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## **Advanced SAR Applications for Canada's Cryosphere (Freshwater Ice and Permafrost)**

van der Sanden, J J; Geldsetzer, T; Short, N; Brisco, B

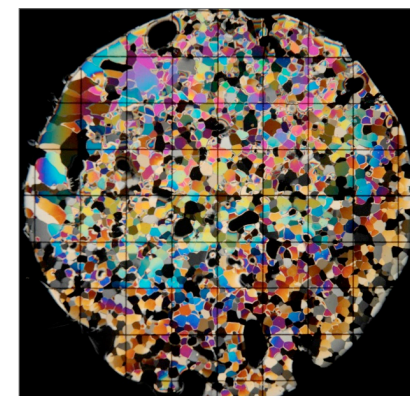
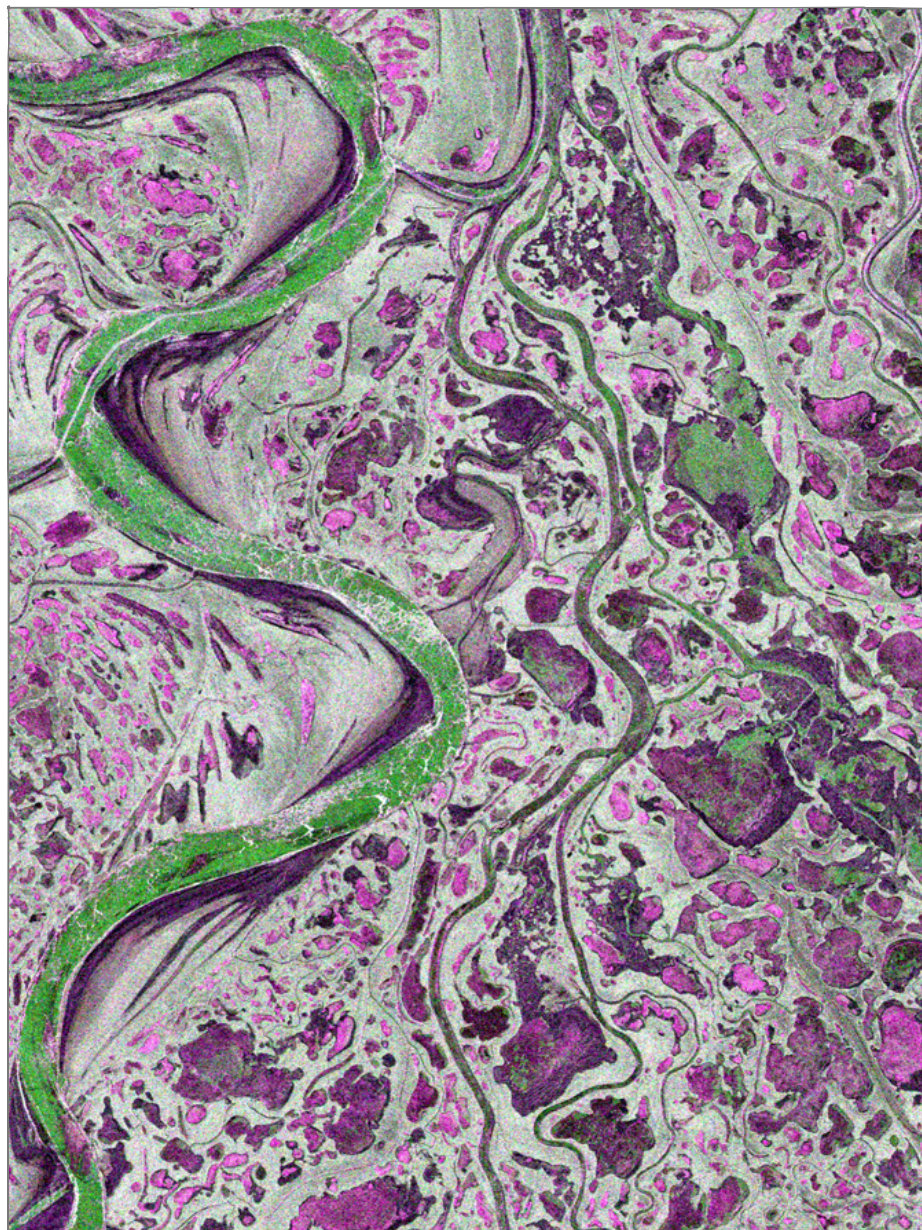
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# Advanced SAR Applications for Canada's Cryosphere









# Advanced SAR Applications for Canada's Cryosphere (Freshwater Ice and Permafrost)

## ***Final Technical Report***

*Submitted to:*

***Government Related Initiatives Program (GRIP)  
Earth Observation Applications and Utilizations  
Canadian Space Agency***

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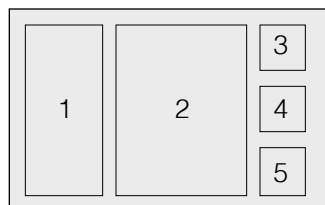
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### Cover illustrations and credits:



1- Measurement of ice cover thickness in the Middle Channel of Mackenzie River at Inuvik by means of a ground penetrating radar mounted on a helicopter.

2- RADARSAT-2 SAR image, March 8, 2009, Mackenzie River Delta.

3- Oblique aerial photo of terrain underlain by continuous permafrost, Herschel Island, Yukon.

4- Coring of ice cover in the Mackenzie River Delta in order to determine its composition in terms of ice types.

5- Horizontal cross section of an ice core seen under polarized light revealing the presence of frazil ice.

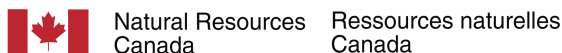
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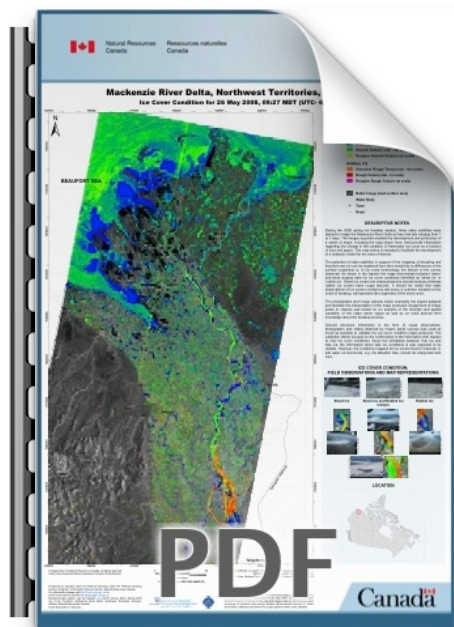


# Executive Summary

This report documents the results of the Canada Centre for Remote Sensing (CCRS) led Government Related Initiatives Program (GRIP) supported Project “*Advanced SAR Applications for Canada's Cryosphere - Freshwater Ice and Permafrost*” (IMOU 10MOA41003) that was carried out from April 2010 to March 2012. In order to provide a more complete picture of our results to date, the report also summarizes the relevant, that is, cryosphere related results of the preceding CCRS led GRIP supported project entitled “Fresh Surface Water Mapping and Monitoring Using SAR Satellites”. The original premise of the project was that freshwater ice and permafrost represent important components of Canada's (sub-)Arctic landscape and are tied to every aspect of the lives of Canadians. More specifically, freshwater ice and permafrost influence hydrological, climatic, biological, cultural and economic systems. Furthermore, both freshwater ice and permafrost are subject to the effects of climate warming in ways that are not yet fully understood. Therefore, the overall project goal was to advance the use of satellite SAR observations together with other forms of geospatial and Earth Observation data, to further the knowledge of the state of Canada's cryosphere, through the specific parameters of freshwater ice and permafrost.

The Canada Centre for Remote Sensing of the Earth Sciences Sector of Natural Resources Canada (NRCan/ESS/CCRS) led the project, the results of which directly contribute to the “Remote Sensing Science” (RSS) Program of NRCan/ESS. Project outputs also supported an Environment Canada-led International Polar Year (IPY) project entitled “Arctic Freshwater Systems: Hydrology and Ecology”. The primary end-users targeted, and involved in the project are Environment Canada (EC), Geological Survey of Canada (GSC), and Parks Canada Agency (PCA).

The project addressed GRIP segment 1 “Research and Development” (R&D) to develop, demonstrate and plan the implementation of innovative approaches for using satellite radar images to map and monitor the location, extent, and dynamics of fresh water ice and permafrost. The study areas selected for the GRIP project were mainly located in the arctic and subarctic regions of northern Canada; some sites for the river ice component were located in Manitoba and Alberta. The information gained from the available radar images and supporting *in situ* information is expected to support the management of northern environments and northern development activities. Overall, the GRIP project research outcomes have been well documented. More than 30 sample information products were generated, accompanied by more than 20 reports and an equal number of presentations; seven posters were prepared and presented at national and international meetings. Some 15 papers on GRIP project research related to lake ice, river ice and permafrost were published in the scientific literature.



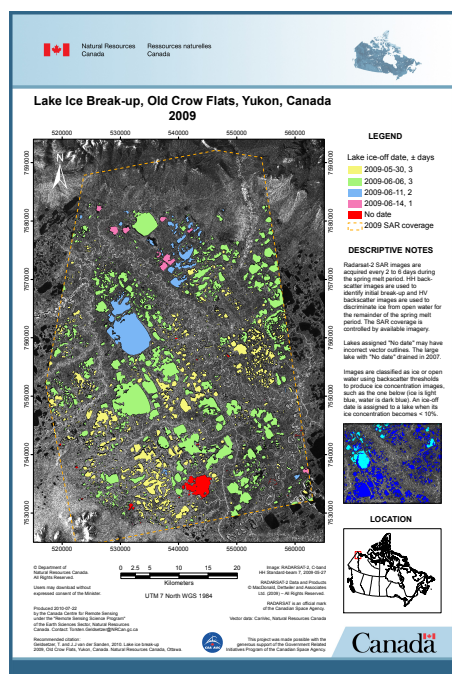
Example of a portfolio of ice condition information products based on SAR image analysis generated by the GRIP project (see APPENDIX for detail.)



The main accomplishments include the following: Lake freeze-up monitoring and lake ice break-up monitoring by means of satellite SAR can now be considered maturing applications; much of the ice characterisation work, including the mapping of bottom fast lake ice, remains still at the R&D stage. The project generated a variety of SAR-based lake ice mapping and monitoring techniques and methods, user guidelines for image acquisition and processing, and information products evaluated with the help of target clients. Many of the lake ice tools developed under the GRIP project were transferred to and are being used by the primary client department, that is, Parks Canada Agency. Furthermore, techniques and approaches developed for the application of SAR to the monitoring of lake ice breakup and freeze-up are in the process of being implemented, with support from CSA's EOADP program, in the commercially available PCI Geomatica software suite.

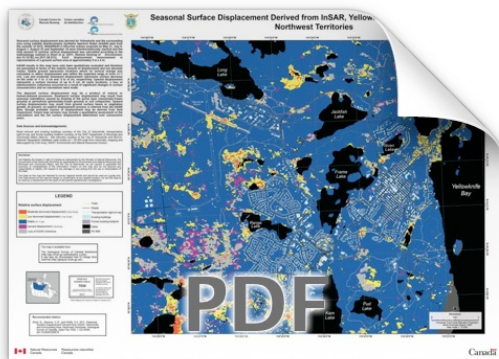
Like lake ice breakup monitoring application, the application of satellite SAR to the monitoring of river ice breakup is approaching maturity. Satellite SAR have been shown to contain much information about river ice cover characteristics (e.g. ice type, afloat/bottom fast) but more R&D towards reliable (automated) extraction of this type of information from SAR images is required. A sensitivity of SAR to river ice cover thickness has been demonstrated, but the application is a challenging one that will require considerable further R&D. Studies in the Mackenzie Delta and in southern Manitoba have shown that satellite SAR can address river ice information requirements at both relatively large and small spatial scales. The project generated a variety of SAR-based river ice mapping and monitoring techniques and methods, as well as ice cover and flood condition information products that were evaluated with the help of target clients.

The permafrost-related GRIP project work has also been very successful. A variety of techniques and methods, publications, presentations as well as information products have been produced. The seasonal InSAR-derived displacement results caught the immediate interest of the GSC, and the uptake was very positive. The work for the Pangnirtung study area was relayed directly to the community, and the terrain stability map was translated into Inuktitut for use as a community planning tool. Overall, the qualitative validation of the research results was very encouraging, although there is still work to be done regarding the quantitative analyses using in-situ thaw tube data. At this point, the InSAR derived seasonal displacement maps can probably be regarded as a proxy for the presence of ground ice, as there is sufficient evidence from the Yellowknife airport engineering study and the Pangnirtung ground penetrating radar study. With regard to InSAR derived displacement maps for long-term monitoring, one can point to the successful application of the C-band and especially the L-band InSAR over Herschel Island. This long-term observation capacity will



Example of a lake ice break-up information products based on RADARSAT-2 SAR image analysis generated by the GRIP project. (See APPENDIX for detail.)





*Permafrost information products based on RADARSAT-2 InSAR image analysis, generated by the GRIP project. (See APPENDIX for detail.)*

continue to evolve as longer time series of InSAR data are acquired. The value of the permafrost work is clearly shown by the rapid uptake by the private sector.

The report concludes with an outlook on future research and development activities involving satellite SAR and lake ice, river ice and permafrost-related applied research activities. Examples of information products generated by the project team are contained in the Appendix.



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# Section 1:

## Introduction

### 1.1 Project Background

This report documents the final outcomes of the Canada Centre for Remote Sensing (CCRS) led GRIP Project “*Advanced SAR Applications for Canada’s Cryosphere - Freshwater Ice and Permafrost*” [1] during the period of April 2009 to March 2012. The main premise of the project was that satellite SAR observations, together with other forms of geospatial and Earth Observation data, can further the knowledge of the state of Canada’s cryosphere through the specific parameters of freshwater ice and permafrost. The project developed, demonstrated and devised an implementation plan for innovative approaches to using satellite radar images for mapping and monitoring the location, extent, and dynamics of fresh water ice and permafrost stability. The information gained supports the management of northern environments and northern development activities. This project built on results and expertise gained in a previous GRIP project entitled “*Fresh Surface Water Mapping and Monitoring Using SAR Satellites*” (April 2007 - March 2010; IMOU 07MOA74822).

The Freshwater ice activity evaluated, established and, to some extent, developed new geospatial techniques and methods for the extraction of freshwater ice information from SAR images and ancillary data sources. The focus was on the application of SAR to the mapping and monitoring of freeze-up and properties of winter ice cover. Thus, the GRIP project team addressed new information requirements from clients such as Parks Canada Agency (PCA) and Environment Canada (EC) who also participated in the preceding GRIP project.

The Permafrost activity used InSAR techniques to detect terrain movement in permafrost areas and identified areas of permafrost that are unstable. The applicability of the technique to the wide variety of permafrost environments found within Canada - from the continuous tundra zones of the High Arctic to the forested discontinuous zones in the northern mainland - was subject of the research activities. PolInSAR methods were also explored for their potential information content regarding the measurement of permafrost stability. The project investigated the latest spaceborne SAR capacities for extracting cryospheric information: specifically the greater penetration of ALOS L-band, the higher resolution and polarization diversity of RADARSAT-2 and the high resolution and short revisit period of TerraSAR-X.

Fieldwork was an integral part of the project providing the field data necessary to validate the EO analysis and results.

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[1] Canada Centre for Remote Sensing / ESS / NRCan (2010) Advanced SAR Applications for Canada’s Cryosphere (Freshwater ice, and Permafrost) Appendix A IMOU No.10MOA41003. July 2, 2010 Proposal to the Canadian Space Agency / Earth Observation Application & Utilizations - Government Related Initiatives Program (GRIP), 24 p. Ottawa.



## 1.2 Project Rationale, Impact, and Benefit

Freshwater ice on rivers and lakes represents an important component of the Arctic and sub-Arctic landscape, influencing hydrological, climatic, biological, cultural and economic systems. The timing or phenology (i.e. dates of ice-on/freeze-up and ice-off/breakup), thickness, and structure of this ice cover can profoundly affect the systems mentioned above. These ice characteristics can exhibit substantial spatial and temporal variability. Therefore, mapping in space, and monitoring in time, are both required. The project team has worked and gained expertise in terms of the mapping and monitoring of freshwater ice through involvement in an earlier GRIP project that focused on the application of C-band single and dual-polarization SAR data to map and monitor river and lake ice breakup. In the present GRIP project the knowledge gained earlier was used to address information needs related to freeze-up and the structure and thickness of ice cover.

From the radar perspective, we built on earlier lake and river ice related work by developing and evaluating the application of data types that offer additional diversity in terms of polarization (i.e. polarimetric data) and/or frequency (incl. X- and L-band). Project partners such as Parks Canada Agency and Environment Canada (Canadian Ice Service and Water Survey Division) had expressed interest in the results of the study. As such, the methods and tools were made available to interested OGD's. PCA has received and used methodologies and tools to monitor lake ice-off developed as part of the earlier project.

Permafrost is ground that remains frozen for two or more consecutive years. About 50% of Canada's landmass is underlain by permafrost. The presence of permafrost presents particular challenges for infrastructure and engineering, and it is an important factor for monitoring environmental and ecological stability. The existence of permafrost is closely correlated with air temperature. Therefore, it is particularly susceptible to change as a result of climate warming. As Canada's resource extraction industries continue to venture into Canada's North, methods for mapping and monitoring permafrost are increasingly needed to manage northern infrastructure. Since permafrost regions are typically remote and logistically difficult to survey, Earth observation satellites are highly desirable as a means to monitor such areas. Satellite interferometry (InSAR) is a particularly attractive technique for measuring ground movement can be measured, which is indicative of changing amounts of ice in the soil. To date, C-band SAR satellite sensors had limited InSAR success in monitoring permafrost regions as the presence of vegetation causes temporal decorrelation, rendering interferograms less useful.



Satellites launched within the last four years offered new capabilities and fresh opportunities for looking at permafrost environments. The improved orbit control, satellite pointing and higher resolution of RADARSAT-2 offers increased chances of successful C-band InSAR in permafrost environments. The longer L-band wavelength of the ALOS-PALSAR sensor more easily penetrates the vegetation and maintain much better coherence. The short revisit period offered by TerraSAR-X may also permit successful InSAR data acquisitions in permafrost zones. Since the potential benefits of this application are large, the research effort in this field remains justified. This GRIP project explored the utility of InSAR for permafrost environments in close cooperation with Geological Survey of Canada partners and territorial partners.

### 1.3 Project Goals and Expected Outcomes

As this project targeted GRIP segment 1 “Research and Development”, the overall goal was to advance the use of satellite SAR observations together with other forms of geospatial and Earth Observation data, to further the knowledge of the state and dynamics of Canada’s cryosphere, through the specific parameters of freshwater ice and permafrost. The project developed and demonstrated innovative approaches, including ways for practical implementation, to utilize satellite radar images for mapping and monitoring location, extent, and dynamics of fresh water ice and permafrost.

The information gained through the GRIP project supports the management of northern environments and northern development activities. In the case of freshwater ice, the project focused on stakeholder information needs and technology not (fully) addressed in the preceding ‘Surface Water’ GRIP project (FY 07/08 to 09/10). Specific objectives of this project included:

- ◆ evaluation of established and, to some extent, new geospatial techniques for the extraction of freshwater ice information and permafrost status from SAR images and ancillary data sources,
- ◆ generation, validation (in collaboration with stakeholders) and demonstration of freshwater ice and permafrost information products, and
- ◆ preparation of a plan for the operational implementation of the techniques developed

Specific outcomes include the following:

- ◆ identification and resolution of technological barriers,
- ◆ demonstrated use of SAR-based freshwater ice and permafrost information products,



- ♦ enhancement of the Government of Canada's capacity for sustainable management of northern environments and infrastructure.

The economic significance of freshwater ice in northern countries such as Canada is substantial and multi-faceted. For instance, freshwater ice:

- ♦ controls the winter flow regime of rivers and compromises the operations of hydrometric stations.
- ♦ provides seasonal road access to locations that lack a regular land-based road network (*e.g.* communities, hunting / fishing grounds, and mining operations).
- ♦ governs the water intake and discharge activities of municipalities and businesses (*e.g.* hydropower and oil sands industries).
- ♦ is hazardous to shipping and, in particular during spring break-up, can create jams and floods that endanger infrastructure (*e.g.* locks, bridges, pipelines) and communities but may also nurture aquatic ecosystems.
- ♦ affects the habitat of wildlife and represents an erosive force that can reshape fluvial landscapes.
- ♦ influences weather patterns and, consequently, weather forecasting and climate modelling.
- ♦ may be used as an indicator of climate change.

It follows that information on freshwater ice cover supports various science, engineering and management activities including hydraulic and hydrological modelling, break-up forecasting, and decision making related to, for example, water intake and discharge, ice road routing, wildlife management, and ice jam flood emergency preparedness.

Information on permafrost conditions is directly useful to northern communities and managers, both for planning infrastructure development and for monitoring the environmental impacts of development. Reducing the need for expensive field surveys brings significant economic benefits for federal and territorial monitoring agencies, as well as northern businesses and industry. A better understanding of permafrost conditions helps in guiding and preserving federal and territorial investments in roads and infrastructure. There is also local and national interest in the state of permafrost as an indicator of climate change, particularly in ecological monitoring agencies within Canada such as Parks Canada. There is also a strong interest in permafrost as an indicator of climate change and a variable of interest for climate change modelling and geomorphological research.



## 1.4 Report Outline

In this GRIP project, the Canada Centre for Remote Sensing led the effort to advance the use of satellite SAR observations, together with other forms of geospatial and Earth Observation data, to further the knowledge of the state and dynamics of Canada's cryosphere, through the specific parameters of freshwater ice and permafrost. Section 2 of this report provides further detail on the lead department's project team and identifies the scientists, partners and operational groups involved in the project. A number of research areas were selected in northern Canada by team members for mapping and monitoring lake ice, river ice, and permafrost. The geographic location of these research areas are highlighted in Section 3. Section 4 details the results of the work on mapping and monitoring of lake ice. Subtopics addressed in the research include monitoring of ice break-up, freeze-up as well as bottom-fast ice mapping. Section 5 concentrates on the research regarding river ice. Three subsections deal with monitoring ice cover condition and flood condition during ice breakup, bottom fast ice mapping, and mapping of ice cover properties involving work conducted with RADARSAT-2 and ALOS PALSAR polarimetric data. In order to provide a more complete picture of our results to date, the Sections 4 and 5 include selected results of the preceding 'Surface Water' GRIP project. Section 6 concentrates on permafrost, detailing seasonal and long-term InSAR displacement results. A summary of the GRIP project outcomes is presented in Section 7. It is based on the various Work Packages specifically identified for the project. A brief outline of future work concludes the report. In accordance with the third objective defined for the project, a plan for (further) operational implementation of the techniques and methods developed will be prepared and delivered to the CSA as a separate report.



## Section 2:

# Participants, Earth Observation Data, Information Needs

### 2.1 Lead Department

The Canada Centre for Remote Sensing of the Earth Sciences Sector of Natural Resources Canada (NRCan/ESS/CCRS) lead the project and carried it out under the umbrella of the Sector's "Remote Sensing Science" (RSS) Program. The RSS program contributes to the governance and understanding of Canada by developing and applying remote sensing techniques for the monitoring of Canada. The project aligns with the role of NRCan for sustainable management of Canada's natural resources and provides the information and understanding necessary for informed decision-making through science and policy expertise.

### 2.2 Project Team and Partners

The project team engaged with the development work comprised of the following NRCan/ESS/CCRS employees (with mention of their field of expertise):

- ◆ *Dr. Joost van der Sanden*, Research Scientist (application R&D, project lead)
- ◆ *Dr. Brian Brisco*, Research Scientist (application R&D, backup project lead)
- ◆ *Mr. Hugo Drouin*, Physical Scientist (term) (application R&D support freshwater ice)
- ◆ *Dr. Torsten Geldsetzer*, Physical Scientist (application R&D support freshwater ice)
- ◆ *Mr. Kevin Murnaghan*, Physical Scientist (application R&D support permafrost)
- ◆ *Ms. Naomi Short*, Physical Scientist (InSAR processing, R&D support permafrost)

The research work regarding freshwater ice and permafrost also relied on the scientific expertise from partner organizations within academe and other government departments, involving the following individuals (with mention of their affiliation and field of expertise):

#### *Freshwater ice partners*

- ◆ *Ms. N. Anilniliak, Mr. J. Sweetman, P. Dixon, and J. Poitevin*, Parks Canada Agency - end-user, information product assessment
- ◆ *Dr. F. Hicks*, University of Alberta – research partner, fieldwork, product assessment
- ◆ *Dr. A Pietroniro*, Environment Canada, Meteorological Services of Canada, Water Survey Division - enduser, information product assessment
- ◆ *Dr. S. Beltaos and Mr. C. Talbot*, Environment Canada, Science and Technology, Hydrological Process and Modelling research partner, fieldwork, product assessment
- ◆ *Mr. Denis Dubé*, Environment Canada, Canadian Ice Service - end-user, information product assessment



- ◆ *Dr. M. Bernier*, Institut National De La Recherche Scientifique (INRS) - Centre Eau, Terre et Environnement (ETE) – research partner, data analysis and methodology development
- ◆ *Dr. L. Lesack*, Simon Fraser University - research partner, fieldwork and product assessment
- ◆ *Mr. Alan Fitzgerald*, Nuna Logistics Ltd. – end-user, fieldwork and information product assessment

#### *Permafrost partners*

- ◆ *Dr. N. Couture*, Geological Survey of Canada – end-user, participation in validation field work and information product assessment
- ◆ *Dr. S. Wolfe*, Geological Survey of Canada – end-user, participation in validation field work and information product assessment
- ◆ *Dr. W. Pollard*, McGill University – research partner, provide ancillary data, and participation in validation field work and information product assessment
- ◆ *Dr. H. Lantuit*, Alfred Wegener Institute - research partner, participation in validation field work and information product assessment.

## 2.3 Targeted Clients, Data Sources, and Information Needs

The GRIP project targeted several operational groups within the federal government, principally Environment Canada and Parks Canada. Memoranda of Understanding have been exchanged with both Departments in order to formalize the activities under the GRIP project.

Environment Canada (EC) has the mandate for the management of fresh water resources with the exception of navigable watercourses. EC typically focuses on water supply, water quality and water levels for natural ecosystems. Prior to the GRIP project, EC had used remote sensing in support of its mandate, but both tool kits for application development as well as seed funding were limited. The main contacts within the Department are: *A. Pietroniro* and *S. Beltaos* (EC/NHRC). The techniques and approaches developed in the project are helping Environment Canada to lower the barriers of integrating applications of remote sensing into its day-to-day operations.

Parks Canada Agency (PCA) was the other principal client targeted by the project. The techniques and approaches developed in the project are helping Parks Canada to exploit satellite SAR data in an operational fashion, supporting its mandate to map and monitor its



parks on a five-year basis (last report in 2010). The commitment of Parks Canada toward the use of Earth observation tools in support of its mandate was exemplified by the secondment of staff to CCRS and the provision of funds for the purchase of RADARSAT-1 images. The principal contacts for the GRIP project within Parks Canada are: *N. Anilniliak* (PCA, Nunavut Field Unit), *J. Sweetman*, and *P. Dixon* (PCA, Resource Conservation).

Other operational groups within Government include the Geological Survey of Canada (GSC). It has the mandate for permafrost mapping and monitoring in Canada and is a partner in this research project. The project team delivered SAR-based information products relevant to permafrost subsidence and uplift to the GSC. Operational implementation by the GSC and other interested parties (*e.g.* territorial agencies and value-added RS industry) will require further validation and development of operational tools.

The main data sources are summarized in **Table 2-1**. The Earth observation related research work relied predominantly on RADARSAT-2 SAR data, supported by digital topographic map data, thematic maps, as well as data collected during fieldwork.

**Table 2-1.**  
*List and description of data sources  
used in the project.*

Data Source	Description
Earth observation satellite data	<ul style="list-style-type: none"> <li>- RADARSAT-1, RADARSAT-2</li> <li>- ALOS-PALSAR</li> <li>- Envisat ASAR, TerraSAR-X</li> <li>- Landsat 5 TM / Landsat 7 ETM+</li> <li>- High resolution optical data (IKONOS, GeoEye, Worldview) and derived elevation products</li> </ul>
Base and framework data	<ul style="list-style-type: none"> <li>- National Topographic Database</li> <li>- Canadian Digital Elevation Data</li> </ul>
Validation data	<ul style="list-style-type: none"> <li>- Information collection through fieldwork, incl. oblique aerial photographs, visual observations, ice cover charts, weather data</li> </ul>



The capacity and interest of target clients to integrate the developed the SAR-based surface water mapping methods in their own operations were assessed during an information needs and planning workshop held in Ottawa on February 14 and 15, 2008. The outcome of the workshop entitled “*Fresh Surface Water Mapping and Monitoring using SAR Satellites*” [2] has been documented by CCRS in 2008.

During the course of this GRIP project, CCRS has contributed technical reports and guidelines for clients to facilitate the operational implementation of SAR lake ice monitoring and mapping during freeze-up and break-up [3], ground-fast ice mapping [4]. Critical assessments of fresh water remote sensing work by Parks Canada and by a team based at the University of Alberta have concentrated on the topic of lake ice [5] and ice cover condition maps for the Mackenzie River delta [6]. In 2011, the Canada Centre for Remote Sensing summarized and documented the end user information needs of federal departments and agencies – principally Environment Canada and Parks Canada Agency – with regard to freshwater ice and permafrost [7]. The document is a deliverable item of the GRIP Project. The main information needs of federal departments for lake ice, river ice and permafrost are listed in *Table 2-2*.

Based on its mandate and technical capabilities, Environment Canada is expected to be in a position to adopt and implement in-house the technology developed under the GRIP project. Other clients that lack the capacity to implement the technology in their operations are envisioned to request information products produced by other providers (possibly CCRS) within the context of the National EO data framework. The long term technical sustainability of the Earth observation data stream is guaranteed by a growing number of orbiting and planned SAR satellites, including Canada’s planned RADARSAT Constellation Mission, RCM.

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[2] CCRS (2008) Information Needs and Planning Workshop Report, Ottawa, 10 p.

[3]CCRS (2011a) Interim guidelines for operational implementation of SAR lake ice monitoring and mapping during freeze-up and break-up. Ottawa, 21 p.

[4] Drouin, H. and J. van der Sanden (2010) Ground-fast Ice Mapping – Mackenzie Delta 2010. Technical Note, Natural Resources Canada / Canada Centre for Remote Sensing, 3 p. Ottawa.

[5] Dixon, P. (2009) Review and path forward on Parks Canada/CCRS Lake Ice Project. Parks Canada, 5 p.

[6] Nafziger, J., F. Hicks & J. Morley (2010) Spring 2008 Ice cover condition maps for the Mackenzie River Delta - An Evaluation. Water Resources Engineering Department of Civil and Environmental Engineering, University of Alberta, Edmonton, 2 p.

[7] CCRS (2011b) End User Information Needs Regarding Freshwater Ice and Permafrost. Deliverable Documentation Related to "Advanced SAR Applications for Canada's Cryosphere (Freshwater ice, and Permafrost) 10MOA41003" Ottawa, 7 p.



**Table 2-2.**  
Main information, tools or product needs  
of federal departments with regard to  
lake ice, river ice, and permafrost under  
the GRIP project (Source: CCRS 2011b,  
see footnote 8 for reference).

Department / Agency	Topic and specific information-, tool- or product needs
Parks Canada Agency:	<p><i>Lake ice:</i></p> <ul style="list-style-type: none"> <li>- Lake ice concentration during spring break-up (per image)</li> <li>- Lake ice break-up date for each lake within study area (annual map)</li> <li>- Lake ice concentration during autumn freeze-up (per image)</li> <li>- Lake ice freeze-up date for each lake within study area (annual map)</li> <li>- Lake ice-cover duration for each lake within study area (annual map)</li> <li>- Lake ice-free duration for each lake within study area (annual map)</li> <li>- Lake ice grounding</li> <li>- Software tools</li> <li>- Lake ice information product samples</li> </ul>
Environment Canada:	<ul style="list-style-type: none"> <li>- Improved satellite products for visual interpretation</li> <li>- Automated methods leading to lake ice info products (large areas)</li> <li>- Lake ice concentration (per lake, from freeze-up to break-up)</li> <li>- Method descriptions</li> <li>- Samples of information products</li> </ul>
Environment Canada:	<p><i>River ice:</i></p> <ul style="list-style-type: none"> <li>- Ice on / ice off information state and dynamics of river ice cover -</li> <li>- Onset of break-up</li> <li>- Ice coverage</li> <li>- Ice type</li> <li>- Location of ice jams</li> <li>- Presence and location of ground fast ice</li> <li>- Support for hydraulic and climate modelling</li> </ul>
Others: Public Safety Canada and provincial / local emergency management	<ul style="list-style-type: none"> <li>- Spring break-up information</li> <li>- Flood assessment in or around communities</li> <li>- Ice type and thickness</li> <li>- Location of afloat and ground fast ice</li> </ul>
Natural Resources Canada:	<p><i>Permafrost:</i></p> <ul style="list-style-type: none"> <li>- Permafrost distribution and properties - Snow cover</li> <li>- Active layer depth</li> <li>- Identification of regions of change and instability</li> <li>- Terrain (permafrost and active layer) stability along transportation corridors</li> <li>- Terrain (permafrost and active layer) stability in and around community infrastructure</li> </ul>

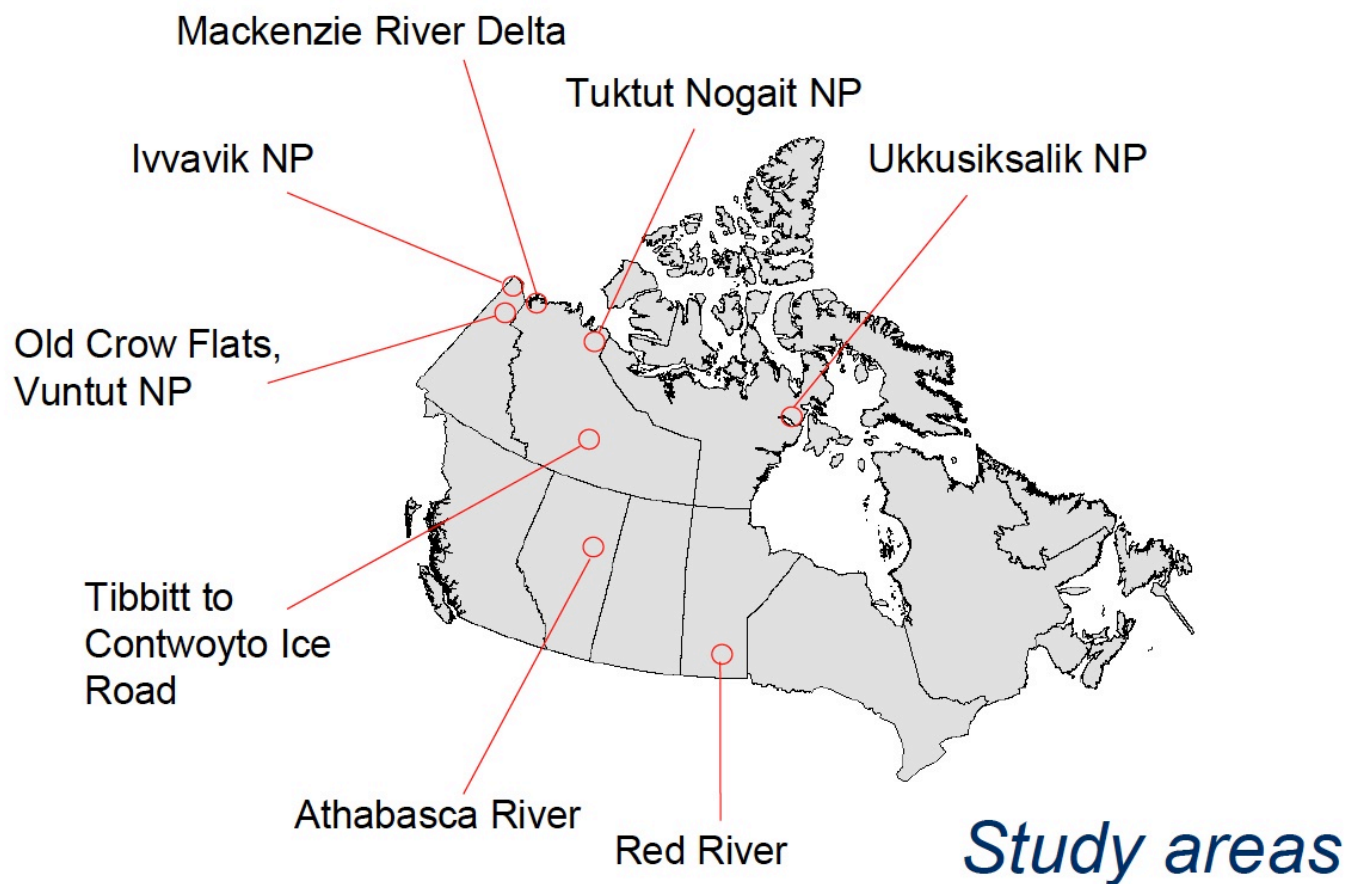


## Section 3:

### Study Areas

#### 3.1 Study Areas for Lake ice and River Ice Investigations

The study areas of the GRIP project are distributed across the country. The majority of the areas are located in northern Canada. **Figure 3-1** provides an overview of areas associated with lake ice and river ice investigations. The lake ice areas were located mainly within National Parks. The primary area for lake ice study was Old Crow Flats, Yukon, because of the profusion of lakes of different sizes and depths. The river ice areas included the Mackenzie River at Inuvik, the ice road from Tibbitt to Contwoyto, NWT, portions of the Athabasca River in Alberta, and the Red River in Southern Manitoba.

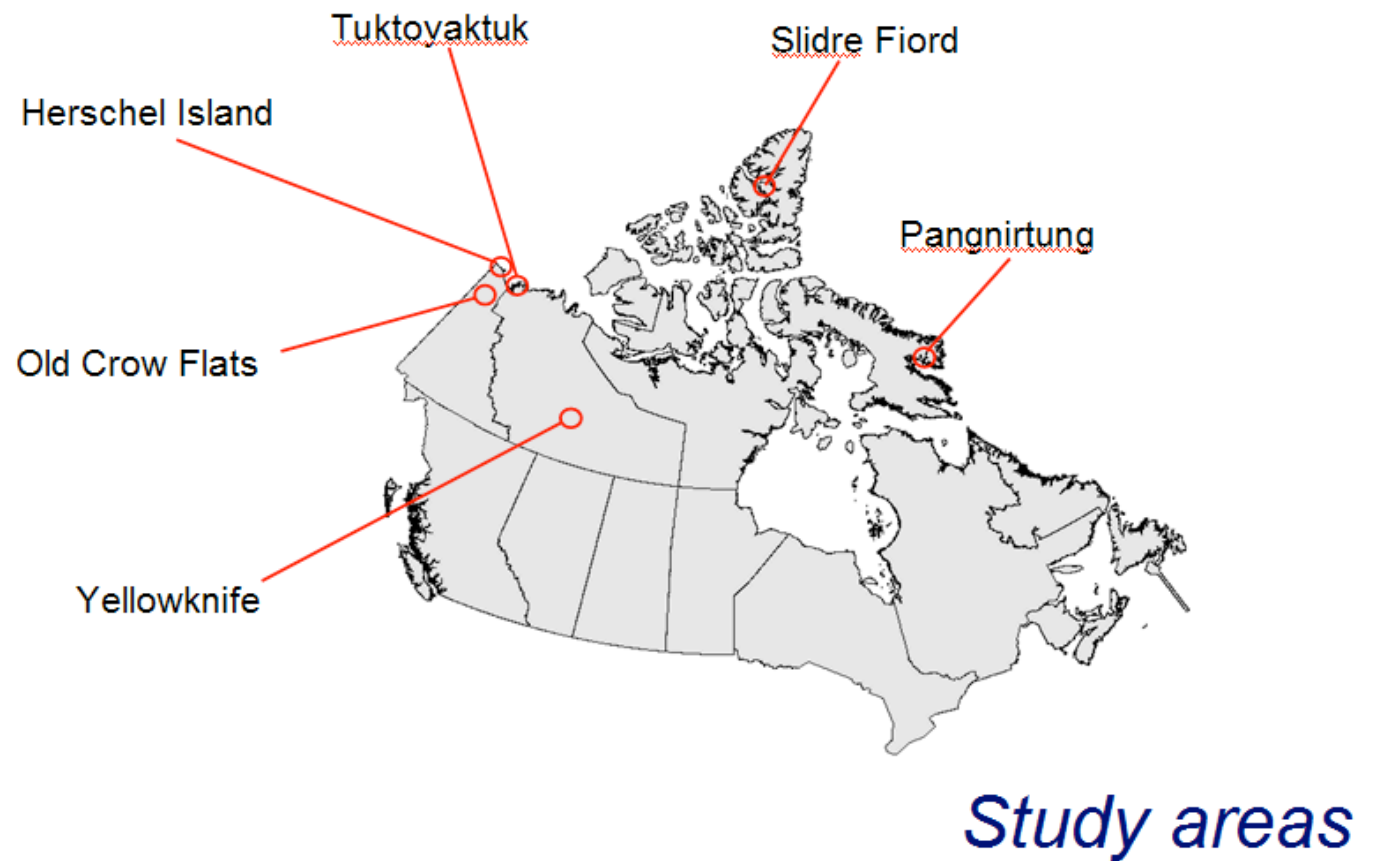


*Figure 3-1.*  
Location map of study areas associated  
with lake and river ice investigations.



### 3.2 Study Areas for Permafrost Investigations

The study areas for the permafrost investigations are located in the Northwest Territories and Nunavut, Canada. The areas include Herschel Island, Tuktoyuktuk (Mackenzie Delta), Yellowknife, Slidre Fiord, and Pangnirtung. **Figure 3-2** contains a location map of the study areas.



*Figure 3-2.*  
Location map of study areas associated  
with permafrost investigations.



## Section 4:

# Mapping and Monitoring of Lake Ice

### 4.1 Overview

Lake ice represents an important component of the Arctic and sub-Arctic landscape, influencing hydrological, climatic, biological, cultural and economic systems. The timing of freeze-up affects these systems, requiring both spatial mapping and temporal monitoring. Within the Government of Canada, monitoring of lake ice freeze-up is an operational matter for Environment Canada (EC) and Parks Canada Agency (PCA). Remote sensing methods are required for monitoring large geographical areas, and Synthetic Aperture Radar (SAR) capabilities are needed to operate during winter darkness and persistent cloud cover.

### 4.2 Lake Ice Freeze-up Monitoring

Lake ice freeze-up is currently monitored by EC using mainly visual interpretation of single-polarized (single-pol) (HH or VV) and dual-co-cross-pol (HH+HV or VV+VH) parameters from C-band SAR imagery. Increased automation would benefit EC operations. PCA also requires a robust automated methodology, especially for its northern parks. Freeze-up monitoring using SAR must discriminate between radar backscatter from open water and from floating lake ice. A number of radar system parameters, for example polarization, look direction, as well as environmental variables such as wind speed and direction can significantly complicate this process. Automated ice/water classification during freeze-up is challenging because potential backscatter similarities are caused by combinations of the variables identified. Polarimetric sensors such as RADARSAT-2 provide a number of additional parameters that may be useful for freeze-up monitoring (*Geldsetzer & van der Sanden 2012*).

The GRIP project provided scientific and operational guidance for monitoring lake ice freeze-up using SAR and evaluated both polarimetric and non-polarimetric parameters for ice/water discrimination. In order to accommodate monitoring at different spatial scales, and to enable the use of historical SAR data, the work focused on the capabilities of the following SAR sensor configurations: polarimetric, dual-co-cross-pol, dual-co-pol, and single-pol. **Table 4-1** contains a summary of the lake ice related documentation produced under the GRIP project in terms of reports, presentations at workshops and conferences, posters exhibited at workshops and conferences, as well as scientific papers published in learned journals or conference proceedings.



RADARSAT-2 Fine-Quad (FQ) and Standard-Quad (SQ) SAR imagery obtained from lakes in the Old Crow Flats, Yukon, yielded a number of useful results. This area has a high density of shallow freshwater lakes. Ten lakes, representing a diversity of ice characteristics, were sampled from imagery for the 2008–2011 freeze-up seasons. The classification of open water is sensitive to a low wind speed threshold. **Figure 4-1** illustrates the extent to which uncorrelated pixels can affect classification: the 0.6 m/s wind speed results in extensive wind slicks. Many of these uncorrelated wind-slick pixels would be classified as ice, if they are not first identified and excluded. Furthermore, classification of ice-covered lakes produces better results at large incidence angles than small ones (**Figure 4-2**). However, new ice slicks occur most often at larger incidence angles. Classification of partially ice-covered lakes must usually contend with uncorrelated pixels. **Figure 4-3** shows that the ice forms first in smaller lakes and along the shores of larger lakes, as expected. Given the moderate wind speed, wind slicks are unlikely, indicating that the uncorrelated pixels are likely associated with new ice.

**Table 4-1.**  
Documentation of GRIP project  
research related to lake ice

Documentation	Author(s), Title, Occasion / Reference
Reports: (n=9)	<ul style="list-style-type: none"> <li>◆ T. Geldsetzer, J.J. van der Sanden (2012) Preliminary analysis for bottom-fast freshwater lake ice detection using polarimetric C-band SAR. Interim CCRS Project Report, 18 p.</li> <li>◆ T. Geldsetzer, J.J. van der Sanden (2012) Monitoring lake ice freeze-up using polarimetric and non-polarimetric C-band SAR. Interim Report, 31 p.</li> <li>◆ T. Geldsetzer, J. van der Sanden (2011) Interim guidelines for operational implementation of SAR applications for lake ice monitoring and mapping: break-up and freeze-up. Technical Report, 21 p.</li> <li>◆ CCRS (2011) SAR polarimetry for lake ice monitoring. Interim Report, 12 p.</li> <li>◆ T. Geldsetzer (2010) Draft Guidelines for lake ice break-up monitoring and mapping using SAR imagery CCRS (2010) Mapping and monitoring lake ice using SAR satellites. CCRS Interim Final Project Report, 49 p.</li> <li>◆ CCRS (2010) Mapping and monitoring lake ice. Interim Report, 3 p.</li> <li>◆ P. Dixon (2009) Review and path forward: Lake ice project, 5 p.</li> <li>◆ CCRS (2009) Mapping &amp; monitoring of lake ice, CCRS Progress Report, 21 p.</li> </ul>
Posters: (n=1)	<ul style="list-style-type: none"> <li>◆ T. Geldsetzer, J.J. van der Sanden, H. Drouin (2011) Advanced SAR applications for Canada's river and lake ice. Poster presented at IGARSS'2011.</li> </ul>

(continued next page)

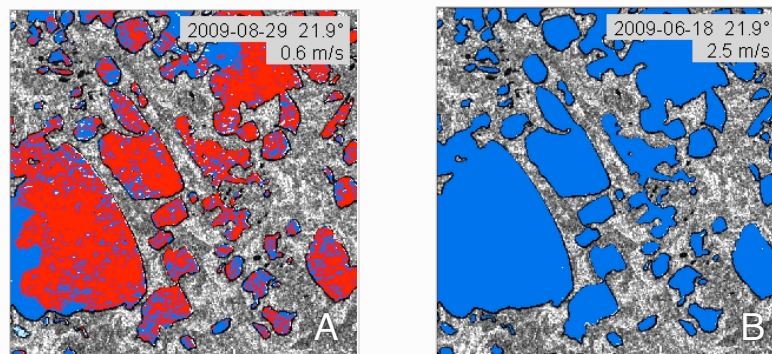


*Table 4-1 (continued).  
Documentation of GRIP project  
research related to lake ice*

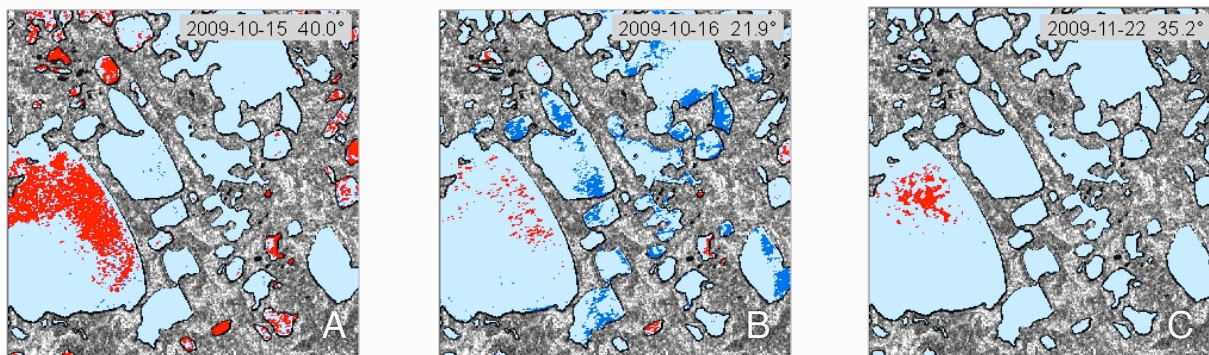
Documentation	Author(s), Title, Occasion / Reference
Presentations: (n=5)	<ul style="list-style-type: none"> <li>◆ T. Geldsetzer, J.J. van der Sanden (2012) Monitoring lake ice with RADARSAT-2, Presentation ParkSpace 2012, (32 slides)</li> <li>◆ J. J. van der Sanden, T. Geldsetzer, H. Drouin (2011) Radar Remote Sensing of Lake and River Ice. Advanced SAR Workshop 2011, St. Hubert (19 slides).</li> <li>◆ T. Geldsetzer, J.J. van der Sanden, B. Brisco (2010) Monitoring lake ice using multi-polarized SAR imagery, Cdn. Remote Sensing Symposium (22 slides)</li> <li>◆ T. Geldsetzer, J.J. van der Sanden (2010) Mapping and monitoring lake ice using radar satellite imagery, Presentation ParkSpace 2010, (30 slides)</li> <li>◆ T. Geldsetzer, J.J. van der Sanden, B. Brisco (2009) Lake ice monitoring using multi-polarized SAR imagery. Presentation at the 30th Cdn. Remote Sensing Symposium, Lethbridge, Alberta, (17 slides).</li> </ul>
Scientific Papers: (n=5)	<ul style="list-style-type: none"> <li>◆ T. Geldsetzer, J.J. van der Sanden (submitted to CJRS). Monitoring lake ice freeze-up using polarimetric and non-polarimetric C-band SAR. 14 p.</li> <li>◆ T. Geldsetzer, J.J. v.d. Sanden, H. Drouin (2011) Advanced SAR applications for Canada's river and lake ice. Proceedings IGARSS'2011, 3 p.</li> <li>◆ T. Geldsetzer, J. van der Sanden, B. Brisco (2010) Monitoring lake ice during spring melt using RADARSAT-2 SAR. CJRS Vol. 36, Supp. 2, pp. S391-S400.</li> <li>◆ T. Geldsetzer, J.J. van der Sanden, B. Brisco (2009) Lake ice monitoring using multi-polarized SAR imagery. Proceeding 31st Can. RS Symposium, 4p.</li> <li>◆ T. Geldsetzer, J.J. van der Sanden, B. Brisco (2009) Lake ice monitoring using multi-polarized SAR imagery. Proceeding 30th Can. Remote Sensing Symposium, Lethbridge, Alberta, Paper No. 465, 10 p.</li> </ul>
Information Products: (n=8)	<ul style="list-style-type: none"> <li>◆ T. Geldsetzer, J.J. van der Sanden (2012) Lake ice freeze-up 2011, Old Crow Flats, Yukon, Canada. Natural Resources Canada, Ottawa.</li> <li>◆ T. Geldsetzer, J.J. van der Sanden (2012) Lake ice break-up 2011, Old Crow Flats, Yukon, Canada. Natural Resources Canada, Ottawa.</li> <li>◆ T. Geldsetzer, J.J. van der Sanden (2012) Draft - Lake ice grounding 2009-2010, Old Crow Flats, Yukon, Canada. NRCan, Ottawa.</li> <li>◆ T. Geldsetzer, J.J. van der Sanden (2012) Lake ice freeze-up 2010, Old Crow Flats, Yukon, Canada. Natural Resources Canada, Ottawa.</li> <li>◆ T. Geldsetzer, J.J. van der Sanden (2012) Lake ice break-up 2010, Old Crow Flats, Yukon, Canada. Natural Resources Canada, Ottawa.</li> <li>◆ T. Geldsetzer, J.J. van der Sanden (2010) Lake ice break-up 2009, Old Crow Flats, Yukon, Canada. Natural Resources Canada, Ottawa.</li> <li>◆ T. Geldsetzer, J.J. van der Sanden (2010) Lake ice break-up 2009, Ukkusiksalik, Nunavut, Canada. Natural Resources Canada, Ottawa.</li> <li>◆ T. Geldsetzer, J.J. van der Sanden (2010) Lake ice break-up 2009, Tukut Nogait, NWT, Canada. Natural Resources Canada, Ottawa.</li> </ul>



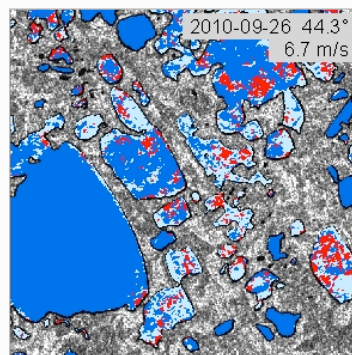
**Figure 4-1.**  
Classified lakes with open water in Old Crow Flats. Image date, incidence angle and wind speed are indicated. Dark blue is water; light blue is ice; red is uncorrelated.  
(A) classified using anisotropic data; (B) classified using sigma-naught backscatter coefficient data.



**Figure 4-2.**  
Classified lakes with complete ice cover in Old Crow Flats. Image date (UTC) and incidence angle are indicated. Dark blue is water; light blue is ice; red is uncorrelated. Different thresholds are used in the classification of A, B and C.

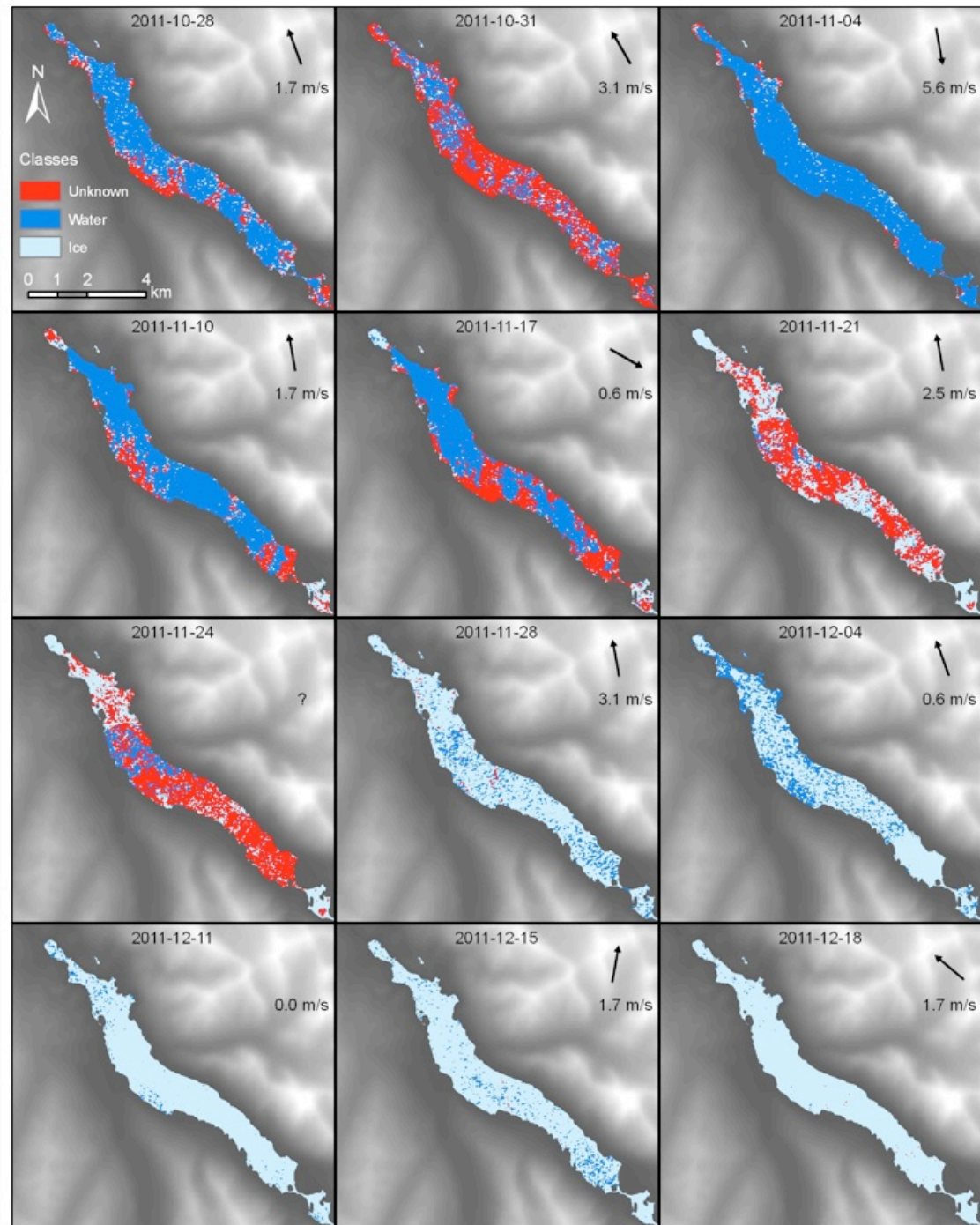


**Figure 4-3.**  
Classified lakes with partial ice cover in Old Crow Flats. Image date (UTC), incidence angle and wind speed are indicated. Dark blue is water; light blue is ice; red is uncorrelated.



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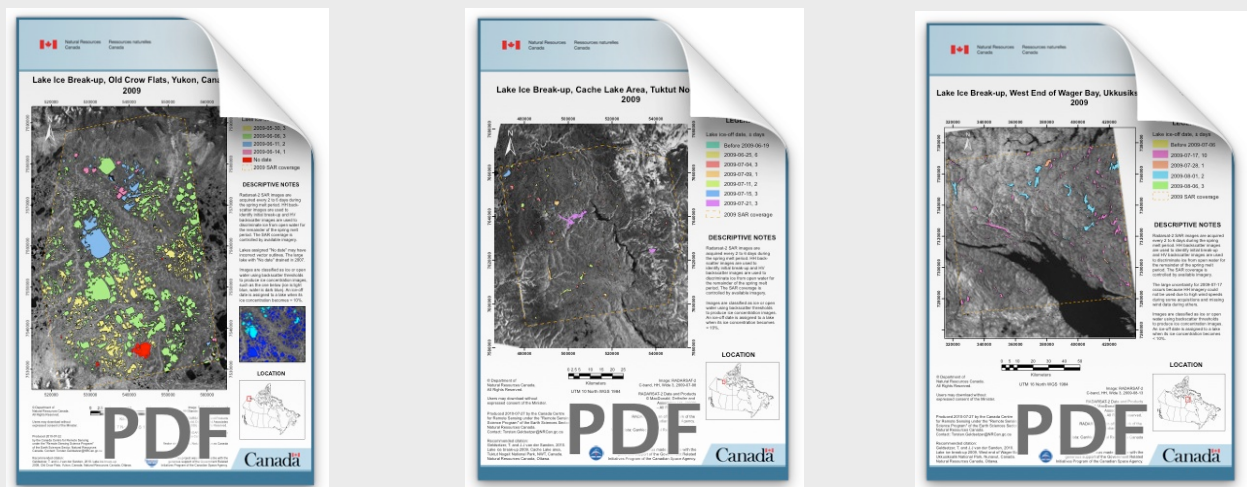
**Figure 4-4.**  
Time series of classified RADARSAT-2 Fine-quad images of Maligne Lake, Jasper National Park for the period of October 28 to December 18, 2011. Dates (UTC) and wind data are for Jasper Warden Station 35 km to the northwest are indicated.



A time series of RADARSAT-2 Fine-quad images acquired over Maligne Lake, Jasper National Park, Alberta, provide additional qualitative assessment of freeze-up conditions (**Figure 4-4**). The 2011 freeze-up season presents a dynamic and challenging test case, as intermittent warm temperatures, and significant rainfall and snowfall following freeze-up, caused both rain-wetted snow and flooded snow conditions. All of the classified images are produced using a specific threshold value in the polarimetric mode.

The discrimination potential for ice/water with C-band SAR is high. Single-pol data must be used with reliable wind data; accuracies in excess of 90% can be achieved if wind speed thresholds are observed. Dual-co-cross-pol data do not provide any improvement, because noise detrimentally affects the cross-pol data. Dual-co-pol data can be used in the absence of wind data; accuracies greater than 76% can be achieved, but the number of unclassified pixels may be high. Polarimetric data can also be used in the absence of wind data, and achieves accuracies greater than 88%. Polarimetric data should be used to identify uncorrelated pixels, resulting in fewer unclassified pixels. Polarimetric data offers the greatest incidence angle range, and can provide ice/water discrimination in all wind conditions. The two most robust polarimetric parameters are the co-pol ratio at medium and larger incidence angles, and anisotropy at small incidence angles.

The lake ice information products (**APPENDIX**, see also **Figure 4-5** and **Figure 4-11**) have the potential to be robust quantifiable climate indicators. However, many more years of data collection are required to identify the trends.



**Figure 4-5.**  
Samples of information products of lake ice break-up, Old Crow Flats (left), Cache Lake (centre) and Ukkusiksalik National Park (right), portable document format, PDF (enlarged versions in **APPENDIX**)

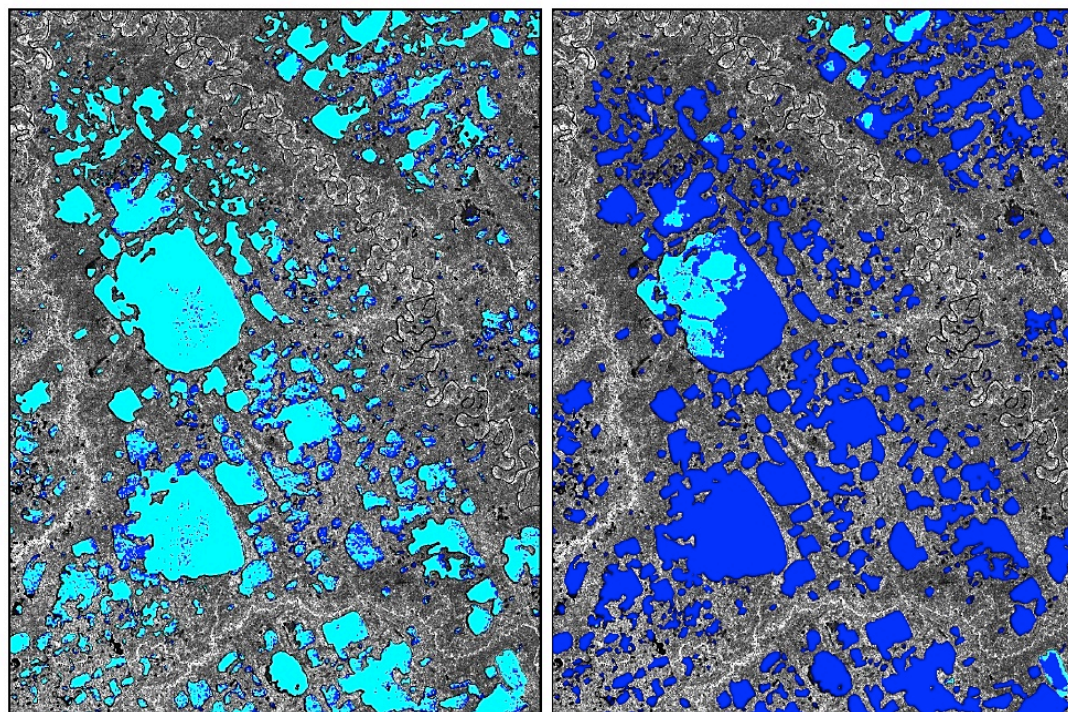


### 4.3 Lake Ice Breakup Monitoring

This component of the GRIP project focused on methods for monitoring and mapping lake ice break-up on Arctic and sub-Arctic lakes using synthetic aperture radar (SAR) imagery from Canada's RADARSAT-2 and other radar satellites. The goal was to provide operational methods and tools to Parks Canada (PC) for their State of the Parks reporting. An additional end-user is the Canadian Ice Service (CIS) of Environment Canada. The research and development activities concentrated primarily data from Old Crow/Vuntut National Park (NP), Yukon. Tests were also conducted for Tuktoyaktuk NP, NWT and Ukkusiksalik NP, Nunavut.

The analysis of Radarsat-2 SAR image data and meteorological data sets concentrated on radar backscatter of lake ice during the spring melt period. A sample classification of lake ice versus open water is shown in **Figure 4-6 (left)** for the initial break-up. During break-up, a sample classification of lake ice versus open water is shown in **Figure 4-6 (right)**. The large areas of open water necessitate the use of HV imagery, because HH imagery is readily wind-

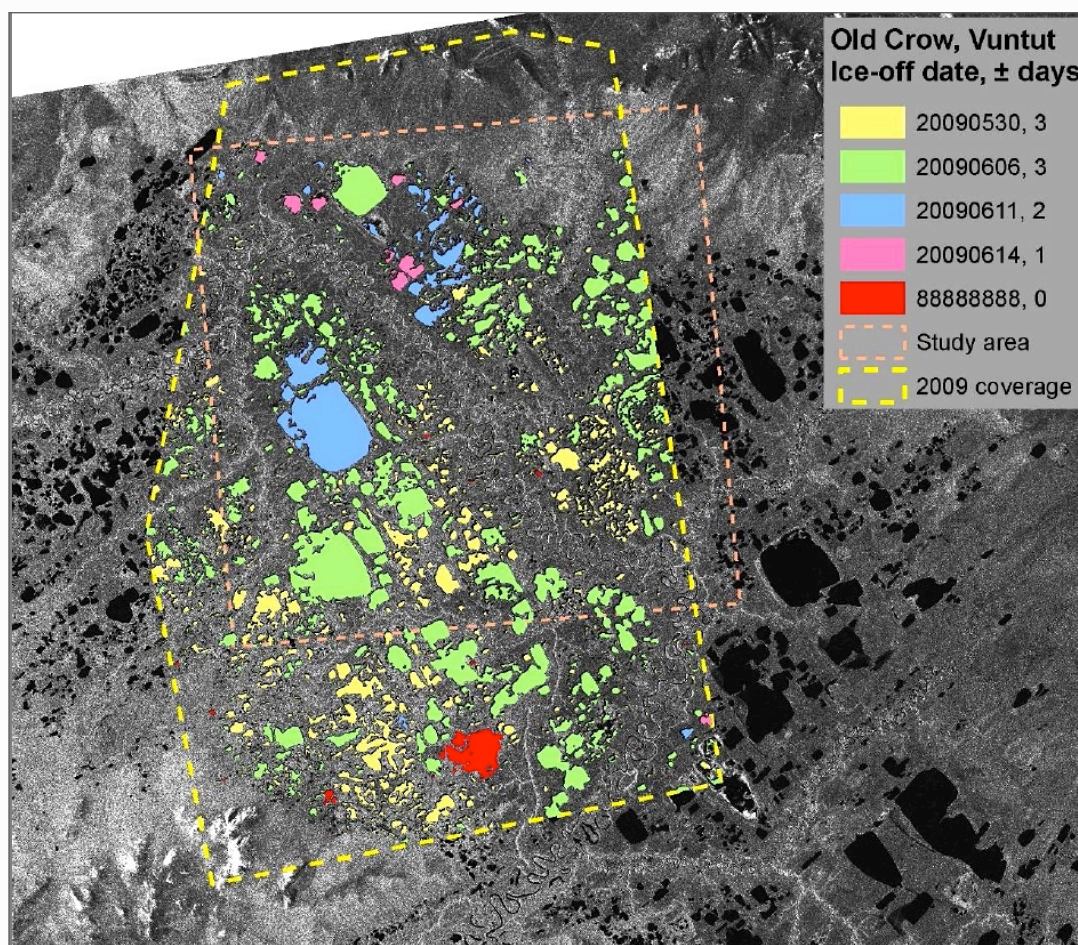
**Figure 4-6.**  
*Lake ice versus open water classification, Old Crow Flats, Vuntut National Park, with subsets of RADARSAT-2 HH image (left) acquired on June 3, 2009 during initial break-up and RADARSAT-2 HV image (right) acquired days later on June 10, 2009. Ice is depicted in light blue, open water is dark blue.*



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affected. These classified SAR images can be used for day-to-day or week-to-week monitoring of lake ice cover. In 2009, all lakes in the Old Crow/Vuntut National Part study area were ice-free by mid June (**Figure 4-7**). Break-up lasted approximately 15 days for the study area. Interestingly, the large lake (Zelma Lake) with “No date”, near the centre-bottom of the map, drained suddenly in 2007, after the creation of the lake polygon dataset. Ice-off mapping can thus be used to identify such recently-drained lakes. Lake ice-off maps were produced for all three National Park study areas. They establish quantitative baseline phenologies for future trend analyses.



**Figure 4-7.**

Map of the Old Crow / Vuntut National Park study area showing lake ice-off dates. Dates are in local time. Projection and datum are UTM 7 WGS 84. Background is a RADARSAT-2 HH Standard mode (S7) image of May 27, 2009.

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The use of satellite SAR data other than the ones mentioned above may enhance the classification accuracy of lake ice and open water during the spring melt period. Visual assessment of the TerraSAR-X imagery suggests that its frequency provides good discrimination of lake ice and open water. X-band has a reduced penetration depth compared to C-band. This may result in a greater sensitivity to snow and ice structure, and may enhance discrimination of lake ice and open water. An examination of RADARSAT-2 Fine-Quad data suggested that the use of the co-pol ratio may be useful if wind data is unavailable.

The examination of ice break-up and its temporal and inter-lake variability has yielded a number of results and observations that provide valuable guidance for practical application of satellite SAR for lake ice break-up monitoring. The studies showed that single co-polarized imagery (*i.e.* HH) can be used to effectively identify the initial break-up; however, the use of HH imagery is limited by the effects of wind once open water is present. Coincident cross-polarized imagery (*i.e.* HV) can be used to effectively discriminate lake ice from open water, even under windy conditions; however, HV imagery has limited capability for identifying initial break-up. Thus, a combination of HH and HV imagery is used to monitor and map lake ice break-up: HH imagery to identify initial breakup, then HV imagery to discriminate lake ice from open water.

Following the encouraging research results, the GRIP project made further contributions toward the operational use of satellite SAR for lake ice break-up mapping and monitoring by establishing application-specific workflow processes and by generating a series of sample information products for Parks Canada. An overview of the workflow associated with monitoring lake ice break-up during the spring melt period is shown in **Figure 4-8**; specific and detailed guidelines for the various steps are provided in the accompanying document "*Interim guidelines for operational implementation of SAR applications for lake ice monitoring and mapping: break-up and freeze-up.*" An overview of the sample information products is shown in **Figure 4-5** and **Figure 4-11**.

The GRIP project highlighted a number of remote sensing related issues concerning the operational implementation process. The size of a study area impacts the choice of SAR imagery. A primary consideration is study area coverage. Standard-beam imagery can reliably cover an area  $< \sim 40 \text{ km} \times 40 \text{ km}$ , for combined ascending and descending passes, and at different beam modes. Similarly, ScanSAR imagery can reliably cover an area  $< \sim 100 \text{ km} \times 100 \text{ km}$ . Furthermore, the size of lakes within a study area may also impact the choice of SAR imagery. Preliminary experience suggests that for lakes larger than 50 ha a coarser



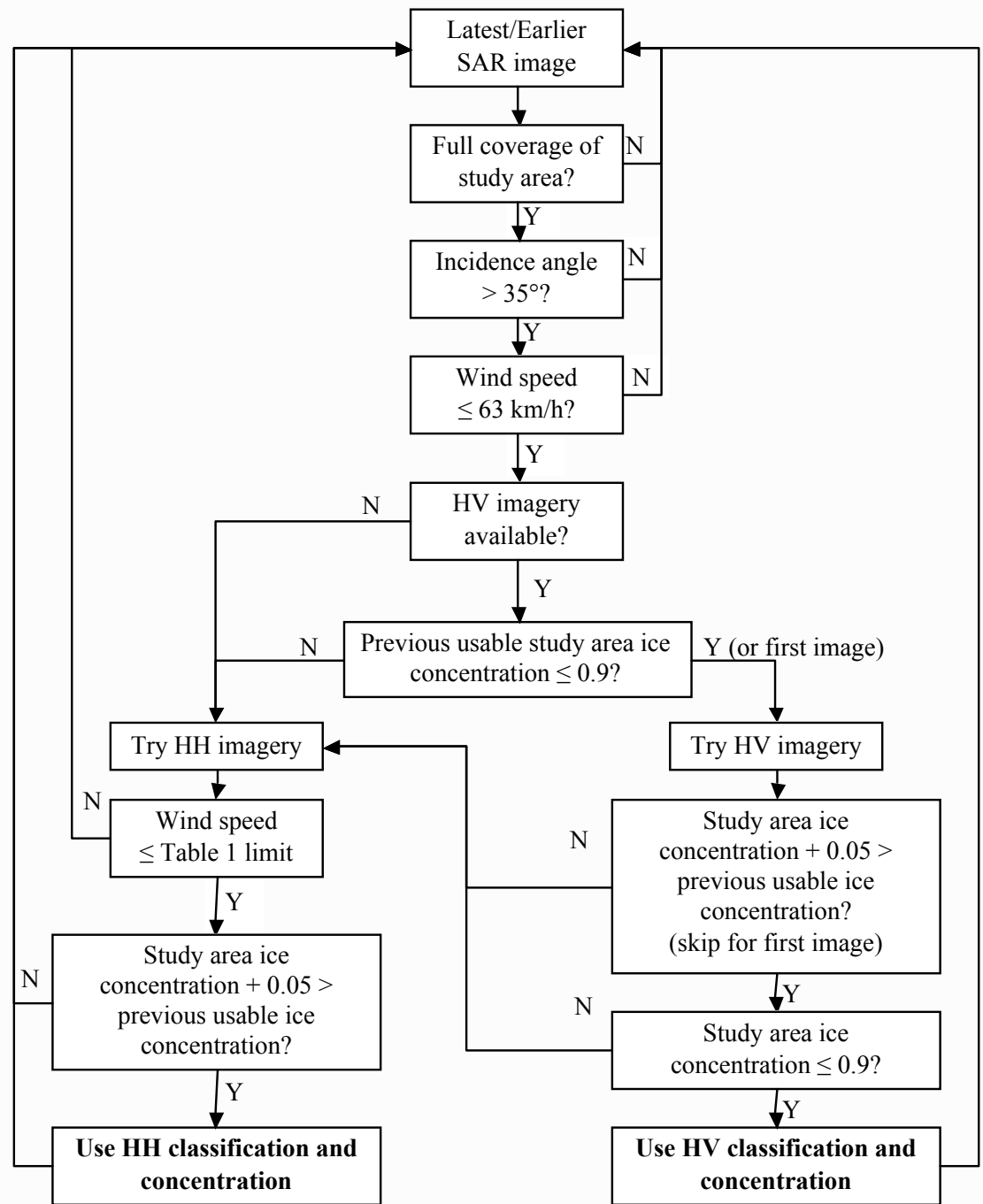


Figure 4-8.  
Workflow steps to monitor lake ice break-up  
during the spring melt period



spatial resolution can be used; however, if the lakes are smaller than 50 ha, then a finer spatial resolution may be needed. In terms of satellite SAR imagery, areas of interest with lakes larger than 50 ha can be readily monitored using ScanSAR Wide imagery (50 m × 50 m pixels); areas with lakes smaller than 50 ha should rely on Standard beam imagery (12.5 m × 12.5 m pixels), or even Fine beam imagery (5 m × 5 m pixels).

Satellite SAR image collection for the spring melt period can be a complex, if not conflicting, undertaking considering actual data acquisition dates and specific radar parameters. Initial estimates to capture the onset of lake ice break-up should be based on air temperature data and on lake ice phenology estimates. For subsequent annual SAR time series, the ice-off data can be used to estimate likely date ranges. The frequency of SAR observations is an operational decision as it is limited by the number and availability of satellite overpasses at the proper beam mode. The accuracy of the available lake vector data may affect the classification of lake ice versus open water.

There are a number of RADARSAT-2 parameters of relevance to lake ice break-up monitoring activities. The following recommendations apply. HH and HV are the polarizations of choice. Either ascending or descending orbital passes of the satellite are suitable for data acquisition; one may be preferred over the other if steep mountains are adjacent to lakes. The “ice” option should be specified for the image scaling lookup table (LUT); “mixed” can also be chosen if the imagery is also used for other purposes. Standard beam modes S5, S6 and S7 are preferred, with SGF processing specification applied; S4 is optional if frequency of coverage and coverage area are an issue. 16-bit ScanSAR Narrow B and ScanSAR Wide A are preferred ScanSAR options, principally because of incidence angle considerations.

#### **4.4 Bottom-fast Lake Ice Mapping**

The identification of grounded, or bottom-fast, ice is useful for various fields, and various radar remote sensing studies have been conducted to study the bottom-fast lake ice phenomena. Combined with lake bathymetry data, the grounding line can be used to estimate the ice thickness; conversely, combining modelled ice thickness with the location of the grounding line can be used to estimate lake bathymetry. Knowledge of whether or not lakes become totally bottom-fast is useful to evaluate the viability of lakes for fish and other wildlife that require water beneath the ice. For northern transportation, water extraction for ice road construction is preferred from lakes that will be grounded.



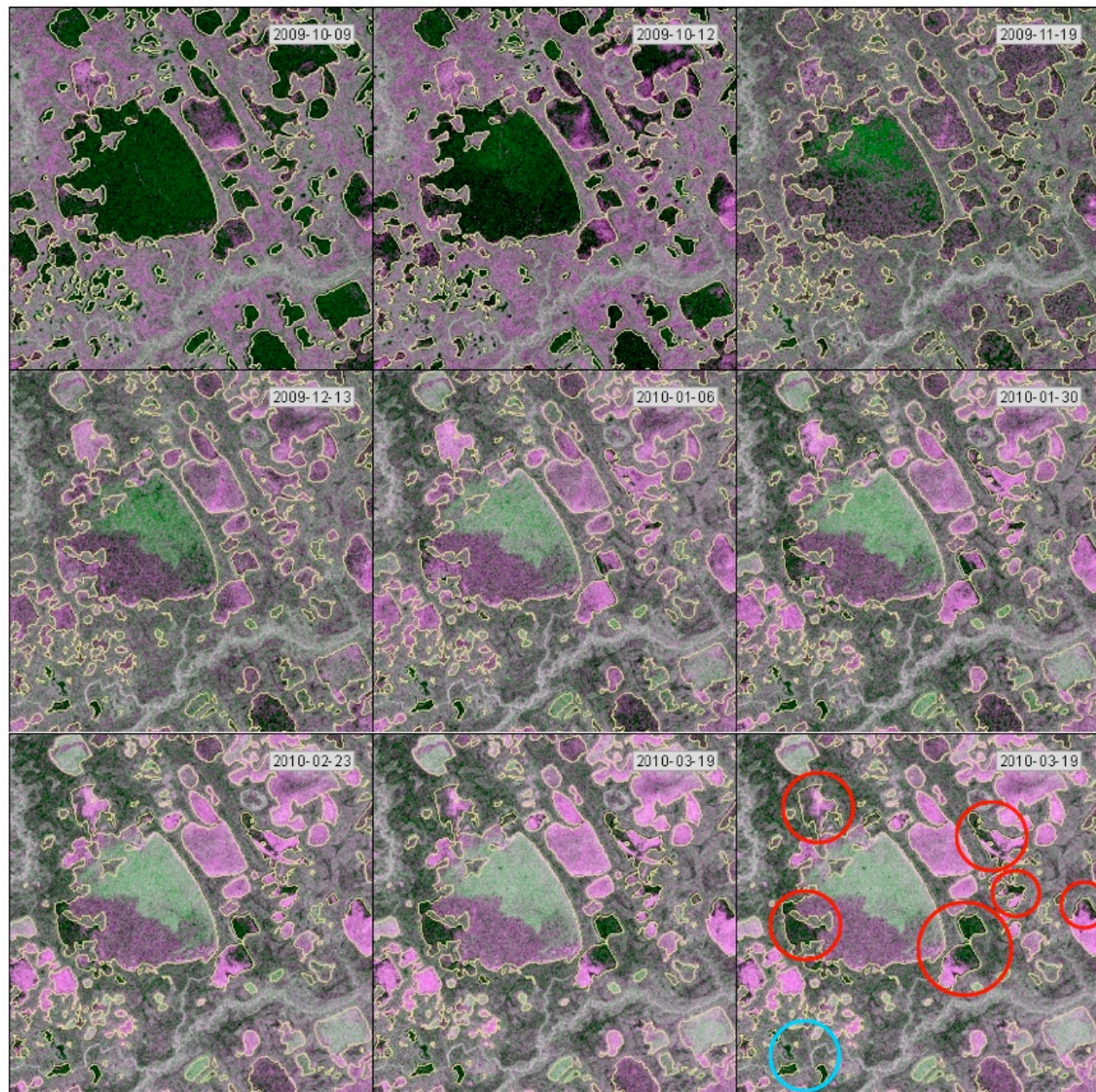
The identification of grounded lakes is possible using satellite SAR in general and RADARSAT in particular. Microwaves readily penetrate a freshwater ice cover to the underlying water or ground; ice penetration depths at C-band are on the order of several meters. Distinct backscatter signatures, exhibited by floating or grounded ice, result from different scattering properties at the base of the ice. At an ice-ground interface, the dielectric mismatch is relatively small: lake ice is  $\sim 3.18$  and the lake bottom sediment is  $\sim 6$ , allowing the incident microwaves to penetrate into the underlying sediments, where absorption occurs. Therefore, the relative backscatter from grounded ice is usually significantly less than the backscatter from floating lake ice.

The GRIP project contributed to an initial assessment of both polarimetric and non-polarimetric C-band SAR parameters for their efficacy in detecting lake ice grounding in the Old Crow Flats study area. This was done using RADARSAT-2 Standard beam and Fine-quad data throughout the incidence angle range to provide guidance for scientific and operational implementation. A time series of a portion of the study area shows expected grounding signatures for several lakes (*Figure 4-9*). The first two images have an incidence angle of  $\sim 24^\circ$ , the rest  $\sim 28^\circ$ . The time series begins a few days after freeze-up. At first, the backscatter from lakes is very low; it increases for most floating ice as winter progresses. The increase in backscatter from floating ice over time is likely caused by increasing air bubble number density. The purple lake areas are likely congelation ice with basal tubular air bubbles. The green lake areas are likely also primarily congelation ice with basal tubular air bubbles, but the higher HV volume scattering a significant layer of snow-ice at the surface. Lake ice grounding is clearly evident for the lakes, or portions of them. Their locations are indicated by red circles in *Figure 4-10*. The expected decrease in backscatter progresses inwards from the lake edge over time. These lakes, or portions of them, are likely shallower than neighbouring lakes. The low backscatter for some lakes does not noticeably increase during the winter (blue circle). These are not necessarily grounded. The mechanism for consistently low backscatter is unclear.

The work indicated that HH has the greatest potential, especially at small incidence angles. It exhibits the greatest floating/grounded difference, in dB. HH is not limited by Fine-quad spatial coverage, and grounded ice values are above the noise floor of all RADARSAT-2 beam modes. VV is the second choice; the floating/grounded difference is not as large as for HH, but it performs well at small incidence angles, as shown by the backscatter graph in *Figure 4-10*.

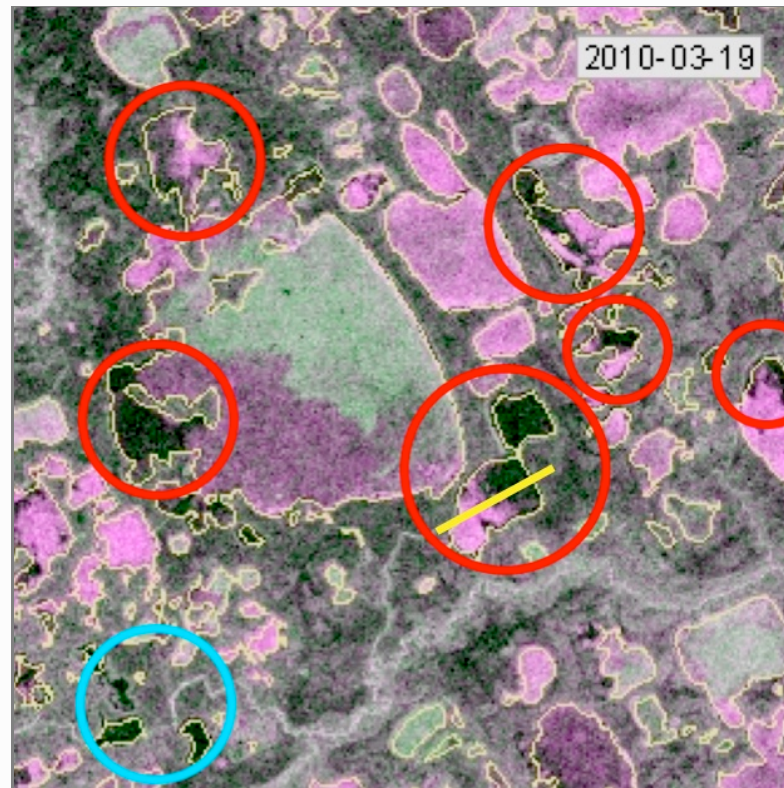


**Figure 4-9.**  
*Time series of 9 RADARSAT-2 Standard  
 beam images taken between October 9,  
 2009 and March 19, 2010 of the Old Crow  
 Flats study area for bottom-fast ice  
 mapping. RGB = C-VV, C-HV and C-VV  
 respectively; all images have a common  
 radiometric scaling.*



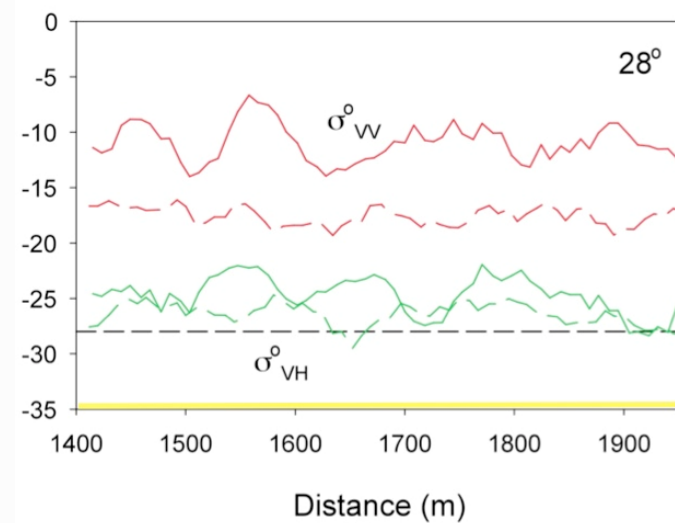
RADARSAT-2 Data and Products (c) MacDonald, Dettwiler and Associates Ltd. 2009, 2010, 2011. All Rights Reserved.





**Figure 4-10.**  
*RADARSAT-2 Standard mode imagery (S2, at 28° incidence angle, VV, HV) taken in late winter on March 19, 2010, showing a portion of the Old Crow Flats. Red circles indicate lake ice grounding (darker areas); blue circle indicates lakes with consistently low backscatter. Yellow line in image refers to the transect of VV and VH backscatter change, shown below; the noise floor is indicated by the stippled line.*

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 Dettwiler and Associates Ltd., 2010  
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The most robust classification method for grounded ice appears to be subtraction of an earlier image from a later one. If this is done for HH or VV in dB, the change is several dB less for grounded ice in the later image. As a working rule-of-thumb, backscatter decreases of less than 3.5 dB are not considered to have grounded. Decreases between 3.5 dB and 5 dB are likely grounded; and decreases of greater than 5 dB (~ 99% confidence level) are very likely grounded.

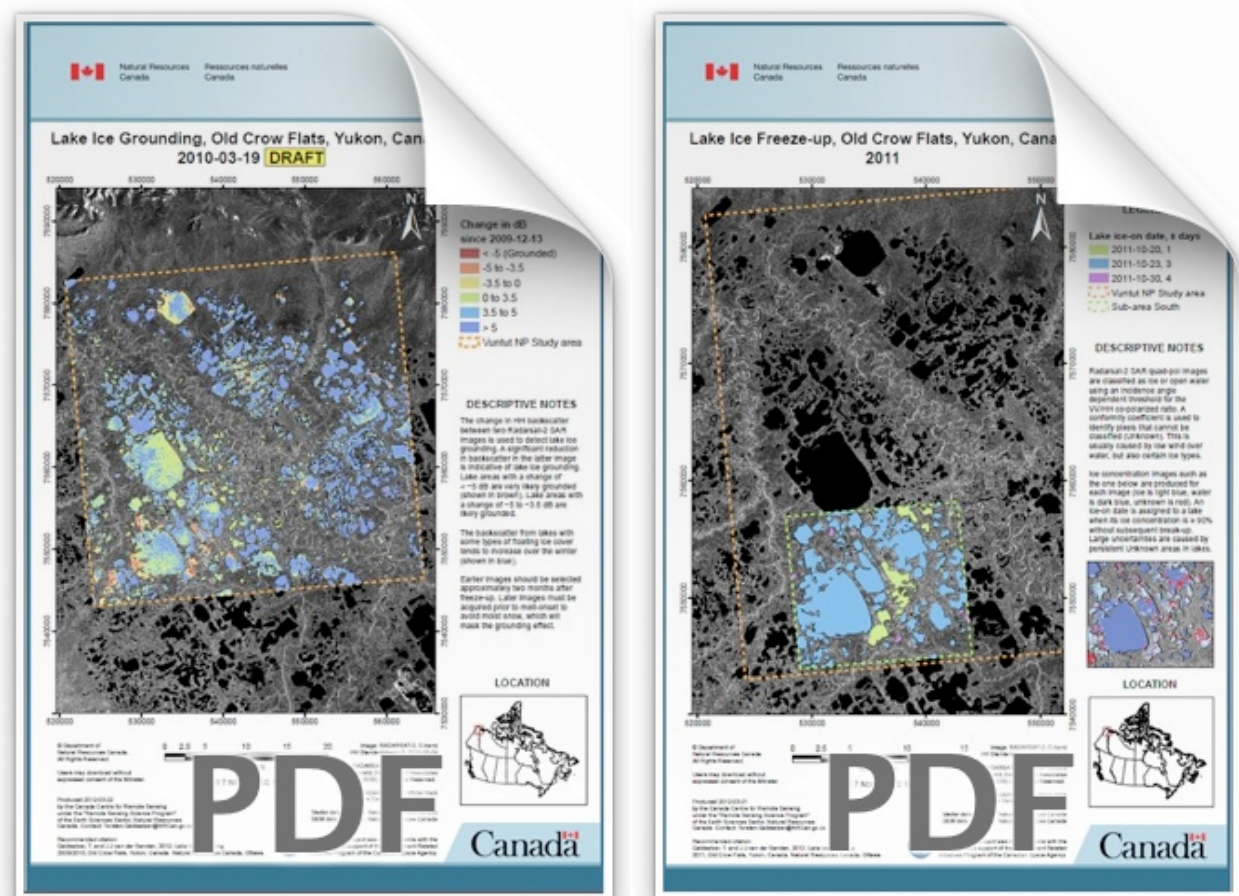


Figure 4-11.

Sample information products of lake ice grounding and lake ice freeze-up for the Old Crow Flats study area, portable document format, PDF (enlarged version in APPENDIX)

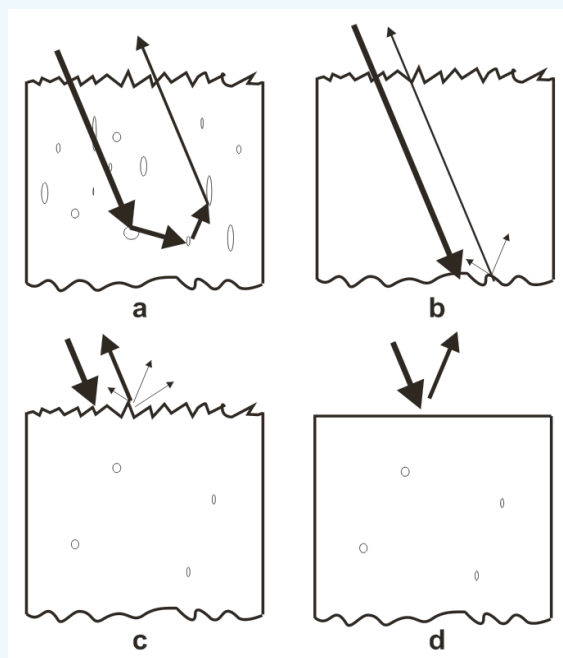


## Section 5:

# Mapping and Monitoring of River Ice

### 5.1 Overview

River ice affects natural processes and human activities and therefore represents a significant component of the environment in northern countries like Canada. Information on river ice cover supports science, engineering and management activities including: hydraulic modelling, breakup forecasting, ice road routing, industrial water intake / discharge, hazard management, and wildlife management. River ice cover variables of interest typically include: coverage, type, thickness, and condition. Synthetic Aperture Radar (SAR) satellites make potentially outstanding tools for collecting up-to-date information on river ice thanks to their capability to routinely and systematically image extensive remote areas independent of weather and daylight conditions. During winter, when the ice is frozen solid, SAR satellites offer sensitivity to the physical structure of ice because radar waves will penetrate 'dry' ice cover and interact with features that define its internal properties. This GRIP project component focused on river ice breakup monitoring, bottom fast river ice monitoring, and on mapping river ice cover conditions.



The scattering behaviour of river ice is dominated by surface scattering and volume scattering mechanisms, as illustrated, at left (a-d). Depending on the nature of the reflection, surface scattering is dominated by either specular or diffuse reflection. Volume scattering occurs when incident microwaves penetrate the surface of a dry snow and/or ice layer and are being reflected repeatedly at dielectric discontinuities within that layer. The dimensions of these discontinuities need to be of a scale similar to the wavelength of the incident microwaves. Volume scattering typically results in a significant amount of radar backscatter. Dielectric discontinuities that may be found in river ice include cracks, air inclusions (e.g. bubbles), liquid water pockets, and impurities. Highly inhomogeneous ice covers (a) can be expected to generate a higher radar return



than ice covers that are more uniform in composition **(b)**. A smooth, wet ice surface (i.e. an ice cover with water ponded on the surface, or on which the lower layers of the snow cover are saturated, both typical conditions at breakup) will specularly reflect or absorb incident microwave energy and hence show relatively dark in a radar image **(d)**. In contrast, diffuse reflection occurs at relatively rough surfaces. A rough, wet ice surface will initiate diffuse scattering, reflecting microwaves nearly uniformly in all directions **(c)**; it will appear relatively bright in a radar image.

**Table 5-1** contains a summary of the river ice related documentation produced under the GRIP project in terms of reports, scientific papers published in learned journals or conference proceedings, presentations at workshops and conferences, posters exhibited at workshops and conferences, as well as sample information products developed for the clients.

**Table 5-1**  
Documentation of GRIP project  
research related to river ice

Documentation	Author(s), Title, Occasion / Reference
Reports: (n=7)	<ul style="list-style-type: none"> <li>◆ H. Drouin, J.J. van der Sanden (2012) Fieldwork report, Winter 2012, Mackenzie Delta, Ice characterization and GPR measurements. CCRS 18 p.</li> <li>◆ J.J. van der Sanden, H, Drouin (2011) Satellite SAR observations of spring breakup, Mackenzie River Delta: Product generation details. CCRS Internal Report, 5 p.</li> <li>◆ H. Drouin (2011) Fieldwork report, Winter 2011, Red River, Manitoba, Characterization of the river ice cover. CCRS 17 pages.</li> <li>◆ H. Drouin, J.J. van der Sanden (2010) Groundfast Ice Mapping – Mackenzie Delta 2010. CCRS, 4 p.</li> <li>◆ H.Drouin and J.J. van der Sanden (2010) Fieldwork report, Winter 2010, Mackenzie Delta, Groundfast, river and lake ice. CCRS 16 pages.</li> <li>◆ J. Nafziger, F. Hicks, J. Morley (2010) Spring 2008 Ice cover condition maps for the Mackenzie River Delta - An Evaluation. Water Resources Engineering Department, University of Alberta, Edmonton, 2 p.</li> <li>◆ H. Drouin, J.J. van der Sanden (2009) Fieldwork report, Winter 2009, Mackenzie Delta River and lake ice. CCRS, 11 p.</li> </ul>

*(continued next page)*



*Table 5-1 (continued).  
Documentation of GRIP project  
research related to river ice*

Documentation	Author(s), Title, Occasion / Reference
Presentations: (n=10)	<ul style="list-style-type: none"> <li>◆ J.J. van der Sanden, T. Geldsetzer, H. Drouin (2011) Radar remote sensing of lake and river ice. 8th Advanced SAR (ASAR) Workshop (19 slides).</li> <li>◆ K. Lindenschmidt, J.J. van der Sanden, A. Demski, H. Drouin, T. Geldsetzer (2011) Characterizing river ice along the Lower Red River using RADARSAT-2 imagery. 16th CRIPE Workshop on River Ice (16 slides).</li> <li>◆ K. Lindenschmidt, J.J. van der Sanden, M. Sydor, R. Carson (2011) Remote sensing for ice monitoring and ice jam modelling of the Red River (42 slides)</li> <li>◆ J.J. van der Sanden, H. Drouin. (2011) Polarimetric RADARSAT-2 for river freeze-up monitoring. POLINSAR 2011 Workshop, Frascati, Italy (10 slides)</li> <li>◆ J.J. van der Sanden, H. Drouin (2011) Satellite SAR observations of river ice cover: A RADARSAT-2 (C-band) and ALOS PALSAR (L-band) comparison. Presentations at the 16th CRIPE Workshop on River Ice, Winnipeg (17 slides)</li> <li>◆ J.J. van der Sanden, H. Drouin, F. E. Hicks, S. Beltaos (2009) Potential of RADARSAT-2 for the monitoring of river freeze-up processes. Proceedings of the 15th CRIPE Workshop on River Ice, St. John's (27 slides)</li> <li>◆ J.J. van der Sanden, H. Drouin (2010) RADARSAT-2 applied to the monitoring of river freeze-up. 3rd RADARSAT-2 Workshop 2010 (9 slides)</li> <li>◆ J.J. van der Sanden, H. Drouin, F. E. Hicks, S. Beltaos (2009) Potential of RADARSAT-2 for the monitoring of river freeze-up processes. 15th CRIPE Workshop on River Ice, St. John's, NL (17 slides)</li> <li>◆ J.J. van der Sanden and H. Drouin (2008). RADARSAT-2 Data Applied to the Monitoring of River Ice. RADARSAT-2 Workshop (17 slides).</li> <li>◆ J.J. van der Sanden (2007) River ice monitoring from space; advances in satellite radar technology and effects on application potential, 14th Workshop of the Committee on River Ice Processes and the Environment (14 slides).</li> </ul>
Information Products: (n=25)	<ul style="list-style-type: none"> <li>◆ J.J. van der Sanden and H. Drouin (2012) Spring 2008 Flood Condition, Mackenzie River Delta, Northwest Territories, Canada. CCRS Map Product Portfolio (11 GIS-ready maps) Ottawa, Natural Resources Canada.</li> <li>◆ J.J. van der Sanden and H. Drouin (2011) 2010 and 2011 Ice Cover Conditions Along the Lower Red River, Manitoba. CCRS Map Product Portfolio (2 maps) Ottawa, Natural Resources Canada.</li> <li>◆ J.J. van der Sanden and H. Drouin (2011) Winter 2010 Bottom Fast Ice Distribution in the Mackenzie River Delta, Northwest Territories. CCRS GIS-ready Map Product, Ottawa, Natural Resources Canada.</li> <li>◆ J.J. van der Sanden and H. Drouin (2010) Spring 2008 Ice Cover Condition, Mackenzie River Delta, Northwest Territories, Canada. CCRS Map Product Portfolio (11 GIS-ready maps) Ottawa, Natural Resources Canada.</li> </ul>

*(continued next page)*



*Table 5-1 (continued).  
Documentation of GRIP project  
research related to river ice*

Documentation	Author(s), Title, Occasion / Reference
Scientific Papers: (n=17)	<ul style="list-style-type: none"> <li>◆ S. Mermoz, S. Allain, M. Bernier, E. Pottier, J.J. van der Sanden, K. Chokmani (2012, in prep.) Retrieval of river ice thickness from C-band PolSAR data. Paper submitted for IGARSS'12, 4 p.</li> <li>◆ K. Lindenschmidt, J.J. van der Sanden, A. Demski, H. Drouin, T. Geldsetzer (2011) Characterizing river ice along the Lower Red River using RADARSAT-2 imagery. Proceedings of the 16th CRIPE Workshop on River Ice, 16 p.</li> <li>◆ J.J. van der Sanden, H. Drouin. (2011) Polarimetric RADARSAT-2 for river freeze-up monitoring - Preliminary results. Proceedings of POLINSAR 2011, Frascati, Italy, 8 p.</li> <li>◆ J.J. van der Sanden, H. Drouin (2011) Satellite SAR observations of river ice cover: A RADARSAT-2 (C-band) and ALOS PALSAR (L-band) comparison. Proceedings of the 16th CRIPE Workshop on River Ice, Winnipeg, pp. 179-197.</li> <li>◆ T. Geldsetzer, J.J. van der Sanden, H. Drouin (2011) Advanced SAR applications for Canada's river and lake ice. Proceedings IGARSS'11, 3 p.</li> <li>◆ J.J. van der Sanden, H. Drouin, F. E. Hicks, S. Beltaos (2009) Potential of RADARSAT-2 for the monitoring of river freeze-up processes. Proceedings of the 15th CRIPE Workshop on River Ice, St. John's, NL, pp. 364-377.</li> <li>◆ K. D. Unterschultz, J.J. van der Sanden, F. Hicks (2009) Potential of RADARSAT-1 for the monitoring of river ice. Cold Regions Science and Technology, Vol. 55, pp. 238-248.</li> </ul>
Posters: (n=6)	<ul style="list-style-type: none"> <li>◆ T. Geldsetzer, J.J. van der Sanden, H. Drouin (2011) Advanced SAR applications for Canada's river and lake ice. IGARSS'11, Hawaii, USA.</li> <li>◆ J. Morley, J. Nafziger, F.E. Hicks, P. Marsh, L. Lesack, S. Beltaos, J.J. van der Sanden, T. Carter (2011) Modelling the effects of ice on flow distributions in the Mackenzie Delta, 16th Workshop on River Ice, Winnipeg, Manitoba.</li> <li>◆ J. Nafziger <i>et al.</i> (2010) Update on Mackenzie Delta hydrodynamic model and 2008 river breakup progression mapping as part of the IPY-SCARF project. Understanding Circumpolar Ecosystems in a Changing World / Outcomes of the International Polar Year, Edmonton, Alberta.</li> <li>◆ K.-E. Lindenschmidt, J.J. van der Sanden (2010) Mapping ice characteristics along the Red River using RADARSAT-2 satellite imagery, Winnipeg.</li> <li>◆ J.J. van der Sanden, H. Drouin, S. Beltaos, F.E. Hicks (2009) Satellite Radar Observations of Spring Ice Breakup in the Mackenzie Delta, Poster presented at: 15th Workshop on River Ice, St. John's, NF, 15-17 June 2009</li> <li>◆ J.J. van der Sanden, H. Drouin (2008) Satellite SAR Applied to the Monitoring of Spring Ice Breakup and Flooding in the Mackenzie River Delta. Arctic Change 2008, Quebec City, QC.</li> </ul>



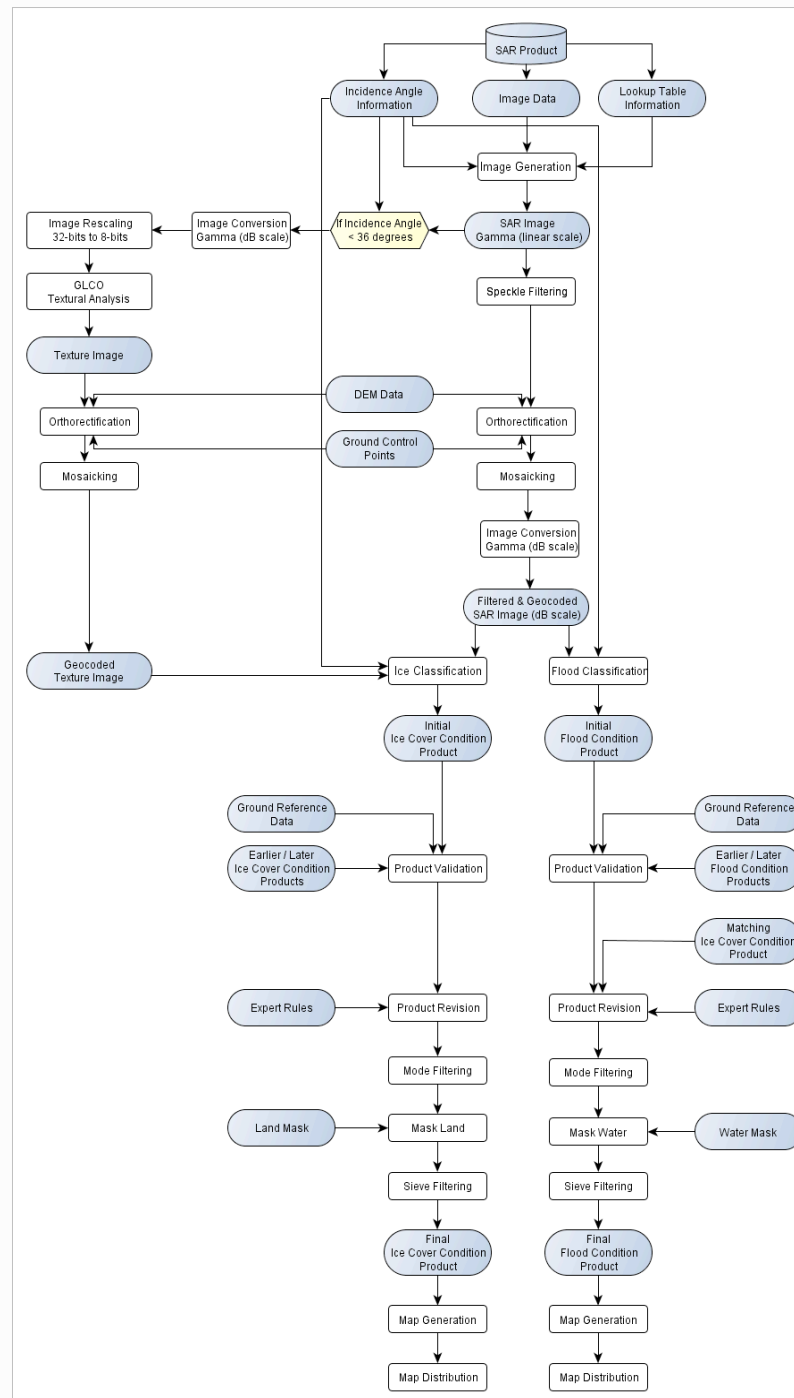
## 5.2 River Ice Breakup Monitoring

Spring breakup in the Mackenzie River Delta is a major hydrologic event that affects many physical, chemical and biological aspects of the delta's ecosystem as well as of the adjoining Arctic Ocean. The breakup of ice cover on the multitude of channels and lakes comprised in the delta is typically accompanied by extensive overland flooding resulting from increased discharge and, at times, the formation of ice jams. The hydraulic processes associated with breakup in the Mackenzie River Delta are presently not well understood.

As part of the 2008 International Polar Year, information about the process of spring breakup in the Mackenzie River Delta was recorded in the form of 22 GIS-ready maps showing ice cover conditions and flood conditions. These maps were based in part on RADARSAT-1, RADARSAT-2 and Envisat ASAR satellite SAR imagery. During the 2008 spring ice breakup season, three radar satellites were tasked to image the Mackenzie River Delta at time intervals ranging from 1 to 3 days. The images acquired enabled partners from the University of Alberta in the development and validation of a hydrodynamic model for the Mackenzie River Delta. The method developed for the generation of the ice cover condition and flood condition products is summarized in *Figure 5-1*. The ice cover condition maps discriminate between 'water' and three classes each for ice cover conditions identified as 'sheet ice' or 'rubble ice' (*Figure 5-2, Figure 5-3, APPENDIX*). The flood condition maps, on the other hand, discriminate between 'floodwater' and three classes each of 'flooded vegetation' and 'other land cover' (*Figure 5-4, Figure 5-5, APPENDIX*). Ground reference information in the form of visual observations, photographs and videos obtained by means aerial surveys was used as much as possible to validate the maps produced. The validation efforts focused on the confirmation of the information with respect to ice cover and flood conditions in the Mackenzie River Delta as opposed to in adjoining areas such as the Beaufort Sea, the Caribou Hills, and the Richardson Mountains.

Apart from the Mackenzie River Delta study, the GRIP project focused on ice conditions on the Red River in Manitoba. The ice cover season along the Lower Red River typically extends from November to April. Once formed, the ice cover tends to remain in place through the entire winter and measures up to 1 m in thickness. Spring flooding is frequently exacerbated by mechanical ice breakup and ice jamming, especially during early and rapid melt events. Since recorded history, ice jams have plagued this area. The river at Selkirk and north of Selkirk are particularly prone to ice jam flooding.





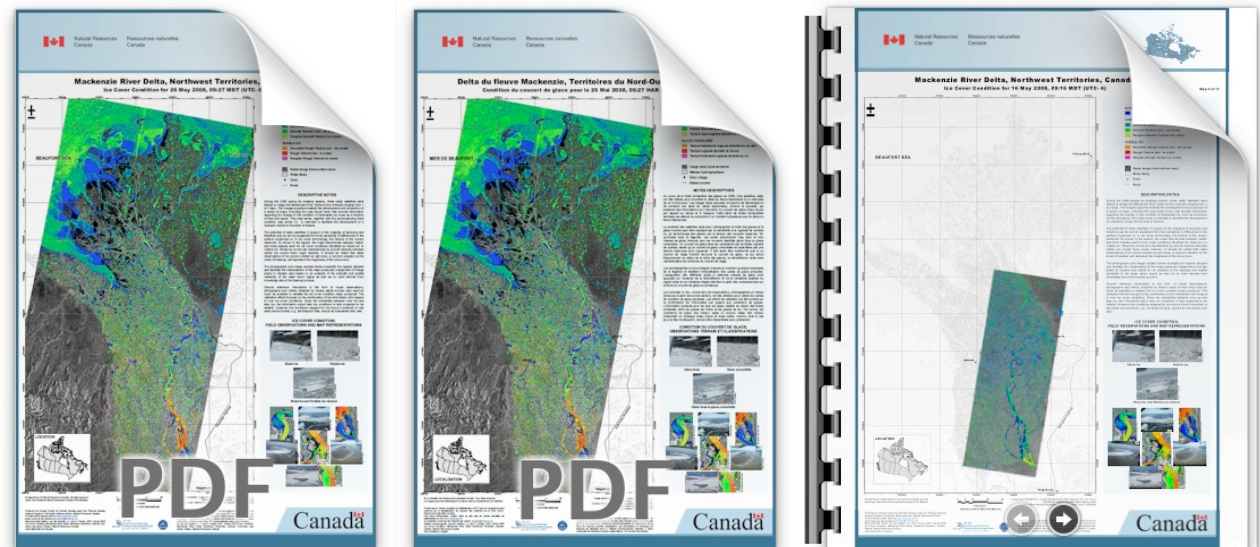
**Figure 5-1.**  
Flowchart summarizing  
the method developed for  
the generation of ice  
cover condition and flood  
condition maps.



The type of ice that forms during freeze-up can have a significant influence on the ice break-up and jamming behaviour during the onset of spring flooding. In response to this tendency of increased frequency and severity of ice jamming and ice jam flooding, provincial and municipal government agencies have implemented ground penetrating radar surveys to map ice thickness and the subsequent deployment of ice cutting and breaking machinery to reduce the risks of jamming and flooding at breakup. There is a need for information on the ice types along the Red River on a large spatial extent acquired with a reasonable time resolution. In particular, space-borne remote sensing has the capability to routinely image the river's ice cover in a systematic, synoptic and repetitive manner. RADARSAT-2 proved useful for monitoring river ice freeze-up (*Figure 5-6*) and the mapping of winter river ice cover (*Figure 5-7*). The ice type map from winter 2011 was successfully implemented to better orient ice thickness surveys using ground penetrating radar technology. The GRIP project research also provides a basis for exploring differences in ice strength and thermal characteristics between the various ice cover types, which is a topic of future work. A detailed account of the Red River ice study was prepared by *Lindenschmidt et al. 2011*.

**Figure 5-2 (left, centre).**  
Sample information product of ice conditions, Mackenzie River Delta, May 26, 2008, in English and French, portable document format, PDF (enlargements in APPENDIX)

**Figure 5-3 (right).**  
Portfolio of information products showing a time series of eleven ice condition maps, Mackenzie River Delta, for the period of May 16 to June 22, 2008 (enlargement in APPENDIX)



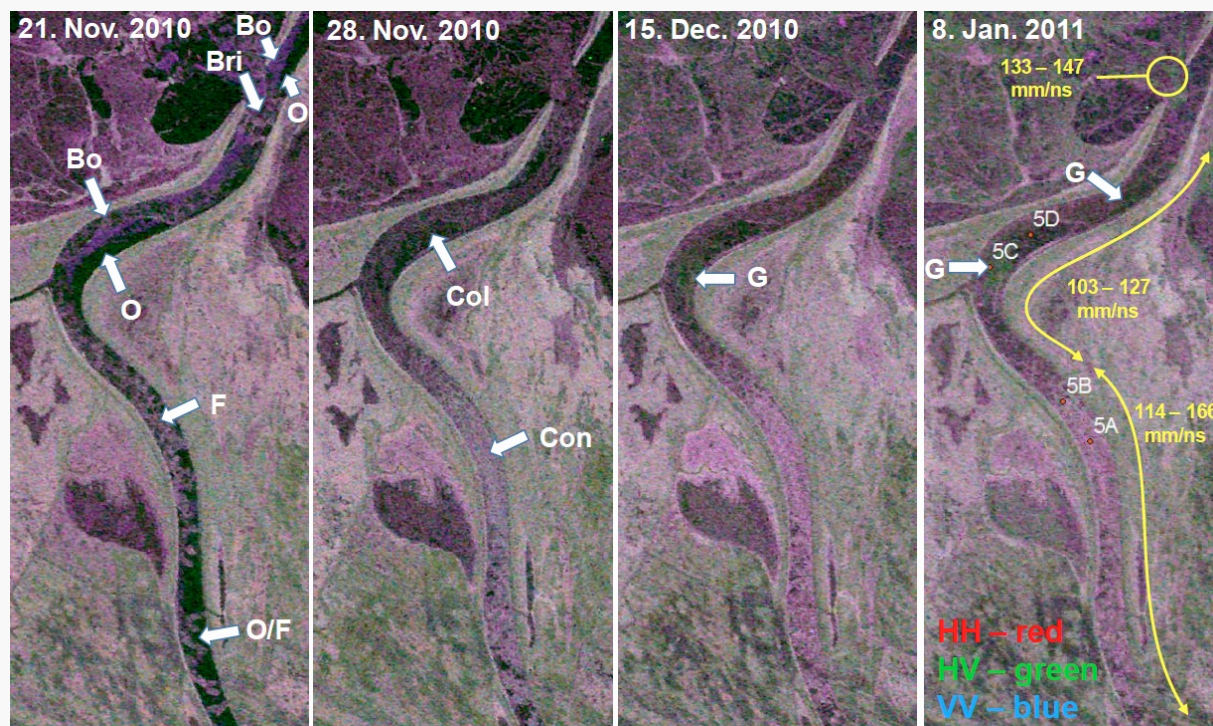


**Figure 5-4 (left, centre).**  
Sample information product of flood conditions, Mackenzie River Delta, May 26, 2008, in English and French, portable document format, PDF (enlargements in APPENDIX)



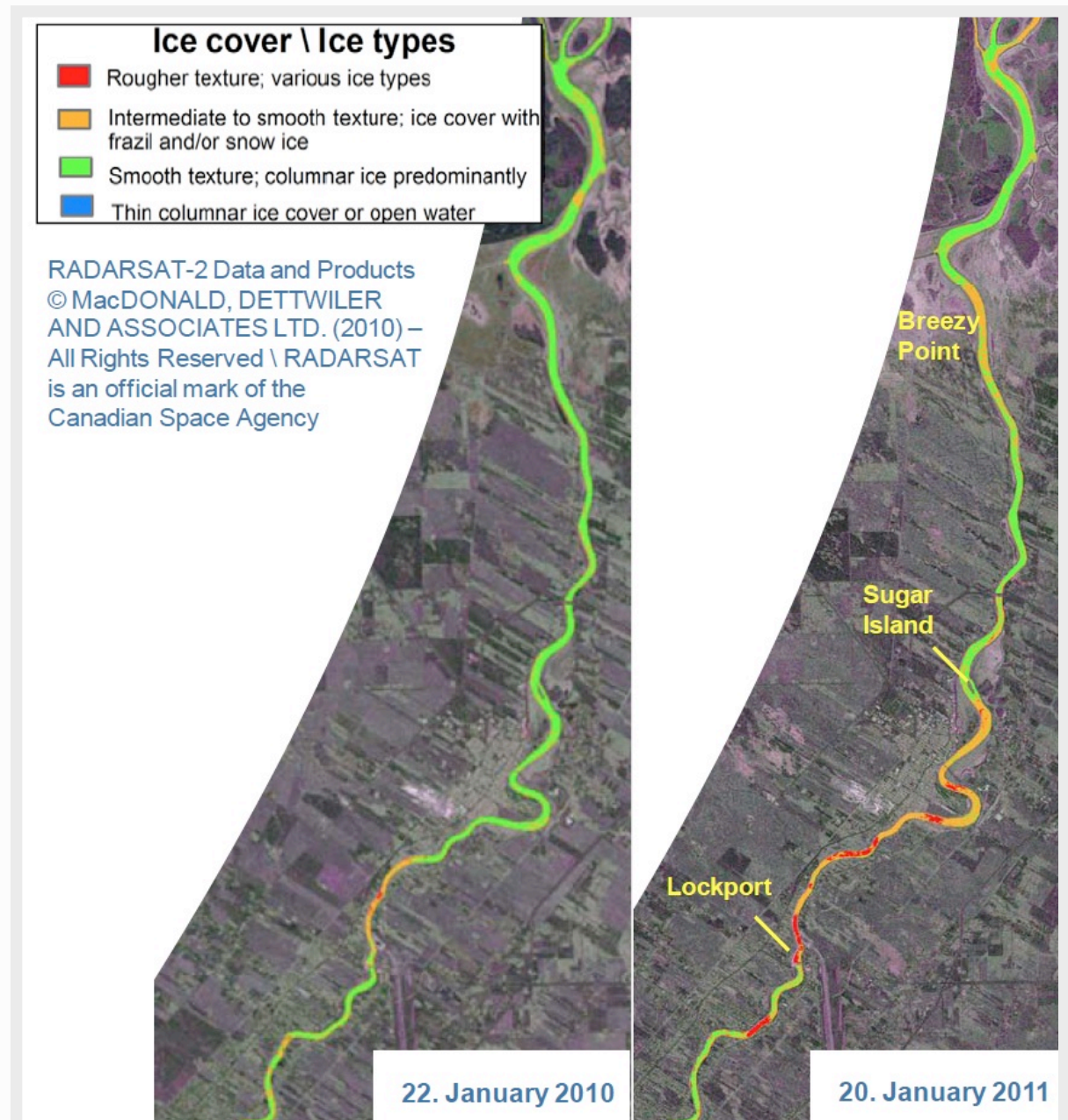
**Figure 5-5 (right).**  
Portfolio of information products showing a time series of eleven flood condition maps, Mackenzie River Delta, for the period of May 16 to June 22, 2008 (enlargement in APPENDIX)

**Figure 5-6.**  
Area detail of RADARSAT-2 Fine-quad SAR imagery tracking the freeze-up processes of the Lower Red River in Manitoba at Breezy Point. HH-, HV- and VV polarizations are shown in red, green and blue, respectively. O = open water, F = floes, Col = columnar ice, Con – consolidated ice, Bo = border ice, Bri = ice bridging, G = frazil or snow ice. Yellow text and markings in far right imagery indicate ranges of ground penetrating radar velocities through the ice cover.



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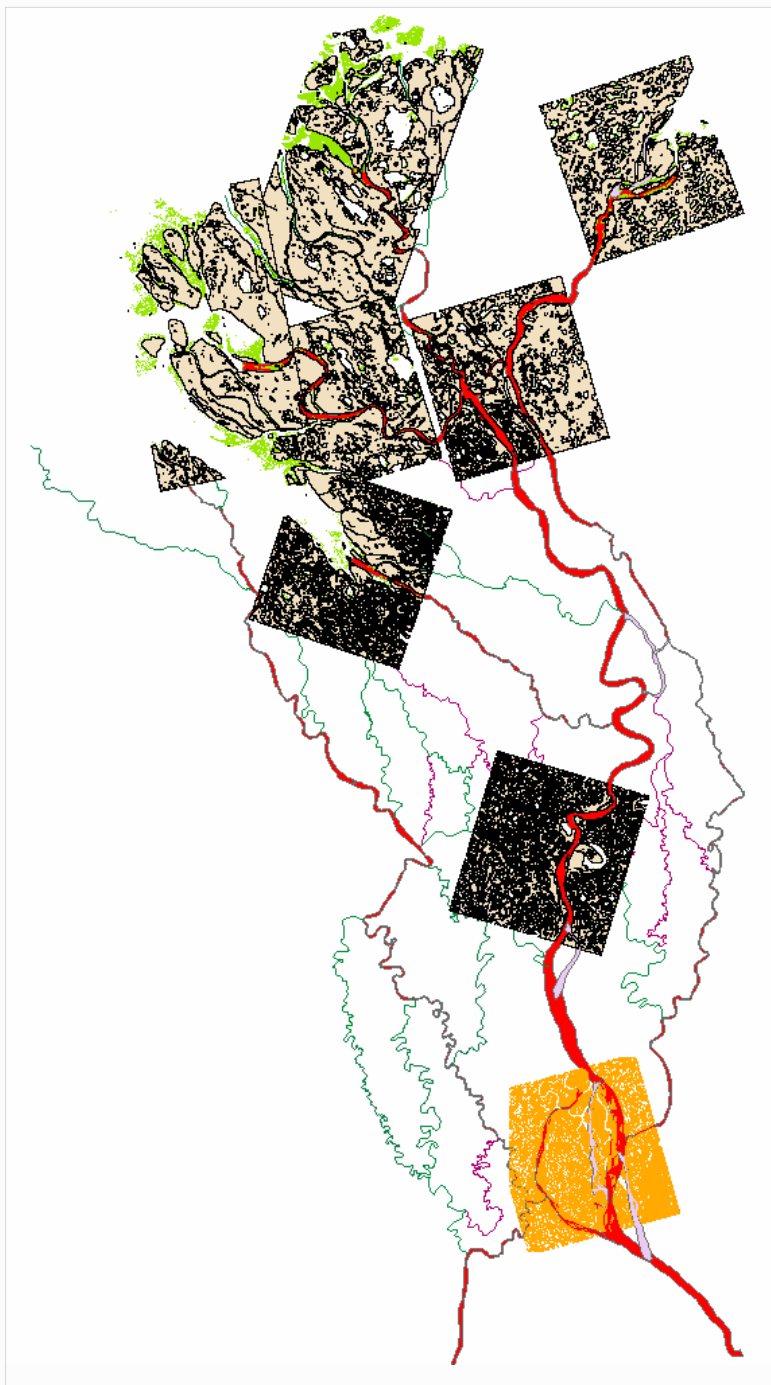




**Figure 5-7.**  
 Different ice cover and ice types along  
 the Lower Red River, Manitoba, for winter  
 2009 – 2010 (left ) and winter 2010 – 2011  
 (right) inferred from RADARSAT-2 SAR  
 image analysis.

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**Figure 5-8.**  
Screenshot of  
information product  
showing the distribution  
of bottom fast ice (in  
green) at selected  
locations in the  
Mackenzie River Delta  
during the winter of  
2009/2010. The network  
for the hydrodynamic  
model in development  
by the University of  
Alberta is shown in the  
background.

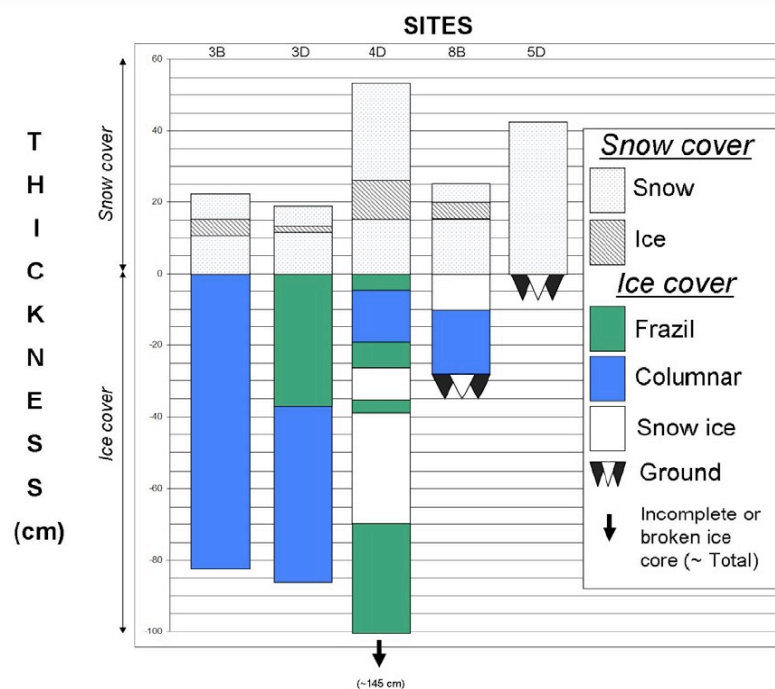
### 5.3 Bottom-fast River Ice Mapping

In the context of the fore mentioned IPY project “Arctic Freshwater Systems: Hydrology and Ecology” RADARSAT-2 data was applied to the mapping of bottom fast river ice in the Mackenzie River Delta. Similar to the information regarding ice breakup and spring flooding dynamics (section 5.2), information about the location and extent of bottom fast river ice facilitates the development of a hydrodynamic model for the area of interest. The mapping exercise focussed on areas corresponding to ‘nodes’ in the layout of the model network. Information regarding the presence of bottom fast ice was derived through thresholding/classification of the backscatter return signals in the HH, HV, and VV polarisations as well as the 24-day coherence of the HH polarisation. A total of seven Geotiff files showing the distribution of bottom fast ice at different locations in the Mackenzie River delta was produced and distributed to IPY partners (*Figure 5-8*). Available ground reference data was used as much as possible to validate the products generated.



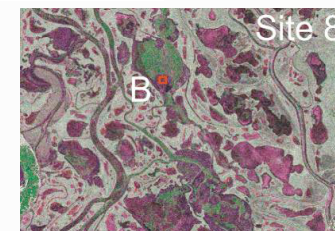
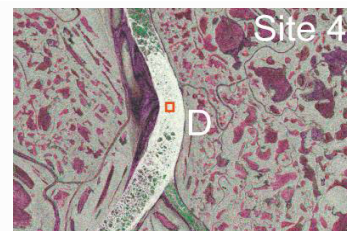
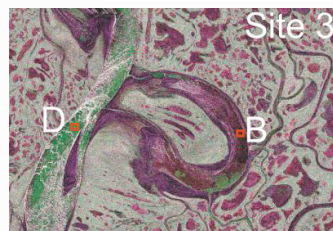
## 5.4 Mapping of River Ice Cover Properties

The GRIP project studied the potential of RADARSAT-2 C-band SAR for the mapping and monitoring of ice cover (winter 2008/2009 and onwards) and the potential of ALOS L-band PALSAR for the mapping of ice cover (winter 2008/2009) in the Middle Channel of the Mackenzie River at Inuvik, NWT. The satellite SAR data acquisition and analysis effort was accompanied by a field work campaigns and in situ data collection of snow and ice cover profiles in February 2009, April 2010 and February 2012 (*Figure 5-9*).



**Figure 5-9.**

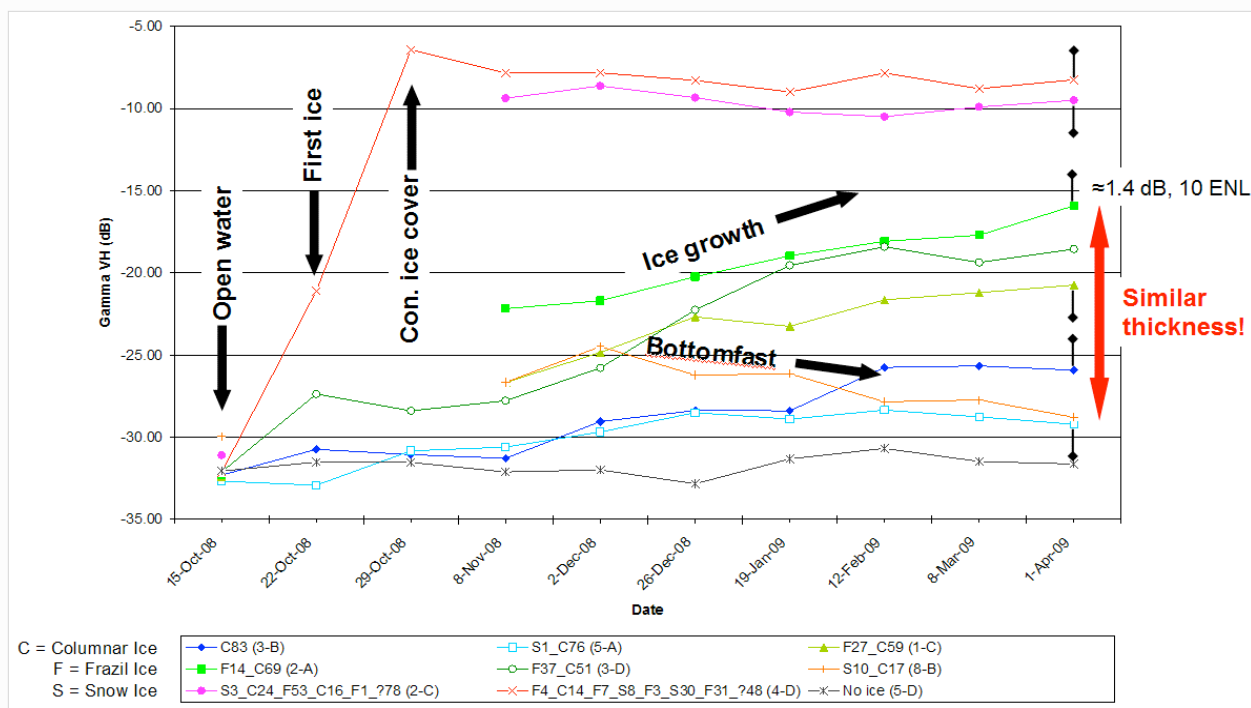
Graph showing the composition of the snow and ice cover core samples at Site 3 B & D, Site 4 D, and Site 8-B. (Note: Site 8-B corresponds to lake ice/snow cover; ice core 4-D only represents the upper 97 cm of a 145 cm thick consolidated ice cover.)



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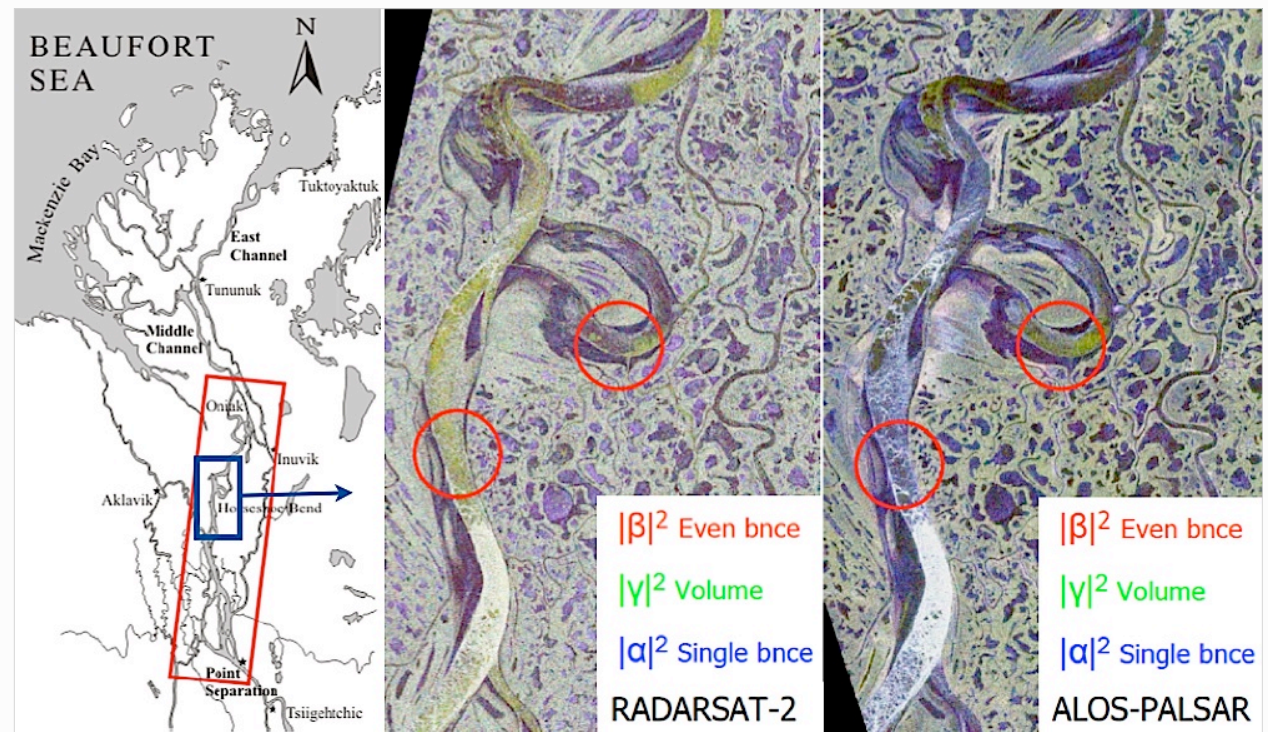
**Figure 5-10** illustrates the potential of RADARSAT-2, operating in VH, for the monitoring of the river ice freeze-up process. The sensitivity of the sensor to the formation of ice at freeze-up, the thickening (and grounding) of ice over the winter season, and ice cover type can be observed. However, the considerable difference in the backscatter of ice covers of a similar thickness but different nature (*e.g.* the columnar ice covers 3-B and 5-A compared to the frazil ice covers 1-C, 2-A, and 3-D) shows that the level of backscatter is not necessarily a good predictor of ice thickness.



**Figure 5-10.**  
Graph showing backscatter change in the VH polarization as a function of time for selected ice covers in the Mackenzie River Delta.



*Figure 5-11* shows some differences in information content of RADARSAT-2 and ALOS PALSAR for river ice cover mapping. The different operating wavelengths of the two SAR systems govern penetration as well as sensitivity to surface roughness and volume scatterers, such as air bubbles in the case of river ice. The results indicated that C-band offers more potential for the classification of river ice cover types than L-band. The HV-polarisation represents the best performing linear polarization, but it performs less well than selected polarimetric variables. Both RADARSAT-2 and ALOS PALSAR backscatter measurements were found to make rather weak predictors of river ice cover thickness, likely because of the very strong effect of ice structure on radar backscatter. Therefore, ice thickness estimation using satellite SAR backscatter measurements remains a challenge.



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**Figure 5-11.**  
Location map of the Mackenzie River Delta study area (left) and Pauli representation of RADARSAT-2 and ALOS PALSAR polarimetric data acquired over the Mackenzie Delta study area at a spatial resolution of ~5 to 10 meters, on April 1 and April 7, 2009, respectively. Red circles outline areas that reveal different backscattering mechanisms at C- and L-band for the same ice feature.

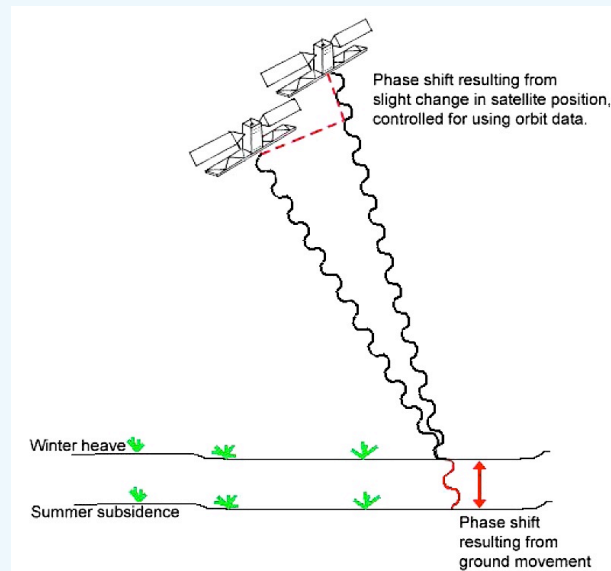


## Section 6:

# Mapping and Monitoring of Permafrost

### 6.1 Overview

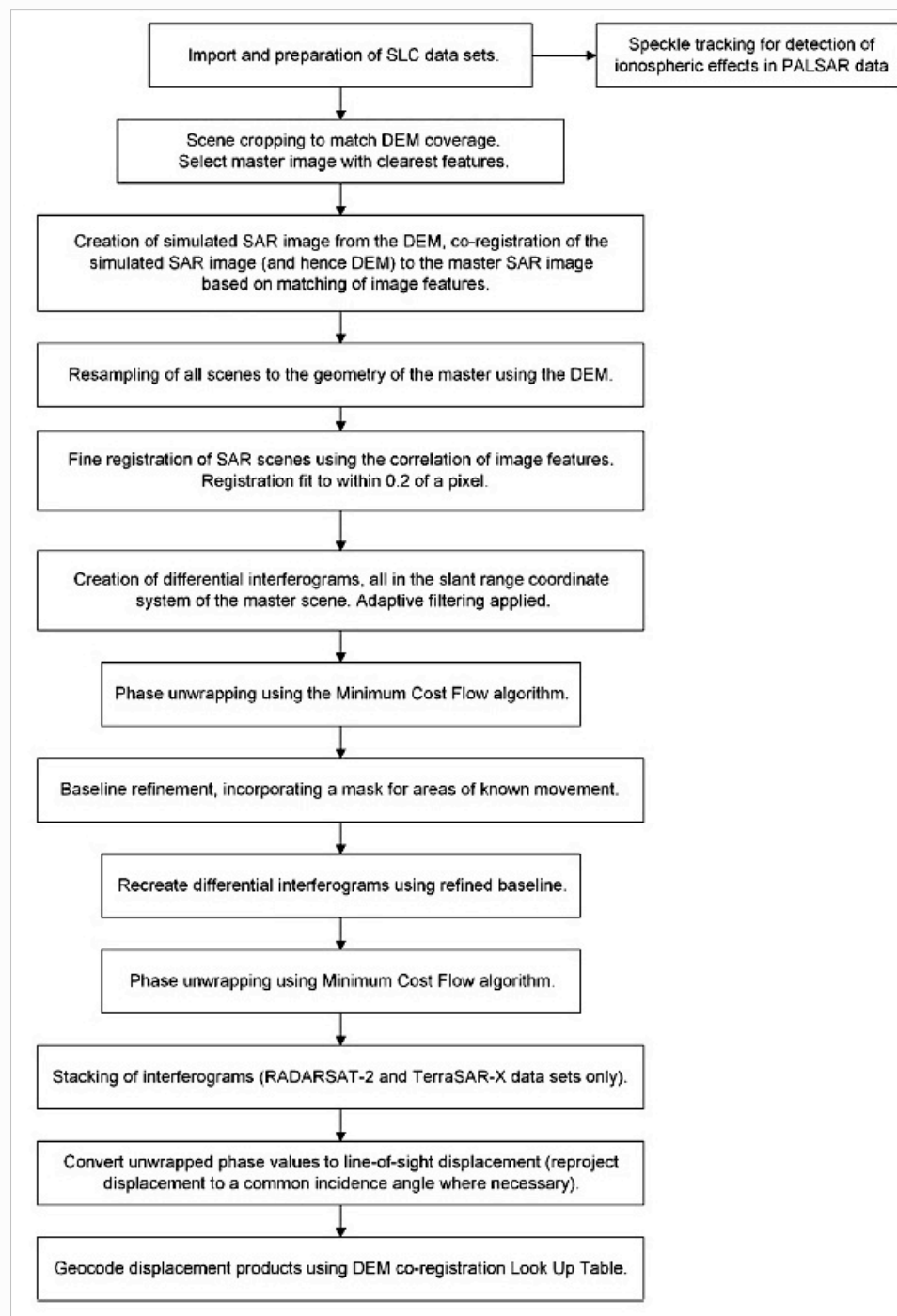
Permafrost is ground that remains frozen for two or more consecutive years. Permafrost is overlain by a layer that thaws and refreezes seasonally, called the active layer. In Canada's arctic and subarctic regions, the presence of permafrost and occurrences of an active layer present particular challenges for infrastructure and engineering, and for monitoring environmental and ecological stability. While permafrost is a subsurface thermal phenomenon, changes in the state of permafrost are eventually manifest at the ground surface, to various degrees depending on the ice content of the permafrost and the surficial geology. Permafrost growth causes ground heave and surface uplift, while permafrost thaw causes ground subsidence. Persistent thaw can lead to the formation of hummocky terrain called thermokarst, and landslides and slumps on significant slopes (*Short et al., 2011*).



The scientific literature suggests that synthetic aperture radar interferometry (InSAR) is now a well established technique for measuring ground movement. Since changes in the active layer and permafrost often result in movement at the ground surface, InSAR is a logical technique to exploit, as illustrated at left. However, until recently, the C-band radars available aboard Envisat and RADARSAT-1 had trouble maintaining coherence over the northern environments with vegetative cover. The tandem mode of ERS-1 and ERS-2 had more success due to short revisit periods. Longer wavelength L-band InSAR can attain greater penetration of vegetative cover, and thus maintain greater coherence over permafrost

environments. The GRIP project utilized primarily RADARSAT-2 C-band as well as TerraSAR X-band and ALOS PALSAR L-band InSAR data sets. InSAR processing was carried out using GAMMA InSAR software in conjunction with high resolution digital elevation models (DEMs). TerraSAR-X and RADARSAT-2 repeat-pass InSAR data sets were stacked to extract small deformation trends by subduing random and atmospheric noise. Useful information on cumulative trends during the summer months was obtained this way. **Figure 6-1** outlines the





*Figure 6-1.*  
*InSAR processing*  
*sequence.*  
*Source:*  
*Short et al., 2011*



InSAR processing sequence. Most processing steps follow conventional InSAR processing practise, apart from the two step co-registration of the single-look complex (SLC) data.

**Table 6-1** contains a summary of the permafrost related documentation produced under the GRIP project in terms of reports, scientific papers published in learned journals or conference proceedings, as well as presentations at workshops and conferences. The following section details the main findings of seasonal and long-term InSAR displacement measurements with illustrations from the Herschel Island, Yellowknife and Pangnirtung study areas.

**Table 6-1.**  
*Documentation of GRIP project  
research related to permafrost*

Documentation	Author(s), Title, Occasion / Reference
Reports: (n=5)	<ul style="list-style-type: none"> <li>♦ N. Short, B. Brisco (2011) Interferometric SAR for terrain stability in the Pangnirtung area, Nunavut. CCRS Interim Report, 17 p.</li> <li>♦ N. Short (2011) Interferometric SAR for terrain stability in the Pangnirtung area, Nunavut - A comparison of RADARSAT-2 and ALOS-PALSAR. CCRS Interim Report, 17 p.</li> <li>♦ N. Short (2011) RADARSAT-2 InSAR for terrain stability in and around Tuktoyaktuk, NWT. Draft Interim Report, CCRS, 10 pages.</li> <li>♦ N. Short, K. Murnaghan, B. Brisco (2012) Impact of the RADARSAT-2 LUT on InSAR displacement results in Canada's permafrost environments. Technical report. CCRS, 11 pages.</li> <li>♦ Pollard, W., D. Fox, M. Angelopoulos, H. Cray-Sloan, J. Simpson, (2012) Field validation of surface changes in permafrost detected using InSAR data, Herschel Island, Yukon Territory. McGill University Report, 27 pages.</li> </ul>
Scientific Papers: (n=3)	<ul style="list-style-type: none"> <li>♦ N. Short, B. Brisco, N. Couture, W. Pollard, K. Murnaghan, P. Budkewitsch (2011) A comparison of TerraSAR-X, RADARSAT-2 and ALOS-PALSAR interferometry for monitoring permafrost environments, case study from Herschel Island, Canada. Remote Sensing of Environment, Vol.155(12): 3491-3506. doi:10.1016/j.rse.2011.08.012, 16 p.</li> <li>♦ N. Short, C.W. Stevens, S.A. Wolfe (2011) Seasonal surface displacement derived from InSAR, Yellowknife and Surrounding Area, Northwest Territories. Geological Survey of Canada Open File 7030, 11 p.</li> <li>♦ Stevens, C.W., N. Short, S.A. Wolfe, (in preparation) Seasonal Surface Displacement and Highway Embankment Grade Derived from InSAR and LiDAR, Highway 3 West of Yellowknife, NWT, GSC Open File 7087</li> </ul>

*(continued next page)*



*Table 6-1 (continued).  
Documentation of GRIP project  
research related to permafrost*

Documentation	Author(s), Title, Occasion / Reference
Presentations: (n=6)	<ul style="list-style-type: none"> <li>♦ N. Short (2011) A comparison of X-, C- and L-band InSAR for monitoring permafrost environments in Canada. Presentation at the ESA DUE Permafrost Workshop, Fairbanks, Alaska, March 1-4, 2011. (12 slides)</li> <li>♦ N. Short, B. Brisco, N. Couture, K. Murnaghan, P. Budkewitsch (2011) A Comparison of X-, C- and L-band SAR Interferometry for Monitoring Permafrost Environments, Case Study from Herschel Island, Canada. ASAR Workshop, Canadian Space Agency, Saint-Hubert (Québec) Canada, June 7-9, 2011.</li> <li>♦ N. Short, S. Wolfe, L. Arenson (2011) SAR Interferometry: applications to infrastructure stability in discontinuous permafrost. 2nd Annual Workshop of the Permafrost Network of Expertise, Inuvik, June 6-9, 2011</li> <li>♦ S. Wolfe, C.W. Stevens, I. Oltoff, N. Short, C. Avey, (2011). Multi-Scale Geoscience Information for Decision-Makers, Great Slave Region, NWT, Presentation at 39th Annual Yellowknife Geoscience Forum, Yellowknife, November 15-17, 2011</li> <li>♦ S. Wolfe (2011) Geoscience for Northern Highways: From Feasibility to Remediation, 2011 Highways Conference, Yellowknife, December 6-7, 2011</li> <li>♦ LeBlanc, Allard, Mathon-Dufour, Short, Oldenborger, L'Hérault, Sladen, Mate, Duguay (2012) Research at the Iqaluit airport, Nunavut, in support of decision-making and planning, Presentation at the Transport Canada and China Collaboration Workshop, China, March 6-8, 2012.</li> </ul>
Sample Product: (n=1)	<ul style="list-style-type: none"> <li>♦ N. Short, C.W. Stevens, S.A. Wolfe (2011) Map of seasonal surface displacement derived from InSAR, Yellowknife and Surrounding Area, Northwest Territories. Geological Survey of Canada Open File 7030</li> </ul>

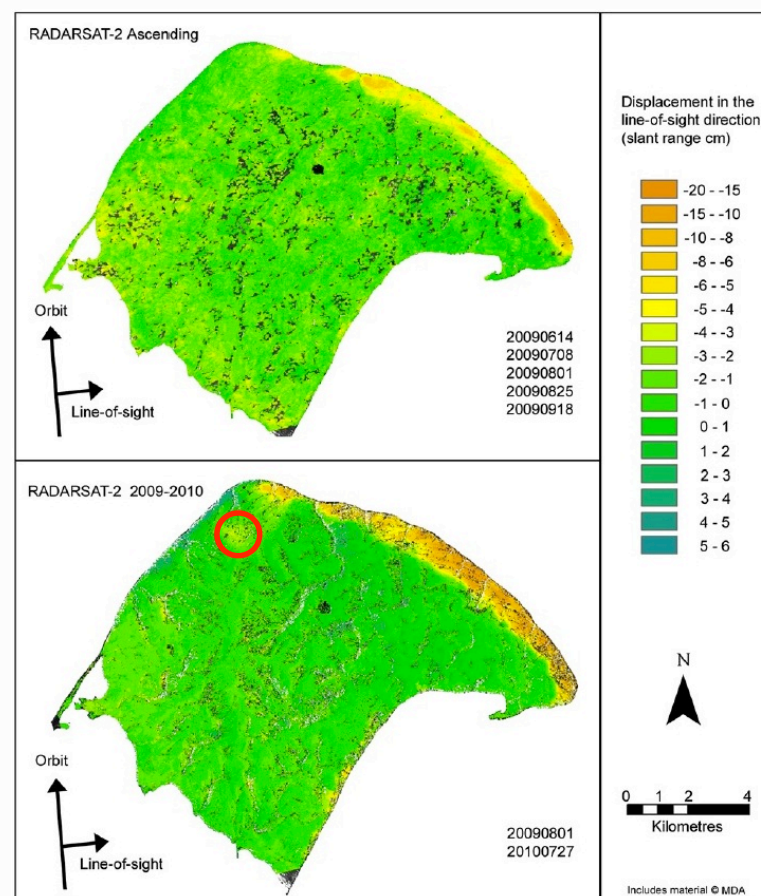
## 6.2 Seasonal and Long-term Displacement Results

The InSAR results for the permafrost environment on Herschel Island are very promising. Broad areas of known instability have been well mapped by all three sensors with a favourable look direction, and with quantitatively consistent results. Having several independent InSAR data sets proved advantageous for identifying and confirming real trends. The results spanning 2007 to 2010 suggest a band of displacement along the north-east coast of Herschel Island of 20 to 30 cm per year. This area is prone to coastal erosion and known to be very unstable. A second region of movement of approximately 5 cm per



year was also detected near the northern tip of the island; this was not previously known and will be the subject of an upcoming field study.

The TerraSAR-X data demonstrated good coherence in the summer data sets, but stacking was essential to overcome noise and extract results. Even after stacking some vegetation effects or tropospheric noise seemed to remain. The RADARSAT-2 C-band results were shown to be reliable. Areas of significant deformation could be identified in single interferograms; stacking further improved the summer results. Areas of known movement were well identified, but some noise related to vegetation or tropospheric effects remained in the stacked products (*Figure 6-2*). The possibility of forming one year interferograms exists



**Figure 6-2.**  
Line-of-sight displacement results from RADARSAT-2 for Herschel Island, NWT. Upper panel is the stacked summer 2009 result, lower panel is the one year separation result. Acquisition dates are listed in the lower right corner of each panel. Red circle outlines the northern region of subtle movement. Underlying background images are SAR intensity, these are visible where there are no displacement data due to loss of coherence (Short et al., 2011).

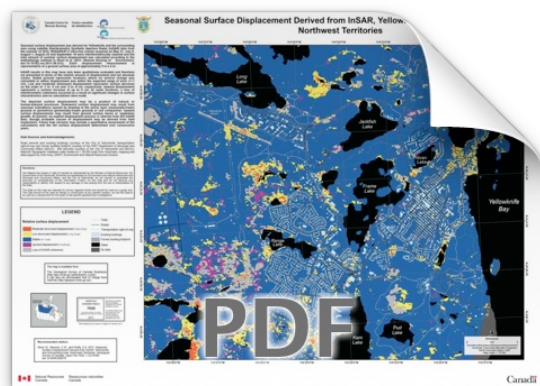
RADARSAT-2 Data and Products (c) MacDonald, Dettwiler and Associates Ltd., 2009. All Rights Reserved



for C-band data, these net annual change interferograms could be particularly valuable for identifying long-term change in a permafrost environment. The ALOS-PALSAR L-band data provided the best coherence and the most complete results. Summer interferograms produced patterns of movement that could be attributed to local topography and active layer dynamics. Areas of significant movement on the island were consistently identified, as well as some more subtle slope processes. The possibility of one year interferograms shows considerable promise for identifying areas of permafrost instability and long-term trends. Multiple year PALSAR data sets can also provide interesting and consistent patterns of movement; but there are currently problems with baseline decorrelation, detection of ionospheric effects, and phase unwrapping in these data sets.

The Herschel Island study reached several important conclusions (see *Short et al. 2011*). Depending on the location, operational monitoring of slump features may need to combine two radar look directions to map the deformation activity; even then, some movement may go undetected. The abrupt and large scale nature of slumping, and the dynamics within slumps, are not ideally suited to the InSAR method. The frequent revisit and high spatial resolution of TerraSAR-X provide the best chance of maintaining coherence over these features. The loss of coherence due to slump activity is the least ambiguous result, therefore coherent change detection may be a more suitable technique for these features. In general, repeat pass InSAR is better suited for detecting broad areas of terrain instability in gentle relief, potentially caused by permafrost thaw or ground ice melt and the removal of water volume, and prior to significant slumping. In terms of monitoring permafrost stability, it is really the long-term changes that are of most interest. Therefore, the ability of RADARSAT-2 and particularly ALOS-PALSAR to form one year and possibly longer interval interferograms is the greatest potential contribution for identifying permafrost and landscape change.

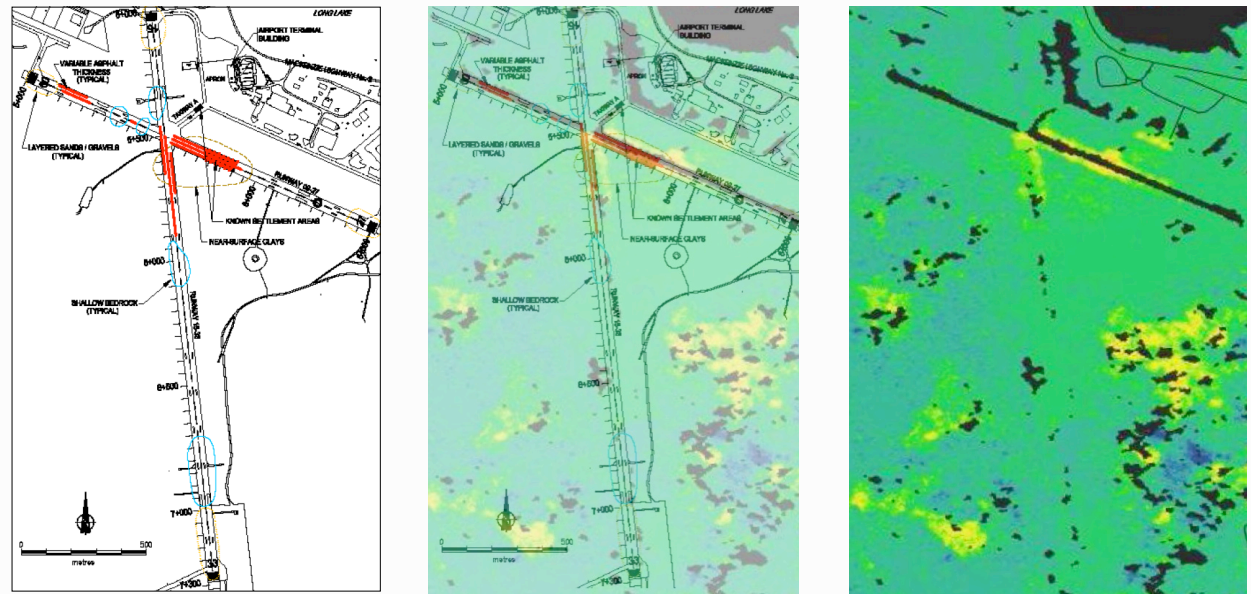
The Yellowknife study utilized six RADARSAT-2 InSAR data pairs collected during the summer of 2010 to calculate and map seasonal surface displacement for Yellowknife, NWT and the surrounding area. The outcome was the first surface displacement map for the NWT capital and its surrounding area (*Figure 6-3*, see also *APPENDIX*). The printed map and accompanying digital versions of the data provide spatial information that may be utilized by city planners for strategic planning related to land use (e.g. future development sites) and the maintenance of infrastructure (e.g. roads, buildings). When combined with existing spatial datasets, the information offers a means to assess the locations and possible causes of seasonal displacement that may impact municipal infrastructure (*Figure 6-4*).



**Figure 6-3.**  
Information product of seasonal surface displacement derived from InSAR for Yellowknife and the surrounding area (enlargement in *APPENDIX*).



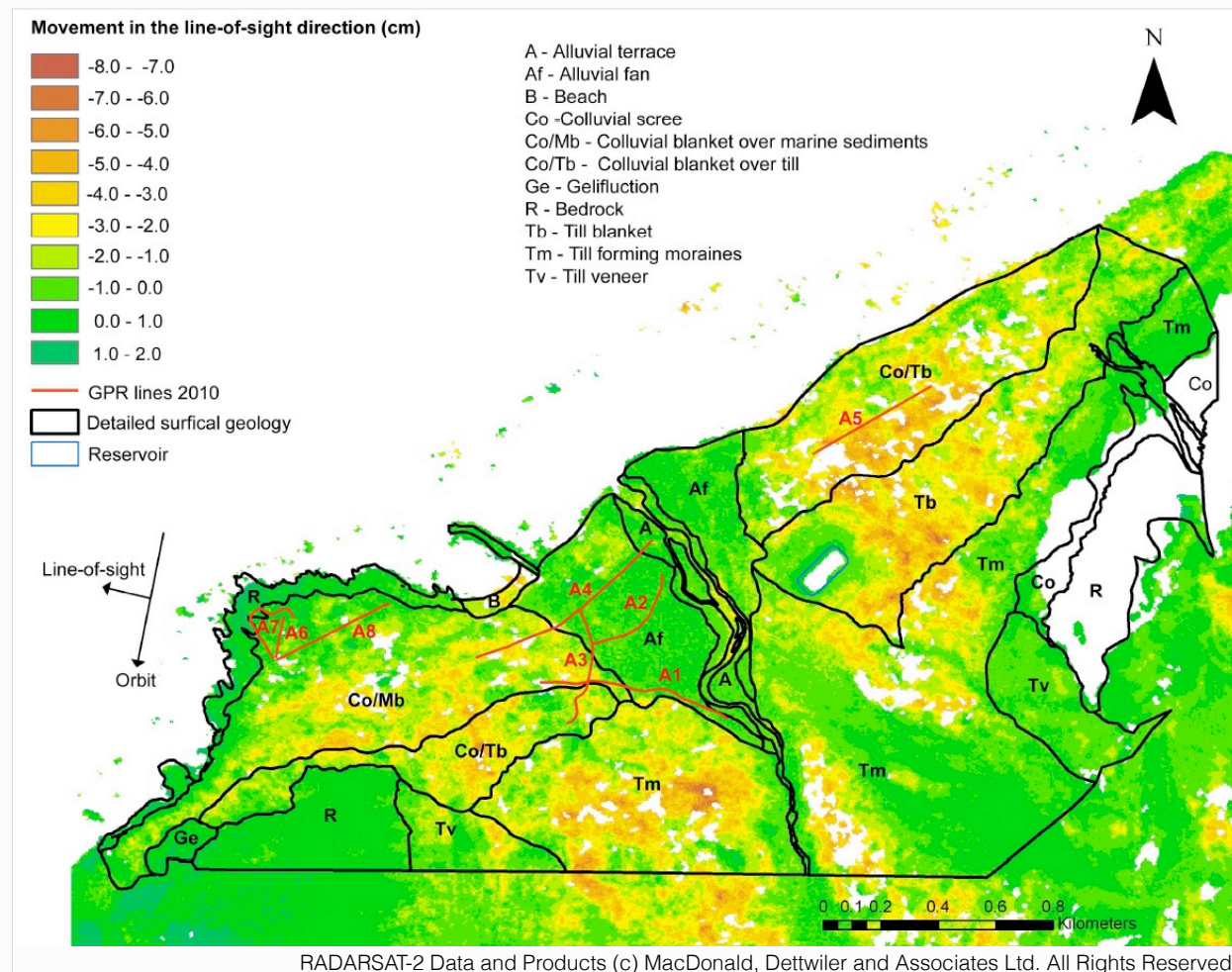
**Figure 6-4.**  
Comparison of detailed engineering map by Seto et al. (2004), at left (scale bar equals 500 m), of the Yellowknife airport area indicating locations of interpreted subsurface features (in red), with RADARSAT-2 InSAR results (at right) of unstable areas (in yellow and orange); merged image of both (at centre) facilitates orientation and location of unstable areas relative to existing or planned installations and infrastructure in the area.



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The Pangnirtung study in the eastern Arctic relied on a wealth of ground data and knowledge of permafrost conditions. The community was selected as a study site for the application of InSAR to High Arctic permafrost zones. Independent InSAR observations by RADARSAT-2 and ALOS PALSAR, in conjunction with detailed DEM data, indicate consistent spatial patterns of summer ground movement. Patterns of ground movement detected by RADARSAT-2 InSAR correlate well with surficial geology and the distribution of ground ice (*Figure 6-5*). Bedrock and alluvial surfaces are identified as very stable. Till deposits are less stable and have significant patterns of variation within them related to the local geomorphology and the presence of ice wedges. Areas with known ice wedges subside the most over the summer, rates of 5 - 8 cm were observed over the eastern terrace of Pangnirtung. The colluvium over marine sediments and till in the west portion of the community are also less stable, movement here is 2 - 6 cm per summer. The stabilizing effects of construction, such as the embankments around the water reservoir can also be seen in the displacement maps. The high resolution RADARSAT-2 C-band data, with 3 m resolution or less produce the best ground movement observations for Pangnirtung. Stacking is required to obtain good results.





**Figure 6-5.**  
 Ground movement map derived from RADARSAT-2 InSAR data acquired during the summer of 2010 for the community of Pangnirtung, Baffin Island, Nunavut. Map overlays detailed surficial geology units and ground penetrating radar lines of LeBlanc et al. 2011 [8].

[8] LeBlanc, A-M., Allard, M., Carbonneau, A-S., Oldenborger, G., L'Hérault, E., Sladen, W., Gosselin, P. and Mate, D., (2011). Assessing permafrost conditions and landscape hazards in support of climate change adaptation in Pangnirtung, Nunavut. Geological Survey of Canada, Open File 6868, doi:10.4095/289548



# Section 7:

## Summary of GRIP Project Work

### 7.1 Project Outputs

The GRIP project has addressed three distinct research and development components concerning satellite SAR applications in lake ice, river ice and permafrost. Over the duration of the project the researchers involved have generated various reports, papers, presentations, posters and information products that document the progress and accomplishments achieved. *Table 7-1* summarizes the project output numerically for the various document types. Overall, 95 documents have been produced. The reports included many deliverable items that CCRS produced for the client departments and agencies under the auspices of the GRIP program. Papers, posters and presentations refer to documentation for workshops, symposia and meetings that were attended by the principal researchers involved in the GRIP project. Papers were either peer-reviewed journal papers or contributions to symposia proceedings. The relatively high number of outputs for the lake ice and river ice research categories reflects that these R&D activities were initiated in the context of the preceding GRIP supported project entitled “*Fresh Surface Water Mapping and Monitoring Using SAR Satellites*” (April 2007 – March 2010).

*Table 7-1.*  
*Summary of GRIP project output products for lake ice, river ice, and permafrost studies.*

Outcome	Lake Ice	River Ice	Permafrost	Total
Sample Products	8	22	1	31
Reports	9	7	5	21
Presentations	5	10	6	21
Scientific Papers	5	7	3	15
Posters	1	6	n.a.	7
Total	28	52	15	95



## 7.2 Project Outcomes

The outcomes defined at the onset of the project read as follows:

- i. *the identification and resolution of technological barriers (re the use of satellite SAR in support of the mapping and monitoring of freshwater ice and permafrost)*
- ii. *demonstrated use of integrated SAR-based freshwater ice and permafrost information products*
- iii. *an enhancement of the Government of Canada's capacity for sustainable management of northern environments and infrastructure.*

The project accomplishments presented in this report and summarized below demonstrate that the team has achieved these outcomes to a large degree.

Lake freeze-up monitoring and lake ice break-up monitoring by means of satellite SAR can now be considered maturing applications, while much of the ice characterisation work, including the mapping of bottom fast lake ice, remains still at the R&D stage. The project generated a variety of SAR-based lake ice mapping and monitoring techniques and methods, user guidelines for image acquisition and processing, publications, presentations and information products evaluated with the help of target clients. Many of the lake ice tools developed under the GRIP project were transferred to and are being used by the primary client department, that is, Parks Canada Agency. Furthermore, techniques and approaches developed for the application of SAR to the monitoring of lake ice breakup and freeze-up are in the process of being implemented, with support from CSA's EOADP program. in the commercially available PCI Geomatica software suite.

Like lake ice breakup monitoring, the application of satellite SAR to the monitoring of river ice breakup is approaching maturity. Satellite SAR have been shown to contain much information about river ice cover characteristics (e.g. ice type, afloat/bottom fast) but more R&D towards reliable (automated) extraction of this type of information from SAR images is required. A sensitivity of SAR to river ice cover thickness has been demonstrated but the application of SAR to the mapping of ice thickness can expected to be challenging and require considerable R&D. Studies in the Mackenzie Delta and in southern Manitoba have shown that satellite SAR can address river ice information requirements at both relatively large and small spatial scales. The project generated a variety of SAR-based river ice mapping and monitoring techniques and methods, publications, presentations as well as ice cover and flood condition information products evaluated with the help of target clients.



The permafrost-related GRIP project work has also been very successful. A variety of techniques and methods, publications, presentations as well as information products have been produced. The seasonal InSAR-derived displacements results caught the immediate interest of the GSC and the uptake was very positive. The work for the Pangnirtung study area was communicated directly to the community and the terrain stability map was translated into Inuktitut for use as a local community planning tool (see APPENDIX). Overall, the qualitative validation of the research results was very encouraging, although there is still work to be done regarding the quantitative analyses using the thaw tube data. At this point, the InSAR derived seasonal displacement maps can probably be regarded as a proxy for the presence of ground ice, as there is sufficient evidence from the Yellowknife airport engineering study and the Pangnirtung ground penetrating radar study. With regard to InSAR derived displacement maps for long-term monitoring, one can point to the successful application of the C-band and especially the L-band InSAR over Herschel Island. This long-term observation capacity will continue to evolve as longer time series of InSAR data are acquired. The value of the permafrost work is clearly shown by the rapid uptake by the private sector. CCRS met with three Canadian companies to share products, ideas and methods, these companies are working in their own way to bring terrain stability mapping for permafrost environments to the market. One company is actively using the CCRS case studies to promote space-borne InSAR monitoring of northern sites at engineering and resource development conferences in North America.

### 7.3 Future Work

Future work will focus on (a) the refinement and validation of the prototype techniques and methods that were developed in the GRIP project and (b) the development and validation of techniques and methods for the application of data from forthcoming satellite missions. The introduction of the RADARSAT and Sentinel-1 constellations over the next five years is expected to offer considerable promise to the applications addressed in this report.

Future lake ice application development will prepare for the RADARSAT Constellation Mission (RCM) by investigating the use of compact polarimetry for lake ice break-up, freeze-up, and grounding. There are plans to build on the current GRIP results with the intention to extend the application to larger lakes and larger geographical areas. One objective of the work will be to reduce dependence on wind data. Further development of lake ice grounding methods, particularly with regard to a full assessment of the incidence angle range, will benefit from recently collected ground reference data. It is also planned to investigate the



use of InSAR methods for ice thickness mapping. Supporting SAR images and ground reference data were acquired in March 2012. An examination of the potential of satellite SAR in support of the mapping / monitoring of ice cover of saline near-coastal lakes would also further our research work on lake ice.

Future river ice application development work will focus on improving the potential of satellite SAR for the mapping of ice cover characteristics (e.g. ice type, ice thickness, grounding). The work will include further study of the potential associated with polarimetric data (started under this GRIP project) and compact polarimetric data (started under the CCRS led RADARSAT Constellation Project) and new studies into the potential of repeat pass InSAR image pairs in support of the mapping of ice thickness, in particular. Both ice type and thickness are critical parameters for mapping of ice loading capacity / trafficability and for guiding activities to prevent ice jamming during breakup. The river ice breakup and flood monitoring applications would benefit from additional work aimed at evaluating the information content of the, less wind sensitive, HV polarization data and of compact polarimetry data. Full polarimetry data provide restricted coverage and therefore offer limited potential for application to river ice breakup and flood monitoring. However, there is a niche for the application of this type of data at strategic locations, *i.e.* locations where one finds critical infrastructure such as bridges, locks, and hydropower plants. In support of this application, a study into the potential of full polarimetry (and compact polarimetry) data for the quantification of the roughness of breaking ice cover, notably of ice jams, would be of particular interest. Finally, the potential of satellite SAR for mapping / monitoring of ice cover on water bodies that show natural fluxes of methane or other gasses is of interest both from a climate warming and a resource exploration perspective and could be developed further.

Future permafrost application development will be directed in two focus areas, both considered critical to further acceptance and implementation of InSAR by client groups such as the GSC. First, quantitative validation of the InSAR results obtained under the GRIP project is required. One component will focus on utilizing in situ data from the thaw tubes installed at Iqaluit airport by the GSC. There are also plans to revisit the settlement stakes on Herschel Island installed by McGill University. Secondly, clients require a more descriptive observation of surface displacement. Specifically, the techniques in this report were limited to measuring line-of-sight displacement. While considered useful, the potential of new techniques that enable two and three-dimensional InSAR-based measurements of subsidence and uplift should and will be explored, ideally with the Herschel Island and Pangnirtung data sets. Using the Yellowknife permafrost test site, follow-on studies will investigate the impact of the RADARSAT-2 look-up tables (LUTs) on differential interferometric SAR (D-InSAR)



measurements. There is also a plan to extend the seasonal permafrost studies and explore the potential applications for long-term InSAR time series to detect permafrost degradation over multi-year periods.

The expectation is that the Government of Canada (GoC) will be in the position to use SAR-based observations to routinely monitor lake ice, river ice, and permafrost stability by the launch of the RCM. The techniques and methods developed in this GRIP project represent a strong foundational basis for the operational implementation of a freshwater ice and permafrost monitoring system. In addition, this project has successfully demonstrated the potential of such a system to GoC users. As described above, work clearly remains to further improve and assess prototype SAR-based techniques and methods. Although designed for good continuity with their heritage missions, the RCM and other future SAR missions will offer capabilities that are sufficiently different to warrant full assessments of their potential to maintain and advance the SAR-based applications developed and described in this report.

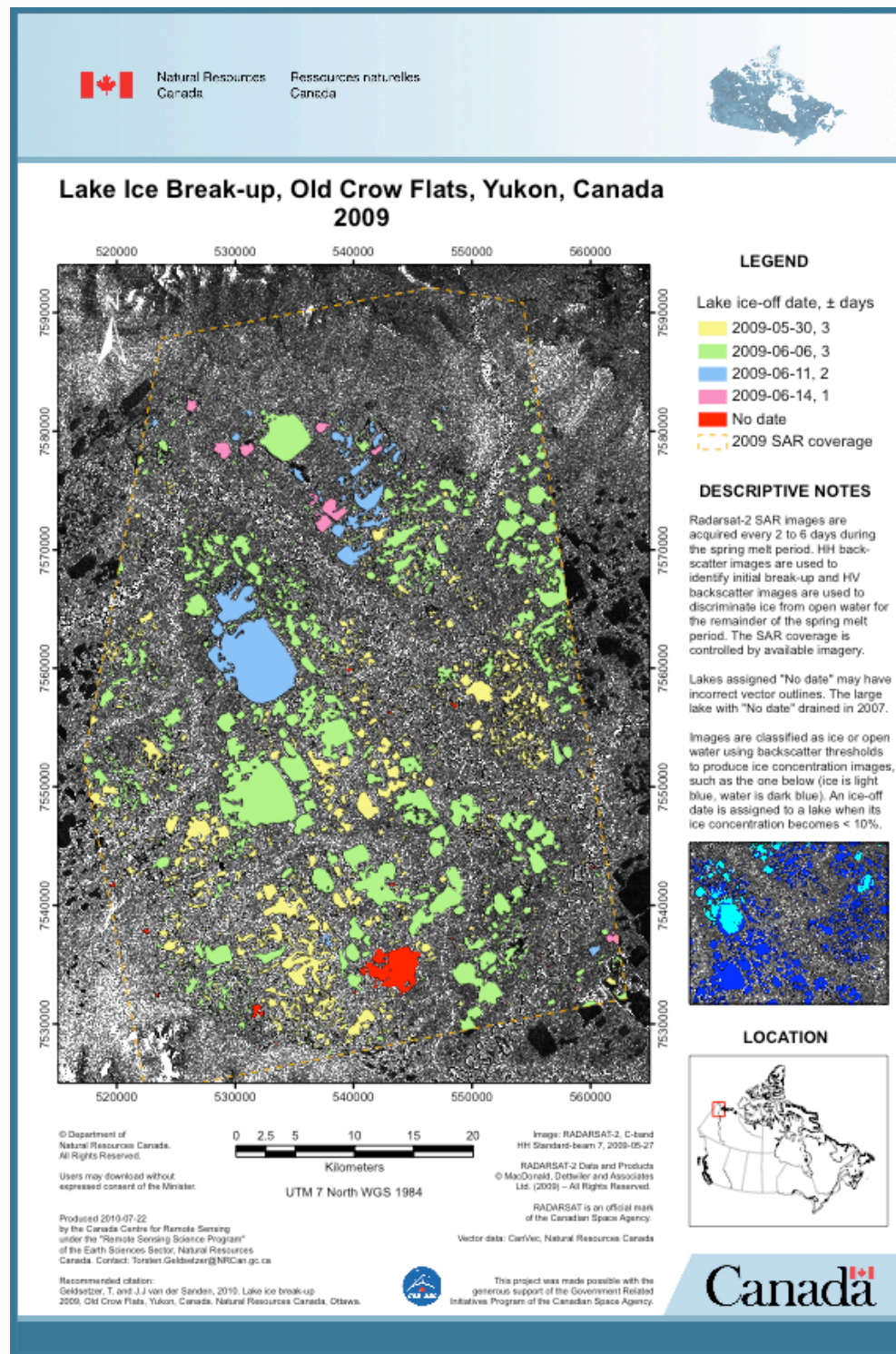


# Appendix:

## Sample Information Products

### Note:

All products in the appendix are displayed at much reduced spatial resolution.





## Sample Information Products

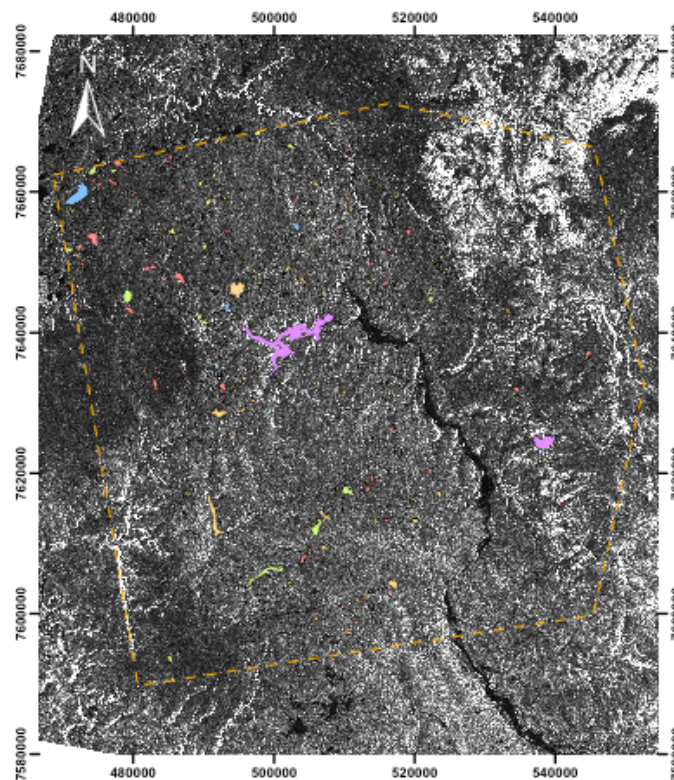


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### Lake Ice Break-up, Cache Lake Area, Tuktu Nogait, NWT, Canada 2009



#### LEGEND

Lake ice-off date,  $\pm$  days

- Before 2009-06-19
- 2009-06-25, 6
- 2009-07-04, 3
- 2009-07-09, 1
- 2009-07-11, 2
- 2009-07-15, 3
- 2009-07-21, 3
- 2009 SAR coverage

#### DESCRIPTIVE NOTES

Radsat-2 SAR images are acquired every 2 to 6 days during the spring melt period. HH backscatter images are used to identify initial break-up and HV backscatter images are used to discriminate ice from open water for the remainder of the spring melt period. The SAR coverage is controlled by available imagery.

Images are classified as ice or open water using backscatter thresholds to produce ice concentration images. An ice-off date is assigned to a lake when its ice concentration becomes  $< 10\%$ .

#### LOCATION



0 2.5 5 10 15 20 25



Kilometers

UTM 10 North WGS 1984

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Produced 2010-07-27 by the Canada Centre  
for Remote Sensing under the "Remote Sensing  
Science Program" of the Earth Sciences Sector,  
Natural Resources Canada.  
Contact: Torsten.Geldsetzer@NRCan.gc.ca

Recommended citation:  
Geldsetzer, T. and J.J. van der Sanden, 2010.  
Lake ice break-up 2009, Cache Lake area,  
Tuktu Nogait National Park, NWT, Canada.  
Natural Resources Canada, Ottawa.

Image: RADARSAT-2  
C-band, HH, Wide 3, 2009-07-08

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Vector data: CanVec, Natural Resources Canada

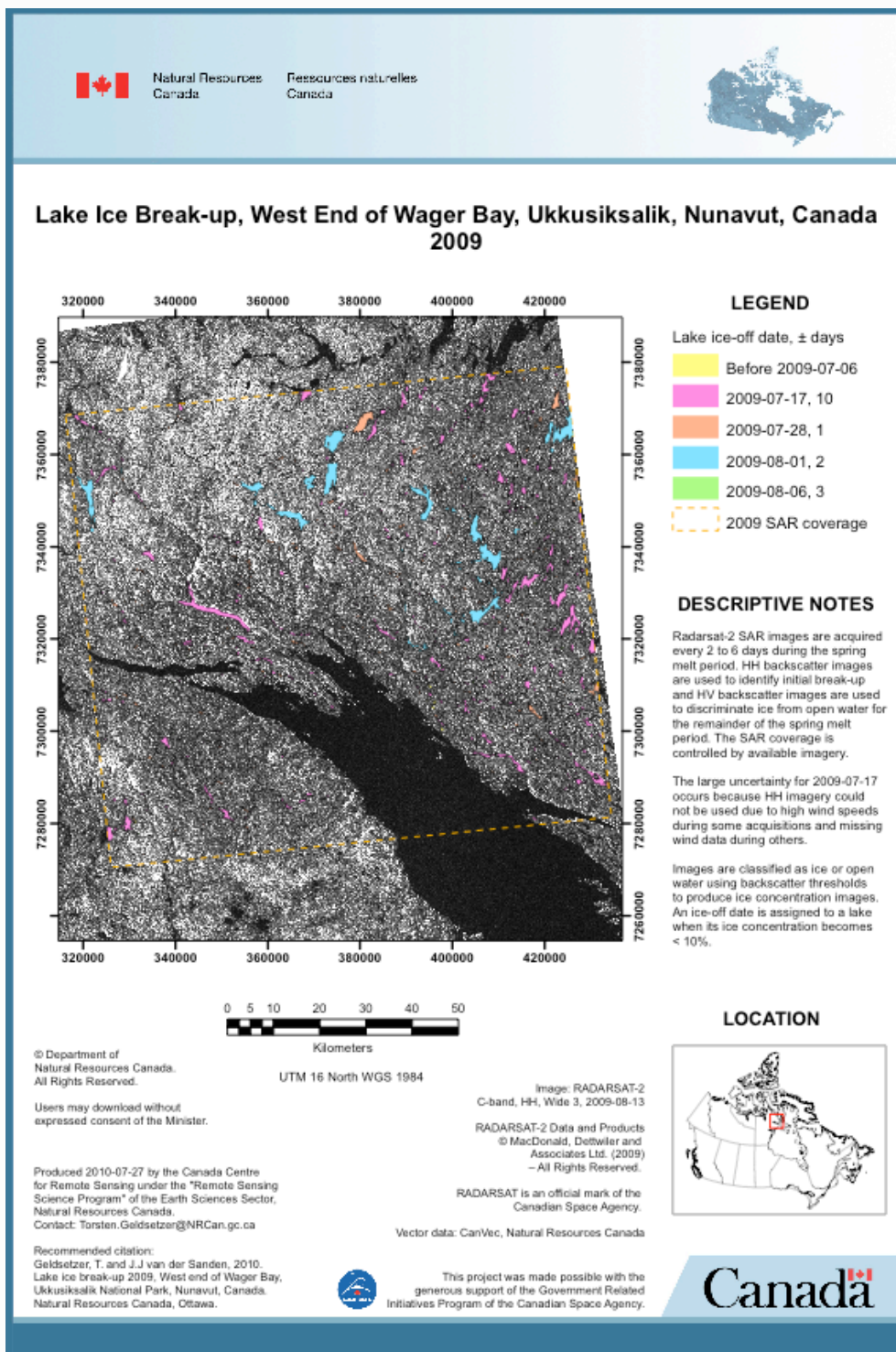


This project was made possible with the  
generous support of the Government Related  
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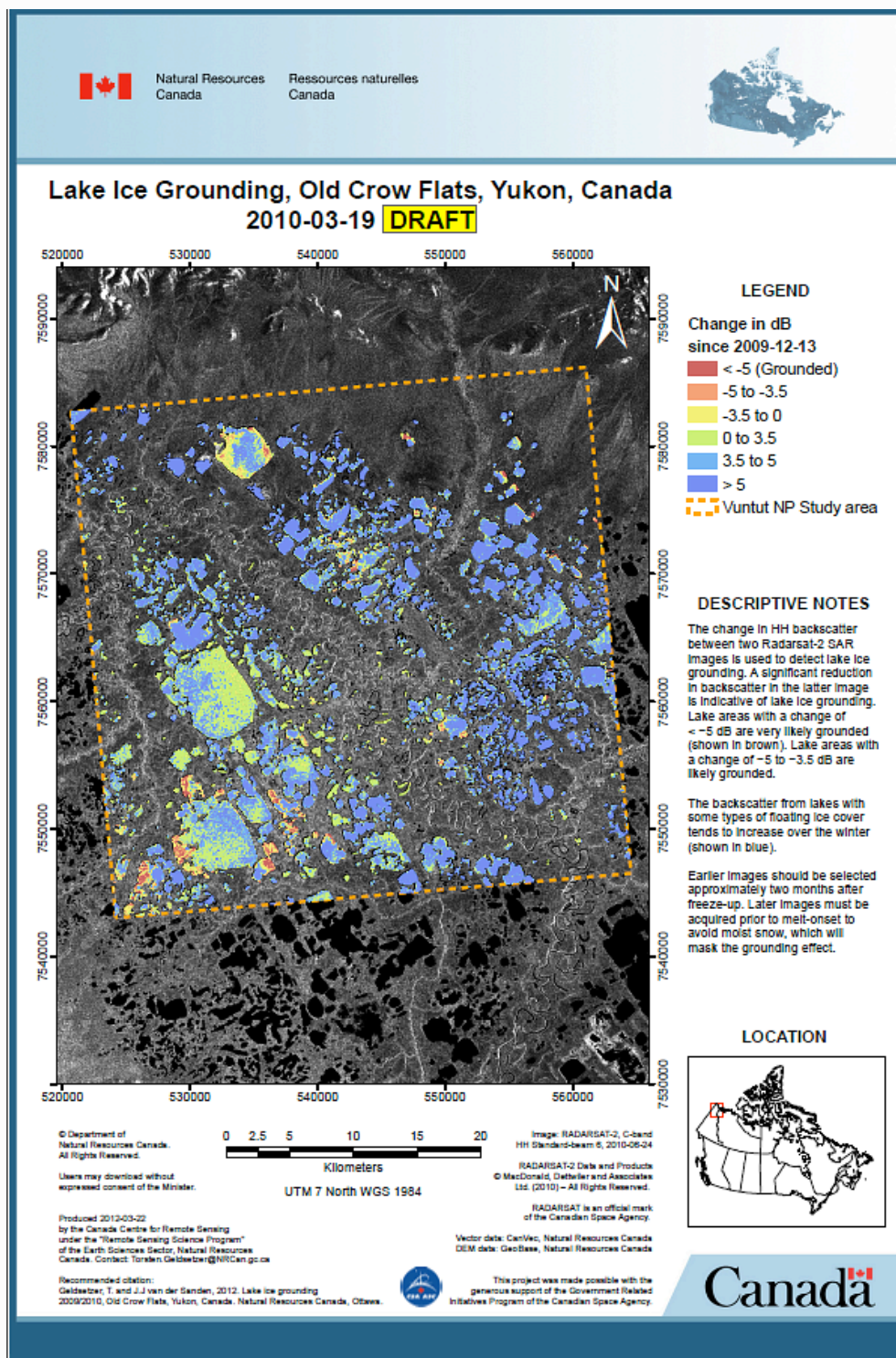


## Sample Information Products



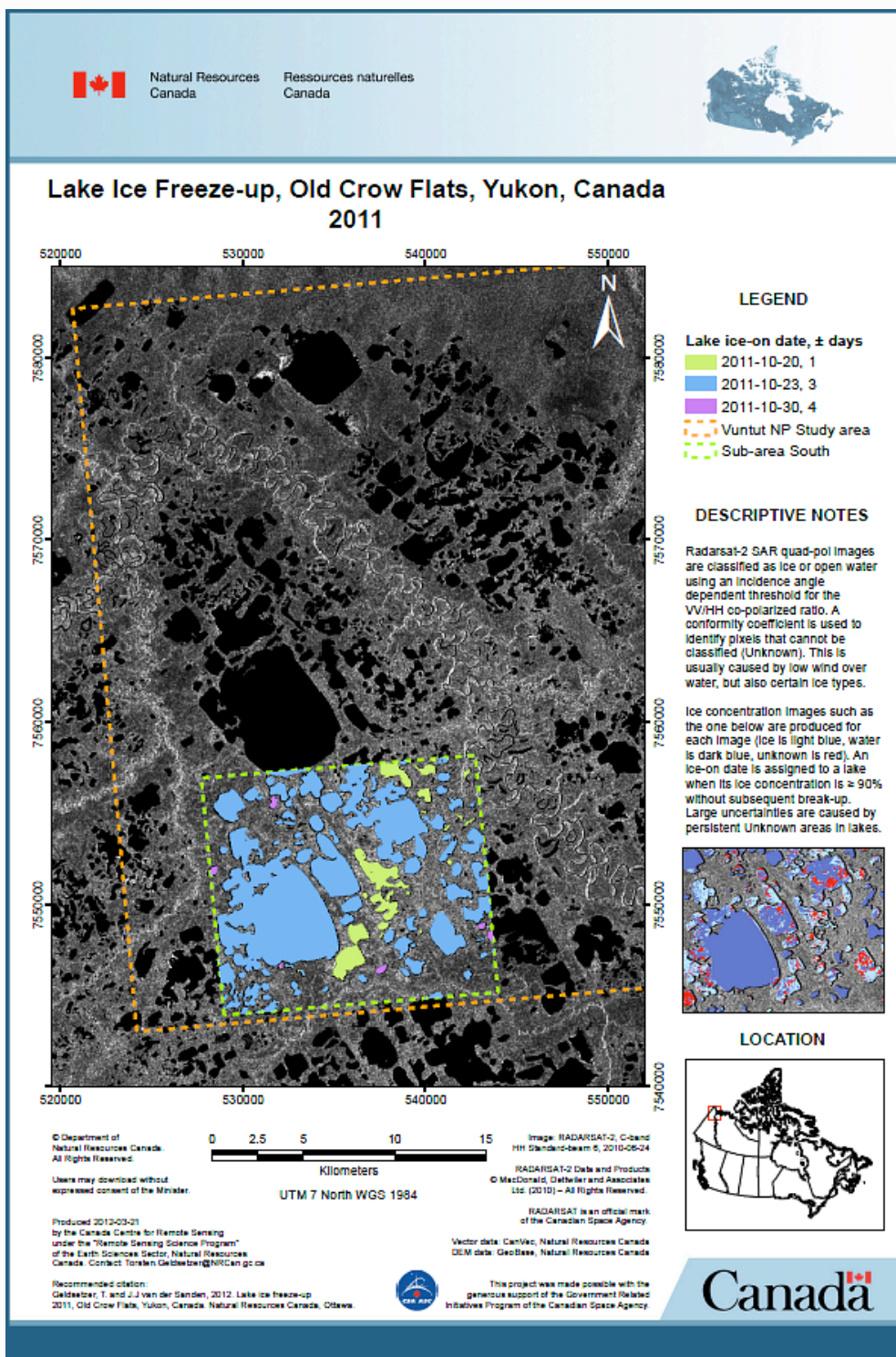


# Sample Information Products





# Sample Information Products

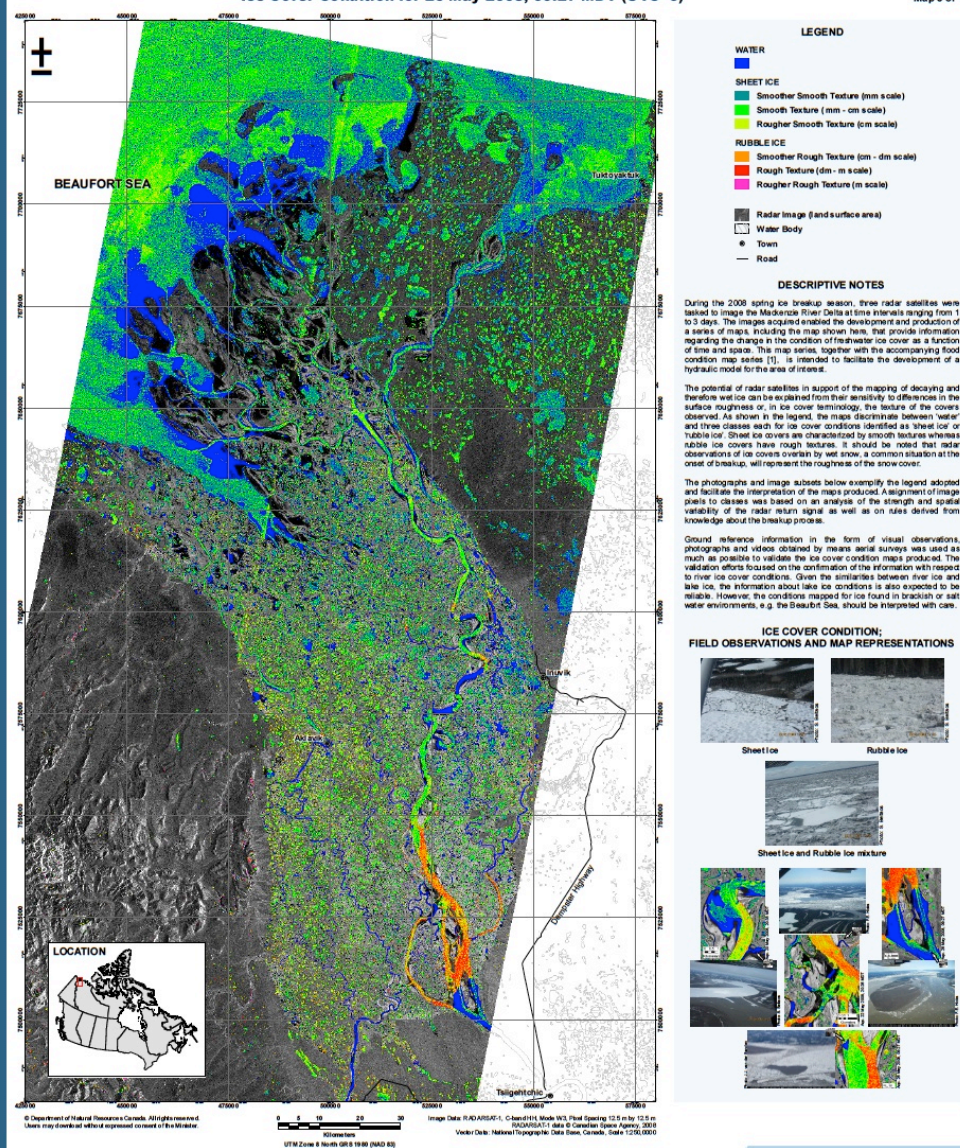






**Ice Cover Condition for 26 May 2008, 09:27 MDT (UTC- 6)**

Map 5 of 11



Produced by Canada Centre for Remote Sensing under the "Remote Sensing Science Program" of the Earth Sciences Sector, Natural Resources Canada.  
For information please visit <http://ccrs.nrcan.gc.ca/> or email [abcol van der Sanden at sanden@nrcan.gc.ca](mailto:abcol van der Sanden at sanden@nrcan.gc.ca)  
Recommended citation: van der Sanden, J.J. and H. Drouin, 2010. Spring 2007 Ice Cover Condition, MacKenzie River Delta, Northwest Territories, Canada. GIS ready map series. Ottawa, Natural Resources Canada.  
Aussi disponible en français.

This project was made possible with the generous support of the Government of Canada Program for International Polar Year (IPY) and the Government Related Initiatives Program of the Canadian Space Agency. Discussions and exchange of validation data with S. Bellas (Environment Canada), F. Holm (University of Alberta) and other IPY project partners were most valuable.

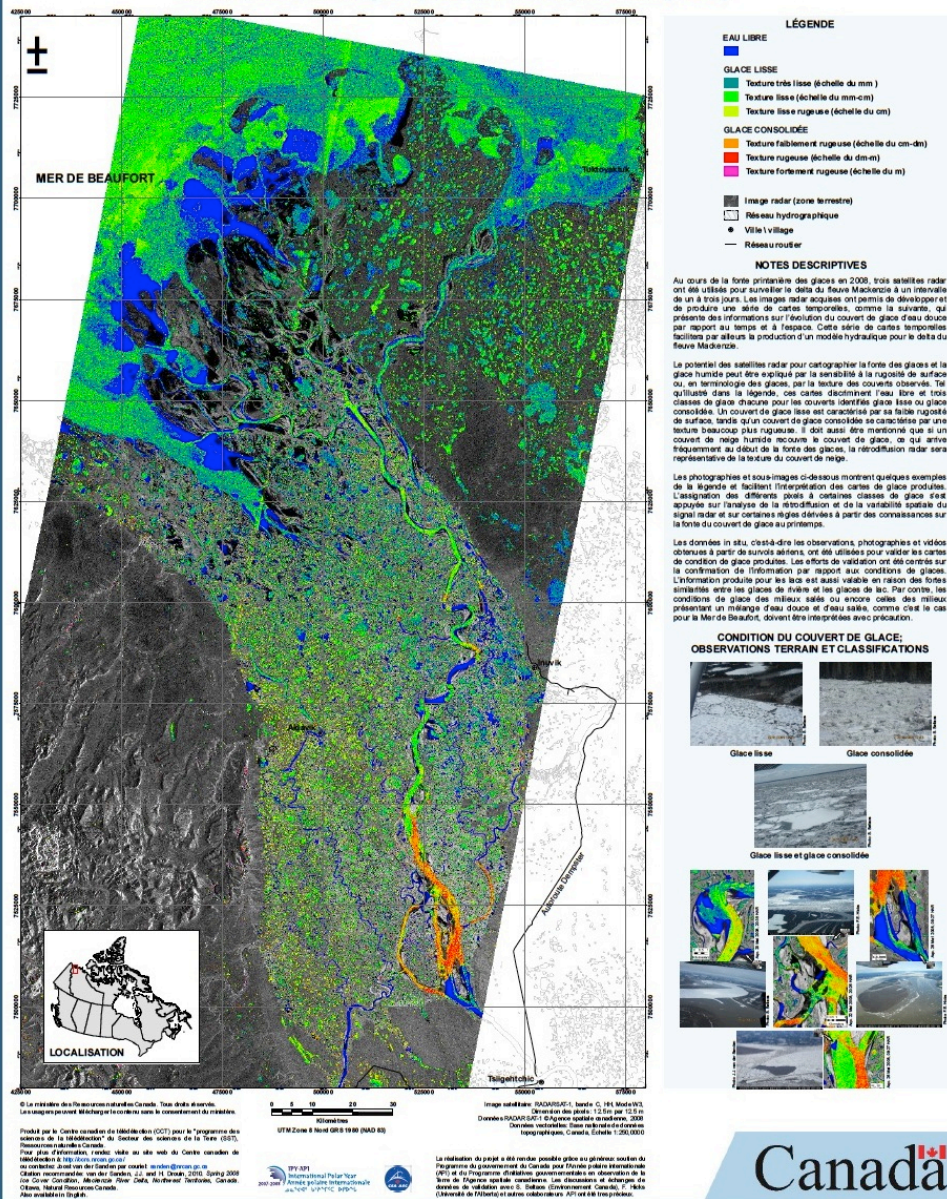
Canada





Carte 5 de 11

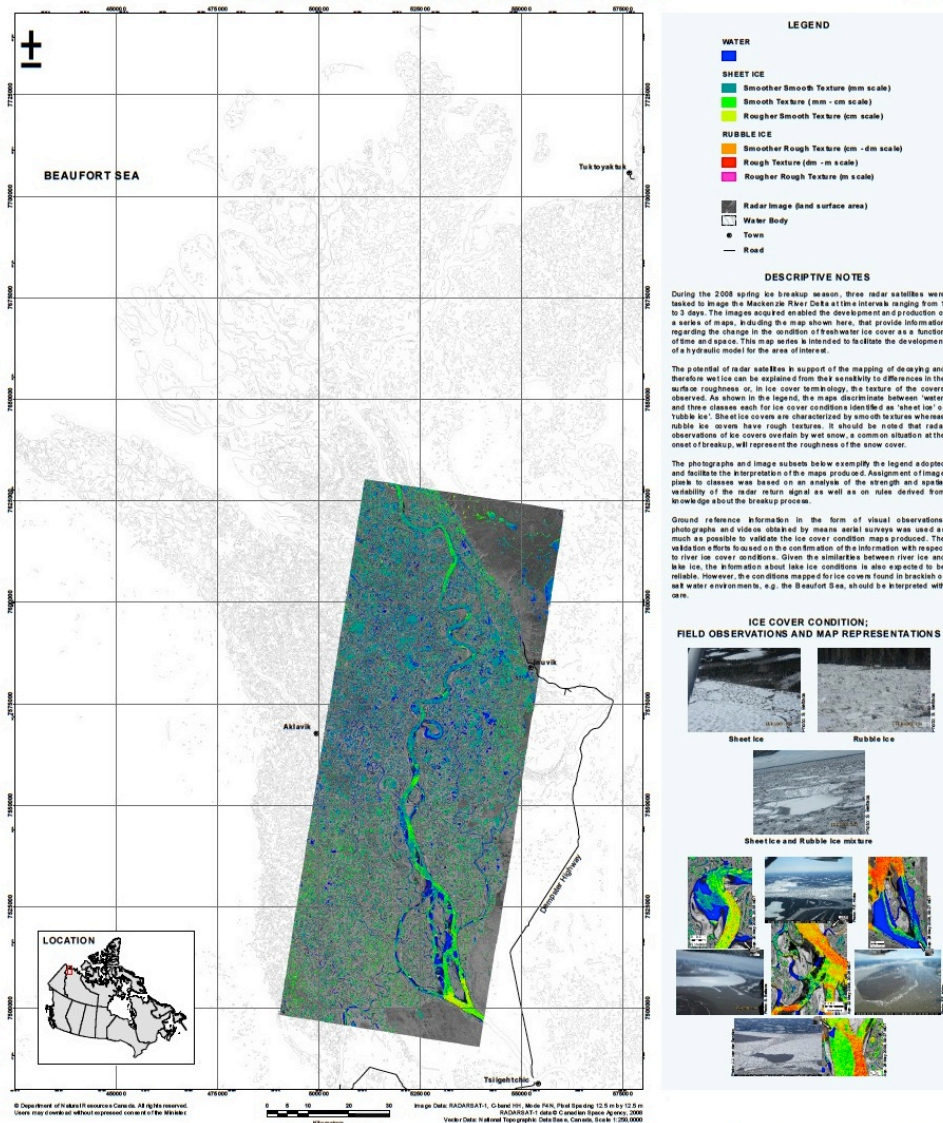
**Condition du couvert de glace pour le 26 Mai 2008, 09:27 HAR (UTC- 6)**





**Ice Cover Condition for 16 May 2008, 09:16 MDT (UTC- 6)**

Map 1 of 11



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For information please visit <http://ccrs.nrcan.gc.ca> or email Joël van der Sanden at [sanden@ccrs.nrcan.gc.ca](mailto:sanden@ccrs.nrcan.gc.ca).  
Recommended citation: van der Sanden, J.J. and H. Drouin, 2010. Spring 2009 Ice Cover Condition, Mackenzie River Delta, Northwest Territories, Canada. Ottawa, Natural Resources Canada.  
Aussi disponible en français.

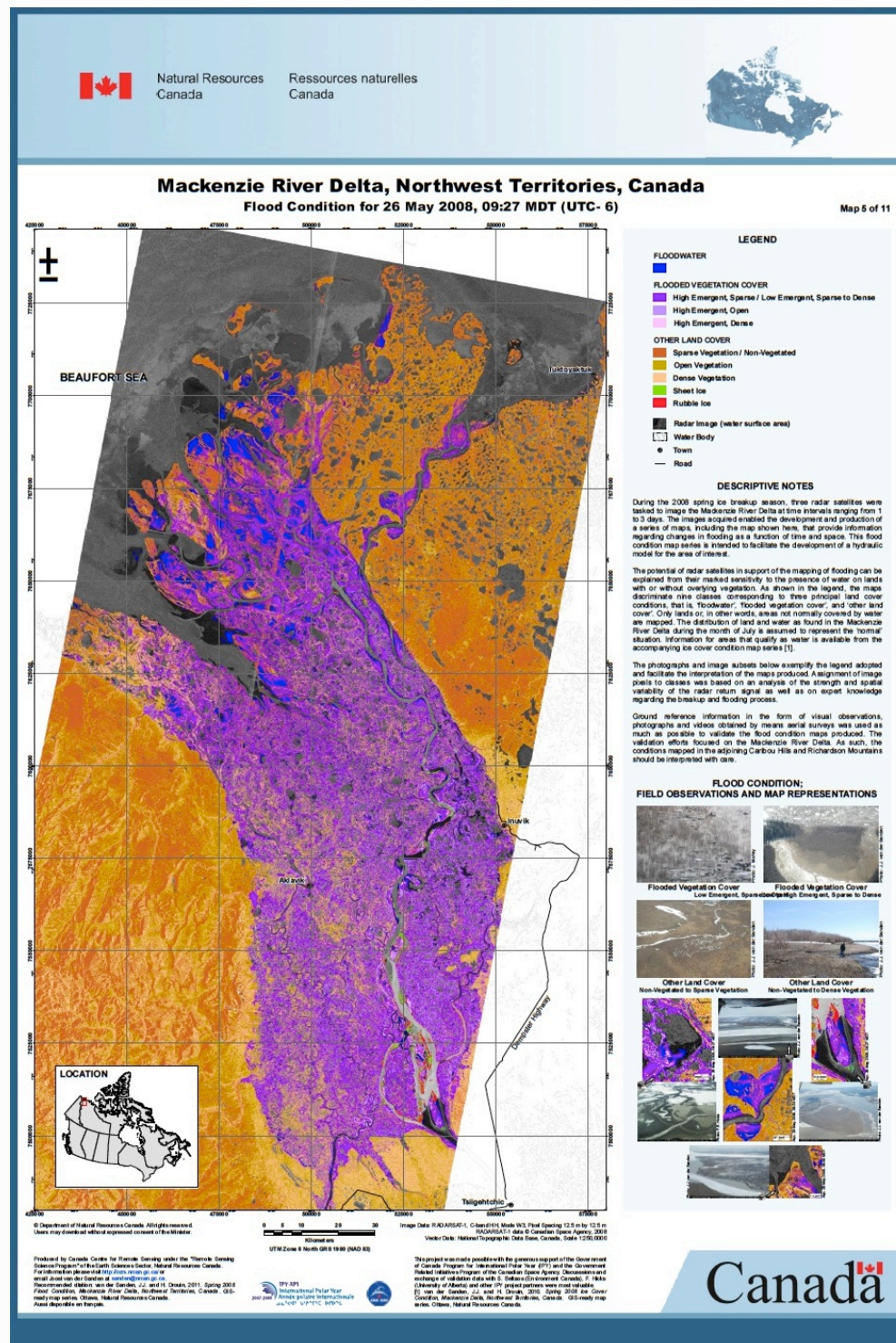
TPY-API  
International Polar Year  
Année polaire internationale  
www.ipy2007-2008.org

This project was made possible with the generous support of the Government of Canada Program for International Polar Year (IPY) and the Government Related Initiatives Program of the Canadian Space Agency. Discussions and exchange of validation data with S. Bellone (Environment Canada), F. Hicks (University of Alberta) and other IPY project partners were most valuable.

Canada



# Sample Information Products

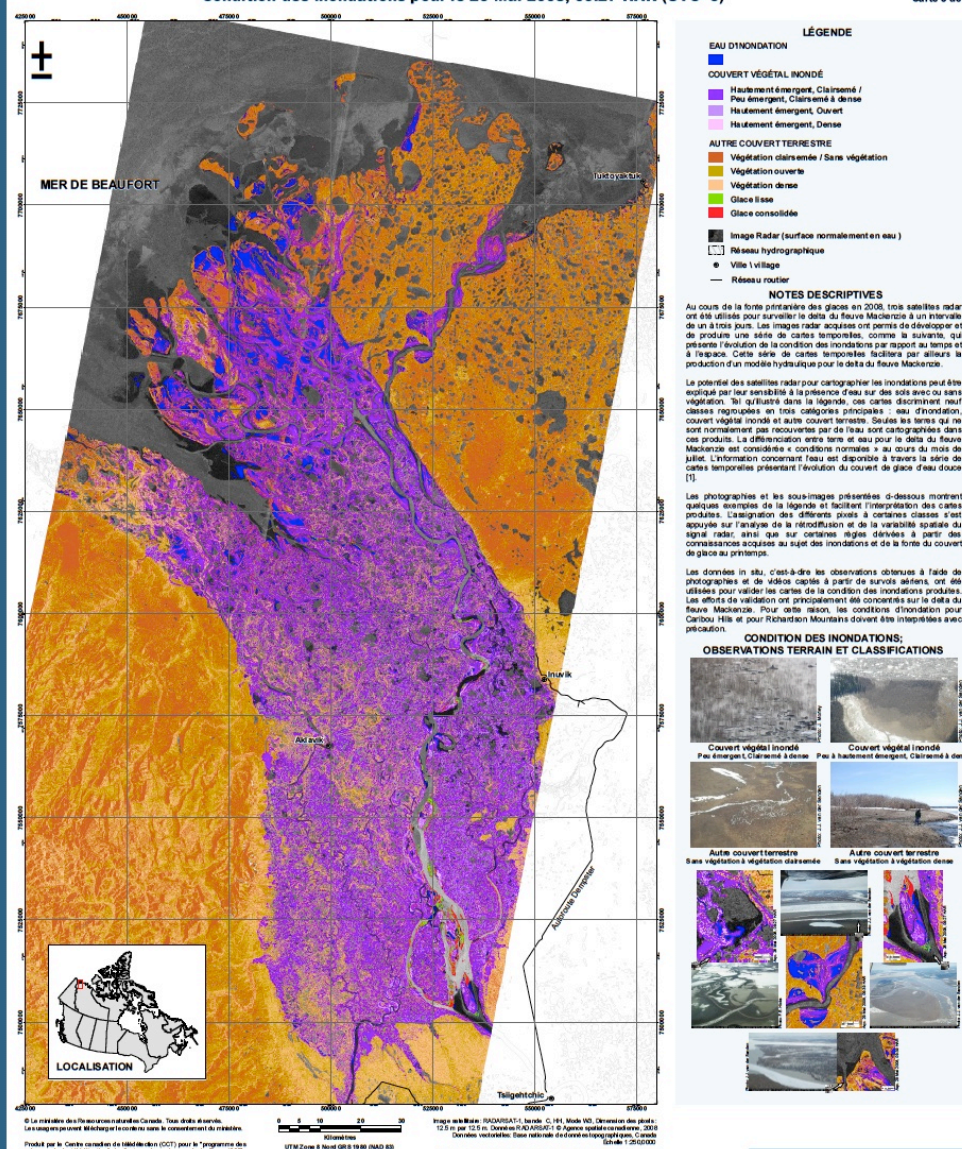






Condition des inondations pour le 26 Mai 2008, 09:27 HAR (UTC- 6)

Carte 5 de 11



Produit par le Centre canadien de l'altération (CCAT) pour le "programme sciences de l'altération" du Secteur des sciences de la Terre (SST) Ressources naturelles Canada.

Pour plus d'information, rendez visite au site web du Centre canadien l'altération à <http://www.cccat.gc.ca/>

En complément: [drivet@drivend.com](mailto:drivet@drivend.com) pour [correspondence@drivend.com](mailto:correspondence@drivend.com)

Glacier recumbens: [www.drivend.com](http://www.drivend.com) et H. Drouin, 2011, Spring 2 Flood Condition, Mclellan River Delta, Northwest Territories, Canada. A ready map series. Ottawa, Natural Resources Canada.

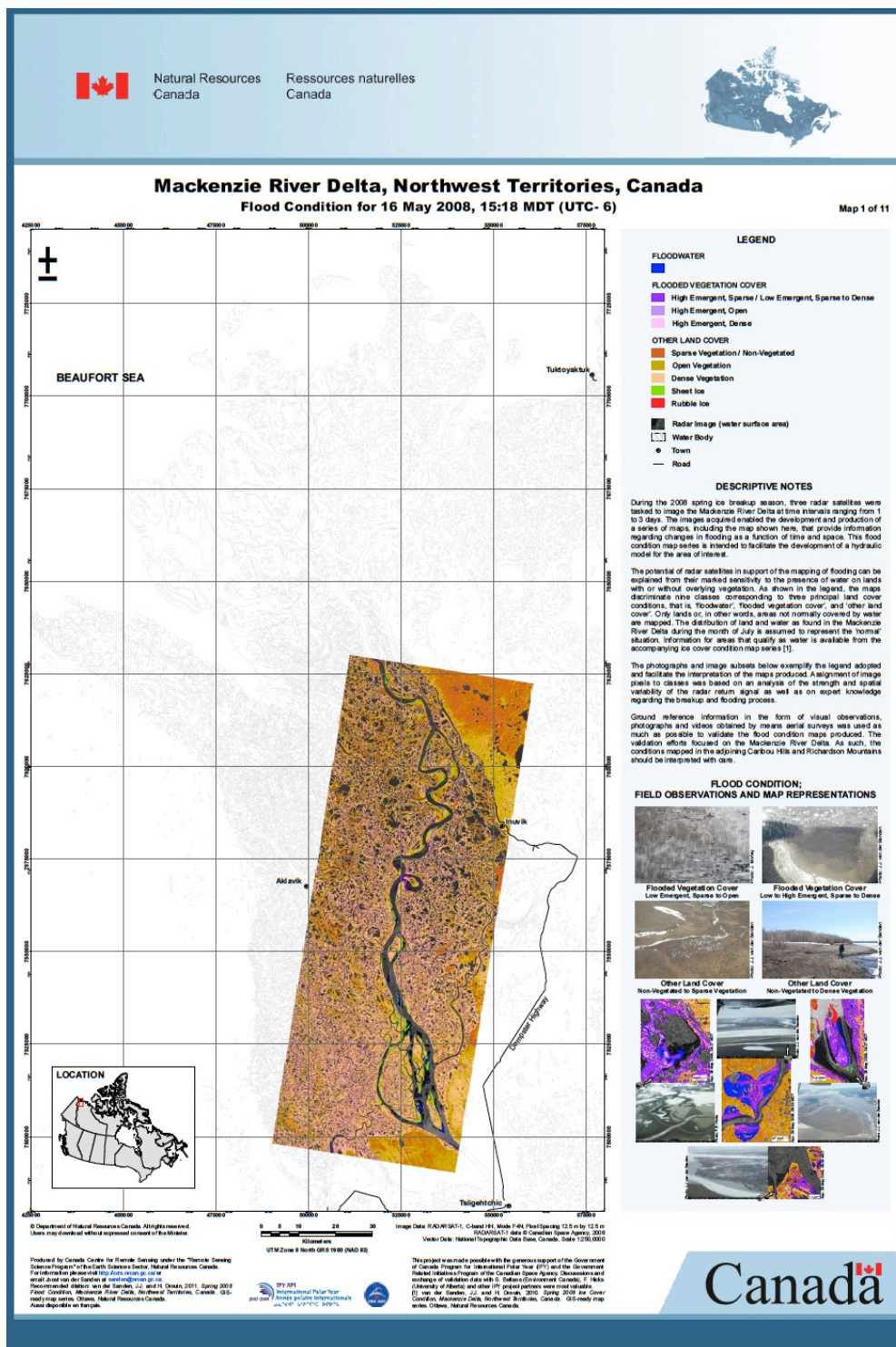
Also published in Shalish.

Image satellite: RADARSAT, bande C, VHI, Mode WS. Dimensions des pixels: 12,5 m par 12,5 m. Source: RADARSAT Canada. © 2008  
Données vectorielles: Base nationale d'endroits topographiques. 2008  
(Schéma 12-5-5500)

Canada



# Sample Information Products







## Seasonal Surface Displacement Derived from InSAR, Yellowknife and Surrounding Area, Northwest Territories

Seasonal surface displacement was derived for Yellowknife and the surrounding area using satellite interferometric Synthetic Aperture Radar (InSAR) data from the summer of 2010. RADARSAT-2 Ultra-wide swaths acquired on May 21, July 8, August 1, August 25 and September 18 were interferometrically stacked and the total amount of summer vertical displacement was calculated according to the methodology outlined in Short et al. (2011). Remote Sensing of Environment, doi:10.1016/j.rse.2011.08.013. Each displacement measurement is representative of a ground surface area of approximately 5 m x 4 m.

InSAR results in this map have only been qualitatively evaluated and therefore are presented in terms of the relative amount of displacement and not absolute values. Stable ground represents locations where no vertical change was calculated or where displacement was within the expected range of error ( $\pm 1$  cm). Low and moderate downward displacement represents surface decrease on the order of -1 to -3 cm and -3 to -6 cm, respectively. Upward displacement represents a surface increase of up to 6 cm. At some locations, a loss of interferometric coherence occurred as a result of significant changes in surface characteristics and no calculations were made.

The depicted surface displacement may be a product of natural or human-induced processes. Downward surface displacement may result from seasonal subsidence caused by thawing of the active layer (seasonally-frozen ground) or permafrost (permanently-frozen ground) or soil compaction. Upward surface displacements may result from ground surface heave or vegetation growth. At present, no explicit displacement process is inferred from the InSAR data, though probable causes of displacement may be derived from field inspections. Future map versions may include a quantitative assessment of the calculations and the net surface displacement determined over consecutive years.

### Data Sources and Acknowledgements:

Road network and existing buildings courtesy of the City of Yellowknife; transportation right-of-way and building footprint courtesy of the NWT Department of Municipal and Community Affairs (MACA); trail networks courtesy of the City of Yellowknife and MACA; National Topographic Database vector bodies at 1:50 000 scale from GeoGratis; mapping and data support by Colin Avey, GNWT, Environment and Natural Resources Division.

### Disclaimer

Her Majesty the Queen in right of Canada as represented by the Minister of Natural Resources, the Government of the Northwest Territories as represented by Environment and Natural Resources and Municipal and Community Affairs, and the City of Yellowknife, do not warrant or guarantee the accuracy or completeness of the information ("Data") on this map and do not assume any responsibility or liability with respect to any damage or loss arising from the use or interpretation of the Data.

The Data on this map are intended to convey regional trends and should be used as a guide only. The Data should not be used for design or construction at any specific location, nor are the Data to be used as a replacement for the types of site-specific geotechnical investigations.

### LEGEND

#### Relative surface displacement

- Moderate downward displacement (-3 to -6 cm)
- Low downward displacement (-1 to -3 cm)
- Stable ( $\pm 1$  cm)
- Upward displacement (1 to 6 cm)
- Loss of InSAR coherence
- Trails
- Roads
- Transportation right-of-way
- Existing buildings
- Former building footprint
- Water
- No data

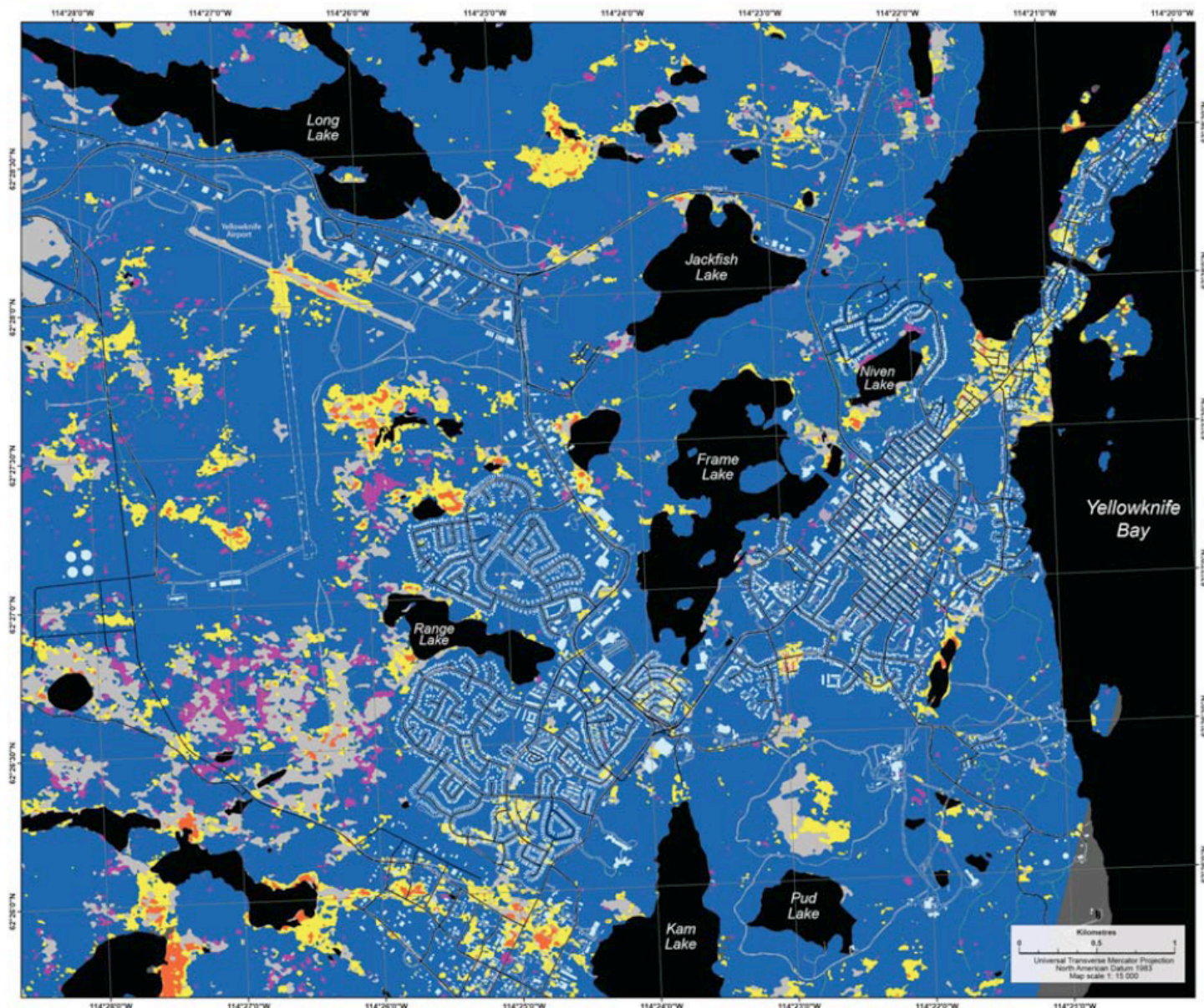
### The map is available from:

The Geological Survey of Canada Bookstore  
<http://gsc.nrcan.gc.ca/bookstore>, a pdf  
 It can also be downloaded free of charge from  
 GeoPub (<http://geopub.nrcan.gc.ca>)



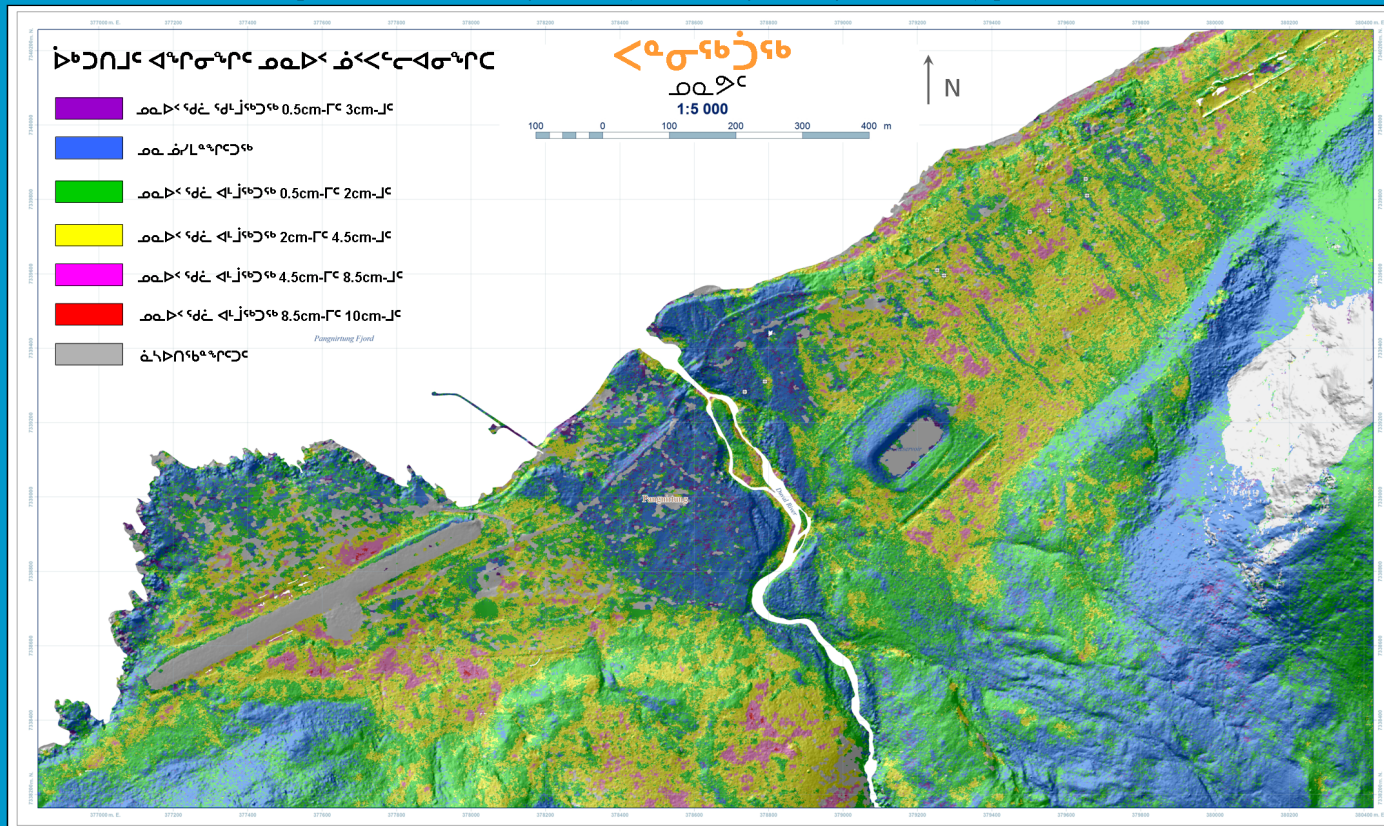
### Recommended citation:

Short, N., Stevens, C.W., and Wolfe, S.A. 2011. Seasonal Surface Displacement Derived from InSAR, Yellowknife and Surrounding Area, Northwest Territories, Geological Survey of Canada, Open File 7030, 1 CD-ROM, doi:10.4095/289578





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Natural Resources Canada      Ressources naturelles Canada

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மேலும் (2023)

محلہ (۲) کے لئے

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