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Physiography and tectonic setting of the subglacial lake district between Vostok and Belgica subglacial highlands (Antarctica)

I. E. Tabacco,[1] P. Cianfarra,[2] A. Forieri,[1] F. Salvini[2] and A. Zirizotti[3]

[1] *Università degli Studi di Milano, Dip. Scienze della Terra, Sez. Geofisica, Via Cicognara* 7, I-20129 *Milano, Italy. E-mail: ignazio.tabacco@unimi.it*
[2] *Università degli Studi Roma Tre, Dip. Scienze Geologiche, Largo S. L. Murialdo* 1, I-00146 *Roma, Italy*
[3] *Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata* 605, I-00143 *Roma, Italy*

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SUMMARY

We present the interpretation of 11 radio echo-sounding (RES) missions carried out over the Vostok–Dome Concordia region during the Italian Antarctic expeditions in the period 1995–2001. The extension and the density of the radar data in the surveyed area allowed to reconstruct a reliable subglacial morphology and to identify four relevant morphological structures namely: the Aurora trench, the Concordia trench, the Concordia ridge and the South Hills. These structures show evidence compatible with the presence of tectonic features. Morphological considerations indicate their development in Cenozoic time. Hybrid cellular automata (HCA)-based numerical modelling allowed to justify a possible role played by the tectonics of the Aurora and Concordia trench evolution. This was accomplished by matching the bed profiles along opportunely projected sections with the modelled surfaces as derived by the activity of normal faults with variable surfaces within the continental crust. The Vostok–Dome C region is characterized by a large number of subglacial lakes. From the analysis of basal reflected power echo, we identified 14 new lakes and obtained information about their physiography as well as their possible relations with tectonics. We propose a grouping of subglacial lakes on the base of their physiography and geological setting, namely relief lakes, basin lakes and trench lakes. Relief lakes located in the Belgica subglacial highlands and are characterized by sharp and steep symmetric edges, suggesting a maximum water depth of the order of 100 m. Their origin may well relate to localized, positive geothermal flux anomalies. Basin lakes located in the Vincennes subglacial basin and are characterized by wider dimension that allow the development of well-defined, flat ice surface anomalies. Trench lakes characterize the Aurora and Concordia trenches as the possible effect of normal fault activity.

Key words: Antarctica, HCA modelling, radio echo sounding, subglacial lakes, tectonic setting.

INTRODUCTION

It is well known that subglacial lakes exist under the Antarctic ice sheet below more than 3 km of ice. In the last decade many authors addressed their attention and scientific interest not only to the largest discovered subglacial lake, Lake Vostok, but also to minor lakes spread all over the Antarctic continent. (Siegert 2000; Bell *et al.* 2002; Popov *et al.* 2002; Tabacco *et al.* 2003). Till now, all over Antarctica 145 lakes have been identified and classified (Siegert *et al.* 2005). In 2000, the Scientific Committee for Antarctic Research promoted the research and interest in subglacial lakes with the creation of a group of specialists. The group produced in 2004 August a final proposal for the exploration of subglacial environments. The main goal of the 8 yr programme is to understand how the evolution of climate, life and tectonics interact to produce the unique and particular environment known as subglacial lake.

Italian Programma Nazionale di Ricerche in Antartide contributes to the discovery and identification of subglacial lakes with an extensive number of radar surveys.

In fact, radio echo-sounding (RES) technique is one of the methods to identify subglacial lakes. Reflection of radio waves occurs at the interface of two different media and the reflection coefficient provides information about their electromagnetic nature. The value of the reflection coefficient R at the interface between two media is given by

$$R = \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}}, \qquad (1)$$

where ε_1 and ε_2 are the complex relative permittivities of the two media. As the permittivity of water (~80) is different from typical rock permittivity (~4 ÷ 12), a much stronger reflection is obtained by the ice–water reflection compared to the ice–rock interface. The transition from a dry to a wet interface is marked by a variation in reflection strength more than 10 dB.

A strong signal alone is not enough to identify a subglacial lake; radar strong reflection from the ice sheet base could be ascribed both to water-saturated basal sediments or to subglacial lakes (Dowdeswell & Siegert 1999; Gorman & Siegert 1999).

Lake identification is possible if other conditions occur: flat and quite horizontal reflectors with nearly constant echo strengths, surrounded by sharp edges similar to the margins of a catchment basin.

We present the interpretation of 11 RES missions (airborne and ground-based survey) carried out over the Vostok–Dome Concordia region during the Antarctic Italian Expeditions of 1995, 1997, 1999 and 2001. The 1995 and 1997 missions were addressed to the exploration of the Dome C area, in the framework of EPICA (Tabacco *et al.* 1998); the other missions were dedicated to the investigation of the Lake Vostok (Tabacco *et al.* 2002) and to the detection of subglacial lakes over the entire area.

In the paper, after technical information about radar system and data collection, we analyse firstly the main features of the ice cap surface and of the bedrock; secondly we discuss the physical features of the ice-base interface as well as the location and physiography of the identified subglacial lakes. In the final part we discuss on the origin of the lakes and of the main bedrock structures. Despite their evidence, no satisfying origin model has yet been proposed. Debate is around the possible relationships between these morphologies and either a sedimentary/erosional or a tectonic setting capable of justifying them (Dalziel 1998). We explore the possible tectonic origin of the observed framework and the reliability of this hypothesis.

RADAR INSTRUMENTATION AND DATA COLLECTION

Radar data were acquired with a radar system operating at 60 MHz frequency. The radar instrumentation has been enhancing and improving since 1995 until 2001 (Tabacco *et al.* 1999): the digital sampling frequency was doubled from 10 to 20 MHz, yielding the accuracy from 100 ns to 50 ns (i.e. from 16 to 8 m in ice); the peak transmitted power was risen from 2 to 3.5 kW, to penetrate ice thickness greater than 4.5 km, the trace acquisition rate was increased from 0.3 to 10 trace/s, in order to have more detailed spatial information, an the pulse width was shortened from 1 μs to 200 ns to have higher vertical resolution in internal layers detection.

We acquired a total of about 1.5 million radar traces along 10 800 km of radar legs over an area of about 250 000 km^2. The entire data set was characterized by differences in radar systems and was processed in order to prepare a homogeneous and comparable database.

The location of radar traces was obtained by a GPS system (Rover) coupled to the radar with a accuracy of about 10 m. The surface elevation was based on the ERS-1 data set (Rémy *et al.* 1999). Fig. 1 shows the surface elevation referred to the WGS84 ellipsoid and the radar tracks. The density and the spacing of the radar tracks are not homogeneously distributed: over the Dome C region there are about 8500 km of radar tracks over an area of 140 000 km^2, while over the Vostok region there are 2300 km over 110 000 km^2.

The ice thickness was computed assuming a constant ice electromagnetic velocity of 168 m μs^{-1} (Glen & Paren 1975). We did not consider the increased electromagnetic velocity due to the firn layer in the first 100–200 m of the ice; however, the error in ice thickness is negligible (less than 10 m) if compared to the total ice thickness (Rasmussen 1986). The bed elevation was obtained by subtracting the ice thickness to the surface elevation. Accuracy in ice thickness gives an rms of $\pm$22 m for the data acquired in 1995 and $\pm$16 m for the data acquired in the following years (Forieri *et al.* 2003). Ice-thickness values were controlled in the crossover points of all radar legs (for a total of over 750 crosspoints); 70 per cent of these show ice thickness differences less than 40 m. Greater differences were observed over the subglacial mountains and they are due to the steep morphology of the mountains and valley flanks, where small error in crosspoints locations should generate substantial differences in ice thicknesses.

Over the entire area, the integration of the new data with those of BEDMAP Consortium (Lythe *et al.* 2000) was unsuccessful, due to consistent differences in ice thickness over the Belgica subglacial highlands. These differences probably relate to the lower precision of the earlier flight locations, on account of the navigation system used during the past surveys. Due to these uncertainties we prepared a bed map using only the new data set.

Local detailed maps with high data density over Dome C area were presented in Forieri *et al.* (2003); the square grid spacing of these maps is, respectively, of 0.4, 1.2 and 4.5 km. For the area investigated in this paper we used a spacing of about 8 km. This spacing induces an excess smoothing of the bedrock features over the Belgica subglacial highlands and in the Dome C area, where the collected data allow a far better resolution (Forieri *et al.* 2004). On the other hand, fictious trends could be added by the numerical algorithm in area with lower data density as well as near the map border. The bed elevation was referred to the WGS84 ellipsoid and it is reported in Fig. 2.

MAIN FEATURES OF THE SURFACE AND OF THE BEDROCK

The ice surface of the area (Fig. 1) is characterized by a regional slope of 1–3 m km^{-1}. Some localized features with slope less than 0.5 m km^{-1} are evident at Lake Vostok, Dome C, Aurora and Vincennes subglacial basins (Rémy *et al.* 1999). The main, well-known (Drewry 1986; Lythe *et al.* 2000) regional bed features (Fig. 2) are: the Lake Vostok rise, the Aurora subglacial basin, the Belgica subglacial highlands and the Vincennes subglacial basin. In this paper we present some new bed features that characterize the regional ones.

The main feature within the Aurora subglacial basin is a large bent depression oriented approximately N–S between longitudes 117°–118°E for a total length of about 600 km. We named it '*Aurora trench*' (Fig. 2). The northern part of this depression, about 280 km long, is well defined, its width ranges from 25 to 35 km, its elevation ranges between −1000 and −1580 m, similar to Lake Vostok bed elevation (Masolov *et al.* 1999). The margins are characterized by a relatively steep slope, up to 70 m km^{-1}. The Aurora trench reaches the maximum depth of −1577 m at 118.277°E, −76.067°S, where we measured an ice thickness of 4755 m, comparable to the maximum ice thickness to date measured in Antarctica over the Astrolabe subglacial basin (Lythe *et al.* 2000).

The prosecution to the South of the Aurora trench is more ambiguous, and it could be confused with the general deepening of the Aurora subglacial basin. Its width ranges from 60 to 70 km, the main elevation is about −600 m and the slopes are less relevant than in the northern part. The southern part of the trench clearly relates to a narrow ice surface feature (77°S, 118°E) characterized by slope less than 0.4 m km^{-1} (Fig. 1).

The Aurora trench divides the region into two subareas:

(i) The area West to the Aurora trench (at the eastern side of Lake Vostok) is characterized by an even bedrock shape, dipping

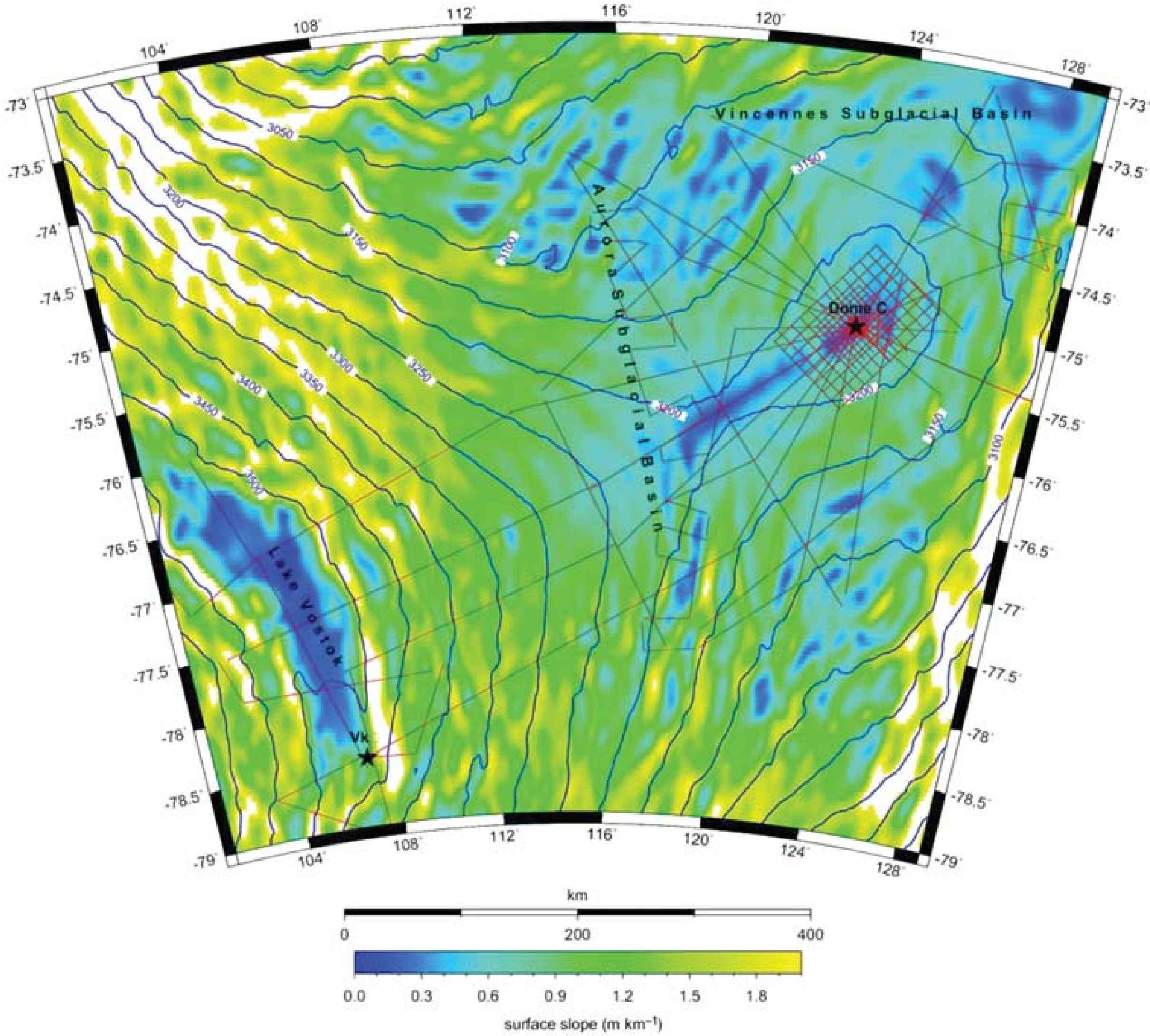

Figure 1. Map of the surface elevation and surface slope of the region between Vostok and Dome C, contour interval 50 m. Red lines: radar profile tracks; Vk: Vostok Station; Dome C: Concordia Station.

from West to East with slope gradients of 4 m km^{-1}. The ice surface is characterized (Fig. 1) by an even surface slope ranging from 1.5 m km^{-1} (West) to less than 0.5 m km^{-1} in the vicinity of the trench.

(ii) The area East to the Aurora trench presents a complex and irregular bed morphology, typical of mountain range (Belgica subglacial highlands). The bedrock rises up from West to East with a main slope rate ranging from 10 m km^{-1} (North), to 3 m km^{-1} (South). Ice surface presents wide relatively flat areas with a surface slope less than 0.5 m km^{-1}, related both to the ice divide and to the topographic Dome of Concordia.

At the Belgica subglacial highlands we observe some local relevant features.

(i) The North–South, '*Concordia trench*', and the associated '*Concordia ridge*' (Fig. 2) located East of Dome C Station between longitude 124–125°E. The Concordia trench (main width about 15–20 km, length 250 km) in its central part reaches its highest elevation −250 m, and dips both to the North and to the South to a maximum depth of −950 m and −750 m, respectively. The *Concordia ridge* reaches the elevation of more than 700 m. The difference in elevation between the trench and the top of the mountains reaches 1300 m.

(ii) A smoothed *South Hills* system develops approximately WNW–ESE. Between the South Hills system and the Concordia trench is located a flat area, the *Dome C Plateau* with an extension of about 2500 km^2 at a main elevation of about 0 m. Its shape presents smoothed undulations with differences of less than 100 m between bumps and troughs (Forieri *et al.* 2004) and several North–South secondary valleys (Rémy & Tabacco 2000).

BASAL PHYSICAL CONDITIONS AND SUBGLACIAL LAKES CLASSIFICATION

The analysis of the basal strength reflection was carried out and the radar tracks interpreted either as possible lakes or as wet basal interface are reported in Fig. 3.

As previously stated, the reflection strength from ice–water and ice–rock interfaces differ by more than 10 dB due to the values of the real part of dielectric constant of water and rock, and to the

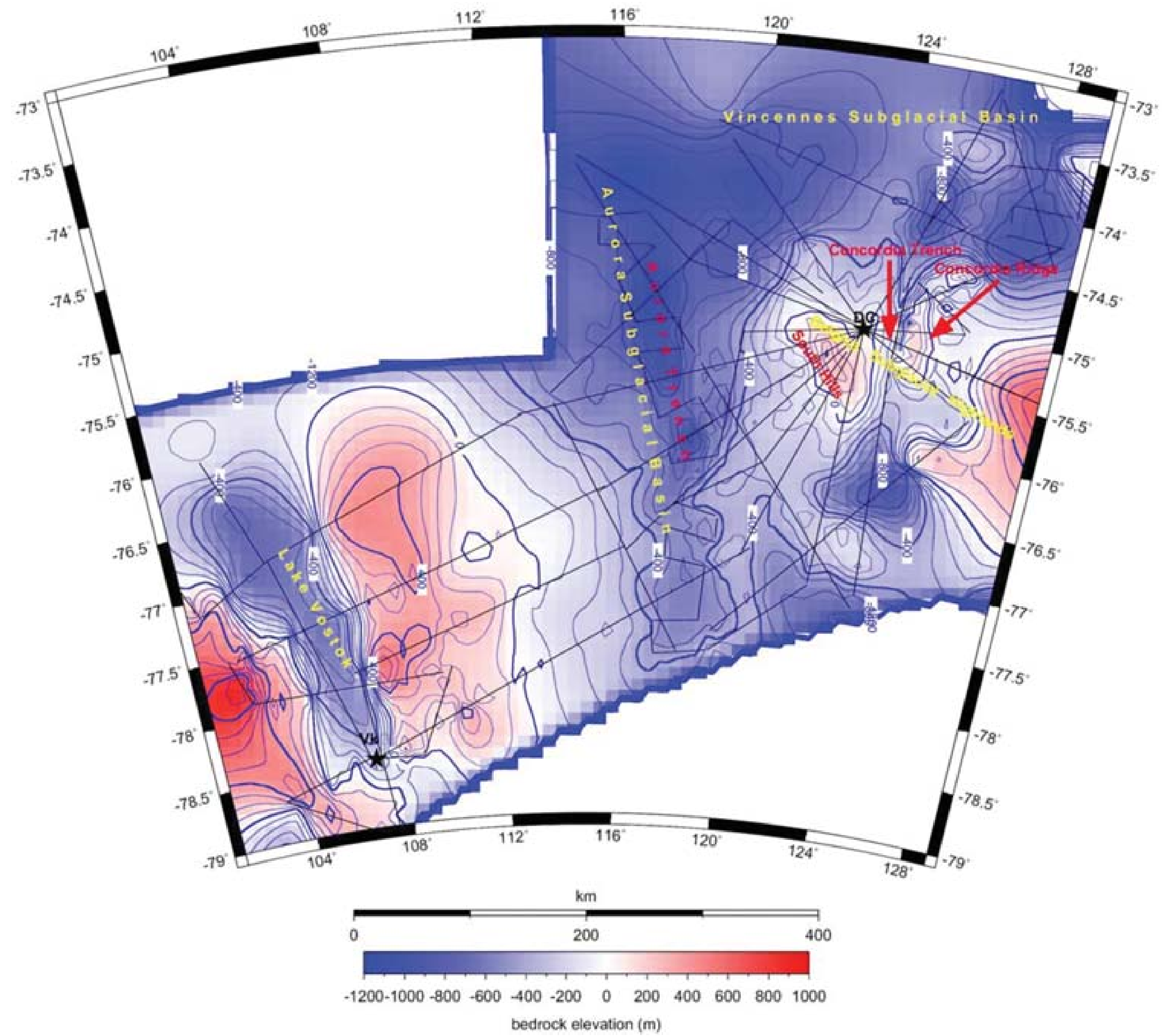

Figure 2. Map of bed elevation of the region between Lake Vostok and Belgica subglacial highlands, contour interval 100 m. Straight black lines: radar profile tracks; Vk: Vostok Station; DC: Concordia Station. Red label: proposed names for the main newly identified morphological structures.

roughness of bedrock (Oswald & Robin 1973; Gorman & Siegert 1999; Siegert 2000).

The reflected power P_R is calculated by:

$$P_R = G^2 \frac{\lambda^2}{16\pi^2 r^2} P_T \cdot Q \cdot \frac{L_f}{L}, \quad (2)$$

where G is the antenna gain, λ the wavelength, r the distance, P_T the transmitted power, Q the refractive gain, L_f the gain/loss due to focusing/defocusing effect of surfaces shape and L the total power loss, due to volume inhomogeneity (L_v), ice surface and ice bottom scattering (L_{si} and L_{sb}), reflection at the ice–air and air–ice interfaces (L_r), polarization (L_p), medium absorption (L_a) and transmission at the bottom interface (L_t).

Expressing eq. (2) in dB we obtain:

$$[P_R] = [P_T] - [L_g] + [Q] - [L_f] - [L_{si}] - [L_v] - [L_p] - [L_r] - [L_a] - [L_t] - [L_{sb}]. \quad (3)$$

The refractive gain Q and the focusing–defocusing effect L_f are 3–4 dB for nearly flat reflecting surfaces (Bogorodky *et al.* 1985). The scattering loss from the ice–air interface, L_{si} ranges from near zero to several dB depending on surface roughness. We assume a value of about 1–2 dB obtained after an averaging of raw data. Moreover, the values L_v, L_p, and L_r may be considered constant along each profile, and their total contribution is approximately 4 dB.

L_g is the geometrical attenuation given by $L_g = 20 \log(4\pi r/G\lambda)$. The absorption in ice is calculated with the relation $L_a = k\sigma d$ where k is a constant, σ the conductivity dependent on temperature and depth, and d the thickness; its estimation is influenced by errors due to uncertainty on the value of conductivity and on its variation with depth.

With the assumptions above, knowing the value of the transmitted power, measuring the amplitude of the echo signals P_R, and the ice thickness to calculate L_g, we can estimate L_t and L_{sb}, that is, the two terms strictly related to the bottom interface. This was done all along the profiles to infer and locate dry or wet basal conditions in the area.

The area East to the Aurora trench, is characterized by many lakes and diffuse wet basal conditions; the area West to the trench shows only one little lake. It seems that the Aurora trench separates the region in two different subareas. The wet area is concentrated over

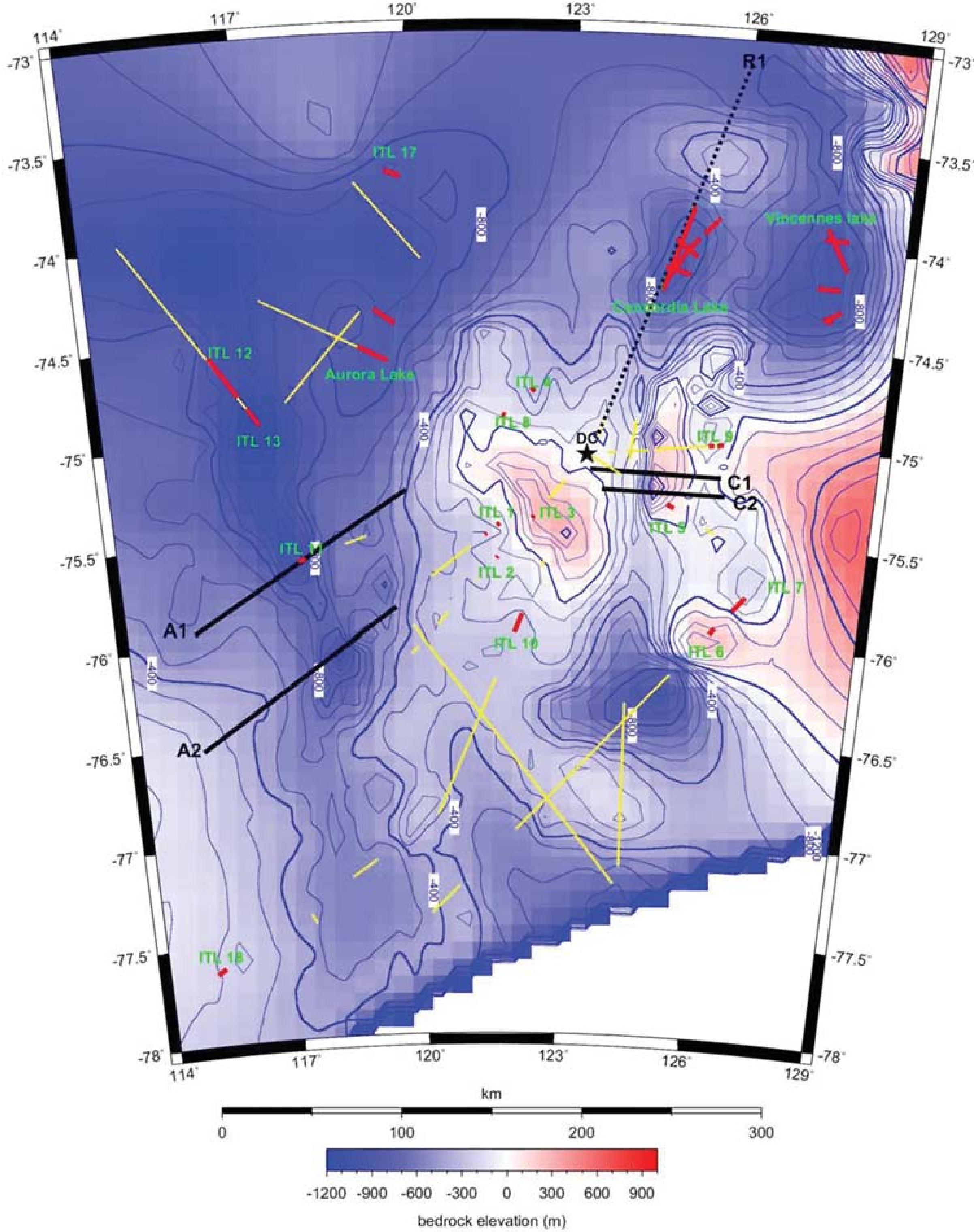

Figure 3. Map of the bed elevation of the Belgica subglacial highlands and of the Vincennes and Aurora basins, contour interval 50 m. Yellow lines: ice bed wet interface tracks; red lines: subglacial lake tracks with id (green label); light green lines contour Vincennes, Concordia, and Aurora lakes extensions; black lines: traces of the tectonic sections; dotted black line: trace of the radar R1 profile.

the Aurora subglacial basin and the southern part of the Belgica subglacial highlands along a WNW–ESE oriented strip belt, with a width of about 200 km. To the NE, the Vincennes subglacial basin is characterized by the presence of four large lakes and does not seem affected by extended wet basal conditions.

We detected 18 lakes in the region (Fig. 3 and summarized in Table 1). (Tabacco *et al.* 2003).

(i) Eight lakes are located on the Belgica subglacial highlands. Their along-track lengths range from 1.5 to 5 km; their ice thickness

Table 1. Inventory of the identified lakes; within parenthesis lake id of the previously known ones.

Lake Id	Classification	Max Lake Track Length (km)	Longitude °E	Latitude °S	Ice Thickness (m)	Elevation (m)
ITL 1	Relief	2.2	121.630	75.460	3570	−354
ITL 2	Relief	1.1	121.607	75.624	3513	−304
ITL 3	Relief	1.7	122.315	75.422	3030	192
ITL 4	Relief	3.1	122.284	74.785	3769	−560
ITL 5	Relief	4.5	125.022	75.345	3150	53
ITL 6	Relief	4.4	126.028	75.954	2975	178
ITL 7 (SPRI 11)	Relief (?)	10.7	126.526	75.811	3408	−259
ITL 8	Relief	2.0	121.732	74.913	3416	−212
ITL 9	Relief	3.3	125.918	75.024	3461	−264
ITL 10 (SPRI 13,14)	Relief (?)	11.5	122.039	75.953	3489	−305
ITL 11	Relief	3.4	117.686	75.608	4457	−1277
ITL 12	Trench	27.2	116.421	74.673	4155	−1037
ITL 13	Trench	11.8	116.936	74.881	4460	−1332
ITL 14	Basin	26.6	127.767	74.005	4126	−990
Vincennes lake						
ITL 15 Concordia	Basin	49.8	124.900	74.059	4053	−872
Lake (SPRI 6)						
ITL 16	Basin	18.3	119.266	74.598	4019	−882
Aurora lake (SPRI 34)						
ITL 17	Basin	9.6	119.715	73.702	4034	−915
ITL 18	?	5.9	115.191	77.626	3500	−243

Longitude, latitude, ice thickness and elevation are referred to the midpoint of the lake track.

ranges from 2975 to 3769 m and their ceiling elevation from −354 to +192 m. Moreover, at the boundary between the Aurora subglacial basin and the Belgica subglacial highlands, two lakes are located over a sharp local depression, reaching an along-track length of 11.5 km, an ice thickness of about 3450 m and an elevation of −280 m. All these lakes have symmetrical, sharp and steep edges whose slopes suggest that the maximum water depth (ITL 7) reaches over 100 m. The radar lake tracks are not associated with local ice surface anomalies. This confirms that the real extensions of the lakes are too small to produce modifications on the ice surface (Dowdeswell & Siegert 1999). These common features allow to group them and they will be referred hereafter as ‘relief lakes’. Fig. 4 shows ITL 5, a representative example of ‘relief lake’. It is clearly visible the slope symmetry.

(ii) Four lakes are located over the Vincennes subglacial basin. Their along-track lengths range from 10 to 50 km, their ice thickness is about 4000 m, and their elevation is at about −900 m. All the radar tracks are associated with local and well-defined surface anomalies characterized by slope gradients less than 0.4 m km^{-1}. On the basis of the surface area with slope gradient less than 0.3 m km^{-1} and the positions of strong radar echoes it is possible to estimate a real extension up to 1000 km^2 of the three larger ones: Lake Concordia, Lake Vincennes and Lake Aurora (Fig. 3). These common features allow to group them and they will be hereafter referred as ‘basin lakes’. Figs 5(a), (b) and (c) show the Lake Concordia, along the radar profile R1, surface and bed elevation, respectively. The profile runs along the regional surface ice flow from S to N. It is important to notice that slope gradient of the lake ceiling and ice surface are opposite, their ratio 1:12 suggests that ice is floating over fresh water (Oswald & Robin 1973). On the basis of the lake shore slopes, the water depth should be estimated in at least 150 m.

(iii) Three lakes are located within the Aurora trench, showing different dimensions. The lake ITL 11 is very small (3.3 km) at a depth of −1277 m with ice coverage of 4477 m. The lakes ITL 12 and ITL 13 are located on the terraced structure of the trench. Their minimum lengths are, respectively, 11.9 and 27.3 km, their ice thickness 4460 and 4155, and their elevation −1332 and −1037. Both these lakes are in correspondence of an elongated surface anomaly with a slope less than 0.5 m km^{-1}, that relates to the presence of the trench. Their location allows to group them and they will be referred hereafter as ‘trench lakes’.

(iv) One lake (ITL 18) apparently does not fit any of the proposed groups. It was detected by a single radar profile over the eastern flank of Lake Vostok (Fig. 3). Its along-track length is about 6 km with an ice thickness of 3500 m at the depth of −243 m. The radar track coincides with a localized surface anomaly with a slope gradient of less than 0.4 m km^{-1}.

Four of the 18 detected lakes were reported in the Siegert *et al.* inventory (1996a), so only 14 new lakes were discovered and have been added to the inventory of Antarctic subglacial lakes (Siegert *et al.* 2005). There were 35 lakes in the area. Dowdeswell & Siegert (1999, 2003) propose a grouping based on lake extension, ice thickness, lake ceiling elevation and distance from the ice divide. These were considered as independent factors to describe significant, different typologies. For the Dome C–Vostok area we suggest to group the newly discovered lakes on the base of their physiography and their location referred to the regional bedrock features, namely: ‘relief lakes’, ‘basin lakes’ and ‘trench lakes’. Fig. 6 reports sketches of the distinctive physiographic features of these lakes, based on the different slope morphology. Basin lakes are characterized by gently dipping slopes on all sides, independent from their shape. Trench lakes have longitudinal profiles, which differ from the transversal one that is characterized by a steep slope on one or both sides. This results in a typically elongated lake shape. Steep slopes on all sides characterize relief lake physiography. The proposed grouping could be extended to all the lakes in Dome C–Vostok region. At the present, a classification based on the whole set of discovered Antarctic subglacial lakes is difficult due to the lack of a comprehensive bibliography. Although the proposed grouping is limited to the Dome C area, we believe that it could be easily extended to other subglacial Antarctic lakes.

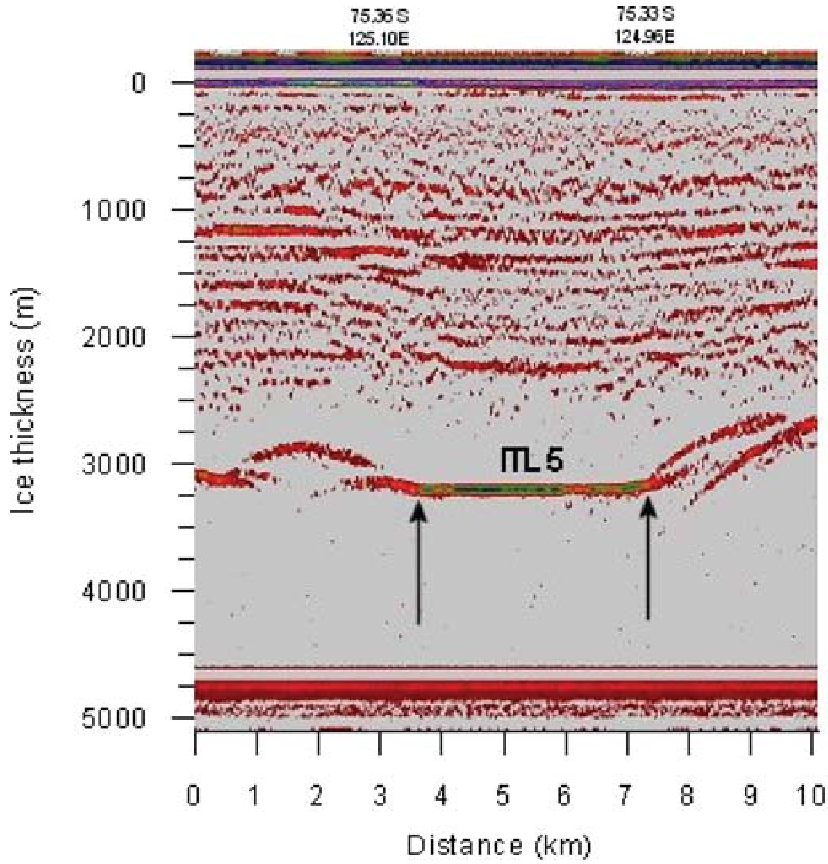

Figure 4. Radar profile of relief lake ITL5.

ORIGIN OF AURORA AND CONCORDIA TRENCHES

The characteristic asymmetrical shape of The Aurora and Concordia trenches resembles the typical morphology resulting from fault activity, and specifically from the development of normal faults with planes of variable dip (Fig. 7 redrawn after Burbank & Anderson 2001). To evaluate this possibility for the Aurora and Concordia trenches, the bedrock morphologies were compared with normal faulting processes by numerical modelling. This modelling was performed by the HCA technique implemented in the FORC2 software, (Salvini *et al.* 2001; Salvini & Storti 2004).

The forward-modelling algorithm (hybrid cellular automata, HCA) is a hybrid methodology that combines the cellular automata (CA) and the finite element method (FEM) principles. It replicates geological layering by using large amounts of cells with simplified links. The links among adjacent cells are simple, first-order geometrical and/or physical laws, thus following the FEM philosophy. Following the CA principle, cells are free to migrate within the mesh. The forward modelling is accomplished by step small enough to provide negligible differences in the resulting geometric/physical law computations. In this way the new position at each step can be computed only considering neighbour cells.

The FORC2 is a 2-D implementation of the HCA and layered rocks are simulated by a polygon of groups of cells with given, homogeneous links. Three type of geometrical links were applied: intralayer relations (i.e. within single layers), interlayer relations (i.e. between different rock layers) and discontinuity relations (i.e. along fault surfaces). This approach guarantees the overall preservation of volumes and surfaces during the experiment run.

The bedrock was simulated in 2-D by a rectangle of homogeneous layered material with a rigidity comparable to upper crustal rheology (Poisson ratio: 0.25; Young Module: $7 \cdot 10^{10}$ Pa), a total thickness of 34 km (according to Studinger *et al.* 2003), and a length of 150 km. The cell initial horizontal dimension was around 1300 m. The models were run to have about 100 m resolution.

Four bedrock profiles by radar flight missions were selected, to provide, as close as possible, across-strike sections of the depressions in their most meaningful zone, that is, where the highest elevation contrast is present. The optimal orientation was achieved by projecting the bedrock elevation data from RES along a nearly perfect across-strike trajectory. This allowed to approximate the faulting as a cylindrical deformation, suitable to be modelled by the 2-D software. Two sections were prepared for each trench, and similar fault geometry and displacement were applied to each couple. Table 2 summarizes the coordinates of the vertexes of the sections and their lengths.

A forward-modelling approach was followed, to visually best fit, within the 100 m resolution, the present-day bedrock morphology with the topography induced by the activity of a listric normal fault, constrained within the 34-km-thick crust, (Studinger *et al.* 2003; Morelli & Danesi 2004), of a given geometry and displacement. Any change in the fault trajectory produces both variations in the hanging wall thickness that is passively transported by the fault displacement, and in the dip of the hanging wall surface that moves over it. The fine tuning of the fault surface geometry and displacement allowed to fit the bedrock morphology with the model.

The Aurora trench. The along-strike sections for the Aurora trench were ENE–WSW oriented and are referenced as sections A1 and A2 respectively (Fig. 3). The former has a length of about 109 km

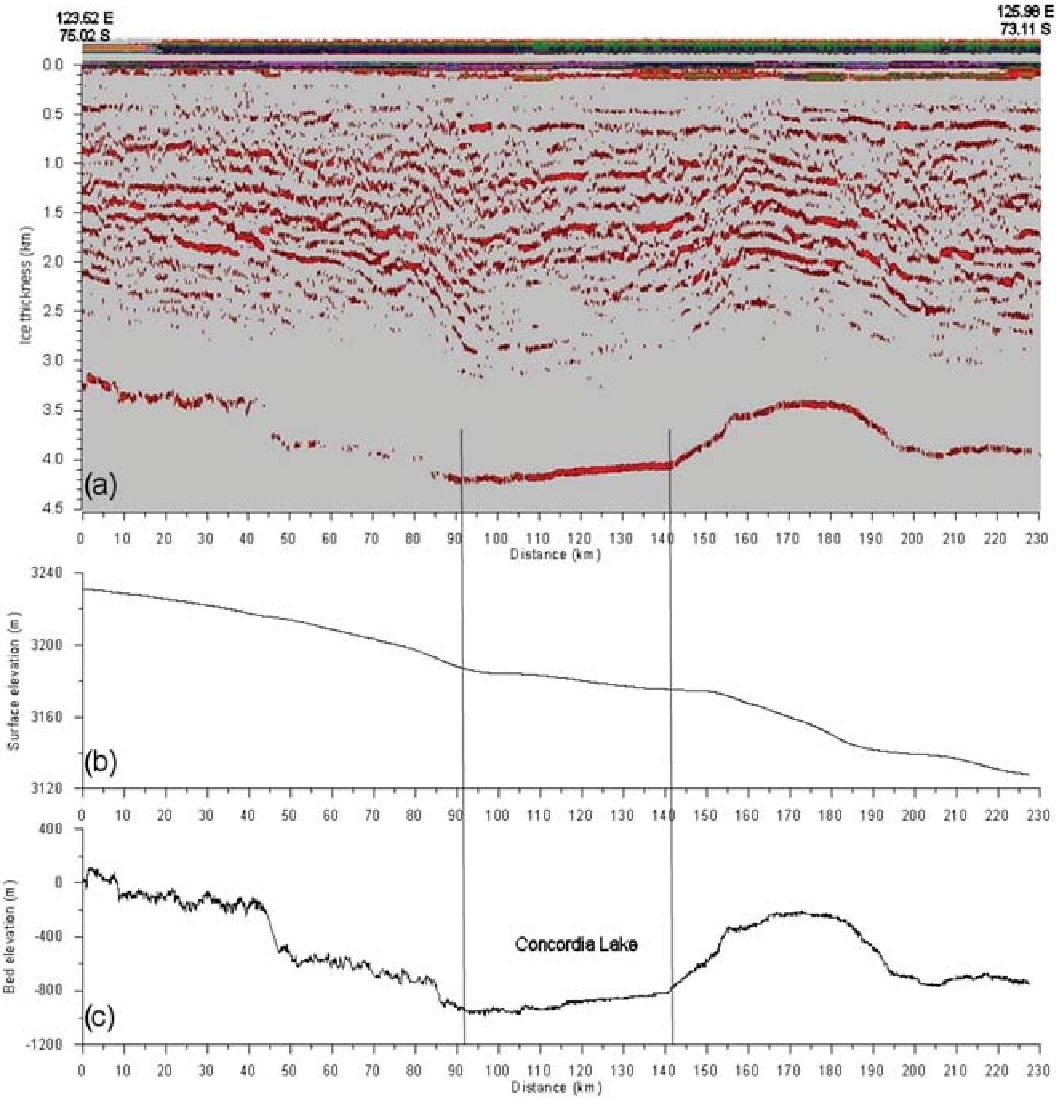

Figure 5. (a) Radar profile R1 and ice thickness; (b) surface elevation and (c) bed elevation along profile.

and are located northwards to the latter, which has a length of about 130 km (Table 2).

Fig. 8 reports the sections A1 and A2 of the Aurora trench and shows, in the upper parts, the match between the bedrock morphology and the modelled surface with a vertical exaggeration of 10:1. In the lower parts is shown the complete modelled sections without vertical exaggeration to visualize the full fault trajectory. The bedrock morphologies in the two sections show the presence of an asymmetry in the trench, the eastern side being the steeper one. The western, gentler slope has a characteristic curved shape. This morphology has been interpreted as the surface expression of the listric geometry of a west-dipping normal fault governing the structural development of the trench. The same fault trace has been used to model the bedrock morphology for both sections, the only difference being in the throws, 420 m for the A1 section, and 630 m for the A2 one.

The Aurora listric fault is characterized by an initial dip, at the bedrock surface, of 63° to the West. This dip remains almost constant until the fault surface reaches a depth of 17 km. Then it gently rotates and its dip reduces to 45° in the next 6 km. At this depth (23 km) the dip reduces progressively until it reaches its basal detachment at the depth of about 34 km. The final fits have an rms for the A1 and A2 sections of, respectively, 59.61 and 98.6 m and includes the presence of the smaller scale topography.

The Concordia trench The Concordia trench has been investigated through the analysis of two E–W sections, respectively, named C1 and C2 (Fig. 3). They have a length of 76 and 80 km, respectively (Table 2). The sections show (Fig. 9), as for the Aurora trench, the presence of a clear asymmetry in the trench slopes, the eastern being steeper than the western one.

The bedrock morphology has been modelled as the result of the activity of a fault having a constant dip of 60° towards the West in the first 20 km. Then the fault surface gently rotates and reaches a dip of 50° at the depth of 28 km. The deepest portion has a constant dip of 45°. The best fit was achieved with a throw of 750 m for the C1 section, and 1050 m for the C2 one. The final fit rms for C1 and C2 section are respectively 54.16 and 54.21 m and includes the presence of the smaller scale topography.

The morphologies of the Aurora and Concordia trenches can hardly relate only to the activity of the 34-Ma-old East Antarctica ice cap (De Conto & Pollard 2003). These trenches are characterized by a remarkable, constant asymmetrical shape, with gentler-dipping

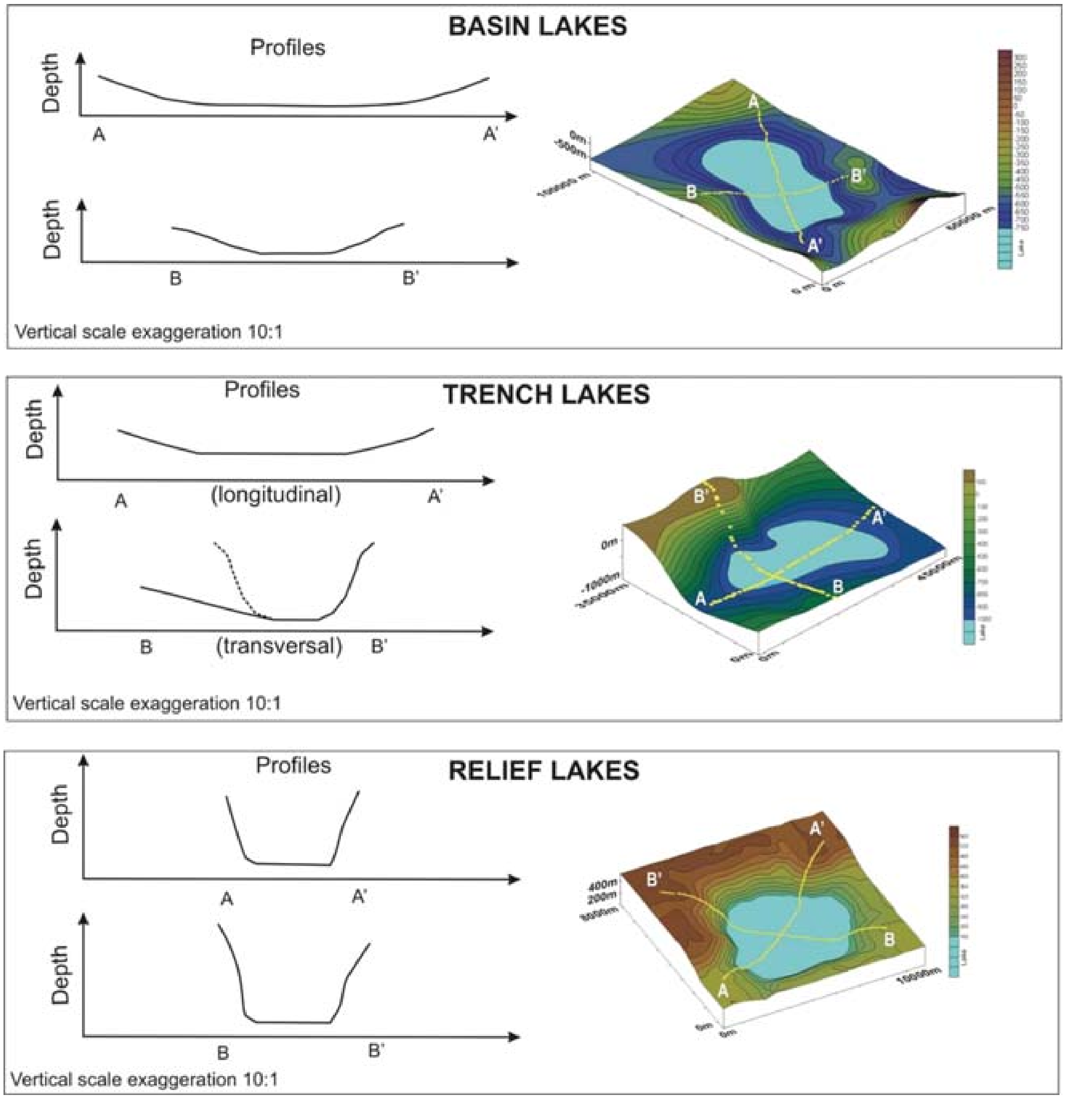

Figure 6. Sketches of relief, basin and trench lakes based on their slope morphology.

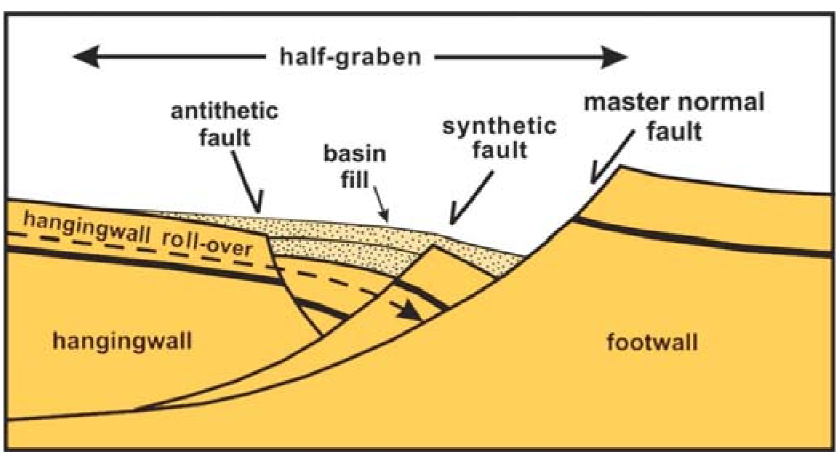

Figure 7. Schematic cross-section (no vertical exaggeration)of normal, listric faults in extensional regime and resulting morphology (redrawn after Burbank & Anderson 2001). Please note that to enhance the resulting morphology, fault displacement is about 2 km and the basal detachment is at a depth of about 6 km.

Table 2. Location and length of tectonic sections.

Section ID	Vertex 1 Lat °S	Vertex 1 Long °E	Vertex 2 Lat °S	Vertex 2 Long °E	Length (km)
A1	75.936	115.390	75.281	119.814	109
A2	76.522	115.327	75.865	119.541	130
C1	75.176	123.421	75.188	125.969	76
C2	75.274	123.663	75.279	126.075	80

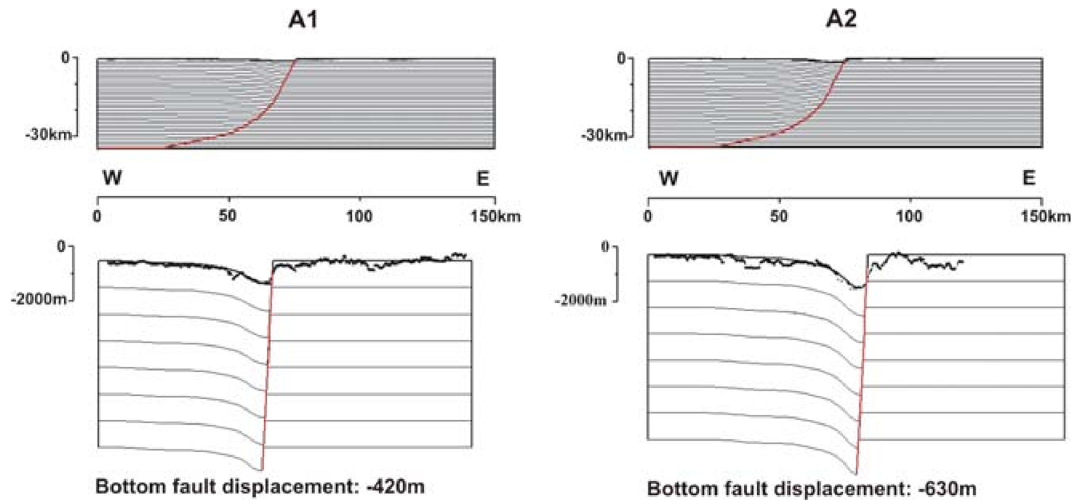

Figure 8. Tectonic models of the Aurora trench development along section A1 and A2. Upper sections show entire models at true scale; lower sections show details of the fit between the observed topography and the model with 10:1 vertical exaggeration.

eastern flanks. These shapes contrast with the expected morphologies resulting from glacial erosional processes, below the flat ice cap, where we expect a rate of erosion proportional to the ice thickness during wet conditions. On the other hand, surface erosional processes would have easily and rapidly obliterated such asymmetry. In this way, the found trenches could either have been generated shortly before the development of the ice cap or during the initial wet ice cap conditions or else under dry ice cap condition (i.e. younger than 34 Ma). The sharp match with the modelled fault hanging wall morphology suggests the absence of long-lasting, subaereal erosional processes. These considerations favour the hypothesis that the present day observed features in the bedrock surface developed during or immediately prior to the ice-cap formation, thus suggesting an Upper Cenozoic or younger age.

DISCUSSION AND CONCLUSIONS

We present the physiography and location of 18 subglacial lakes in the district between Vostok and Belgica subglacial highlands, 14 of them being newly discovered. This brings to 35 the total number of lakes up to now known in the Dome C–Vostok region. We propose the grouping of the subglacial lakes on the base of their physiography, and geological setting, namely relief lakes, basin lakes, trench lakes. The distribution of subglacial lakes and the presence of areas with wet/dry basal condition identifies two different zones. The eastern flank of Lake Vostok as far as to the Aurora trench is characterized by dry rock–ice interface and by only one lake. On the other hand, East to the trench, over Belgica subglacial highlands and part of the Aurora and Vincennes subglacial basin, there are evidences of several lakes and of diffused areas with wet rock–ice interface. New RES profiles are necessary to confirm the substantial lack of subglacial lakes West to the Aurora trench as well as to complete the information of the basin lakes and to improve the lake inventory over the Belgica subglacial highlands.

We consider that:

(i) the two areas are similar on respect of the ice thickness and the average elevation;
(ii) the main ice divides cut symmetrically both the areas;
(iii) the ice flow velocity is, all over the region, too low to suggest consistent differences in frictional heat productions and
(iv) the ice surface temperatures are basically similar over all the area.

A geothermal flux value of about 45 mW m^{-2} (as proposed for Vostok lake area in Siegert *et al.* 1996b) justifies, on the base of the measured ice thickness and of the available accumulation rate data, the bottom dry condition of the area east of Aurora trench and the existence of trench and basin lakes. On the other hand, this value is too low to explain the presence of several relief lakes and the existence of the bottom wet condition west of the Aurora trench and over the Belgica Highlands.

Therefore, we could suggest that the different basal behaviour of the two areas mainly relates to geothermal flux variations due to the geological setting.

Possible link between the tectonic origin of the Aurora and Concordia trenches and the distribution of the subglacial lakes are supported by some evidence. The trench lakes ITL 12 and ITL 13 are located along the tectonic depressions in correspondence of the footwall of the Aurora and Concordia regional faults, and the basin lakes develop at the termination of the fault controlled trench valleys. Numerous relief lakes are located in a relatively higher region, the Belgica subglacial highlands, that contrasts with the surrounding region, where, despite the increased ice thickness, only few subglacial lakes have been identified. For the origin of these lakes we suggest the presence of localized, positive geothermal flux anomalies. These may, in turn, be the result of the presence of volcanic/hydrothermal activity of recent age.

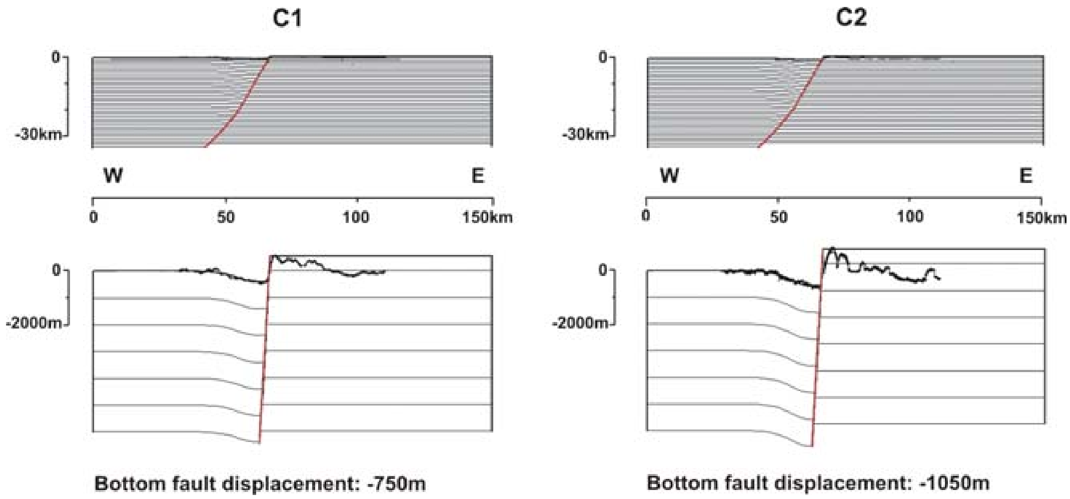

Figure 9. Tectonic models of the Concordia trench development along section C1 and C2. Upper sections show entire models at true scale; lower sections show details of the fit between the observed topography and the model with 10:1 vertical exaggeration.

Basin lakes and trench lakes concentrate in the deepest zones with an ice coverage more than 4000 m where more favourable melting conditions are likely to occur. These depressions may well relate to the tectonics of the region resulting from the activity of listric, regional normal faults of Upper Cenozoic time (i.e. 34 Ma, after ice cap onset or younger). These depressions may represent preferential accumulation zones fed by a hydrological subglacial network (Rémy *et al.* 2002).

This interpretation may well be extended to the Vostok depression, about 400 km West of the Aurora trench. The origin of Lake Vostok is still on debate, being the tectonic rifting a very reasonable one (Leitchenkov *et al.* 1999; Dalziel 1998). This interpretation reveals the existence of a ENE–WSW trending, regional extension within this subglacial district that may well justify the lake development. A rifting activity in the area, extending from the Amery basin inwards to the Vostok lake has been suggested by Leitchenkov *et al.* (1999) giving a Palaeozoinc activity age. A Cenozoic tectonic age has been proposed by Salvini *et al.* (1997) for the Victoria Land and Ross Sea region to the east. On the basis of our results, we propose that the activity of the Aurora and Concordia faults, or the younger history of it, may be ascribed to Cenozoic times.

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