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# Lakes and subglacial hydrological networks around Dome C, East Antarctica

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ABSTRACT. Precise topography from European Remote-sensing Satellite radar altimetry and high density of airborne radio-echo sounding in the area surrounding Dome C, Antarctica, show a link between surface features and subglacial lakes. In this paper, we extend the study to fine structures by computing a curvature-based coefficient ($c_y$) related to surface undulations. These coefficient variations reveal many surface undulations, and some elongated features of this parameter seem to link known subglacial lakes. A population of high values of this coefficient, assumed to correspond to transitions between sliding and non-sliding flow regime, strengthen the appearance of a network which would link most of the lakes in the area. The existence of such a network impacts on ice-flow dynamics and on subglacial-lake studies.

## INTRODUCTION

The Dome C area (Fig. 1) was chosen for the deep-drilling project EPICA (European Project for Ice Coring in Antarctica). The importance of precise surface topography, bedrock morphology and internal layering geometry for both the selection of the best site for deep drilling and the interpretation of ice-core samples led to an extensive compilation of satellite and in situ measurements.

These data also allow several surface or subsurface features, such as lakes or elongated channels, to be distinguished, which may affect the ice flow. Indeed, about 30 lakes are listed by Siegert and Ridley (1998a), and approximately 16 lakes by Tabacco and others (1998), in the vicinity of the Dome C area. Also, a dense radio-echo sounding (RES) network established by Tabacco and others (1998) during December 1995 made it possible to draw up a very precise bedrock map with a grid size of 3 km. Rémy and Tabacco (2000) carefully analyzed this precise bedrock topography and pointed out a clear network of elongated valleys in the north–south direction. These features are probably buried pre-ice-sheet landforms that have a tectonic origin but were extensively modified by mountain-glacier erosion before the present ice sheet formed. This network was also detectable in the surface topography, leading to elongated undulations a few metres high, a few kilometres wide and a few tens of kilometres long around Dome C and suggesting a large-scale network.

These subglacial lakes and deep bedrock valleys can play a role in the ice dynamics around Dome C and thus in the ice-core dating. Moreover, it is interesting to see if there is a relation between lakes and these subglacial features and if hydrological systems can be detected. Indeed, Siegert and Ridley (1998b) and Testut and others (2000) already suspected the existence of such a system above the Adventure Subglacial Trench.

The aim of this paper is to use the European Remote-sensing Satellite (ERS-1) precise topography from Rémy and others (1999) and the position of the known lakes in order to carefully study the relation between lakes, surface features and the subglacial networks. We focus on the area around Dome C where most of the lakes were discovered (Fig. 1a).

## DETECTION OF SURFACE NETWORKS

Surface topography exhibits several features related to ice flow: flat areas related to lakes, inland slope breaks, glacier flowlines, en echelon structures due to lateral shear stress, bumps and troughs associated with longitudinal stress, 100 km scale undulations and, above all, undulations on a 10 km scale due to ice flow over rough bedrock (Rémy and others, 1999, 2001). All these features are mixed and superimposed so that the identification and the description of one particular feature are ambiguous. Rémy and Tabacco (2000) used the curvature of the surface topography and showed that this method is particularly useful in interpreting the slight surface and bedrock undulation networks. This technique allows us to filter out the topography at a given scale.

Here, we choose the principal curvature in the direction perpendicular to the slope over a 5 km scale, to characterize the strength of the topographic features. We choose to normalize it by the surface slope in order to emphasize the weak features usually found over flat areas. Namely, if $x$ is the slope direction, $y$ the across-slope direction and $h(x, y)$ the surface topography, we consider:

$$c_y = -[\partial^2 h(x,y)/(\partial x \partial y)]/[\partial h(x,y)/\partial x]\,. \qquad (1)$$

At each point, we first fit a biquadratic function with a search radius of 5 km. Two principal-curvature radii can be

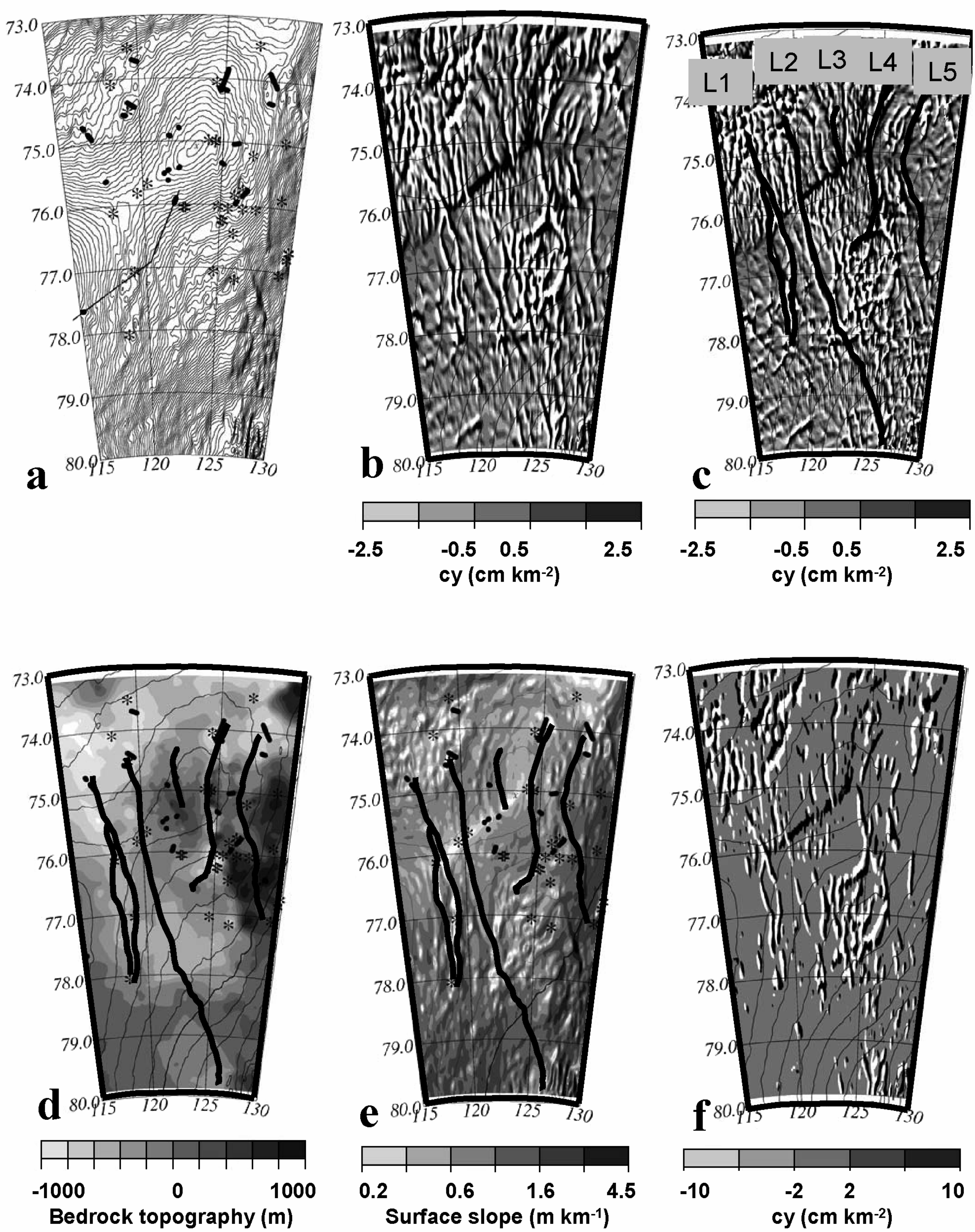


*Fig. 1. (a) Topography from the ERS-1 geodetic orbit of the area studied. Siegert's lakes (Siegert and Ridley, 1998a) are starred; Tabacco's lakes (Tabacco and others, 1998) are shown with a thick line. The track used in Figure 2 is shown. (b) $c_y$ parameter over the area; (c) the most interesting features are highlighted; (d) bedrock topography; (e) surface slope; (f) absolute $c_y$ values higher than 5 cm km$^{-2}$.*

deduced from the first and second derivatives using standard laws. The slope is estimated on a 20 km scale. Note that this expression is also directly linked to the ice-flow convergence or divergence. Indeed, the ice flow is controlled by the accumulation rate $b(x)$, the ice thickness $H(x)$ and by the convergence or divergence of the flowlines. In case of steady state, the change in flow velocity $U(x)$ along the greatest slope direction $x$ in a channel of width $l(x)$ can be estimated by stating that the flows coming in and out of an ice column are equal:

$$\partial[H(x)U(x)l(x)]/\partial x = b(x)l(x)\,, \qquad (2)$$

so that

$$\partial[H(x)U(x)]/\partial x + \mathrm{sh}(x)H(x)U(x) = b(x)\,. \qquad (3)$$

The convergence or divergence of the flowlines, which



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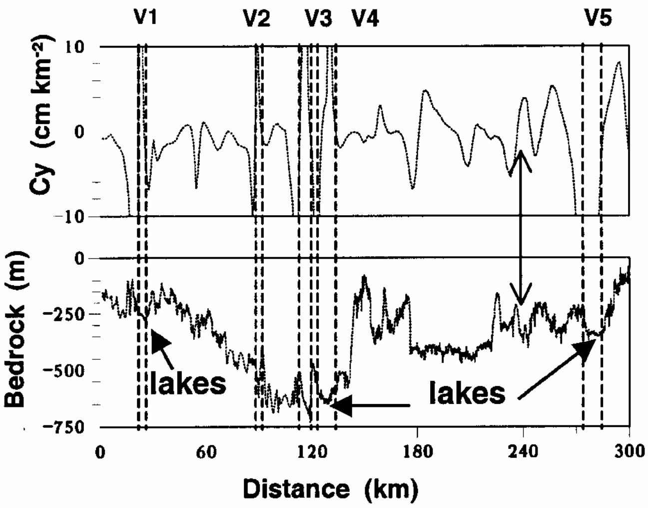


*Fig. 2. Bedrock (bottom) and $c_y$ (top) profiles along the track shown in Figure 1a from longitude 115° E (0 km) to 122° E (300 km). The high values of $c_y$ (V1–V5) reach $\pm 10$ cm km$^{-2}$. Three of them (Nos. V1, V4 and V5) correspond to subglacial lakes.*

mostly controls the ice velocity, is then described by the term $\mathrm{sh}(x)$, namely, $1/l(x)\partial l(x)/\partial x$. This term is mathematically equal to the ratio between the derivative of the slope in the $y$ direction and the slope, that is the $Y$ curvature normalized by the surface slope or $c_y$.

Curvatures are defined as positive for ridges and negative for valleys, and are mapped in Figure 1b. The $c_y$ map reveals a series of longitudinal features. These are very coherent and can be followed through the selected area. Some of them stand out clearly on the surface map (Fig. 1a).

In Figure 1c, we highlight in black the most interesting features in order to distinguish them. We recognize the parallel arcs (labelled L3) already mapped by Rémy and Tabacco (2000). For the first time, we point out several 100 km long features, crossing the area from the southwest to the northeast, labelled L1–L5. In particular, L2 can be tracked over a distance of $>500$ km.

These features, underlined in Figure 1c, are superimposed on the bedrock topography (Fig. 1d) derived from the BEDMAP experiments (Lythe and others, 2001), and on the surface slope (Fig. 1e) deduced from the topography. In Figure 1d and e, the lakes' positions are also superimposed. The bedrock topography and the $c_y$ are also displayed in Figure 2, along the 300 km track shown in Figure 1a.

Feature L1 is 330 km long and links three lakes in the north and three lakes in the south of the area. The strength of this feature seems to decrease towards the south, and vanishes within the confused pattern observed on the flat area, heading north. This very flat area corresponds to the Vincennes subglacial basin. This feature separates into two different branches that correspond to the two deep valleys numbered V3 and V4 in Figure 2. This feature clearly runs along a large bedrock valley (Fig. 1d) and along a weak surface slope area (Fig. 1e). Moreover, from south to north, this feature seems to follow the downslope direction of the bedrock topography.

Feature L2 is the longest feature that we can distinguish. At the southern limit, corresponding to the ERS coverage, the feature rises in a flat area (see Fig. 1e) corresponding to a bedrock basin (Fig. 1d). At 78° S, the feature crosses a flat area, then runs along a weak slope area before joining one of Siegert's lakes (Siegert and Ridley, 1998a) to two of Tabacco's lakes (Tabacco and others, 1998). As with feature L1, we lose track of it towards the north when it arrives in the large Vincennes subglacial basin. This feature also runs along a bedrock valley. The bedrock topography shows a pass at 78.5° S, from which L2 runs in a southerly and a northerly direction, initially following the upslope direction.

Feature L3 belongs to the network of arch-shaped undulations around Dome C, already found by Rémy and Tabacco (2000). The last two features, L4 and L5, have the same characteristics as the others. Each is 300 km long, links more than five lakes, runs along the bedrock valleys and follows the downslope direction of the bedrock.

The surface networks pointed out here are clearly linked with the bedrock topography and with the spatial distribution of lakes: the elongated surface features run along the bedrock valley and link the lakes together.

The question, therefore, is whether these surface features correspond to subglacial networks, i.e. are some lakes linked together? Rémy and Tabacco (2000) already suspected that the pattern near Dome C (feature L2 here) is linked with a basal hydrological system. Indeed, the basal temperature of this area is at the pressure-melting point, and the basal melting rate is estimated at 1 mm a$^{-1}$ (Ritz, 1989). Several lakes are detected in the surrounding area, and a few strong radar echoes are observed, suggesting the presence of water.

## EVIDENCE OF HYDROLOGICAL NETWORKS

The high density of lakes along these features suggests that parts of these subglacial networks shelter hydrological networks. The fact that we clearly observe a topographic connection between such a large number of lakes is also an indication of this.

In this area, the bedrock topography exhibits impressive mountains, bowls and deep valleys. Some of these features are probably tectonic, but others are probably due to erosion. Current glacial erosion is unlikely because of the very slow ice flow in this sector. It is assumed that some of these elongated valleys were formed by erosion by mountain glaciers at the beginning of the ice-sheet build-up. The distribution of lakes along these bedrock features can easily be explained. Indeed, if one assumed that the geothermal flux was more-or-less constant over such a small area, the formation of lakes would occur naturally where the ice layer is thicker (e.g. in the deep bedrock valleys). Also, the bottom topography of these valleys prevents the water from being ejected: this is why the ice thickness over lakes V1 and V5 in Figure 2 is less than the ice thickness in the middle of the track.

Another way of looking at the connection between lakes is by detecting basal sliding areas. The technique used in this paper shows up any change in ice flow due to sliding. Indeed, Rémy and others (1999) showed that the sliding areas are surrounded by two symmetrical topographic anomalies. These bumps and troughs in the topography, of a few metres in amplitude and a few km in wavelength, are associated with abrupt transition, respectively from weak to strong friction and from strong to weak friction. They can be explained by longitudinal extension followed by longitudinal compression for a transition between deformation and sliding, and inversely. The characteristic scale of these longitudinal variations corresponding to the scale where longitudinal stress occurs was estimated to be approximately 10 km around



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Vostok lake. This results in a strong negative curvature value followed by a strong positive one.

The mean $c_y$ value over the whole sector is $4 \times 10^{-2}$ cm km$^{-2}$, slightly positive because of the natural ice-sheet large-scale curvature. The rms is 4.4 cm km$^{-2}$. However, >82% of the values are between −4.4 and 4.4 cm km$^{-1}$. This suggests that most of the curvatures are of a few cm km$^{-2}$, while some curvatures can reach very high values.

The bedrock topography and $c_y$ are plotted along a 300 km track in Figure 2. In order to see the $c_y$ details, we limit the scale to −10 and 10 cm km$^{-2}$. Most of the $c_y$ values fluctuate between −4 and 4 cm km$^{-2}$; only five $c_y$ values exceed −10 and 10 cm km$^{-2}$.

The locations where extreme values occur are indicated in Figure 2. All of them correspond to deep bedrock valleys. First, note that most of the bedrock valleys, even the deeper ones, do not create such high $c_y$ values (see, e.g., km 155, 170, 240 and 260). Second, the ice viscosity is quite constant over distances of a few hundred km, so the ratio between bedrock and surface roughness (damping factor) may also be assumed to be constant. Therefore, the extreme values can only be explained by additional disturbance. Indeed, three of the $c_y$ extreme values (Nos. V1, V4 and V5) are directly above lakes (see km 25, 130, 285 in Fig. 2, and the plot of this track in Fig. 1a). This is in good agreement with the high-topography curvature observed around Vostok lake which was associated with a change in the ice-flow regime (Rémy and others, 1999). The strength of the $c_y$ parameter can thus be a means of detecting subglacial changes in flow, probably due to sliding.

In Figure 1f, we have mapped only extreme $c_y$ values over the whole area. In some places, they appear to be aligned and form very coherent lines. The geographical pattern of the high $c_y$ values is also an indication of the nature of these values and confirms the hypothesis that large $c_y$ values are generated by sliding due to basal melting. Indeed, the large $c_y$ values are concentrated where bedrock is deep (cf. Fig. 1e): the average ice thickness over the whole area is 3378 m, while the average ice thickness beneath large $c_y$ values is 3536 m. First, the basal temperature, and thus the probability of finding water, is likely to increase with ice thickness. Second, both theoretical and empirical studies suggest that the ratio between bedrock and surface roughness (the damping factor) decreases when ice thickness increases (Budd and Carter, 1971; Rémy and others, 1999), although this ratio also depends on wavelength roughness. These high values are thus not likely to be generated by the bedrock topography.

Assuming high $c_y$ values can be used to detect sliding areas, the occurrence of such areas along the surface networks provides strong evidence of the presence of hydrological networks. High $c_y$ values are found all along the two branches of the L1 and L4 features (Fig. 1f), suggesting sliding over most of these portions. Some sections of the L2 feature exhibit high $c_y$ values, namely at the southern extremity, near latitudes 77° and 78° S and at the northern extremity, as do a few portions of the L3 and L5 features.

These connections between lakes should be taken into account when modelling flow in this sector. Indeed, Testut and others (2000) observed a major anomaly in the ice flow just above the Adventure Subglacial Trench, between Dome C and Terra Nova Bay, where Siegert and Ridley (1998b) suspected the presence of a hydrological system. The estimated basal temperature was at the melting point. This trench was associated with a very high surface curvature and with a surface anomaly 10 km wide and several hundred km long crossing the area. Testut and others (2000) showed that a strong disturbance was affecting the ice flow locally due to ice sliding, even when the topography was smoothed out for up to 20 times the ice thickness.

## CONCLUSION

The precision of the topography around Dome C, and the location of the numerous lakes around this sector, allows us to point out the existence of a subglacial hydrological system. Indeed, we have mapped a surface parameter that is sensitive to subglacial features and that enables either bedrock valleys or changes in ice flow to be detected. An analysis of these surface features exhibits elongated features that link little-known lakes and run along the bedrock valleys in a downslope direction. Moreover, there is evidence to suggest that some portions of these features exhibit sliding, suggesting that some lakes are connected together.

This has an impact on the ice flow around the sector. It has already been acknowledged that lakes affect the ice flow (Siegert and Ridley, 1998b; Legrésy and others, 2000). Here, we show that the induced effect transcends the lake areas and plays a role over a larger region. Indeed, the parameter we have chosen, $c_y$, is directly related to the convergence or divergence of the flow. The flow tends to accelerate over negative $c_y$ areas (convergent flow) and diminish over positive $c_y$ areas (divergent flow). These features therefore play a role in flow patterns, and they certainly affect the estimation of flow-line direction and ice velocity derived from topographic maps. Moreover, high $c_y$ values related to the presence of lakes demonstrate that ice is probably sliding over these areas and that longitudinal stresses play a local role in ice dynamics.

The presence of a hydrological system, linking the lakes to each other, also has an impact on the dynamics and formation of lakes. The lakes in Antarctica are the focus of a major project supported by the Scientific Committee on Antarctic Research (SCAR) Group of Specialists on Subglacial Antarctic Lake Exploration to understand or estimate the nature of resident biota, the age of the lakes, the tectonic forces responsible for forming them, and the record of Antarctic climate history contained within the sediment beneath them. These studies should take into account the active connection between certain lakes.

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