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Des défis du Nord au Sud

Detection and inventorying of slope movements in the Brooks Range, Alaska using DInSAR: a test study

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ABSTRACT
This study investigates the potential of inventorying slope movements in a continuous permafrost and mountainous Arctic environment, namely along the Dalton Highway corridor in the Brooks Range, Alaska, applying a satellite-based radar interferometric (DInSAR) approach developed for use in the Swiss Alps. The exploration of the DInSAR dataset was conducted in two stages: a) systematic analysis of two approximately 50 km^2 sub-regions, and b) identification of specific features over the entire region. Using archived ERS and ALOS SAR data, as well as recent TerraSAR data, 77 high reliability movements were detected in the sub-regions. The main mass wasting categories identified were lobes (frozen debris lobes (FDL) or rock glaciers), landslides, solifluction slopes, and areas of heave/subsidence, with velocities ranging in magnitude order from cm/year to cm/day. Twenty FDLs have so far been identified using DInSAR, 75% of which were detected at a velocity rate of cm/day.

RÉSUMÉ
Cette étude examine le potentiel d'inventorier des mouvements de terrain dans une région de pergélisol continu et montagneuse de l'Arctique, à savoir le long du corridor de la Dalton Highway (Brooks Range, Alaska) en utilisant une approche basée sur des données d'interférométrie radar satellitaire (DInSAR) développée dans les Alpes suisses. L'exploration des données DInSAR a été faite en deux étapes: a) analyse systématique de deux sous-régions d'environ 50 km^2, et b) identification de signaux spécifiques dans toute la région. L'utilisation de données d'archive ERS et ALOS, ainsi que de données TerraSAR récentes, a permis de manière fiable 77 zones de mouvements dans les sous-régions. Les principaux types de mouvement de terrain identifiés ont été des lobes (“lobes de débris gelés” (FDLs) ou glaciers rocheux), des glissements de terrain, de la solifluxion, et des zones de soulèvement/ subsidence, avec des vitesses allant de l'ordre du cm/an au cm/jour. Vingt FDLs ont été identifié à ce jour, dont 75% se déplaçant à une vitesse de l'ordre du cm/jour.

1 INTRODUCTION

Differential satellite-borne SAR Interferometry (DInSAR) is a technique that can be used at a regional scale for the remote detection and mapping of slope movements whose displacement rate lies on the order of cm/day to cm/year (Barboux et al., 2014). DInSAR-based inventories of slope movements have been successfully elaborated above the treeline in temperate mountain regions, mainly in discontinuous permafrost areas (Delaloye et al. 2007a, Echelard et al., 2013; Liu et al., 2013). The current study investigates the potential of inventorying slope movements using DInSAR in a continuous permafrost and mountainous Arctic setting, namely along the Dalton Highway corridor, south central Brooks Range, Alaska.

In the Swiss Alps (lat. 45 N), for instance, DInSAR has been used to create large inventories of alpine slope movements in regions spanning several hundreds of square-kilometers. It has permitted the detection of thousands of moving landforms and the determination of their surface geometry and activity (displacement rate) (Delaloye et al., 2007a, 2007b, 2008, 2010; Lambiel et al., 2008, Barboux et al., 2014). Excluding glaciers, landforms detected by DInSAR analysis in an alpine context primarily include rock glaciers, push-moraines, debris-covered glaciers, dead ice remnants, solifluction slopes and landslides.

The central Brooks Range is much too large an area for extensive ground-based observations of mass wasting processes. The use of remote sensing techniques, however, offers promising potential for inventorying and monitoring mass movements. The present analysis is conducted using a similar approach as is used in the Swiss Alps, being particularly aware that vegetation and snow conditions, as well as mass wasting phenomena, may strongly differ between the two environments. Analysis is primarily based on TerraSAR-X scenes acquired in summer and fall 2013. The study serves as a test for using previously developed DInSAR techniques to inventory mass movements in a continuous Arctic mountain permafrost setting.

1.1 Area of interest

The studied area is located in the south central Brooks Range, about 90 km north of Coldfoot and 240 km south of Deadhorse (Figure 1). It is about 56 km long, extending from 67°35'N to 68°06'N. Elevation ranges mostly

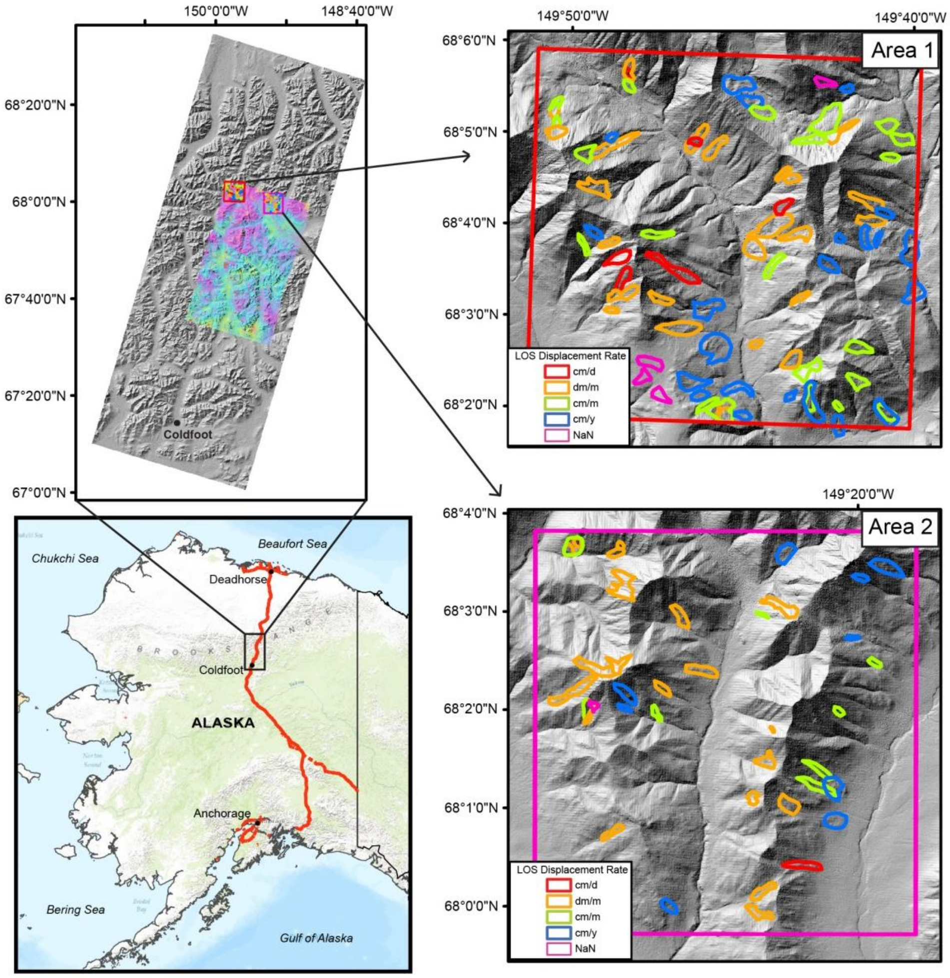

Figure 1. Location of study area and two sub-regions of more detailed analysis, Area 1 and 2. The top left image reveals the extent of TSX descending images on the 5 m Atigun Pass DEM. Area 1 and 2 show the distribution of DInSAR detected movements (polygons) and the associated line of sight (LOS) displacement rate (color of polygon).

between 600 and 1850 m asl. The investigated region comprises not only the main corridor along the Dalton Highway, but also adjacent and parallel valleys in a band of about 15 km on each side. The total area is about 1700 km^2. Two sub-regions have been investigated in greater detail, namely Area 1 and Area 2. These areas are located at the northern edge of the Dietrich river watershed, just south of the Atigun pass and the continental divide. Both sub-regions are characterized by steep mountain slopes and grassy vegetation located in the valley bottoms. South of Areas 1 and 2, elevation tends to decrease and vegetation cover becomes denser with a forest cover reaching up to roughly 900 m asl. The area of interest is mapped as continuous permafrost, although permafrost in the valleys is relatively warm and shallow (-1.0°C at 24 m depth in 2010) (CADIS, 2010).

Hamilton (1978a, b; 1979a, b; 1980; 1981) mapped the most striking geomorphological elements of the Central Brooks Range using aerial photographs and helicopter traverse, being the first to identify and locate mass wasting features in the region. Mapped landforms included rock glaciers, talus cones, rock slides and open system pingos, as well as lobate mass wasting features which he called flow slides. These features are now referred to as frozen debris lobes (FDL). In more recent years, geomorphological studies have focused on the development and the dynamics of FDLs along the Dalton Highway corridor, using both ground based and remote sensing methods (Daanen et al., 2012).

2 METHODOLOGY

2.1 Background

Since a pilot study in 2005, DInSAR technique has been used in the Swiss Alps to set up several regional inventories of slope instabilities, primarily based on SAR data dating back to the mid-1990s (ERS, JERS) on a 25 m raster resolution (Delaloye et al. 2007a, b, 2010). More recently, newer data (e.g ALOS, Envisat, TerraSAR, Radarsat) has permitted the improvement of the raster resolution to about 5 m, as well as the upgrading and updating of former inventories. Barboux et al. (2014) introduce the systematic procedure which has been used to locate and estimate the displacement rate of slope movements, based on interpretations of DInSAR signals from a large dataset. The proposed method was successfully applied to the Western Swiss Alps, detecting nearly 1500 moving objects (landforms) located above the treeline with displacement rates ranging from a few centimeters to several meters per year. DInSAR-derived inventories were also identified as a possible preliminary tool for natural hazard management and understanding slope movement processes in mountainous areas (Delaloye et al. 2010, Barboux et al., 2014). Despite important efforts to improve the methodology, thus far there is no automatic procedure which allows for the setting up of an inventory, and therefore the work still has to be performed manually (visually).

As an extreme simplification, an interferogram can be described as a map of topographical changes calculated from the combination of two SAR scenes acquired at different times over the same region from slightly different orbits (baselines). On landforms with a rough surface, "coherent" signals, those with similar values in adjacent pixels, can be observed on the interferogram when there is no movement or when the absolute displacement between the two acquisitions is less than about half the wavelength of the radar signal (that is, less than 1.55, 2.8 and 11.8 cm for the X-, C- and L-band respectively). The DInSAR signal is considered "decorrelated" when values differ strongly between two neighboring pixels (noisy signal). Decorrelation is due to displacement that is too large, or due to disturbances by vegetation, snow or water.

2.2 Methodological settings in the AOI

Archived ERS (1995, C-band) and ALOS (2007-2009, L-band) SAR data, as well as recent TerraSAR data (2013, X-band) specifically acquired for this project have been used to create a dataset comprising 1- day ERS, 11-, 22-, 33-, and 44-day TSX , and 46-, 92-days and 1-year ALOS (2007-2009) interferograms. The DInSAR interferograms were processed using the 2-pass approach with the commercial software 'GAMMA' and a 5 m resolution digital elevation model (DEM) of the Atigun pass region. Performing an analysis on the produced dataset, it must be kept in mind that the SAR data is spread over a time span of 18 years, during which the activity rate of some landforms could have changed significantly.

The exploration of the DInSAR dataset was conducted in two stages: a) systematic analysis of the two approximately 7 km by 7 km sub-regions, Areas 1 and 2, and b) identification of specific features in the entire region. Analysis was conducted according to the methods outlined in Barboux et al. (2014). Polygons were manually drawn in GIS software, outlining areas (min size of 3600 m^2) where a surface topographical change could be detected on an interferogram (or a set of interferograms). Polygons were then categorized into 4 velocity classes, recording the reliability of the identification of movement and outline, the elevation of the landform, and the geomorphological interpretation of the landform.

The four velocity classes were defined as follows: 'cm/day' refers to features detected on 1-day ERS interferograms and decorrelated at larger time intervals, 'dm/month' for features undetected on 1-day ERS but detected on 11-day TSX interferograms and decorrelated at larger time intervals, 'cm/month' for features detected on 22-, 33-, 44-day TSX interferograms or 1-2 month ALOS interferograms and decorrelated at larger time intervals, and 'cm/year' for features detected only on 1- or 2-year ALOS interferograms. The velocity class is related to the observation period (interferogram time interval), which is generally in summer or fall, and therefore may not be representative of the velocity at another given time of the year.

With the available DInSAR data, the main expected "active" geomorphological features or processes to be observed include mass wasting phenomena such as landslides, and landforms associated with permafrost creep (rock glaciers, FDLs, solifluction slopes) as well as areas affected by heave or subsidence, such as pingos.

Due to the subjectivity of polygon drawing and interpretation, a second user verified polygon outlines and displacement rate class to improve the quality of the inventory. Reliability (high, medium, low) was also recorded for any third user of the inventory to know the accuracy of any detected polygon.

Major limiting factors in the analysis include the quality of the InSAR data (and aerial images), presence of snow, vegetation, and atmospheric effects, introducing noise to the interferograms. Due to these factors, the two sub-regions investigated in greater detail were chosen due to the occurrence of apparently clearer DInSAR signals, favoring an easier analysis. However, it is still important to recognize that some areas within this region may be difficult to analyze due to an abundance of noise in most images, increasing the difficulty of conducting a complete analysis of the entire region.

3 RESULTS

In the two areas of systematic analysis, the main mass wasting processes identified were lobes (FDLs or rock glaciers), landslides, and solifluction slopes, with velocities ranging effectively from cm/day to cm/year. It was noted when a distinction could be made between rock glacier or FDL, but otherwise a landform with a large lobate structure was considered a 'lobe'. Outside Areas 1 and 2, areas of heave and subsidence were also identified, possibly related to pingo fields. Multiple polygons might be attributed to the same landform if different sections were detected at different velocities.

3.1 Area 1 (Northwest Region)

In Area 1, located west of the Dalton highway, 77 detected movements were associated with 69 landforms, ranging in velocity from cm/day to cm/year. Of the 77 detected movements, 51 were categorized with a high reliability and are thus used for further analysis (Table 1). Nearly half of the high reliability polygons were detected with a displacement rate of dm/month, and nearly half of all landforms were categorized as a lobe feature. Six polygons appear to have moved rapidly (cm/day).

This area was particularly difficult to determine the landform typologies on the aerial images available, so most landforms were categorized using the DEM only and are subject to discussion.

Table 1. Frequency of DInSAR polygons in Area 1 related to mass wasting process according to their typology and velocity.

	Velocity of DInSAR Polygons				
Typology	cm/day	dm/month	cm/month	cm/year	**Total**
Landslide	2	7	1	7	17
Lobe	3	13	3	4	23
Solifluction	0	1	0	0	1
Unknown	1	2	3	4	10
Total	**6**	**23**	**7**	**15**	**51**

3.2 Area 2 (North Central Region)

In Area 2, located east of the Dalton Highway, 36 total detected movements were associated with 31 landforms, with 26 polygons considered of high reliability. Over half the high reliability movements had a displacement rate of dm/month, with only 1 on the order of cm/day, 4 at cm/month, and 6 at cm/year (Table 2).

Table 2. Frequency of DInSAR polygons in Area 2 related to mass wasting process according to their typology and velocity.

	Velocity of DInSAR Polygons				
Typology	cm/day	dm/month	cm/month	cm/year	**Total**
Landslide	0	4	1	0	5
Lobe	1	10	3	2	16
Solifluction	0	0	0	0	0
Heave/ Subsidence	0	1	0	0	1
Unknown	0	0	0	4	4
Total	**1**	**15**	**4**	**6**	**26**

3.3 Frozen Debris Lobes

This study also focuses on a preliminary detection of fast moving FDLs along a 45 km stretch of the Dalton Highway corridor (south of Areas 1 and 2). FDLs were identified using a combination of DInSAR data, location of FDLs as mapped by Hamilton (1978), and distinct morphology on the DEM. Of the 20 mapped FDLs outside Area 1 and 2, 75% were detected with a cm/day displacement rate using the ERS 1-day interferograms, and the remaining were detected at a dm/month displacement rate, or rate was indeterminable (Table 3). It must be noted that a systematic analysis of the Dalton Highway corridor was not performed, but rather an initial investigation on the detection and velocity of FDLs.

Table 3. Frequency of DInSAR polygons with a typology of frozen debris lobe according to their velocity.

Velocity of FDL DInSAR Polygons					
cm/day	dm/month	cm/month	cm/year	NaN	**Total**
15	2	0	0	3	20

3.4 Pingo Fields

Mostly decorrelated, but also partly coherent, signals could be repeatedly observed on 11-day TSX interferograms (and on larger time spans) in several zones close to the valley bottom along the Dalton Highway corridor. Affected zones are located in the lowermost section of the valley side, ending just before the river bed. First assessment indicates that the observed movements tend to be dominantly heave. One of the largest zones in question is located in the pingo field at the bottom of Sukakpak Mountain (Figure 5).

4 DISCUSSION

4.1 Lobes (FDLs and rock glaciers)

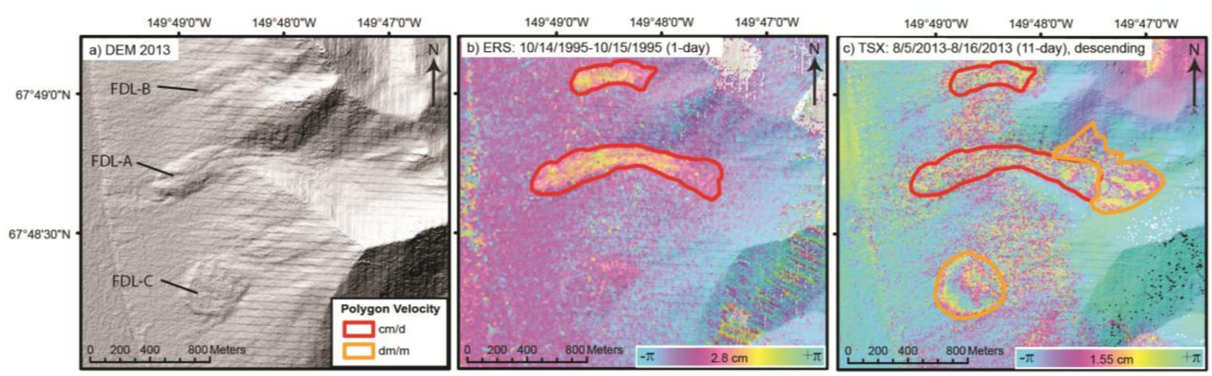

Figure 2. Example of images of frozen debris lobes on a) the DEM, b) ERS 1-day interferogram, and c) TSX 11-day interferogram. FDL-A and FDL-B have a clear, correlated signal on a 1-day interval (b), whereas this signal becomes decorrelated on an 11-day interval (c). The front of FDL-C shows a clear fringe at an 11-day interval, as well as the upper valley above FDL-A.

4.1.1 Frozen debris lobes

Frozen debris lobes (FDLs) often resemble rock glaciers, although they differ in composition, source area, elevation extent, and rate and mechanism of movement (Daanen et al., 2012). They mostly occur at the bottom of steep valleys, with movement continuing in the downslope direction (Figure 2). FDLs were originally identified as active landforms by Hamilton (1978a, b, 1981), but were later classified as inactive rock glaciers (Kreig and Reger, 1982; Brown and Kreig, 1983). Few investigations were performed until the landforms were rediscovered in 2008 as a possible sign of climate change. Field work has since been conducted by the University of Alaska Fairbanks on FDLs with potential hazards to the infrastructure (i.e. the Dalton Highway and the Trans-Alaska Pipeline System (TAPS)). Daanen et al. (2012) monitored FDL-A using DGPS measurements during the years 2008-2010. Between April and August 2008, 1.3 m of movement was recorded, indicating an average velocity rate of a little greater than 1 cm/day.

In the present study, 75% of the identified FDLs, including FDL-A, were detected using the ERS 1-day interferograms at a displacement rate of cm/day (Figure 2). The DGPS measurements from 2008 reveal a similar order of velocity rate as detected by DInSAR data, indicating that FDL-A has been moving at a cm/day velocity at least since 1995. Many landforms mapped as 'flow slides' by Hamilton (1978) do not appear on the DInSAR signal; however, most landforms that are detected on DInSAR data were also mapped by Hamilton. The use of the ERS 1-day interferograms, however restricted to the second half of the 1990s, proves to be an excellent tool for detecting rapidly moving FDLs using DInSAR data.

4.1.2 Rock glaciers

The majority of the study area is located below the 1200 m asl lower limit of rock glaciers as defined by Ellis and Calkin (1979). However, a few rock glaciers were able to be specifically identified in Area 1, all located at or above 1200 m asl. A few rock glacier-like lobate forms were also detected at Sukakpak Mountain at the base of rock walls at about 500 m asl, but here there were difficulties in specifically outlining the movements (see Figure 5). Rock glaciers were differentiated from FDLs by their location, where FDLs are generally found channelized in valley bottoms and rock glaciers can be found at the base of foot walls or slopes, unsourced by valleys and/or solifluction.

4.2 Solifluction

Solifluction slopes are generally widespread above the treeline. Although few solifluction slopes were observed within Area 1 or 2, these types of slopes seem to be more present in areas further south. Their multi-lobate typology is easily highlighted when a little snow is present in aerial photos, emphasizing the surficial lobe structures. A solifluction lobe is generally 20-50 m wide and usually occurs on non-vegetated or grassy slopes. One single lobe is usually too small to be distinguished from its neighbors on an interferogram, but the coalescence with multiple other lobes creates a solifluction slope. As is the case in the Alps, it could be expected that the topographical changes at the surface of a solifluction slope are extremely heterogeneous. This would then be reflected on DInSAR data as a noisy (decorrelated) pattern, whose intensity and size should grow with an increasing time interval. In the solifluction zones of the Brooks Range, a decorrelated signal is often observed in the center and lower parts of solifluction zones, but a board coherent InSAR signal can also be seen extending around the noise pattern (Figure 3). Such a coherent signal has not been observed in solifluction zones in the Alps.

The presence of both DInSAR signals suggests the occurrence of two different processes, possibly interacting: one concerning the solifluction lobes themselves which creates the heterogeneous surficial morphology, and another deeper creep or slide process which affects the entire solifluction slope in a more homogeneous way. Further investigation would nevertheless be necessary to understand more precisely the ongoing sub-surficial process, but we could consider what is occurring here to be deep-seated solifluction.

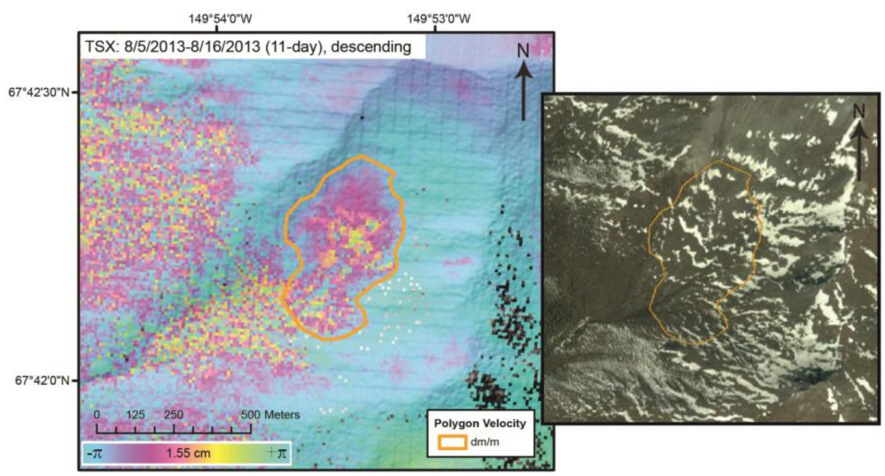

Figure 3. DInSAR signal of a typical solifluction area found in the area of interest on an 11-day interval interferogram and the corresponding aerial image displaying surficial geomorphology.

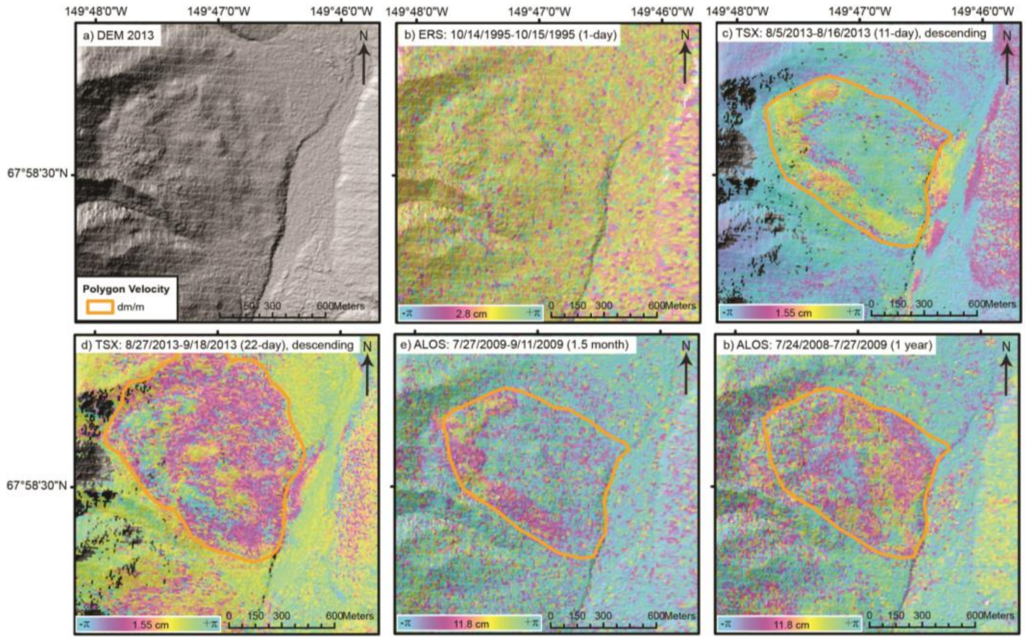

Figure 4. Detection of a landslide using all sets of DInSAR data: a) DEM showing the morphology of the landslide, b) ERS 1-day with no signal, c) TSX 11-day with a coherent signal around the upper scar and along the left side. The signal along the bottom is likely due to water and therefore cannot be interpreted, d) TSX 22-day showing a decorrelated signal over a larger area, e) and f) ALOS 1 month and 1 year, respectively.

FDLs appear to be sourced or fed by solifluction lobes (similar to those identified as deep seated solifluction), which converge into the FDLs (also see Figure 2). Daanen et al. (2012) also recognized this connection, describing the transfer of debris from solifluction lobes to the top of FDLs.

4.3 Landslides

Landslides compose nearly 30% of the detected movements in Area 1 and Area 2, and are generally attributed to slopes with clear (and coherent, as opposed to solifluction slopes) signal of movement but with no tongue-shaped or lobate terminal morphology. In some cases, nearly the entire slope is moving at a velocity of dm/month or cm/month, and movements are most easily detected with TSX interferograms. Figure 4 provides an example of the identification and signal of a large landslide found west of the Dalton Highway corridor, just south of Area 1.

4.4 Uplift/Subsidence Fields

Some large areas of partly coherent and partly decorrelated signal were observed near the valley bottom on 11- and 22-day interferograms, such as at the western base of Sukakpak Mountain (Figure 5). Apart from a shallowly inclined and homogeneous slope, no particular geomorphological feature can be observed on the DEM. However, the occurrence of the signal on multiple interferograms indicates a real movement. Brown and Kreig (1983) described such an area as containing several hundred low, ice-cored mounds, with an average height of 0.95 m and an average width and length of 4.6 m and 7.4 m, respectively. They hypothesized that these mounds are governed by closed-system freezing, strongly

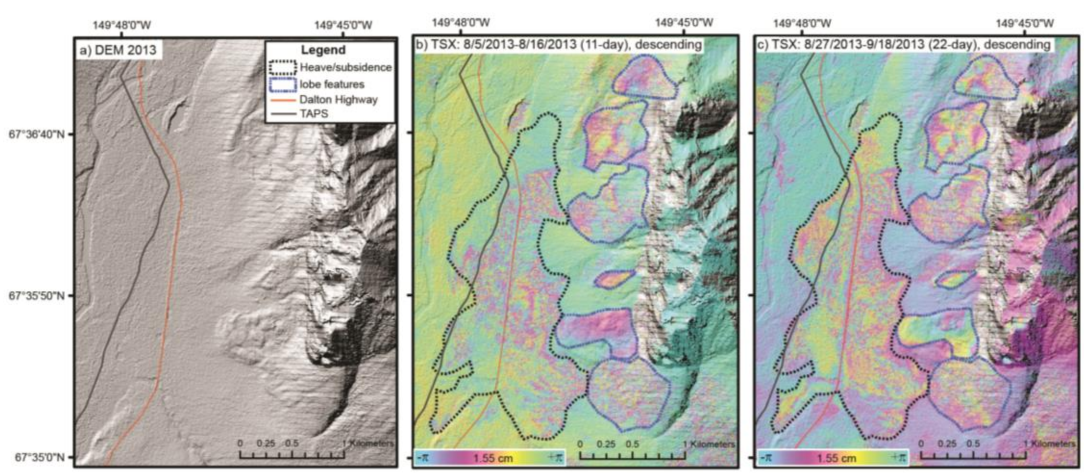

Figure 5. Sukakpak Mountain a) DEM and interferograms using TSX data at b) 11-day and c) 22-day intervals, showing the approximate outline of heave/subsidence fields (black) and lobe features (blue) at the base of the mountain footwalls.

dependent on local variations in soil moisture. Another hypothesis is that the mounds form by groundwater injection, with water sourced from the infiltration of meltwater at the base of the mountain headwall (open system pingo field) (Walker et al., 2009). The occurrence of the DInSAR signal close to the valley bottom and the absence of a mass wasting morphology indicate the presence of a heave/subsidence mechanism, which can surpass 1 cm in 11 days. Due to the large extent of the affected area and the local occurrence of zones with coherent signal, the process can be considered widespread. Changes in groundwater pressure affecting the permafrost roof may cause - at least partly - the observed heave/subsidence signals, which would support the open-system hypothesis of the pingo field.

4.5 Correspondence between DInSAR signal and geomorphology

The DInSAR-derived inventory often shows good agreement between detected movements and the geomorphological interpretation of the digital elevation model (DEM), particularly for lobe features and some landslides. The correspondence of a DInSAR-detected movement to a landform increases the reliability of the detection. However, not all detected movements have a clear associated landform. This is the case for zones affected by deep-seated solifluction, where observation of a distinct geomorphological outline is not possible on a DEM. For zones suffering heave/subsidence close to the valley bottom, it is also the case that no specific morphology is recognizable on a 5 m DEM.

4.6 General comments

Within the approximately 100 km^2 total area of Area 1 and Area 2, 77 total high reliability movements (69 landforms) were detected. If we assume a similar rate of frequency over the entire 1700 km^2 study area, we could expect to find on the order of 1300 movements if a systematic widespread analysis would be performed.

For areas where there are no known movements, this kind of analysis could be useful to detect movements too slow or remote to have been previously observed. Evaluation of a change in velocity over time could also be possible thanks to data available from different time periods, although compatibility of sensors must be taken into consideration. This study also provides a comparison tool for future inventories to monitor changes in detected movements and could serve as a reference for future studies.

C-band 1-day interferograms created on the basis of the ERS archives are useful for detecting FDLs and other rapidly moving landforms (cm/day). The available data is however restricted to the mid-1990s, in our case to October and December 1995. ALOS (L-band) interferograms are most useful for detecting movements at a velocity of cm/year; the longer wavelength of the ALOS sensor is less disturbed by vegetation growth. TSX (X-band, 11-day return period), however, is most useful in general, particularly for identifying movements with a displacement rate of dm/month to cm/month. For future studies, X-band Cosmo-SkyMed acquisitions with 1-, 3- or 4-day time interval could be a solution for the monitoring of changes in the displacement rate of FDLs.

5 CONCLUSIONS

As an initial test study investigating the potential of inventorying slope movements in the south central Brooks Range, Alaska by applying a DInSAR approach developed for use in the Swiss Alps, this study reveals promising results. A systematic analysis of two approximately 50 km^2 areas, Area 1 and 2, resulted in a detection of 77 high reliability movements moving with a velocity on the order of cm/day to cm/year. Assuming a consistent density of movements over the entire 1700 km^2 study area, nearly 1300 movements could be expected to be detected if a systematic widespread analysis was conducted. Analysis within Area 1 and 2 also revealed the presence of landforms and mass movement processes typical to the region, namely lobes (frozen debris lobes (FDL) or rock glaciers), landslides, solifluction slopes, and areas of heave/subsidence, possibly related to pingo fields. Of the identified typologies, solifluction slopes and their associated deep-seated solifluction, as well as the areas of heave/subsidence, could be particularly interesting to further investigate the DInSAR signal and

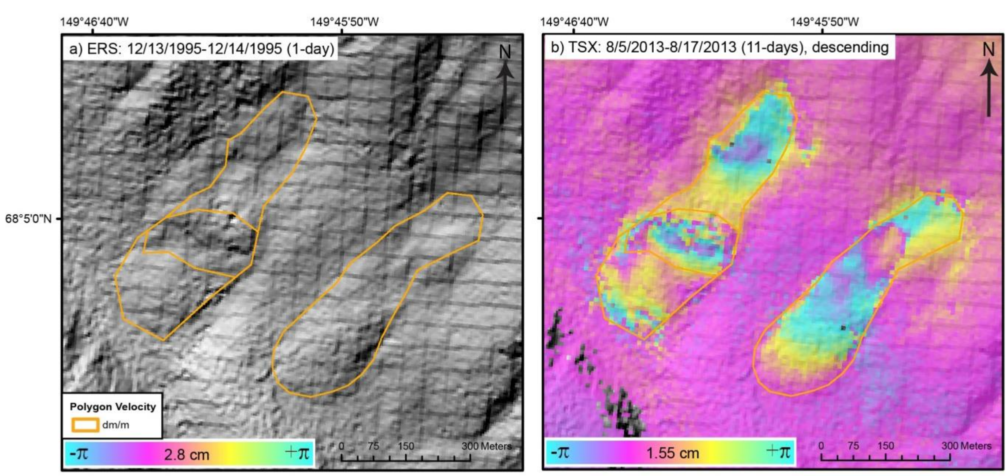

Figure 6. Comparison of a) the shaded DEM to b) the DInSAR signal (11-day TSX) for two lobe features. The polygons created on the basis of the detected DInSAR signal closely resembles the landform.

the corresponding physical movement.

Taking a preliminarily look into the detection of fast-moving FDLs along the Dalton Highway corridor, the use of the ERS 1-day interferograms, however restricted to the second half of the 1990s, proves to be an excellent tool. DGPS measurements were also used to validate the velocity of detected FDLs, 75% of which were detected at a cm/day velocity rate using ERS 1-day interferograms. X-band Cosmo-SkyMed acquisitions with 1-, 3- or 4-day time interval could also be a useful tool for future studies to monitor the changes in the displacement rate of FDLs and to perform a more systematic analysis of the Dalton Highway corridor.

The use of the DInSAR approach described by Barboux et al. (2014) seems applicable for detecting and characterizing slope movements within the continuous permafrost and mountainous Arctic setting of the south central Brooks Range, although further refinement of techniques and typology definitions could enhance the quality of the inventory.

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