ERS InSAR for Assessing Rock Glacier Activity

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Abstract

The potential of space-borne synthetic aperture radar interferometry (InSAR) to estimate both magnitude and spatial pattern of slope motion in a periglacial environment has been evaluated over a large area of the western Swiss Alps, using data from the ERS-1 and ERS-2 satellites. About 280 active rock glaciers with different classes of velocities have been identified on the analysed interferograms. The velocities range from a few centimetres per year to several meters per year. This data was validated by some differential GPS measurements and compared to numerous field observations. The resulting classification permits a better description of the full range of rock glaciers velocities and dynamics. Therefore, ERS InSAR reveals to be an efficient remote sensing technique, not only for inventorying active rock glaciers over a wide area, but also to estimate and categorize their displacement velocities.

Keywords: InSAR, permafrost creep, rock glacier activity, Swiss Alps.

Introduction

The study of rock glacier dynamics constitutes one of the major topics in alpine periglacial research (e.g. Haeberli et al. 2006). The abundant literature related to the creeping of ice-rich permafrost attests the great diversity of rock glacier velocities, from a few centimetres per year for the slowest ones to more than 5 m per year for the fastest ones (see for ex. Roer 2005). Recent studies in the European Alps have evidenced (1) the great inter-annual variation of rock glacier velocities (Delaloye et al. 2008a), (2) an acceleration since the 1980s (Kääb et al. 2007) and (3) the partial or complete destabilization of some rock glaciers (e.g. Delaloye et al. 2008b, Roer et al. 2008). For these reasons, it appears that the usual classification – active, inactive, relict – does not permit the whole range of rock glacier velocities and dynamics to be described accurately. Therefore, a more precise classification of rock glacier velocities would be desirable.

Space-borne Synthetic Aperture Radar Interferometry (InSAR) is a well established technique for mapping cm temporal changes in surface topography (Bamler & Hartl 1998, Rosen et al. 2000, Strozzi et al. 2001). In mountain areas, above the tree line, it is possible to detect mass movements mostly during the snow-free period (Rott et al. 1999, Delaloye et al. 2007a). In particular, several studies have demonstrated the efficiency of InSAR for estimating rock glacier displacements (e.g. Kenyi & Kaufmann 2003, Strozzi et al. 2004, Kääb et al. 2005, Kaufmann et al. 2007). In the framework of the ESA (European Space Agency) SLAM (Service for Landslide Monitoring) project and with the support of the Swiss Federal Office for the Environment, the potential of InSAR to inventory mass wasting in the alpine periglacial belt has been tested. Both magnitude and spatial pattern of slope instabilities have been evaluated over a large area of the western Swiss Alps (50 x 30 km) (Fig. 1), using data of the European Remote Sensing satellites ERS-1 and ERS-2 dating back from 1995 to 2000.

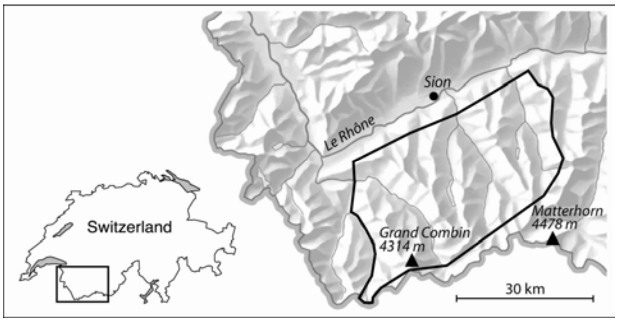


Fig. 1. Area investigated.

This paper focuses on the various rates of rock glacier activity, which can be evaluated by ERS InSAR. After presenting the method and the dataset, the paper proposes a classification of rock glaciers, according to their typical ERS InSAR signals and morphological characteristics. Special attention was put on destabilization signs, which indicate a change in rock glacier dynamics.

Methods and Datasets

For this study, a total of 34 interferograms computed from ERS SAR images acquired at C-band (wavelength: 5.6 cm) between 1995 and 2000, with baselines shorter than 100-150 m, were used. Time lapse ranges between 1 day and 1085 days (in fact multiples of 35 days +/- 1 day). The topographic reference was determined from an external digital elevation model with a spatial resolution of 25 m and an estimated vertical accuracy of 3 m (DHM25 © 2003 swisstopo). The InSAR products were also computed at 25 m spatial resolution. A change of the InSAR phase of one cycle is related to a movement of half the wavelength (2.8 cm) in the satellite line-of-sight direction, which is inclined at ~23° from the nadir and, in the western Swiss Alps, oriented toward the east +~12° for ascending orbits and toward the west -~12° for descending orbits. Thus, phase signals (i.e. change in the InSAR phase) detected on 1-day lag, 35-days lag and 1-year lag interferograms can be interpreted as three orders of velocities, that is, respectively, centimeters per day, per month and per year.

Important limiting factors of InSAR in mountainous terrain arise from temporal decorrelation, the satellite viewing geometry, and inhomogeneities in the tropospheric path delay. Atmospheric perturbations may cause phase changes related to the altitude. Among the other disruptive parameters, the wet snow, typically, can strongly reduce the reliability of an interferogram. This problem is especially present when working in alpine periglacial areas. In the Alps, above 2500 m a.s.l., the snow free period is reduced to a few months, between July and early October. In addition, summer snowfalls are not uncommon at these altitudes, which can make many acquisitions unusable. On the other hand, cold snow is almost transparent to a radar wave. Thus, if the snow cover does not evolve, which may be possible only for few days, rapid movements can be identified in winter (Strozzi et al. 2004). Another limitation is the vegetation, which disturbs the radar backscatter and prevents any analysis in forest areas. Rock walls appear also strongly decorrelated, because of topographic effects. Finally, it is not possible to identify creeping landforms smaller than at least 2 x 2 grid cells (i.e. 50 x 50 m).

In order to identify the various rates of activity of active rock glaciers, different steps were followed:

- Evaluation of the reliability of the different interferograms. In particular, it was necessary to select the images for which the signal was not perturbed by the snow cover (both from the previous winter and from recent snowfalls). As a result, several interferograms could not be used in this study. The eight most reliable interferograms are listed in Table 1.
- Identification and delimitation of areas showing signals of potential slope motion by analysing the selected interferograms with various time scales and with different zoom levels.
- Determination of the corresponding geomorphological process (or landform) by orthophoto analysis or field observations.
- When available, comparing the InSAR estimated velocities to differential GPS data or air-borne photogrammetric analysis.

Table 1. Dates of the best suited ERS SAR interferograms.

Dates	Direction	Days
11-12 March 1997	asc./desc.	1
29-30 July 1997	asc./desc.	1
3 Sept. - 8 Oct. 1997	descending	35
29 July - 3 Sept. 1997	ascending	35
18 Sept. 1996 - 30 July 1997	descending	315
8 Oct. 1997 - 23 Sept. 1998	descending	350
15 July 1998 - 8 Sept. 1999	descending	420
7 Oct. 1997 - 14 July 1998	ascending	279

InSAR-detected Velocities

About 600 polygons corresponding to spatially limited slope movements were identified throughout the whole investigated area. Among these polygons, about 280 were attributed to "active" rock glaciers. The other ones correspond to landslides, solifluction, push moraines or debris-covered glaciers.

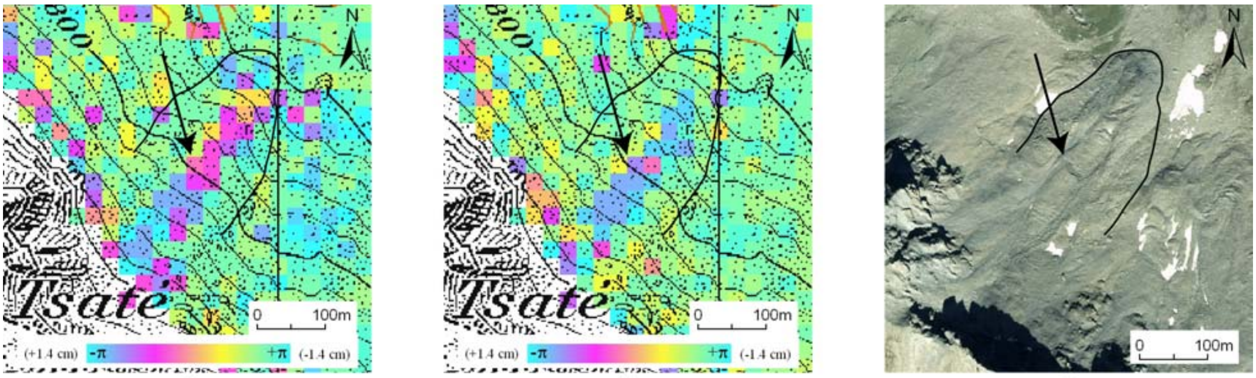
For four rock glaciers of the inventory, an obvious phase signal is detected on 1-day lag interferograms. Figure 2 illustrates the data for the Tsaté-Moiry rock glacier. The summer interferogram displays a very clear signal all along the rock glacier (Fig. 2a). On the winter interferogram (Fig. 2b), the signal is a little less marked, which may indicate slower winter velocities. This data means that the motion is in the cm range per day, which corresponds to more than 3 m a^{-1}. Terrestrial measurements with differential GPS carried out on the rock glacier revealed velocities even up to 7 m a^{-1} between 2006 and 2007. Similar InSAR signals were observed on the Petit Vélan rock glacier, where seasonal velocities up to 2 cm per day were measured in summer 2005 and 2007 (Delaloye et al. 2008b).

Some rock glaciers display a low 1-day phase signal, whereas the 1-month signal is decorrelated, that is larger than one phase cycle (2.8 cm). This is, for example, the case for the Tsarmine rock glacier (Fig. 3). In Figure 3a, a low signal can be detected on the 1-day summer interferogram (arrow), even if it is close to the noise level. The corresponding velocity can be estimated to a few millimetres per day, that is 1-2 m a^{-1}, which is confirmed by differential GPS measurements carried out since 2004 (see also Lambiel 2006). On the 1-month interferogram, the decorrelation is widespread over the landform (Fig. 3b).

Rock glaciers with velocities corresponding to the two previous categories constitute 5% maximum of the sample. On most of the InSAR-identified rock glaciers, a signal can only be detected with a 1-month interval. These rock glaciers can appear widely decorrelated, as it is the case for the Becs-de-Bosson rock glacier (Fig. 4) (Perruchoud &

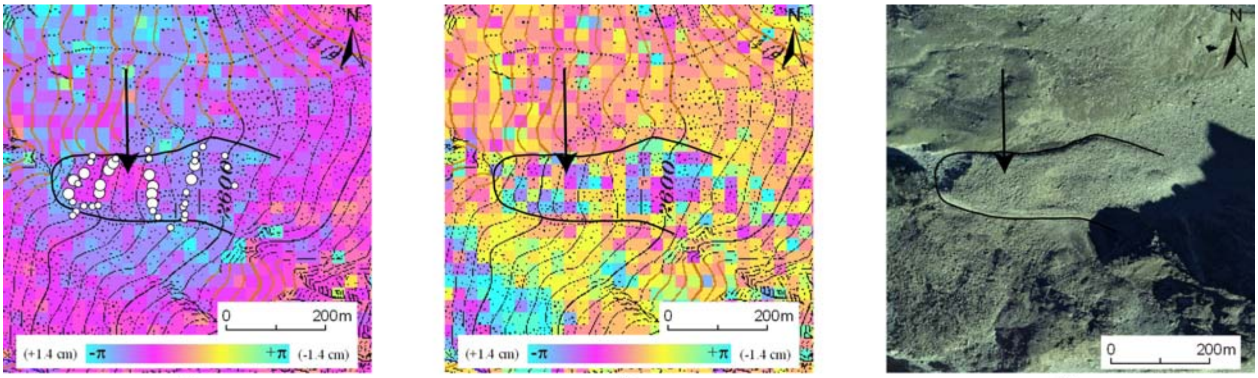
Delaloye 2007). This corresponds to minimum velocities of 20-30 cm a^{-1}. Another example is the Milon east rock glacier (Fig. 5a).

On numerous rock glaciers, the signal is hardly detectable at a 35-days lag, but is evident at a 1-year interval. The Milon west rock glacier is a nice example of this type (Fig. 5). Whereas only a very low signal occurs on the 1-month interferogram, the signal is evident on the 1-year interferogram. However, it remains rather correlated on the major part of the landform, which indicates a surface velocity of 2-3 cm a^{-1}.



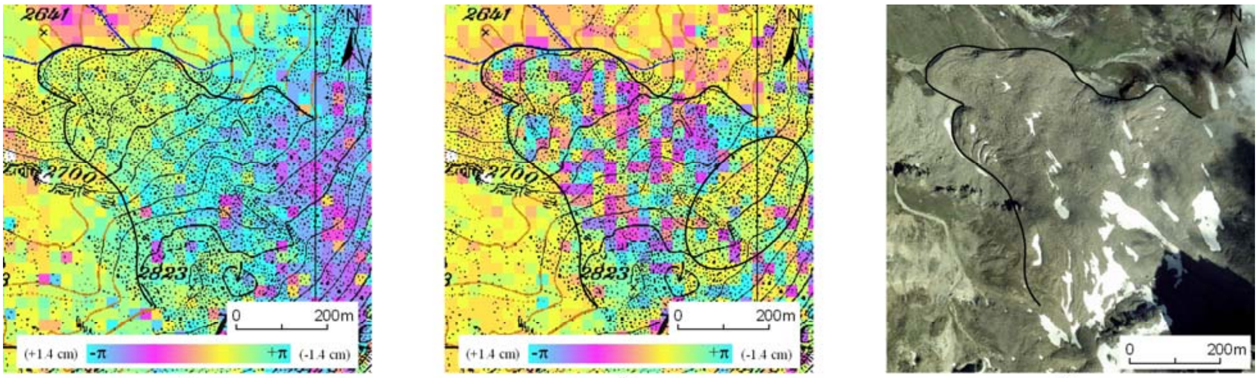
(a) (b) (c)

Fig. 2. The active Tsaté-Moiry rock glacier. (a) 29-30 July 1997 (1d), ascending orbit; (b) 11-12 March 1997 (1d), ascending orbit; (c) orthoimage (Sept. 1999); scars are clearly visible on the centre of the rock glacier (arrow). Reproduced by permission of swisstopo (BA081058).



(a) (b) (c)

Fig. 3. The active Tsarmine rock glacier. (a) 29-30 July 1997 (1d), descending orbit; white dots indicate horizontal surface velocities measured with differential GPS between 2004 and 2005; big dots = velocities > 4 mm/day; small dots = velocities < 4 mm/day; (b) 3 Sept. - 8 Oct. 1997 (35d), descending orbit; (c) orthoimage (Sept. 1999). Reproduced by permission of swisstopo (BA081058).



(a) (b) (c)

Fig. 4. The active Becs-de-Bosson rock glacier. (a) 29-30 July 1997 (1d), descending orbit; (b) 3 Sept. - 8 Oct. 1997 (35d), descending orbit; the circled area indicates an absence of movement, which is confirmed by GPS data (Perruchoud & Delaloye 2007); (c) orthoimage (Sept. 1999). Reproduced by permission of swisstopo (BA081058).

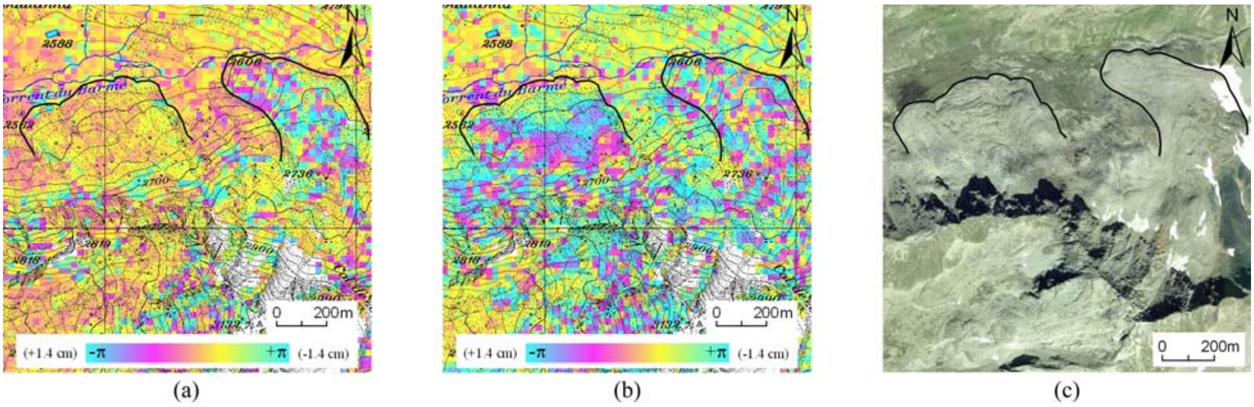


Fig. 5. The active Milon east (right) and low active Milon west (left) rock glaciers. (a) 3 Sept. - 8 Oct. 1997 (35d), descending orbit; (b) 18 Sept. 1996 - 30 July 1997 (315d), descending orbit; (c) orthoimage (Sept. 1999). Reproduced by permission of swisstopo (BA081058).

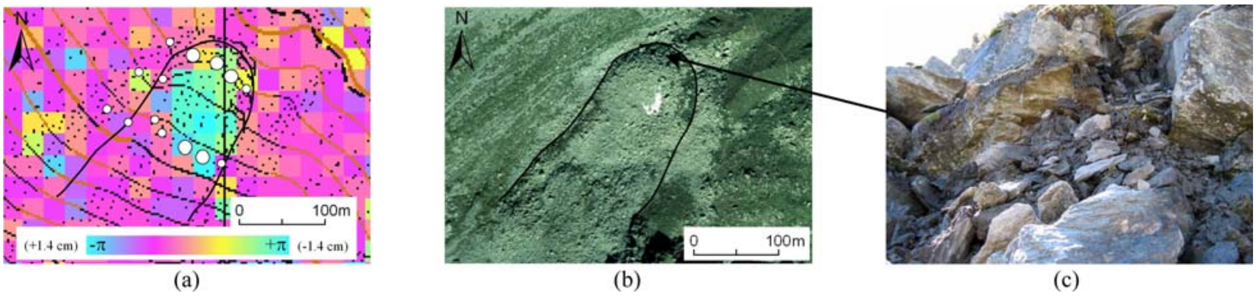


Fig. 6. Les Lués Rares rock glacier. (a) 29 July - 3 Sept. 1997 (35d), ascending orbit; white dots indicate horizontal surface velocities measured with differential GPS between 2006 and 2007; big dots = velocities of 1-2 cm/35 days; small dots = velocities < 0.5 cm/35 days or no movement; (b) orthoimage (Sept. 1999); (c) view on the destabilised front. Reproduced by permission of swisstopo (BA081058).

Finally, rock glaciers showing only a low 1-year ERS InSAR signal or no signal at all creep with velocities slower than the phase cycle, i.e. 2.8 cm a^{-1}.

Interpretation

The presented examples show the strength of InSAR for distinguishing the large range of active rock glaciers velocities. Table 2 summarizes the ERS InSAR-detected velocities and the corresponding classification which can be proposed. The frequency of destabilization indices for each category, which attests a change in the rock glacier dynamics, is also reported in the table.

Very high velocity

Phase signals observed on 1-day lag interferograms allowed movements in the order of a centimeter per day, which means several meters per year, to be identified. This magnitude of velocities, which can be qualified of *very high*, has rarely been mentioned hitherto. However, recent studies have reported the existence of other unusually rapid rock glaciers (e.g. Roer et al. 2008). Landslide-like features, like well developed scars and crevasses, are often observed on these landforms (Fig. 2c), which indicates a strong destabilization and a complete change in the rock glacier dynamics.

High velocity

Rock glaciers showing a low 1-day and a decorrelated 1-month ERS InSAR signal move with a speed of 1-2 m a^{-1}. Such velocities are in the upper range of the typical rock glacier velocities. These landforms may creep with such velocities because of a large amount of ice, relatively warm temperature or steep slope, but some of them display indices of a recent acceleration. Among these indices, the thinning of the upper part and associated thickening of the lower part is frequently observed, as it is the case for the Tsarmine rock glacier (Fig. 3c). On such landforms,

Table 2. Classification of the rock glaciers according to their surface velocities.

Classical classification	ERS InSAR signal	Estimated surface velocity	Velocity classification	Destabilization
Active	1 day	> 2 m a^{-1}	very high	very frequent
	(1 day)/ 35 days decorrelated	1-2 m a^{-1}	high	Frequent
	35 days	0.2-1 m a^{-1}	medium	Possible
	(35 days correlated) / 1 year	0.03-0.2 m a^{-1}	low	Rare
Inactive	(1 year)	up to a few cm a^{-1}	very low	No
Relict	No	-	-	No

destabilization signs, like scars and crevasses, are frequent, but are often not as pronounced and obvious as for rock glaciers of the previous category.

Medium velocity

Rock glaciers only detected with a 1-month interval and for which the signal is decorrelated correspond to the classical active rock glaciers. Velocities are comprised between 20 cm a^{-1} and about 1 m a^{-1}. Indices of destabilization are occasionally observed. They may result from strong activity periods, as for the Mont Gelé B rock glacier, which moved with velocities of 120 cm a^{-1} between 2003 and 2004, whereas the velocities measured since 2000 are normally comprised between 20 to 60 cm a^{-1} (Lambiel 2006, Delaloye et al. 2008a).

Low velocity

Rock glaciers showing a correlated or a low signal on 35-days interferograms and a decorrelated signal on 1-year interferograms are active, but the deformation rate is only a few cm a^{-1} (max. 0.2 m a^{-1}). A cold permafrost temperature, low ice content or low inclined slope generally explain these moderate velocities. Even if they are rare, destabilization indices occur in some cases, as for example on Les Lués Rares rock glacier (Fig. 6). On this landform, which is located below the regional lower limit of permafrost (front at 2320 m a.s.l), numerous indices, such as subsidence features, blocks densely covered with lichens and bushes on the front should indicate a very low activity. However, fresh scars in the front underline the current instability of the rock glacier (Fig. 6c), which is confirmed by the obvious and coherent signal visible on the 35-days lag interferogram, indicating velocities of about 10-20 cm a^{-1} (Fig. 6a). Both these velocities and the limit of the moving area are confirmed by GPS measurements. About ten rock glaciers of the inventory display such characteristics. They all show evidences of a former inactivity or at least a very low activity (like vegetation growth and abundance of lichens), but display some recent destabilization indices.

Very low velocity

The rock glaciers which are only detected on 1-year lag interferograms correspond to the classical *inactive* landforms. Their velocity is in the cm range per year.

Discussion

The inventory of creeping frozen debris bodies over a wide area is rarely exhaustive and the delimitation of the landforms can be highly subjective, whatever the method used. This is particularly the case with InSAR, as a potential signal may be due to other causes than a change in topography (atmospheric perturbations, vegetation, snow cover, etc.). Thus, the successfulness of such a study depends mainly on the availability of reliable interferograms. In this project, the discovery of a few very rapid rock glaciers was possible thanks the availability of very good quality summer and winter 1-day lag interferograms. Likewise, two excellent 35-days interval images, both in the ascending and descending mode, permitted us to delimitate classical active rock glaciers with a good accuracy. On the other hand, 1-year interferograms were not as reliable, but the identification of several low active rock glaciers was nonetheless possible.

In some cases, the signal is very low, such as, for example, the Tsarmine rock glacier on the 1-day interferogram (Fig. 3a) and the Milon west rock on the 35-days interferogram (Fig. 5a). For the Tsarmine rock glacier, the reliability of the signal was confirmed by GPS measurements. In the absence of terrestrial data, only the analysis of several interferograms and a good knowledge of the corresponding geomorphology allow the signal to be interpreted as a movement and not attributed to noise or atmospheric artefacts. However, the presence of a clear signal on a wider time interval, which confirms the activity of the landform, is an absolute prerequisite for attributing the signal to a change in the topography rather to noise.

One limiting factor for using InSAR in the study of rock glacier velocities is the fact that this technique gives an estimation of the movement for a time-delimited period. For this study, most of the interferograms used correspond to the period 1996-1997. Thus, the observed velocities should be valid only for this period. In addition, numerous active rock glaciers are in an acceleration phase since the 1980s (Kääb et al. 2007) and some of them are suffering strong changes in the process regime (Roer et al. 2008). Thus, the phase signal detected on the available interferograms may no longer reflect the current state of activity of the corresponding rock glaciers. However, the comparison of the ERS InSAR-detected signals to velocities measured with differential GPS on 15 landforms since 2004, that is nearly 10 years later, permitted us to validate the InSAR data. Moreover, additional field observations on several tens of rock glaciers allowed us to understand the cause of such and such range of velocities, like, for instance, the observation of destabilization processes, which are clearly connected to the very high velocities observed on some rock glaciers (Roer et al. 2008). Thus, even if the velocities may have changed since the end of the 1990s, it is very probable that most of the rock glaciers are still in the same range of velocities as ten years before.

Conclusion and Perspectives

ERS InSAR has revealed to be an efficient remote sensing technique, not only for inventorying active rock glaciers over wide areas, and more generally the creeping landforms of the alpine periglacial belt, but also to estimate and categorize their displacement velocities. Thus, InSAR constitutes an interesting tool for the study of rock glacier dynamics in the context of a general acceleration of these landforms. However, the detected signal can be sometimes close to the noise level. Thus, reliable interferograms, orthophotos and a good knowledge of the local geomorphology are necessary to interpret the detected signal correctly.

Further InSAR studies are feasible with the SAR sensors on board of the European Environmental Satellite ENVISAT (C-band, 5.6 cm wavelength, 35 days repeat cycle), the Japanese Advanced Land Observing Satellite ALOS (L-band, 23.6 cm wavelength, 46 days repeat cycle) and the German TerraSAR-X mission (X-band, 3.1 cm wavelength, 11 days repeat cycle), in orbit since 2002, 2006 and 2007, respectively. They should permit recent data on rock glacier velocities throughout wide areas to be obtained. However, no one is able to provide reliable data on rock glaciers with very high velocities anymore (Delaloye et al. 2008b), as did the ERS-1/2 tandem between 1995 and 1999.

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