Satellite Monitoring of Permafrost Instability — Validation, Evaluation and Evolution

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Prepared for:
European Space Agency

December 2007

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Prepared for:
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Prepared by:
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EXECUTIVE SUMMARY

Permafrost is a thermally sensitive geo-material where the thermal conditions define the mechanical strength and behaviour of the soil. The trend of global warming has a significant destabilizing effect on the mechanical behaviour of permafrost terrain. For thaw-susceptible soils, permafrost degradation has the potential to significantly reduce the geotechnical load carrying capacity, which may trigger process-related geohazards such as slope instability, slides, debris flows and subsidence. This will often impact water quality, as well as infrastructure such as highways, pipelines and communication links. It is therefore required to identify the areas and the timing of these events as well as to measure the movement rates. It is speculated that EO can be used as a tool for this purpose. As such, the objective of this project was to demonstrate the capability of Earth Observation (EO), and in particular spaceborne Synthetic Aperture Radar (SAR), to identify, monitor and assess geohazards in permafrost terrain. EO was investigated as a complementary tool to existing practice, such as terrain analysis, permafrost science and geotechnical engineering. In this case, the EO tool under consideration is Interferometric Synthetic Aperture Radar (InSAR), which has been demonstrated to be useful for subsidence and slope stability monitoring. Thus, the objective of this project is to apply InSAR techniques for the assessment of geohazards in permafrost terrain. The end users required geohazard mapping tools that define the spatial extent, temporal variation, amplitude and rate of ground movement that can be integrated within a risk management framework. Permafrost terrain is generally located in remote, northern locations with constraints on physical access, logistics, and economics for conducting conventional *in-situ* ground movement monitoring programs.

To carry out the stated objectives, candidate sites (five in total) with permafrost degradation were identified for further monitoring with InSAR. Once these sites were identified, traditional monitoring methods were applied coincident with the satellite InSAR analyses. This allowed for a comparison of the validity and utility of InSAR monitoring and traditional techniques. This report summarizes the findings of this study by providing a complete assessment of the EO products delivered through the project activities. The report combines two of the deliverables required by ESA into one complete document, including the *Validation, Evaluation and Evolution Report* (D37) and the *Final Report* (D41). Quantitative comparisons are made between the ground motion derived from Interferometric SAR (InSAR) analyses - from the areas of reasonable temporal coherence - to the GPS survey data collected at numerous points at each site. At the two Beaver Creek sites, radar reflectors were installed to aid in obtaining InSAR measurements in areas of potentially low coherence, the ground motion data derived from these reflectors are also compared to the GPS survey data. Finally, the project participants evaluated the success in achieving the overall project goals, as well as consider possibilities for further implementation.

The use of traditional forms of terrain analysis using remote and field measurement systems allows specific features and landforms to be identified, and their potential impact on infrastructure quantified. In many cases, proposed development routing studies allow the greatest risks to be avoided; however, many geohazards cannot be eliminated from design and mitigation strategies must be developed. One approach is to undertake a monitoring program of specific geohazards, such that any destabilization that results in increased risk to development facilities is observed prior to causing significant disruption. Many landforms react relatively slowly to changes in equilibrium conditions and are suitable for long term monitoring programs. Movements are generally seasonal as ground thaws during summer, and result in a cumulative displacement field year-to-year. Such gradual movement, particularly if it has a vertical component, is likely to be suitable for InSAR monitoring. The findings of this study support this hypothesis. In particular, gradual movement over relatively flat terrain was shown qualitatively to be measurable with InSAR. The technique is also suitable for slope stability monitoring if the ground movement is either slowly creeping or of moderate magnitude (<10cm/year). On the other hand, this study demonstrated that significant ground motion along steep slopes, particularly if most of the movement occurred over a short time period, could cause the movement to be undersampled by the SAR sensor, leading to an underestimation of ground movement. In this case, InSAR is unsuitable for monitoring these types of geohazards, such as fast moving translational or debris slides with displacements on the order of many 10s of centimeters per year.

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1 INTRODUCTION

Permafrost is a thermally sensitive geo-material where the thermal conditions define the mechanical strength and behaviour of the soil. The trend of global warming has a significant destabilizing effect on the mechanical behaviour of permafrost terrain. For thaw-susceptible soils, permafrost degradation has the potential to significantly reduce the geotechnical load carrying capacity, which may trigger process-related geohazards such as slope instability, slides, debris flows and subsidence. This will often impact water quality, as well as infrastructure such as highways, pipelines and communication links. It is therefore required to identify the areas and the timing of these events as well as to measure the movement rates.

It is anticipated that the use of Earth Observation (EO) technology will become increasingly important with the impending development of pipelines through the vast, remote areas of Alaska, Canada and Russia. The presence of continuous and discontinuous permafrost terrain over large areas, presents significant engineering challenges for the design, construction and operation of northern pipelines. In anticipation of these multi-billion Euro developments, as well as other impending railroad and highway projects, there is a critical need for wide-scale monitoring of geohazards and permafrost dynamics in the context of climate change. Monitoring permafrost instability with satellite interferometry may provide an additional tool that could reduce the cost and increase the effectiveness of geohazard monitoring.

1.1 Objective

The objective of this project was to demonstrate the capability of Earth Observation (EO), and in particular spaceborne Synthetic Aperture Radar (SAR), to identify, monitor and assess geohazards in permafrost terrain. EO was investigated as a complementary tool to existing practice, such as terrain analysis, permafrost science and geotechnical engineering. In this case, the EO tool under consideration is Interferometric Synthetic Aperture Radar (InSAR), which has been demonstrated to be useful for subsidence and slope stability monitoring in non-permafrost environments. Thus, the objective of this project is to apply InSAR techniques for the assessment of geohazards in permafrost terrain. The end users required geohazard mapping tools that define the spatial extent, temporal variation, amplitude and rate of ground movement that can be integrated within a risk management framework. Permafrost terrain is generally located in remote, northern locations with constraints on physical access, logistics, and economics for conducting conventional *in-situ* ground movement monitoring programs.

To carry out the stated objectives, candidate sites (five in total) with permafrost degradation were identified for further monitoring with InSAR. Once these sites were identified, traditional monitoring methods were applied coincident with the satellite InSAR analyses. This allowed for a comparison of the validity and utility of InSAR monitoring and traditional techniques.

Quantitative comparisons are made between the ground motion derived from InSAR analyses - from the areas of reasonable temporal coherence - to the GPS survey data collected at numerous points at each site. At the two Beaver Creek sites, radar reflectors were installed to aid in obtaining InSAR measurements in areas of potentially low coherence, the ground motion data derived from these reflectors are also compared to the GPS survey data. Finally, the project participants evaluated the success in achieving the overall project goals, as well as consider possibilities for further implementation.

1.2 InSAR Overview

In the last decade, InSAR has received much attention for its ability to generate deformation maps with unprecedented accuracy. For SAR sensors, ground movement information can be estimated to an accuracy of millimetres. Although it is becoming more accepted, the technique to date has been used in a limited number of operational applications.

SAR is an active sensor that was developed as a means of overcoming the limitations of real aperture radars. SAR achieves relatively good resolution using a small radar antenna, which is an important consideration when dealing with satellites that are limited in size and are typically launched into orbits that are hundreds of miles above the Earth. To achieve this high resolution, SAR uses the motion of the radar along a flight path (or orbit) to form a ‘synthetic antenna’ that is much larger than its real aperture. This improves the resolution of the radar in the direction parallel to the satellite track, namely, the azimuth direction, as shown in Figure 1. To achieve a high resolution in the across track or range direction, the radar uses a frequency modulated waveform and pulse compression to simulate a very short pulse, hence a high-resolution echo. The typical horizontal, spatial resolution obtained via current satellite SAR ranges from 8-150 m, and resolutions typically used for InSAR are 8-30 m.

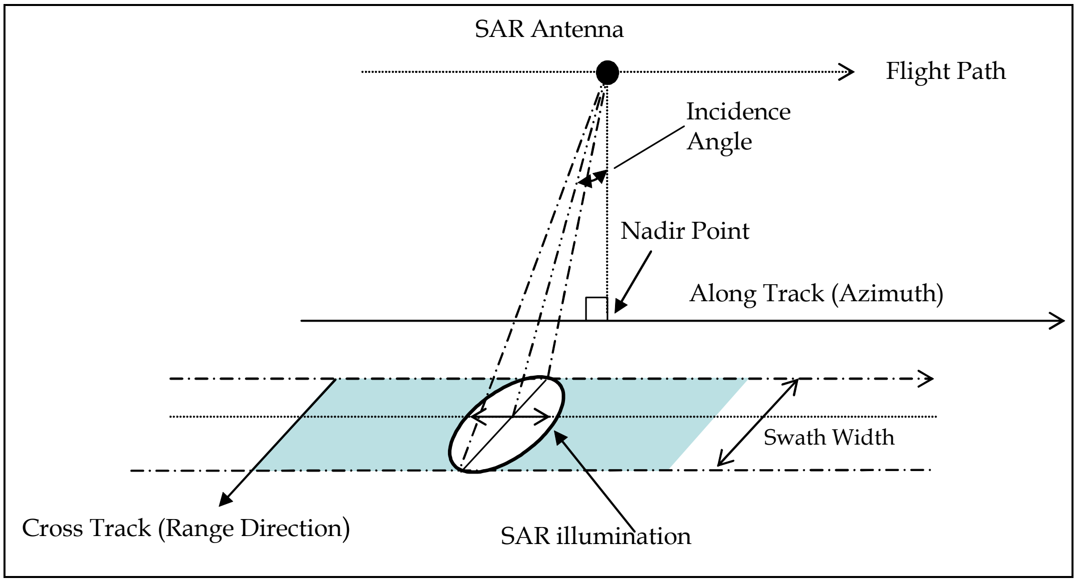

Figure 1 Geometry of Synthetic Aperture Radar

Since the radar image contains the phase (ϕ) as well as the magnitude (*A*) of the backscattered radiation, topographic information can be derived from the difference in the phase, that is, the interferogram, between two images. In particular, Figure 2 is a simplified illustration of the variation in phase due to ground movement. The change in the distance (*d*) between the satellite and any point on the ground (change along the look direction of the SAR) is simply the fraction, as determined from the interferogram phase ($\phi_2 - \phi_1$) for the two images, of half the radar wavelength (λ). The conversion from measured change along the look direction to the actual ground movement relies on an understanding of the ground dynamics in order to interpret the direction, and hence magnitude, of movement. When possible, measurements from another look direction may also be used to help decipher the actual ground movement.

To illustrate the power of InSAR, consider the deformation map (Figure 3) that has been derived from an interferogram of two ERS-2 images. Interferometric fringes, which come from phase changes in the radar data, were extracted using the InSAR technique. From this analysis, deformation can be mapped to indicate subsidence (red and yellow) and heave (blue and green), which in this case is due to oil production and water injection, respectively.

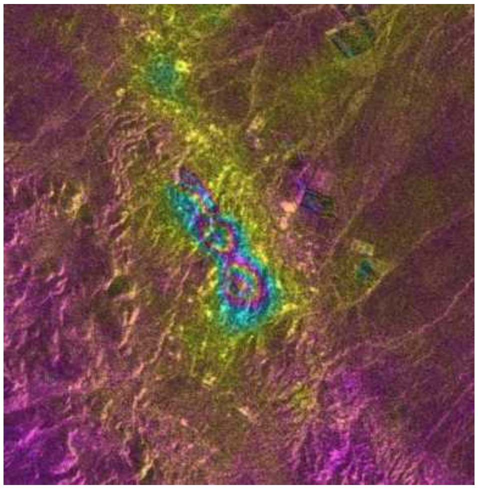

Figure 2 ERS-2 interferogram

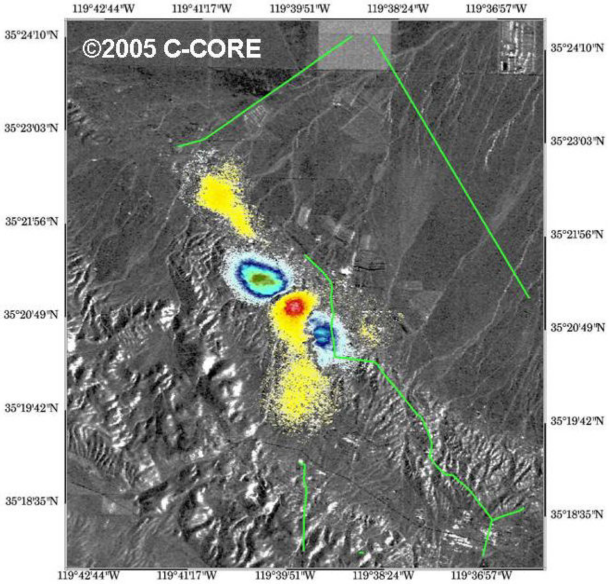

Figure 3 ERS -2 derived deformation map

1.3 Regional Overview of Permafrost Instability in Southern Yukon Territory

Permafrost is defined as ground which has been frozen year-round for at least 2 years. All five study sites are located in southern Yukon Territory near the southern boundary of the extensive discontinuous permafrost zone in North America (Figure 4). In the extensive discontinuous permafrost zone, 50-90% of the surface is underlain by permafrost of variable thickness and ice-content. Near the southern margin of this zone, permafrost is typically less than 15 m thick, and its temperature is generally warmer than -1°C. For this reason, it is more susceptible to degradation than the colder and thicker permafrost found further north. In the discontinuous permafrost zone, permafrost is most commonly found on north-facing slopes and in valley-bottoms. Its distribution and thickness is largely controlled by the thickness of the surface organic horizon and the climatic regime. Duration and depth of snow cover, surface moisture, slope aspect and elevation are also important local controls (Burn, 2004).

The ground surface layer that thaws each summer, but refreezes each winter is called the active layer. This layer is generally less than 2 m thick, and is often less than 1 m thick in southern Yukon. Local hydrological conditions and soil texture control the ice-content of the permafrost. Ice-content is generally higher in fine-grained silt-rich soils in valley-bottoms and along the base of bedrock slopes (Rampton et al., 1983).

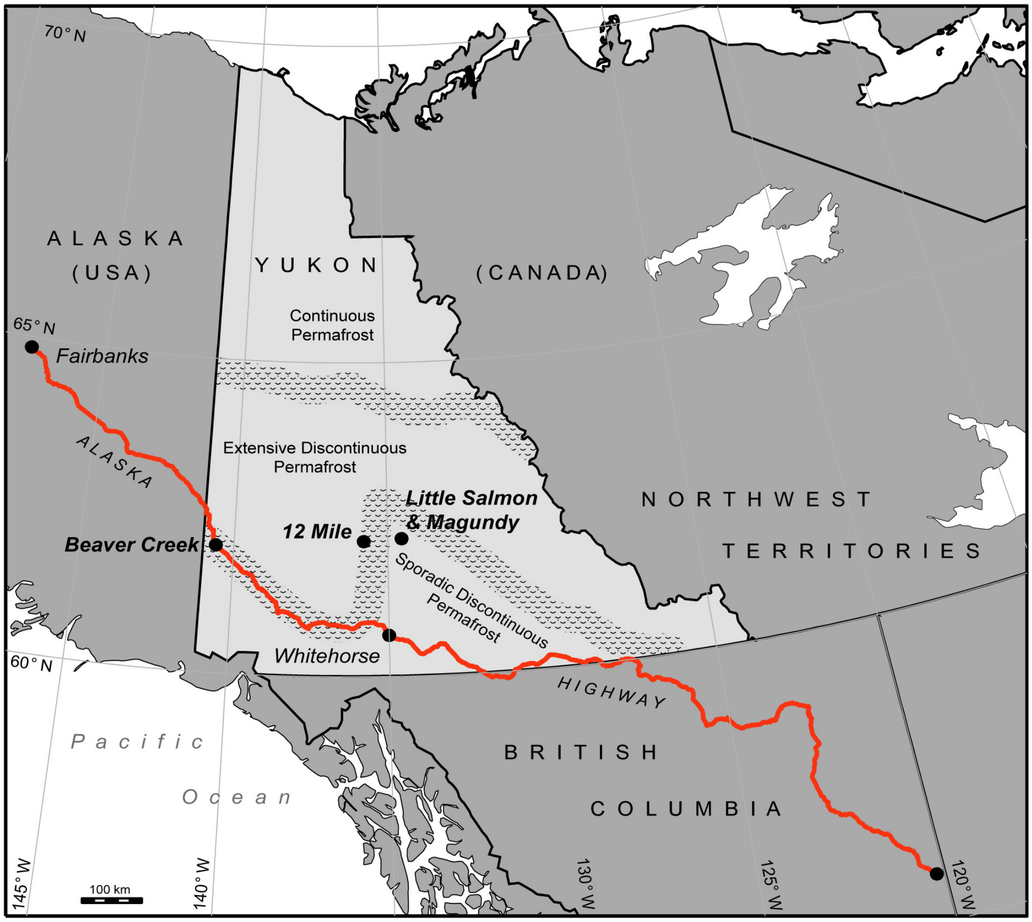

Figure 4 Location map showing regional context of permafrost and study sites within Yukon Territory. Hatched areas represent boundaries between generalized permafrost zones (after Heginbottom, 1995).

Thawing of ice within the permafrost or within the active layer leads to various types of terrain hazards in southern Yukon, including thermokarst, landslides (retrogressive thaw failures and active-layer detachments) and thaw settlement (subsidence).

Permafrost plays an important role in slope stability by affecting soil strength and soil moisture. The permafrost table, the top surface of permafrost that is found at the base of the active layer, is an impermeable barrier that restricts drainage and commonly acts as a failure plane on slopes. When frozen ground thaws, the soil also loses structural strength because soil particles are no longer bonded together. In permafrost with high ice-contents, thawing releases excess water that cannot be absorbed by the soil pores. In addition, the base of the permafrost can confine high groundwater pressures below the base of the permafrost. This can raise pore pressures and can create highly unstable conditions on slopes. Finally, thawed soil will settle to fill the volume formerly occupied by ice and the ground surface will subside.

A variety of ground disturbances can initiate or accelerate thawing of ground ice, including direct exposure of ice-rich permafrost, changes to the surface energy budget that lead to an increasing active layer depth (through climate change or alteration of surface characteristics), and changes in local hydrology (surface runoff and groundwater flow). Infrastructure construction, residential development, river erosion, forest fires or a changing climatic regime have been shown to initiate significant and long-lasting permafrost instability in various locations throughout southern Yukon (Burn, 1998; Huscroft, 2004; Lipovsky et al., 2006; Lipovsky and Huscroft, 2007).

Two of the five study sites are located on the Alaska Highway, which is the largest and most heavily- traveled highway in the Yukon Territory. It is a critical infrastructure route for both Canada and the USA, being the primary land-based connection between Alaska and the rest of the United States. More than 80% of the 315 000 tonnes of goods shipped into the Yukon each year are transported on the Alaska Highway. In addition, 85% of Yukon's population resides along the highway corridor and 70% of tourists visiting the Yukon travel the highway (Huscroft et al., 2004). Thermokarst (Figure 5) and subsidence (Figure 6) is currently an ongoing geotechnical problem along much of the highway in SW Yukon.

Figure 5 Thermokarst ponds occur along both sides of the Alaska Highway (in background) at this location 50 km south of Beaver Creek. The ground surface here used to be level before gravel was stripped from the surface for road construction in the early 1990's.

Figure 6 Subsidence along the Alaska Highway due to permafrost degradation, 50 km south of Beaver Creek.

The Alaska Highway corridor also includes a proposed route for a railway and a pipeline linking Alaskan natural gas reserves near Prudhoe Bay to the Midwestern United States. Potential railway routes through south or central Yukon are also undergoing feasibility studies, with one possible route following the Robert Campbell Highway, which is located near the remaining three sites at 12 Mile Creek and Little Salmon Lake. Should any of these megaprojects proceed, permafrost and slope stability issues will be a major concern during construction and operation. In anticipation of this fact, it will be important to have proven methods of stability monitoring tested and documented in permafrost terrain to ensure appropriate monitoring is undertaken in the future.

1.4 The Study Areas

In consultation with the end users, the Yukon Geological Survey (YGS) and TransCanada PipeLines (TCPL), five sites located in the Yukon Territory (Canada) were selected. In order of suitability, the five candidate sites were:

- Beaver Creek, Site 1 (Km 1955 on the Alaska Highway)
- Beaver Creek, Site 2 (Km 1928 on the Alaska Highway)
- 12-Mile Slope
- Magundy River Slide
- Little Salmon Lake Slide

Factors considered in the site selection process included:

- Image coherence of satellite data to monitor ground deformation and the need for installation of *in-situ* reflectors;
- Orientation and slope gradient of land features within the regions of interest;
- Quantity and quality of archived satellite data;
- Ground failure mechanisms, deformation pattern, historical and future trends, areal extent, direction, displacement magnitude and movement rate;
- Quantity and quality of available aerial photographs, topographic data and digital terrain models;
- Quantity and quality of ground truth data relating to climate, air temperature, soil and vegetation conditions, ground ice characteristics, geological conditions, as well as ground movement data — whether from the existing archive or yet to be acquired data;
- *In-situ* logistical support and access;
- Proximity to civil infrastructure, pipelines and environmental assets; and

- Other physical data sets such as borehole logs and slope inclinometers.

1.4.1 End-user participation

The YGS and the Yukon Department of Highways provided logistical support and resources to install radar reflectors, conduct centimeter-scale surveying and perform field investigations at the two Beaver Creek sites. The YGS also installed survey monuments and performed GPS surveys of the remaining three sites. This represents a significant resource allocation to the project and was a great contribution to the overall success of this initiative.

1.4.2 Beaver Creek, Site 1

Beaver Creek, Site 1, is located at kilometer post 1955 on the Alaska Highway, at 62°31’48” N latitude and 140°58’48” W longitude (20 km north of the town of Beaver Creek). The Alaska Highway was realigned in this area in 1995, and was cut into the side of a bedrock slope. Waste rock from the cut was used to construct an embankment on the other side of the highway. Since then, the fill has settled on the order of a meter per summer in a zone running across the middle of the slope (between Reflectors 2 and 3 in Figure 7). This has created conjugate sets of near-vertical scarps that define a series of grabens. Significant highway maintenance is required annually at this site, including regrading of the embankment slope and the addition of large volumes of fill. This work was postponed for the duration of the InSAR monitoring at this site.

The position of this site at the base of a bedrock slope is a common setting for ground ice to form due to the convergence of groundwater flow into fine-grained valley bottom sediments (Rampton et al., 1982). Boreholes in the embankment revealed between 2.8 and 3.7 m ice-rich silt beneath 8-12 m of gravel fill (Paine and Associates, 1997b). Thaw of this ice is likely being accelerated by a number of factors including disruption of an underground creek at toe of failure, water ponded by the grabens, and thermal heat transfer from dark-coloured fill (Paine and Associates, 1997b).

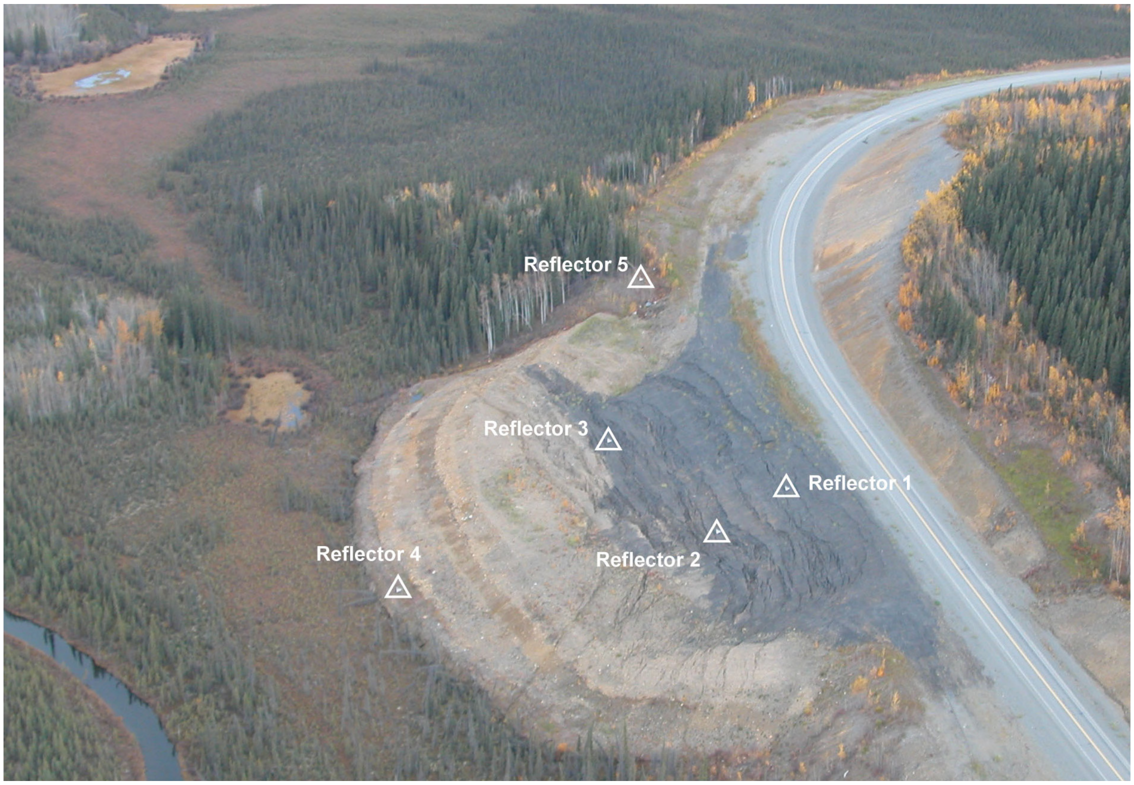

Figure 7 Embankment failure due to permafrost degradation at Beaver Creek, Site 1, along the Alaska Highway.

It was anticipated that ground movement monitoring based on space borne SAR would only succeed at this site as long as the rate of movement remained within the detection limits of InSAR, both with respect to coherence and phase unwrapping. The surface of the gravel slope is well-drained and therefore moisture variation was not expected to limit coherence. However, as visible in Figure 7, the local relief along the slope resembles that of a crevasse field on a glacier, with numerous tension cracks along which multiple blocks of soil have dropped approximately 1-2 m. If these blocks continued to drop at magnitudes more than the phase unwrapping limit between successive image acquisitions, then the ability to measure the absolute ground movement would be limited. In addition, the horizontal spatial variability in the magnitude of ground movements at this site appeared to be on a scale less than 10 m. This makes it difficult to resolve the movement of discrete blocks with the resolutions currently provided by the space borne sensors.

1.4.3 Beaver Creek, Site 2

Beaver Creek, Site 2, is located 5 km south of the town of Beaver Creek, along a 300-m long segment of the Alaska Highway (Figure 8) at kilometer-post 1928.5 (62°20.5' N latitude and 140°50' W longitude). The site was selected based on reports by the Yukon Department of Highways that this location has experienced some of the highest rates of thaw settlement along the Alaska Highway in recent years. The highway was constructed at this site in the early 1990s and the road is built up to approximately 6 m above the level of the surrounding natural ground. A borehole drilled through a gravel stabilization berm encountered 3 m of ice-rich silt at 7.3 m depth, (the top 3.4 m was gravel fill). Immediately adjacent to the highway, in natural ground, 5.5 m of ice-rich silt was found at 1.8 m depth (Paine and Associates, 1997a).

The width of the paved highway and its gravel stabilization berms is approximately 40 m; within this corridor, which is entirely unvegetated, the InSAR coherence was expected to be reasonable. The coherence in the poorly-drained sparsely forested swamp adjacent to the highway depends on the amount of surface water and vegetation change throughout the summer.

Figure 8 Oblique aerial photograph of the stretch of the Alaska Highway monitored at Beaver Creek Site 2. The distance between reflectors 1 and 2 is 370 m.

Since 1997, the Yukon Department of Highways has been monitoring ground temperatures down to a depth of 10 m at this site. Three separate thermistors were installed: one beneath the highway centre line, on in the stabilization berm, and one adjacent to the highway in natural ground. Using these data, the thermal performance of the highway was analyzed in detail by Dore (2005). He reported that ground temperatures were rising beneath the highway centerline and berm as a result of highway construction, despite local cooling climatic trends in the area between 1997 and 2003. He also determined that greater amounts of warming were occurring beneath the berm than beneath the centerline and that the road appears to induce thawing of the underlying ice-rich ground. This would likely lead to the large number of longitudinal cracks that continually develop in the road surface (as shown in Figure 9) each year.

Figure 9 Patched cracks in the road are evidence of thaw settlement along the Alaska Highway at Beaver Creek, Site 2.

Ground temperature profiles generated from the Yukon Department of Highways thermistor strings for between March, 2006 and July, 2007 are shown in the following pages (Figure 10, 11 and 12). Several interesting facts are observed in these figures.

In Figure 10, beneath the highway centerline, no ground temperature change occurs at any time throughout the year below the original natural ground surface (now covered by 6.3 m of highway fill). However, the ground temperature below this level (to a depth of 10 m from the surface of the road), is only marginally below 0 degrees all year round and may in fact have already been thawed.

In Figure 11, beneath the berm, summer temperatures warm the ground to a depth of approximately 1.5 m below the original ground surface (now covered beneath 3.5 m of gravel fill). This warming extends much farther into the natural ground than occurs in undisturbed areas where the active layer is generally less than 0.6 m.

In Figure 12, ground temperatures are shown for the "natural" site, located 20 m from the toe of the highway berm in the undisturbed muskeg (Paine and Associates, 1997a). The active layer thickness portrayed in this figure is approximately 0.8 m thick. While the ground beneath this always remains frozen year-round, the temperature still fluctuates a few degrees at 8m depth.

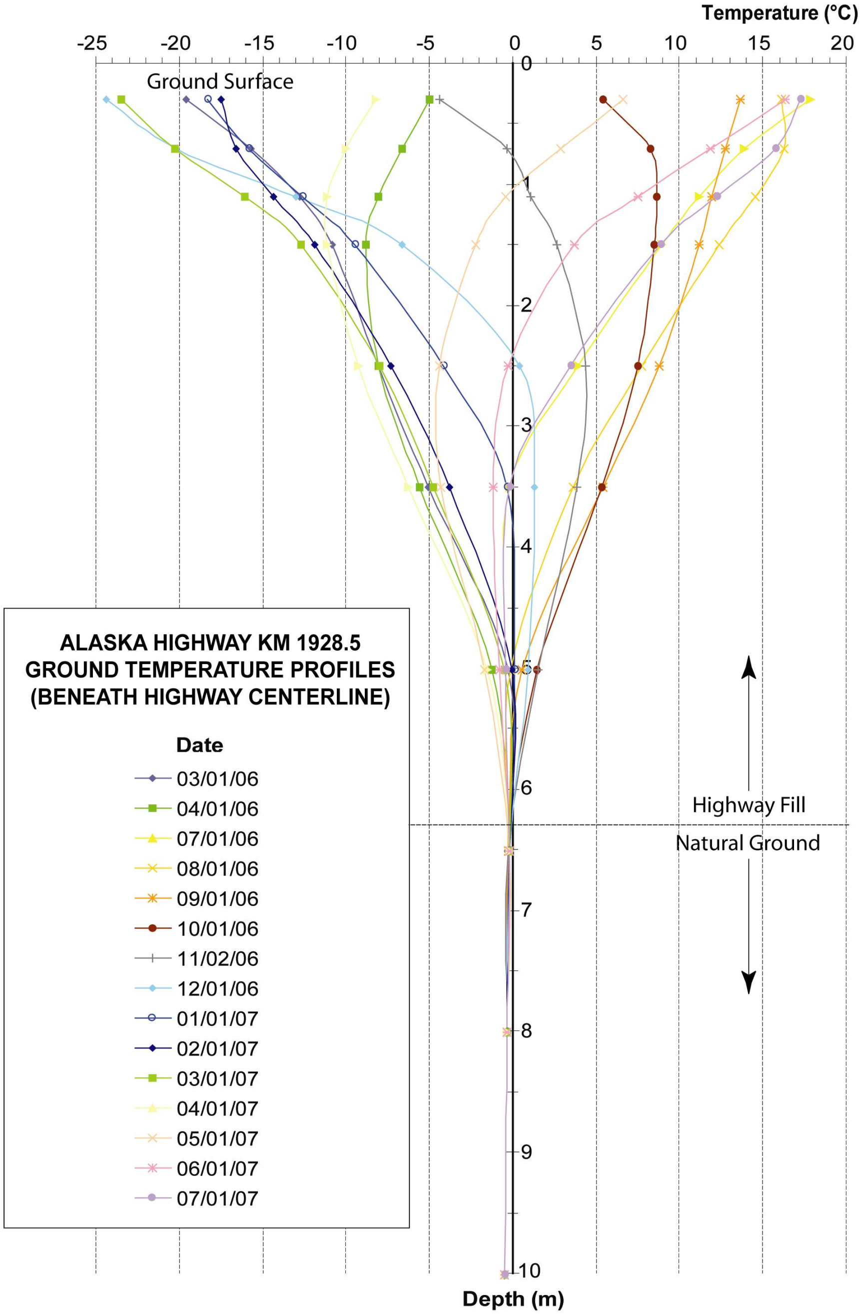

Figure 10 Ground temperature profiles between March 2006 and July 2007 beneath the centerline of the Alaska Highway at km 1928.5.

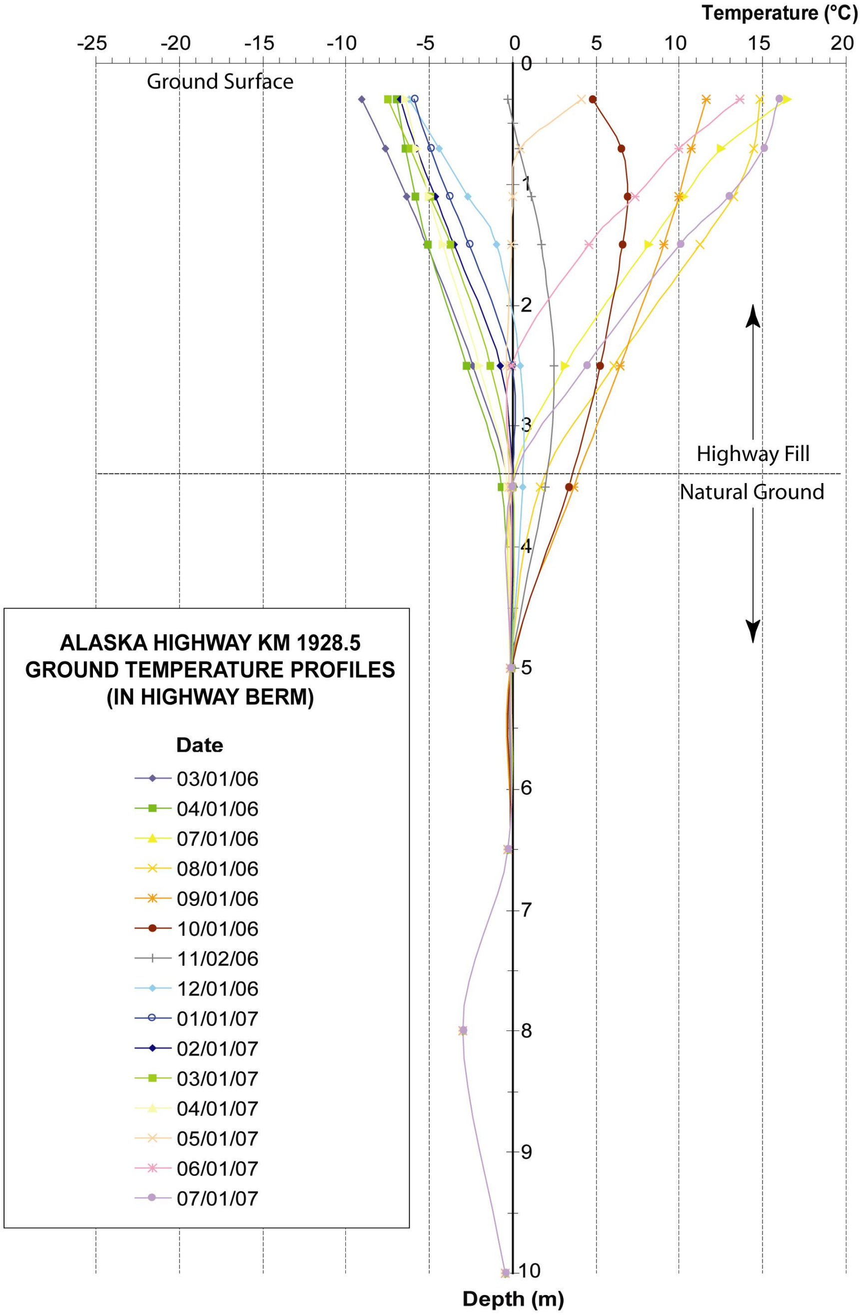

Figure 11 Ground temperature profiles between March 2006 and July 2007 beneath the stabilization berm for the Alaska Highway at km 1928.5.

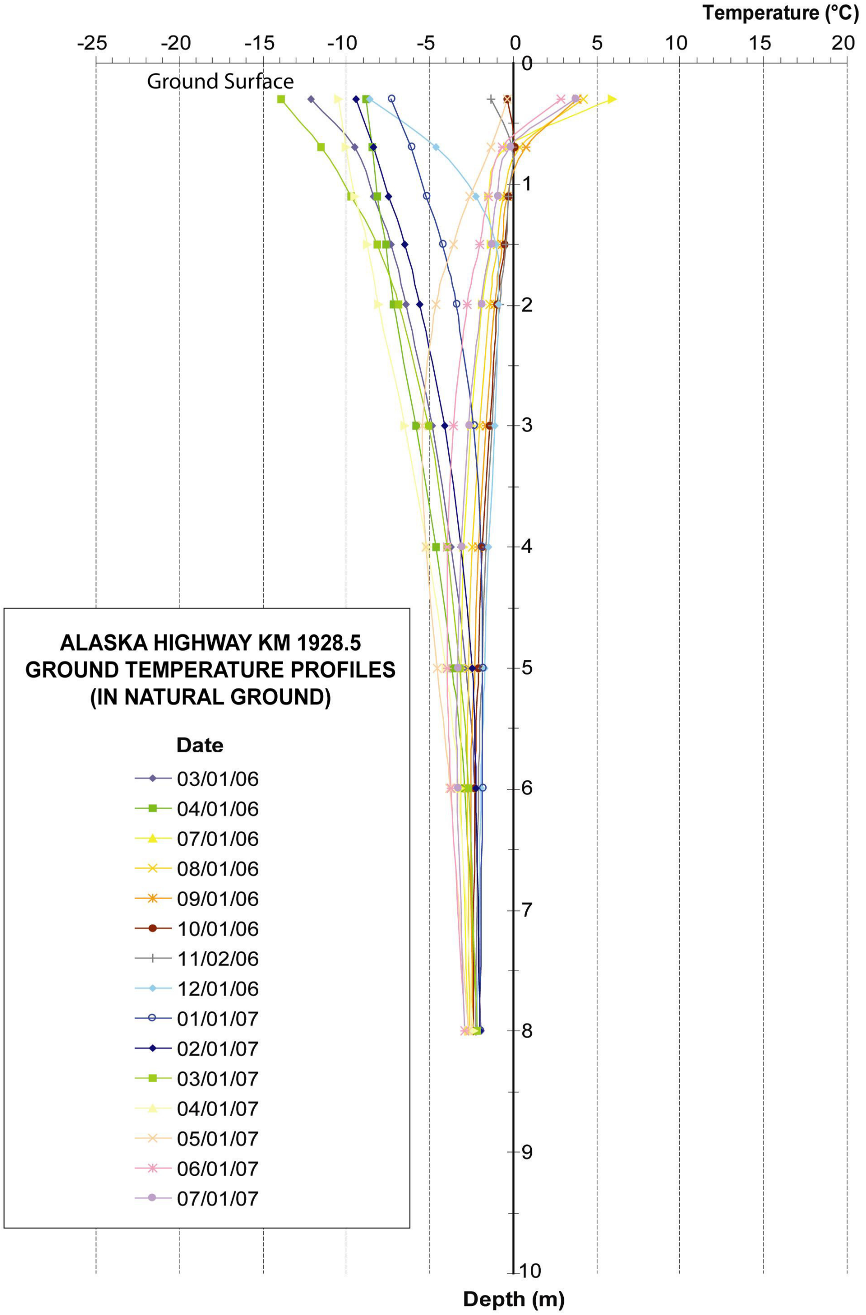

Figure 12 Ground temperature profiles between March 2006 and July 2007 in natural ground adjacent to the Alaska Highway at km 1928.5.

1.4.4 12-Mile Slope

The 12-Mile Slope site is located 13 km south of the town of Carmacks, at 61°59’ N latitude and 136°07’ W longitude. The slide is not accessible by road, but can be reached by either hiking 4 km upslope from the North Klondike Highway, or flying 10-minutes by helicopter from Carmacks. The region is characterized as mountainous with discontinuous permafrost and boreal forest vegetation.

The slide, which is shown in Figure 13, was initiated in June 2002 and occurred on a moderately-steep north-facing slope composed of 15 m of till overlying at least 15 m of highly permeable glaciofluvial delta deposits that rest on bedrock. It is believed that the frozen till acted as an impermeable cap that confined the highly permeable glaciofluvial aquifer below. Large amounts of snowmelt likely raised local groundwater pressure and triggered a highly destructive debris torrent that reached speeds up to 40 km /hr and cleared a swath of trees averaging 30 m wide all the way down the stream channel to where 12 Mile Creek crosses the North Klondike Highway (4 km downstream). The total volume of material involved is estimated to be approximately 250,000 m^3. The bowl-shaped headwall of the slide ranges from 12 m to 30 m high, with slopes of 30° to 42°. The width of the source area is about 115 m, and the footprint area is approximately 12,250 m^2.

Since the original failure in 2002, ongoing activity has been occurring at this site. Permafrost exposed in the steep headwall has been actively thawing in the summer months (June to September), causing parts of the headwall to gradually retreat. Thawed material from this retrogression accumulates at the base of the headwall, while slide debris from the original failure continues to settle and shift. This continued activity has had ongoing downstream impacts on highways maintenance, water quality and salmon habitat.

Snowmelt in early summer contributes significant surface runoff at this site, which likely contributes to the majority of current slope movement. During this period, reasonable InSAR coherence was not expected. Nonetheless, it was hoped that InSAR would reveal smaller ground movements that might occur later in the summer when the ground surface is generally drier and sufficient coherence is expected. Another EO limitation at this site was the fact that the steep sections of the headwall could not be imaged with the current incidence angles employed by space borne SAR.

Figure 13 Bowl-shaped source zone for the 12-Mile Slope site landslide (photo taken May 20, 2006). The bowl is 115 m wide and the headwall is 12-30 m high.

1.4.5 Magundy River Slide

The Magundy River slide is a large retrogressive thaw failure on a heavily-forested, gentle (13°) north-facing slope. It is located at 62°20’82” N latitude and 134°11’23” W longitude.

One of the most interesting features of this slide is its rapid rate of growth, as interpreted from analysis of air photos, satellite imagery and GPS surveys (Lyle, 2006). The landslide started in 1996 as a small groundwater piping failure less than 10 m wide. Subsequent activity has followed the typical sequence documented for retrogressive thaw flows. The initial disturbance exposed massive ground ice to the air. The exposed ice-rich material quickly thawed, releasing large amounts of water which has carried the debris up to 2 km down into the Magundy River valley bottom. The debris is transported in highly viscous mud and debris flows which have the appearance of lava flows. These flows travel on very gentle slopes due to the high moisture content provided from the thawing massive ice. The ongoing process has caused steady retreat of steep headscarps and accumulation of debris on the two distinct depositional fans visible in Figure 14.

This process is still very active and the source zone is now 350 m wide. It is estimated that the slide has moved over 3 million cubic meters of soil and covers nearly half a million square meters in area (Lyle, 2006). Between 1998 and 2004, headscarp rates averaged 12-16 m/year in the southern (upper) portion of the source zone, while they were 30-40 m/year in the northern part of the source zone (Lyle, 2006). Over the course of the summer monitoring period in 2006, a 125 m segment of the headscarp in the north part of the source zone retreated from 8 to 12 m.

Continued ground movements at the Magundy River Slide are a product of ongoing melting of the head scarps and gradual deposition of material along flow channels, levees and debris fans. This activity is expected to continue until either no more ice becomes exposed in the headscarp or the headscarp becomes stabilized by an insulating cover of thick organic matter or debris that falls from above.

No single event appears to have triggered this slide, but ground ice contents up to 50%, hydrogeological conditions and piping, record precipitation in the spring of 1996, and possibly long-term climate change appear to be contributing factors (Lyle, 2006).

The issues associated with InSAR measurements of the Magundy River Slide are similar to those discussed for the 12-Mile Slope, especially with respect to the excess surface water during the spring snowmelt season. However, in contrast to the 12-Mile Slope, the head scarp is not as steep, and the area of the runout is larger.

Figure 14 The Magundy Slide retrogressive thaw failure is comprised of three main components: the squarish source zone at the top of the slide (350 m wide), the smaller west fan deposition zone at the mid-right of the photo, and the larger east fan deposition zone in the lower left of the photo.

1.4.6 Little Salmon Lake Slide

The Little Salmon Lake site is located at 62°21’04” N latitude and 134°30’42” W longitude. The slide is 350 m wide, and the elevation difference between the top of the scarp and the lake is 100 meters. As shown in Figure 15, several large rotational slump blocks have displaced up to 20 m along multiple steep scarps. The largest scarp, which forms the upper boundary of the slide, developed first some time before 1989. Between 1989 and 1998 an additional scarp developed just below the upper one. Then between 1998 and 2004, two more major scarps developed further down the slide. Between 2004 and 2005, the largest amount of movement occurred when the lower half of the slide moved translationally into the lake and disappeared (Figure 15).

Figure 15 Translational ground movement at the Little Salmon Lake Slide between August 2004 (top photo courtesy of R. Lyle) and August 2005 (bottom photo courtesy of A. von Finster).

The slide occurs on a 16-degree north-facing slope, with a cover of thick moss (0.40 m to 0.50 m of organic material underlain by permafrost) and spruce. The scarp exposures show over 10 m of till underlain by an ice proximal package of mostly clean sand and gravel at least 15 m thick. Layers of muddy diamicton and glaciolacustrine clayey silt also occur. This is further underlain by what appears to be a pre-glacial debris flow layer at least 15 m thick. The lowest lake level scarp contains massive, segregated ice with significant (>50%) ice content, likely produced by the intrusion of high pressure groundwater flow beneath the frozen till. Thermal erosion of ice-rich sediment at the toe, and slow permafrost creep deformation throughout the underlying slope are some of the factors contributing to the extensional ruptures (Lyle, 2006).

The Little Salmon Lake site is generally forested, with large blocks sliding towards the lake. The success of InSAR measurements at the slide depends on the temporal coherence between image acquisitions, especially as it relates to the vegetation and the moisture content at the surface, as well as the rate of movement of the blocks.

2 BEAVER CREEK SITE #1

2.1 Installation of Radar Reflectors and Survey Monuments

Five radar corner reflectors were installed to ensure that, at a minimum, point measurements of ground motion could be made at this site. Four radar reflectors were placed on the active part of the slope, with an additional one installed to the northwest outside the active slide zone on ground that was assumed to be stable. The reflectors were anchored by driving three 50 mm diameter metal support posts into the ground as far as possible (approximately 50 cm). The photograph in Figure 16 shows reflectors 1 and 2 (in the distance) installed near the centre of the slope. The locations of the radar reflectors and the rebar monuments are shown in Figure 17.

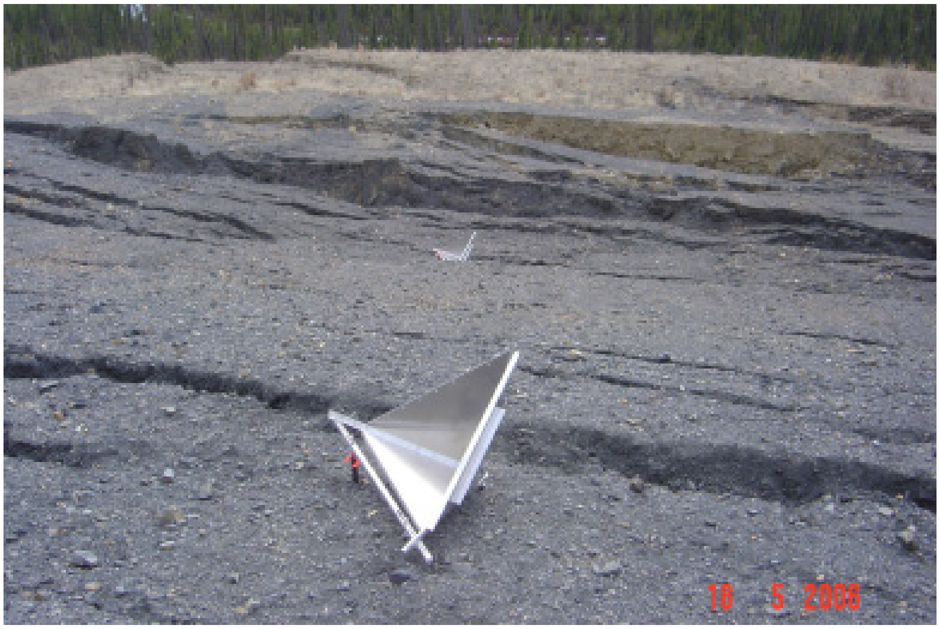

Figure 16 Reflectors 1 and 2 installed along the slope at Beaver Creek, Site 1. View looking downslope from the highway.

The Department of Highways contracted a professional survey crew to install 14 rebar monuments (60 cm lengths hammered into the ground) and survey their locations, as well as that of the reflectors. The monuments were placed along the SW shoulder of the highway, and along a transect running up the center of the slide (Figure 17). The monuments were surveyed on May 18 and September 19, 2006 using a conventional total station level system with a reported accuracy of ±1 cm. The results of the surveys are shown graphically in Figure 28 and in a tabular form in Appendix A.

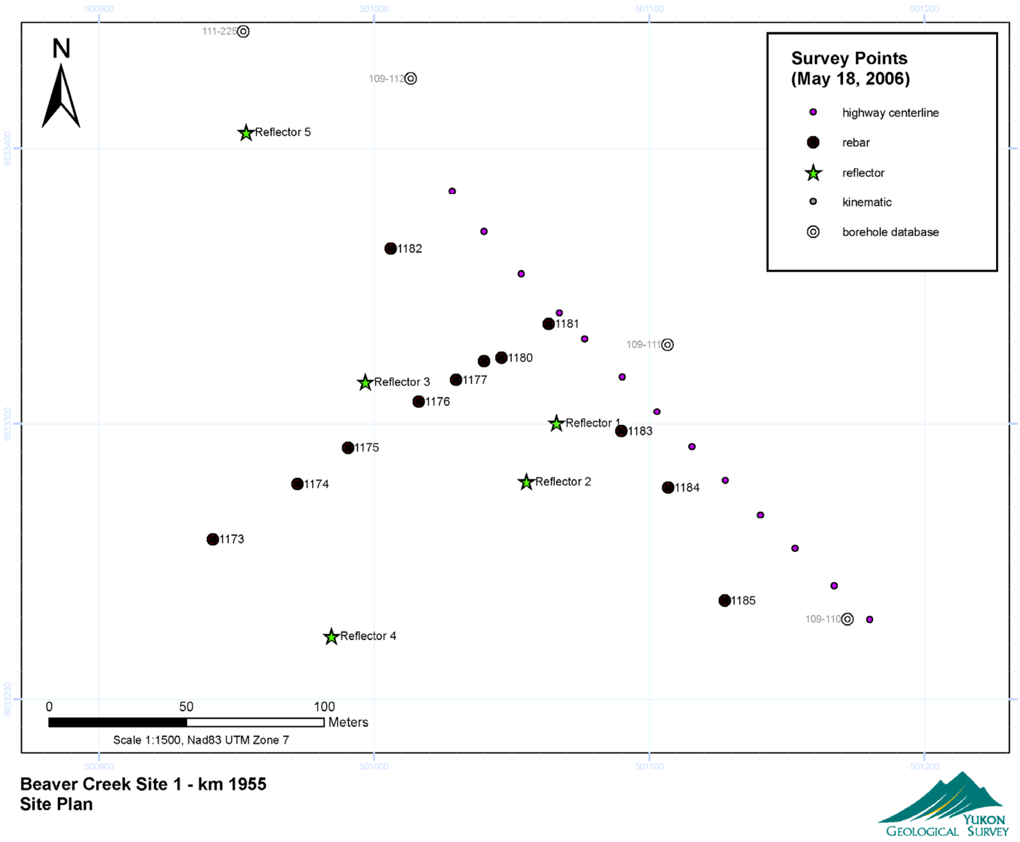

Figure 17 Locations of the reflectors and survey monuments at Beaver Creek, Site 1

2.2 SAR Imagery

The ENVISAT and RADARSAT imagery that were programmed for acquisition (or purchased from the archive for 2004) to be used for InSAR processing is listed in Table 1 along with the prevailing weather conditions at the time of acquisition. The ENVISAT data covering the Beaver Creek sites acquired by the satellite in 2004 that is listed in the table was purchased and analyzed following the Review Meeting 2. These additional data were purchased because it was known that Beaver Creek site #2 showed evidence of ground movement during the summer of 2004. Note that the 2004 data is from the ascending pass compared to the 2006 data which is from the descending pass. While these 2004 data were used for Beaver Creek Site 2 they were not suitable for use with Beaver Creek Site 1 due to the poor alignment of the satellite look direction with the slope.

Table 1 SAR acquisitions for the Beaver Creek Sites

Satellite	Beam Mode	Acquisition Date	Status	Weather
ENVISAT (25m resolution)	IS2 – Ascending Track 278 Frame 1251			Burwash
		2004-May-02	Purchased	3°C rain
		2004-Jun-06	Purchased	11°C cloudy
		2004-Aug-15	Purchased	13°C clear
		2004-Sep-19	Purchased	-5°C unknown
		2004-Oct-24	Purchased	-2°C unknown
ENVISAT (25m resolution)	IS2 – Descending Track 429 Frame 2340			
		2006-May-17	Purchased	13°C cloudy
		2006-Jun-21	Purchased	12°C cloudy
		2006-Jul-26	Purchased	15°C rain
		2006-Aug-30	Purchased	13°C cloudy
		2006-Oct-04	Purchased	10°C cloudy
RADARSAT-1 (8m resolution)	F4F – Descending Orbit 54381			
		2006-May-23	Purchased	10°C cloudy
		2006-Jun-16	Abandoned	-
		2006-Jul-10	Purchased	15°C rain
		2006-Aug-03	Purchased	17°C cloudy
		2006-Aug-27	Purchased	2°C cloudy
		2006-Sep-20	Purchased	10°C cloudy

Table 2 Beaver Creek satellite image pairs is a list of the satellite image pairs that were determined to be suitable for InSAR processing. Note that the weather conditions (listed in Table 2) on May 2, 2006, July 10 and July 26, 2006 acquisitions were not ideal, due to precipitation in the form of rain that was recorded for both these dates. Also, the perpendicular baselines of the September to October, 2004 pair and the August to October, 2006 pair are above the critical baseline (approx. 1100 meters) for ENVISAT, and were not processed. They are included in the table for reference only. The RADARSAT imagery was used to retrieve data from the radar reflectors installed at the two sites, while the ENVISAT imagery was used for 'traditional' InSAR processing techniques.

Table 2 Beaver Creek satellite image pairs

Satellite	Date	Satellite	Date	Interval (Days)	Perpendicular Baseline (m)
RADARSAT (8m resolution)		RADARSAT (8m resolution)			
	2006-May-23		2006-Jul-10	48	64
	2006-Jul-10		2006-Aug-03	24	459
	2006-Aug-03		2006-Aug-27	24	-237
	2006-Aug-27		2006-Sep-20	24	-175
ENVISAT (25m resolution)		ENVISAT (25m resolution)			
	2004-May-02		2004-Jun-06	35	-155
	2004-Jun-06		2004-Aug-15	70	949
	2004-Aug-15		2004-Sep-19	35	187
	2004-Sep-19		2004-Oct-24	35	-1574
ENVISAT (25m resolution)		ENVISAT (25m resolution)			
	2006-May-17		2006-Jun-21	35	215
	2006-Jun-21		2006-Jul-26	35	504
	2006-Jul-26		2006-Aug-30	35	93
	2006-Aug-30		2006-Oct-04	35	-1455

2.3 InSAR Coherence Maps

Figures 18 through 20 show the variation of the ENVISAT coherence at Beaver Creek site 1, kilometer post 1955. Note that the data for 2004 is not shown for this site since the geometry between the satellite orbit and the orientation of the slope was not optimal to resolve the expected ground movement.

In general the coherence maps suggest that ground movement estimates can be derived from these image pairs using traditional interferometric techniques. It should be noted that the areas of low coherence – likely caused by variation in soil moisture content - for the June to July image pair (Figure 19) will cause phase unwrapping problems which will negatively effect the movement estimates derived from this data. Conversely the image pair for July to August displays very good coherence which results in more reliable estimates of ground motion results.

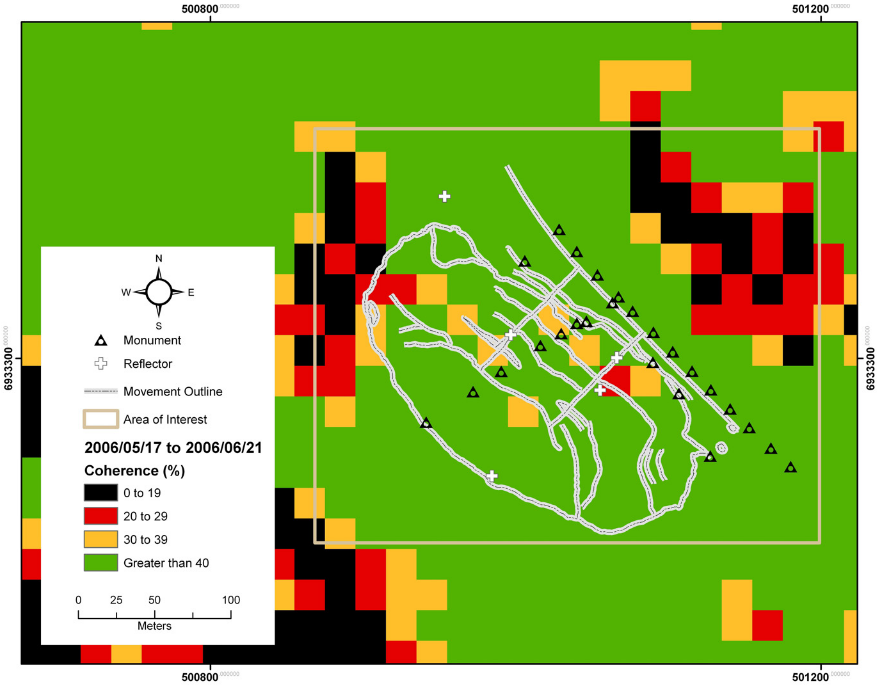

Figure 18 Coherence map derived from ENVISAT data for Beaver Creek site 1 (May 17 to June 21, 2006).

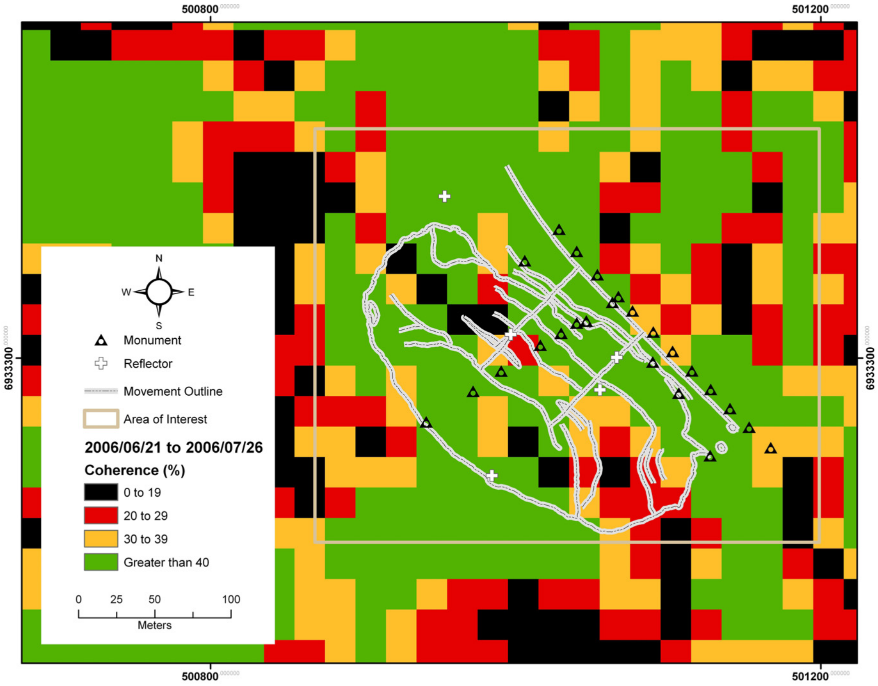

Figure 19 Coherence map derived from ENVISAT data for Beaver Creek site 1 (June 21 to July 26, 2006).

Figure 20 Coherence map derived from ENVISAT data for Beaver Creek site 1 (July 26 to August 30, 2006).

Figures 21 through 24 show the variation of the RADARSAT coherence at Beaver Creek site 1, kilometer post 1955. These figures clearly show the interspersion of good coherence (> 30%) and poor coherence (< 30%). This type of coherence pattern makes phase unwrapping challenging and likely introduces errors in ground motion estimates when phase unwrapping errors occur. The radar reflector data from these image pairs however provide useable phase data from the coherent point targets. This phase data was used to estimate ground movement values as opposed to traditional InSAR processing techniques. See Section 2.5 for these results.

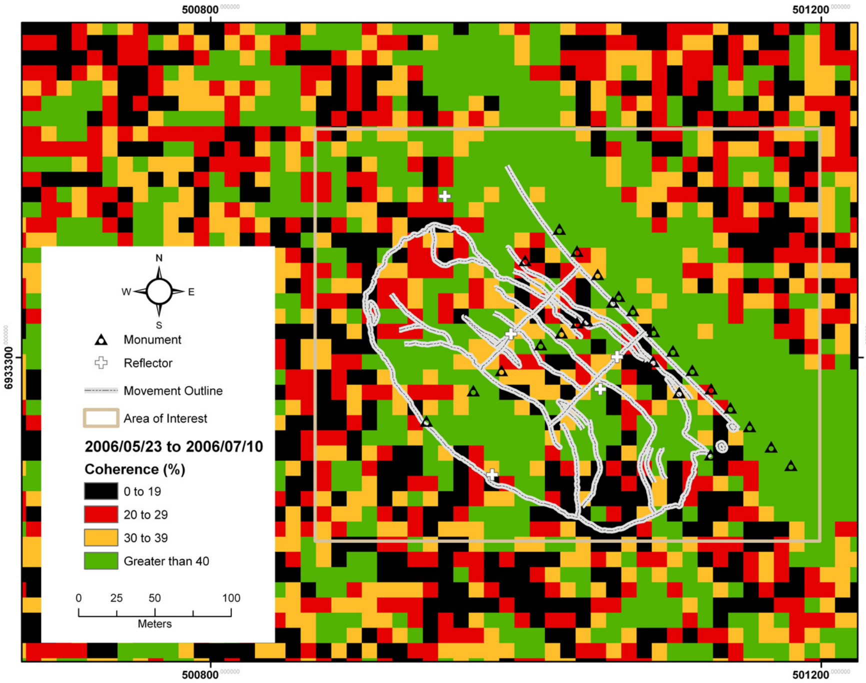

Figure 21 Coherence map derived from RADARSAT data for Beaver Creek site 1 (May 23 to July 10, 2006)

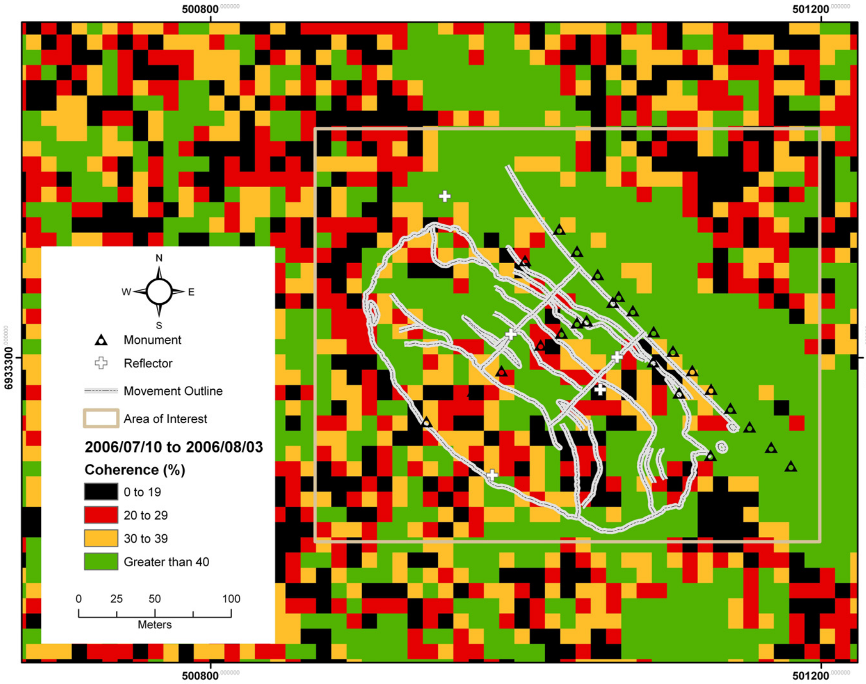

Figure 22 Coherence map derived from RADARSAT data for Beaver Creek site 1 July 10 to August 03, 2006)

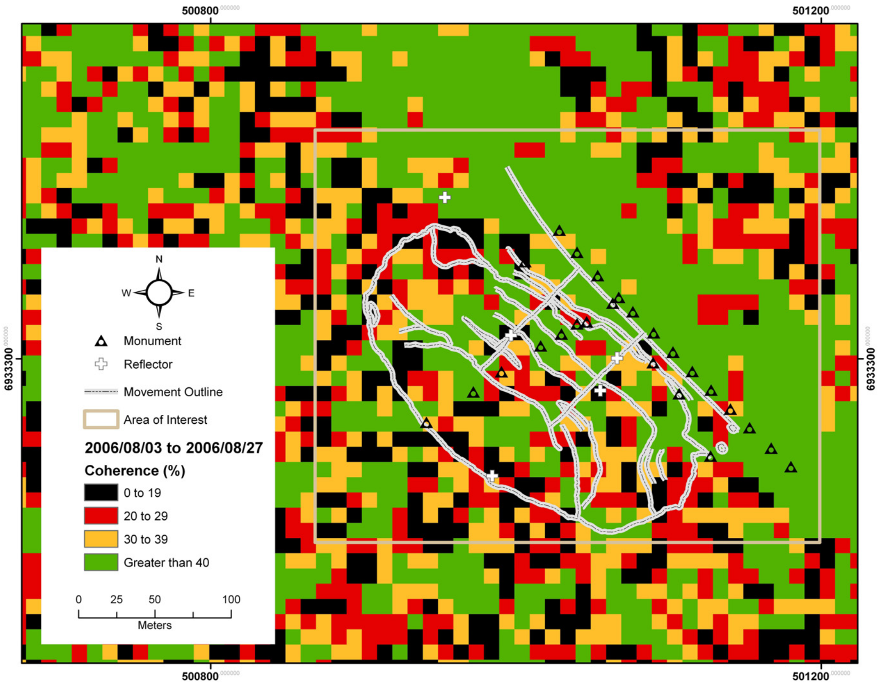

Figure 23 Coherence map derived from RADARSAT data for Beaver Creek site 1 (August 03 to August 27, 2006)

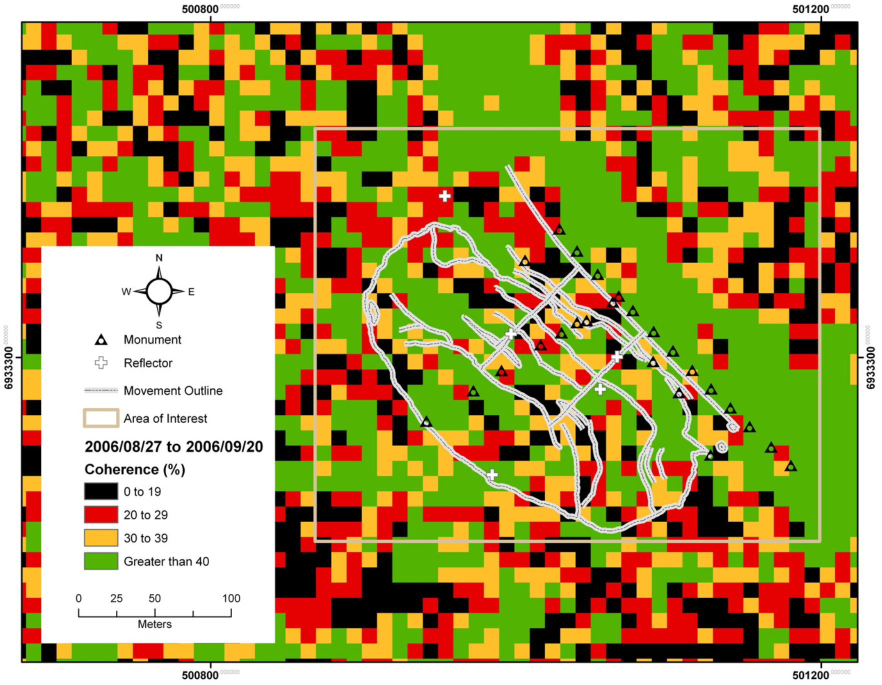

Figure 24 Coherence map derived from RADARSAT data for Beaver Creek site 1 (August 27 to September 20, 2006)

2.4 InSAR Movement Maps

Figures 25 through 27 are movement map products derived from the ENVISAT imagery acquired over Beaver Creek site 1. As stated previously, the ground motion estimates for the June to July image pair (Figure 26) should be viewed with some skepticism due to the relatively low coherence experienced. In particular, Figure 25 shows >2 cm of subsidence along the Alaska Highway, while the ground surveys showed no significant movement immediately along the highway. Also, Figure 26 shows uplift (heaving) movement which is highly unlikely for this area during summer months. On the other hand, Figure 27 shows reasonable movement signatures which are consistent with the movement expectations for this area (i.e., no significant movement along the highway, and maximum subsidence in the mid to lower part of the slide). It is possible that for the time period of Figure 26 (June 21 to July 26) there was significant movement along this slope; if this was the case, the movement could be undersampled leading to false readings of ground movement. July is generally the warmest and wettest month in Beaver Creek (according to Environment Canada climate normals between 1971 and 2000) so it is reasonable to expect that the greatest amount of permafrost degradation would occur during this time. The Environment Canada climate station at Beaver Creek was scaled back in 2005, so there is no complete daily or monthly data from 2006 to verify the actual climate conditions.

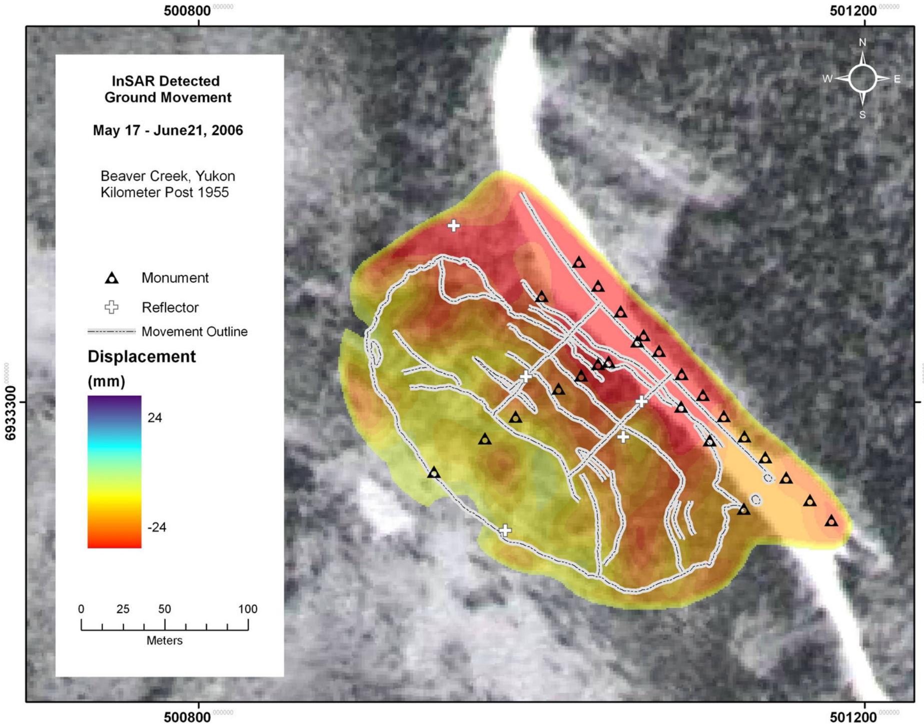

Figure 25 Movement map derived from ENVISAT data (May 17 to June 21, 2006)

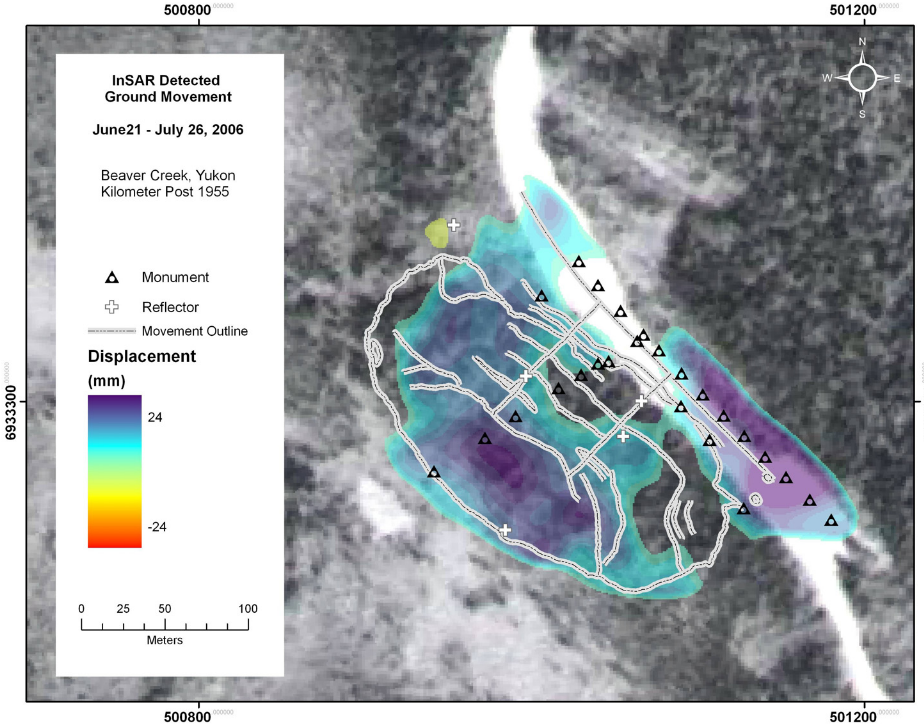

Figure 26 Movement map derived from ENVISAT data (June 21 to July 26, 2006)

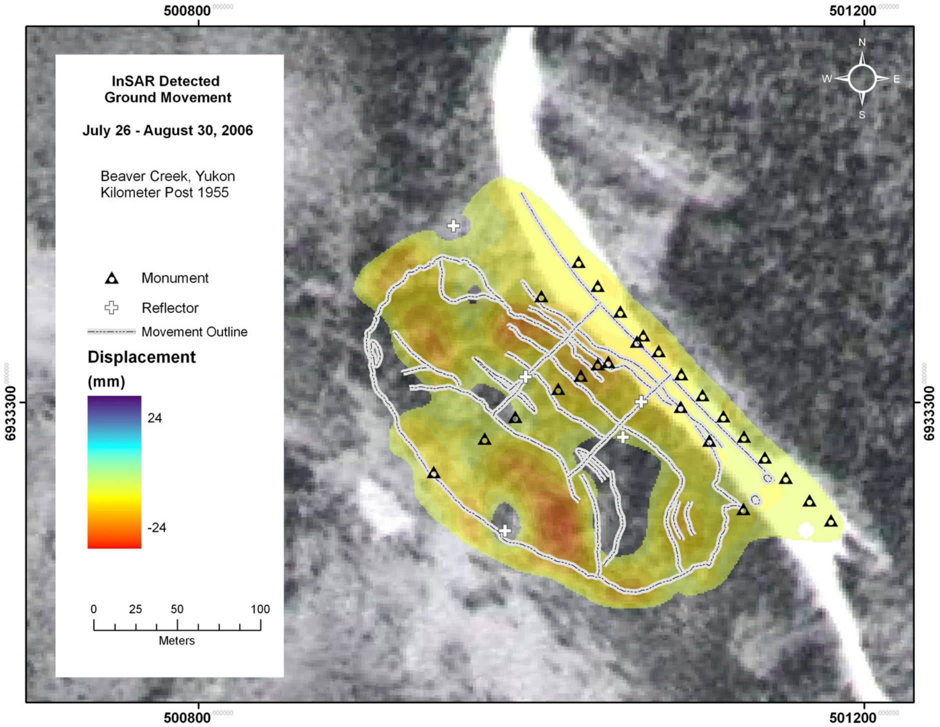

Figure 27 Movement map derived from ENVISAT data (July 26 to August 30, 2006)

2.5 Ground Survey Results

To aid in the verification of the InSAR measurements, surveys were arranged through the Yukon Department of Highways, and were made on May 18 and September 19, 2006. Conventional total station level surveys were performed on the five radar reflectors, and on 14 rebar monuments along the top and down the centre of the slide. Figure 28 shows the results of the surveys, and this data is used in the validation of the InSAR results (Section 2.7).

Substantial ground deformation was shown by the survey results, particularly near the centre of the slope. Figure 28 indicates that slope movement in the maximum settlement zone is on the order of 40 to 50 cm of vertical movement, and up to 82 cm of translational movement.

Considering that the slope is only about 100 metres deep, the total movement would translate into roughly 15 to 18 fringes in an interferogram. Given that the ENVISAT ASAR spatial resolution is only on the order of 25 metres, it can be deduced that the movement will be undersampled by the SAR sensor, particularly if most of the movement occurred over a short time period. Given that the coherence was spotty for the June 21 to

July 26 time period (Figure 26), it is likely that there was significant movement over this time period leading to a false interpretation of the movement, and could explain why uplift is observed in this movement map.

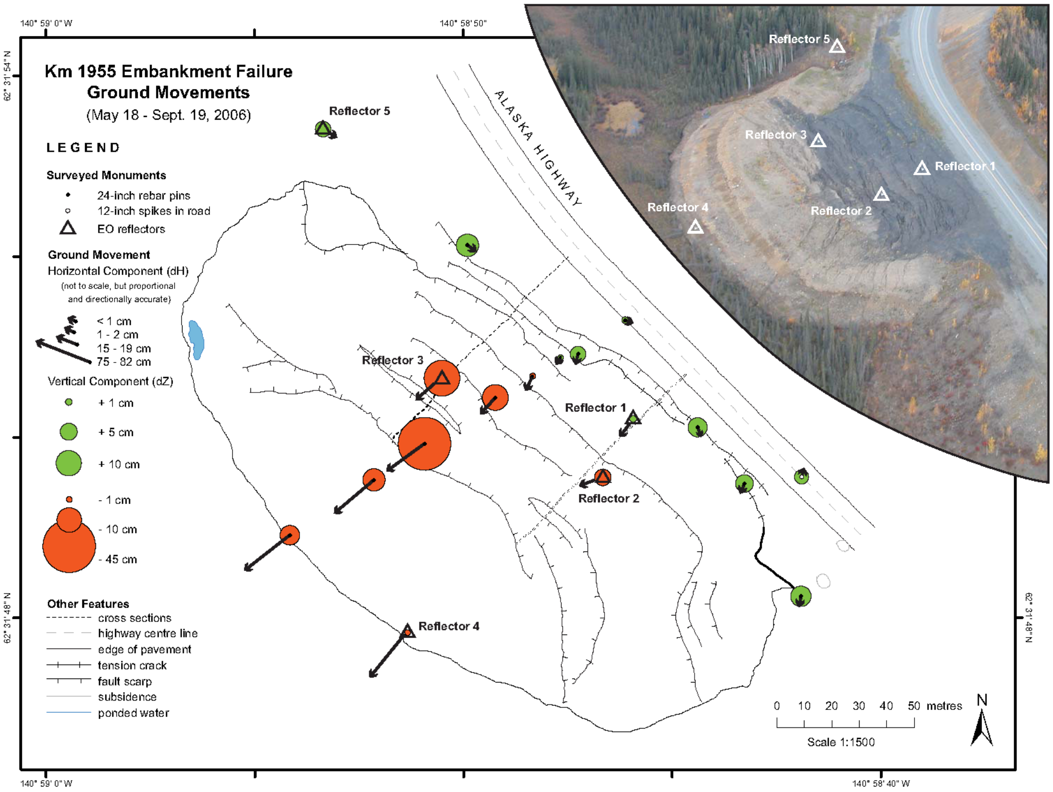

Figure 28 Beaver Creek Km 1955 GPS ground movement measurements

2.6 Radar Reflector Results

Figure 29 shows a LANDSAT image as well as a portion of the RADARSAT Fine Beam Mode image over the Beaver Creek site. The radar reflectors are clearly visible in the RADARSAT satellite image as bright white pixels.

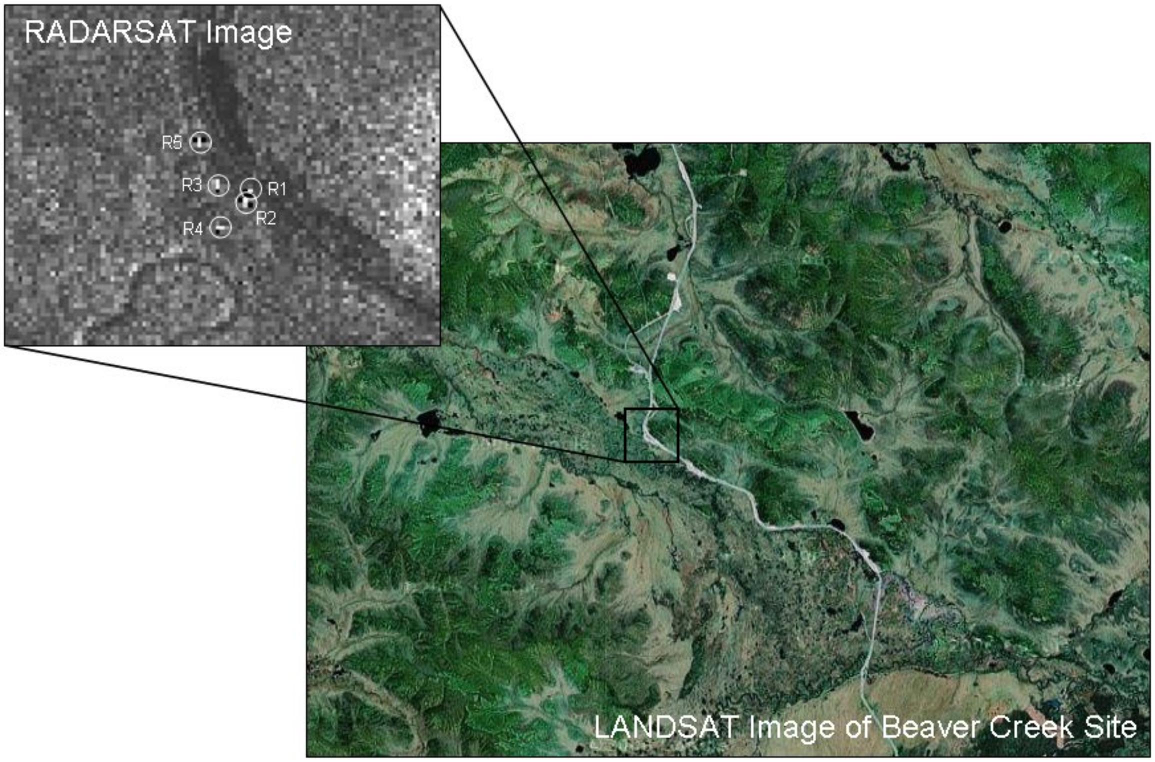

Figure 29 RADARSAT image showing radar reflectors

Table 3 shows the slant range movement estimates derived from the reflectors for the time period from May 23 to September 20, 2006. The wrapped phase[1] column has had the phase value measured at the reference reflector subtracted from the phase values measured at the other reflectors. In the case of the unwrapped phase column, it was not possible to unwrap the phase unambiguously for reflectors 3 and 4 due to the amount of movement experienced at these two reflectors. As a result, the error associated with reflectors 3 and 4 are misleading.

Given the fact that the reflectors' movement could not be manually unwrapped, the reflector data were processed using GAMMA IPTA (Interferometric Point Target Analysis) software. This software uses the point scatterers technique and a movement model to unwrap the phase. In this case, favorable results were obtainable, but only if the order of magnitude of the ground movement was known apriori and input into the IPTA

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[1] Since phase can only be represented by 0-2π radians, the interferogram phase contains a 2πn ambiguity, which needs to be unwrapped, typically when the phase jumps by 2π, either spatially or temporally.

software as a maximum movement search point. This indicates that the IPTA software would not be able to independently resolve the movement of reflectors 3 and 4 for this case.

Table 3 Reflector ground movement data

Reflector #	Wrapped Phase (radians)	Unwrapped Phase (radians)	Slant Range Change (m)	Error compared to ground survey (m)
1	4.91	4.91	0.022	-0.007
2	3.32	15.88	0.071	-0.004
3	6.48	44.16	0.197	-0.006
4	-1.59	80.05	0.357	-0.012
5 (reference)	0.00	6.28	0.028	0.001

2.7 Validation

In this section, the InSAR derived ground motion results are compared to the conventional total station level survey results provided by the Yukon Department of Highways. The ground survey results cover the entire timeframe from May 18 to September 19, 2006. However, the 'useable' ENVISAT InSAR results cover two discrete timeframes May 17 to June 21, 2006 and July 26 to August 30, 2006. Note that the June 21 to July 26 results have not been used in the validation because of the poor coherence and suspect movement results. As a result, only general trends between the two datasets can be discussed.

The ground survey results show slight heave of approximately 5 cm along the top of the slide area, immediately adjacent to the shoulder of the Alaska Highway. Because the highway shows no signs of such deformation, and because it is highly improbable that heave could occur during the summer months, this movement is interpreted to be misrepresentative due to cumulative surveying errors. Despite the fact that the survey data is reported to be accurate to ±1 cm, it is believed that the accuracy is actually on the order of ±5 cm, and that no significant movement occurred at those locations. The main slide area to the south of the highway does show significant subsidence which gradually increases to a maximum of 45 cm near the center of the slide and then decreases towards the toe of the slide. However, horizontal translational movement increases toward the toe of the slide up to a value of 82 cm.

The ENVISAT InSAR derived results for May to June show subsidence of approximately 2 cm along the highway gradually decreasing to near 0 cm towards the toe of the slide. The results for July to August show subsidence values of approximately 1 cm around the perimeter of the slide area, gradually increasing to approximately 2 cm near the central region of the slide.

The overall movement signature is generally consistent with the expected and surveyed movement occurring on the slide; however this cannot be quantified due to the dropped movement interval for June and July. If additional surveys had been conducted throughout the summer, it may have been possible to provide a better validation of the two useful InSAR intervals. Overall, it is suggested that InSAR is only suitable for monitoring this type of slope if slow movements of 10 cm per year or less are experienced. For substantial permafrost degradation along slopes, InSAR is not deemed suitable.

3 BEAVER CREEK SITE #2

3.1 Installation of Radar Reflectors and Survey Monuments

Two radar reflectors were installed at this site, and their locations are shown in Figure 31. Reflector #1 was anchored in stable ground, and was intended to serve as a reference point for the InSAR measurements. Reflector #2 (Figure 30) was installed to ensure sufficient coherence for measuring potential thaw settlement in the undisturbed ground adjacent to the highway. However, when this reflector was installed on May 18, the ground was still completely frozen beneath the surface organic layer and the supporting posts could only be hammered into the ground to approximately 50 cm depth. During the site visit on September 19, measurements of the thawed active layer in this area were in the range of 30 to 60 cm, and it appeared that the reflector supports had shifted in this thawed layer. It is therefore unlikely that the movement of this reflector will correlate to the actual thaw settlement.

This highlights the challenge with anchoring reflectors in permafrost terrain where thaw settlement is a desired phenomenon for SAR detection. If thaw settlement is what one is attempting to detect, the reflector needs to be either anchored in the active layer, or somehow anchored to the ground surface to reflect this movement. It should not be anchored deeper down in the permafrost which would never thaw, and hence would not reflect any settlement movement. However, it is difficult to anchor the posts in a medium that freezes and thaws seasonally due to the inherent changes in volume and moisture in this layer.

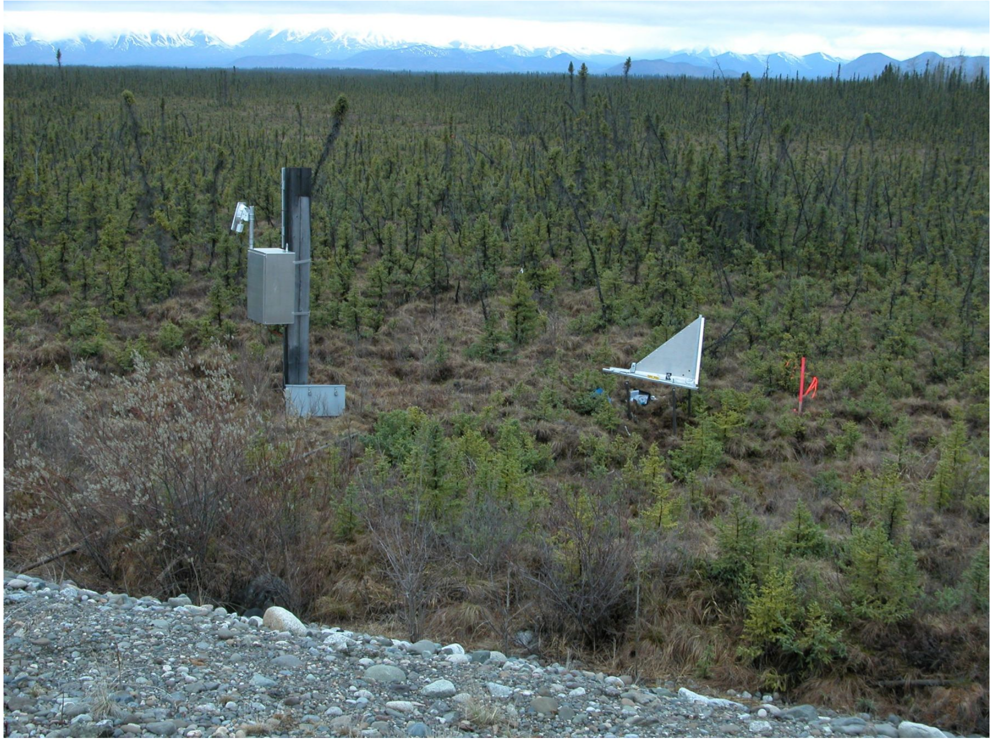


Figure 30 Radar reflector (to the right) and pre-existing data logger (to the left) used to monitor ground temperatures beneath and adjacent to the Alaska Highway at Beaver Creek, Site 2

As for Beaver Creek, Site 1, the Yukon Department of Highways contracted two conventional total station level surveys for this area. A total of 20 monuments were installed across the highway in 4 separate transects at locations where pavement deformation indicated significant thaw settlement in previous years. The locations of these monuments are shown in Figure 31. In each transect, the centre monument was at the highway centerline, the two end monuments were placed in the stabilization berm, and the remaining two monuments were placed at the edge of the pavement, in the road shoulder. The results of the May 18 and September 19, 2006 surveys are shown graphically in Figure 46 and in a tabular form in Appendix A.

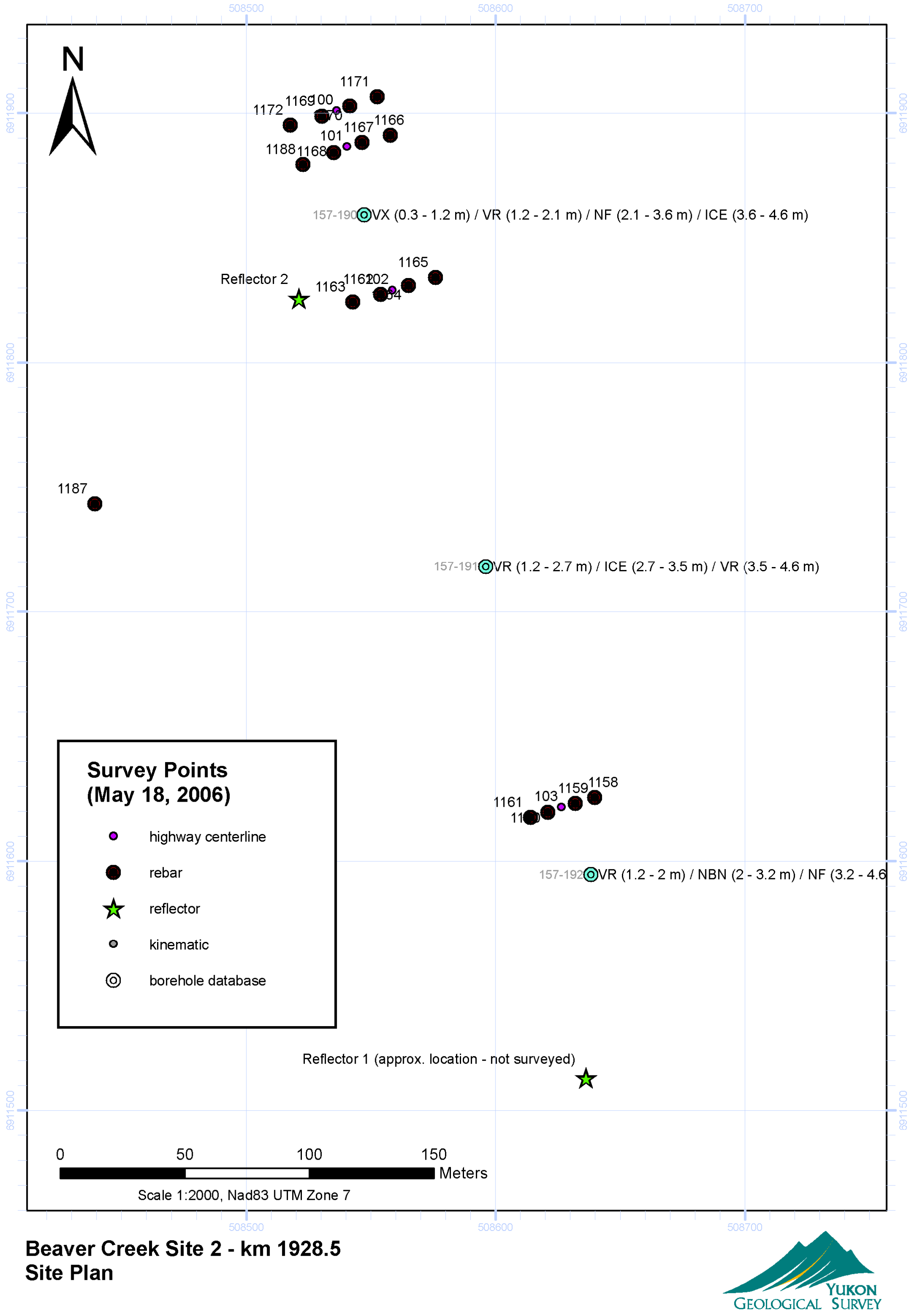


Figure 31 Locations of the reflectors and survey monuments and boreholes at Beaver Creek, Site 2

3.2 SAR Imagery

Refer to Section 2.2 for a list of the SAR imagery used for this site.

3.3 InSAR Coherence Maps

Figure 32 through 34 show the variation of the ENVISAT coherence over the May to September 2006 timeframe at Beaver Creek site 2, kilometer post 1928. The favorable distribution of coherence throughout these maps suggest that ground movement estimates derived from these image pairs using traditional interferometric techniques would produce reliable results.

It should be noted that in these coherence maps (Figure 32 to 34), only the centerline of the Alaska Highway is shown (represented by the white line). The actual width of the entire 40-m wide road structure (road plus stabilization berms) is represented by the width of the each line of monuments crossing the highway in four locations.

It is also interesting that the coherence is very good between nearly all image pairs in the well-vegetated (stunted spruce forest / muskeg) and very-poorly drained natural ground adjacent to the highway. The ground surface in this area is covered by patches of moss 20-30 cm thick, interspersed with grass tussocks and occasionally small water-filled depressions. The ground beneath the organic material typically only thaws to a depth of approximately 10 cm each summer. Because the active layer is so thin and thaws so slowly, surface moisture may only change by very minor amounts throughout the summer, and vegetation also grows extremely slowly.

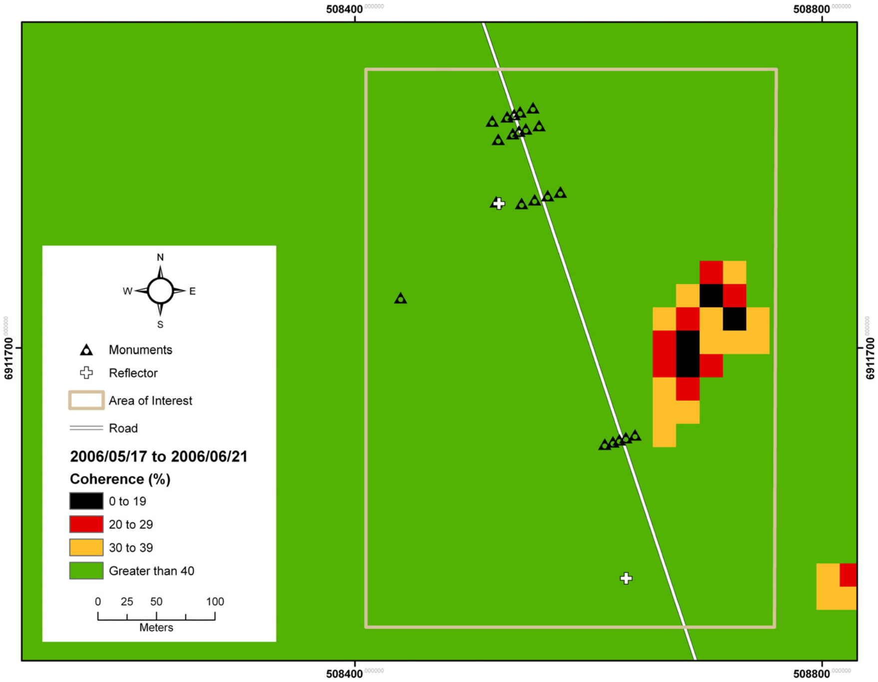


Figure 32 Coherence map derived from ENVISAT data for Beaver Creek site 2 (May 17 to June 21, 2006)

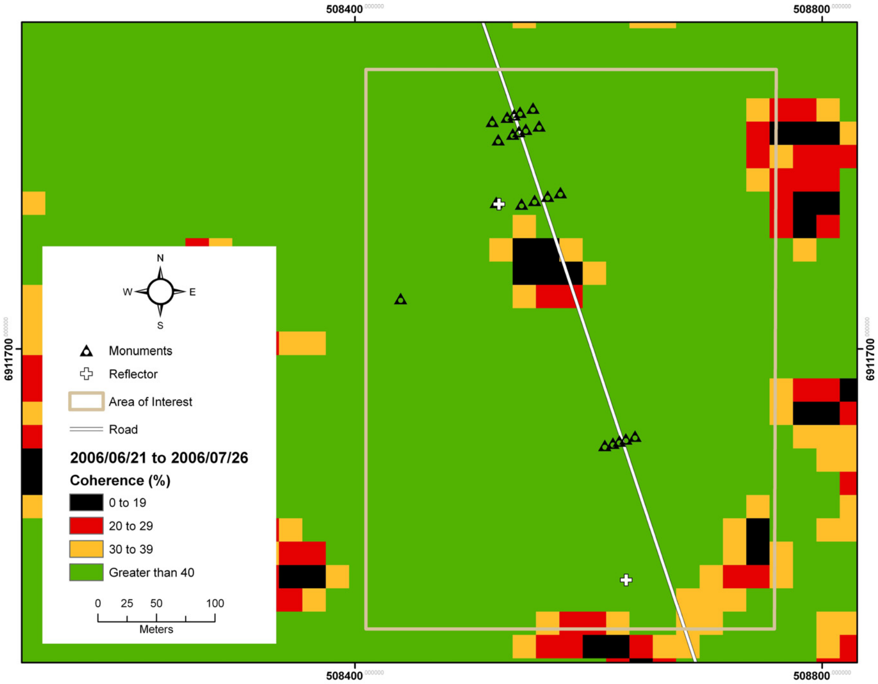


Figure 33 Coherence map derived from ENVISAT data for Beaver Creek site 2 (June 21 to July 26, 2006)

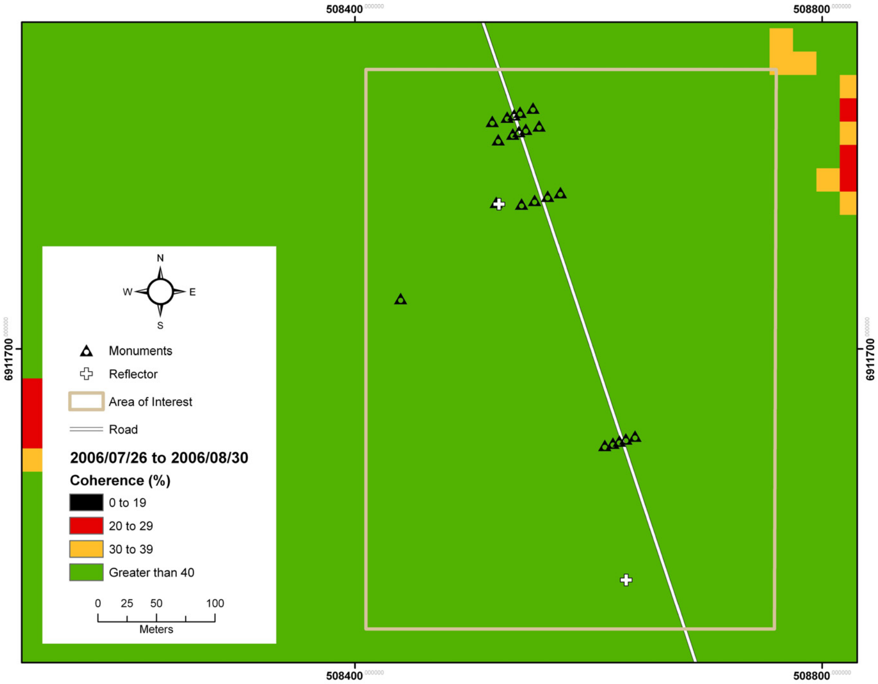


Figure 34 Coherence map derived from ENVISAT data for Beaver Creek site 2 (July 26 to August 30, 2006)

Figure 35 through 37 show the variation of the ENVISAT coherence over the May to September 2004 timeframe at Beaver Creek site 2 in 2004. These were acquired to compare the ground displacement patterns at the site over multiple summers. However, only one movement map could be generated for the May to June 2004 dataset because of the relatively low coherence values observed for the June to August, 2004 and the August to September, 2004 image pairs.

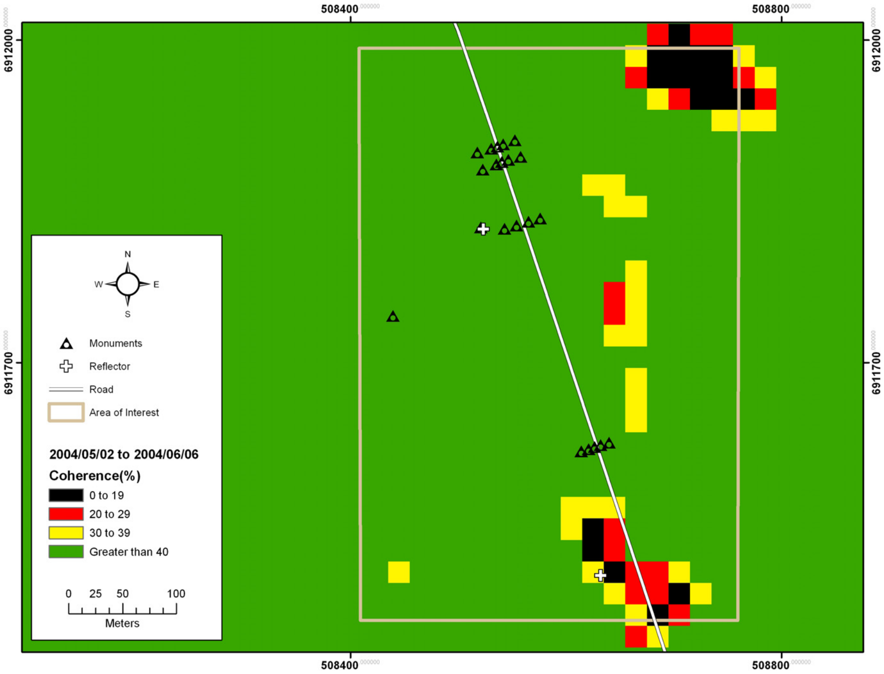


Figure 35 Coherence map derived from ENVISAT data for Beaver Creek site 2 (May to June 2004)

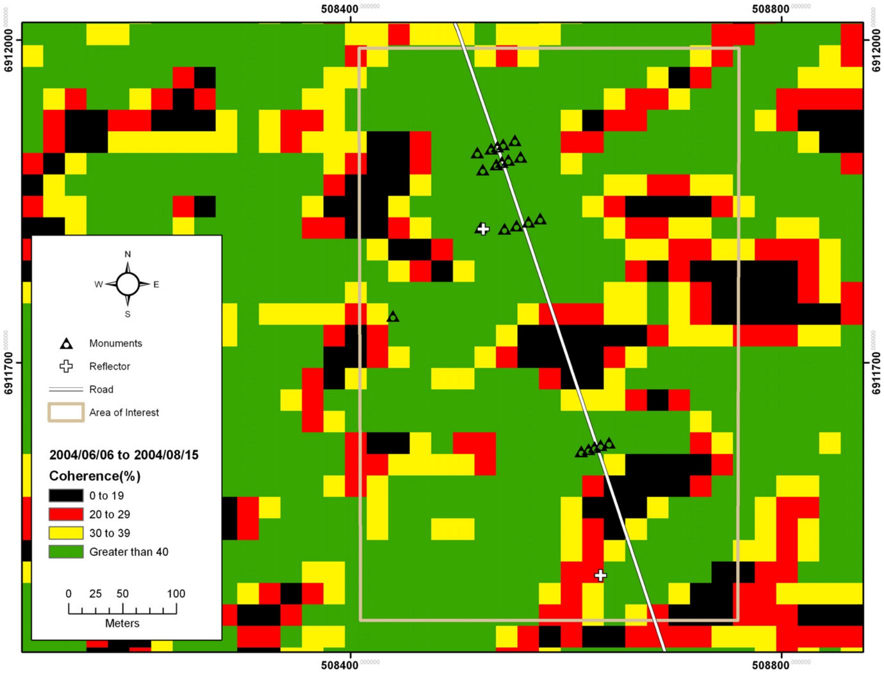


Figure 36 Coherence map derived from ENVISAT data for Beaver Creek site 2 (June to August 2004)

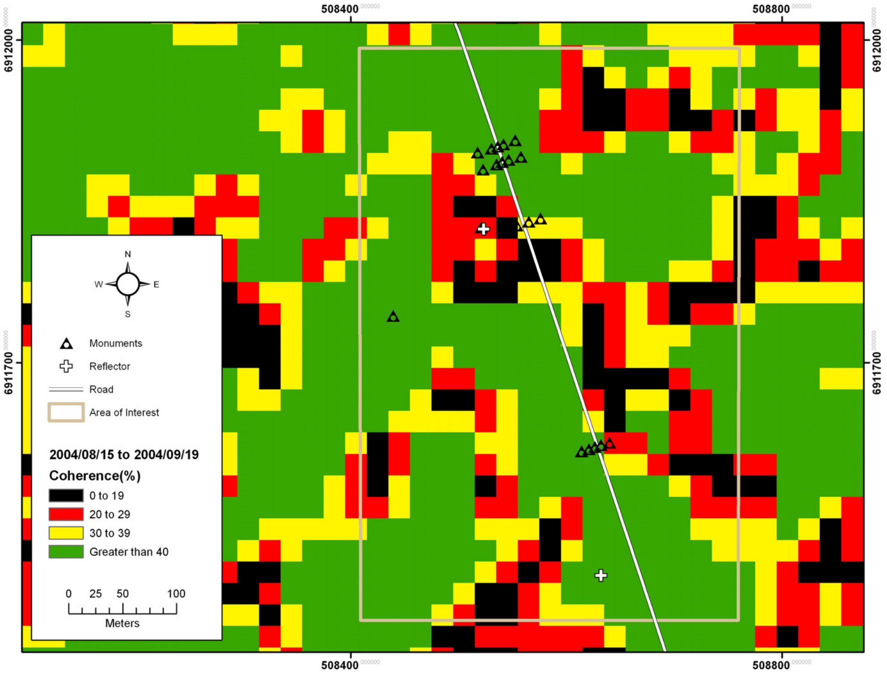


Figure 37 Coherence map derived from ENVISAT data for Beaver Creek site 2 (August to September 2004)

Figure 38 through 41 show the variation of the RADARSAT coherence at Beaver Creek site 2, kilometer post 1928. These figures also show the interspersion of good coherence (> 30%) and poor coherence (< 30%), which makes phase unwrapping challenging. It is interesting to note that although the RADARSAT data have better resolution than the ENVISAT data, it seems generally to have much poorer coherence. This is likely due to the higher level of nulti-looking (averaging) on the ENVISAT data that serves to reduce speckle noise. These data sets were not used to estimate ground motion due to the failure (due to tilting) of the radar reflector installed at this site.

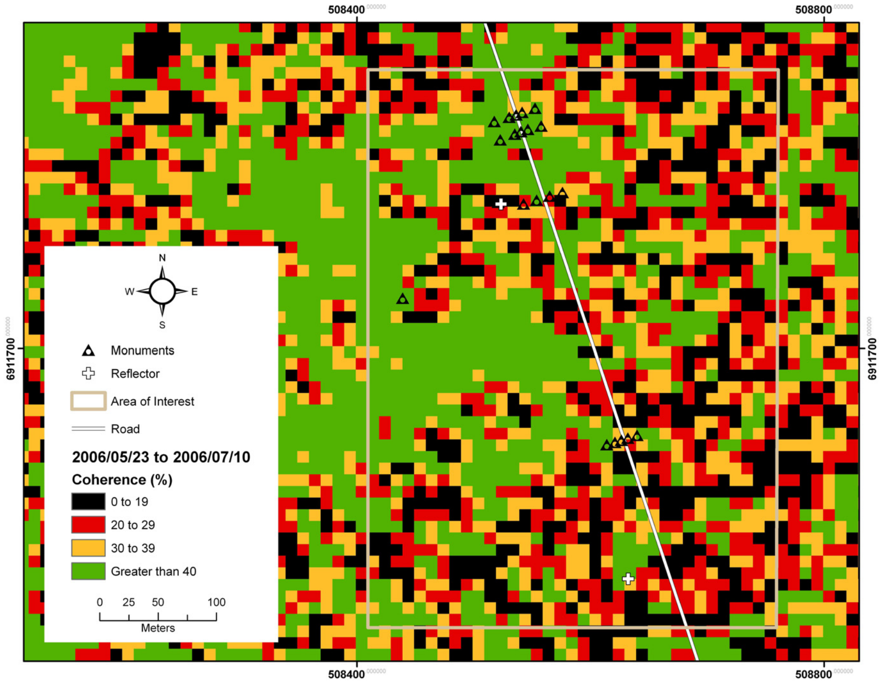


Figure 38 Coherence map derived from RADARSAT data for Beaver Creek site 2 (May 23 to July 10, 2006)

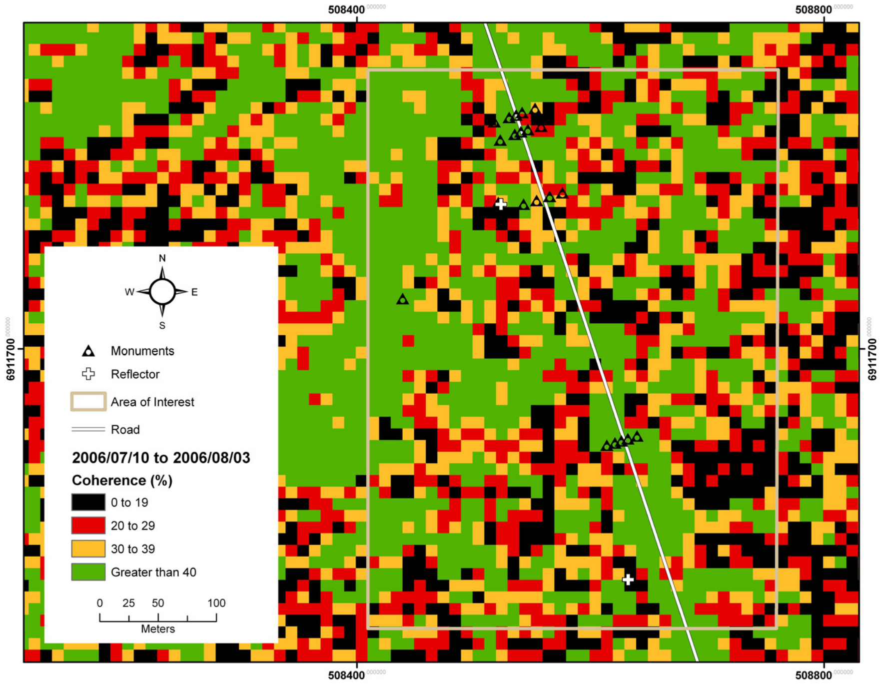


Figure 39 Coherence map derived from RADARSAT data for Beaver Creek site 2 (July 10 to August 03, 2006)

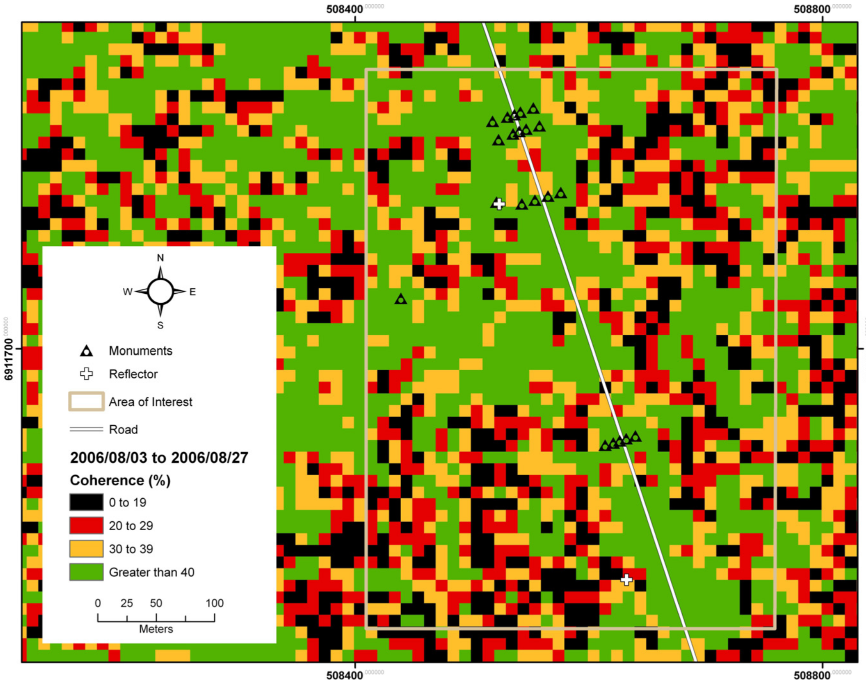


Figure 40 Coherence map derived from RADARSAT data for Beaver Creek site 2 (August 03 to August 27, 2006)

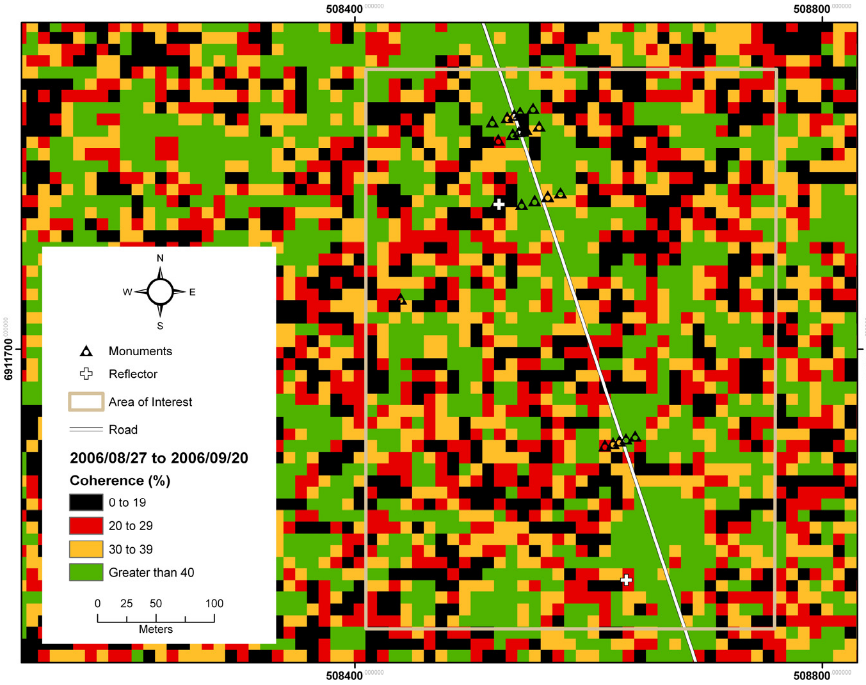


Figure 41 Coherence map derived from RADARSAT data for Beaver Creek site 2 (August 27 to September 20, 2006)

3.4 InSAR Movement Maps

Figure 42 through 44 are movement map products derived from the ENVISAT imagery acquired over Beaver Creek site 2 in 2006. These movement maps show very little movement (0 to 2 cm subsidence) over the monitoring period.

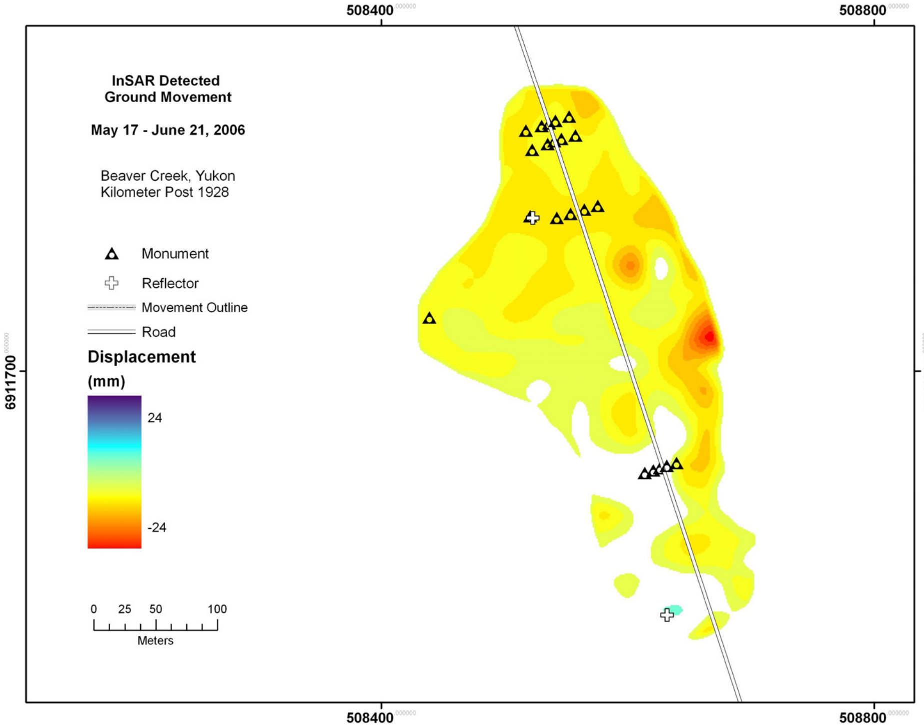


Figure 42 Movement map derived from ENVISAT data (May 17 to June 21, 2006)

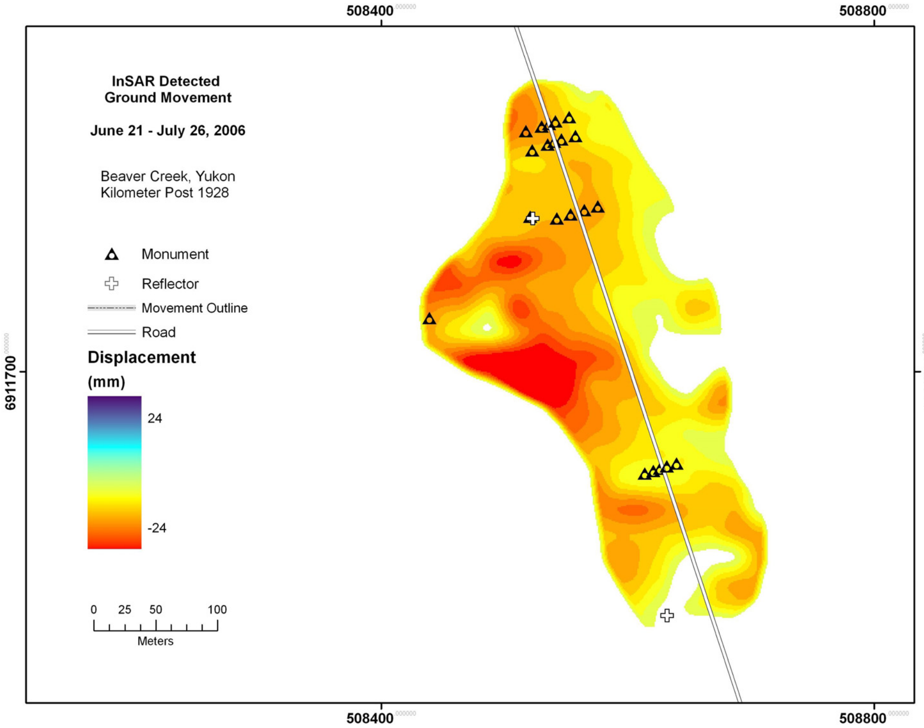


Figure 43 Movement map derived from ENVISAT data (June 21 to July 26, 2006)

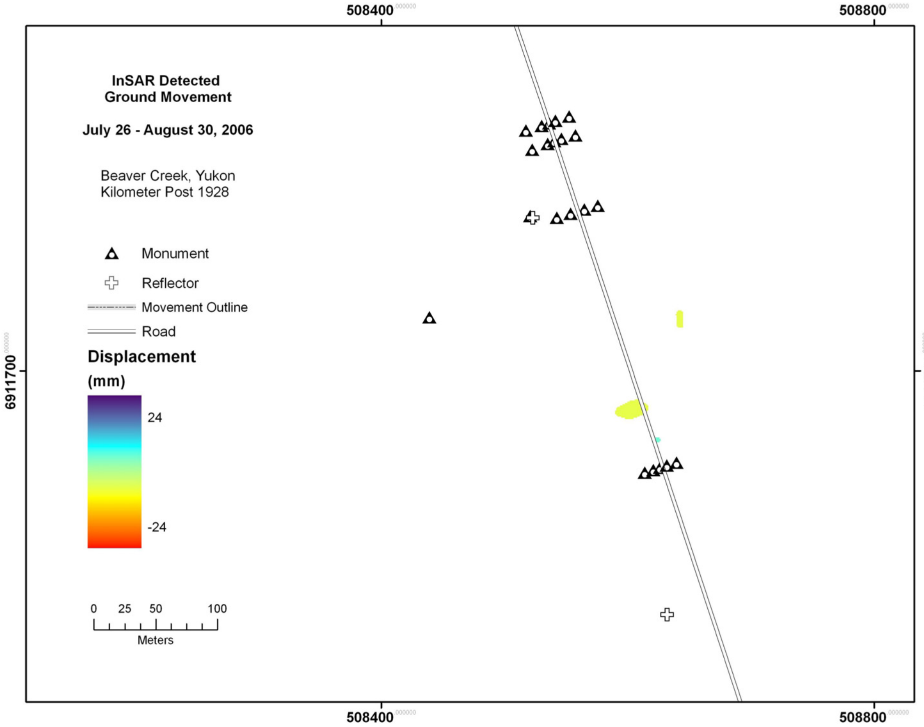


Figure 44 Movement map derived from ENVISAT data (July 26 to August 30, 2006)

Figure 45 is the movement map product derived from the ENVISAT image pair acquired over Beaver Creek site 2 in 2004 which displayed sufficient coherence for processing. This map shows 1 to 2 cm of heave over the area flanking the highway near radar reflector #2 and two very small areas of subsidence along the highway near the location that radar reflector #1 was installed.

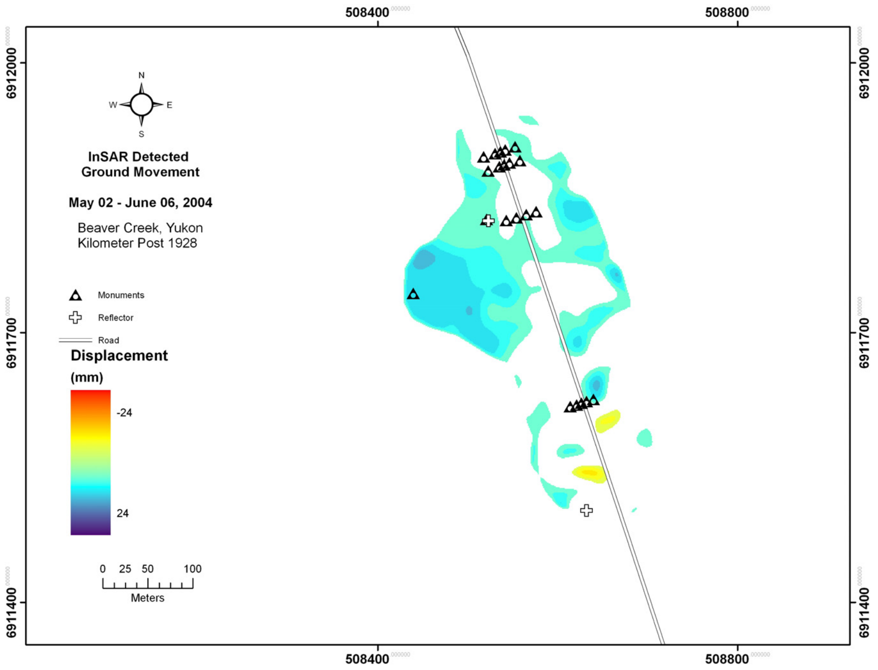


Figure 45 Movement map derived from ENVISAT data (May to June, 2004)

3.5 Ground Survey Results

Figure 46 shows the results of the conventional total station level surveys performed in the Spring and again in the Fall of 2006 by the Yukon Department of Highways at km 1928. Surveys were performed on 20 rebar and nail monuments forming four transects across the highway, as well as one rebar monument and the radar reflector #1 installed in the frozen peat bog. Unfortunately the second reflector could not be installed before the spring survey was conducted. Observations of the reflectors on September 19 indicate that the supporting posts of reflector #1 had shifted, making it unlikely that the movement of this reflector correlates to the actual thaw settlement. This survey data was used in the validation of the ‘traditional’ InSAR results.

The ground survey results show slight heave of up to 1.5 cm occurred in the three survey lines at the north end of the region of interest along the Alaska Highway. As for Beaver Creek site 1, it is likely that the cumulative effects of small errors generated by the surveying instruments, surveying technique and monument anchoring methodology actually gives rise to a larger uncertainty than originally reported by the survey crews (±1 cm). Because it is highly unlikely that heave could occur at this site over the course of the summer, it could be inferred that the uncertainty is actually closer to ±2 cm, suggesting that no significant ground movement occurred at all for those lines. The results for Line 4, however, indicate higher displacement values, and show that subsidence of up to 3 cm occurred. This mechanism of movement is much more plausible during the summer months, so these results seem far more convincing and could be regarded as significant.

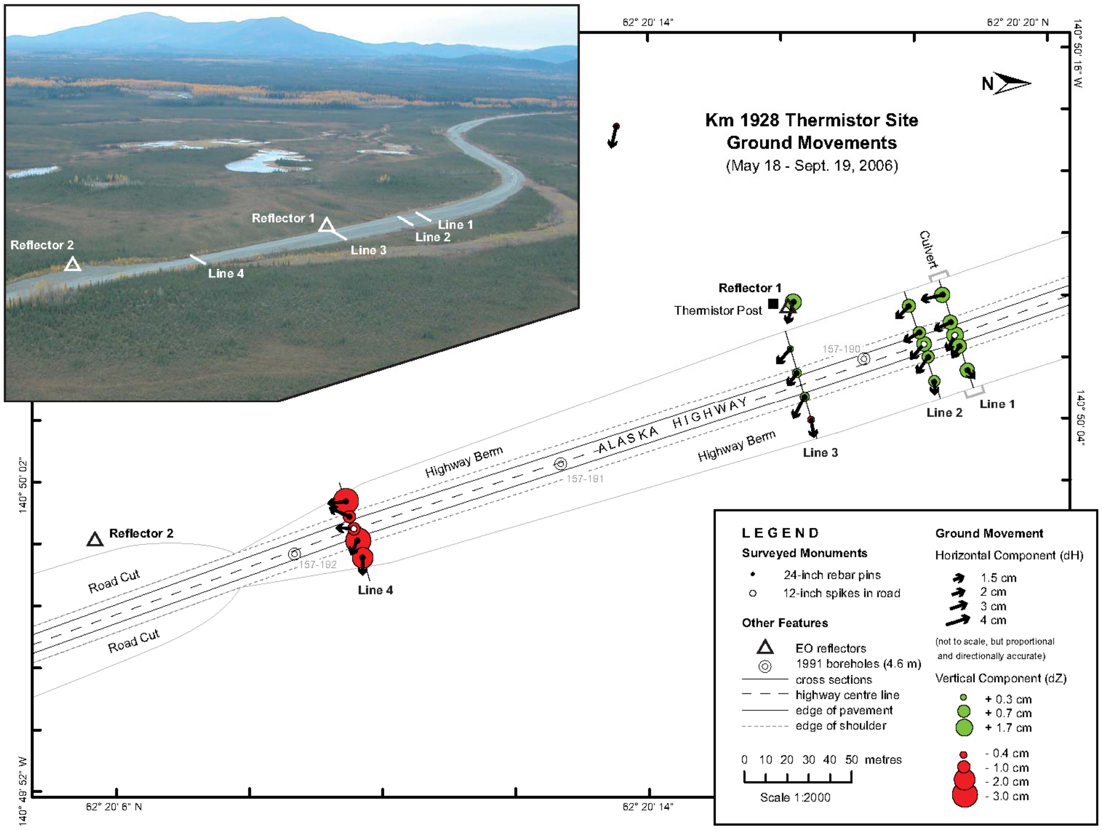


Figure 46 Beaver Creek Km 1928 GPS ground movement measurements

3.6 Validation

The InSAR derived ground motion results are compared to the conventional total station survey results provided by the Yukon Department of Highways. The survey results cover the entire timeframe from May 18 to September 19, 2006. The ENVISAT InSAR results cover three discrete timeframes May 17 to June 21, 2006 June 21 to July 26, 2006 and July 26 to August 30, 2006.

The ENVISAT InSAR derived results for May to June show subsidence of approximately 2 cm along the highway in the northern portion of the study area, gradually decreasing to near 0 cm towards the south. The June to July results show a slight increase in the subsidence values, which could be expected considering July is normally the warmest month of the year. The results for July to August show virtually no movement over the whole area of interest. This compares to the insignificant amount of heaving reported by the ground surveys for the same area over the entire course of the summer.

The InSAR results (Figure 42 and 43) also indicate that smaller amounts of subsidence occurred in the southern portion of the study area (in the vicinity of Line 4) than in the northern portion, which is reverse to the trend shown in the ground survey data, so some inconsistency is noted in this case.

The maximum amount of subsidence (on the order of 3 cm) detected by InSAR west of the highway in late June and July (Figure 43) may be indicative of seasonal thaw settlement in the active-layer of the undisturbed muskeg. While very good coherence was obtained for this area (Figure 33), no survey data is available to validate this.

Based on the May to September ground survey data, and assuming a linear deformation rate, one would not expect to see any significant movement along the highway per InSAR cycle (35 days). Indeed the values measure using InSAR are near the lower limits possible. Therefore, aside from the subsidence shown in vicinity of Line 4 of the ground surveys, it can be stated qualitatively that the InSAR and survey monument results are generally consistent with each other.

4 12 MILE SLOPE

4.1 Installation of Survey Monuments

The Yukon Geological Survey installed 14 rebar monuments around the periphery of the movement area on May 22, 2006, and surveyed them with a Thales ProMark 3 differential GPS system. The locations of the rebar monuments are shown in Figure 47. The Yukon Geological Survey revisited the site on September 21, 2006, at which time the monuments were surveyed again. The results of this survey are included in Section 4.5.

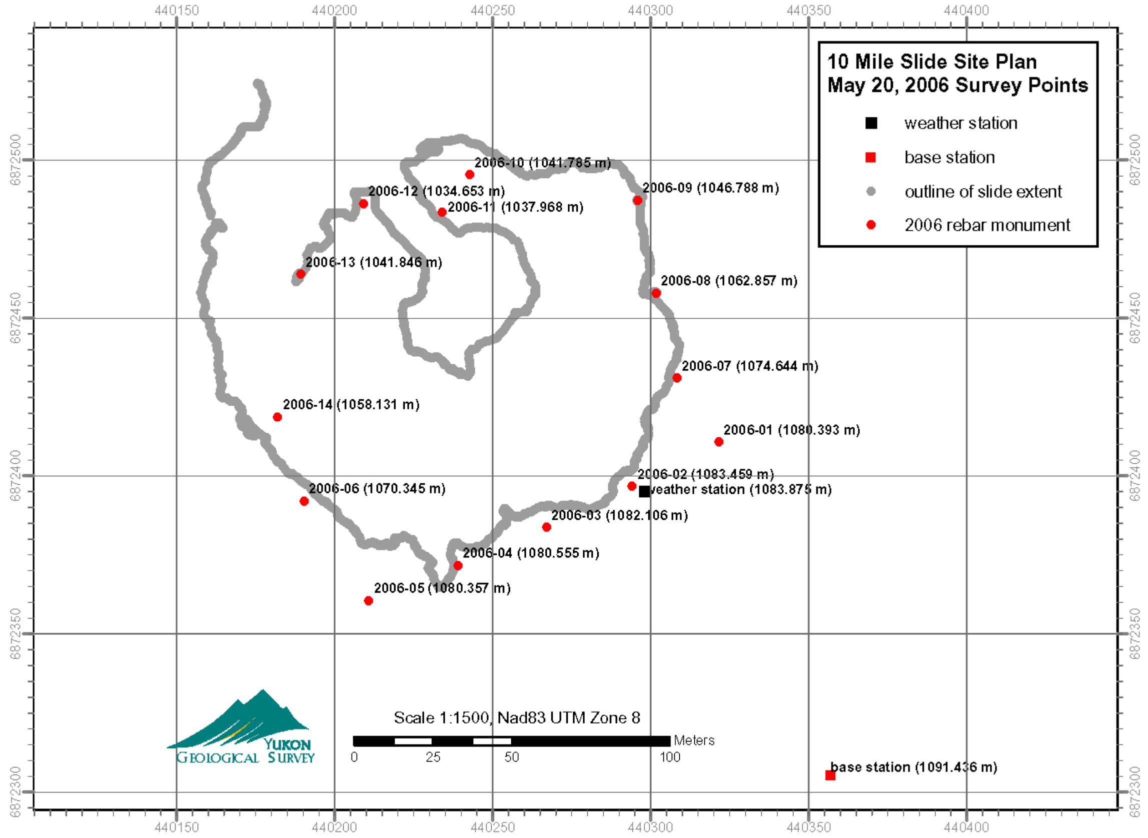


Figure 47 Locations of the survey monuments at 12-Mile Slope

4.2 SAR Imagery

The ENVISAT imagery that was programmed for acquisition (or purchased from the archive) to be used for InSAR processing is listed in Table 4 along with the prevailing weather conditions at the time of acquisition.

Table 4 SAR Acquisitions (25m resolution) for the 12-Mile Slope

Satellite	Beam Mode	Acquisition Date	Status	Weather
ENVISAT	IS1 – Descending Track 300 Frame 2349			Burwash
		2006-May-08	Purchased	11°C overcast
		2006-Jun-12	Purchased	20°C cloudy
		2006-Jul-17	Purchased	19°C cloudy
		2006-Aug-21	Purchased	20°C cloudy
		2006-Sep-25	Purchased	8°C cloudy

Table 5 is a list of the satellite image pairs that were determined to be suitable for InSAR processing. Note however, the perpendicular baseline of the August to September pair is above the critical baseline (approx. 1100m) for ENVISAT. This image pair was not processed and is included in the table for reference only.

Table 5 12-Mile Slope satellite image pairs

Satellite	Date	Satellite	Date	Interval (Days)	Perpendicular Baseline (m)
ENVISAT		ENVISAT			
	2006-May-08		2006-Jun-12	35	20
	2006-Jun-12		2006-Jul-17	35	714
	2006-Jul-17		2006-Aug-21	35	-8
	2006-Aug-21		2006-Sep-25	35	-1451

4.3 InSAR Coherence Maps

Figure 48 through 50 show the variation of the ENVISAT coherence at 12 Mile Slope. With the exception of the data pair for July to August, 2006 shown in Figure 49, it is unlikely that ground movement estimates can be derived from these image pairs using traditional interferometric techniques.

The causes of the very low coherence values are most likely due to major changes in soil moisture and/or large-magnitude ground displacements (large variations in the shape and texture of the soil surface) between satellite acquisitions. Indeed, patches of snow were still observed in the slide area in late May, and much of the floor of the bowl was highly saturated. Conversely, the ground surface moisture on subsequent visits in early June and late September was almost entirely dry.

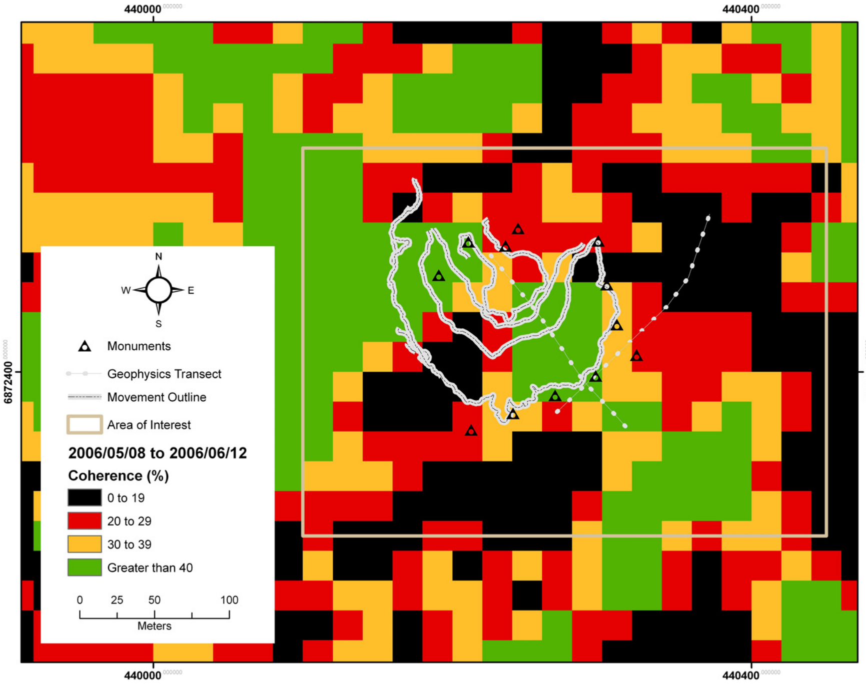


Figure 48 Coherence map derived from ENVISAT data for 12 Mile Slope (May 08 to June 12, 2006)

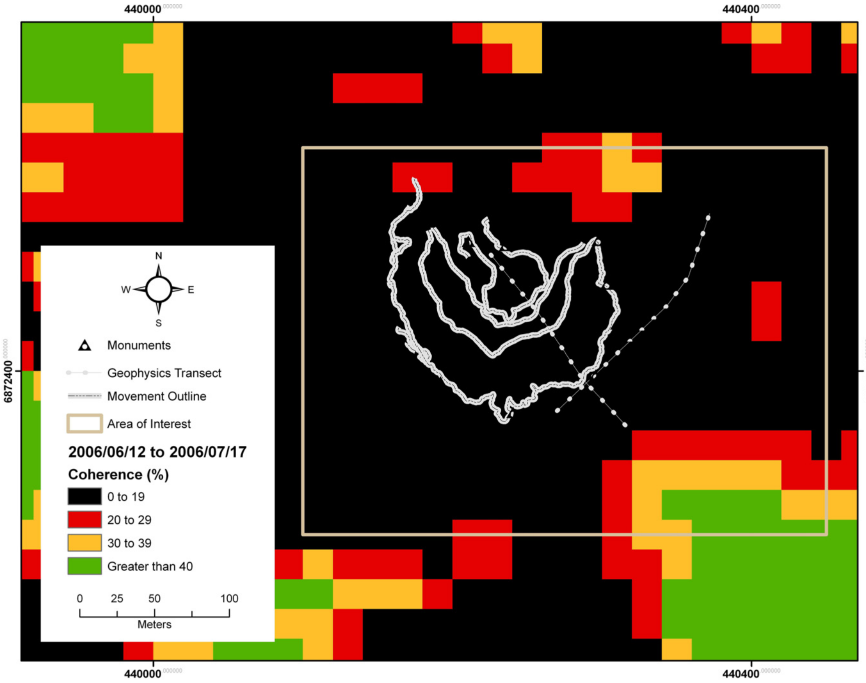


Figure 49 Coherence map derived from ENVISAT data for 12 Mile Slope (June 12 to July 17, 2006)

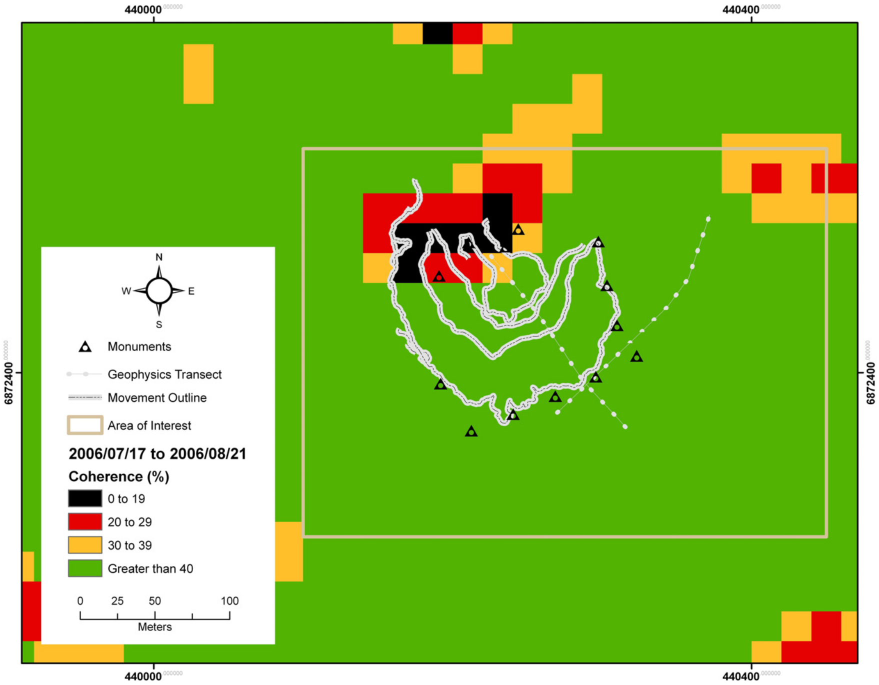


Figure 50 Coherence map derived from ENVISAT data for 12 Mile Slope (July 17 to August 21, 2006)

4.4 InSAR Movement Maps

Because of the low coherence levels attained for the May to June and the June to July timeframes movement maps were not generated for these timeframes. Figure 51 is the movement map derived for the July to August image pair. This movement map shows that there is no movement over the most of the slide area and very small amounts of heave in the range of 1 to 2 cm over the rest of the region of interest.

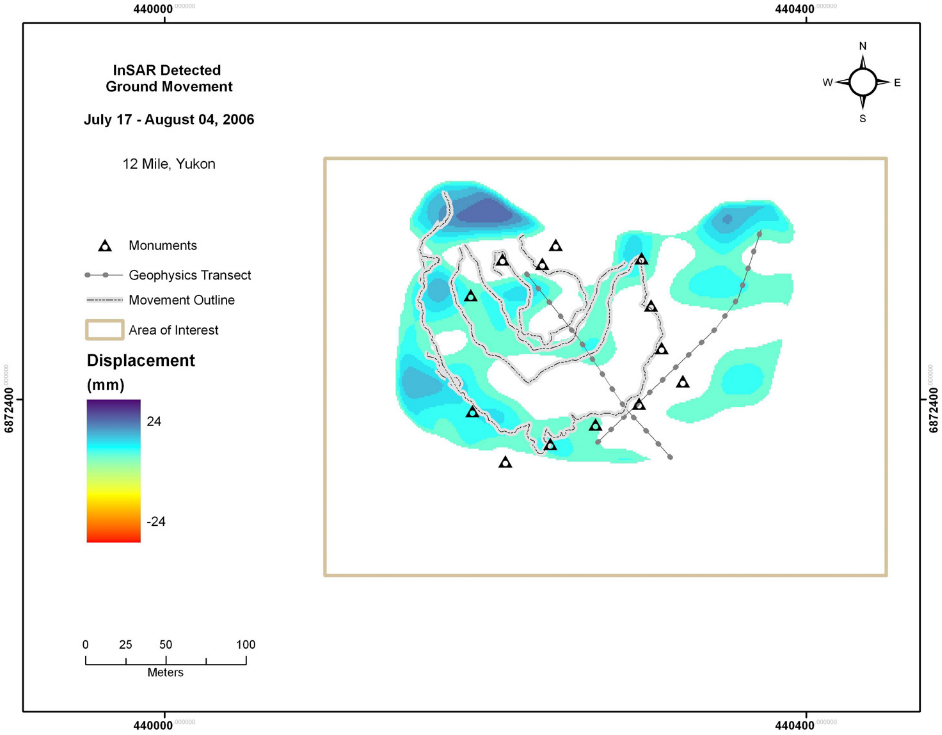


Figure 51 Movement map derived from ENVISAT data (July 26 to August 30, 2006)

4.5 Ground Survey Results

Figure 52 shows the results of the differential GPS surveys performed by the Yukon Geological Survey. The measurement error reported by the GPS was consistently much less than 1 cm in both the horizontal and vertical positions. However, the surveys indicated 1-3 cm of heaving at all monuments surrounding the rim of the headwall. It is extremely unlikely that heaving could occur at these locations during the summer months when the active-layer is thawing and the ground surface should be settling slightly. The effective margin of error is therefore interpreted to be closer to 3 cm, and the monuments along the rim of the headwall are inferred to have not moved significantly over the course of the summer. In the lower bowl of the slide source area, the GPS surveys did show lateral ground movements up to 53 cm horizontally and settling of up to 34 cm. These results seem reasonable given the mechanism of instability described previously for this site (ongoing settlement and shifting of slide debris).

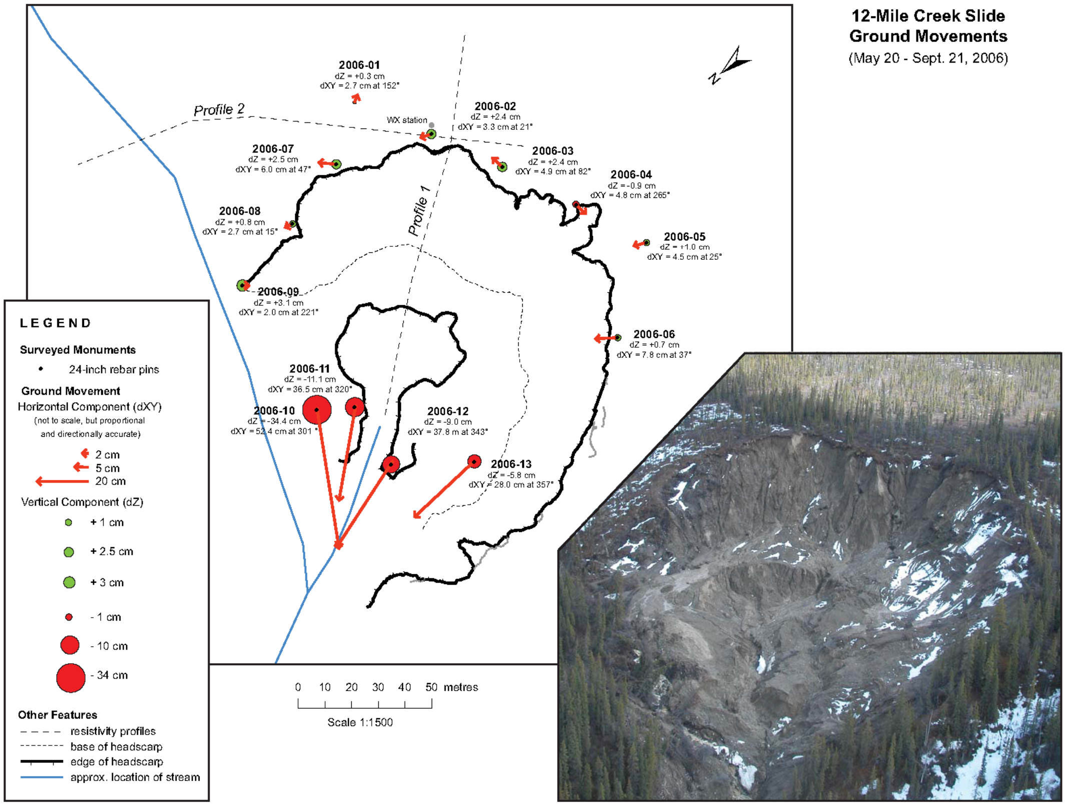


Figure 52 12 Mile Slope differential GPS survey — ground movement measurements

On June 1, 2006, geophysical (3-resistivity) surveys were performed by Dr. Bernd Etzelmüller from the University of Norway to determine the local permafrost configuration. Results from this survey suggest extremely spatially variable permafrost distribution with thicknesses ranging between 0-10 m along a transect immediately behind the headwall (Profile 2 in Figure 59). Along the same transect, the active-layer appeared to be between 2-5 m thick. A second transect running down the headwall (Profile 1 in Figure 59) suggested a complete lack of permafrost in the headwall, probably due to rapid lateral thaw inward from the headwall since the original slide occurred in 2002. These results, however, can only be considered preliminary without calibration from a borehole (Etzelmüller, 2006).

4.6 Validation

A rigorous validation of the InSAR derived ground movement results to the YGS survey data was not attempted. This was partially due to the fact that only the July to August, 2006 dataset showed sufficient coherence to attempt the creation of a movement map.

However, it is worth noting that the only significant motion indicated by the GPS surveys between May and September occurred in the form of subsidence and translation in the lower portion of the bowl, in the northern part of the landslide source zone.

The InSAR results for July to August, 2006 reflect the YGS survey results. The perimeter of the slope area is characterized by movement values on the order of 1 to 2 cm of heave, which is consistent with the YGS survey. However, as stated above, any heaving motion in the summer months at these locations is highly unlikely, and it is interpreted that no upward displacement could have actually occurred, so movements of 1-2 cm may represent the error margin of this technique at this site. The more significant subsidence indicated by the GPS surveys within the "bowl" of the slide was not captured by the InSAR. Note that the InSAR coherence map showed good coherence within the bowl of the slide for the July 17 to August 4 time period and thus one would expect that the movement data coming from that area is reliable. Indeed, the Beaver Creek site also showed good coherence for the same time period. Therefore, it is speculated that the significant movement events within the slope bowl occurred outside the time interval of this InSAR pair (and probably prior). Unfortunately, the survey data are not available to support this theory.

Overall, given that the significant movement within the slope likely occurred earlier in the season when the soil moisture was higher and coherence was poor, InSAR does not appear to be suitable for measuring this type of slide. In addition, the large magnitude of the translational movements indicated by the GPS surveys is probably outside the detection limits for InSAR for the same reasons described for the Beaver Creek 1 site. However, the poor InSAR coherence in the early summer could possibly be used as a qualitative indicator of these larger ground movements. On the other hand, InSAR does appear to be suitable for measuring smaller movement (on the order of 10 cm per year) so could be applied to slides with this level of movement. This is the same conclusion that was reached for Beaver Creek Site 1.

5 LITTLE SALMON LAKE AND MAGUNDY RIVER

5.1 Installation of Survey Monuments

The Yukon Geological Survey installed 13 rebar monuments at various locations throughout the movement areas at both the Little Salmon Lake and Magundy River slides. Due to access difficulties and logistical constraints, reflectors could not be installed at either site. The sites were visited on May 21, 2006 and surveyed on June 22 and June 23 using the Thales ProMark 3 differential GPS system. The locations of the rebar monuments for Magundy River are shown in Figure 53, while the locations for Little Salmon Lake are shown in Figure 61. A second survey was completed at both sites on September 27 and September 28, 2006. The results of these surveys are included in Section 5.5.

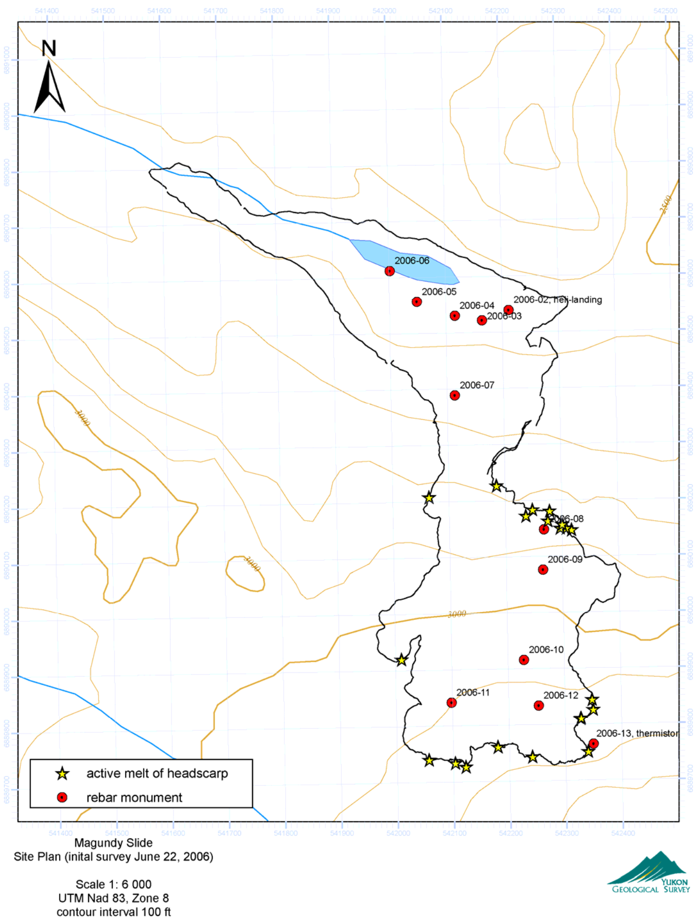


Figure 53 Approximate outline of source zone and west debris fan at the Magundy Slide. Locations of the survey monuments are shown, as well as active thawing zones noted along the headscarp on June 22. The larger east debris fan is not shown as it was not included in the survey due to relative inactivity.

5.2 SAR Imagery

The ENVISAT imagery that was programmed for acquisition (or purchased from the archive) to be used for InSAR processing is listed in Table 6 along with the prevailing weather conditions at the time of acquisition.

Table 6 SAR acquisitions (25m resolution) for the Magundy River and Little Salmon Lake Slides

Satellite	Beam Mode	Acquisition Date	Status	Weather
ENVISAT	IS2 – Descending Track 349 Frame 2349			Burwash
		2006-May-05	Purchased	9°C unknown
		2006-Jun-09	Purchased	23°C cloudy
		2006-Jul-14	Purchased	19°C thunderstorm
		2006-Aug-18	Purchased	14°C cloudy
		2006-Sep-22	Purchased	14°C cloudy

Table 7 is a list of the satellite image pairs that were determined to be suitable for InSAR processing. However, the perpendicular baseline of the August to September pair is above the critical baseline (approx. 1100m) for ENVISAT. This image pair was not processed and is included in the table for reference only. Also noteworthy were the weather conditions (thunderstorm) experienced on July 14 which may have negatively affected the coherence values of InSAR pairs generated with this image.

Table 7 Little Salmon Lake and Magundy River satellite image pairs

Satellite	Date	Satellite	Date	Interval (Days)	Perpendicular Baseline (m)
ENVISAT		ENVISAT			
	2006-May-05		2006-Jun-09	35	-211
	2006-Jun-09		2006-Jul-14	35	879
	2006-Jul-14		2006-Aug-18	35	41
	2006-Aug-18		2006-Sep-22	35	-1644

5.3 InSAR Coherence Maps

Figure 54 through 56 show the variation of the ENVISAT coherence at Little Salmon Lake. These figures show poor coherence over the majority of the slide area, suggesting that ground movement estimates will be difficult or impossible to derive using traditional interferometric techniques.

The possible cause of the very low coherence values is most likely due to the vegetation and the large amount of ground movement.

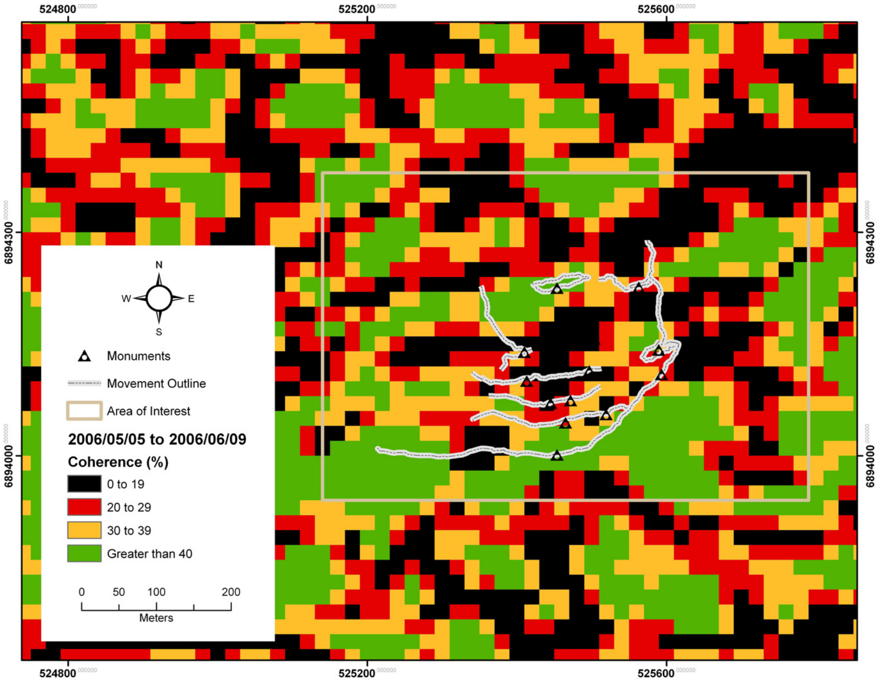


Figure 54 Coherence map derived from ENVISAT data for Little Salmon Lake (May 05 to June 09, 2006)

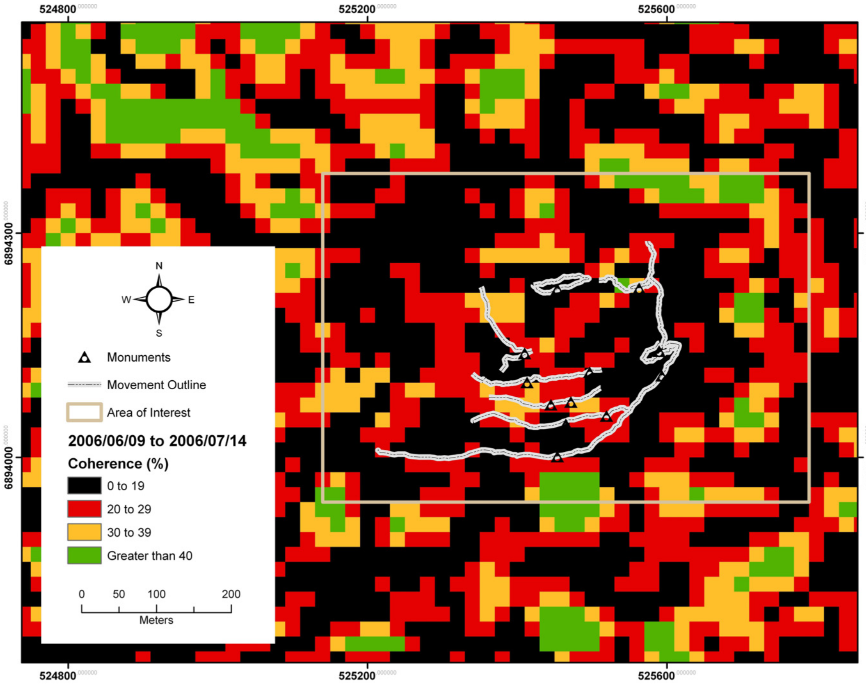


Figure 55 Coherence map derived from ENVISAT data for Little Salmon Lake (June 09 to July 14, 2006)

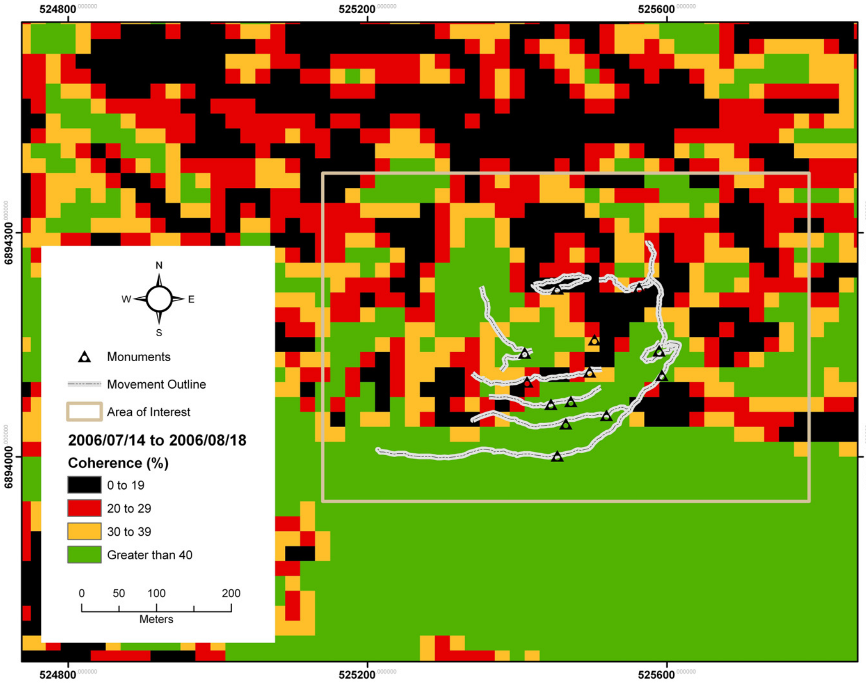


Figure 56 Coherence map derived from ENVISAT data for Little Salmon Lake (July 14 to August 18, 2006)

Figure 57 through 59 show the variation of the ENVISAT coherence at Magundy River. With the exception of Figure 59, these figures also show poor coherence over the majority of the slide area, suggesting again that ground movement estimates will be difficult or impossible to derive using traditional interferometric techniques.

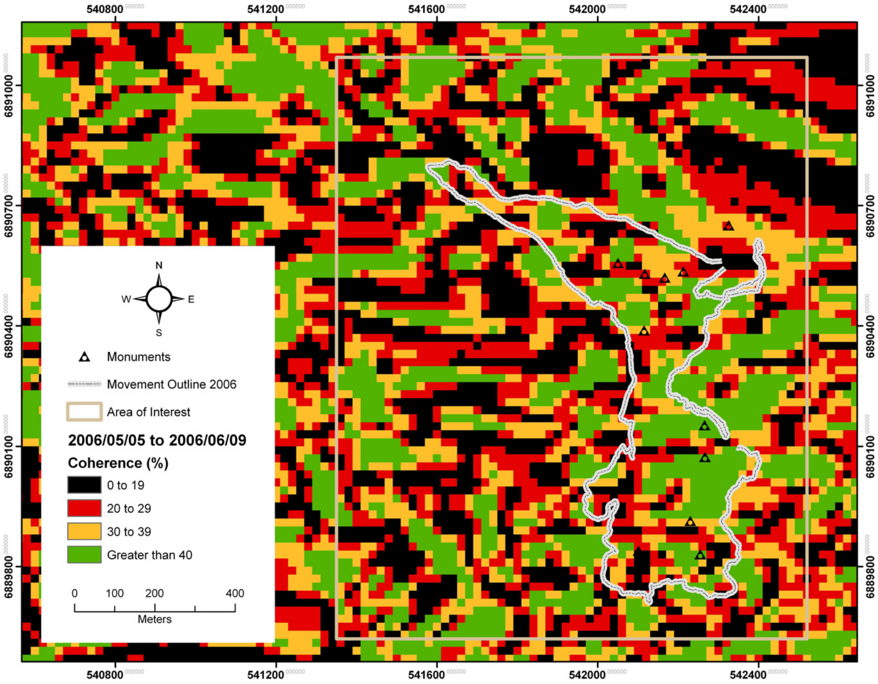


Figure 57 Coherence map derived from ENVISAT data for Magundy River (May 05 to June 09, 2006)

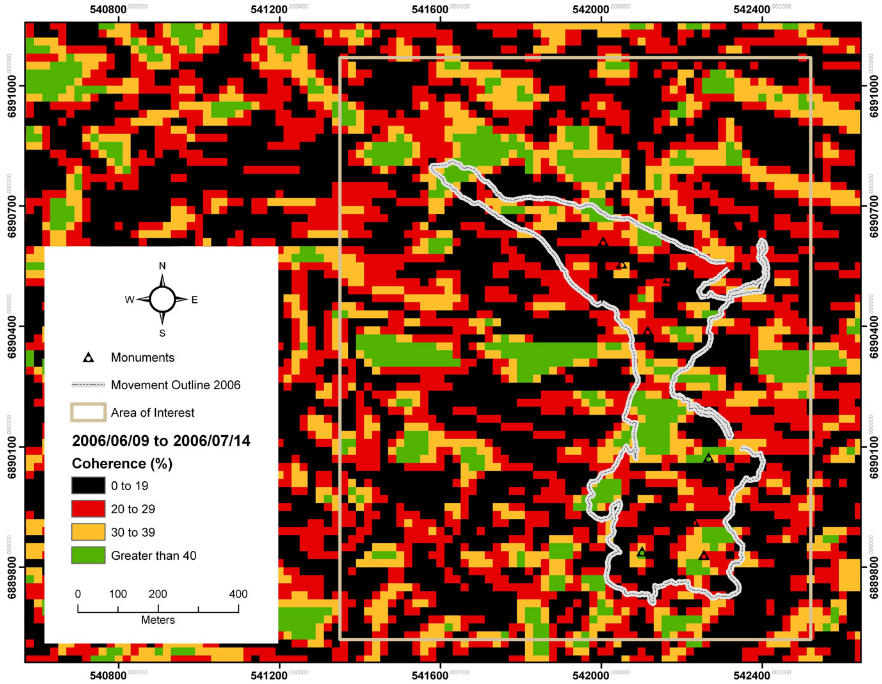


Figure 58 Coherence map derived from ENVISAT data for Magundy River (June 09 to July 14, 2006)

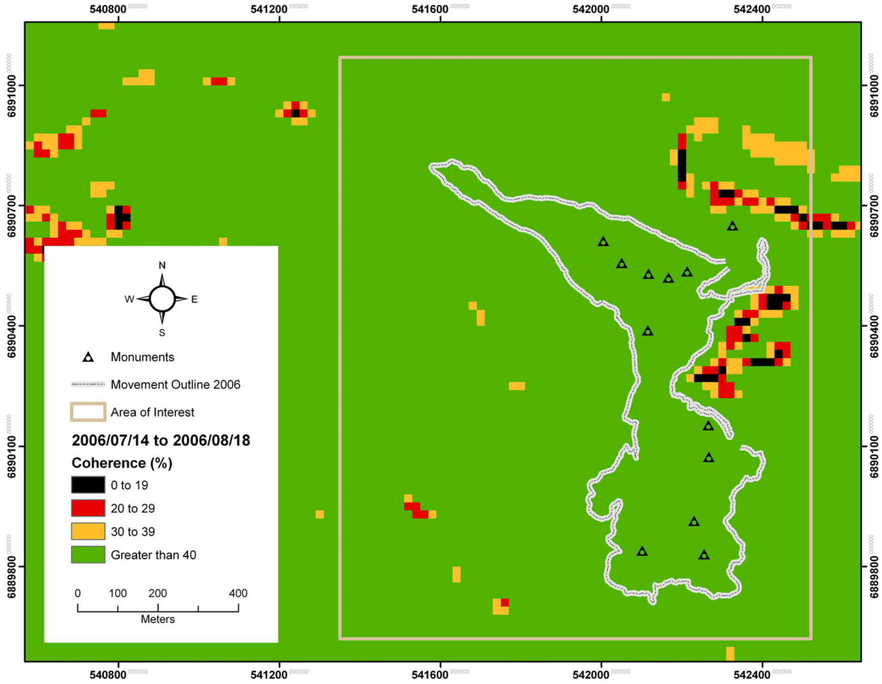


Figure 59 Coherence map derived from ENVISAT data for Magundy River (July 14 to August 18, 2006)

5.4 InSAR Movement Maps

Unfortunately, movement maps could not be generated for the Little Salmon Lake slide because of the low coherence levels attained for all image pairs.

For the Magundy River slide, movement maps were not generated for the May to June and the June to July image pairs also because of low coherence levels during those timeframes. Figure 60 is the movement map derived for the July to August image pair. The coherence for this pair was good, so the data should be quite reliable. This time period is also consistent with the periods where good coherence was attained for the Beaver Creek and 12 Mile Slope sites.

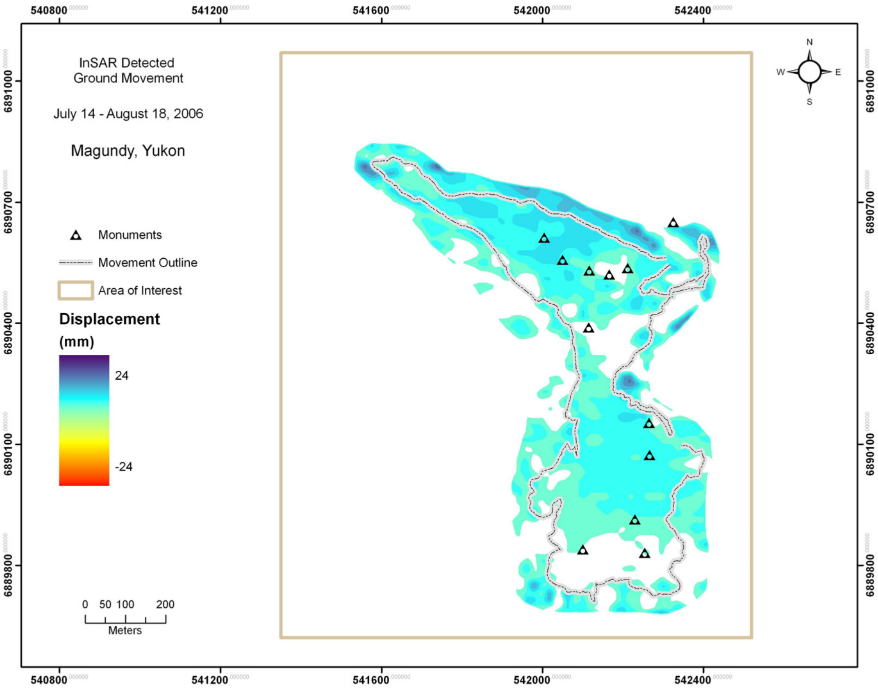


Figure 60 Movement map derived from ENVISAT data (July 14 to August 18, 2006)

5.5 Ground Survey Results

Figure 61 shows the differential GPS survey results at the Little Salmon Lake site. The reported measurement error was generally less than or equal to 0.5 cm. However, in several instances during the June survey, errors were between 2 and 10 cm. Difficulties anchoring some monuments in loose gravelly materials also introduced significant errors, as several monuments became tilted over the course of the summer.

Nonetheless, the most significant survey results indicate that the low scarp dropped up to 33 cm in elevation, and moved 92 cm horizontally toward the lake over the course of the summer of 2006. The main scarp, low scarp and that portion of the slide immediately below the low scarp seem to have been most active throughout the summer. At site 2006-11 (solid green circle) on the west flank, the elevation increased by 39 cm, indicating that rotational tilting of that portion of the slope likely occurred toward the west.

In addition, a tree located immediately above the top scarp (near the middle of the slide) had split open over the course of the summer, indicating at least 17 cm of horizontal movement toward the lake.

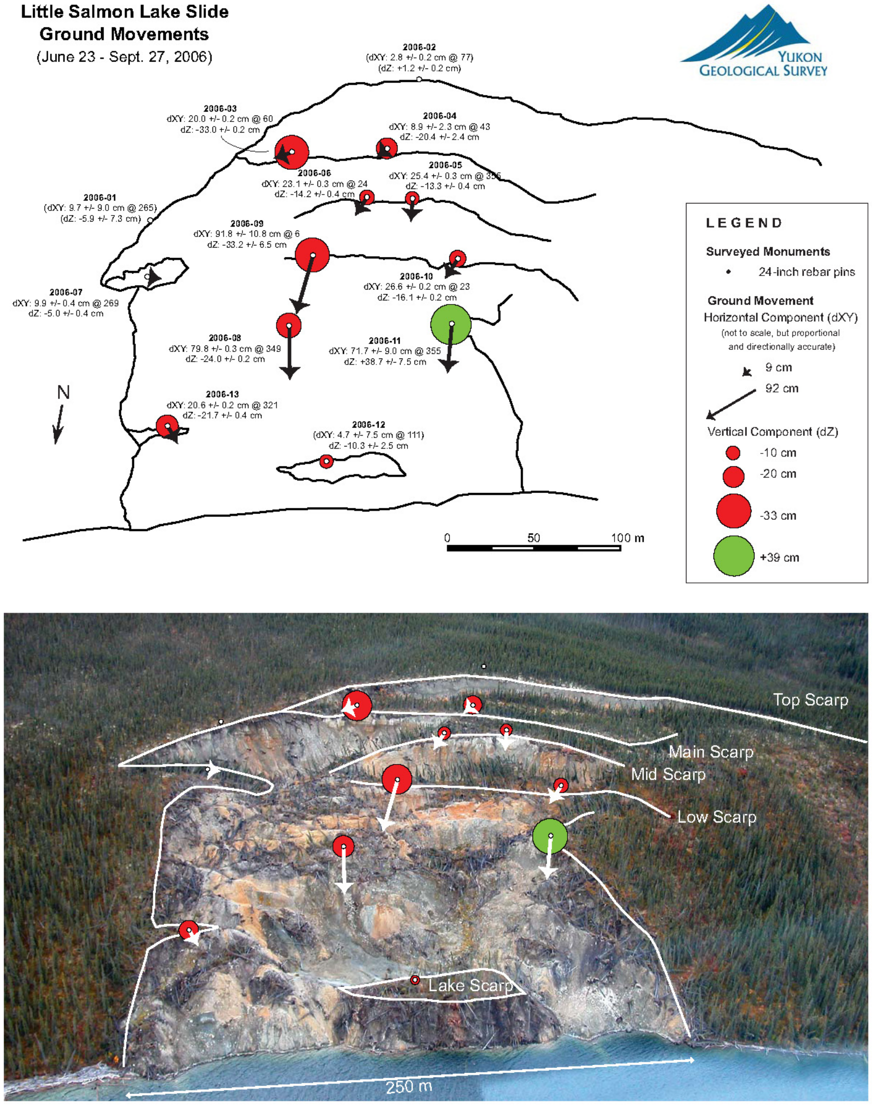


Figure 61 Little Salmon Lake differential GPS survey — ground movement measurements

Figure 62 shows the Magundy slide. Unfortunately the differential GPS results were disappointing at this site. This may have been due to poor satellite geometry during the measurements, or poor geometry of the site with respect to the satellite configurations. The positional errors varied between 0.1 and 15 cm in the horizontal; and 0 to 8 cm (with one at 30 cm) in the vertical. Only 5 of the 10 rebar monitoring pins showed a change in position over the summer that was significantly greater than the error reported by the

GPS. Of these, 3 (2006-10, 11 and 12) showed that the pins had moved uphill, which seems unlikely, so no positive results can be gained from these surveys.

The greatest amount of activity at the Magundy Slide occurred along the north scarp shown in Figure 62. A 125-m segment of this scarp retreated between 8-12 m during the summer of 2006. Thawed debris from this activity was deposited by mudflows concentrated in the area outlined in pink in Figure 62. Smaller amounts of headscarp retreat also occurred along the sections of the source zone indicated by the remaining yellow lines in Figure 62. Very little debris was transported onto either the west or east fans, so little change in the ground surface would be expected in those zones.

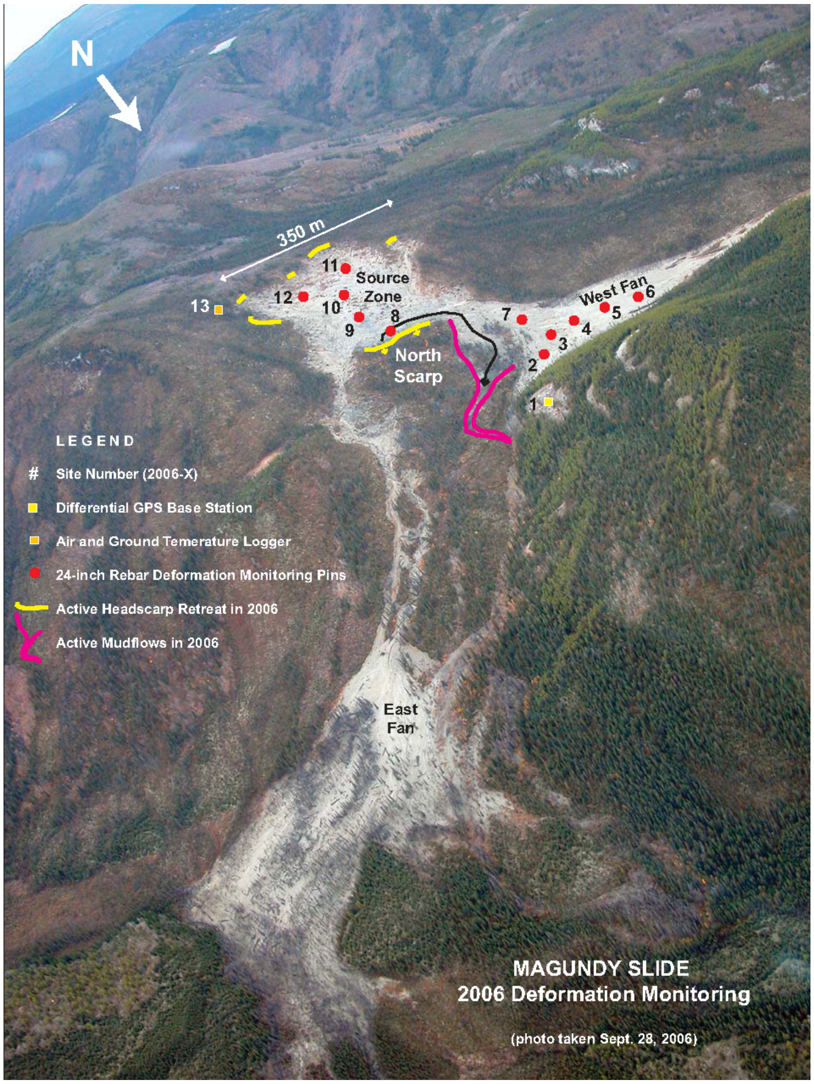


Figure 62 Deformation monitoring at the Magundy River Slide in 2006 (note that the horizon is rotated about 45° counter clockwise in this image)

5.6 Validation

No attempt was made to validate the Little Salmon Lake and the Magundy River InSAR results to the GPS measurements, because of the large positional errors associated with the GPS survey results and the poor coherence of the satellite imagery.

6 LINK WITH TRADITIONAL GEOHAZARD ASSESSMENT METHODS

6.1 Terrain Analysis and Interpretation

Airphoto interpretation is the main tool and technique used in terrain analysis. From airphotos, and to an extent satellite images, natural and built landscapes can be identified using a combination of training, background knowledge and experience in recognizing landforms, and therefore their origin and composition from indicator clues. This identification provides information necessary to infer properties and conditions e.g., wet/dry, soft/hard, frozen/unfrozen of soil and rock materials on and below the ground surface. This operation is possible because recognized landforms are genetic products of geological, geotechnical and hydrological processes and environments that are known and understood and can therefore be described once identified and named e.g., rock slide, debris flow, sand dune, esker ridge, pingo thermokarst pond, etc.

Airphoto mosaics of various kinds and degrees of accuracy are assembled by matching identified points on overlapping vertical airphotos taken from different camera positions. Mosaics are useful because most contact airphotos cover a small area and used alone do not show the regional distribution of terrain types and conditions whose mapping and evaluation are required by study objectives.

Interpretation and terrain analysis using airphoto techniques are supported with information from procurable relevant maps, literature sources, networking and fieldwork as well as from expertise in computer-based geospatial mapping of natural and built landscapes, geodata integration, digital modeling and GIS management.

Interpretation of the earth’s processes, landforms, materials and their properties calls for the integration of these techniques as illustrated in Figure 63. The various sources of information allow the most or least desirable terrain types for a particular development scenario to be recognized, outlined and avoided where practical. Selection of proposed highway, pipeline or transmission line corridors are evaluated in the context of natural and cultural features that affect project objectives, costs and environmental and social constraints.

The performance of field work is usually required to confirm interpretation from airphoto or other remote sensing application in a cost effective manner. This is achieved by directing field staff to the most rewarding information sites or critical problem locations based on experience and understanding of the interpretation of the airphoto imagery.

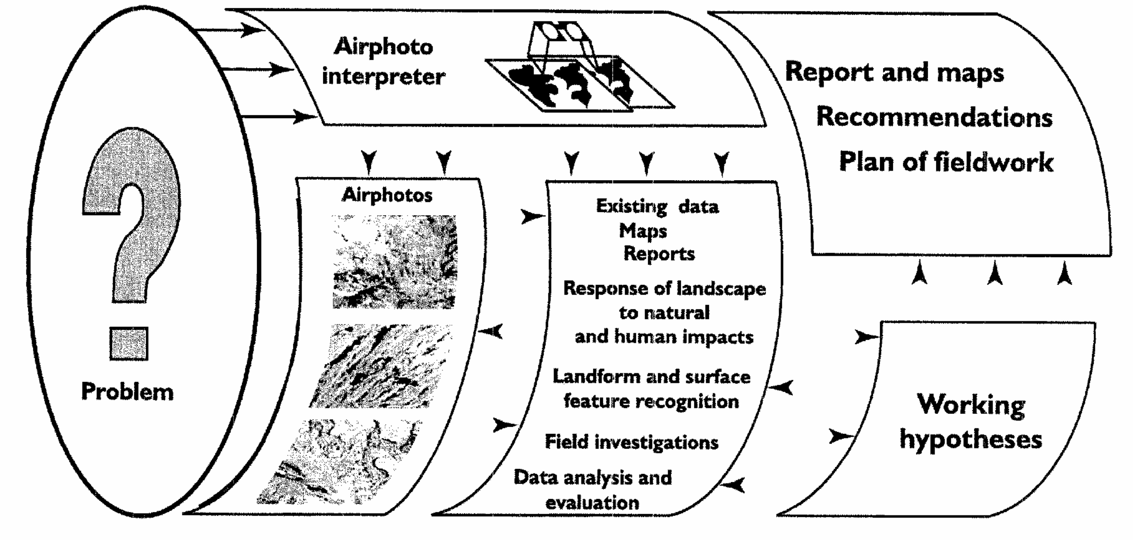


Figure 63 Schematic of interrelated photo-interpretation and filed studies in terrain analysis

Key issues to be considered when undertaking terrain analysis to map and evaluate depositional landforms include:

- The geomorphic process that created the landform under observation;
- The landscape-modifying processes such as weathering, erosion and human activity to alter its appearance;
- The environment of deposition;
- Potential sorting and stratification by water or wind, or non-sorted material deposited directly by glacier ice;
- Variability of material composition and properties within the outlined area;
- The properties of the landform material – coarse or fine grained material, plastic or non-plastic, permeability;
- The ground water table elevation relative to the surface, and its seasonal fluctuation;
- The thickness of sub-surface material, and its degree of saturation;
- The relative elevation of the landform compared to neighbouring areas, such that it sheds or receives surface water run-off;
- The presence of perennial or seasonal frost, and the material's susceptibility to thaw settlement or frost heave action;

- The organic matter of the surface material;

6.2 Arctic and Sub-Arctic Terrain Features

Arctic and sub-Arctic regions are made up of various micro and macro-landforms, which are mainly the result of the cold climate and/or drainage or water conditions that are the result of the presence of permafrost (ground that has remained frozen for two or more consecutive years). Processes involved in the formation of these features include mass-wasting, frost action, thawing and erosion. These features are usually indicative of troublesome conditions that would be a concern to potential development. Features may be restricted to the seasonally frozen active layer, or may be more deep-seated through degradation or aggradation of permafrost. A number of the terrain features that are specific to northern permafrost regions include:

- Patterned ground (Figure 64) – demonstrating features such as circles, polygons, nets, steps and stripes which usually signify ground movement in the active layer as a result of processes such as frost creep, solifluction, thermal cracking or vegetation growth. Ice wedge polygons also result in patterns as a result of contraction cracking due to extremely low winter temperatures, with the resulting vertical cracks infilled with snow melt water which subsequently freezes, forming large wedge-shaped ice masses. The net effect of movements associated with patterned ground within the active layer is gradual movement of material downslope.
- Slope instability and movement (Figure 65) – usually occurs during thawing of frozen ground, when water pressure and lack of drainage result in soil strengths that are lower than the gravitational driving forces. A land-slide classification system has been developed for slope movements in permafrost regions as shown in Figure 66. Flows generally refer to viscous fluid characteristics during downslope movement with associated rapid movements, whereas slides involve blocks of relatively solid soil sliding along a shear plane. Falls tend to involve toppling motions of soil blocks. Each of these slope movement types results in characteristic features that can be used to identify the likely failure mechanism.
- Thermokarst (Figure 67) – this describes topographic depressions resulting from thawing ground ice, which can occur as a function of warming climate, disturbance or removal of insulating vegetation or ponding of water at the ground surface. Thermokarst topography is uneven and is usually seen in the form of thaw lakes, sinkholes or beaded streams.

- Pingos, palsas and Peat Plateaus (Figures 68 and 69) – Pingos are large ice-cored mounds formed by water under pressure from the ground, which freezes as a function of proximity to colder air temperatures or perennially frozen ground. Palsas and peat plateaus result from aggradation of permafrost into organic soils such that a high ice content raises their surface above the surrounding terrain.

Figure 64 Patterned ground in permafrost terrain

Figure 65 Slope instability (block failure) in permafrost terrain

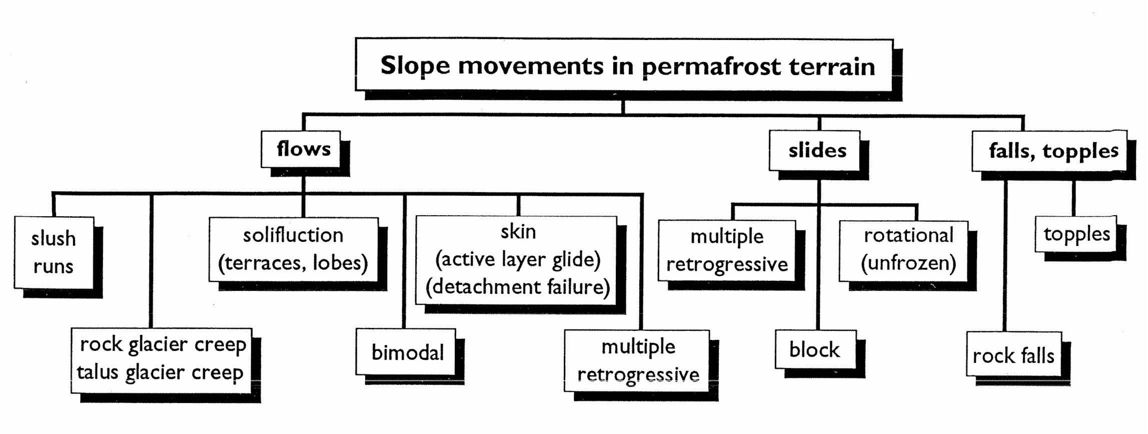


Figure 66 Land-slide classification in permafrost terrain

Figure 67 Thermokarst lakes in permafrost terrain

Figure 68 Pingo formations in permafrost terrain

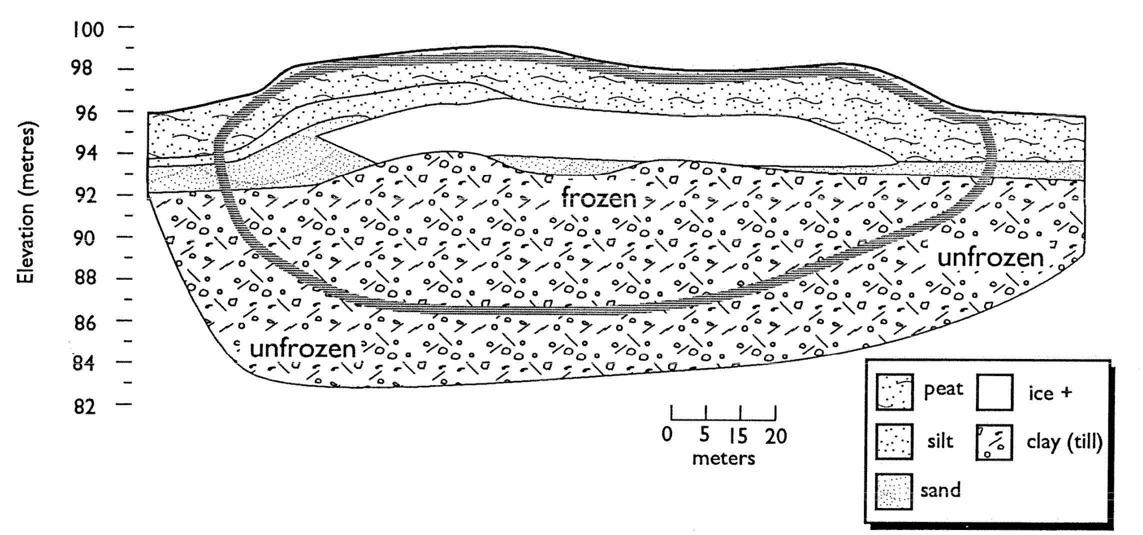


Figure 69 Cross-section through peat plateau in permafrost terrain

Each of these features can be considered as a geohazard in terms of potential instability and large scale ground movement when equilibrium conditions are disturbed. Identification of such features, and an understanding of associated movement mechanisms are critical to providing the required level of continued monitoring and mitigation for existing and proposed developments in these regions.

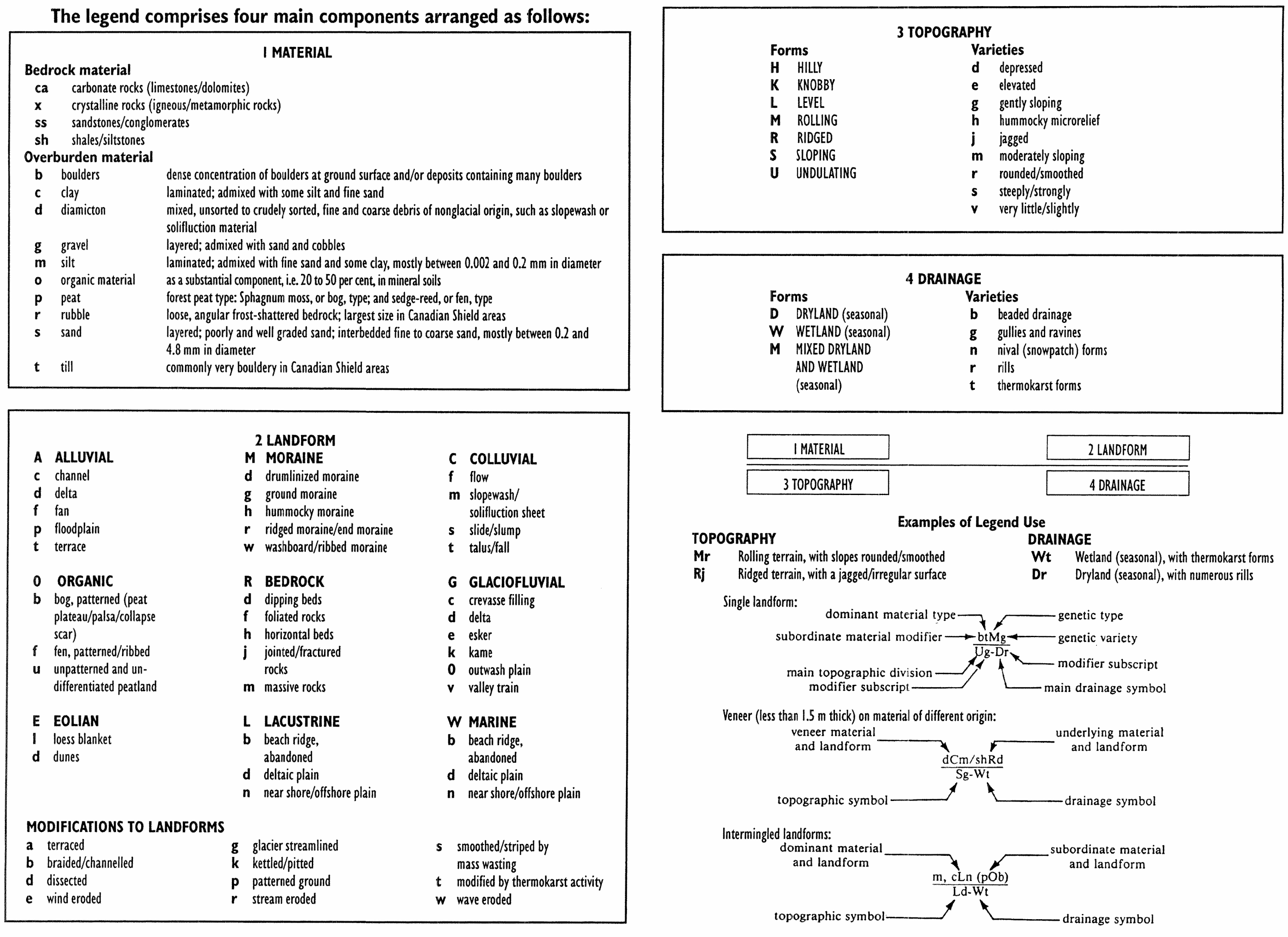
The use of standard identifying characteristics is key to communicating the results of the terrain analysis, as shown by the terrain legend shown in Figure 70 for Canada's Arctic and sub-Arctic regions. A typical map derived from terrain analysis in a northern location containing permafrost is presented in Figures 71 and 72 (provided by the Geological Survey of Canada) for portions of the Mackenzie Valley in North-West Territories, Canada. These figures demonstrate the effectiveness of combined remote and ground-based methods in identifying landforms and potential geohazards.

6.3 Recommendations for Application of InSAR Monitoring

The use of traditional forms of terrain analysis using remote and field measurement systems allows specific features and landforms to be identified, and their potential impact on infrastructure quantified. In many cases, proposed development routing studies allow the greatest risks to be avoided; however, many geohazards cannot be eliminated from design and mitigation strategies must be developed.

One approach is to undertake a monitoring program of specific geohazards, such that any destabilization that results in increased risk to development facilities is observed prior to causing significant disruption. Many of the landforms discussed above react relatively slowly to changes in equilibrium conditions and are suitable for long term monitoring programs. Movements are generally seasonal as ground thaws during spring, and result in a cumulative displacement field year-to-year. Such gradual movement, particularly if it has a vertical component, is likely to be suitable for InSAR monitoring.

The findings of this study support this hypothesis. In particular, gradual movement over relatively flat terrain was shown qualitatively to be measurable with InSAR. The technique is also suitable for slope stability monitoring if movement is either creeping or moderate movement (say <10cm/year). On the other hand, this study demonstrated that significant ground motion along steep slopes, particularly if most of the movement occurred over a short time period, could cause the movement to be under sampled by the SAR sensor, leading to an underestimation of ground movement. In this case, InSAR is unsuitable for monitoring those types of geohazards, such as fast moving translational or debris slides with movements on the order of many 10s of centimeters per year.



The legend comprises four main components arranged as follows:

1 MATERIAL

Bedrock material

ca	carbonate rocks (limestones/dolomites)
x	crystalline rocks (igneous/metamorphic rocks)
ss	sandstones/conglomerates
sh	shales/siltstones

Overburden material

b	boulders	dense concentration of boulders at ground surface and/or deposits containing many boulders
c	clay	laminated; admixed with some silt and fine sand
d	diamicton	mixed, unsorted to crudely sorted, fine and coarse debris of nonglacial origin, such as slopewash or solifluction material
g	gravel	layered; admixed with sand and cobbles
m	silt	laminated; admixed with fine sand and some clay, mostly between 0.002 and 0.2 mm in diameter
o	organic material	as a substantial component, i.e. 20 to 50 per cent, in mineral soils
p	peat	forest peat type: Sphagnum moss, or bog, type; and sedge-reed, or fen, type
r	rubble	loose, angular frost-shattered bedrock; largest size in Canadian Shield areas
s	sand	layered; poorly and well graded sand; interbedded fine to coarse sand, mostly between 0.2 and 4.8 mm in diameter
t	till	commonly very bouldery in Canadian Shield areas

2 LANDFORM

A ALLUVIAL
- c channel
- d delta
- f fan
- p floodplain
- t terrace

O ORGANIC
- b bog, patterned (peat plateau/palsa/collapse scar)
- f fen, patterned/ribbed
- u unpatterned and undifferentiated peatland

E EOLIAN
- l loess blanket
- d dunes

M MORAINE
- d drumlinized moraine
- g ground moraine
- h hummocky moraine
- r ridged moraine/end moraine
- w washboard/ribbed moraine

R BEDROCK
- d dipping beds
- f foliated rocks
- h horizontal beds
- j jointed/fractured rocks
- m massive rocks

L LACUSTRINE
- b beach ridge, abandoned
- d deltaic plain
- n near shore/offshore plain

C COLLUVIAL
- f flow
- m slopewash/solifluction sheet
- s slide/slump
- t talus/fall

G GLACIOFLUVIAL
- c crevasse filling
- d delta
- e esker
- k kame
- 0 outwash plain
- v valley train

W MARINE
- b beach ridge, abandoned
- d deltaic plain
- n near shore/offshore plain

MODIFICATIONS TO LANDFORMS
- a terraced
- b braided/channelled
- d dissected
- e wind eroded
- g glacier streamlined
- k kettled/pitted
- p patterned ground
- r stream eroded
- s smoothed/striped by mass wasting
- t modified by thermokarst activity
- w wave eroded

3 TOPOGRAPHY

Forms		Varieties	
H	HILLY	d	depressed
K	KNOBBY	e	elevated
L	LEVEL	g	gently sloping
M	ROLLING	h	hummocky microrelief
R	RIDGED	j	jagged
S	SLOPING	m	moderately sloping
U	UNDULATING	r	rounded/smoothed
		s	steeply/strongly
		v	very little/slightly

4 DRAINAGE

Forms		Varieties	
D	DRYLAND (seasonal)	b	beaded drainage
W	WETLAND (seasonal)	g	gullies and ravines
M	MIXED DRYLAND AND WETLAND (seasonal)	n	nival (snowpatch) forms
		r	rills
		t	thermokarst forms

$$\frac{\boxed{\text{1 MATERIAL}}\qquad\boxed{\text{2 LANDFORM}}}{\boxed{\text{3 TOPOGRAPHY}}\qquad\boxed{\text{4 DRAINAGE}}}$$

Examples of Legend Use

TOPOGRAPHY
- **Mr** Rolling terrain, with slopes rounded/smoothed
- **Rj** Ridged terrain, with a jagged/irregular surface

DRAINAGE
- **Wt** Wetland (seasonal), with thermokarst forms
- **Dr** Dryland (seasonal), with numerous rills

Single landform:

$$\frac{\text{btMg}}{\text{Ug-Dr}}$$

Veneer (less than 1.5 m thick) on material of different origin:

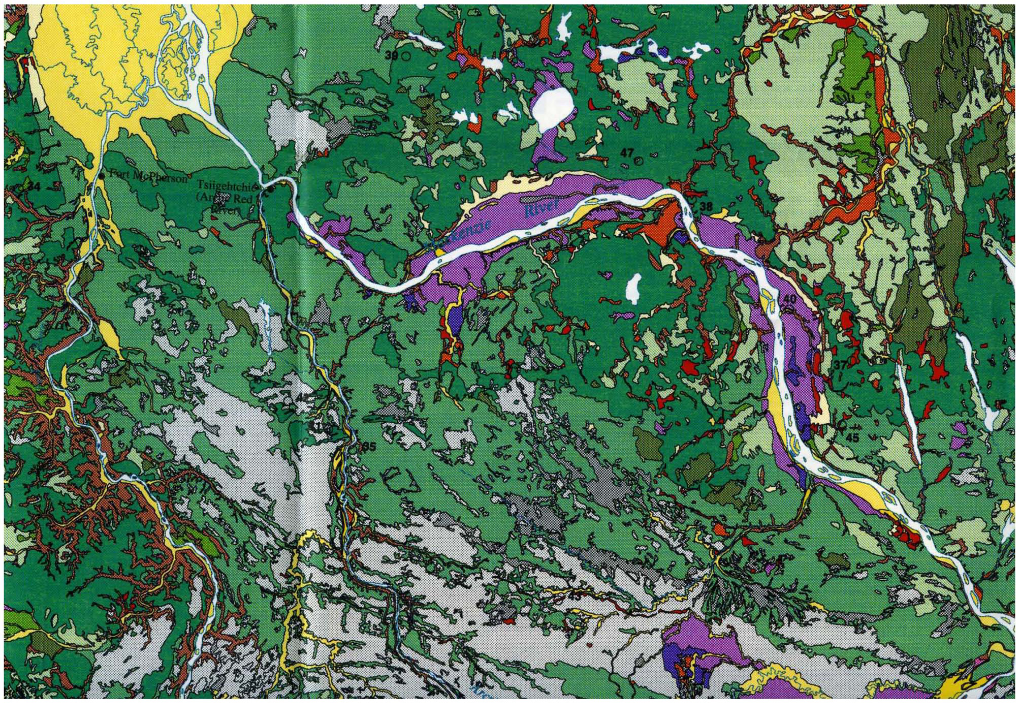
$$\frac{\text{dCm/shRd}}{\text{Sg-Wt}}$$

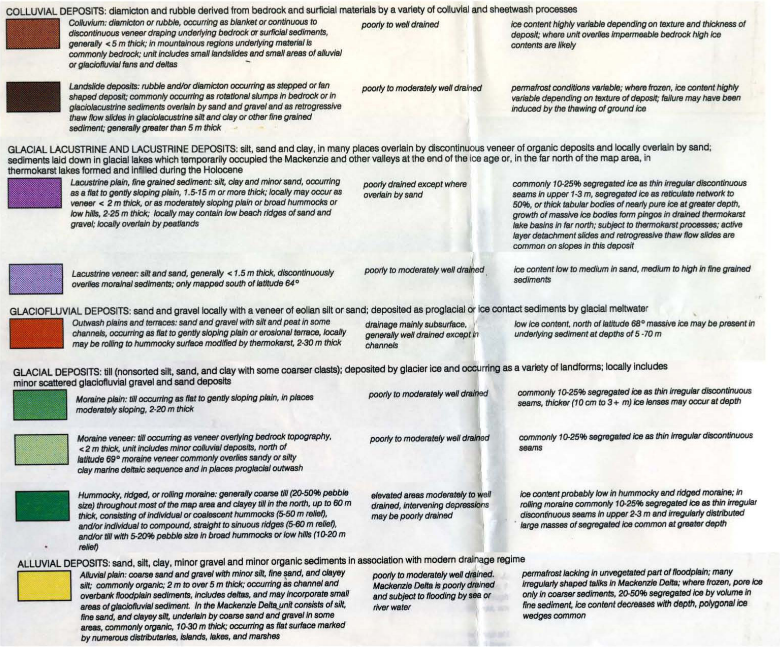
Intermingled landforms:

$$\frac{\text{m, cLn (pOb)}}{\text{Ld-Wt}}$$

Fig. 2-18: Terrain legend for road, pipeline, and transmission line route location and evaluation in Canada's arctic and subarctic.

Figure 70 Terrain legend for terrain analysis in Canada's Arctic and sub-Arctic regions





COLLUVIAL DEPOSITS: diamicton and rubble derived from bedrock and surficial materials by a variety of colluvial and sheetwash processes

🟫	Colluvium: diamicton or rubble, occurring as blanket or continuous to discontinuous veneer draping underlying bedrock or surficial sediments, generally < 5 m thick; in mountainous regions underlying material is commonly bedrock; unit includes small landslides and small areas of alluvial or glaciofluvial fans and deltas	poorly to well drained	ice content highly variable depending on texture and thickness of deposit; where unit overlies impermeable bedrock high ice contents are likely
🟫	Landslide deposits: rubble and/or diamicton occurring as stepped or fan shaped deposit; commonly occurring as rotational slumps in bedrock or in glaciolacustrine sediments overlain by sand and gravel and as retrogressive thaw flow slides in glaciolacustrine silt and clay or other fine grained sediment; generally greater than 5 m thick	poorly to moderately well drained	permafrost conditions variable; where frozen, ice content highly variable depending on texture of deposit; failure may have been induced by the thawing of ground ice

GLACIAL LACUSTRINE AND LACUSTRINE DEPOSITS: silt, sand and clay, in many places overlain by discontinuous veneer of organic deposits and locally overlain by sand; sediments laid down in glacial lakes which temporarily occupied the Mackenzie and other valleys at the end of the ice age or, in the far north of the map area, in thermokarst lakes formed and infilled during the Holocene

🟪	Lacustrine plain, fine grained sediment: silt, clay and minor sand, occurring as a flat to gently sloping plain, 1.5-15 m or more thick; locally may occur as veneer < 2 m thick, or as moderately sloping plain or broad hummocks or low hills, 2-25 m thick; locally may contain low beach ridges of sand and gravel; locally overlain by peatlands	poorly drained except where overlain by sand	commonly 10-25% segregated ice as thin irregular discontinuous seams in upper 1-3 m, segregated ice as reticulate network to 50%, or thick tabular bodies of nearly pure ice at greater depth, growth of massive ice bodies form pingos in drained thermokarst lake basins in far north; subject to thermokarst processes; active layer detachment slides and retrogressive thaw flow slides are common on slopes in this deposit
🟪	Lacustrine veneer: silt and sand, generally < 1.5 m thick, discontinuously overlies morainal sediments; only mapped south of latitude 64°	poorly to moderately well drained	ice content low to medium in sand, medium to high in fine grained sediments

GLACIOFLUVIAL DEPOSITS: sand and gravel locally with a veneer of eolian silt or sand; deposited as proglacial or ice contact sediments by glacial meltwater

🟧	Outwash plains and terraces: sand and gravel with silt and peat in some channels, occurring as flat to gently sloping plain or erosional terrace, locally may be rolling to hummocky surface modified by thermokarst, 2-30 m thick	drainage mainly subsurface, generally well drained except in channels	low ice content, north of latitude 68° massive ice may be present in underlying sediment at depths of 5 -70 m

GLACIAL DEPOSITS: till (nonsorted silt, sand, and clay with some coarser clasts); deposited by glacier ice and occurring as a variety of landforms; locally includes minor scattered glaciofluvial gravel and sand deposits

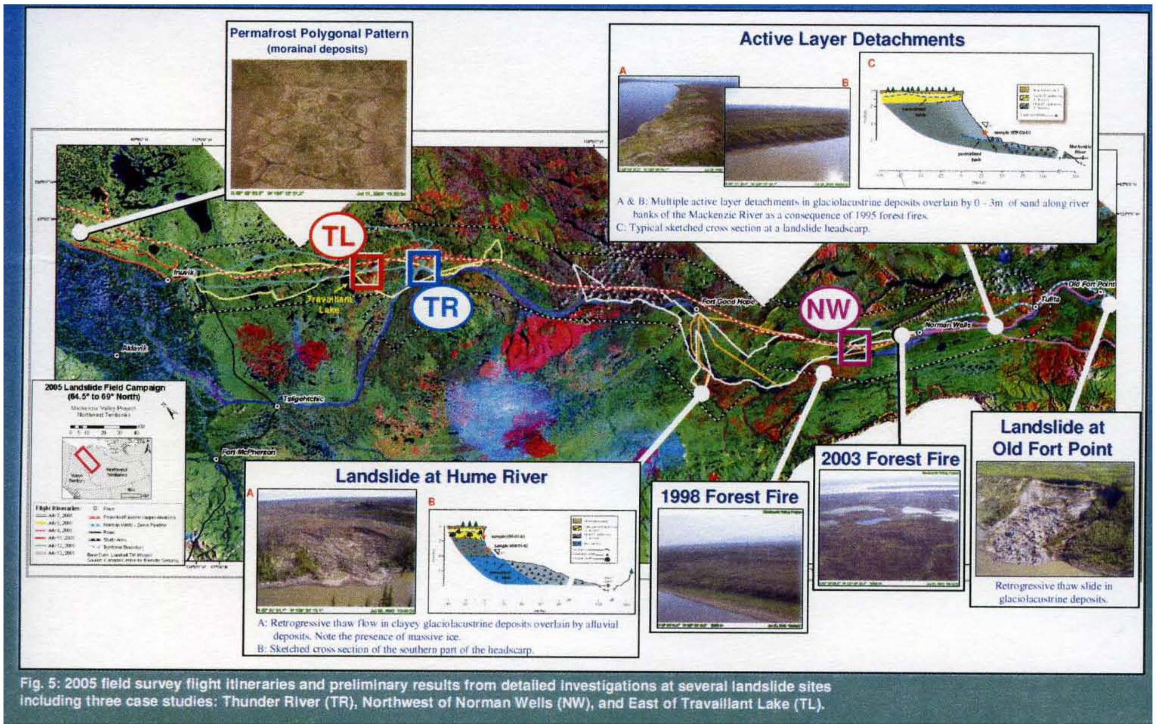
🟩	Moraine plain: till occurring as flat to gently sloping plain, in places moderately sloping, 2-20 m thick	poorly to moderately well drained	commonly 10-25% segregated ice as thin irregular discontinuous seams, thicker (10 cm to 3+ m) ice lenses may occur at depth
🟩	Moraine veneer: till occurring as veneer overlying bedrock topography, < 2 m thick, unit includes minor colluvial deposits, north of latitude 69° moraine veneer commonly overlies sandy or silty clay marine deltaic sequence and in places proglacial outwash	poorly to moderately well drained	commonly 10-25% segregated ice as thin irregular discontinuous seams
🟩	Hummocky, ridged, or rolling moraine: generally coarse till (20-50% pebble size) throughout most of the map area and clayey till in the north, up to 60 m thick, consisting of individual or coalescent hummocks (5-50 m relief), and/or individual to compound, straight to sinuous ridges (5-60 m relief), and/or till with 5-20% pebble size in broad hummocks or low hills (10-20 m relief)	elevated areas moderately to well drained, intervening depressions may be poorly drained	ice content probably low in hummocky and ridged moraine; in rolling moraine commonly 10-25% segregated ice as thin irregular discontinuous seams in upper 2-3 m and irregularly distributed large masses of segregated ice common at greater depth

ALLUVIAL DEPOSITS: sand, silt, clay, minor gravel and minor organic sediments in association with modern drainage regime

🟨	Alluvial plain: coarse sand and gravel with minor silt, fine sand, and clayey silt; commonly organic; 2 m to over 5 m thick; occurring as channel and overbank floodplain sediments, includes deltas, and may incorporate small areas of glaciofluvial sediment. In the Mackenzie Delta unit consists of silt, fine sand, and clayey silt, underlain by coarse sand and gravel in some areas, commonly organic, 10-30 m thick; occurring as flat surface marked by numerous distributaries, islands, lakes, and marshes	poorly to moderately well drained. Mackenzie Delta is poorly drained and subject to flooding by sea or river water	permafrost lacking in unvegetated part of floodplain; many irregularly shaped taliks in Mackenzie Delta; where frozen, pore ice only in coarser sediments, 20-50% segregated ice by volume in fine sediment, ice content decreases with depth, polygonal ice wedges common

SURFICIAL GEOLOGY MAP WITH INFRASTRUCTURE GEOHAZARDS:
1) colluvial deposits, 2) landslides, 3) drainage classes, 4) permafrost data from borehole logs.
(Portion of Open file GSC map, compiled by Jan Aylsworth)
Date: unknown

Figure 71 Surficial geology map with identified geohazards as output of terrain analysis (by GSC)



A & B: Multiple active layer detachments in glaciolacustrine deposits overlain by 0 - 3m of sand along river banks of the Mackenzie River as a consequence of 1995 forest fires.
C: Typical sketched cross section at a landslide headscarp.

A: Retrogressive thaw flow in clayey glaciolacustrine deposits overlain by alluvial deposits. Note the presence of massive ice.
B: Sketched cross section of the southern part of the headscarp.

Retrogressive thaw slide in glaciolacustrine deposits.

Fig. 5: 2005 field survey flight itineraries and preliminary results from detailed investigations at several landslide sites including three case studies: Thunder River (TR), Northwest of Norman Wells (NW), and East of Travaillant Lake (TL).

Figure 72 Terrain analysis for mapping potential landslide hazards in the Mackenzie Valley, NWT, Canada (by GSC)

7 EVALUATION AND EVOLUTION

The accuracy and utility of the InSAR results were evaluated in consultation with the Yukon Geological Survey. After the evaluation process, the Yukon Geological Survey was asked to comment on the likely integration plans within their ongoing monitoring approaches and programs. Representatives at TransCanada Pipelines were also asked to comment on the likely use of InSAR within their monitoring programs.

7.1 End-users Assessment Yukon Geological Survey

7.1.1 A posteriori assessment of the requirements

Adequacy of the product specification requirements (including accuracy requirements) specified before projects start	Evaluation*:		
	L	M	H
			X
User needs were well-assessed by C-CORE before the project started.			

* L: Low M: Medium H: High

7.1.2 Products conformance with requirements

Product completeness versus the User Requirements	Evaluation:		
	L	M	H
		X	
YGS user requirements were primarily the detection of small-scale displacement magnitudes and seasonal patterns therein. The main products of interest consisted of movement maps. These were well-presented and complete for the intervals that exhibited acceptable coherence. However, several maps could not be generated due to low coherence. So overall, we can only consider the final product delivery as partially complete, although we appreciate that all possible efforts were made to produce a complete set of movement maps.			

<table>
<tr><td rowspan="3">Confidence in estimated product accuracy:</td><td colspan="3">Evaluation:</td></tr>
<tr><td>L</td><td>M</td><td>H</td></tr>
<tr><td>X</td><td></td><td></td></tr>
<tr><td colspan="4">While some displacements shown on the movement maps seemed to agree with the ground surveying data (e.g. Figures 27 and 44), in many instances they seemed either underestimated or inconsistent (e.g. Figure 25 – maximum settlement should not be along highway, but should be along central zone of slide; Figures 42, 43 and 45 show more heaving at north end of highway than south end, which is opposite to surveying data). Also, the heaving displacement shown on some maps (e.g. Figures 26, 51 and 60) is highly unlikely, so I have lower confidence in those particular images. Also, for the movement maps that were generated, it is unclear what the inherent accuracy is for those individual pixels where the coherence was shown to be poor (<40%). Is it really valid to smooth data across pixels of poor coherence, when in fact those pixels may actually be experiencing the most movement (because soil conditions are likely wetter)?</td></tr>
</table>

<table>
<tr><td rowspan="3">Product accuracy versus the User Requirements</td><td colspan="3">Evaluation:</td></tr>
<tr><td>L</td><td>M</td><td>H</td></tr>
<tr><td>X</td><td></td><td></td></tr>
<tr><td colspan="4">As mentioned above, in a few cases the accuracy was within our requirements, but for many others the accuracy did not seem adequate to reflect ground surveys and field observations.</td></tr>
</table>

7.1.3 Utility assessment

Benefits or cost-savings from demonstrated products/service versus current practices:	Evaluation:		
	L	M	H
	X	X	
Current practices consist of annual or biannual field observations and ground surveys. No significant cost-savings were realized from this specific service, since these practices were already being carried out and our information requirements were largely fulfilled by them. However, if more frequent surveys had been required, multiple surveys would likely not have been economically feasible. In this case EO monitoring may have provided a cost-savings (although this is difficult to estimate without knowing a concrete figure for the actual per site cost for the EO monitoring work performed in this project). It was interesting to see some approximate seasonal patterns that could not be shown by the biannual surveys. It was also interesting to compare a new monitoring technique against traditions ground surveying methods.			

Impact of products/service	Evaluation:		
	L	M	H
		X	
One of the roles of the YGS is to distribute information on geological baseline data and mapping techniques to a variety of end-users, including government regulatory agencies, academia and private industry. Various colleagues throughout the Yukon and Canada have expressed a keen interest in reviewing the results of this project to assess how the technology may potentially be of use to their own work. Because the final report has not been complete, however, I have not distributed these results, and do not have a sense of the impact of this project on these other agencies. Internally, the project has added to our knowledge-base regarding monitoring methods, geomorphology, relative magnitude and the seasonal nature of permafrost terrain hazards, and this information will be passed on to various clients in the future to support sustainable development in permafrost terrain.			

7.1.4 Future

<table>
<tr><td rowspan="3">Feasibility of integrating the products in the working practices:</td><td colspan="3">Evaluation:</td></tr>
<tr><td>L</td><td>M</td><td>H</td></tr>
<tr><td>X</td><td></td><td></td></tr>
<tr><td colspan="4">The major limitations of this technology that currently need to be improved for our purposes before we could realistically integrate the technology into our working practices include:
1) image resolution (Critical for monitoring small-scale sites or long narrow road and pipeline corridors – it is not very useful to have averaged displacement values across large pixels when the area of interest is only a few pixels wide);
2) accuracy (Our confidence in the accuracy needs to be improved significantly. I realize that much of the reduced accuracy is a result of complex, highly spatially variable ground displacements, often of large magnitude exceeding the detection capability of the technology. However, it is not always possible to anticipate these issues before monitoring begins – the purpose of the monitoring project is often to determine these values);
3) coherence (At all sites, it was difficult to obtain adequate coherence during the early summer when the ground is likely wetter, and when most of the ground movement likely takes place – the fact that we couldn't generate movement maps during this time period was a major limitation. Also if monitoring were to occur over broader regions in the Yukon, they will almost always be vegetated by a variety of surface cover types, so it is impossible to eliminate their effects).
4) satellite geometry (In the discontinuous permafrost zone of southern Yukon, permafrost is most common on north-facing slopes, and most instability takes place on steeper slopes. From what I understand this is a very poor slope configuration for satellite data acquisition with the current orbit configuration).
5) installation of corner reflectors in permafrost terrain (This was a costly and time-consuming process, especially in remote regions. A better method is required to install and anchor the reflectors without disturbing the natural ground thermal regime. If EO monitoring could be done reliably and accurately without having to install reflectors it would be ideal. Because permafrost terrain is so highly variable, and so poorly mapped on the ground, you really need to monitor broad areas rather than only a few points.)</td></tr>
</table>

Probability of product integration in working practices (if necessary improvements made)	Evaluation:		
	L	M	H
		X	
Potential applications if necessary improvements are made could include: - back-analysis using several years of archival data at each of the sites (for years when no field surveys were performed). - monitoring selected sites over the long term to investigate links to climate change. - monitoring longer stretches of the Alaska Highway (i.e. 50-100 km) near Beaver Creek; - assessing rates of crustal deformation and tectonic strain due to subduction along nearby plate boundaries and related activity along the Denali Fault in southwestern Yukon (likely on the order of 1-2 mm /year). - mapping permafrost based on snow cover			

Approximate threshold price of operational product/service (including necessary improvements) for uptake	X € per …
For small scale sites: less than biannual surveying costs (approximately €3000 per site per year) For larger areas: a very rough estimate of €10 000 per year	

Desired improvements of product:	Evaluation:		
	L	M	H
See previous comment.			

Additional comments
It would have been beneficial if the EO analysis had extended further outside the areas of known instability, so that areas of instability previously unknown to us could also potentially be identified. For example, at the Beaver Creek site #1 and at the 12 Mile Creek site, good coherence was observed outside the active slide area, despite that fact that it was heavily vegetated by mature forest. Would it have been much more work to use the complete images in the final processing, rather than clipping them only to the immediate area of the slides? How much more effort/cost would this have involved?

<table>
<tr><td rowspan="3">Overall evaluation</td><td colspan="3">Evaluation:</td></tr>
<tr><td>L</td><td>M</td><td>H</td></tr>
<tr><td></td><td>X</td><td></td></tr>
<tr><td colspan="4">As outlined above, we were faced with many challenges and limitations at all the monitoring sites so that the accuracy and completeness of the desired products was somewhat disappointing. However, I think we are now able to define several thresholds and error margins that can be used to better constrain future EO projects, which in itself is very valuable.</td></tr>
</table>

7.2 TransCanada PipeLines Limited

7.2.1 A posteriori assessment of the requirements

Adequacy of the product specification requirements (including accuracy requirements) specified before projects start	Evaluation*:		
	L	M	H
		X	
Comment: Monitoring the pipeline Right-of-Way for thaw settlement and frost heave through ice rich regions is very complex. TransCanada was in search of a comprehensive, non-invasive approach to this problem. The monitoring of complex terrain to small amounts of movement is the most desirable to foresee and plan for possible problems.			

* L: Low M: Medium H: High

7.2.2 Products conformance with requirements

Product completeness versus the User Requirements	Evaluation:		
	L	M	H
		X	
Comment: This product is accuracy and usability is acceptable to weather conditions and other issues such as cloud cover, ground cover (summer: foliage, winter: snow) to over come this problem multiple images per month to may be need to verify problems.			

Confidence in estimated product accuracy:	Evaluation:		
	L	M	H
		X	
Comment: From the sites that were observed and correlated to survey data shows about the same level of error to the survey data in area that had relative movement less have 10 cm. It is able to deliver a level of confidence between areas that had a minimal amount to no movement to areas that sustain a substantial amount of movement			

Product accuracy versus the User Requirements	Evaluation:		
	L	M	H
		X	
Comment: The project showed that the movement of less that 10 cm between images was more accurately measure able than a greater movement of 10 cm or more, on flat terrain which is difficult to detect. Large movements of thaw settle and frost heave can be determined by aerial surveillance and internal pipeline inspections.			

7.2.3 Utility Assessments

Benefits or cost-savings from demonstrated products/service versus current practices:	Evaluation:		
	L	M	H
			X
Comment: The benefit is not a replacement of the current products but as a tool that can monitor for early signs of problems that can be further verified by survey, aerial surveillance and internal pipeline inspections. However, the main cost-saving is on the products ability to scan the entire Right-of-Way with out ground disturbance.			

Impact of products/service	Evaluation:		
	L	M	H
			X
Comment: The ability to scan the entire Right-of-Way with out ground disturbance is the main advantage of the product, but the down side is the poor accuracy on slopes and sits with large amounts of movement. The product does fill a void in the geotechnical assessment right-of-way scanning tool box.			

7.2.4 Future

Feasibility of integrating the products in the working practices:	Evaluation:		
	L	M	H
		X	
Comment (please list necessary improvements without which the products will not be used): Automation of the working process Interactive database of the images and image process capabilities.			

Probability of product integration in working practices (if necessary improvements made)	Evaluation:		
	L	M	H
			X
Comment: Probability of utilization of the product in the first years that an artic pipeline is in operation is very high, multiple images per month to verify problems. However, after five years, the need for aggressive continuous monitoring will wane slightly.			

Approximate threshold price of operational product/service (including necessary improvements) for uptake	X € per …
Comment: A cost study would be required.	

Desired improvements of product:	Evaluation:		
	L	M	H
			X
Comment: Automation of the working process Interactive database of the images and image process capabilities.			

Overall evaluation	Evaluation:		
	L	M	H
		X	
Comment: Overall this product has the potential to become part of the pipeline integrity group of tools used for geotechnical Right-of-Way assessment.			

7.3 Summary and Conclusions

Good coherence was noted in stable areas surrounding all instabilities, despite the fact that these areas are heavily vegetated by coniferous forest and/or muskeg. This highlights the potential to use the InSAR technique across broad, inaccessible heavily vegetated areas, potentially without the need for reflectors. Where reflectors are required, there is need for better reflector installation methods in permafrost areas and challenge of anchoring reflectors in the active layer. Figure 73 shows an example of an improved method of installing radar reflectors using rebar for the footings.

Figure 73 Example of improved reflector installation method (photo courtesy of Canadian Centre for Remote Sensing)

Low coherence at the sites was most likely related to rapidly changing surface moisture characteristics due to spring snowmelt. In addition, large magnitude ground movements are expected to occur under these wetter ground conditions. The very low coherence values experienced in June at all sites could possibly be used to indicate or infer periods of more rapid movement.

InSAR is applicable to areas whose movement along the look direction of the SAR satellite exceeds the measurement noise level of the satellite, or 0.5 – 1.0 cm per revisit interval. However, InSAR is not suitable if the expected movement is sufficiently high to result in reduced coherence or skipped phase intervals on the InSAR interferogram. The practical upper limit of this movement was not determined by this study; however to avoid skipping of phase intervals in the interferogram, the upper limit of the movement gradient should be less than 28 mm (the satellite's $\lambda/2$ at C-Band) per resolution cell, or 8 m for RADARSAT Fine and 30 m for ERS/ENVISAT. To use the movement gradient criteria, consider the distance from the point of maximum movement to the outer perimeter of the sliding region and divide that by the resolution cell size to get the number of resolution cells between the point of maximum movement and stable ground. Multiplying this by 28 mm gives the maximum movement within the InSAR monitoring interval. Creeping slopes may require short revisit intervals coupled with an extended series of satellite images (10–15) to improve movement measurement relative to noise limits.

The estimated accuracy of InSAR, based on results at the sites used for this study is 0.5 cm when using radar reflectors and several cm when not employing reflectors.

The estimated cost of InSAR is $4.5k to $7.5k for an initial analysis of a site, and $2.5k to $3.5k per movement update. The cost of data, which ranges between $150 and $2000 per image is not included in the figures above.

It is worth noting that there was a certain amount of difficulty obtaining adequate surveying data for validation due to compounding instrument, methodology and equipment errors. Despite reported survey accuracies of ±1 cm, in reality it seems difficult to believe that survey accuracies for both differential GPS and total station level survey techniques were better than ±3 cm.

Overall, except in the case of thaw settlement, the InSAR technique was not highly successful for determining ground movements at the complex small scale sites outlined in this report. However, the technique did highlight some qualitative seasonal ground movement patterns, as well as relative zones of higher and lower movement.

Other potential applications for InSAR in permafrost areas in the future could include:

- back-analysis of archival data over several years;
- analysis of infrastructure routes (pipelines and highways) that are accessible by road and would have good coherence. This will become more useful as SAR image resolution increases (i.e., with launch of the new RADARSAT-2 and various x-Band {cosmo-skymed, Terrasar-X} satellites in near future).

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APPENDIX A — Ground Survey Results

Beaver Creek Site 1 – Department of Highways Survey Results

		POSITIONAL DIFFERENCES			
Point	Delta Northing	Delta Easting	Delta Elevation	2D Difference	3D difference
1	0.03	0.02	-0.01	0.03	0.03
2	0.03	0.07	0.06	0.08	0.10
3	0.12	0.14	0.23	0.19	0.29
4	0.61	0.49	0.00	0.78	0.78
5	0.00	-0.01	-0.04	0.01	0.04
98		NO COMPARISON POSSIBLE			
99	0.00	0.00	-0.04	0.00	0.04
1173	0.50	0.65	0.08	0.82	0.83
1174	0.48	0.58	0.10	0.75	0.75
1175	0.35	0.48	0.45	0.59	0.74
1176	0.11	0.10	0.13	0.15	0.20
1177	0.03	0.01	0.01	0.04	0.04
1179	0.01	0.01	-0.01	0.01	0.01
1180	0.02	0.01	-0.04	0.02	0.05
1181	0.00	-0.01	-0.01	0.01	0.01
1182	0.01	-0.01	-0.08	0.02	0.08
1183	0.02	-0.01	-0.06	0.02	0.06
1184	0.02	0.01	-0.05	0.02	0.06
1185	0.02	0.00	-0.07	0.02	0.07

Beaver Creek Site 2 — Department of Highways Survey Results

		POSITIONAL DIFFERENCES			
Point	Delta Northing	Delta Easting	Delta Elevation	2D Difference	3D difference
100	0.01	-0.03	-0.02	0.03	0.03
101	0.02	-0.02	-0.01	0.03	0.04
102	NO COMPARISON POSSIBLE				
103	0.03	0.00	0.01	0.03	0.03
1158	0.00	-0.03	0.02	0.03	0.03
1159	0.01	-0.02	0.03	0.02	0.04
1160	0.03	0.01	0.01	0.03	0.04
1161	0.03	0.00	0.03	0.03	0.04
1162	0.01	-0.02	-0.01	0.02	0.02
1163	0.02	-0.02	0.00	0.03	0.03
1164	0.02	-0.04	-0.01	0.04	0.04
1165	0.00	-0.03	0.00	0.03	0.03
1166	0.00	-0.02	-0.01	0.02	0.02
1167	0.02	-0.03	-0.01	0.03	0.03
1168	0.02	-0.01	-0.01	0.03	0.03
1169	0.03	-0.01	-0.01	0.03	0.03
1170	0.01	-0.02	-0.01	0.02	0.02
1171	-0.01	-0.01	-0.01	0.01	0.02
1172	0.03	-0.01	-0.01	0.03	0.04
1186	0.01	-0.03	-0.02	0.04	0.04
1187	0.01	-0.03	0.00	0.03	0.04
1188	0.02	-0.02	-0.01	0.03	0.03
400	NO COMPARISON POSSIBLE				
401	NO COMPARISON POSSIBLE				

12 Mile Slope — YGS Survey Results

Ground Movements (May 20 - Sept. 21, 2006)					
	Horizontal Change Direction	Horizontal Change Distance dXY (cm)	dXY error (+/- cm)	Vertical Change dZ (cm)	dZ error (+/- cm)
2006-01	152	2.7	0.6	0.3	0.7
2006-02	21	3.3	0.6	2.4	0.8
2006-03	82	4.9	0.6	2.3	0.8
2006-04	265	4.8	0.6	-0.9	0.7
2006-05	25	4.5	0.7	1.0	0.8
2006-06	37	7.8	0.6	0.8	0.8
2006-07	47	6.0	0.6	2.5	0.7
2006-08	15	2.7	0.6	0.8	0.7
2006-09	221	2.0	0.6	3.1	0.8
2006-10	301	53.0	0.5	-34.4	0.6
2006-11	320	35.9	0.5	-11.1	0.6
2006-12	343	38.2	0.5	-9.0	0.7
2006-13	357	29.4	0.5	-5.8	0.7
wx stn	333	0.7	0.7	-0.7	0.7
No significant change (i.e. change is < 2x error)					
Accuracies/errors are 95% confidence levels calculated by DGPS					

Little Salmon Lake — YGS Survey Results

Ground Movements (June 22 - Sept. 28, 2006)					
	Horizontal Change Direction	Horizontal Change Distance dXY (cm)	dXY error (+/- cm)	Vertical Change dZ (cm)	dZ error (+/- cm)
2006-01	265	9.7	9.0	-0.1	7.3
2006-02	77	2.8	0.2	+1.2	0.2
2006-03	60	20.0	0.2	-33.0	0.2
2006-04	43	8.9	2.3	-20.4	2.4
2006-05	355	25.4	0.3	-13.3	0.4
2006-06	24	23.1	0.3	-14.2	0.4
2006-07	269	9.9	0.4	-5.0	0.4
2006-08	349	79.8	0.3	-24.0	0.2
2006-09	6	91.8	10.8	-33.2	6.5
2006-10	23	26.6	0.2	-16.1	0.2
2006-11	355	71.7	9.0	+38.7	7.5
2006-12	111	4.7	7.5	-10.3	2.5
2006-13	321	20.6	0.2	-21.7	0.4

No significant change (i.e. change is < 2x error)

Accuracies/errors are 95% confidence levels calculated by DGPS

Magundy River — YGS Survey Results

Ground Movements (June 22 - Sept. 28, 2006)					
	Horizontal Change Direction	**Horizontal Change Distance dXY (cm)**	**dXY error (+/- cm)**	**Vertical Change dZ (cm)**	**dZ error (+/- cm)**
2006-01 (Base)	n/a - PPP position fixed as local control point				
2006-02	103	17.7	10.5	7.0	6.2
2006-03	242	25.0	10.5	4.2	6.4
2006-04	279	1.2	0.1	-2.4	0.2
2006-05	15	24.7	10.6	-9.6	6.2
2006-06	299	2.5	8.9	-0.3	7.3
2006-07	329	1.2	0.1	-1.5	0.1
2006-08	Monument carried away and lost in active mud flows.				
2006-09	297	0.4	8.4	1.4	7.7
2006-10	215	3.5	0.2	-1.2	0.2
2006-11	180	59.4	8.5	49.1	7.9
2006-12	201	1.9	0.2	-0.7	0.3
2006-13	No satellite lock in dense trees				
2006-14	New monument established Sept. 28				
No significant change (i.e. change is < 2x error)					
Accuracies/errors are 95% confidence levels calculated by DGPS					

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