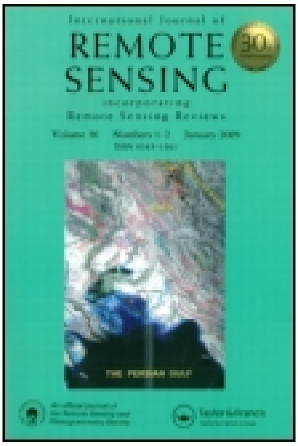

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Use of COSMO-SkyMed imagery for recognition of geomorphological features in the Martel Inlet ice-free areas, King George Island, Antarctica

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COSMO-SkyMed (Constellation of Small Satellites for Mediterranean Basin Observation) images in spotlight mode (1 m spatial resolution) were used for recognition of geomorphological features in Martel Inlet ice-free areas, King George Island, South Shetland Islands, Antarctica. This article shows the results from texture analysis and filtering of four X-band images with HH and VV polarization, acquired during fieldworks carried out in January and February 2011. Based on field checking and visual interpretation techniques, we identified several glacial landforms such as moraines, flutes, outwash, arêtes, glacial lineations, meltwater channels, lakes, lagoons, and shorelines. Some glacial linear features, such as lateral moraines, flutings, and arêtes are better identified with VV polarization, while supraglacial debris, debris flow, and shorelines are better discriminated with HH polarization. Meltwater channels, lakes, and lagoons were easily distinguished under both co-polarizations. Focal variance texture analysis and specific kernel size convolution filters yielded the best enhanced images for landform visual interpretation. For this propose, the Wallis adaptative, morphological Close, Prewitt with northwesterly and southeasterly directions, and some high-pass filters described in this study are the best filters. Images processed with these filters can be used for studies of geomorphic changes in Antarctica.

1. Introduction

Radar remote sensing has brought a new dimension for understanding glacial geomorphological processes. Cloudy conditions over Antarctic sub-polar maritime regions frequently limit the use of optical images for the monitoring of these areas. However, microwave energy can penetrate clouds and most types of rain (CCRS 2002).

Variations in backscatter values in radar images result from changes in the physical characteristics of terrain surfaces illuminated by the radar beam such as sediment, moisture content, surface roughness, and geometry (e.g. local incidence angle), as cited by Sarapirome et al. (1995). The sideways viewing geometry of imaging radar systems improves the recognition of glacial linear features such as morainic ridges, flutings, and meltwater channels. Several studies have confirmed the usefulness of RADARSAT,

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European Remote Sensing (ERS) satellite synthetic aperture radar (SAR), and Envisat advanced SAR (ASAR) images (C-band, 5.6 GHz) for geomorphological mapping (Sarapirome et al. 1995; Lewis et al. 1998; RAO D P 2002; Jensen 2007).

COSMO-SkyMed (Constellation of Small Satellites for Mediterranean Basin Observation) provides SAR data and the possibility of observing the Earth's surface at high temporal and spatial resolution at different polarizations. It is the largest Italian investment in space systems for Earth observation, commissioned and funded by the Italian Space Agency (ASI). This system consists of four low Earth orbit mid-sized satellites, each equipped with a multi-mode, high-resolution SAR operating at the X-band (9.6 GHz), acquiring images every 12 hours for a 600 km swath width. The COSMO-SkyMed satellites allow full global coverage, all weather, day/night acquisition capability, fast revisit/response time, and interferometric/polarimetric capabilities. These high-resolution, X-band SAR satellites thus allow the image interpreter to distinguish more details and can further support glacial geomorphological studies (ASI 2007; Battazza et al. 2007; Caltagirone et al. 2007; Coletta et al. 2008; Covello et al. 2010).

This article assesses the use of COSMO-SkyMed imagery at HH and VV polarizations to discriminate glacial landforms in the ice-free areas of the Antarctic region, and their application in geomorphological mapping. The study of landform development and its spatial distribution is critical in the characterization of proglacial zones for monitoring the ice-free areas of Antarctica. Landform mapping is also useful for glacier reconstruction (Lowe and Walker 1997).

2. Regional setting

In this study, we used four COSMO-SkyMed images covering Martel Inlet, located in the northern sector of Admiralty Bay, King George Island (KGI), South Shetlands archipelago (between 61° 54′ S–62° 16′ S and 57° 35′ W–59° 02′ W), at the northwestern tip of the Antarctic Peninsula (Figure 1).

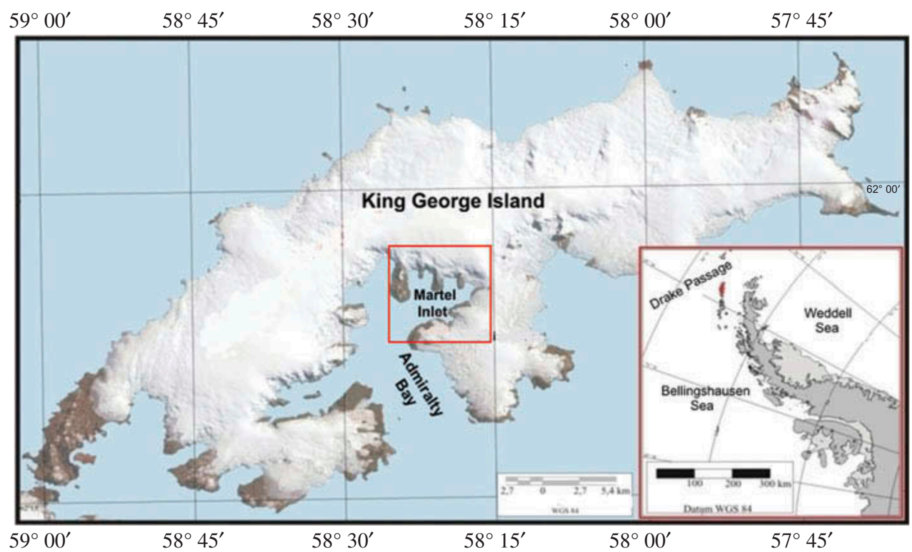

Figure 1. Location of Martel Inlet, King George Island, Antarctica. The red square indicates the ground coverage area of COSMO-SkyMed scenes used in this study.

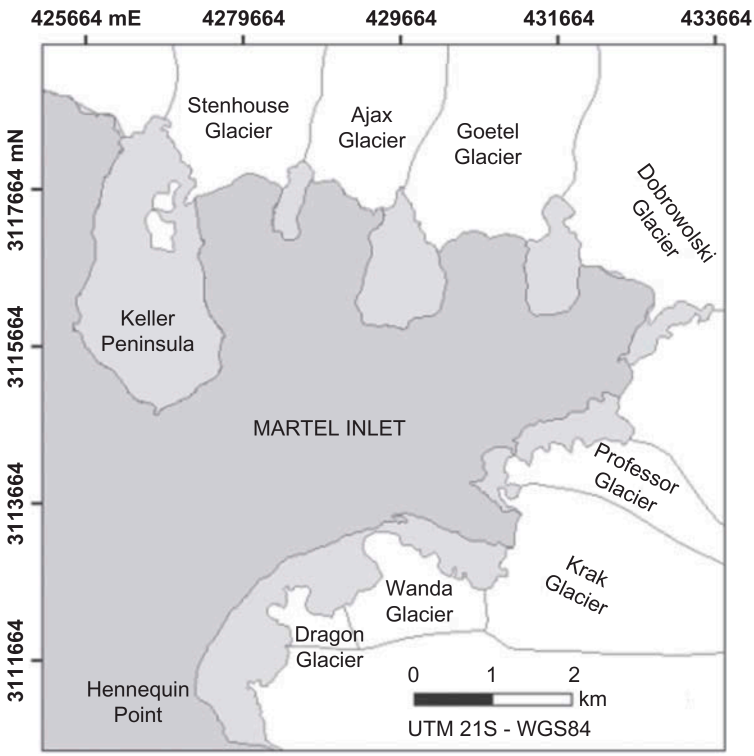

Figure 2. Glaciers at Martel Inlet, with their drainage basin boundaries. Data provided by the Admiralty Bay Map Server prototype – Centro Polar e Climático/UFRGS (2011).

Most of the Martel Inlet is surrounded by tidewater glaciers with steep slopes, high ice flow velocities, and extensive crevasse fields. Some glaciers have termini on land, such as Wanda, Dragon, and Professor (Figure 2). Glacier retreat processes have formed ice-free areas and consequently exposed several landforms (Rosa et al. 2010).

3. Materials and methods

3.1. Data set characteristics

The imagery used in this study consists of two horizontally polarized (HH) and two vertically polarized (VV) COSMO-SkyMed images acquired in spotlight mode, with 1 m spatial resolution and approximately 100 km^2 of ground coverage area. These images were acquired in descending orbits during fieldwork carried out in January and February, 2011. Various characteristics of these images are described in Table 1. Sediment samples were collected during three summer field seasons (2007, 2010, and 2011) in the proglacial area, covering varying microenvironments and geomorphic features, for the identification and mapping of landforms. The samples were analysed at the Laboratory of Sedimentology of CECO (Centre for Marine and Coastal Studies – UFRGS).

Table 1. Characteristics of COSMO-SkyMed (CSK) images used in this study (Agência Espacial Italiana (© ASI)).

Acquisition date	Acquisition time (hours: minutes: seconds) (UTC)	Satellite mission	Orbit number	Look angles (near range–far range) (°)	Polarization mode
22 January 2011	19:58:45	CSK3	12142	43.023–43.431	VV
25 January 2011	20:22:40	CSK1	19904	28.329–28.992	HH
10 February 2011	20:22:30	CSK1	19667	28.295–28.958	VV
11 February 2011	19:52:34	CSK2	17193	45.553–45.916	HH

3.2. Image processing

We used COSMO-SkyMed level 1A products (also termed single-look complex slant), which consist of focused data, with internal radiometric calibration, in slant range-geometric projection, and with associated ancillary data.

Conversion from intensity to amplitude in decibels, orthorectification, speckle filtering, and statistical evaluation of the COSMO-SkyMed data were performed using the open source software Next ESA SAR Toolbox (NEST; Array Systems Computing Inc., Toronto, ON, Canada). Slant-to-ground range correction was performed using image metadata and a high-resolution digital elevation model (DEM). We generated a DEM and an orthophotomosaic of the study area.

In the orthorectification of COSMO-SkyMed images and Servicio Hidrográfico y Oceanográfico de La Armada de Chile (SHOA) aerial photographs, the original pixel size was resampled to 0.7 m and 1 m, respectively, using bilinear interpolation. All data were represented in UTM projection and referenced to the WGS84 ellipsoid.

A median filter (Rees and Satchell 1997) of 5 × 5 kernel size was applied for speckle reduction of COSMO-SkyMed orthorectified images. This filter effectively reduced speckle noise, preserving the edges between homogeneous areas and allowing good identification of geomorphological features. An experimental study carried out by Arigony-Neto (2006) with ERS SAR and Envisat ASAR images showed that the median filter is one of the best algorithms for speckle reduction in glacial environments, with high computational efficiency.

3.3. Image enhancement and interpretation

SAR image interpretation was based on visual examination in regard to distinct image tones, textures, size, shape and target patterns, radar shadows, topographic position, orientation, and the regional geomorphic context. Landform identification was based on Glasser and Jansson (2005), Glasser et al. (2005), Smith and Clark (2005), Gustavsson et al. (2006), and Benn and Evans (2010); information acquired in the field; visual interpretation of COSMO-SkyMed images, including comparison with the orthophotomosaic described in Section 3.1; and a co-registered Quickbird fused image acquired in October 2006.

We evaluated the use of COSMO-SkyMed images with HH and VV polarization to discriminate geomorphological features in the Martel Inlet ice-free areas. Focal variance texture analysis, the Wallis adaptative filter, morphological filter, Prewitt filter, and some high-pass filters were applied to the COSMO-SkyMed data set to enhance linear structures in those images used to identify geomorphological features. Texture enhancement was performed by focal variance calculation of images (i.e. within a moving window). The Wallis adaptative filter is designed to adjust images' contrast stretch using only values within the window size. We applied a linear stretch with two standard deviations to this kernel. We also evaluated the following filters: morphological Erode (focal minimum value), Dilate (focal maximum value), Open (Erode followed by dilate), and Close (Dilate followed by erode). Finally, we analysed image edge enhancement resulting from the use of high-pass and Prewitt directional filters. In Table 2, we present the 3 × 3 kernel definition of the high-pass and directional filters tested in this study and the filters that best enhance geomorphic features in COSMO–SkyMed images. Tests were also carried out using 5 × 5 and 7 × 7 kernel sizes.

4. Results and discussion

Based on visual interpretation of pre-processed COSMO-SkyMed images, we identified several well-preserved glacial and periglacial landforms in the Martel Inlet, including moraines, flutes, outwash, arêtes, glacial lineations, meltwater channels, lakes, and shorelines.

Lateral and end moraines composed of single linear and curved ridges with positive relief provide geomorphological evidence of the maximum extent of the Wanda Glacier (Rosa et al. 2010). Most of these lateral moraines have northeasterly orientation, while for those located on the most recent depositional margins it is northwesterly. These features were best identified in vertically co-polarized images. In general, VV and HH data correspond to information resulting from surface-scattering contributions (e.g. from morainic deposits in the Wanda proglacial area), while a combination of HV and VH provides information on polarization properties impacting mainly on volume scattering (Rott and Davis 1993).

The lateral moraines' northeasterly orientation points to an ancient Wanda Glacier ice flow that formed a U-shaped valley (Rosa et al. 2010). These depositional features are of low moisture content and they can be identified on COSMO-SkyMed images by medium grey tones due to their boulder content, which increases backscattering and radar shadows (steep slopes shielding radar illumination), and because of their linear morphology. Vertical edge detection and morphological Close filters (with 3 × 3 windows) showed better results for lateral moraine identification (Figure 3).

A lateral moraine located at a recent ice-free area along the Wanda Glacier front is aligned northwesterly. A 3 × 3 Prewitt filter of the same orientation enhanced this glacial feature (Figure 4).

Meltwater channels and flutings (Figures 4 and 5) were visually distinguished by their linear forms and medium to dark grey tonalities because of water content in these deposits. Flutings are parallel features indicating a wet thermal regime and the ancient northwesterly ice flow direction of the Wanda Glacier (Rosa et al. 2010). Meltwater channels occur at different locations in proglacial areas. According to Rodhe (1988), these features are most common in the ablation area of glaciers. At Wanda Glacier terminus, they appear as small, ice-marginal channels that run parallel to ice margins and mark the recent ice retreat. Flutings were better identified at VV polarization, while meltwater channels were easily identified at both HH and VV polarization. These linear features were better enhanced by a 3 × 3 Prewitt filter with northwesterly direction.

Exposed striated pavements at the Wanda Glacier proglacial area (Figure 6) were identified in COSMO-SkyMed images by their dark grey tones (lower backscattering) due to their smooth surfaces and basaltic lithology, which have a higher dielectric constant

Table 2. Kernel definition of high-pass and Prewitt filters with 3 × 3 pixels tested in this study. Filters that best enhance geomorphic features in COSMO-SkyMed images are highlighted in grey.

High-pass filters							
–1 –1 –1 –1 8 –1 –1 –1 –1 **Edge detection**	–1 –1 –1 –1 9 –1 –1 –1 –1 **Highpass**	–1 –1 –1 –1 10 –1 –1 –1 –1 **Summary**	–1 –1 –1 –1 17 –1 –1 –1 –1 **Edge enhancement**	–1 –1 –1 2 2 2 –1 –1 –1 **Horizontal**	–1 2 –1 –1 2 –1 –1 2 –1 **Vertical**		
–1 –2 –1 0 0 0 1 2 1 **Horizontal edge**	–1 0 1 –2 0 2 –1 0 1 **Vertical edge**	0 –1 0 –1 0 1 0 1 0 **Cross edge**	0 1 2 –1 0 1 –2 –1 0 **Left diagonal**	–2 –1 0 –1 0 1 0 1 2 **Right diagonal**	1 4 1 4 –20 4 1 4 1 **Laplacian edge**		
Prewitt directional filter							
1 1 1 1 –2 1 –1 –1 –1 **North**	1 1 1 1 –2 –1 1 –1 –1 **Northwest**	1 1 –1 1 –2 –1 1 1 –1 **West**	1 –1 –1 1 –2 –1 1 1 1 **Southwest**	–1 –1 –1 1 –2 1 1 1 1 **South**	–1 –1 1 –1 – 2 1 1 1 1 **Southeast**	–1 1 1 –1 –2 1 –1 1 1 **East**	1 1 1 –1 –2 1 –1 –1 1 **Northeast**

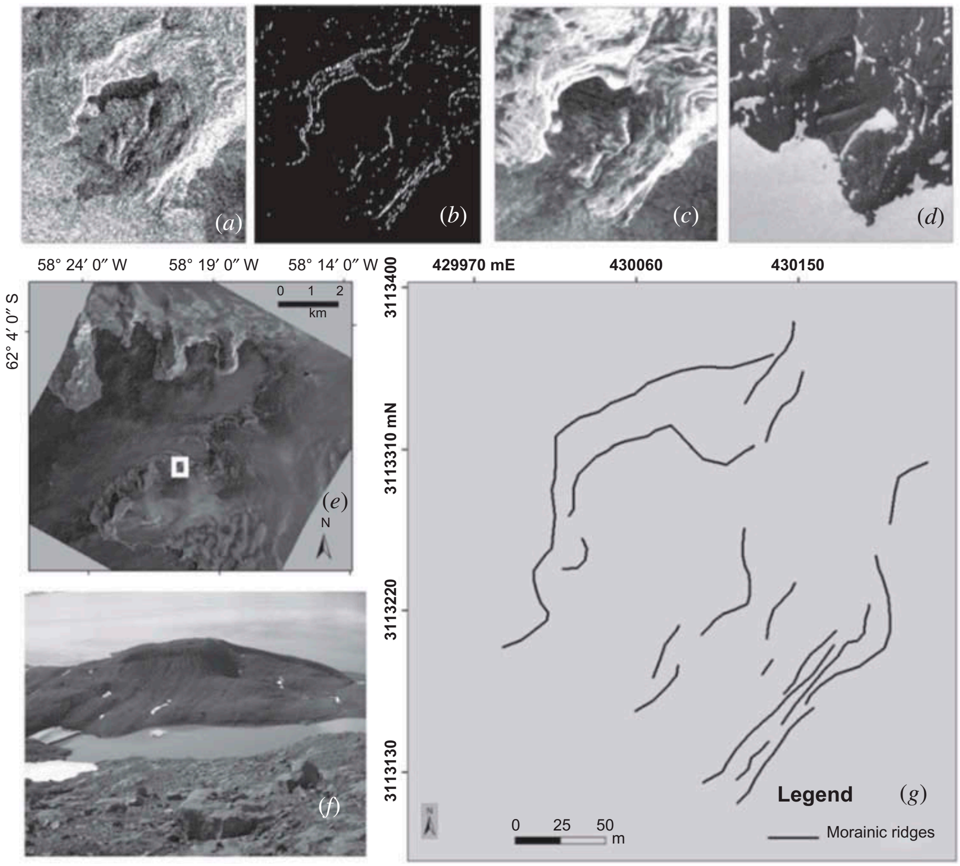

Figure 3. A lateral moraine on Wanda glacier: (*a*) subscene of an orthorectified COSMO-SkyMed image (Agência Espacial Italiana (© ASI)); (*b*) image enhanced by a 3 × 3 vertical edge detection filter; (*c*) image enhanced by a 3 × 3 morphological Close filter; (*d*) subscene of an orthorectified SHOA aerial photograph acquired on 22 January 2003; (*e*) at VV polarization (22 January 2011), speckle-reduced by a 5 × 5 median filter; (*f*) image of a Wanda lateral moraine taken on 17 January 2011; (*g*) geomorphic map of lateral morainic ridges, compiled from Figures 3(*b*) and (*c*) and shown in the white square of Figure 3(*e*).

(about 12) than adjacent sedimentary deposits composed of dry silt and sand (3.5 and 2.5, respectively).

Coastal features with sand deposition (Figure 7) showed a smooth surface, low slope, and high water content, resulting in low backscattering and dark grey tones in COSMO-SkyMed images. The surface roughness of boulder pavements produces high backscattering and consequently lighter grey tones in SAR images. These deposits are found parallel to the coastline and were better identified in COSMO-SkyMed images with HH polarization. The 3 × 3 texture analysis and vertical edge detection were the best methods to discriminate these coastal features.

The coastline delineation on COSMO-SkyMed imagery could have been carried out even in despeckled images without any high-pass filtering because of land (surface and volume scattering mechanisms) and water (specular reflection mechanism) high contrast in the radar return. Besides the frequency and polarization characteristics, the high SAR sensor incidence angles provided more details about glacial feature surface roughness.

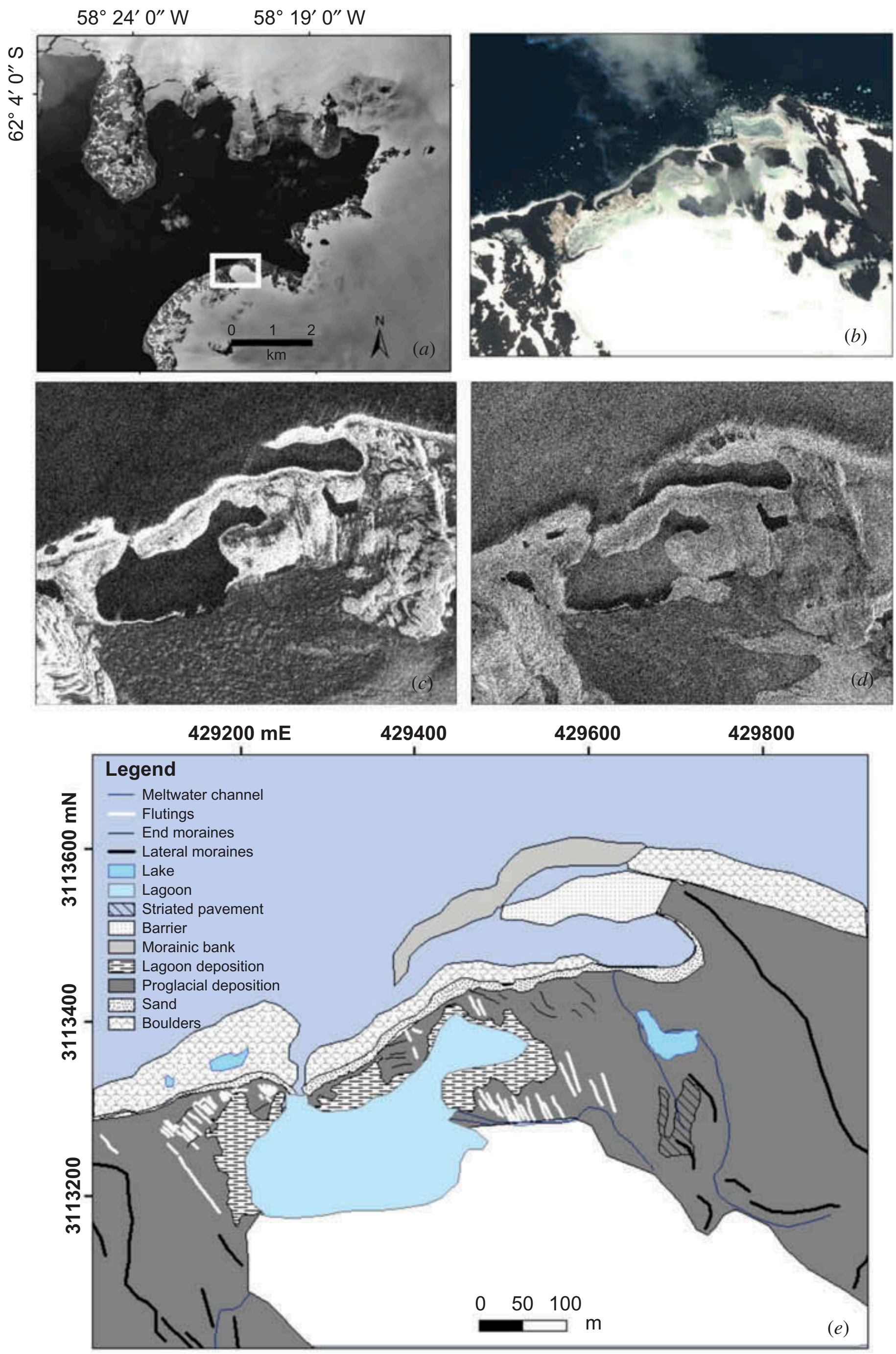

Figure 4. Recently exposed Wanda Glacier proglacial area. (*a*) Study area location on an orthophotomosaic (22 January 2003); (*b*) subscene of a Quickbird fused image (October 2006); (*c*) COSMO-SkyMed image covering the same area as (*b*) acquired at HH polarization (25 January 2011) and enhanced by a 3 × 3 vertical edge detection filter; (*d*) COSMO-SkyMed image covering the same area as (*b*) acquired at VV polarization (22 January 2011) and processed with a 3 × 3 edge enhancement filter (Agência Espacial Italiana (© ASI)); (*e*) geomorphic map of landforms at Wanda Glacier proglacial area, compiled from Figures 4(*c*) and (*d*).

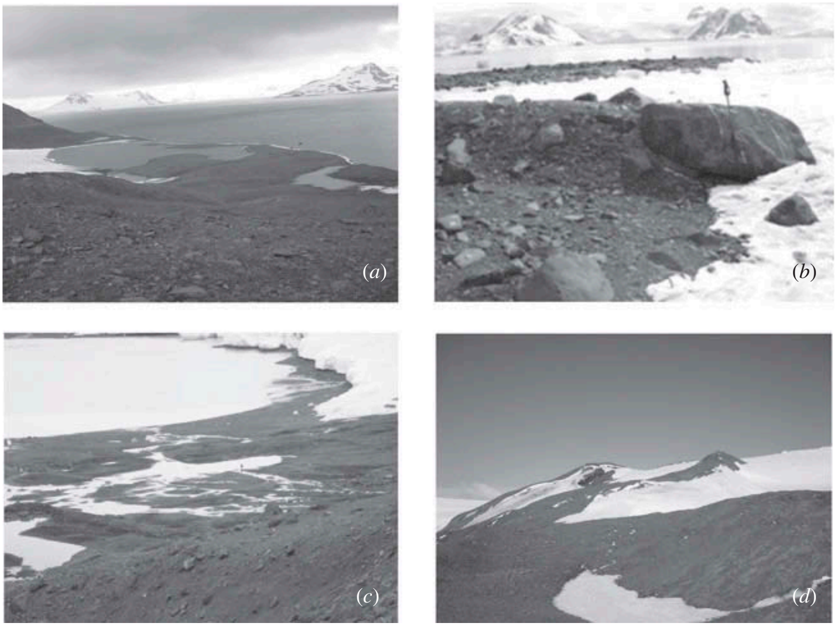

Figure 5. Wanda Glacier landform photographs taken on 17 January 2011. (*a*) Lagoon and meltwater channels, (*b*) flutings, (*c*) channels exposed at proglacial area, and (*d*) lagoon deposition and meltwater channels.

According to Leconte and Pultz (1991) and Lewis et al. (1998), the ability of radar data to delineate land/water boundaries and to map geomorphological features depends largely on the incident angle. Thus, at areas of low proglacial elevation, SAR images acquired at high incident angles (i.e. on 22 January and 11 February 2011; Table 1) have higher terrain texture contrast than others.

Lagoons and lakes at the Wanda Glacier proglacial area act like specular reflectors and reflect back most of the incident radar energy. For these reasons, they appear as very dark grey tones in COSMO-SkyMed images (Figures 4 and 5). Ice-free lagoon areas usually indicate large volumes of glacier meltwater. At the time of image acquisition, Martel Inlet was not very susceptible to wind-induced waves and thus it appeared predominantly dark grey on HH and VV polarization images. Lacustrine deposits also appear very dark grey (Figures 4 and 5) due to their high moisture content, fine-textured surfaces, and low slope shores. The 3 × 3 texture analysis and edge enhancement filter were the best choices for delineating these waterbodies.

COSMO-SkyMed images could be used in underwater morphology detection, for example morainic banks. However, high radar signal absorption by deep water during high tides or turbulence precluded the use of these images: only in the COSMO-SkyMed image acquired on 22 January 2011 (Figure *4*(*d*)), under low tide (i.e. shallow water) and low turbulence conditions, could we identify a morainic bank.

Supraglacial debris at the Wanda Glacier ablation zone was identified by its medium grey tones, while the wet-snow zone appeared dark grey in COSMO-SkyMed images. The speckle-filtered images were adequate to discriminate these targets (Figure 8). Vertically co-polarized images better discriminated the wet-snow zone from other study area glacier aspects (i.e. frozen percolation and bare ice zones) than horizontally co-polarized scenes.

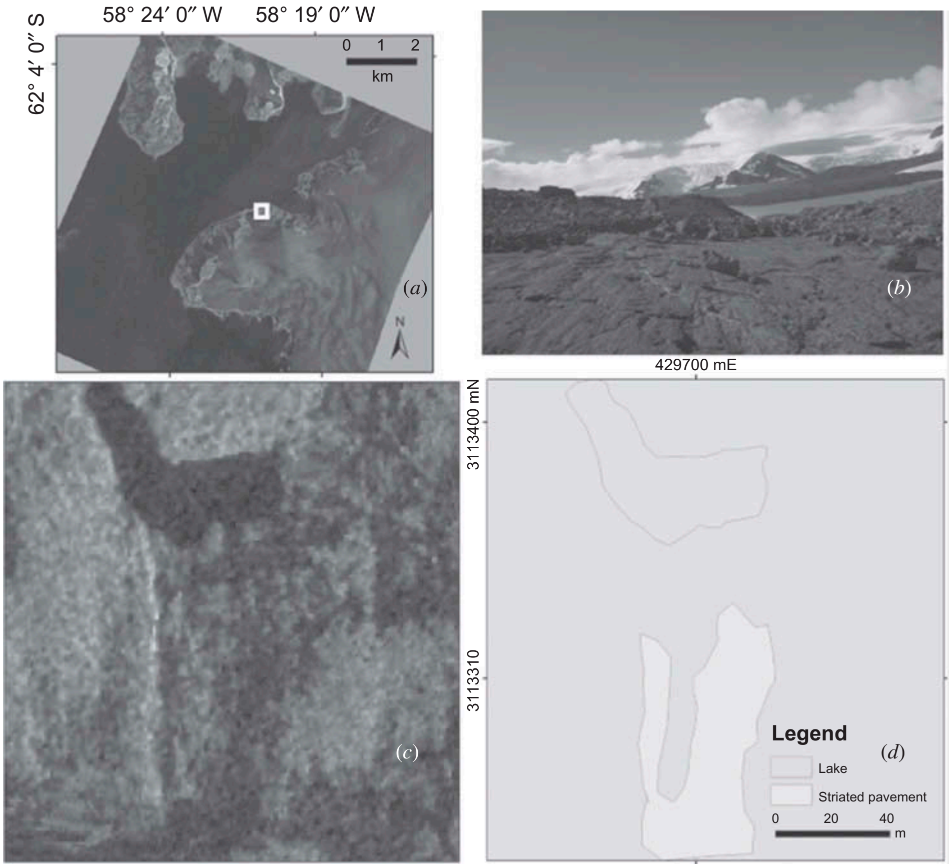

Figure 6. Exposed striated pavements on Wanda Glacier. (*a*) Orthorectified COSMO-SkyMed image at HH polarization (25 January 2011), speckle-reduced by a 5 × 5 median filter; (*b*) image of a striated pavement (17 January 2011); (*c*) subscene of COSMO-SkyMed image (location indicated by the small white square in Figure 6(*a*)); (*d*) lake and striated pavement geomorphic map, compiled from Figure 6(*c*).

In SAR images, wet-snow zones can generally be distinguished from ice-free terrains and this discriminatory ability increases with frequency, so the X- and C-bands are generally used for this purpose (Shi and Dozier 1993).

Beach ridges have linear and curved forms aligned parallel to the coast, indicating local sea level changes. Raised beaches on the South Shetland Islands coast were formed by the isostatic uplift that accompanied post-LGM (last glacial maximum) deglaciation (John and Sugden 1971; Sugden and Clapperton 1977; Del Valle et al. 2002; Bentley et al. 2005). In COSMO-SkyMed images, these features were identified at Hennequin Point with a northeasterly orientation (Figure 9). Their eastern aspect, facing the radar sensor, generated high backscatter values and consequently lighter grey tones than lower areas with seasonal snow accumulation, meltwater, organic activity, and medium to light grey tones in SAR images. They could be better identified in images with VV polarization, enhanced by a Prewitt filter with southeasterly direction and by a vertical edge detection filter, both with 3 × 3 pixels. The 7 × 7 Wallis adaptive filter also improved the contrast of raised beaches.

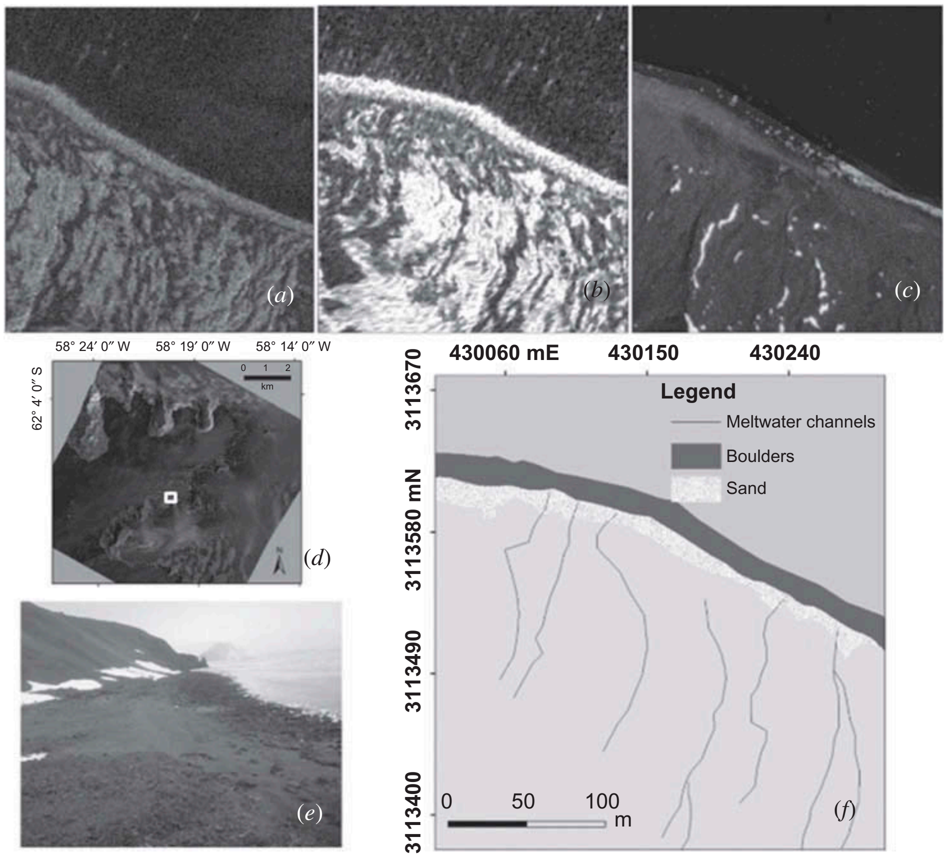

Figure 7. Coastal features of Dragon Glacier. (*a*) Subscene of an orthorectified COSMO-SkyMed image (Agência Espacial Italiana (© ASI)); (*b*) image enhanced by a 3 × 3 vertical edge detection filter; (*c*) image enhanced by texture focal variance of 3 × 3 pixels; (*d*) at HH polarization (25 January 2011), speckle-reduced by a 5 × 5 median filter; (*e*) image of coastal features (17 January 2011); (*f*) geomorphic map of boulders, sand deposition, and meltwater channels, compiled from Figures 7(*b*) and (*c*). The small white square in Figure 7(*d*) indicates the location for Figures 7 (*a*)–(*c*) and (*f*).

Debris flow deposits were found only on high-elevation parts of the study area with steeper slopes facing the radar sensor, which were responsible for foreshortening and layover effects and higher backscatter values, while opposing directions generated shadow effects as described by Lillesand et al. (2008). Furthermore, their very coarse superficial texture resulted in higher backscattering and light grey tones, allowing their identification on COSMO-SkyMed images. Because shadow made it difficult to discriminate waterbodies in these areas, we used the orthophotomosaic and high-resolution DEM generated in this study (Section 3.2) and a Quickbird fused image (Section 3.3) as ancillary information to identify certain waterbodies.

Arêtes in the Martel Inlet proglacial environment are predominantly northerly and northeasterly orientated (Figure 10) because of the strong structural geological control in the area. These features are best identified on VV polarized images.

Table 3 summarizes the optimum filters and polarizations to identify landforms of Antarctic maritime areas on COSMO-SkyMed images.

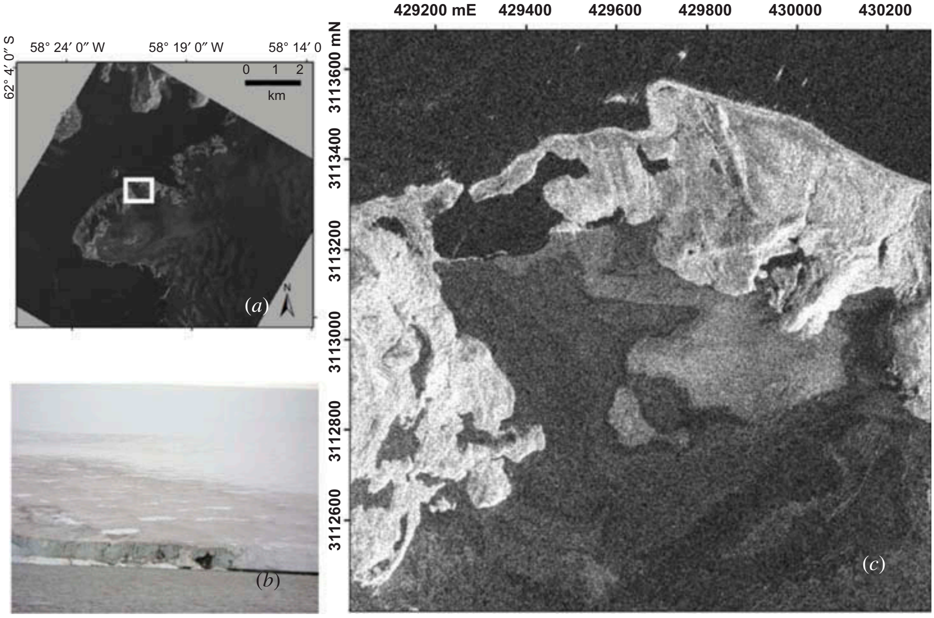

Figure 8. Supraglacial debris at Wanda Glacier ablation zone. (*a*) Orthorectified COSMO-SkyMed image (Agência Espacial Italiana (© ASI)); (*b*) image of supraglacial debris (10 January 2011); (*c*) the image at HH polarization (11 February 2011), speckle-reduced by a 5 × 5 median filter. The small square (Figure 8(*a*)) indicates the location for Figure 8(*c*).

5. Conclusions

We presented a preliminary evaluation on the use of COSMO-SkyMed images in spotlight mode for geomorphic analysis of sub-polar Antarctic areas. Images acquired at HH and VV polarization are suitable for identification of marine, glaciofluvial, glaciolagunar, glacial, and paraglacial landforms. High spatial resolution data and the repeated observation possibilities of COSMO-SkyMed provide a good option for macro- or mesorelief classification. However, in the complex glacial depositional environment of the Martel Inlet, it is difficult to identify mesoscale features because of their heterogeneous composition. Furthermore, the presence of several targets in the instantaneous field of view of this high-resolution SAR sensor produces complex return signals and considerable speckle.

Geomorphological features have different responses in regard to radar signals, depending on the co-polarization mode. In this study, some glacial linear features such as lateral moraines, flutings, and arêtes were better identified in VV polarized images. On the other hand, HH polarization produced stronger return signals from supraglacial debris, debris flow, and shorelines than VV and, thus, a better discrimination of these glacial features. Meltwater channels, lakes, and lagoons were easily distinguished in both co-polarizations.

This article also evaluated the application of several convolution filters in COSMO-SkyMed images at HH and VV polarizations to improve visual interpretation of glacial and paraglacial landforms in Antarctic maritime regions. Texture analysis of focal variance and specific kernel size of the Wallis adaptative filter, morphological Close filter, certain high-pass filters, and the Prewitt filter with northwesterly and southeasterly directions yielded the best results for this purpose.

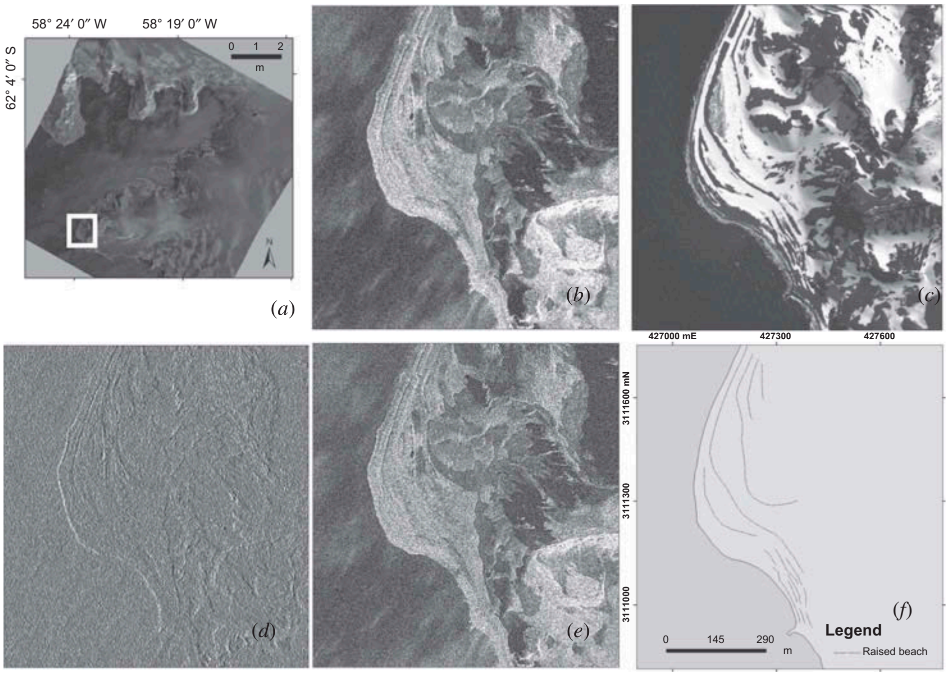

Figure 9. Beach ridges at Hennequin Point. (*a*) Orthorectified COSMO-SkyMed image at VV polarization (22 January 2011), speckle-reduced by a 5 × 5 median filter (Agência Espacial Italiana (© ASI)); (*b*) subscene of Figure 9(*a*); (*c*) corresponding subscene of an orthorectified Quickbird image (October 2006); (*d*) COSMO-SkyMed image enhanced by 3 × 3 vertical edge detection; (*e*) COSMO-SkyMed image enhanced by a 7 × 7 Wallis adaptative filter; (*f*) geomorphic map of raised beaches, compiled from Figures 9(*d*) and (*e*).

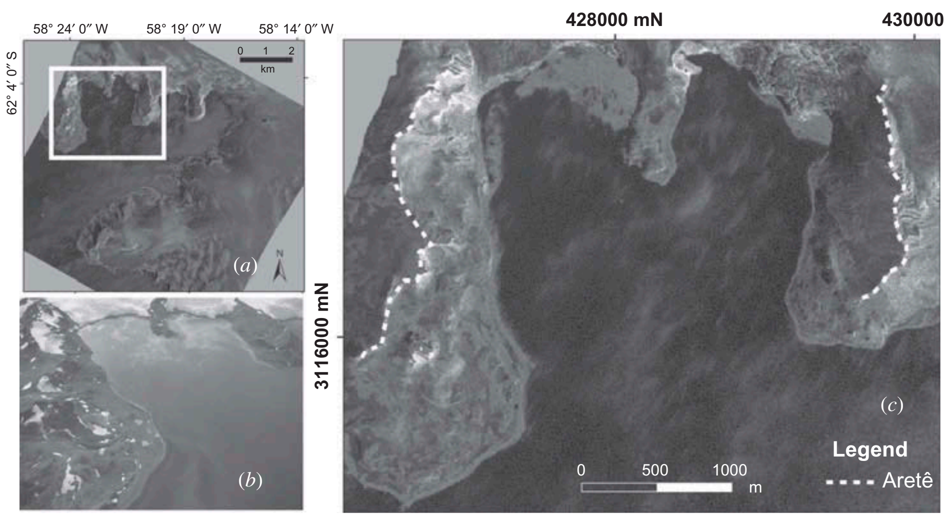

Figure 10. Predominantly northerly and northeasterly orientated arêtes at the Keller Peninsula and Ullman Point. (*a*) Orthorectified COSMO-SkyMed image at VV polarization (22 January 2011; Agência Espacial Italiana (© ASI)), speckle-reduced by a 5 × 5 median filter; (*b*) oblique image (January 2007) captured by an aerial detachment on board the vessel Ary Rongel (Brazilian Navy); (*c*) subscene with arête delineation; the white square in Figure 10(*a*) indicates the location.

Table 3. Martel Inlet ice-free landform areas identified in the COSMO-SkyMed images used in this study, with the characteristic grey tone and texture used for visual interpretation and the best co-polarization mode and filters used to enhance these features.

Landform/feature	Polarization	Grey tones	Texture	Best filters	Kernel
Arêtes	VV	Medium	Coarse	Edge enhancement filter and texture analysis	3 × 3
Boulders	HH	Lighter	Coarse	Texture analysis	3 × 3
Coastal sand	HH	Medium	Fine	Texture analysis	3 × 3
Coastline	HH and VV	Medium	Smooth	Vertical edge detection filter	3 × 3
Debris flow	HH and VV	Medium	Coarse	Edge enhancement filter and texture analysis	3 × 3
Flutings	VV	Medium	Coarse	Prewitt with northwesterly direction	3 × 3
Lacustrine deposits	HH and VV	Dark	Fine	Edge enhancement filter and texture analysis	3 × 3
Lagoon and lakes	HH and VV	Dark	Fine	Edge enhancement filter and texture analysis and	3 × 3
Lateral moraines	VV	Medium	Coarse	Morphological Close, Prewitt with northwesterly direction, and vertical edge detection filters	3 × 3
Meltwater channels	HH and VV	Dark	Fine	Prewitt filter with northwesterly direction	3 × 3
Morainal bank	HH and VV	Medium	Coarse	Edge enhancement filter	3 × 3
Raised beach	VV	Medium	Coarse	Wallis adaptative filter, Prewitt with southeasterly direction, and vertical edge detection filters	7 × 7 3 × 3
Striated pavement	HH and VV	Dark	Fine	Edge enhancement filter	3 × 3
Supraglacial debris	HH and VV	Medium	Smooth	Edge enhancement filter	3 × 3

In general, HH and VV polarized COSMO-SkyMed images acquired in spotlight mode, enhanced by focal variance analysis and specific convolution filters, were suitable for recognizing glacial geomorphological features. Images processed with these filters are suitable for use in studies of geomorphic changes in Antarctica.

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