THE CONTRIBUTION OF INSAR DATA TO THE EARLY DETECTION OF POTENTIALLY HAZARDOUS ACTIVE ROCK GLACIERS IN MOUNTAIN AREAS

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ABSTRACT

Analysis of InSAR data permits the systematic detection of mass wasting phenomena in mountain areas, particularly rock glaciers. ERS 1-day and 3-day InSAR scenes have been used successfully to evidence the occurrence of rapidly moving rock glaciers (> 2-3 m/year). The availability of InSAR data with short time lag – what is still no more the case since a decade ago – has proven to be an important tool for the assessment of natural hazards in mountain permafrost areas.

1. INTRODUCTION

InSAR (space-borne Synthetic Aperture Radar interferometry) has revealed to be a useful tool to set up regional overviews on permafrost creep (rock glacier) and landslide activity above the tree line in mountain areas [1, 2]. The capability of InSAR for detecting and inventorying both location and magnitude of slope mass wasting in a mountain periglacial environment has been successfully applied in several regions of the Swiss Alps within the framework of the activities (or with the support) of the Swiss Federal Office of the Environment (Fig. 1). Data provided by the ERS-1/2, ENVISAT ASAR, JERS, ALOS PALSAR and TerraSAR-X have been used for these projects.

In the Swiss Alps, the distinct elevation of the tree line, the lower limit of discontinuous permafrost and the equilibrium line of glaciers at about 2000, 2400 and 2700-3500 m a.s.l. respectively, makes the context for the use of InSAR scenes for investigating permafrost related slope movements and more generally landslides on mountain slopes almost well suited. There is indeed a band of roughly 1000 m of elevation above the tree line and below the glaciers zone that can be investigated by this way.

Five inventories containing a total amount of about 3000 moving areas (hereafter called InSAR polygons) from more than 2000 different landforms have thus been established so far in the Swiss Alps. The exploitation of the InSAR data and the set up of the inventories have been carried out subjectively (visually) on the basis of a large set of interferograms comprising various time-lapses (from 1-day to 3-years or more) [1]. The polygons outline areas where InSAR signals corresponding to a possible slope movement have been detected [2]. Different magnitude orders of the slope displacement rate can be distinguished: cm/day, dm/month, cm/month, cm/year. Most polygons correspond actually to active parts of rock glaciers or landslides. The frequency of detected polygons may locally and regionally differ strongly (Figs. 2-3) depending on (i) the effective frequency of moving landforms – which depends itself on site factors like topography, geology, climate and glacier extent –, (ii) the quality of the interferogram set – e.g. number of available scenes, variety of time-lapse – and (iii) the SAR illumination of the relief – which depends almost on the orientation and the steepness of the valley sides. Due to the occurrence of numerous site factors disturbing the quality of SAR data (snow cover, soil moisture, vegetation, etc.), there is however so far, despite of encouraging attempts [e.g. 3], no reliable technique permitting the systematic and automatic extraction of InSAR polygons.

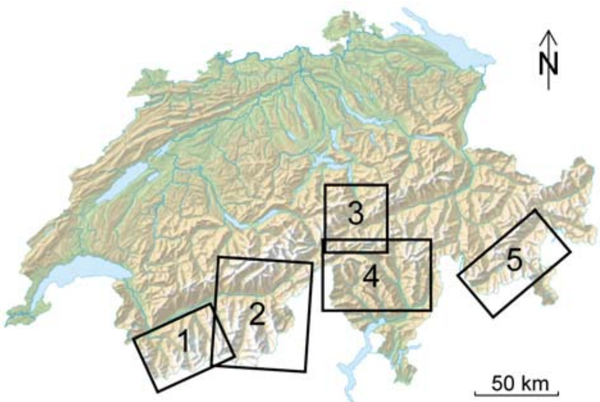

Fig. 1. Project areas of recent and ongoing systematic mass wasting inventories based on InSAR data in the Swiss Alps: lower Valais (1), upper Valais (2), Gotthard-North (3), Tessin (4), Upper Engadine (5). Map © Swisstopo.

The elaborated inventories contribute to the finer assessment of the ongoing sediment transfer in the catchments of many alpine torrents and can be seen as a useful tool for natural hazard management and process understanding of slope movement in permafrost areas. The paper focuses on potentially hazardous rock glaciers and more specifically on the recent destabilization of the Grabengufer rock glacier (Valais Alps, Switzerland). It describes in particular the strengths and limits of InSAR for detecting and analyzing rapidly moving rock glaciers.

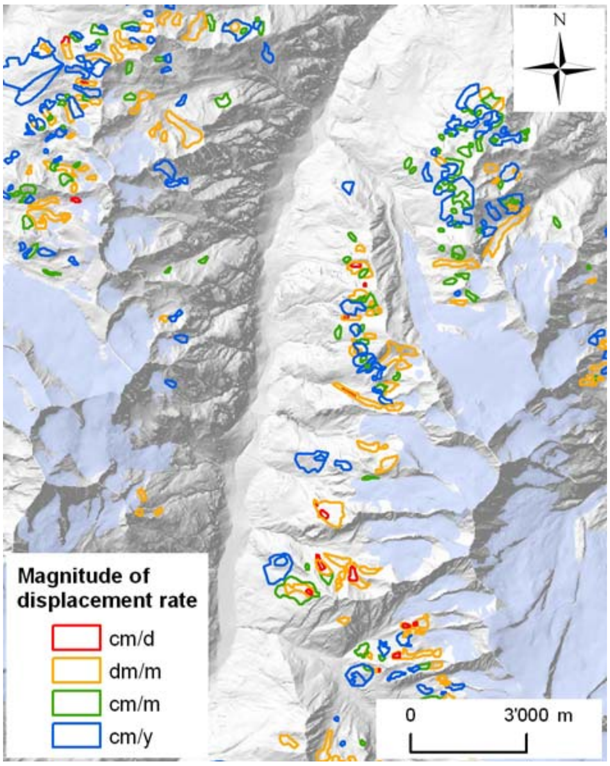

Fig. 2 . High frequency and complex arrangement of InSAR polygons above the tree line (example from Upper Valais). Highest peaks culminate above 4'000 m a.s.l. Glaciers in light blue.

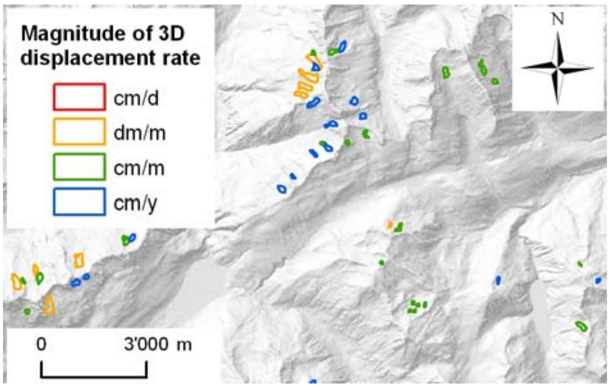

Fig. 3 . Low frequency and simple arrangement of InSAR polygons above the tree line (example from Gotthard-north). Highest peaks reach 3'000 m a.s.l. maximally. Almost no glacier in the area.

2. HAZARDS RELATED TO ROCK GLACIERS

Perennially frozen ground supersaturated with ice may be affected by slow deformation (permafrost creep). The process leads to the formation of rock glaciers that are large masses of ice/rock debris mixture, more than 10 m thick, acting as sediments conveyors (Fig. 4). They move typically in the order of 0.1 to 1.0 m/year [4], hence contributing significantly to the so-called sediment cascade on mountain slopes (Fig. 5). At their snout rock glaciers deliver regularly loose unfrozen material. Involved quantities depend on the rock glacier velocity, dimension (width, thickness) and rock content. They are usually ranging from a few cubic meters per year to a few hundreds. Whereas some rock glaciers termini are positioned on steep topography and transfer significant quantities of loose sediments into the head part of steep torrential gullies (Fig. 6), many others are located on almost flat terrain or are not connected with any torrential system (Fig. 7).

Fig. 4 . Blocky perennially frozen (permafrost) material supersaturated with cementing ice on the Grabengufer rock glacier. The outcrop height is about 10 m.

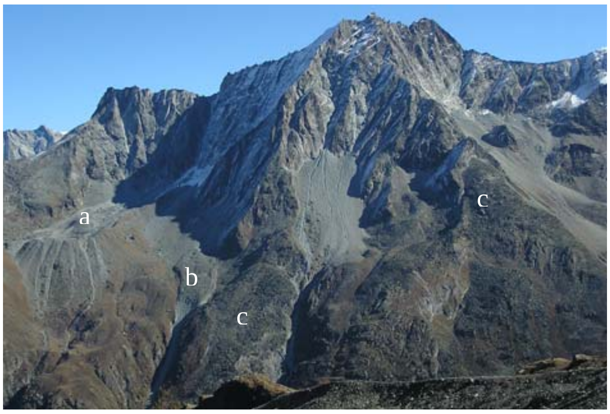

Fig. 5. A typical periglacial Alpine valley slope (Arolla valley, Swiss Alps) to assess with InSAR (see also [1]). Beneath headwalls, debris-covered glacier (a), rock glacier (b) and landslides (c) transfer sediments further downslope. The Tsarmine rock glacier (b), moving1-2 m/year, is located at the top a steep gully reaching directly the inhabited valley bottom (not visible here).

Fig. 6 . The Tsarmine rock glacier: the material transferred by the rock glacier is actively delivered (arrows) in a steep gully, from which it can be remobilized by a debris flow event

Fig. 7 . An example of rapidly moving rock glacier (Petit-Vélan, 5 m/year, black arrow) ending in a gently inclined remote area and being not directly connected to any torrential system, that can affect human activities downward.

Potential hazards associated with a rock glacier are almost indirect and consist mainly of debris flows originating from a gully located beneath a rock glacier front, or less frequently from the rock glacier front itself. Rock glacier-derived debris flows are usually triggered by high runoff occurring during intense snow melt periods or heavy rainfall events. Direct hazards consist of rock fall activity from the front, but are restricted to steep topography. The partial or complete collapse of a rock glacier – as it was for instance the case for the Bérard rock glacier in 2006– is so far an exceptional phenomenon that has only been rarely reported [5].

In response to the rapid increase in air temperature that has occurred in the European Alps since the 1980s, permafrost has warmed of about 0.5 to 1°C and rock glaciers are since that time moving significantly faster [6]. The rate of sediment supply from rock glacier fronts is thus increasing, which may, by refilling the gullies in sediment more rapidly, modify the frequency/magnitude rate of debris flow activity in downward connected torrents. It is hence important in inhabited mountain areas to assess and survey the activity rate of the most as possible rock glaciers located on top or side of torrential gullies that may directly or indirectly endanger human activities or infrastructures. A specific focus has then to be put on the rock glaciers moving fast (more than 1-2 m/year).

3. RAPIDLY MOVING ROCK GLACIERS

Rock glaciers moving between about 20 cm to 1 m/year can be well assessed by ERS-1/2 and ENVISAT 35-day interferograms and rock glaciers moving until about 2 m/year can be almost finely determined by TerraSAR 11-day and ALOS PALSAR 44-day interferograms. Several hundreds of active rock glaciers are moving between 0.2 and 2 (or slightly more) m/year in the Swiss Alps. Only a few tens may be of concern paying regard to natural hazards (Fig. 8).

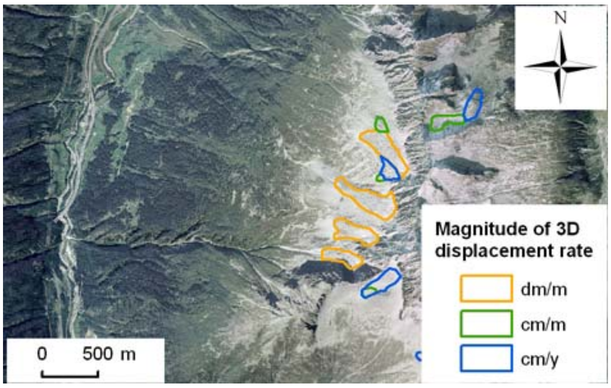

Fig. 8 . Example of four active rock glaciers whose velocity rate (dm/month, orange outline) has been assessed by InSAR (Gotthard-north). Only the southernmost one is of concern paying regard to natural hazards, the others being not directly connected to any torrential gully.

The analysis of ERS-1/2 1-day interferograms in the 5 zones investigated so far in the Swiss Alps has permitted to evidence somewhat surprisingly at least 11 rock glaciers (and a few other landslides) that were affected by very rapid movement in 1995-1999. For these rock glaciers, which are all located in the Valais Alps, obvious coherent signals are visible on the 1-day interferograms, at least in summer (Fig. 9) and for some of them in winter as well, indicating a displacement rate in the order of about 1 cm/day or more (i.e. 2-5 m/year) in the satellite line-of-sight direction [7].

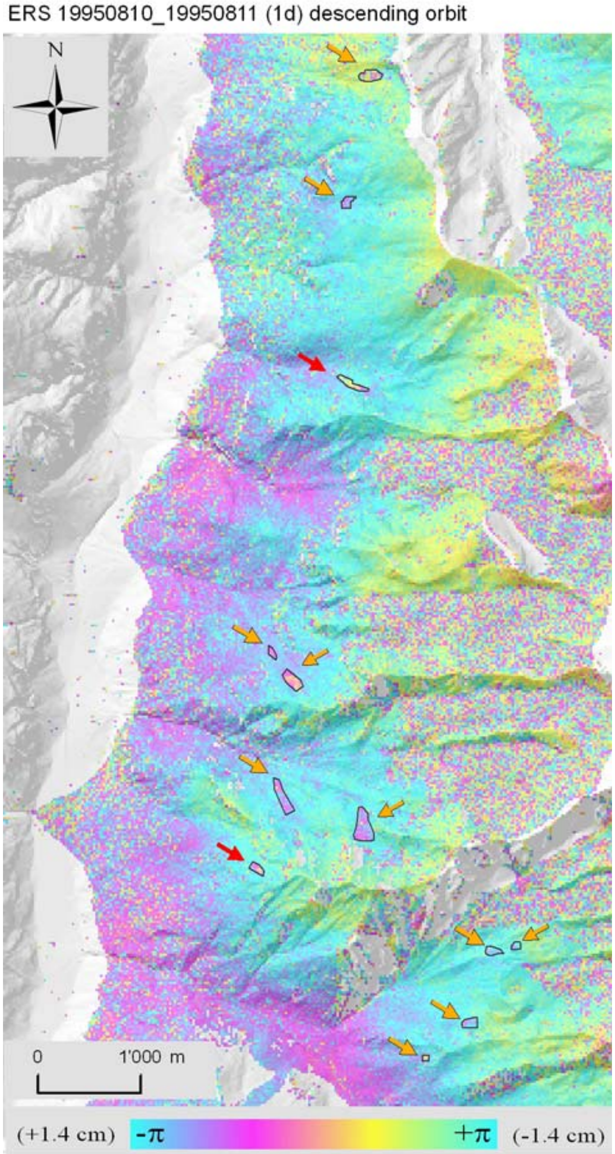

Fig. 9. Rapidly moving rock glaciers and landslides identified on a 1-day ERS-1/2 interferogram. Red arrows: obvious signals both in summer and winter. Orange arrows: obvious signal in summer, low or almost no signal in winter. Decorrelated areas occurring upslope (i.e. on the right side of the figure) are mostly fitting with glaciers.

Recent investigations carried out on some of these rock glaciers confirm the high rate of velocity. They point out even faster velocities than expected (up to 10 m/year) and permit to observe the quite systematical development of landslide-like features (scarps, crevasses), indicating a probable change in the mass wasting process (sliding phase ?). It has been shown that in some cases the "crisis" began during the early 1990s or so, whereas for others it seems to have been initiated much earlier [7-10].

4. THE GRABENGUFER ROCK GLACIER SURGE

Since at least the winter 2008/2009 the whole of the Grabengufer rock glacier (Zermatt valley, Switzerland) has suffered extraordinary surge-like mass wasting (Figs. 10-11). The displacement rate between summer 2009 and early summer 2010 has been extremely rapid, ranging between 30 and 100 m/year, with maximal seasonal velocities of about 150 m/year during the second half of 2009 [11]. Current displacement rates (up to more than 40 cm/day) are much too big to be precisely detected and surveyed by InSAR techniques (Fig. 12). However ground-based radar interferometry has given excellent results permitting to determine the displacement rate precisely after a few hours of survey in summertime as well as in wintertime (Fig. 13) [12].

Fig. 10 . The surging Grabengufer rock glacier is a 100 m width and 450 m long landform (doted line) dominating a steep gully. The rockfall activity from the front is almost continuous and debris flows also triggered occasionally from the gully.

Fig. 11 . Due to the exceptionally high displacement rate of the rock glacier and the steepness of the slope, the erosion of the Grabengufer rock glacier front is strong and almost continuous even in wintertime (March 17th, 2010).

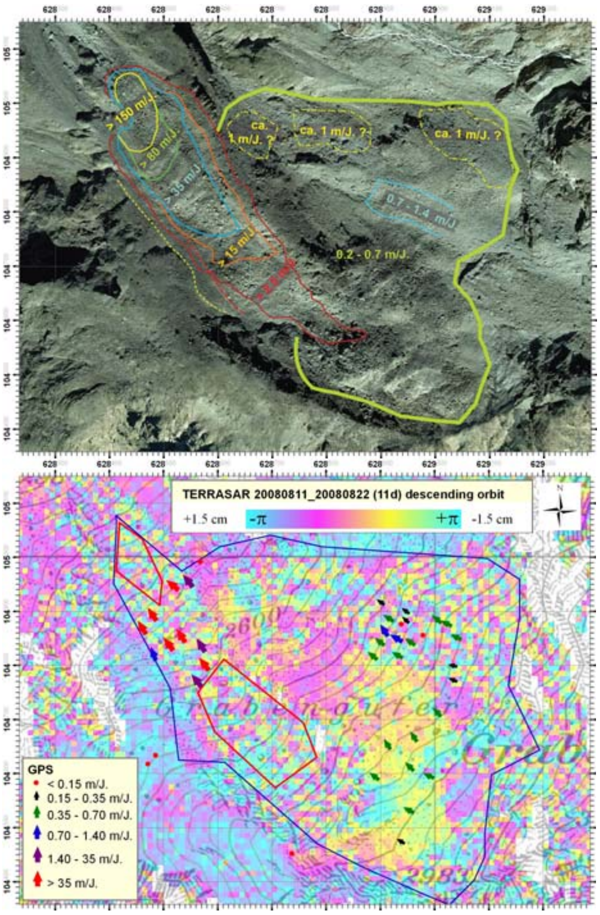

Fig. 12. Grabengufer rock glacier : (up) displacement rate during summer 2009 (in m/year); orthoimage © 1999 swisstopo; (down) 2008 TerraSAR-X 11-day interferogram and summer 2009 GPS survey (in m/year), red and blue outlines are polygons determined on ERS InSAR scenes (1995-1999) for cm/day and dm/month displacement rates respectively.

InSAR has been conversely helpful to reconstruct the development of the "crisis" during the 1990s. The first available ERS-1 3-day and 9-day interferograms in 1991 highlight the occurrence of a significant motion in the upper rooting zone of the rock glacier (Figs. 14A-B). The latter is confirmed by photogrammetrical analysis of aerial photos taken in 1982 and 1988, which shows that the origin of the "crisis" took place actually in the uppermost part of the rock glacier source area. At that time a landslide (or accelerated permafrost creep) developed above 2700 m a.s.l. The movement did not exceed 0.5 cm/day at that time.

The 1-day available ERS-1/2 interferograms in 1995-1997 tend to indicate, especially in 1995, both the migration of the "landslide" downward in the rooting zone of the rock glacier and the acceleration of the movement (up to 1 cm/day or so). The more obvious signal in summer 1995 (Fig. 14C) than in summer 1997 (Fig. 14E) corresponds to a higher displacement rate in the first year, which appears to have been consecutive to the development (and subsequently the melting) of a much thicker winter snowcover. In winter 1996 (Fig. 14D) there was almost no signal visible, what indicates the probable occurrence of seasonal fluctuations of the displacement rate. At that time the motion was already much too high to be distinguished on a 35-day ERS interferogram (Fig. 14E). Both the 9-day and 35-day interferograms allow to evidence significant slope movement not only restricted to the rock glacier. They are interpreted as a large and complex deep-seated active landslide on which the rock glacier in partly located. The landslide area is roughly outlined by the dm/month corresponding polygon on most sketches of Figures 12-14.

Aerial photos show that the intermediate section of the rock glacier compressed strongly in the early 2000s. The front of the rock glacier was only destabilized recently (after 2005 ?). Once it did, the whole rock glacier began to move extremely fast (> 10 cm/day) !

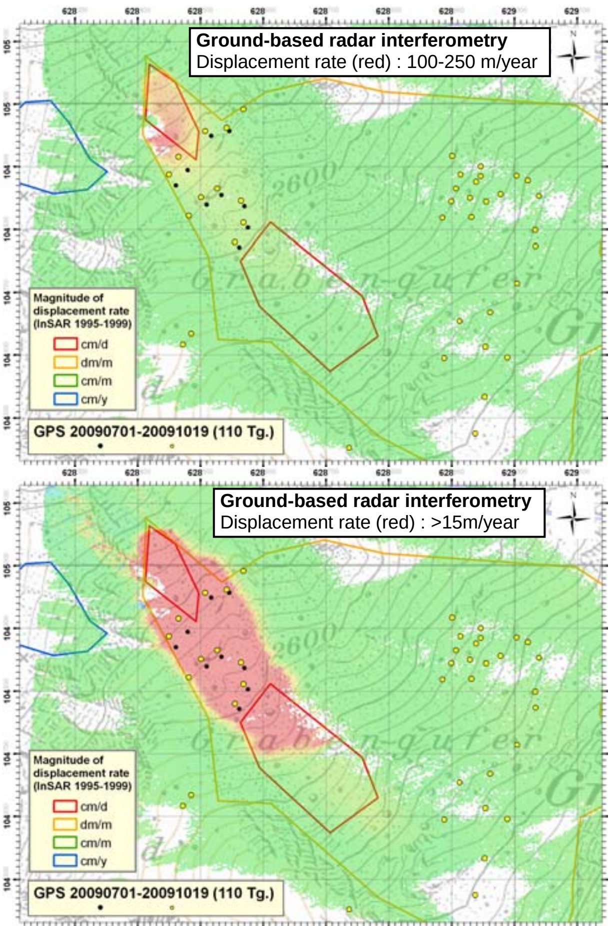

Fig. 13 . Ground-based InSAR (August 5th, 2009) and GPS survey (July and October 2009, 110 days). Red orange and blue outlines are polygons determined on ERS InSAR scenes (1995-1999) for cm/day, dm/month and cm/year displacement rates respectively.

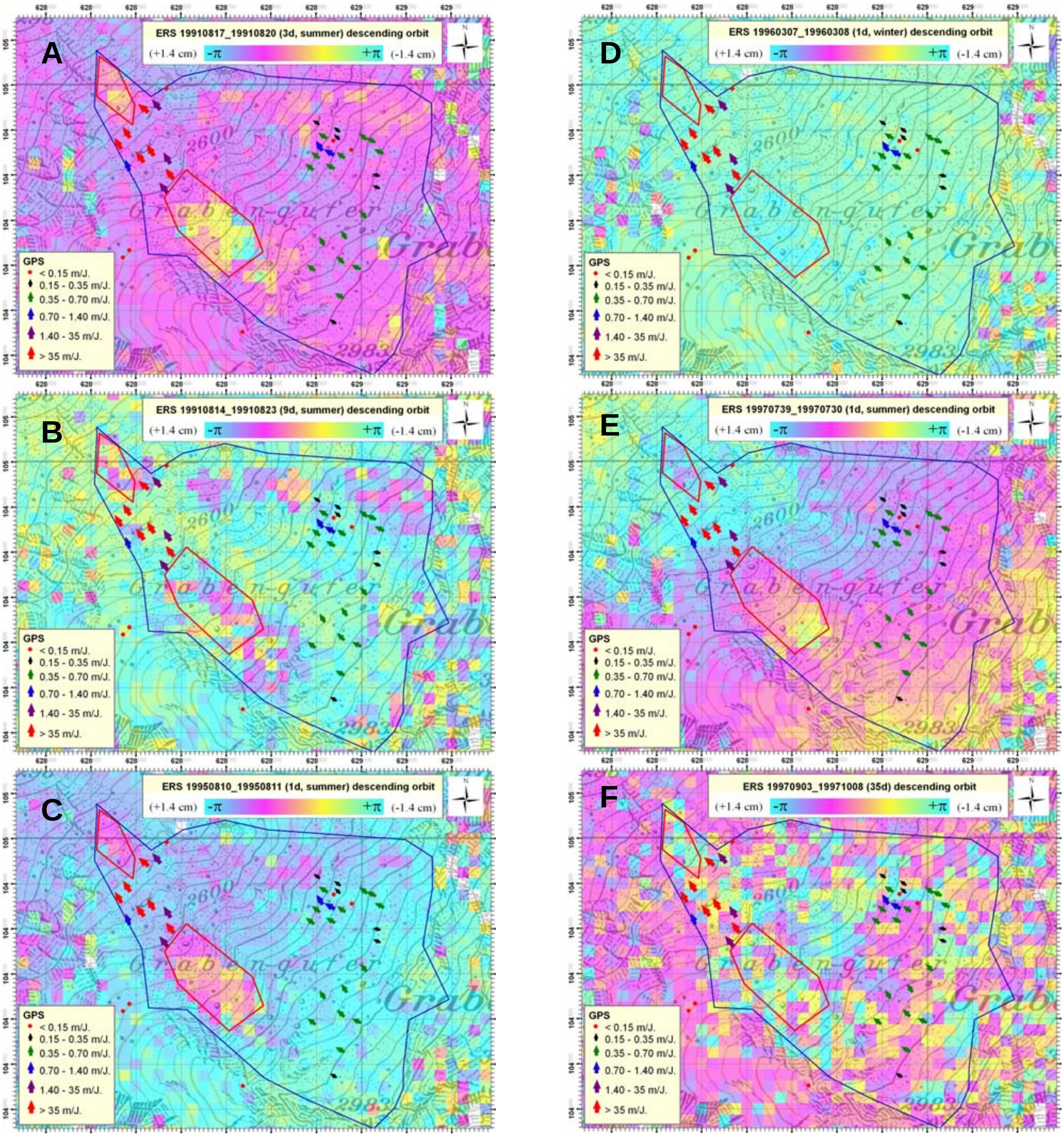

Fig. 14 . ERS-1/2 interferograms on the Grabengufer rock glacier for the period 1991-1997, and summer 2009 GPS survey (in m/year). Red and blue outlines are polygons determined on ERS InSAR scenes (1995-1999) for cm/day and dm/month displacement rates respectively.

5. CONCLUSIONS AND OUTLOOK

Analysis of available data provided by the ERS-1/2, ENVISAT ASAR, JERS, ALOS PALSAR and TerraSAR-X satellites has permitted for the last years the systematic detection of mass wasting in the periglacial belt of various regions of the Swiss Alps, what contributes to the finer assessment of natural hazards and process understanding of slope movement in mountain permafrost areas.

The analysis of ERS-1/2 differential interferograms dating back from the 1990s has evidenced several rock glaciers, that were moving rapidly (> 2-3 m/year) at that time. These rock glaciers were detected on ERS-1/2 1-day and ERS-1 3-day interferograms only.

Since the extinction of the ERS-1/2 tandem data a decade ago there is still no more InSAR data permitting the detection of slope movements faster than about 0.5 cm/day. The Cosmo-Skymed constellation of (currently) three satellites would however permit to acquire X-band interferograms with 1 day time interval. Such acquisitions were programmed for the summer of 2010. In addition to Cosmo-Skymed, also an ERS-2 3-day mission would permit updating the inventory of very active landslides in the Alps.

6. REFERENCES

1. Delaloye, R., Lambiel, C., Lugon, R., Raetzo, H., Strozzi, T. (2007). ERS InSAR for detecting slope movement in a periglacial mountain environment (western Valais Alps, Switzerland). Proceedings HMRSC-IX, Graz, 14-15 Sept. 2006, *Grazer Schriften der Geographie und Raumforschung 43*, pp. 113-120.

2. Lambiel, C., Delaloye, R., Strozzi, T., Lugon & R., Raetzo, H. (2008). ERS InSAR for detecting the rock glacier activity. *Proceedings of the Ninth International Conference on Permafrost, July 2008, Fairbanks, Alaska*, 1, pp. 1019-1024.

3. Barboux, C., Gay, M., Vasile, G. (2009). Permafrost Detection in the French Southern Alps, 2009. European PermaNet project of Alpine Space program 2008-2011. Gipsa Lab/DIS departement, Grenoble (unpublished).

4. Barsch, D. (1996). *Rock glaciers. Indicators for the present and former geoecology in high mountain environments.* Springer, Berlin: 331 pp.

5. Krysiecki, J.-M., Leroux, O., Bodin, X., Schoeneich, P. (2010). State and evolution of the Bérard rock glacier (southern French Alps) after its collapse in 2006: insights from geophysical, geodetic and thermal datasets. *Abstract, 3rd European Permafrost Conference*, Svalbard, p. 60.

6. Kääb, A., Frauenfelder, R., Roer, I. (2007). On the response of rockglacier creep to surface temperature increase. *Global and Planetary Change* 56: pp.172-187.

7. Delaloye, R., Strozzi, T., Lambiel, C., Perruchoud, E., Raetzo, H. (2008). Landslide-like development of rockglaciers detected with ERS-1/2 SAR interferometry. *Proceedings of the FRINGE 2007 Workshop, Frascati, Italy, 26-30 November 2007 (ESA SP-649, February 2008).*

8. Roer, I., Haeberli, W., Avian, M., Kaufmann, V., Delaloye, R., Lambiel, C. & Kääb A. (2008). Observations and considerations on collapsing active rockglaciers in the Alps. *Proceedings of the Ninth International Conference on Permafrost, July 2008, Fairbanks, Alaska*, 2, pp. 1505-1510

9. Delaloye, R., Lambiel, C., Gärtner-Roer, I. (2010). Overview of rock glacier kinematics research in the Swiss Alps. *Geographica Helvetica* (in press).

10. Lambiel C. (2010). Kinematics and morphological characteristics of a destabilized rock glacier, Swiss Alps. *Abstract, 3rd European Permafrost Conference*, Svalbard, p. 62.

11. Delaloye R., Morard, S., Abbet, D., Hilbich, C. (2010). The slump of the Grabengufer rock glacier (Swiss Alps). *Abstract, 3rd European Permafrost Conference*, Svalbard, p. 157.

12. Strozzi, T., Delaloye, R., Raetzo, H., Wegmüller, U. (2009). Radar interferometric observations of destabilized rockglaciers. *Proceedings of the FRINGE 2009 Workshop, Frascati, Italy, 30 November - 4 December 2009.*

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