TYPICAL ERS INSAR SIGNATURE OF SLOPE MOVEMENTS IN A PERIGLACIAL MOUNTAIN ENVIRONMENT (SWISS ALPS)

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ABSTRACT

ERS InSAR has been used for mapping and assessing slope movements in an alpine periglacial test region. A large number of areas have thus been recognized as affected by mass wasting related to permafrost or not. Glaciers and most of the active geomorphic landforms display in fact typical ERS InSAR signals. A typology has been established. It can be seen as a useful tool to interpret ERS InSAR data in such a mountain environment.

1. INTRODUCTION

Permafrost is a widespread thermal phenomenon in mountain areas, especially above the timberline. In such a periglacial environment, accumulations of loose debris may be perennially frozen and consolidated by ice down to several tens of metres beneath the surface. The super-saturation with ice induces the steady-state creep of the ice-rock mixture and leads to the development of rock glaciers [1]. The surface horizontal motion of rock glaciers ranges typically from 0.1 to more than 1 m a^{-1}. Changes are susceptible to occur with time (seasonally, annually and after decade) in response to permafrost temperature shifts [2-5]: an increase of the permafrost temperature causing a higher deformation rate, especially when the temperature gets closer to 0°C [6]. The velocity of rock glaciers has thus risen significantly since the 1980s over the whole alpine range [7] in response to a significant permafrost warming.

Where rock glaciers are supplying steep slopes and gullies in unconsolidated debris, the connection between both periglacial and hydrological (torrent) systems may be critical [8]. In fact, many debris flows started from the belt of the discontinuous permafrost and a modification of the permafrost creep may affect the dynamics of the debris flow activity. The management of natural hazard related to debris flow triggering in a periglacial area requires an assessment of the permafrost conditions (location and dynamics) in the upper catchment zone to be carried out. It can be performed individually for a single torrent system, but also at a regional scale. The analysis of SAR interferometry (InSAR) data appears to be a potential tool to fill in this task by providing, at least partially, this regional overview. InSAR is a well established technique for mapping surface displacement at mm to cm resolution [9-11] over alpine areas, where dense vegetation is no longer present. Observations of mass wasting in the satellite line-of-sight direction are however only feasible during the snow free period (between early summer and mid fall). In addition, the coverage may be incomplete due to the rugged topography [12-15]. Therefore, not only permafrost creeping features can be revealed by InSAR, but also further mass movements (landslides, sagging, etc.) [16].

With the support of ESA (European Space Agency) SLAM (Service for Landslide Monitoring) project and the Swiss Federal Office for the Environment (FOEN), the capability of InSAR for detecting and inventorying slope instabilities in a periglacial mountain area was tested in the western Valais Alps (50 x 30 km) with ERS SAR data [17]. The reliability of the results (location of “instable” zones and movement rate) was supported by the often excellent fitting with control data (rock glacier inventories, GPS measurements and air-borne photogrammetry) [16]. The comparison of InSAR-derived data with geomorphic features detected on orthoimages permitted to categorise the nature of the slope movement. After summarizing the applied methodology, this paper provides an overview of the typical ERS InSAR signature that can be attributed to the most frequent landforms with various rate of activity.

2. DATASET AND PROCEDURE

Thirty-four interferograms (with time lapse of 1 day or multiple of 35 days +/- 1 day) were computed from SAR images acquired by ERS-1 and ERS-2 satellites along ascending and descending orbits between 1995 to 2000 with baselines shorter than 100-150 m. 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. The InSAR products were also computed at 25 m spatial resolution.

The procedure applied for the detection and qualification of moving areas comprised following steps [16] :

- Estimation of the (old and fresh) snow conditions at SAR image dates. Aim is to avoid misinterpretation of the InSAR signal.
- Combined visualization of valid interferograms with various time lags (1 day, 1-2 months, 1-3 years) over smaller areas (about 5 x 5 km) in order to detect the "polygons" potentially related to slope instabilities and to determine the magnitude order of the deformation (three classes: cm/day, cm/month, cm/year).
- Determination of the cause of the slope movement by comparison to geomorphology (superimposition with topographic maps and orthophotos).
- Comparison with "terrestrial" slope motion measurements, where existing, and additional field observations (geomorphic mapping, GPS survey) to precise or to confirm locally the InSAR results.

An inventory of more than 600 polygons identified as ERS InSAR-detected slope instabilities was built up. The list did not comprise all the slope instabilities in the studied area, but is a subjective inventory of all "polygons" showing any kind of signal on ERS SAR interferograms that can be interpreted as a possible slope movement. Therefore, it must be kept in mind the limitations of InSAR arising from layover and shadowing, that prevent the coverage of steep rock walls and deep valleys, and from the sensitivity of the interferometric phase to the deformation component along the radar look direction (23° from nadir). Moreover, north and south slopes are not favourably illuminated by the ERS SAR, what decreases the capacity for detecting mass movements in these orientations.

3. MAIN DETECTED LANDFORMS

Tab. 1 summarises the ERS InSAR signals that were usually observed on the different types of landform. They are described and illustrated hereafter.

3.1 Glaciers

Glaciers and glaciers covered by a thin layer of debris (type I in tab. 1) provide coherent and often fringed signals at daily interval in wintertime – and in summertime by cold snow. For longer time lapse, the InSAR signal is decorrelated due to the excessive glacier deformation. During the melting season decorrelation is also provided by wet snowcover and water on the glacier surface.

3.2 Debris-covered glaciers

Glaciers covered by a thick mantle of debris (type II) are frequently residual glacier masses that are (quite) no more connected to any supplying glacier. They move slowly and often do not provide any signal at daily interval. Decorrelated signals occur at monthly time lapse in summertime. They can be caused by the rapid settlement (dm range) of the glacier surface and/or by a significant glacier motion.

3.3 Push-moraines

Push-moraines are glacio-tectonically deformed frozen sediments [18]. In the Alps, many push-moraines date back to the Little Ice Age (LIA) period (1350-1850 AD), when former frozen materials were pushed up laterally and frontally by a glacier advance. Movements that are currently susceptible to occur in such landforms are the back-creeping of still frozen sediments towards the glacier valley floor and/or the surface subsidence due to melting of massive ice at depth [19]. As for the

Table 1. Potential of ERS InSAR for detecting slope movement

	Time Lapse			
Landform	1 day (winter)	1 day (summer)	35-105 days (summer)	year(s)
Glacier	c	d	d	d
Debris-covered glacier I	c	d	d	d
Debris-covered glacier II	-	d	d	d
Push-moraine	-	-	c/d	d
Active rock glacier				
Surging	c	c	d	d
Very active	-	(c)	d	d
Active	-	-	d	d
Low active	-	-	c	d
Very low active (inactive)	-	-	-	c
Landslide / sagging				
Active	-	-	c/d	d
Slow	-	-	-	c
Gelifluction	-	(d)	d	d
Subsidence by drainage in bedrock	-	-	(c)	c

- : no signal; c : coherent signal; (c) : possible coherent signal; d : decorrelated signal; (d) : possible signal (decorrelated); c/d : coherent or decorraleted signal impressive edifice of push-moraines surrounding the LIA forefield of the Lire Rose glacier, an obvious signal – that can be decorrelated – is distinguishable on 35-days summer SAR interferograms (fig. 1).

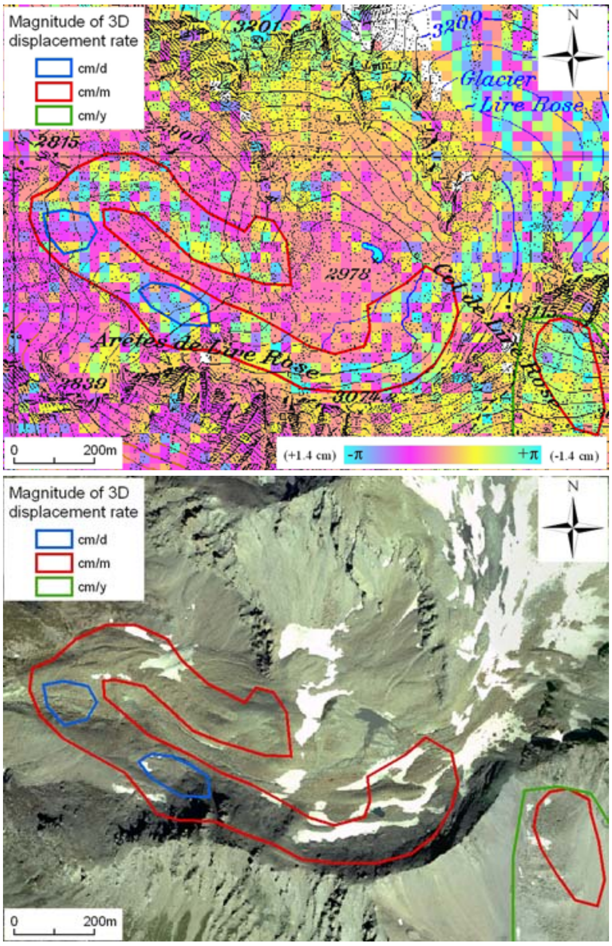

Figure 1. The push-moraine complex in theLittle Ice Age forefield of the Lire Rose glacier, Bagnes Valley. Up: 03.09.1997-08.10.1997 (35d), descending orbit; note the occurrence of a low active rock glacier at the south-eastern corner. Down : orthoimage (by swisstopo) with reported InSAR-detected polygons.

3.4 Active rock glaciers

The velocity range of active rock glaciers is large. For most active features, an obvious signal is detectable at monthly interval (fig. 2). For the most active, a low signal may be already detected at 1-day interval in summer and decorrelation is widespread over the landform at monthly interval. For the slowest, any signal can be difficult to be evidenced at monthly time lapse but becomes evident, sometimes decorrelated at yearly interval.

A peculiar case is the so-called "surging" rock glacier, that is a (part of) rock glacier moving very fast (up to more than 5 m a^{-1}) and exposing crevasses and/or collapse features [20]. At least two surging rock glaciers have thus been detected by InSAR in the study area: the Petit-Vélan and the Tsaté rock glaciers [16, 17]: an obvious signal is already observed at daily interval both in winter and summertime (fig. 3). GPS survey has confirmed the rapid surface velocity of the two "surging" rock glaciers, which is effectively too large for any coherent detection on 35-days ERS interferograms, but fits with well the 1-day detection range. Some rapidly moving (and probably "surging") rock glaciers display 1-day signal only in summertime.

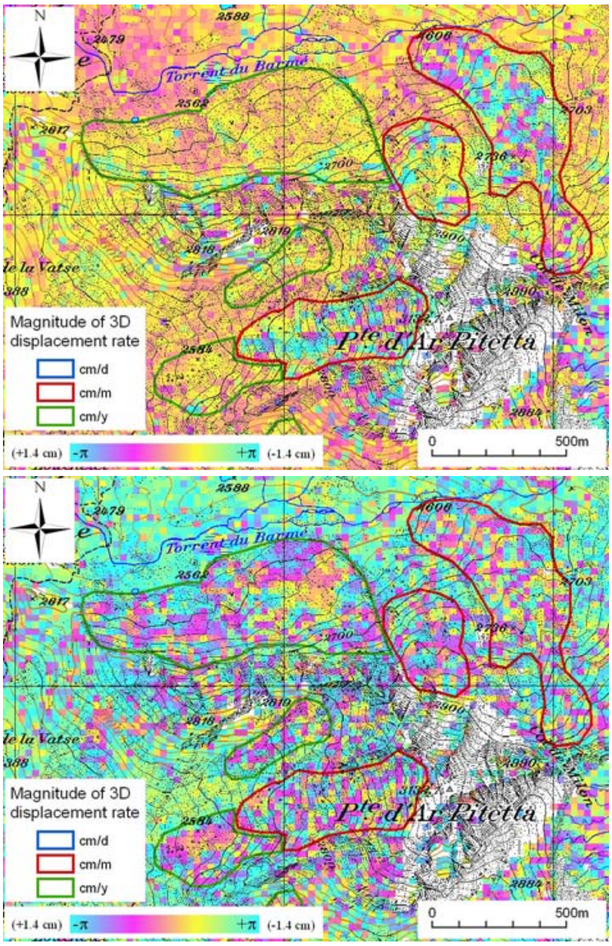

Figure 2. Well developed rock glaciers around Pointe d'Ar Pitteta, Zinal Valley, exhibiting various rates of activity. Descending orbit; up : 03.09.1997-08.10.1997 (35d); down : 15.07.1998-08.09.1999 (420d).

3.5 Landslides and sagging

Superficial landslides and deep-seated sagging are slope movements that are not related to glacier or permafrost occurrence. They are frequent in the alpine periglacial belt and can be detected by ERS InSAR with various rate of activity. The Péterey landslide for instance is a well detectable active feature at monthly time lapse (fig. 4), what reveals a subsidence rate of about 10 cm a^{-1}. Slower sagging or landslides can be detected only on a 1-year interferogram.

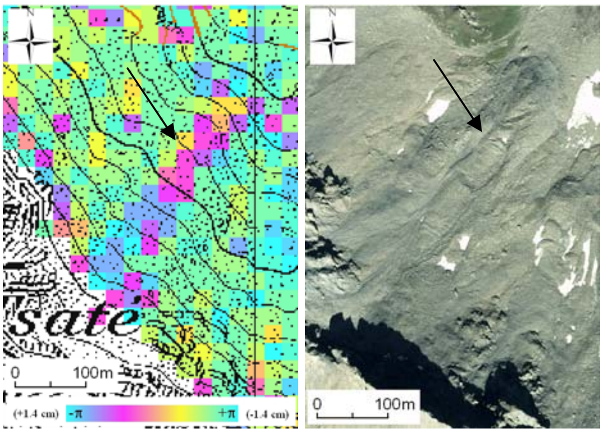

Figure 3. The "surging" Tsaté rock glacier (arrows) in the Moiry Valley (north-eastern slope). Left : 29.07.1997-30.07.1997 (1d), ascending orbit. Right : orthoimage (by swisstopo).

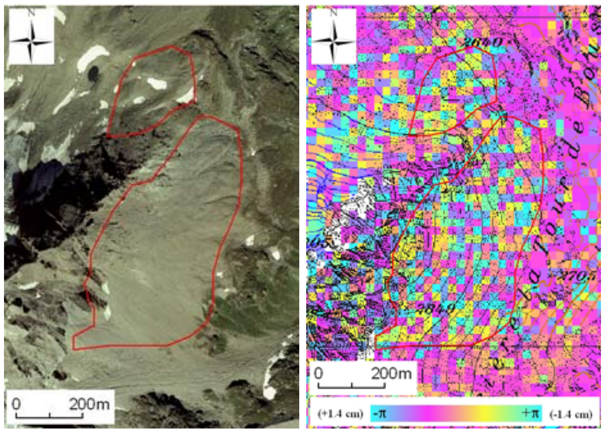

Figure 5. Gelifluction on talus slope at Derrière la Tour de Boussine (Bagnes Valley): Left: orthoimage (by swisstopo) with reported InSAR-detected polygons. Right : 08.10.1997-14.07.1998 (279d), ascending orbit.

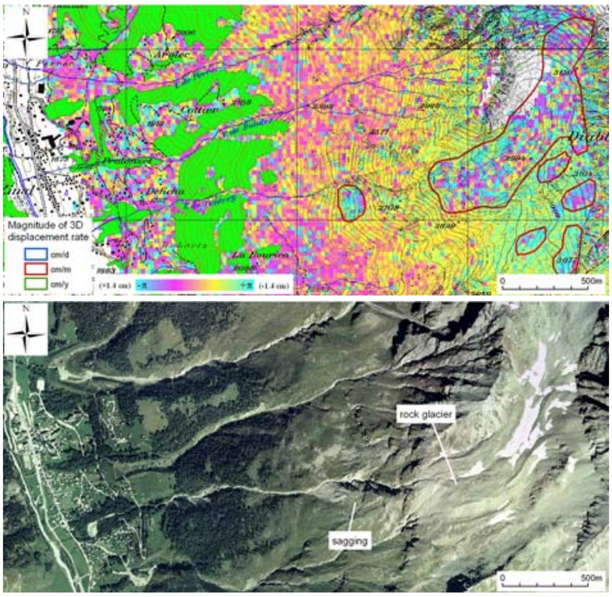

Figure 4. Sagging(landslide) and large active rock glacier at Péterey (Zinal Valley). Up : 03.09.1997-08.10.1997 (35d), desending orbit, with InSAR-detected polygons. Down : orthoimage (by swisstopo).

3.6 Gelifluction

Gelifluction is the superficial deformation of ground supersaturated by (melt)water during the thawing season. The process affects many periglacial slopes covered with unconsolidated materials. Generally, the InSAR signal is decorrelated at a 1-year lag (fig. 5). This is probably due to the heterogeneity of the movement, according to varying velocities of several (many) juxtaposed lobes of variable dimension. Decorrelation at 1-day interval is sometimes observed. An explanation in this case could be that water impregnation of the ground surface disturbs the reflection of the radar wave and not that the terrain is moving fast.

4. COMPLEX SLOPE SYSTEMS

Worth is to note that all the above described types of moving landforms are often juxtaposed, when not superimposed. They compose «complex slope systems» as perfectly illustrated by the orographic right side of the Arolla Valley (fig. 6) where moving features including debris-covered glaciers, push-moraines, rock glacier, landslides and sagging are coalescent. At Perroc (center of fig. 6), an active rock glacier is even located on a large slow sagging affecting a larger part of the slope. Such a configuration is not unique. The same situation is observed for the low active rock glacier east of « Col de Lire Rose » (fig. 1), which is located in the upper part of a larger sagging (not visible on the figure).

5. CONCLUSION AND PERSPECTIVE

The application of the ERS InSAR technique has revealed to be an interesting tool for detecting and inventorying slope instabilities in a periglacial mountain environment above the timberline. Many moving areas can be identified and delimited. Moreover, the magnitude order of the displacement rate can be estimated. As a further result, a typology of ERS InSAR signatures has been established for different landforms with various rate of activity. It appears that such a typology may be useful to interpret ERS InSAR data for users who are not well familiarised with the mountain periglacial geomorphology or with this radar remote sensing technique.

Being aware of the limitations of the method, the detection of slope instabilities by means of ERS InSAR can be seen as a preliminary tool compiled at regional scale that can be useful for both natural hazard management and process understanding of slope movement in mountain (periglacial) areas. Data used in this study is already about 10 year old. But most of the moving landforms would keep a similar magnitude order of motion over decades. However, shifting climate is potentially inducing local strong changes in the dynamics of alpine permafrost and more recent SAR data, available e.g. from the European Environmental Satellite ENVISAT launched in 2003 or the Japanese Advanced Land Observing Satellite ALOS launched in 2006, would be appreciated for further studies.

ERS SAR data courtesy of C1P.2338 (© ESA, processing GAMMA). DHM25 © 2003 swisstopo.

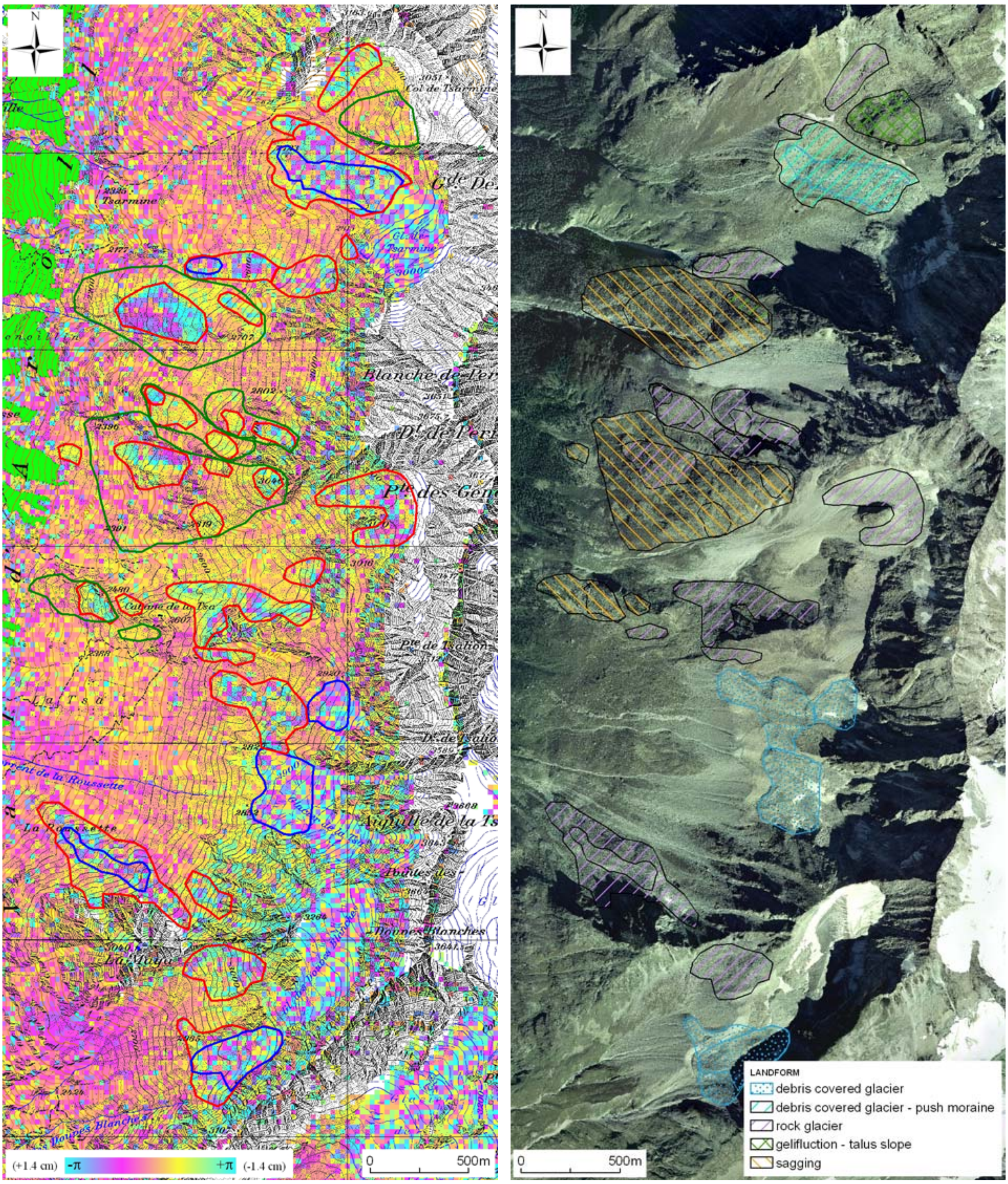

Figure 6. The complex orographic right side of the Arolla Valley. Left : 03.09.1997-08.10.1997 (35 d), descending orbit. Right : orthoimage (by swisstopo) with the geomorphological interpretation of the InSAR-detected polygons.

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