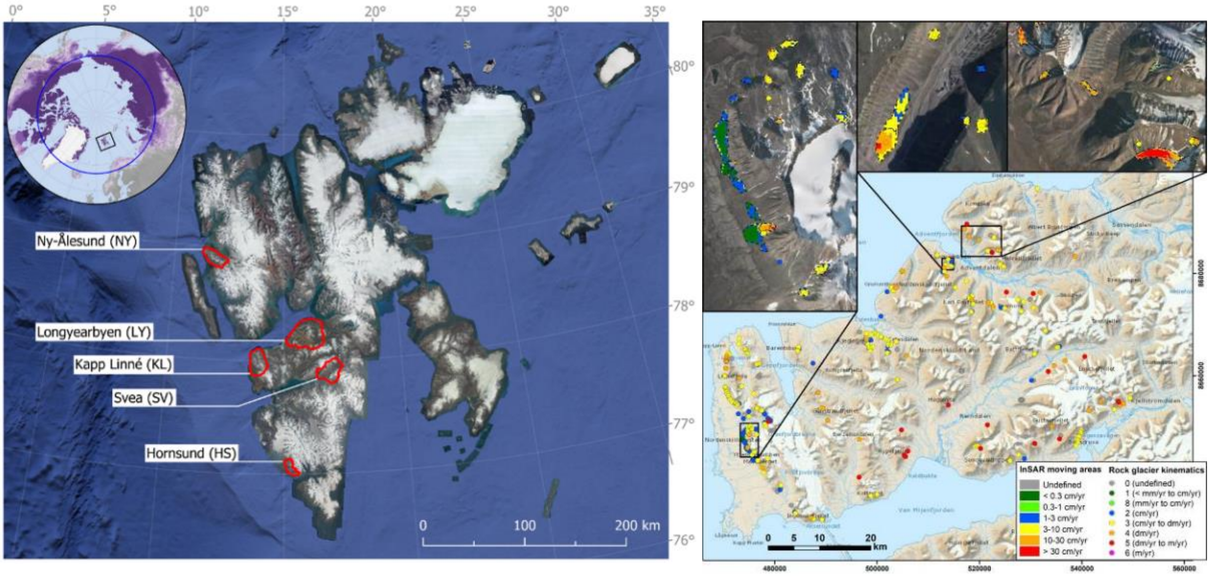

Figure 5. *Left: Overview of the five study areas covered by the InSAR Svalbard Ground Motion Service (https://svalbard.insar.no; Bredal et al., 2026). Right: Permafrost_cci Phase 1 RoGI in Nordenskiöld Land [RD-8] (Bertone et al., 2022), including the Longyearbyen and Kapp Linné areas also covered by InSAR Svalbard.*

Table 2. *Characteristics of the sites selected for RGV production in Permafrost_cci Phase 2 and Legacy*

Partner institutions	Country, region	Name	Location	Elevation	Slope aspect	Surface Velocity (from in-situ or RoGI kinematics)	Main applied method(s)	Validation data
UNIFR GAMMA	**Switzerland, Valais**	Augstbordpass 1	Turtmann Valley	2630–2850	W		InSAR	
		Augstbordpass 2	Turtmann Valley	2760–2850	W		InSAR	
		Breonna	Moiry	2690–2840	NNE		InSAR	
		Bru	Zermatt Valley	2840–2950	WSW	0.5–1 m/yr (GNSS)	InSAR	GNSS (periodic)
		Chaudière	Val d'Entremont	2400–2700	W		InSAR	
		Cliosses	Val d'Hérens	2460–2590	WNW		InSAR	
		Creux Magnin	Arpette	2300–2500	N		InSAR	
		Distelhorn	Zermatt Valley	2370–2650	NW		InSAR	
		Grosses Gufer	Aletsch Valley	2340–2650	NW	0.5–3 m/yr (GNSS)	InSAR	GNSS (periodic+permanent)
		Mattwald	Saas Valley	2540–2830	WNW		InSAR	
		Moiry	Moiry	2720–2850	W		InSAR	
		Prafleuri	Val des Dix	2620–2980	WNW		InSAR	
		Schwarzhoru	Turtmann Valley	2550–2760	WNW		InSAR	
		Steintälli	Zermatt Valley	2960–3150	WSW	0.2–1 m/yr (GNSS)	InSAR	GNSS (periodic)
		Tsevalire	Vallon de Réchy	2800–2900	NW	0.6–1.4 m/yr (GNSS)	InSAR	GNSS (permanent)
UNIFR GAMMA	**Switzerland, Graubünden**	Muragl	Upper Engadine	2490–2750	NW	0.5–2.5 m/yr (GNSS)	InSAR	GNSS (permanent)
UNIBO GAMMA	**Italy, Aosta**	La Thuile	Pietra Rossa	2580–2790	NE	dm/a (InSAR-RoGI)	InSAR	
		Luseney	Becca di Luseney	2480–2950	E	dm–m/a (InSAR-RoGI)	InSAR	
		Moline	Vallone di Menouve	2720–2890	E	dm/a (InSAR-RoGI)	InSAR	
		Monte Emilius Range 1	Val de Saint-Marcel	2690–2820	NW	dm–m/a (InSAR-RoGI)	InSAR	
		Monte Emilius Range 2	Vallone di Arbolle	2600–2950	WNW		InSAR	
		Rhemes	Val di Rhêmes	2490–2700	NW	dm–m/a (InSAR-RoGI)	InSAR	
		Val Grisenche 1	Val Grisenche	2350–2450	NW	cm–dm/a (InSAR-RoGI)	InSAR	
		Val Grisenche 2	Val Grisenche	2990–3200	W	dm–m/a (InSAR-RoGI)	InSAR	
		Val Grisenche 3	Val Grisenche	2760–3200	WSW		InSAR	
		Valnontey	Valnontey	2400–2800	NW	dm–m/a (InSAR-RoGI)	InSAR	

		Valsavarenche 1	Valsavarenche	2550–2880	NE	dm–m/a (InSAR-RoGI)	InSAR	
		Valsavarenche 2	Valsavarenche	3040–3220	S	> m/yr (InSAR-RoGI)	InSAR	
		Valsavarenche 3	Valsavarenche	2780–2930	W	dm–m/a (InSAR-RoGI)	InSAR	
UNIBO GAMMA	**Italy, Venosta**	Hintergrat	Val di Solda (SV)	2630–2830	NE	dm–m/a (InSAR-RoGI)	InSAR	
		Lago Lungo	Val d'Ultimo (SV)	2385–2550	NW	dm/a–m/a (InSAR-RoGI)	InSAR	
		Lazaun	Val Senales (NV)	2485–2750	NE	m/a (InSAR-RoGI)	InSAR	GNSS & UAV SfM
		Razoi	Val di Solda (SV)	2545–2820	W	dm–m/a (InSAR-RoGI)	InSAR	
		Rossbank	Val d'Ultimo (SV)	2450–2785	NE	dm/a–m/a (InSAR-RoGI)	InSAR	
		Serristori 1	Val di Solda (SV)	2790–2920	WSW	dm/a (InSAR-RoGI)	InSAR	
		Serristori 2	Val di Solda (SV)	2720–2780	NW	dm/a (InSAR-RoGI)	InSAR	
		Similaun	Val Senales (NV)	2560–2900	SW		InSAR	
		Sternai 1	Val d'Ultimo (SV)	2700–3005	E	dm/a–m/a (InSAR-RoGI)	InSAR	
		Sternai 2	Val d'Ultimo (SV)	2690–2875	E	dm/a–m/a (InSAR-RoGI)	InSAR	
		Zay	Val di Solda (SV)	2395–2740	W	dm–m/a (InSAR-RoGI)	InSAR	
NORCE UIO	**Norway, Troms, Svalbard**	Adjet RGU fid 32	Skitbotndalen, Troms	600–1295	SW	cm–dm/yr (InSAR-RoGI)	InSAR	Cross-validation optical/radar remote sensing
		Adjet RGU fid 33				> m/yr (InSAR-RoGI)	OT/FT	
		Adjet RGU fid 36				> m/yr (InSAR-RoGI)	OT/FT	
		Adjet RGU fid 37				dm/yr (InSAR-RoGI)	InSAR	
		Adjet RGU fid 39				m/yr (InSAR-RoGI)	InSAR/OT/FT	
		Adjet RGU fid 40				> m/yr (InSAR-RoGI)	OT/FT	
		Adjet RGU fid 41				dm/yr (InSAR-RoGI)	InSAR	
		Adjet RGU fid 93				dm/yr (InSAR-RoGI)	InSAR	
		Adjet RGU fid 103				dm–m/yr (InSAR-RoGI)	InSAR/OT/FT	
		LY 10–15 RGU	Longyeardalen, Svalbard	100–800	SW–NW, SE–NE	≥ cm–dm/yr (InSAR-RoGI)	InSAR	
		KL 10–15 RGU	Kapp Linné, Svalbard	50–400	SW–NW, SE–NE	≥ cm–dm/yr (InSAR-RoGI)	InSAR	

3 Products specifications and formats

3.1 Rock Glacier Inventory (RoGI)

3.1.1 Product description

Rock Glacier Inventories (RoGIs) aim to identify, locate, outline and characterise all rock glaciers in selected areas (see Section 2.3), following the definitions and mapping procedure recommended by RGIK [RD-4] (Brardinoni et al., 2025). RoGI products consist of three vector files:

- The Primary Markers (PMs), i.e. the points identifying and locating rock glaciers within all areas. "Certain" and "Uncertain" RGUs can be differentiated and landforms that could be misinterpreted as rock glaciers but are not attributed to permafrost creep (e.g. glacial features, solifluction lobes, landslides) have in some cases been highlighted with an extra category "Not a rock glacier". Attributes documenting the morpho-kinematic characteristics of the identified landforms are assigned to each "Certain" RGU.
- The Moving Areas (MAs), i.e. the polygons detected, delineated, and characterized (assignment of a velocity class) using InSAR data. The MA files were used to categorise the kinematic attribute in the PM files.
- The Geomorphological Outlines (GOs), i.e. the polygons outlining the restricted and/or extended geomorphological footprints of the RGUs categorised as "Certain".

3.1.2 Input data

Each RoGI folder delivered to the operators included: 1) the subfolder "INSTRUCTIONS" with the documents and links to applicable guidelines; 2) the subfolder "VECTOR", including the initial GeoPackage (gpkg) templates for digitalizing the PMs, MAs and GOs; 3) the subfolder "INSAR-DATA", including wrapped interferograms from Sentinel-1 (and where available from ALOS, SAOCOM, Cosmo-SkyMed, TerraSAR-X and/or NISAR), potential complementary InSAR products processed with alternative methods (e.g. velocity maps from Stacking or Persistent Scatterer Interferometry algorithms), a layer displaying an index to reproject the LOS displacement along the direction of the steepest slope (normalization factor) or a mask highlighting N–S facing slopes where the movement is likely to be underestimated on InSAR data; 4) the QGIS project structuring the available data and in which the operators performed the work. In addition to the InSAR data and initial vector files (gpkg templates), each GIS project incorporates links to Web Map Services (WMS) such as Google Earth, Bing and ESRI orthoimages. Before delivery to the operators, some PIs have added additional data (high-resolution DEM-based products and orthophotos available at the PI institutions or from other national/regional mapping services).

3.1.3 Temporal coverage

Rock glacier identification (PM points) and outlining (GO polygons) are performed using the most recent optical imagery from Google Earth, Bing and ESRI WMS, potentially complemented by national/regional datasets (additional high-resolution DEM-based products and orthophotos). The imagery date varies between the areas but is similar within each inventory team.

MA polygons are spatially identified and characterised using InSAR images acquired during the snow-free periods. The velocity class assigned to the MA is expressed in cm/yr. Sentinel-1 is the primary data source with images since 2016. Additional data based on ALOS, SAOCOM, Cosmo-SkyMed, TerraSAR-X and NISAR sensors are used where/when available.

The kinematic attribute refers to a category of annual velocity, expressed in cm/yr, dm/yr or m/yr. Specific translation rules are followed to derive the rock glacier kinematic attributes from the original velocity classes of the MAs. These rules are defined in the InSAR guidelines [RD-5].

3.1.4 Spatial coverage

In total, 22 study areas have been selected to produce Permafrost_cci RoGIs, with the objective to cover diverse mountain ranges worldwide. In Phase 2 iteration 1, RoGI were generated in 12 areas selected in Romania, Switzerland, Norway, France, Italy, Greenland, Kazakhstan, Alaska U.S.A., Argentina, and New Zealand. In Phase 2 iteration 2, 8 additional areas were added in Switzerland, Italy, Bulgaria, Nepal, Boliva–Chile, Mongolia, India and Bhutan. In Permafrost_cci Legacy, we initiate the work in six additional areas in Antarctica, Canada, USA, Romania, Greater Kashmir and Peru.

The InSAR data are clipped to the AOI extent. However, the actual coverage of interpretable InSAR information depends on the signal quality (e.g. low on wet, snow-covered, or vegetated surfaces), as well as on the topography in respect to the sensor viewing geometry. Some areas cannot be documented with InSAR due to low coherence (decorrelation of the interferometric signal), layover or shadow. When the coverage is reduced on specific rock glaciers, the kinematic attribute remains "Undefined".

3.1.5 Temporal resolution

The temporal resolution of the InSAR data depends on the repeat-pass of the SAR sensor and the time interval used to generate the interferograms. For Sentinel-1, the maximal temporal resolution is 6 days over Europe and Greenland, and 12 fays for the other regions. In spring 2026 (mid-April to mid-June), a unique three-satellite operational window (Sentinel-1A, -1C and 1D) also enables 1-day repeat-pass InSAR capabilities, which is considered for the new Legacy sites. Fast movements were identified using summer interferograms, using time intervals from 6 days up to several months. Slow movements were identified using annual interferograms computed between two or more consecutive summers.

3.1.6 Spatial resolution

The recommended minimum size of rock glaciers to be included in a RoGI is about 0.01 km^2 [RD-4]. The PM positioning on the RGU should avoid, as far as possible, any temporal variation and updating. The point must be located somewhere in the lower half of the RGU [RD-4]. Optical aerial/satellite images and DEMs were used for the morphological interpretation and the rock glacier delineation (outlines). The resolution typically varies between < 0.5 m and a few of metres depending on the data sources used for generating the orthomosaics in the WMS services, and the potential use of additional high-resolution datasets. The MAs related to the inventoried rock glaciers are outlined based on Sentinel-1 InSAR (20–40 m final resolution). Additional InSAR products with higher resolution (e.g. 3–10 m final resolution for CosmoSky-Med and TerraSAR-X) were used where/when available.

3.1.7 Product accuracy

Permafrost_cci RoGIs are produced following a morpho-kinematic approach for which both rock glaciers that are moving and those that are not moving were identified. The movement rates of the active rock glaciers were documented using InSAR, primarily based on the Sentinel-1 SAR satellites. Rock glaciers that are not moving have also been morphologically identified. They are either characterised with a kinematic attribute < cm/yr or remain kinematically undefined, depending on the InSAR signal quality. Minimum detectable displacement rates from Sentinel-1 InSAR are in the order of 1/10 of a wavelength (i.e. around 5–6 mm). For time intervals of 48 and 6 days, this translates to minimum detectable rates of around 4 and 34 cm/yr, respectively. Slower displacements can be detected using annual or bi-annual temporal baselines. The maximum detectable displacement is limited by phase coherence loss due to high deformation and is in the order of 1/2 wavelength (i.e. around 2.8 cm) during the time interval used to build the interferograms, i.e. 20 and 170 cm/yr for time intervals of 48 and 6 days, respectively. For a specific time interval, any movement higher than the maximum detectable velocity will be decorrelated in the interferogram. In this case, a moving area can be outlined but the velocity class must remain undefined [RD-5].

The product accuracy is documented according to the Goal Requirement of URq_10 [RD-1]. For the MAs, the reliability of the detection is qualitatively estimated (low, medium, high) based on the difficulty to interpret the signal and/or delineate the moving area. Similarly, the kinematic attribute of the RGUs is documented with low, medium and high categories depending on the quality and the spatial representativeness of the detected MAs. The reliability of the outlines is estimated with a scale from 0 (low) to 2 (high) for each boundary (front, lateral margins and upslope limit) and summed up to give a reliability estimate for the entire landform. The sources of uncertainties can be further described in “Comments” fields. Discussion about product accuracy and uncertainties are further detailed in Rouyet et al. (2025b).

3.1.8 Product attributes

For the Primary Markers (PM), the following attributes are documented:

- ID (unique alpha-numerical identifier of the RGU).
- X and Y coordinates (WGS84 coordinate system).
- Morphological type (simple, complex).
  Additional related attribute: the “Completeness” defining if the rock glacier is completely visible or not (complete, unclear connection the upslope, truncated front, uncertain).
- Spatial connection to the upslope unit (talus-, debris mantle-, landslide-, glacier-, glacier forefield-, poly-connected, other, uncertain, unknown).
  Additional related attributes: the “Upslope Current” defining if the rock glacier is currently connected to the upslope unit or not, and a “Comment” field to further describe morphological characteristics.
- Kinematic attribute (< cm/yr, cm/yr, cm/yr to dm/yr, dm/yr, dm/yr to m/yr, m/yr, > m/yr, undefined).
  Additional related attributes: the “Type of Data” to define the type of data used to assign the kinematic attribute (Optical, Radar, Lidar, Geodetic, Other), the “Kinematic Period” to document the applicable period of the kinematic attribute (year(s) with available data), the Reliability of the kinematic attribute (low, medium, high, undefined) and a specific “Comment” field to further document the applied method and the data quality.
- Activity (active, active uncertain, transitional, transitional uncertain, relict, relict uncertain, uncertain) and the “Activity Assessment” documenting how the activity has been assessed (morphological evidence only or with kinematic data).
- Destabilization signs (yes - ongoing, yes - completed, no, undefined).

For the Moving Areas (MA), the following attributes are documented:

- ID (unique alpha-numerical identifier of the moving area)
- Velocity class (< 1 cm/yr, 1–3 cm/yr, 3–10 cm/yr, 10–30 cm/yr, 30–100 m/yr, > 100 cm/yr).
- Time observation window (text documenting the time window when the detection and characterization of the moving area has been performed).
- Reliability of the detected moving area (low, medium, high).
- Additional comments.

For the Geomorphological Outlines (GO), the following attributes are documented:

- ID (unique alpha-numerical identifier of the outline)
- Outline type (extended, restricted, other).
- Reliability of the front, the left margin, the right margin, and upslope limit (2 – high, 1 – medium, 0 – low) and Reliability Index (automatic summation of the values assigned to the reliability attributes of these four different boundaries).
- Additional comments.

3.1.9 Data documentation and dissemination

The 12 RoGI data and metadata from Phase 2 iteration 1 are openly available (Rouyet et al., 2025a; 2025b). The results can also be viewed in the UNIFR WebGIS tool (https://bigweb.unifr.ch/Science/Geosciences/Geomorphology/Pub/Website/CCI/CCI_qgis2web_2025_04/#2/28.5/0.0). These results and the 10 new RoGIs from Phase 2 iteration 2 and Permafrost_cci Legacy will be included in a RoGI database currently under development at UNIFR.

3.1.10 Product projection system

The Coordinate Reference System (CRS) used for the RoGI products is the World Geodetic System 1984 (WGS84). The coordinates are in decimal degrees.

3.1.11 Metadata

The metadata should include information about the type and properties of the input data: the orthoimages, the DEMs and the SAR satellite scenes used for InSAR analysis. The name of the PI and the reference time period of the RoGI production should be reported, as should references be cited, and acknowledgments or any other important metainformation be mentioned.

3.1.12 File formats

All datasets are provided in a geopackage vector format (.gpkg), a platform-independent database container that is a more flexible alternative to the shapefile (.shp) format. The inventory with the Primary Markers (PM layer) is a point vector file. The InSAR-based Moving Areas (MA layer) and the Geomorphological Outlines (GO layer) are polygon vector files.

3.1.13 Product file naming conventions

ESACCI-<CCI Project>-<Processing Level>_<Data Type>_<Product String>-<Additional Segregator>_<Layer Type>_<Indicative Date>-fv<File version>.gpkg

<CCI Project>
PERMAFROST for Permafrost_cci

<Processing Level>

Indicator (IND)

<Data Type>
This should be structured as: <SENSOR>-<METHOD>
<SENSOR> is the primary remote sensing data source used to document the kinematics, in this case: SENTINEL-1. <METHOD> is the primary method used to process the data, in this case: INSAR.

<Product String>
ROGI, when the product is Rock Glacier Inventory.

<Additional Segregator>
This should be structured as: SUBAREA_<REGION_NUMBER>-<AREA_NUMBER>.
<REGION_NUMBER> follows a consistent numbering across all Permafrost_cci Phases (**bold** regions are used for RoGI products, *italic* regions are used for other Permafrost_cci products): *1–Global*; *2–North America*; *3–Eurasia*; *4–Northern Hemisphere*; **5–Carpathians, Romania**; **6–Western Alps, Switzerland**; **7–Troms, Norway**; **8–Finnmark, Norway**; **9–Nordenskiöld Land, Svalbard**; **10–Vanoise Massif, France**; **11–Venosta, Italy**; **12–Disko Island (Greenland)**; **13–Tien Shan (Kazakhstan)**; **14–Brooks Range, Alaska**; **15–Central Andes, Argentina**; **16–Southern Alps (New Zealand)**; *17–Arctic tundra*; *18–Northern Finland*, *19–North Slope, Alaska*; *20–Central Lena Delta, Russia*; *21–Central Yamal, Russia*; *22–Lac du Gras, Canada*; **23–Balkan Mountains, Bulgaria**, **24–Manaslu, Nepal**; **25–Sajama, Bolivia–Chile**; **26–Tsengel, Mongolia**; *27–Antarctica*; **28–Baralacha La, India**; **29–Thana, Bhutan**; **30–Northwest Antarctic Peninsula, Antarctica**; **31–Hazelton Mountains, Canada**; **32–North Cascades, USA**; **33–Karakoram, Greater Kashmir**; **34–Ampato–Coropuna, Peru**.
<AREA_NUMBER> is a number of one or more digit(s), depending on the area(s) in the region.

<Layer Type>
The individual layers of the vector product are provided as different files. The code of each layer is as follows:

- PM: layer 1, corresponding to the rock glacier Primary Markers
- MA: layer 2, corresponding to the associated Moving Areas
- GO: layer 3, corresponding to the Geomorphological Outlines of the rock glaciers

<Indicative Date>
Format is YYYYMMDD, where YYYY is the four digits year, MM is the two digits month from 01 to 12 and DD is the two digits day of the month from 01 to 31. Annual or multi-annual products are represented with YYYY only.

fv<File Version>
File version number in the form n{1,}[.n{1,}] (two digits followed by a point and one or more digits).

<u>Example:</u>
ESACCI-PERMAFROST-IND_SENTINEL1-INSAR_ROGI-AREA_6-1_RG_2027-fv01.0.gpkg

3.2 Rock Glacier Velocity (RGV)

3.2.1 Product description

Rock Glacier Velocity (RGV) is defined as a time series of annualised surface velocity values expressed in m/y and measured/computed on a RGU or a part of it [RD-6]. RGV is produced with the objective to document the long-term changes of rock glacier creep rate in a climate-oriented perspective. RGV is a quantity of the ECV Permafrost aiming to complement the two other quantities (Permafrost Temperature and Active Layer Thickness) to monitor changing permafrost conditions in mountains [AD-2 to AD-4]. Permafrost_cci RGV products are primarily produced using InSAR at selected sites chosen for their technical suitability and climatic relevance (see Section 2.4). SAR offset-tracking and optional feature tracking are also used as secondary methods. Spatially, RGV products are aggregated for pixels assumed to be representative of the permafrost creep. Temporally, the initial InSAR measurements are aggregated during a consistent observation time window each year.

3.2.2 Input data

Sentinel-1 Single-Look Complex (SLC) SAR images in Interferometric Wide (IW) swath mode are the primary data source. For SAR offset tracking, higher resolution SAR images (TerraSAR-X and CosmoSky-Med) may be used. RGV processed with optical feature tracking is based on airphotos from manned aircrafts or Unmanned Aerial Vehicles (UAV).

3.2.3 Temporal coverage

Using Sentinel-1 12-days temporal baselines, 2015–2025 (10 years) years can be processed. Using 6-days temporal baselines, the temporal coverage is reduced to 2017–2021 (6 years). All time series are within the URq_15 Breakthrough Requirement (5–10 years) [RD-1]. When processing historical archives of aerial photos, the URq_15 Goal Requirement (> 10 years) may be reached [RD-1].

3.2.4 Spatial coverage

The RGV product represents the remotely sensed velocity field measured over one or more area(s) and representing the downslope movement of a RGU (Goal Requirement of URq_17 [RD-1]). Velocity time series are produced for several pixels across the Permafrost_cci sites to document the variability of the velocity patterns, evaluate these differences and potentially divide the landforms into areas affected by different kinematics. The final time series either correspond to selected pixel(s) assumed to be representative of the landform behaviour, or to a spatially averaged velocity based on a group of pixels. For each site, the selected pixel(s) and/or the aggregation procedure (e.g. size and location of the considered area(s), number of pixels used to average the time series) are documented and remain consistent over time.

3.2.5 Temporal resolution

The initial velocity data is based on Sentinel-1 InSAR time series with a 6–12 days frequency collected during snow-free periods for the years 2015–2025 (observation time window < 1 year but covering at least one month). The velocity data is then annualised, following the URq_13 Breakthrough Requirement [RD-1]. The observation time window will be at least one month (between June and October), following the URq_14 Breakthrough Requirement [RD-1]. The chosen period is documented and remains consistent throughout the entire time series for each pilot site (max. ±15 days of difference), as required by URq_14 [RD-1]. Using SAR offset tracking, longer intervals may be considered (several weeks to a year) but URq_13 and URq_14 are still fulfilled. When processing historical archives of aerial photos, the measurement frequency may be over 1 year (up to a few decades), corresponding to the URq_13 Threshold Requirement [RD-1].

3.2.6 Spatial resolution

Sentinel-1 data used for RGV production has a 20–30 m resolution. Additional SAR images have higher resolution (< 10 m). For optical feature tracking, the image resolutions will range from a few metres (e.g. Corona spy images) to a few decimetres (e.g. 10–40 cm for airphotos). Using UAV images, the resolution can go down to cm resolution. The final RGV products correspond to several pixels, provided separately and/or averaged spatially. The size of the total contributing area varies from site to site.

3.2.7 Product accuracy

Based on a single interferogram procedure, the expected accuracy of Sentinel-1 InSAR is 6 to 7 mm for each measurement (Strozzi et al., 2020). The accuracy can go down to a mm accuracy using multi-temporal InSAR, but these techniques are mostly applicable for slow-moving landforms. Accuracy using SAR offset tracking and optical feature tracking will vary between mm–dm depending on the image resolution. As a rule of thumb, the precision of SAR offset tracking is on the order of $1/10^{th}$ of a pixel and that of optical feature tracking is on the order of 1 pixel. For each site, the applied method(s) will be selected based on the minimum to maximum velocity of the landform and the detection capability of the technique. The accuracy is expected to have a relative error lower or equal to 20%, corresponding to the threshold requirement of URq_18 [RD-1].

3.2.8 Product attributes

For each RGV time series the following attributes are documented:

- ID (unique alpha-numerical identifier of the RGV time series).
- Reference ID of the related RGU (when a RoGI is available).
- Technique used (description of the platform, sensor type and processing approach).
- Area considered for RGV processing (area-based, several discrete points, three discrete points or one single discrete point, and related specifications).
- Start date (date of first observation).
- Velocity data (computed RGV data in m/yr).

For each velocity data (each annual increment of the time series), the following attributes are documented:

- ID (unique alpha-numerical identifier of the RGV data).
- Reference ID of the related 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/yr).
- Relative error of the velocity data (ideal: < 5%, medium: 5–20%, minimal: 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).

3.2.9 Data documentation and dissemination

At the end of Permafrost_cci Legacy, data and documentation will be made available in an openly accessible data repository such as Zenodo and/or partner institutions' websites. In the future, other locations may be considered for hosting the international RGV database, in the framework of the RGIK IPA Standing Committee, in collaboration with GTN-P.

3.2.10 Product projection system

The Coordinate Reference System (CRS) used for the RGV products is the World Geodetic System 84 (WGS84). The coordinates are in decimal degrees.

3.2.11 Metadata

Metadata should indicate the methodology used for deriving the RGV products (InSAR, GNSS, optical photogrammetry, etc.), as well as additional information regarding observation time window, temporal and horizontal resolution, and the spatio-temporal aggregation procedure applied to provide the RGV. The producer and the date of production should be indicated.

3.2.12 File formats

All datasets will be provided in comma-separated values (csv) format.

3.2.13 Product file naming conventions

ESACCI-<CCI Project>-<Processing Level>_<Data Type>_<Product String>-<Additional Segregator>_<Indicative Date>-fv<File version>.csv

<CCI Project>
PERMAFROST for permafrost_cci

<Processing Level>
Indicator (IND)

<Data Type>
This should be structured as: <SENSOR>-<METHOD>
<SENSOR> is the primary remote sensing data source used to document the kinematics, in this case: SENTINEL-1. <METHOD> is the primary method used to process the data, in this case: INSAR.

<Product String>
RGV, when the product is Rock Glacier Velocity.

<Additional Segregator>
This should be structured as: SUBAREA_<COUNTRY_CODE>-<SITE_NAME>.
<COUNTRY_CODE> includes: CH–Switzerland; IT–Italy, NO–Norway.

<SITE_NAME> includes: Augstbordpass1; Augstbordpass2; Breonna; Bru, Chaudiere; Cliosses; CreuxMagnin; Distelhorn; GrossesGufer; Mattwald; Moiry; Prafleuri; Schwarzhoru; Steintalli; Tsevalire; Muragl; LaThuile; Luseney; Moline; MonteEmiliusRange1; MonteEmiliusRange2; Rhemes; ValGrisenche1; ValGrisenche2; ValGrisenche3; Valnontey; Valsavaranche1; Valsavaranche2; Valavaranche3; Hintergrat; LagoLungo; Lazaun; Razoi; Rossbank; Serristori1; Serristori2; Similaun; Sternai1, Sternai2; Zay; Adjet32; Adjet33; Adjet36; Adjet37; Adjet39; Adjet40; Adjet41; Adjet93; Adjet103; LY1–LY15; KL1–KL15.

<Indicative Date>
Format is YYYYMMDD, where YYYY is the four digits year, MM is the two digits month from 01 to 12 and DD is the two digits day of the month from 01 to 31. Annual products are represented with YYYY only.

fv<File Version>
File version number in the form n{1,}[.n{1,}] (two digits followed by a point and one or more digits).

Example:
ESACCI-PERMAFROST-IND_SENTINEL1-INSAR_RGV_CH-Distelhorn_2027-fv01.1.csv

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4.2 Acronyms

AD	Applicable Document
ALT	Active Layer Thickness
B.GEOS	b.geos GmbH
BR	Breakthrough Requirement
CCI	Climate Change Initiative
CCN	Contract Change Notice
DEM	Digital Elevation Model
ECV	Essential Climate Variable
EO	Earth Observation
ESA	European Space Agency
FT	Feature Tracking
GAMMA	Gamma Remote Sensing AG
GCOS	Global Climate Observing System
GR	Goal Requirement
GT	Ground Temperature
GTOS	Global Terrestrial Observing System
IANIGLA	Instituto Argentino de Nivología, Glaciología y Ciencias Ambientale
InSAR	Interferometric Synthetic Aperture Radar
IPA	International Permafrost Association
MAGT	Mean Annual Ground Temperature
MAGST	Mean Annual Ground Surface Temperature
NORCE	Norwegian Research Centre AS
OT	Offset Tracking
PSD	Product Specification Document
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
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
SfM	Surface from Motion
TR	Threshold Requirement
WUT	West University of Timisoara