Geosphere, published online on 15 October 2014 as doi:10.1130/GES01074.1

Geosphere

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Ice sheet surface lineaments as nonconventional indicators of East Antarctica bedrock tectonics

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ABSTRACT

A recent focus of major international exploration in East Antarctica has been aimed at revealing its bedrock topography and imaging its tectonic architecture and evolution. Here we present the tectonic interpretation of regional-scale lineaments revealed by the Radarsat mosaic of Antarctica on the ice sheet surface in the Vostok–Dome C–Adventure Basin region. These lineaments appear in the radar backscatter textures as alignments of marked tonal variations with lengths of tens to hundreds of kilometers and were identified using an automated methodology. We explore the origin scenarios for the ice sheet surface lineaments by comparing their azimuthal trends and spatial distribution with the main morphotectonic features of the bedrock. Azimuthal analysis reveals that lineaments cluster around two preferential directions interpreted as structural or tectonic domains. These show strong correlations with azimuths of tectonic fabrics in the bedrock. The main lineament domain parallels the morphotectonic features of the study area, namely the Adventure Basin and the Concordia and Aurora Trenches. The second lineament set corresponds to the mean orientation of the Lake Vostok depression. The spatial analyses of the two lineament domains strengthen our findings and interpretations. Comparisons with wind and ice flow directions exclude their influence on the identified lineament pattern. Results reveal the tectonic origin of the lineament domains, and demonstrate the method's usefulness as a tool for tectonic studies of regions characterized by thick covers. These regions include other areas of the East Antarctic craton such as the Gamburtsev Subglacial Mountains, as well as deserts or surfaces of other planets.

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INTRODUCTION

Geophysical investigations by the international scientific community in the past decades revealed the bedrock physiography of the East Antarctic craton beneath its ice sheet (Fretwell et al., 2013; Popov et al., 2007). A series of regional-scale, elongated depressions in bedrock have been described and inferred to have a tectonic origin (Kapitsa et al., 1996; Leitchenkov et al., 1999; Ferraccioli et al., 2001, 2009, 2011; Studinger et al., 2003, 2004; Forieri et al., 2004; Bell et al., 2006; Cianfarra et al., 2009a, 2009b; Phillips and Läufer, 2009; Jordan et al., 2013; Aitken et al., 2014). Many major subglacial lakes are located in these tectonically controlled depressions, thus raising the interest of the scientific community in these features, resulting in detailed geophysical data (Studinger et al., 2003; Forieri et al., 2004; Tikku et al., 2005; Tabacco et al., 2006; Bell et al., 2007; Filina et al., 2008; Wright and Siegert, 2012; Zirizzotti et al., 2012). The recent release of the BEDMAP2 data set (Fretwell et al., 2013), the digital elevation model (DEM) of Antarctic bedrock topography, affords the opportunity to constrain the geometry of these depressions. The resulting images of bedrock morphological complexity contrasts with the smooth and flat topography of the East Antarctica Ice Sheet (EAIS). Available radar satellite images, specifically the Radarsat mosaic of Antarctica with 125 m spatial resolution (Jezek, 2003), revealed that the ice sheet surface is characterized by (slight) backscatter-related textures. These textures show abrupt changes in tones that extend across the mosaic for lengths of hundreds to thousands of kilometers. The radar images reveal the presence of regional-scale subparallel linear features on the ice sheet surface, expressed as sharp tonal variations and marked textural anisotropies. These features, as much as several hundreds of kilometers long and <4–5 km wide, are the lineaments (Hobbs, 1904; Wise, 1969; O'Leary et al., 1976). In other contexts, including ocean floors and ice-free continents, such lineaments cluster around preferential orientations, called domains, which can be closely related to their regional tectonic settings (e.g., Cardamone et al., 1976; Funiciello et al., 1977; Wise et al., 1985; Mazzarini and Salvini, 1994; Mazzarini and D'Orazio, 2003; Solomon and Ghebreab, 2006; Rahiman and Pettinga, 2008; Pardo et al., 2009, Giordano et al., 2013; Pischiutta et al., 2013; Cianfarra and Salvini, 2014).

In this work we explore possible origins for the ice sheet surface lineaments and their possible relation to the morphotectonic framework of the bedrock. The study focuses on the Vostok–Dome C–Adventure Basin region between long 98°E and 140°E and lat 71°S and 80°S, where Italian geophysical and tectonic investigations highlighted the bedrock physiography and its tectonic setting (Tabacco et al., 2006; Cianfarra et al., 2009a, 2009b; Fretwell et al., 2013).

A subset of the Radarsat mosaic covering the study region (~570 km × 1150 km) was used for the lineament investigation (Fig. 1A). A DEM (with an original 200 m spatial resolution; Liu et al., 2001) of the area was analyzed to further characterize and interpret the Radarsat lineaments.

Radio echo sounding data collected in the Vostok–Dome C–Adventure Basin region revealed the presence of regional, elongated subglacial valleys: the Aurora Trench within the Aurora Basin, the Concordia Trench, and the Adventure Basin (Fig. 1B) (Forieri et al., 2004; Tabacco et al., 2006; Fretwell et al., 2013). Their morphology has been related to the tectonic activity of crustal, listric faults in either extensional (Leitchenkov et al., 1999; Ferraccioli et al., 2001; Cianfarra et al., 2009a, 2009b) or compressional geodynamic settings (Studinger et al., 2003, 2004). Proposed ages of tectonic activity span from Proterozoic (Aitken et al., 2014) and Paleozoic (Dalziel, 1998; Leitchenkov et al., 1999; Studinger et al., 2003) to Cenozoic (Tabacco et al., 2006; Cianfarra et al., 2009a, 2009b; Cianfarra and Salvini, 2013).

Geosphere; December 2014; v. 10; no. 6; doi:10.1130/GES01074.1; 4 figures.
Received 13 May 2014 ♦ Revision received 12 August 2014 ♦ Accepted 24 August 2014

Geosphere, published online on 15 October 2014 as doi:10.1130/GES01074.1

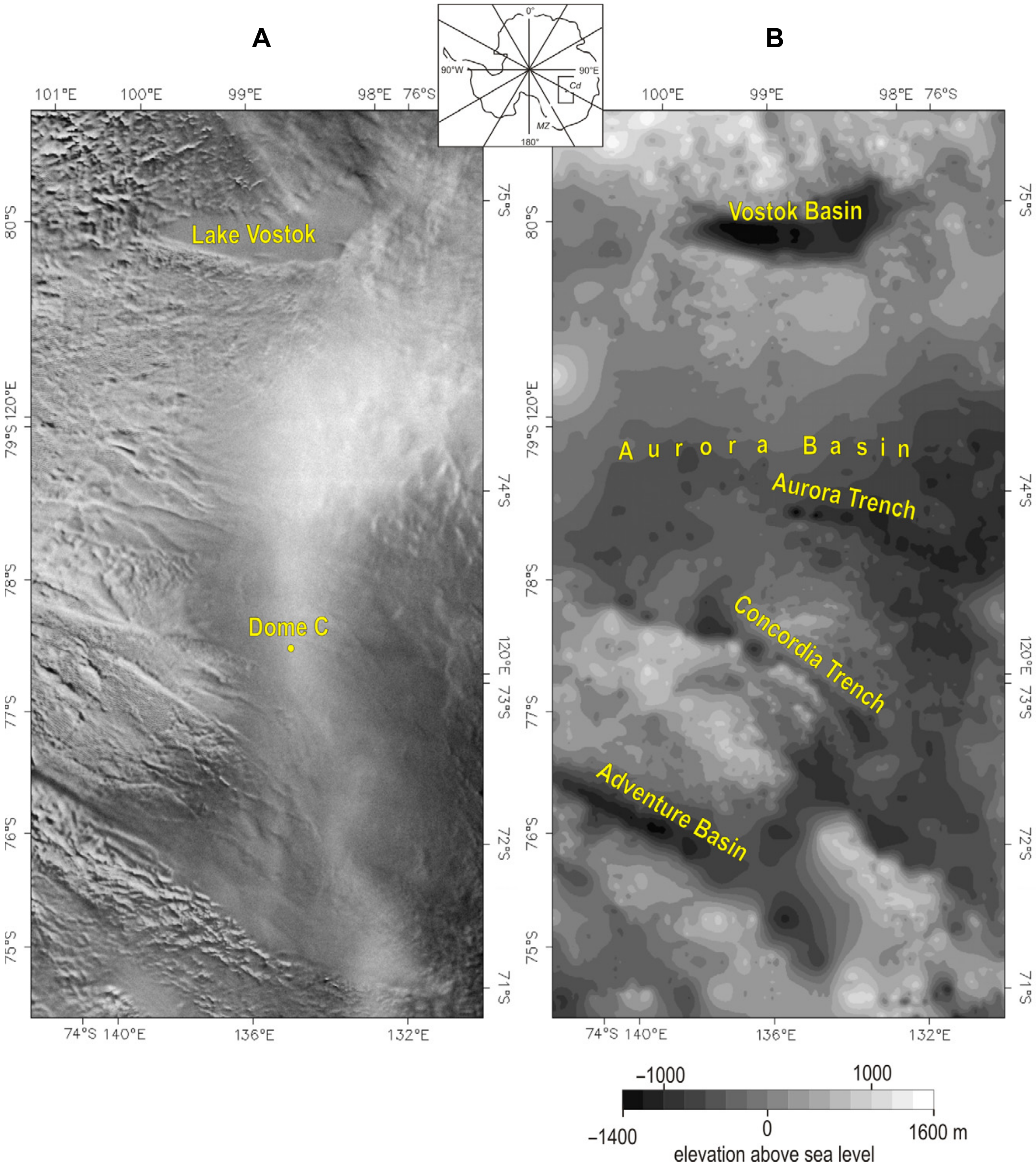

Figure 1. Vostok–Dome C–Adventure study region. (A) Subset of the Radarsat mosaic (Jezek, 2003) of the ice sheet surface. (B) Bedrock physiography from the BEDMAP2 data set (Fretwell et al., 2013). Upper map of Antarctica shows the location of the investigated region. Cd—Concordia Station located near Dome C; MZ—Mario Zucchelli Station.

The ice sheet surface represents a dynamic equilibrium surface resulting from the physical, dynamic, kinematic, and climatological processes acting on it, including its flow over the bedrock (Paterson, 1994). It therefore contains the signature of the main exogenous and endogenous processes, active or recent, from the regional to the local scale (Testut et al., 2000; Rémy et al., 2001; Frezzotti et al., 2002). Estimated ice velocities in the EAIS range from ~1 m/yr in the domal and/or ice divide regions to several tens of meters per year at its margin (Rignot et al., 2011). At the continental scale, the ice sheet surface topography is characterized by a quasi-parabolic shape, as predicted

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by Orowan (1949) and theoretically explained by Glen (1955). At this scale, the ice sheet profile is governed by ice viscosity and the flow boundary condition between ice and bedrock (Rémy et al., 1999). At the scale of hundreds of kilometers, the ice sheet topography is primarily controlled by surface undulations attributed to the processes of ice flow above an irregular bedrock (Rémy et al., 1999). Robin (1967) explained surface slope fluctuations in terms of variation in the longitudinal stress produced by ice flow over the bedrock. Budd (1970) defined a damping factor to describe the transfer of morphological bedrock features to the ice surface, depending on bedrock morphology wavelength, ice thickness, and viscosity of the ice. Hutter et al. (1981) derived a filter function to define the fraction of the bedrock amplitude transmitted to the ice sheet surface, suggesting an increasing surface response at longer bedrock wavelengths. The Hutter et al. (1981) hypothesis was confirmed by a spectral analysis of the surface topography (McIntyre, 1986). Rémy et al. (1999) found that 10 km wavelength undulations on the EAIS are elongated and frequently oriented at 45° to the flow line directions. Undulating topography on the EAIS was attributed by Seko et al. (1993) to snow redistribution by katabatic winds.

Surface roughness is also controlled by katabatic winds that carve surface features from the meter scale to several hundreds of meters. The most significant structures are due to erosion (sastrugi) or deposition (megadunes). Megadune fields characterize several areas of the interior of the EAIS (Frezzotti et al., 2002), for example, the field located ~200 km southeast of Dome C (barely visible in Fig. 1A due to its spatial resolution).

The Radarsat mosaic of Antarctica shows the integrated response of the main features controlling the ice surface topography, from tens of centimeters, related to the interaction of the radar pulse with the ice outcrop at the scale of the signal wavelength, to hundreds of kilometers (Drury, 2001). Thus, the Radarsat images allow identification of alignments of several backscatter contrasts (from marked to faint) along segments with lengths exceeding tens of kilometers; that is more than one order of magnitude longer than the EAIS thickness (2–4 km). However, lineaments from DEMs of the nearly flat surface of the ice sheet are limited to regional topographic contrasts related to the presence of regional-scale morphologies in the bedrock (e.g., Aurora Basin and Lake Vostok). Based on the considerations mentioned here, the Radarsat images, with their integrated response, represent the best available tool to explore the relation between regional lineaments (sensu Wise et al., 1985) and the buried bedrock morphology. Therefore, we analyzed the subset of the Radarsat mosaic in the study area, limiting the DEM lineament analyses to the comparison with Radarsat lineaments.

LINEAMENT METHODOLOGY

Lineaments consist of alignments of tonal variation on the observed images. Depending on the relative importance of straightness of the alignment versus the intensity of tonal variations, different techniques for their identification have been developed (Wise, 1969; Wise et al., 1985; Karnieli et al., 1996; Panagiotakis et al., 2011; Giordano et al., 2013). In this work, we follow the methodology proposed by Wise (1969) and Wise et al. (1985), consisting of lineament identification as subtle features (i.e., including small tonal contrasts characterized by a strictly rectilinear appearance in the image). This methodology has been implemented into an automatic technique that identifies all possible straight segments of tonal contrast above a threshold value and with a minimum given length (Cianfarra, 2006; Pardo et al., 2009; Pischiutta et al., 2013; Cianfarra and Salvini, 2014). The Sid in-house software (Cianfarra and Salvini, 2014) was used to detect lineaments automatically on the Radarsat mosaic of Antarctica and on the DEMs of the ice surface morphology in the study region. The algorithm allowed the detection of pixel alignments in raster images through a systematic search of all possible segments in all possible azimuthal pixel alignments as a function of the pixel dimension within a given range of parameters. Lineament enhancement was performed on each image through dedicated algorithms and specific filters in order to evaluate the impact of regional scale factors on the morphology and texture of the ice surface.

Processing of the Radarsat image included despeckling to eliminate random noise that could bias the tone contrast analysis. The resulting image was resampled to 2000 m spatial resolution, which represents the best compromise between the geographical extent of the investigated area and the reasonable level of detail for regional tectonic investigations. We then applied a high-pass spatial filter that consisted of subtracting from the despeckled and resampled image its low-pass spatially filtered image, by a 28 × 28 km convolution matrix (Drury, 2001). The image was then refiltered twice by a low-pass 8 × 8 km kernel to reduce scattering. The tone contrast variation was obtained by applying a Laplacian filter with stretching and a threshold. Eventually, residual scatter noise was reduced by the LIFE filter (after Conway's game of life, Gardner, 1970). This filter compares each significant pixel (i.e., DN, or digital number, value higher than the threshold slicing) with its surrounding pixels, and zeroes it when the number of significant surrounding pixels is below a given threshold (five in our analysis; Cianfarra and Salvini, 2014).

This final image was then input into the Sid software for lineament detection. The search was set for lineaments with a minimum length of 70 km, a maximum width of 6 km, and a density factor of 0.3 (equivalent to 1 pixel-lineament every 3 pixels along the lineament strike).

Ice surface DEM processing followed a slightly different approach. The original DEM data were resampled with the same 2000 m spatial resolution applied to the Radarsat image; 16 directional derivative images were prepared simulating radar lighting conditions every 22.5° of azimuth. The technique was used to override the lighting condition bias on lineament detection (Wise, 1969), although this influence is rather negligible due to the nearly flat topography of the ice sheet surface. A low-pass spatial filter with a 6 × 6 km kernel was applied to each image to suppress local superficial features. Further processing followed the steps applied to the Radarsat image. Filtering included a Laplacian kernel followed by threshold and LIFE processing. The obtained enhanced images were used for Sid lineament extraction. The search was set for lineaments with a minimum length of 80 km, a maximum width of 6 km, and a density factor of 0.3, similar to the lineament search in the Radarsat image.

Lineaments detected from the 16 analyses were cumulated to provide the final lineament data set from DEM analysis.

LINEAMENT DOMAIN AZIMUTHAL ANALYSIS

The lineament azimuths of the two data sets, the Radarsat mosaic and the DEM, were statistically analyzed by polymodal Gaussian fitting (Wise et al., 1985; Salvini et al., 1999) to identify the lineament domains. The two azimuthal frequency analyses are graphically presented as wind rose frequency diagrams and as gray shades in a graphic table (Fig. 2) to aid the comparison between lineament domain azimuths and the directions of the main known morphotectonic features of the bedrock in the study region (Lake Vostok, the Aurora and Concordia Trenches, and the Adventure Basin; Drewry, 1976; Ferraccioli et al., 2001, 2009; Studinger et al., 2003; Forieri et al., 2004; Tabacco et al., 2006; Cianfarra et al., 2009a, 2009b; Cianfarra and Salvini, 2013; Fretwell et al., 2013; Jordan et al., 2013). The adopted azimuth convention in the rose diagrams and graphic table refers to

Geosphere, published online on 15 October 2014 as doi:10.1130/GES01074.1

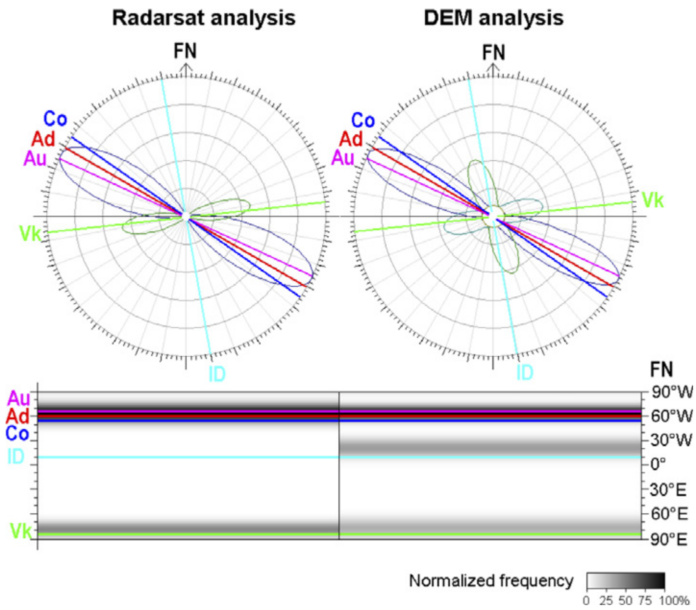

Figure 2. Azimuthal frequency analysis of the lineaments detected from the Radarsat mosaic (left) and the digital elevation model of the ice surface (right). Results are presented both as wind rose frequency diagrams and as graphic tables to make it easy to compare the lineament domain azimuths (i.e., petals in the wind rose and gray stripes in the graphic table; Wise et al., 1985) with the main morphotectonic features of the study region. The comparison shows their correspondence with the lineament domains. Azimuths of the main features: Co—Concordia Trench; Ad—Adventure Trench; Au—Aurora Trench; Vk—Vostok Basin; ID—ice divide. FN—false northing.

a false northing (FN) parallel to the y axis of the analyzed images, and azimuths are indicated with the prefix FN.

Lineament detection in the Radarsat image identified 112 lineaments with a mean length of 95.1 km and a standard deviation (sd) of 23.2 km. The analysis shows the presence of two domains (Fig. 2). The main domain (69% of total lineaments) is oriented FN63°W ± 13.1°, and the other is oriented FN80°E ± 11.1°.

Sid analysis of the DEM image identified 605 lineaments with a mean length of 103.6 km (sd 20.3 km). The statistical azimuthal analysis shows the presence of three domains (Fig. 2); the main (41.6% of total lineaments) is oriented FN63°W ± 10.2°, and the other two are oriented FN20°W ± 13.3° and FN77°E ± 14.1°.

The resulting lineament domain orientations correlate well with the main elongated morphotectonic depressions of the bedrock in the investigated area (Figs. 1B and 2). The main lineament domains trending FN63°W are present on both images and correspond to the Aurora and Concordia Trenches and the Adventure Basin, which have average orientations of FN65°W, FN55°W, and FN60°W, respectively (corresponding to ~N2°W, ~N1°E, and ~N15°W with respect to their true north). These domains are referred to herein as the Adventure domain. The lineament domains around FN77°E–FN80°E were identified on both images. This direction corresponds to the average elongation of Lake Vostok, around FN84°E (corresponding to ~N20°W). These domains are referred to herein as the Vostok domain. The third lineament domain direction was identified only on the DEM image and is nearly parallel to the ice divide in the Vostok–Dome C–Adventure Basin region, around FN10°W (corresponding to N41°E–53°E). The resulting angular difference among these morpho-tectonic elements and the corresponding lineament domains are always well within their standard deviations.

The strong correspondence between the lineament domains on the ice sheet surface detected from the Radarsat image and the orientation of the buried morphotectonic structures confirms the tectonic origin of the Adventure and Vostok domains, in agreement with the interpretations of lineament domains in other tectonically active regions of our planet (Funiciello et al., 1977; Wise et al., 1985; Mazzarini and Salvini, 1994; Mazzarini and D'Orazio, 2003; Pardo et al., 2009; Giordano et al., 2013; Pischiutta et al., 2013; Cianfarra and Salvini, 2014).

LINEAMENT DOMAIN SPATIAL ANALYSIS

The analysis of the spatial distribution of the lineament domains further supports their tectonic origin and significance.

The areal distribution of the lineaments identified in the DEM of the ice surface is strongly biased by the nearly flat topography of the ice divide–dome area. For this reason they are spatially concentrated where the ice topography is influenced by the larger bedrock depressions, namely the Adventure Basin and Lake Vostok.

Lineaments from the Radarsat image were classified on the basis of their statistical distance from the mean azimuth of the domains, with a threshold of ±2 sd. The classification associated 62 lineaments with the Adventure domain and 38 with the Vostok domain, leaving 12 lineaments unclassified. Lineaments that belong to the Adventure and Vostok domains were plotted separately on the Radarsat image to analyze their spatial distribution over the investigated region (Fig. 3).

The lineaments of the Adventure domain are characterized by an almost uniform spatial distribution left of the ice divide, throughout the region ranging from the Adventure Basin to Lake Vostok (Fig. 3A).

Nearly all the lineaments of the Vostok domain are present and cluster only in the Vostok area (Fig. 3B). The spatial distribution of the classified lineaments confirms that the Vostok domain correlates with the tectonic fabric of the Lake Vostok area. The Adventure domain, with its widespread distribution, relates to the regional tectonic setting.

The right-side border of the Adventure domain, toward the ice divide, is characterized by a saw-tooth shape. This geometry may relate to the en echelon pattern of the tectonic subglacial depressions in the Vostok–Dome C–Adventure Basin region that form a subcontinental left-lateral strike-slip corridor, where the local extension conditions are compatible with listric normal faulting responsible for the formation of the elongated depressions (Forieri et al., 2004; Tabacco et al., 2006; Cianfarra et al., 2009a, 2009b; Cianfarra and Salvini, 2013).

TECTONIC ORIGIN OF ICE SHEET SURFACE LINEAMENTS

The relations between lineament domains and the tectonic setting of the study area allow us to highlight the origin of the ice sheet surface

Geosphere, published online on 15 October 2014 as doi:10.1130/GES01074.1

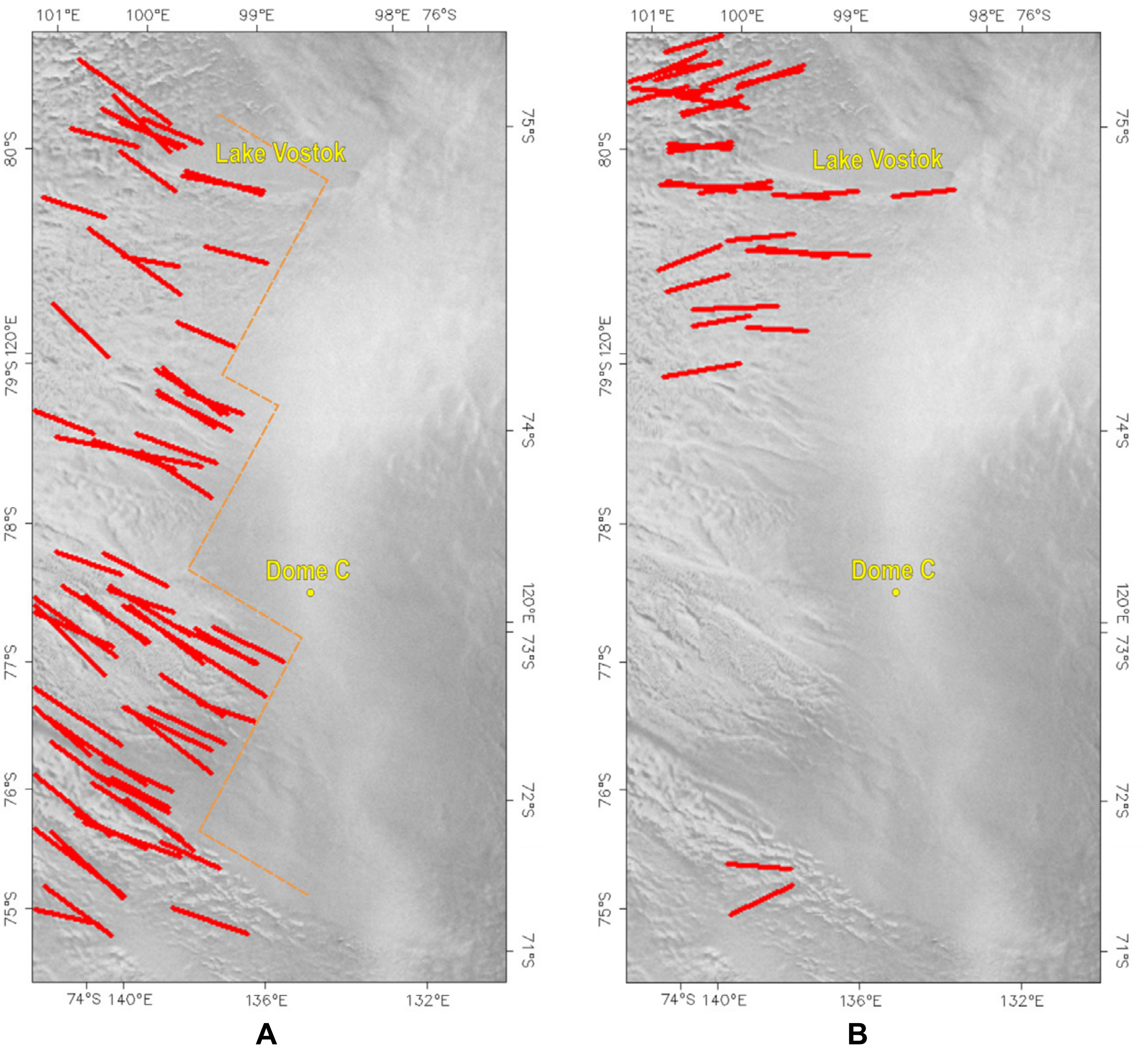

Figure 3. (A) Spatial distribution of the Adventure lineament domain. Dashed orange line follows the saw-tooth boundary of the Adventure domain toward the ice divide. The Adventure domain is characterized by a uniform spatial distribution from Lake Vostok to the Adventure Basin (left side of image), corresponding to the region south of the ice divide. (B) Spatial distribution of the Vostok lineament domain. The Vostok domain mainly clusters in the Lake Vostok region. Background images compose the subset of the Radarsat mosaic used for lineament detection.

lineaments. The relation between the surface morphology of the Antarctic ice sheet and its bedrock has been discussed in the literature (e.g., Rémy and Minster, 1997; Ross et al., 2014). In the following we briefly explore and reject some alternative hypotheses to further confirm the tectonic significance of the Radarsat lineament domains. With these hypotheses, we attempt to relate the development of regionally sized lineaments to the physical processes acting on the ice sheet surface. Lineaments could be the surface effect of the ice sheet drainage pattern; in this case, we expect either a parallelism between the ice drainage (as derived from the ice cap surface elevation) and the detected lineaments, or at least a constant angular relation. Figure 4A shows the ice drainage pattern recomputed from Rémy et al. (2001). At the regional scale, i.e., 20 times the ice thickness, a shallow ice approximation is valid to order zero (Morland, 1984), and ice sheet flow at any depth is directed along the steepest slope of the surface. This allows us to compute the ice sheet drainage pattern. Comparison with Radarsat lineaments in the study area (Fig. 4B) shows that these are not affected by changes in the direction of ice drainage. The preservation of the lineament strikes throughout their lengths, despite the changing direction of the crosscutting ice drainage patterns, makes this hypothesis untenable, at least for lineaments with lengths of the order of several tens to hundreds of kilometers.

The same poor correlation exists between the Radarsat lineaments (Fig. 4B) and regional katabatic wind directions (Fig. 4C) redrawn from scatterometer data (Long and Drinkwater, 2000). The colder and denser air of the Antarctica interior rushing down the slope of the ice sheet induces strong and direction-constant katabatic winds (Parish and Bromwich, 1987) that increase in magnitude as they approach the coast. Assuming a genetic relation between

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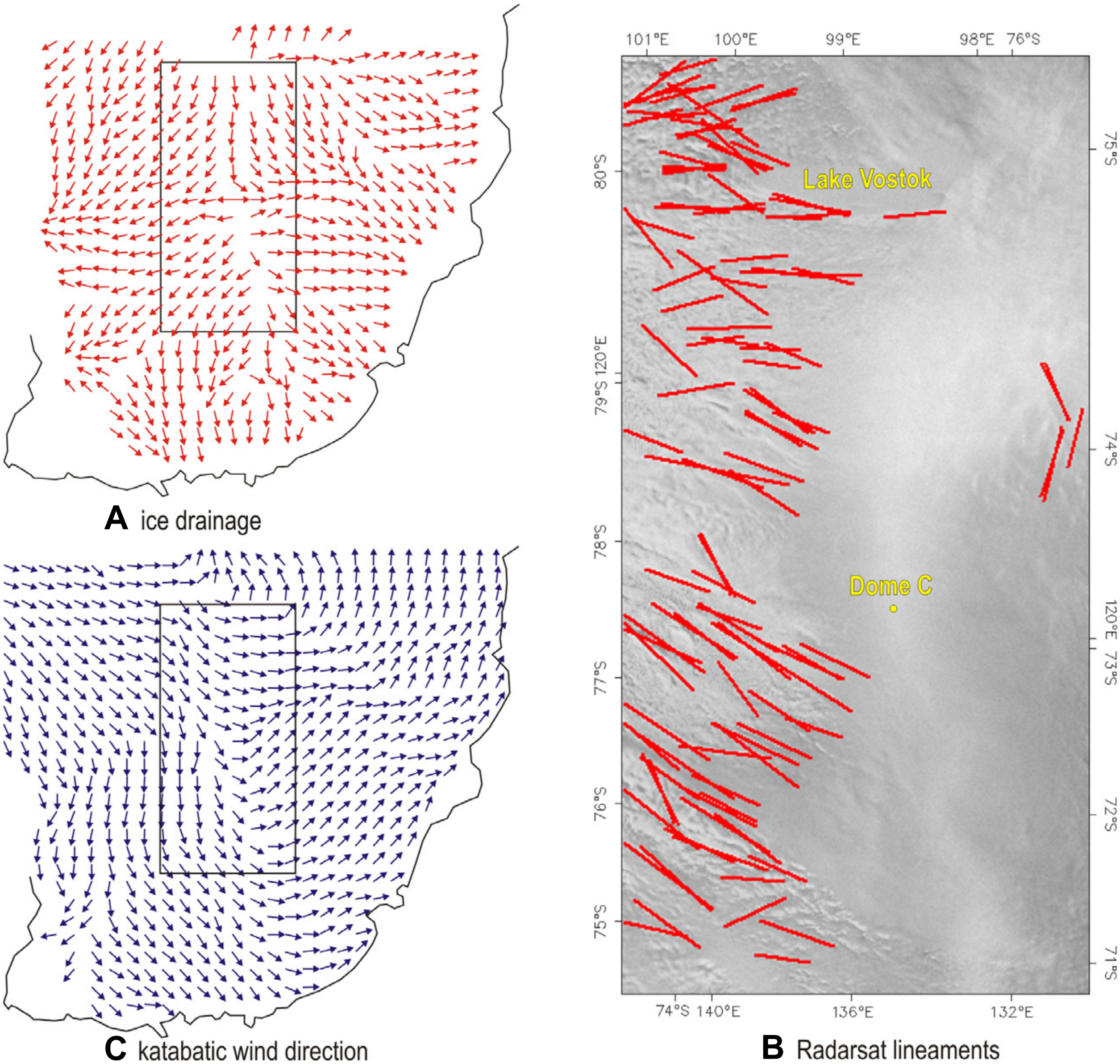

Figure 4. Comparison of lineament data with the main physical agents controlling the ice sheet surface. Black rectangles mark the location of the study region in the Radarsat image. (A) Ice drainage pattern (derived from the ice sheet surface elevation) derived from Rémy et al. (2001) data. (B) Lineaments detected from the Radarsat image. (C) Katabatic wind directions redrawn from scatterometer data (Long and Drinkwater, 2000). The comparisons between lineament azimuths with the ice drainage and the wind directions show the preservation of lineament strikes despite changes in wind direction and ice flow; this strengthens the correlation of ice sheet surface lineaments with the bedrock tectonics.

these wind direction and ice fabric lineaments, it should be reasonable to find a congruence (i.e., constant angular relation) between regional lineament strikes and the wind directions. The comparison shows that lineaments are not affected by changes in the directions of the wind field.

Given the correlation between Radarsat lineament domains and the tectonic setting of the investigated area, a more reliable hypothesis is to consider ice surface lineaments as the effect of the interaction between ice dynamics and bedrock morphology, that in turn relates to tectonics (Forieri et al., 2004; Tabacco et al., 2006; Cianfarra et al., 2009a; Cianfarra and Salvini, 2013).

Radar backscatter depends on the interaction between the radar pulse and the physical properties of the near surface, since microwave energy penetrates the glacier surface (Drury, 2001). These physical properties are intrinsically linked to ice grain size and the dielectric constant of ice. Legrésy (1995) showed that at scales of >1 km, the C-band radar echo is very insensitive to surface slope and curvature, but is strongly influenced by ice penetration because of the negligible extinction due to diffusion by snow and ice grains. Moreover, for a dry snow cover, such as that of the interior of the EAIS (where the surface temperature is almost always below 0 °C), the surface scattering component is low and the absorption loss within the snow is low, resulting in a penetration depth of ~20 m at the C-band (Hamran, 1997).

For example, the influence of the ice physical properties is clearly visible in the divide region on the Radarsat image (Fig. 1A); in correspondence with a thicker firn cover, the image presents a more uniform and brighter response and lacks of any textural anisotropy (clearly visible on the left of Fig. 1A). The origin of the regional-scale lineaments identified on the Radarsat mosaic may be in the at-depth ice layer arrangement and/or architecture resulting from the ice sheet flow over the bedrock morphology. The ice sheet dynamics over these morphologies produces vertical movements of the ice layers that are levelled at the ice-atmosphere equilibrium surface. The significant variation of radar brightness, or backscatter, associated with the ice surface lineaments is produced by the variation of the dielectric constant of the near-surface ice layers, with different fabrics resulting from different burial and/or exhumation histories. These variations result from the interaction between the ice sheet dynamics and the buried morphotectonic features. This explains the relation between the regional-scale ice sheet surface lineament domains and the structural setting of the underlying bedrock.

CONCLUSIONS

Lineaments detected on the Radarsat mosaic of Antarctica cluster in domains (sensu Wise et al., 1985), as for lineaments present in other, nonglaciated, regions. The two Radarsat lineament domains, Adventure and Vostok, have been confirmed by the comparison with the analysis of DEM images. Both the spatial distributions and the azimuthal correlations of the Adventure and Vostok domains to the main buried morphotectonic features of the study region confirm the strong correlation between regional scale lineament domains and upper crustal tectonics. This relation is evident in the EAIS, which represents a thin film, 2–4 km thick, when compared with the ~34-km-thick continental crust. The EAIS records the tectonic processes of the more brittle upper crust, despite differences in the velocity (to 2 orders of magnitude) between ice dynamics and tectonics.

Lineament domain analysis of Radarsat images proved to be an effective tool for investigating bedrock tectonics beneath the ice sheets. This methodology can be used to further highlight the tectonic architecture of the Gamburtsev Subglacial Mountains, an enigmatic mountain range located under a major divide area of the EAIS that is not characterized by notable texture in the ice surface satellite imagery (Bell et al., 2011; Ferraccioli et al., 2011; Rose et al., 2013). Analogously, the lineament approach can be successfully extended to the entire EAIS and to other glaciated regions of our planet, as well as to the exploration of the crustal tectonics of other planetary bodies such as Europa, the moon of Jupiter that is characterized by an ice cover.

ACKNOWLEDGMENTS

Research was carried out in the framework of the Project CABILA (Caratterizzazione Biogeochirnica dei Laghi Subglaciali Antartici) of the PNRA-MIUR (Programma Nazionale Di Ricerche in Antartide–Ministry of Education, University and Research) and financially supported by the PNRA Consortium through collaboration with ENEA (Agenzia Nazionale per le Nuove Tecnologie, L'Energia e lo Sviluppo Economico Sostenibile). We thank reviewers for insightful comments that improved the manuscript.

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