MULTI-POLARIZED AIRBORNE C-SAR IMAGES FOR GEOLOGICAL MAPPING AT LAC VOLANT, QUÉBEC*

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ABSTRACT

This investigation explores the utility of multi-polarized airborne SAR images for geological mapping at the lac Volant site in eastern Québec.

The discovery of the Voisey's Bay massive sulphide deposit triggered a considerable interest in the Canadian mining community. In August 1996, a discovery with similar mineralogical associations was made near Lac Volant, 65 km NE of Sept-Îles, Québec. The Lac Volant showing started an unprecedented exploration rush in the area and geological mapping is now still in progress. Preliminary interpretation of a RADARSAT S6 image led to the acquisition of an airborne quad-polarization C-SAR image for MIR Télédétection Inc.

Our results show that the use of C-HH, C-VH and C-VV, airborne SAR images provide information on the distribution and orientation of lineaments. Analysis of the individual polarimetric images shows that the C-VH image provides a different enhancement of certain directions. The difference can be explained by a depolarization of the signal by vegetation combined to a geometrical effect of the topography.

These results are particularly relevant to RADARSAT-2, currently scheduled for 2001, which will have multiple polarization capability.

1. INTRODUCTION

Current imaging radar satellites, such as ERS-1 and ERS-2 (European Community), JERS-1 (Japan) and RADARSAT-1 (Canada) are typically single band, single polarization Synthetic Aperture Radar (SAR) sensors. The next generation of spaceborne SAR sensors will likely carry multi-band polarimetric systems. The latest SIR-C mission (Jordan *et al*., 1995) and several airborne investigations have demonstrated the enhanced capabilities of these sensors for geological studies. RADARSAT-2 will provide multi-resolution, multi-incidence, multi-polarization data. Therefore, it is important to understand what is the potential of multi-polarization imagery with regards to geological mapping in representative shield terrains.

Many studies have been done for geological mapping in arid environment (Evans, D.L., *et al*., 1986) or for forestry applications (Ahern, F.J., *et al*., 1996). Rheault *et al*. (1998), presented some preliminary results concerning the evaluation of airborne polarimetric SAR data for lithological mapping and noted that although not clearly explained, the cross-polarized imagery showed a significant difference with the like polarized imagery. Until now, no extensive reference has been found on the usefulness of polarimetric imagery for geological applications or geomorphological mapping in boreal forested environments.

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1.1 OBJECTIVES AND METHODOLOGY

The objective of this investigation is to determine the nature of the variation observed on the backscatter of the like and cross-polarized C-band over the lac Volant area. To do this, we need to understand the correspondence between the features observed on the imagery and the morphology of the surface and, to document and characterize the nature, the density and the variability of the vegetation cover.

In early August 1996, a RADARSAT Standard mode, beam 6, C-band Synthetic Aperture Radar (SAR) image of the lac Volant area was acquired by the Canada Centre for Remote Sensing (CCRS). The imagery showed an impressive amount of geological details over the area. Considering the quality of the spaceborne data and the interest it generated in the geological community, MIR Télédétection Inc. decided to contract CCRS for the acquisition of an airborne C-band, quad-polarization high resolution SAR imagery of the Lac Volant area. The airborne Narrow Swath mode, 6 m resolution, 7-look imagery was acquired on February 25, 1997.

2. BACKGROUND

The utility of SAR imagery for geological applications in the Canadian Shield boreal forest environment is well understood (Singhroy, *et al*., 1998, 1997; Saint-Jean, *et al*., 1997). Under a complete vegetation cover, the SAR signal only partially penetrates the vegetation canopy (Zebker *et al*., 1990) but nonetheless, the information obtained from the morphology of the vegetation canopy is of great utility for structural interpretation. Texture has also been shown to provide substantial information for geological mapping in forested environments (Azzibrouck *et al*., 1997).

Polarimetric SAR imagery has been studied in details for arid and semi-arid environments (D'Iorio *et al*., 1996; Evans *et al*., 1986, 1991). Their results show that polarimetric SAR is a good tool to differentiate rock types and to produce a classification map of lithological units. Observations show that vegetation canopies are strong volume scatterers that commonly exhibit a high cross-polarized component. In addition, cross-polarized returns result only from second-order effects involving tree canopy surfaces multiple scatter and subsurface volume scatter. Most theories predict domination of cross-polarized return by subsurface volume scattering (Evans *et al*., 1986).

The airborne imagery was acquired in February 1997 when threes were completely frozen. Ahern *et al*., (1996) reports several studies that have shown a backscatter decrease of the order of 3 to 5 dB when trees are frozen.

3. STUDY AREA

The lac Volant study area is located approximately 60 km NE of Sept-Îles (Fig. 1) along the north shore of the St-Laurence river in eastern Québec. The area is fairly remote as it can be accessed only by air. The general morphology consist of a plateau at an altitude of 730 m bounded to the NE by the Monts Tortue at 900 m and to the W by the lac Nipisso depression at 360 m. The highly dissected plateau is covered by a thin glacial drift which sustains a relatively uniform vegetation cover. Outcrop exposure in important (5-10% outcrop). We were able to identify 4 main vegetation types: Black spruce - balsam fir - Jack pine, balsam poplar - paper birch - tamarack, alder-willow shrubs and, bog - fen - non forest. The surface of the ground is covered by caribou lichen where drainage is good and by sphagnum moss where drainage is poor. Drainage is relatively poor on most of the Matamec Igneous Complex (plateau area) while it is significantly better in the lac Tortue Anorthosite Complex and the Havre-Saint-Pierre Anorthosite Complex (mountainous area) or above the Manitou Gneiss Complex (western lowlands). For the purpose of this paper, we will focus our work on the lac Dauphin test site, located 3 km SE of lac Volant.

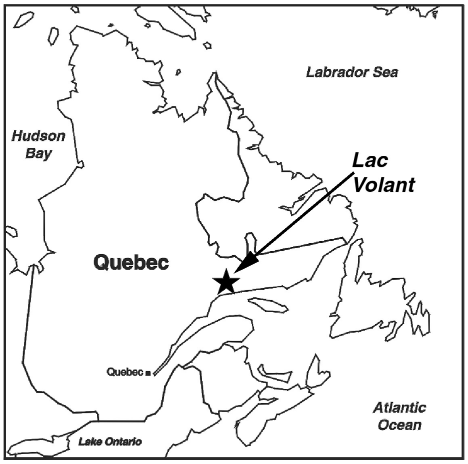

Figure 1. Location of the lac Volant area.

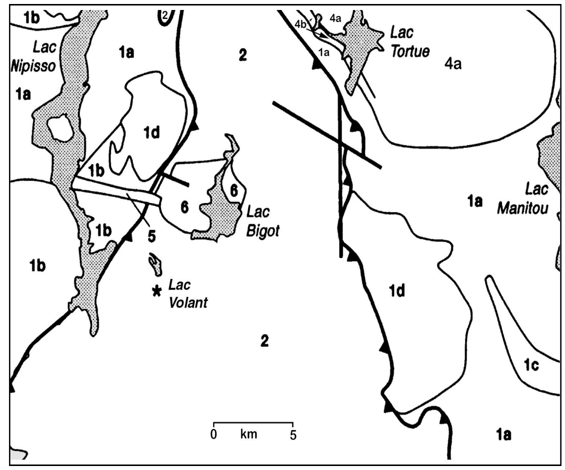

Figure 2. Simplified geological map of the lac Volant area. Manitou Gneiss Complex 1a: Qz Gneiss, 1b: Granitic Gneiss, 1c: Foliated Gabbro, 1d: Foliated Granite. Matamec Igneous Complex 2: Gabbronorite. Anorthosite Complex 4a: Anorthosite, 4b: Bedded Anorthosite. Late intrusives 5: Gabbro, 6: Undeformed Granite.

4. GEOLOGICAL SETTING

The lac Volant showing was discovered in August 1996 by a mapping team of the Ministère des Ressources naturelles (MRN) of Québec. The three bodies of massive sulphides (> 65% sulphides) are composed if pyrrhotite, chalcopyrite, pentlandite and pyrite. The assays showed an average of 2% Ni, 2.3% Cu and 0.1% Co. The announcement of the discovery and the similarities with the Voisey's Bay deposit triggered a "claim rush" over the area during the fall of 1996. By the end of 1996, 11200 claims have been staked by mining companies in the Nipisso and Manitou lakes area. Regional mapping at scale of 1:50 000 was done by the MRN over the entire area. In the fall of 1996, detailed mapping at scale 1:1000 was done over the mineralized area and completed with a Beep Mat survey (shallow EM survey) and finally, a helicopter-borne EM-Mag survey with 200 m line spacing covering four 1:50 000 NTS sheets.

The region is part of the allochtonous polycyclic belt of the Grenville geological province. It comprises four distinct geological units (Perreault *et al*., 1997):

- The Manitou Gneiss Complex is composed mainly of quartzofeldspathic gneiss and hornblende-biotite gneiss. The rocks are deformed and metamorphosed to the upper amphibolite or granulite facies.
- The Matamec Igneous Complex, hosting the showing, is a large tectonic slice transported onto the Manitou Gneiss Complex. The Complex is bounded by ductile shear zone mylonites. The Matamec Complex is composed of fine-grained gabbronorite, mangerite, monzonite, granite with K-feldspar phenocrysts, and few olivine gabbronorite intrusions. These rocks are partially to totally recrystallized to granulite facies assemblages. Syn to late Grenvillian gabbro and gabbronorite dikes and granitic intrusions (the lac Bigot granite) have been injected into the preceding units.
- The lac Tortue Anorthosite Complex and the west lobe of the Havre-Saint-Pierre Anorthosite Complex were formed by multiple injections of leuconorite, leucogabbro, anorthosite *sensu stricto*, and, in the border zones, of pyroxenite.

The lac Volant sector is underlain mainly by gabbronorite of the Matamec Igneous Complex. Figure 2 shows a simplified geology map of the lac Volant area.

5. DATA SET, FIELD METHODOLOGY AND OBSERVATIONS

5.1 THE AIRBORNE SAR DATA

The original C-band airborne SAR was flown on Feb. 25, 1997. The RADARSAT imagery was acquired on August 3, 1996. Table 1 gives a resume of the acquisition parameters for both type of imagery. The airborne SAR VV, HH and VH imagery serves as the basic data for this study. Figure 3 presents the RADARSAT imagery and a subset of the airborne SAR imagery covering the area. Note that the RADARSAT imagery and the airborne SAR do not have the same resolution or illumination direction. These differences explain the different feature enhancements seen on the two SAR images.

Figure 4 presents the full resolution airborne SAR imagery for the HH, VV and VH polarizations, the RADARSAT (HH) imagery, the scanned 1:40 000 airphoto and the scanned 1:50 000 topographic map (contour interval at 50

Table 1. Acquisition parameters for SAR imagery

	RADARSAT	Airborne SAR
Frequency / Wavelength / Band	5.30 GHz, 5.66 cm, C-Band	5.30 GHz, 5.66 cm, C-Band
Polarization	HH	HH, VV, HV, VH
Azimuth and range resolution	27.6 m, 27 m	6 m, 6 m
Encoding	16 bit, amplitude	8 bit, amplitude
Image size	7845 col., 8732 lines (109 by 98 km)	4096 col., 12776 lines (24 by 77 km)
Direction of trajectory, illumination	N352º, N82º (ascending orbit)	N 62º, N152º
Number of effective looks	4	7
Sensor altitude	796 km	6500 m
Incidence angle (near range, far range)	30º to 37º	45º to 76º

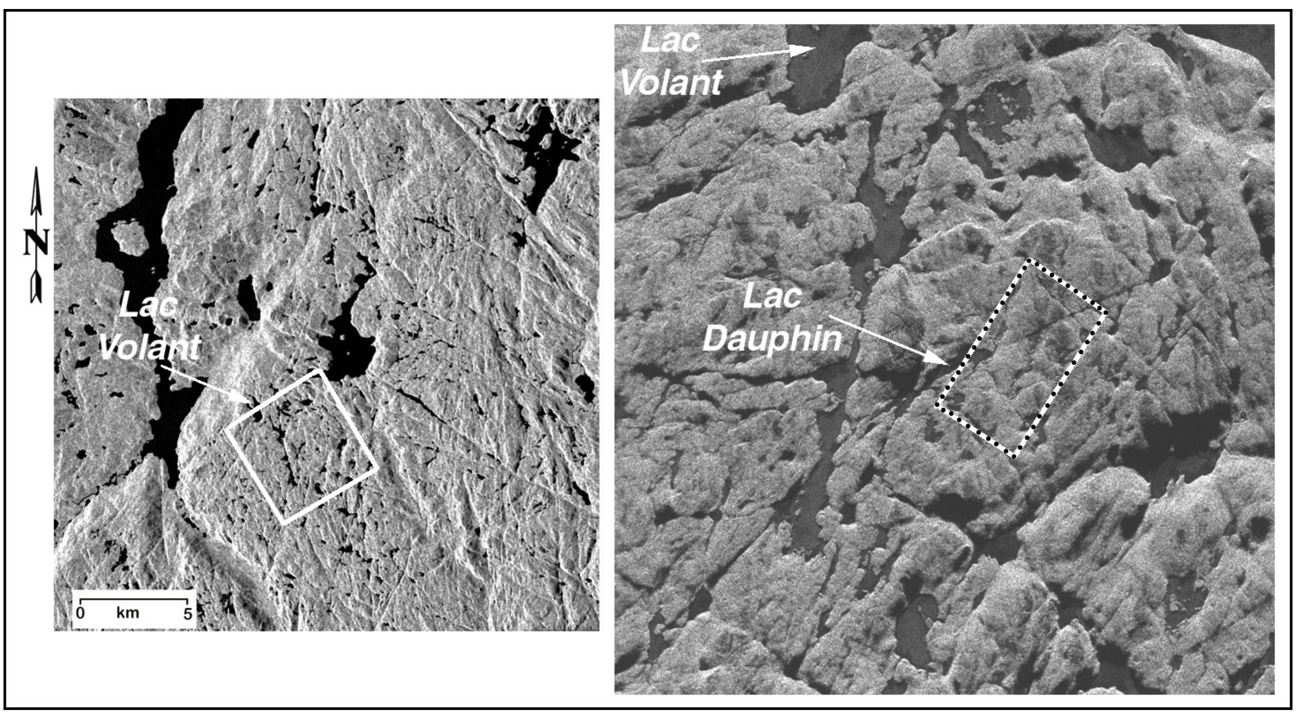

Figure 3. RADARSAT Standard mode beam 6 SAR image of the lac Volant area (left). The white square indicates the airborne SAR image of the surroundings of lac Dauphin (right). The dotted rectangle represents the lac Dauphin study area.

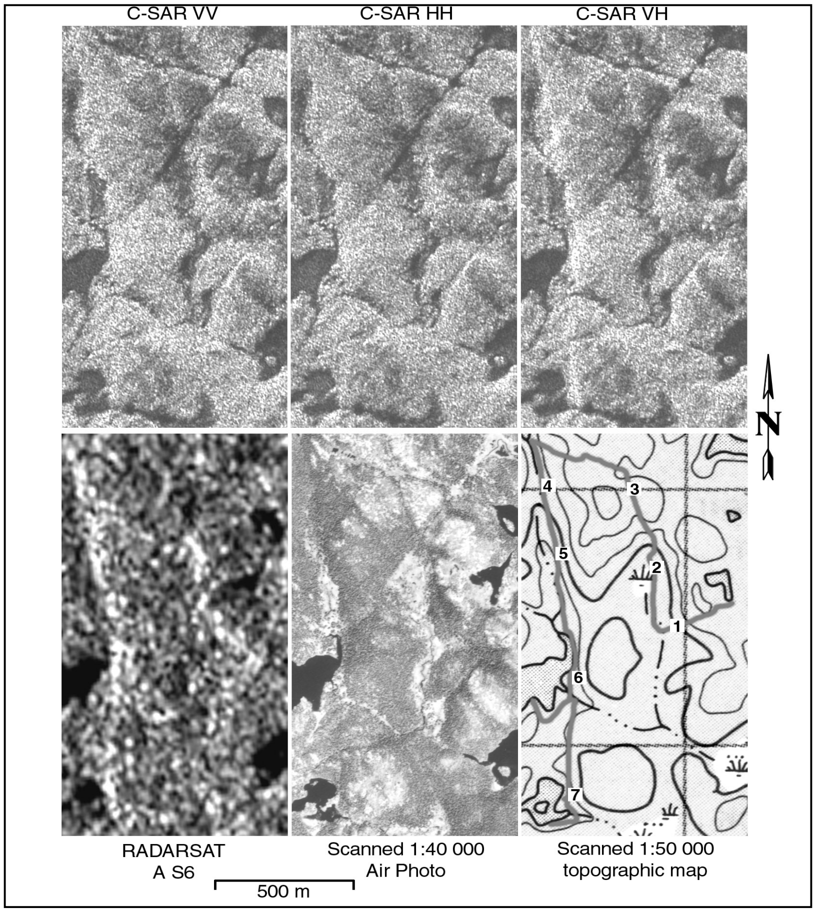

Figure 4. SAR imagery, airphoto and topographic map of the lac Dauphin area. The topographical map shows the stations numbers along the traverse. The grey line on the topographic map indicates the trace of the traverse, while the small rectangles shows the location of the 7 stations where topographic and vegetation profiles were collected.

feet). The visual interpretation of the imagery show subtle differences between the HH and VV polarizations; the HH polarization gives information on lake surface roughness variations, and surface vegetation changes (dark patches relate to well drained caribou moss lichen covered soil). In both the HH and VV polarization, lineament expression is very similar. The VH imagery shows a significant difference in the expression of some lineaments (oriented around N350º and N100º) when compared to like polarized imagery. On the VH imagery, lineaments along these directions show a stronger backscatter that is expressed as a bright signature that make them more easy to detect, as their contrast with surrounding environment is increased.

Table 2. Observations made at each station along the lac Dauphin traverse.

STATION	**SLOPE**			**VEGETATION**		**CANOPY OPENING***	
	Δh (m)	Δx (m)	Azimuth (º)	Mean height (m)	Mean diam. (cm)	90º (%)	45º (%)
1	25	30	330	8 - 10	10 - 15	0 - 10	0
2	25	25	345	2 - 4	5 - 10	50	20 - 30
3	10	20	345	2 - 10	-	60	30
4	30	100	345	5	10 - 15	70 - 80	30 - 40
5	45	65	345	5	10	60 - 80	30 - 50
6	25	50	350	6	15	70	30 - 40
7	25	50	350	-	-	80	40

*Canopy opening: Evaluation of ground visibility from 90º (directly above) and from 45º from horizontal.

To support the observations made on the imagery, a site verification was performed during the first week of July so that we could obtain a better understanding of the ongoing processes. This site was selected to obtain a solid comprehension of the effects of vegetation on the backscatter and for its typical representation of the area's morphology. Most important, the cross polarized imagery shows a good enhancement of N350º and N100º lineaments. Table 2 presents the synthesis of the observations made at each of the 7 stations made along the traverse.

Over the lac Dauphin area, slopes were quite uniform in their aspect. In all stations, the slope would start in a flat, poorly drained open swamp. At the foot of the slope, trees are biggest both in height and in diameter; the slopes consist of 2-3 m sub-vertical outcropping faces followed by "steps" where vegetation can grow. As we get to the top of the slope, inclination would decrease, as would the tree size.

5.2 VEGETATION COVER

From the observations made at the lac Dauphin site and elsewhere in the area, the vegetation cover has the following aspect. Flat areas have a poor drainage to which are associated swamps and marshes with the associated vegetation of grasses, sphagnum moss, caribou lichen, tamarack and a few black spruces. The slopes are covered by northern boreal forest composed mostly of black spruce. We have noted that the vegetation is densest at the base of the relief, and thinnest at the top. Generally, bedrock exposure is low because it is hidden under the vegetation canopy. At higher altitude, the outcrop exposure is good, as the vegetation cover is very thin (sub-arctic environment).

At the base of slopes, soils are better drained, vegetation is somewhat protected from the elements thus, vegetation is much healthier and trees can grow to impressive size (locally up to 75 cm in diameter). Vegetation is composed mostly of black spruce (±95%), with minor balsam fir, tamarack and some birches or balsam poplar. Ground is covered by sphagnum moss and caribou lichen. The vegetation density is high and canopy opening is low to intermediate. In the slope, vegetation cover varies depending on the steepness. Slopes up to 60-70 degrees will show a good density of trees but density is quite variable. Due to the harsh conditions, trees are tall and thin (5-10 cm diameter at breast height). Ground is covered by caribou lichen and sphagnum moss. Outcrop is important, as are displaced boulders and dislocated rocks. Canopy opening is low to intermediate.

At the top of the slopes, often corresponding to the regional plateau, vegetation is exposed to the elements and often show typical sub-arctic morphology: At the base of the tree, trunk is very large (15-25 cm diameter), much branches in the first 50 cm; at 1 m from the ground, trunk is 5 cm or less, branches are weak; tree reaches 3 to 4 m. Drainage is good and ground is covered by caribou moss. Canopy opening is intermediate to high.

6. DATA INTERPRETATION

6.1 MORPHOLOGY OF THE SURFACE

SAR sensors are very sensitive to surface morphology and surface roughness. On the RADARSAT imagery, the Matamec Igneous Complex shows a very interesting rendition of morphology. The gabbronorite show a detailed pattern reflecting the foliation, faults, fractures that lead to the structural interpretation of the geology of the area.

Figure 5 shows a typical profile of the slopes along a lineament studied around lac Dauphin. In the swamp, the morphology is flat to lightly undulating with occasional "islands" of rocks or outcrops, where tamarack and some black spruce can grow. As we get to the base of the relief, the concave slope increases slowly and gradually. Dislodged boulders are frequent. On the face of the lineament, the slope is maximal and varies from 30 degrees to vertical (locally over vertical distances extending from 1 to 15 m). In many instances, the slope is not continuous but is made of a series of steps with vertical rock faces (1-2 m) followed by 1-2 m less inclined "steps", etc. The roughness of the slope is relatively high as much dislodged blocs are observed. At the top of the cliff, the convex slope rapidly flattens and roughness is moderate. In the area of our study site, the main factor influencing morphology is structure. The gabbronorite assemblages of the Matamec Igneous Complex are broken-up by very obvious lineaments. The main lineament directions observed on the image are N340-350º, N40-55º and, N110º. A more regional interpretation of the imagery as shown on the RADARSAT imagery show that the N340-350º direction relates to the regional structural grain (foliation) of the gabbronorite while the N40º direction and N110º relate to major faults and fractures.

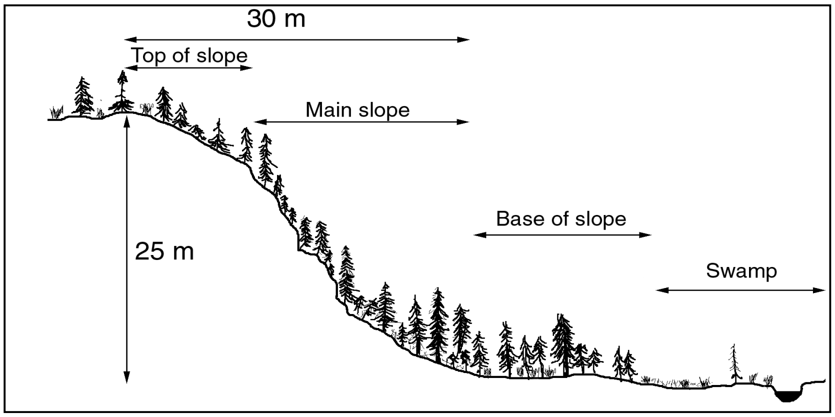

Figure 5. Typical profile of a structure related topographic feature in the lac Dauphin test site.

6.2 BACKSCATTER OF THE LIKE AND CROSS POLARIZED C-BAND

On figure 4, the VV, HH and VH imagery shows a significant difference between like and cross polarization images. The differences between the like polarized images are visually subtle; the VV image shows slightly more contrast and the HH image shows more roughness details above lakes. The VH imagery however shows a distinct enhancement of lineaments oriented N340-355º as well as N95-120º (although the enhancement is not as clear as for the first set of directions).

Geometry of the topographic features cannot explain the differences observed on the cross-polarized image as all images have exactly the same geometry. We will look at two explanations to understand the observed enhancement.

The first involves the depolarization of the signal by vegetation, a phenomena well known using polarimetric SAR. When the signal reaches the vegetation canopy, part of it is backscattered by leaves, part of it enters the canopy where it bounces on branches, trunk and on the surface before being backscattered toward the sensor. During this process, the polarization plane of the signal is changed as a result of second-order effects involving tree canopy surfaces multiple scatter and subsurface volume scatter. This explanation suffers from the fact that since the vegetation cover is relatively homogeneous; all vegetated surfaces should show a similar enhancement.

The second explanation, which we believe is more realistic, involves depolarization as explained above, with a simultaneous effect by the geometry of the topographic features. The aspect (orientation) and the inclination of the slopes are two factors well known to be significant for interpretation. A slope facing the radar will produce a maximum backscatter while a planar feature parallel to the signal wavefront will reflect the energy toward the sensor. The corner effect, which involve 90º angles (trees in water, cliff above a swamp, trees in a swamp, etc.) is much more common and produce the same effect. The combined effect of slope aspect and inclination can be seen on all polarization images; the VV, HH and VH image all show an enhancement of slopes facing radar (also known as the cardinal effect). On the VH image, the topographical features oriented N340-355º and N95-120º are as visually enhanced as the topographical features oriented ±20º from N62º (the direction perpendicular to the SAR illumination). The alternation of flat swamps and topographical reliefs may also contribute to the effect. Since the swamps are flat and relatively smooth to the radar wavelength, swamps produce specular reflections of the signal onto the slopes of the topographic features that can be thereafter backscattered toward the sensor.

7. CONCLUSION

- The use of C-HH, C-VH and C-VV, airborne SAR images provide information on the distribution and orientation of lineaments. Analysis of the individual polarimetric images shows that the C-VH image provides a different enhancement of certain directions.
- The combined effect of slope aspect and inclination can be seen on all polarization images; the VV, HH and VH image all show an enhancement of slopes facing radar.

- The enhancement of linear features oriented N340-355º and N95-120º on the VH imagery correspond to topographic reliefs having an amplitude in the range 15 to 60 m with fairly steep slopes (average slope of 30 degrees). This morphology is representative of the gabbronorite of the Matamec Igneous Complex.
- The enhancement observed on the airborne VH polarization image reflects the topography. Enhancement of these directions cannot be explained by depolarization by vegetation or by topographic effects only. We suspect that the enhancement is produced by a combined effect of vegetation depolarization and topography. The alternation of swamps and topographic reliefs may also contribute to the enhancement of the lineaments.
- The RADARSAT imagery provides regional information through which we can infer that this morphology correspond to regional foliation of the gabbronorite.

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