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Geological setting of the Concordia Trench-Lake system in East Antarctica

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SUMMARY

This study presents the interpretation of radio echo-sounding (RES) data collected during the 2003 geophysical campaign of PNRA (Italian National Research Project in Antarctica), which focused on the exploration of the Concordia Trench-Lake system in East Antarctica. The data allow us to identify a new lake (ITL-28) at the southern edge of the Concordia Trench and a series of N–S trending subglacial troughs cutting through the Belgica Highlands. We have mapped the bedrock morphology at 3 km resolution, which led to an improved geographical and geomorphological characterization of the Concordia Trench, Concordia Ridge, Concordia Lake and South Hills. Improved knowledge of the Concordia Trench allowed us to model the 3-D geometry of the Concordia fault, suggesting that it played a role in governing the morpho-tectonic evolution of the bedrock in the Dome C region, and to propose a Cenozoic age for its activity. We recognize the importance of catchment basin morphology in hosting subglacial lakes, and discuss the role played by tectonics, glacial scouring and volcanism in the origin of the trench lakes, basin lakes and relief lakes, respectively.

Key words: Intra-plate processes; Cratons; Tectonics and landscape evolution; Antarctica.

INTRODUCTION

Analysis and interpretation of geophysical data collected in the Vostok–Dome C region, central East Antarctica (Fig. 1), have helped to explain the role played by tectonics in the development of the subglacial landscape (Leitchenkov *et al.* 1999; Studinger *et al.* 2003; Bell *et al.* 2006; Lipenkov 2006; Tabacco *et al.* 2006). This region is characterized by a series of N–S trending elongated valleys (troughs), the major ones of these being the 'Aurora Trench' and the 'Concordia Trench' (Forieri *et al.* 2004). Three basins comprise a total area exceeding 500 km^2, and together with the Vostok subglacial depression, they host the largest Antarctic subglacial lakes namely Vostok, Concordia, Aurora and Vincennes lakes (Tabacco *et al.* 2003; Siegert *et al.* 2005).

The age and tectonics that produced the subglacial depressions are subjects of active debate. Proposed models include the existence of an intracontinental rift system branching off the Lambert rift (Kapitsa *et al.* 1996; Leitchenkov *et al.* 1999; Masolov *et al.* 2001), the normal reactivation of a regional thrust sheet (Studinger *et al.* 2003, 2004; Bell *et al.* 2006) or the existence of a NW–SE intraplate extensional corridor running from Lake Vostok to the Aurora Trench (Cianfarra *et al.* 2003; Tabacco *et al.* 2006). Proposed ages range from Paleozoic (Leitchenkov *et al.* 1999; Studinger *et al.* 2003; Dalziel 2006) to Cenozoic times (Cianfarra *et al.* 2006; Tabacco *et al.* 2006).

Based on the bedrock physiography and geological setting derived from an 8 km resolution map of the Vostok–Dome C area (Forieri *et al.* 2004), Tabacco *et al.* (2006) proposed a lake classification for the district between the Vostok Lake and the Belgica Subglacial Highlands, which included basin, trench and relief lakes. Morpho-tectonic analyses showed that the main depression was compatible with the development of two crustal listric normal faults, the Aurora and Concordia Faults.

This paper presents the results of the 2003 geophysical campaign of PNRA (Italian National Research Project in Antarctica), which focused on the exploration of the Concordia Trench-Lake system. The new RES data profiles in the Concordia Trench were used to better constrain the along- and across-strike geometry of the Concordia Fault. Additionally, a 3-D model of the surface of the fault was prepared. Collected data are used to realize a higher resolution (3 km) map of the investigated area. The improved resolution of this map highlights the catchment basin morphology hosting subglacial lakes, which strengthens our understanding of the role played by tectonics, glacial scouring and volcanism in the origin of the subglacial lakes in the Concordia Trench area.

RADAR SURVEY AND MAP COMPILATION

During the 2003–2004 austral summer, the PNRA geophysical team collected about 7700 km of new RES profile data in the Dome C area. As shown in Figs 2 and 3, the new survey mainly covers the area of the Concordia Trench and Concordia Lake to improve the characterization of these two subglacial features.

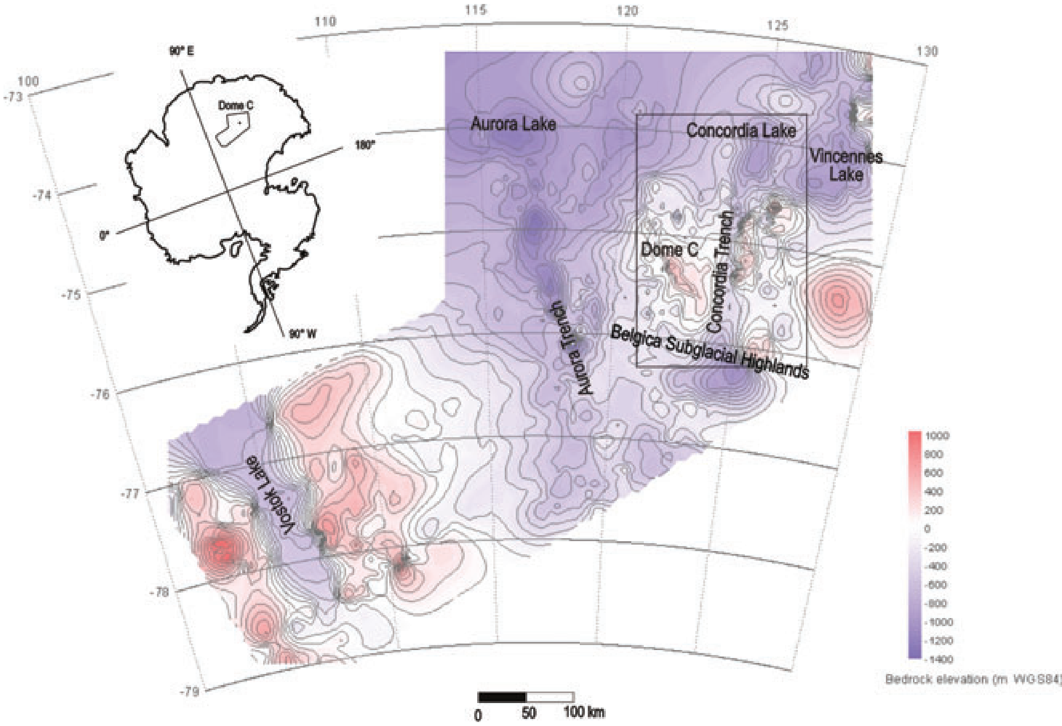

Figure 1. Location of the investigated area within the East Antarctic craton and the main physiographic units. From W to E: Vostok Lake; Aurora Trench and Lake within the Aurora Basin; Concordia Trench-Lake system and Concordia Ridge within the Belgica Subglacial Highlands; Dome C and Vincennes Lake. The inset map of Antarctica indicates the map location, and the rectangle shows the location of the investigated area.

Radar data were collected with the INGV-IT radar instrumentation, which is characterized by a high power (3.5 kW) envelope system, an operating frequency of 60 MHz, a vertical resolution of 1280 samples, a sampling frequency of 20 MHz and a variable pulse length (from 0.2 to 1 μs). The radar instrumentation has not been changed from the instrumentation used in the earlier 1999–2001 surveys, and details are given in Tabacco *et al.* (1999). These specifications provide a vertical resolution of about 2.3 m.

Reflected echoes from the bottom of the ice sheet are present in over 75 per cent of the survey, allowing the reconstruction of the subglacial morphology along nearly the entire flight track, although the strength of the reflected signal is not constant throughout the area. This variation in signal strength likely reflects differences in ice thickness (the Concordia Trench is more than 1000 m deeper than surrounding topography) and variable basal conditions beneath the ice sheet caused by the variable temperature distribution. This paper focuses on bedrock morphology.

Data filtering, analyses and ice thickness calculations were performed using the same procedures as those used in the previous campaign to enables comparisons between the different data sets. Therefore, we did not migrate the original data, and we used a constant electromagnetic velocity in ice of 168 m μs^{-1} without any firm correction.

In 2003, 1900 km of RES data in the survey area were added to the previous 4700 km mapping. It is important to note that 3000 km were surveyed in 1995 with the first INGV-IT instrumentation in a restricted area around Dome C, and the other 1700 km were surveyed during the geophysical campaign of 1999–2001.

Airborne radar data collected from 1999 onward are densely sampled along flight transect with an along track resolution of 7 m. The average distance between adjacent transect is 20 km. Most interpolation algorithms have difficulty in resolving such an uneven pattern. The map shown in Figs 2 and 3 was made using the entire set of raw RES data by applying a kriging method with an appropriate asymmetry in the selection to produce a 3 km grid along with a Gaussian five-point low-pass filter to smooth contours. The cell grid resolution of 3 km was chosen as a compromise between the along and across transect resolution, thus improving the 5 km resolution of the BEDMAP that was prepared in this region with a significant lower resolution data set. This resolution allows us to eliminate along tracks numerical artefacts and minimize fictitious features in the final map although caution should be observed in interpreting across strike structures smaller than the distance between adjacent transect (i.e. the SE sector if the map in Fig. 3). The bedrock elevation was computed by subtracting the detected ice thickness from the ice surface elevation data from Remy *et al.* (1999).

For all radar profiles, raw radar data of ice thickness were compared with the values resulting from the map. Computed differences were less than 30 m nearly everywhere. Larger differences arose near the boundaries of the map and along the steepest part of the Concordia Trench, where the interpolation method was less accurate due to the complex subglacial morphology and the asymmetry in the RES data distribution. Nevertheless, these errors did not significantly affect the map, and therefore, 100 m contour lines can be traced.

CONCORDIA TRENCH-LAKE SYSTEM: PHYSIOGRAPHIC SETTING

The Concordia Trench, the Concordia Ridge, the South Hills and the depression hosting Concordia Lake are the main bedrock physiographic features of the investigated region (Fig. 3). The new RES profiles allow us to improve their geographical and

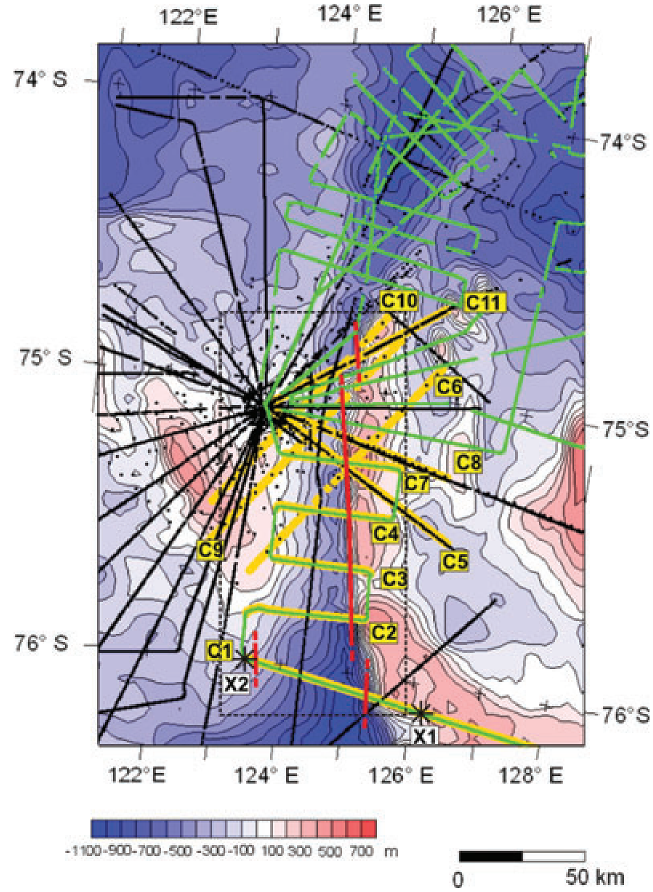

Figure 2. Traces of RES data used to produce the 3 km gridded map of the Concordia Trench-Lake system. Black dots refer to RES data collected in the 1995–2001 period (partial set). Green dots refer to the RES data collected during the 2003 PNRA campaign. Yellow larger dots refer to the RES profiles used for fault modelling. Refer to Table 1 for edge coordinates. Red lines show the trajectory of the Concordia Fault. Stars indicate the edges of the RES profile in Fig. 8 (Lake ITL-28). The rectangle shows the location of the bedrock rendering in Fig. 7.

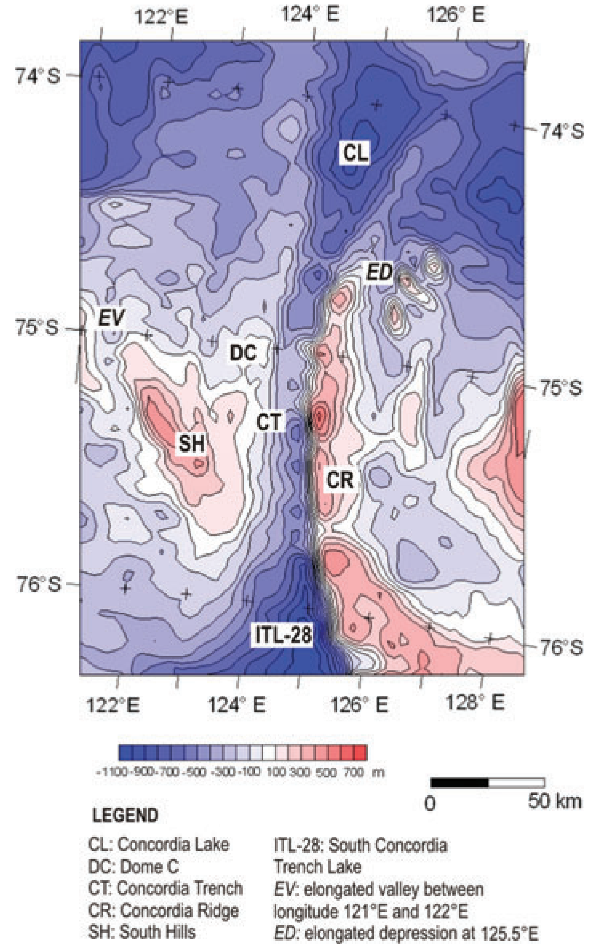

Figure 3. 3 km gridded map in polar stereographic projection (WGS 84) of the Concordia Trench-Lake system and the main physiographic features of the investigated area. CL, Concordia Lake; DC, Dome C; CT, Concordia Trench; CR, Concordia Ridge; SH, South Hills; ITL 28, South Concordia Trench Lake; EV, elongated valley between longitude 121°E and 122°E; ED, elongated depression at 125.5°E.

geomorphological characterization. A series of smaller, N–S trending subglacial troughs cutting through the Belgica Subglacial Highlands are also revealed.

The Concordia Trench (124.5°E, 74.6°–76°S) is a trough more than 200 km long and about 20 km wide. The trough has a steep across-strike profile that contrasts with a flatter along-strike profile. New RES data confirm the across-strike asymmetry that characterizes this regional subglacial trough, with a steeper eastern slope and a gentler western slope characterized by a convex shape (see Fig. 3).

The trough is characterized by a saddle in the subglacial topography (124.3°E, 75.2°S), which is visible in the longitudinal profiles, and which gives the depression two opposing 'drainage' directions. This saddle reaches an elevation of about −200 m. On the northern edge of the saddle, the Concordia Trench strike gently rotates 13° in a clockwise sense.

A smaller elongated valley (EV in Fig. 3) is located between 121° and 122°E, and is about 50 km long and 10 km wide. This depression is also characterized by a strong dip asymmetry with a steeper eastern slope and a gentler western slope, along with a variable dip and smoothly rounded profile. The two valley shoulders rise up to the same elevation (about 100 m asl). The northern projection of this valley is not well defined due to the lack of radar data (Fig. 2). The southern termination follows the general southwestward topographic deepening of the South Hills.

A third elongated subglacial depression, N–S trending and about 15 km wide, is located at 125.5°E (ED in Fig. 3). The valley floor is characterized by a general northward widening and deepening down to −600 m.

The map in Fig. 3 shows the presence of the saddle at about 75.2°S, 126°E rising up to an elevation of 0 m. The lower spatial density of the collected RES data in this part of the investigated area prevents a more detailed reconstruction of the morphology as well as the definition of the southward projection of the valley.

The South Hills are a NW–SE trending relief system bounding the Concordia Trench on the west. They reach a maximum elevation of 400 m asl, and are characterized by smooth topography. At the southeastern terminus, there is a 400 km^2 plateau at a mean elevation of 100 m asl Another flat area, the Dome C plateau (with an areal extent of about 2500 km^2), is located NE of the South Hills at an elevation of about 0 m.

The Concordia Ridge is the N–S trending relief system bounding the Concordia Trench on the east. It is more than 100 km long and about 20–30 km wide. The ridge reaches its maximum height of

600 m a.s.l. at about 75.3°S, 125.5°E. The highest topographic contrast of 1300 m between the trench and the top of the ridge is found in the southernmost portion of the ridge.

A depression with an extension of about 1500 km^2, slightly elongated in the NE–SW direction, is located at the northern termination of the Concordia Trench. This basin hosts one of the largest Antarctic subglacial lakes, the Concordia Lake (Tikku *et al.* 2005). It is characterized by relatively smooth slopes all around, and reaches a maximum depth of about −900 m. A water depth of about 150 m has been estimated based on the lake shore slopes (Tabacco *et al.* 2006). Extension and depth make Concordia Lake a reliable candidate for future detailed studies of subglacial lakes, including drilling experiments.

TECTONIC ORIGIN OF THE CONCORDIA TRENCH: THE CONCORDIA FAULT

Tabacco *et al.* (2006) proposed a tectonic origin for the Aurora and Concordia Trenches as the result of crustal normal faulting. This work uses tracks from the oldest data set (not represented in Fig. 2, Forieri *et al.* 2004) and the improved raw data set of RES profiles on the Concordia Trench-Lake region for an improved characterization of the along- and across-strike geometry of the Concordia Fault. Tectonic numerical modelling of the bedrock topography is conducted to reconstruct the 3-D geometry of the fault. The modelling consists of replicating along the RES profiles (i.e. with a resolution of 7 m) the development of the present day bedrock morphology by the hangingwall sliding of a normal, listric fault following Tabacco *et al.* (2006). The modelled fault produces the observed asymmetry in the topographic expression of its hangingwall region. The length of the trench implies a horizontal length of more than 100 km for the Concordia Fault, which implies that the vertical dimension must be on the order of tens of kilometres to be compatible with a displacement of 1–2 km (Walsh & Watterson 1988). These dimensions confirm that this fault has crustal significance.

Methodology: tectonic numerical modelling

The numerical modelling was performed following the methodology used by Tabacco *et al.* (2006) in the same geodynamic context. This technique includes the simulation of the hangingwall kinematic evolution during its sliding along a fixed fault section by the FORCtre software, a Hybrid Cellular Automata (HCA)-derived numerical algorithm particularly suited to replicate the evolution of complex, dip-slip geological structures (Salvini *et al.* 2001; Salvini & Storti 2004).

The crust is modelled as a series of 2-D sections of layered material with a rigidity comparable to that of the upper crust in an intracratonic setting (Poisson's ratio: 0.25; Young's modulus: 7×10^{10} Pa, e.g. Turcotte & Schubert 2002), a total thickness of 34 km (according to Studinger *et al.* 2003 and Morelli & Danesi 2004) and a length ranging from 46 to 130 km. The initial horizontal dimension of the cell was 1336 m, and the model resolution was roughly 100 m.

A total of 11 georeferenced radar tracks were selected and projected along an across-fault strike trajectory. This operation allowed us to model the evolution of the morphology along sections where all cell movements are constrained (i.e. no cell flow going in or out of the section during fault evolution) and to model the true fault and morphology dips.

The same fault setting was applied to all sections by slightly tuning fault geometry and displacement to minimize the final morphology misfit. The tuning neglects minor topographic variations with wavelengths shorter than 5 km that are considered to result from local scale factors not affecting the crustal structural setting of the investigated area at the regional scale. Careful tuning of fault geometry includes the comparison of each model section with the adjacent sections to better constrain the along-strike fault geometry and displacement. Results from this comparison were then used to improve the fit of the adjacent sections in an iterative process. This process was repeated for all the analysed sections, using a trial-and-error forward modelling approach, until a satisfactory approximation (about 100 m) was reached. The modelled profiles were then re-projected along their original strike, and eventually the 2-D georeferenced fault traces were gridded using the kriking method (Cressie 1990). A N–S trending asymmetric interpolation was used according to the trench (and fault) strike to reproduce the overall 3-D geometry of the Concordia fault. The resulting 3-D fault grid is characterized by an 1870 m grid cell.

3-D geometry of the Concordia Fault

The Concordia Fault was modelled using sections trending between WNW–ESE and NE–SW. The locations of the modelled RES profiles are indicated in Fig. 2, and the length and vertex coordinates of each section are reported in Table 1. All the analysed profiles show the previously described asymmetry in the trench slopes, with the eastern slope steeper than the western slope (see Fig. 4). This asymmetry is interpreted as the result of a crustal normal fault with a westward dip that decreases with depth. The location and the initial dip of the fault trace are inferred from the position of the steeper, eastern slope in the bedrock morphology, which is clearly

Table 1. Length and vertex coordinates of the modelled sections.

Profile	Length (m)	Vertex 1 longitude °E	Vertex 1 latitude °S	Vertex 2 longitude °E	Vertex 2 latitude °S
C1	127 915.39	123.47415	−76.00237	128.21233	−76.17647
C2	48 977.1	123.39931	−75.84373	125.13776	−75.81339
C3	39 333.33	123.73115	−75.6372	125.1368	−75.64782
C4	46 409.09	123.67191	−75.45912	125.30838	−75.44622
C5	91 311.97536	123.35732	−75.09776	126.15871	−75.50191
C6	111 781.5202	123.37909	−75.68816	125.74377	−74.887
C7	48 520	123.70434	−75.2638	125.36614	−75.27429
C8	76 026.65937	123.43011	−75.10419	126.01248	−75.27022
C9	110 259.6082	122.76893	−75.59084	125.1217	−74.80705
C10	102 317.2855	122.73606	−75.45647	124.91008	−74.7303
C11	81 277.99806	123.38015	−75.09602	125.67579	−74.68167

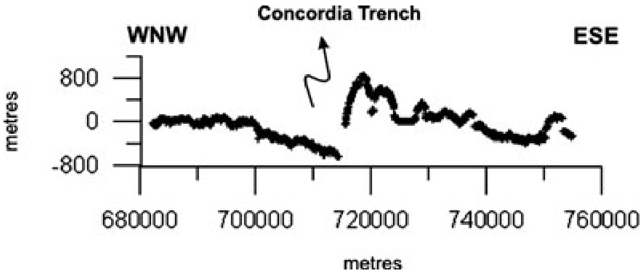

Figure 4. Across-strike profile of the Concordia Trench (Section C5) showing the characteristic steeper ESE side and the gentler WNW slope with a convex shape. Vertical exaggeration 10 : 1.

visible in the RES profiles (see Fig. 5). Where the regional scale bedrock physiography is more articulated, agreement between the model and the bedrock is achieved by introducing secondary faults. This is the case for the C1 section where an antithetic, secondary fault is necessary to replicate the surface of the hangingwall block sliding on the main west-dipping, listric fault. The upper sections of each profile of Fig. 5 shows the match between the bedrock morphology and the modelled fault profile (with a vertical exaggeration of 10:1) for each section. The full fault trajectory is shown in the lower sections, where the modelled sections are presented without vertical exaggeration.

The bedrock morphology of the Concordia Trench is modelled as the result of the activity of a normal fault with a constant dip of about 60° toward the west in the first 20 km of the crust. Below 20 km, the modelled fault surface rotates slowly and its dip falls to 50° at a depth of about 28 km. The deepest portion of the crustal fault has a constant dip of about 45°.

The computed normal throws for the agreement of the models with the observed morphology are shown in Table 2. The range has a maximum of 1300 m in the southernmost portion of the Concordia Fault and reduces linearly to about 500 m in the northern part (Fig. 6). The maximum displacement of 1300 m corresponds to the largest topographic contrast observed between the Concordia Ridge and the trench valley floor in the southern sector. The computed along-strike fault displacement indicates that either the Concordia fault extends southwards, where no RES profiles are available, or it is truncated by the presence of a transverse fault(s).

Fig. 7 illustrates the 3-D geometry of the Concordia fault. The black dots represent the 2-D georeferenced fault trace, determined by the bedrock modelling, that were used for the fault gridding. The upper part of the figure displays the corresponding bedrock morphology of the Concordia Trench with a vertical exaggeration of 10:1.

The Concordia fault is a regional, N–S trending normal fault cutting through the 34 km thick East Antarctic craton crust. It is characterized by a length of at least 100 km and an initial dip of about 60° to the West that progressively decreases to about 45° in the deepest part of the crust. At both edges the fault seems to lose its continuity, as evidenced by visible footwall-ward offsets (Fig. 2). These offsets may relate to the presence of tear faulting between profiles 1–2 and 9–11. On the other hand, these eastward offsets may partly relate to an intensification of post-faulting erosional processes. Such erosional processes would have widened the valley, thus producing an apparent eastward migration of the east trough slope, used here as a reference to locate the fault–bedrock intersection.

Concordia Trench development and age constraints

A saddle in the mid-portion characterizes the valley floor of the Concordia Trench. This saddle provides evidence that this depression formed from the joining of two symmetrical valleys that developed along a pre-existing or contemporaneous morphotectonic lineament of the bedrock. Such saddles are characteristic features of tectonically controlled valleys and are observed at various scales on Earth, from the Val Roveto in the Appennines (Italy)—a greater than 70 km elongated valley with opposed drainage that developed along a major fault (Montone & Salvini 1991)—to the Rhine graben in Europe (Weissel & Karner 1989). In particular, the asymmetry of the Rhine graben in the across-valley profiles closely resembles the asymmetry observed in RES profiles across the central zone of the Concordia Trench. In both troughs, the steeper side of the valley is characterized by the presence of topographic relief that may relate to the flexural uplift of the structure produced by the unloading (Weissel & Karner 1989).

The modelling is constrained to replicate the evolution of the hangingwall sector kinematics relative to the displacement on the fault footwall side. In this context, the flexural uplift induced by the development of the tectonic valley can be evaluated on the order of few tens to hundreds of metres and distributed along the entire profiles, depending on the considered elastic equivalent thickness of the lithosphere (Turcotte & Schubert 2002). It has to be stressed that the local, relative uplift effect is very reduced and fully included in the modelling (even if not identified) since this is done under volume preservation conditions (i.e. area preservation in the sections) without affecting the fault throw.

The evolution of the landscape in the Concordia Trench area began with the presence of a partly peneplanated mountain range, the Belgica Subglacial Highlands. The displacement induced by the activity of a crustal normal fault is responsible for the formation of an elongated, tectonic valley with a strike transverse to the pre-existing mountain range. The evolution of the two drainage basins, governed by the typical regressive erosion of their network of channels, results in the preservation of the original fluvial divide (or the new formation of an interfluve if the original landscape was characterized by a planar surface morphology). In an alternative (and younger) scenario, the erosional processes might have been initiated by a wet-based glacial network, or the trench may even have formed beneath a wet-based ice cap. In this scenario, the asymmetry of the slopes would have been enhanced by variable erosional rates resulting from variations in ice thickness. This latest erosional process may have occurred at the onset of ice cap formation, characterized by wet basal conditions, or even more recently (Remy & Tabacco 2000; Wingham *et al.* 2006).

According to the little information available on the bedrock geology of the region, the Belgica Highlands partly predate the development of the Concordia Trench/Fault and might represent a relict of harder rock structures on a long-lasting peneplanated continental craton. Topographic highs that are relicts of the pre-Palaeozoic age have been observed in several locations across the planet. If this interpretation is valid for topographic highs, it is hardly applicable to depressions. Depressions do not have the same strength-to-landscape evolution as higher topography, since sedimentary processes would completely fill them in a relatively short period of time. This provides a constraint on the age of the Concordia Fault activity relative to that of the valley formation. An example of an old, intracratonic depression is Lake Baikal (42 Ma), preserved by long-lasting and still active tectonics (Tapponnier & Molnar 1979; ten Brink & Taylor 2002). Based on these considerations, we propose a

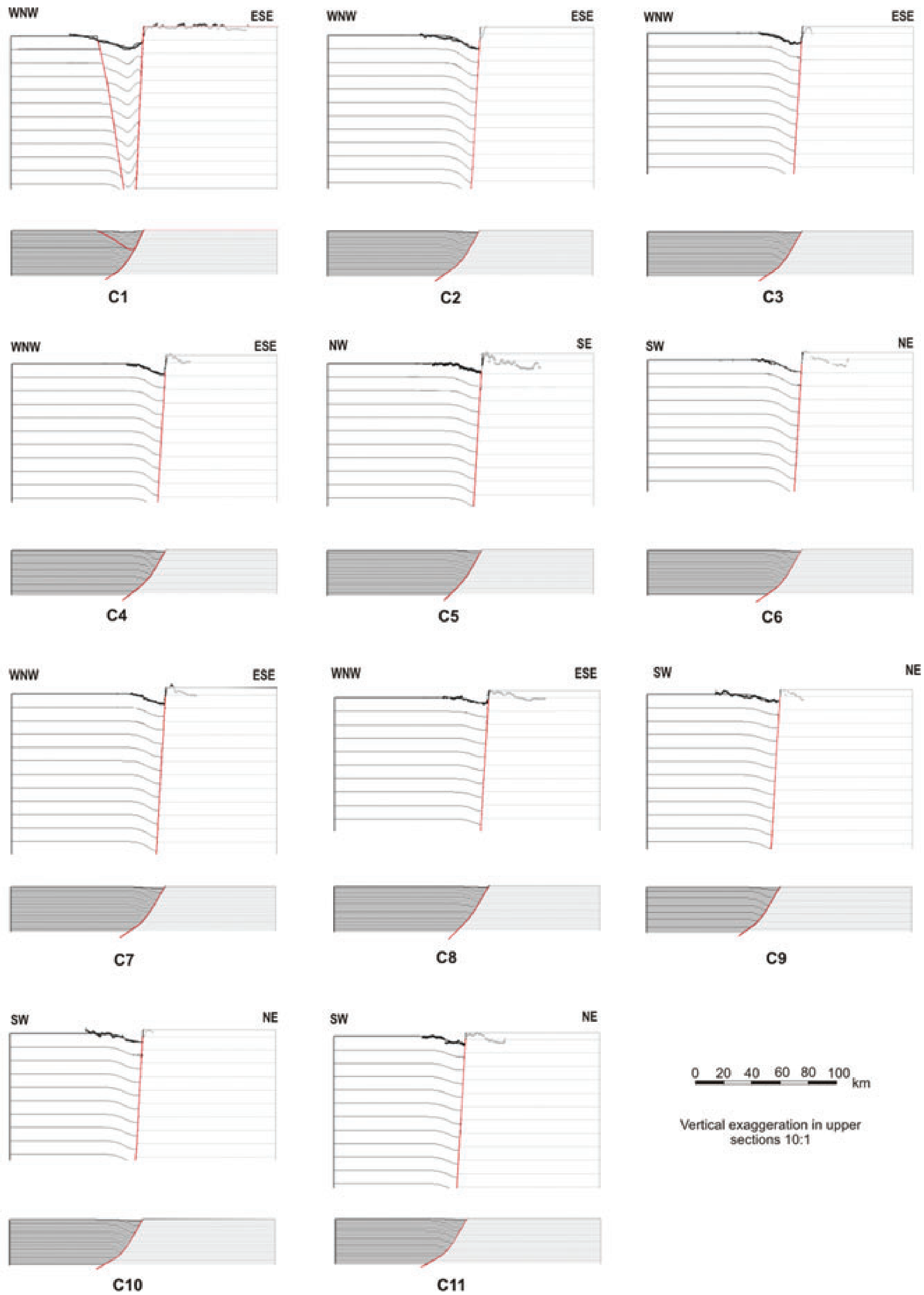

Figure 5. Comparison between the 11 RES profiles of the Concordia Trench and the HCA fault models with a vertical exaggeration of 10 : 1 (upper sections); complete modelled sections (no vertical exaggeration to visualize the full fault trajectory (lower sections). The total thickness of the modelled section is 34 km. The modelling was limited to the hangingwall evolution. See the text for details.

constraint for the age of the faulting event responsible for the Concordia Trench formation. The formation of present-day subglacial landscapes in East Antarctica has been ascribed to the tectonics that affected this craton during the pre-Palaeozoic fragmentation of the Gondwanaland Precambrian shield (Dalziel 2006; Fitzsimonson 2000). However, the absence of a flat floor in the depression of the Concordia Trench provides evidence that the most recent morphological event (apart from the formation of lakes at both edges) was not a sedimentary filling episode. The asymmetrical nature of the valley landscape is clearly evident and has not been significantly obliterated by successive erosional episodes or by the formation of secondary river/glacial valleys, which has included periods of wet

Table 2. Computed Concordia fault throws at each modelled section.

Profile	Throw (m)
C1	1300
C2	1100
C3	900
C4	1000
C5	1050
C6	1000
C7	800
C8	750
C9	600
C10	600
C11	500

ice-bedrock contact. This lack of further erosion is to be expected in the evolution of the bedrock landscape after the dry-based ice cap settled (about 34 Ma, De Conto & Pollard 2003). Therefore, we propose a potential age range for this valley development that begins immediately prior to the ice cap formation and continues to more recent times while the valley was beneath the dry ice cap-bedrock contact. In the oldest age case, the shape of the valley would be the result of the interaction between fault and fluvial erosional processes that occurred prior to the development of a glacial environment. In the youngest age case, the valley would have formed during periods of wet contact with glaciers.

Based on the present-day valley morphology, we can exclude the existence of significant fluvial erosional activity between the fault emplacement and the ice cap formation. This constrains the fault activity to at least Cenozoic time, confirming the recently proposed ages for faulting in the Dome C region (Tabacco *et al.* 2006).

CONCORDIA LAKE AND THE ORIGIN OF SUBGLACIAL LAKES

The morphology of the topographic depressions catching lakes on the Earth's surface results from the main geological processes shaping the landscapes (Selby 1985). The main basin-forming processes include tectonic and volcanic activity, glacial scouring and meteoritic impacts (Cohen 2003). The deepest and oldest lakes on Earth are tectonically controlled (Meybeck 1995). This is the case for Lake Tanganika and Lake Malawi in the East African rift system, and for the already-cited Lake Baikal in the intracontinental left-lateral shear zone in the northeastern part of the Eurasian plate (Storti *et al.* 2003). These lakes occupy fault-controlled, elongated depressions characterized by increasing bathymetry (and sediment thickness) in the direction of the bounding, listric master fault, responsible for their half-graben geometry.

Across-strike profiles of these lakes show that they are asymmetric, with a steep, fault-controlled slope that faces a gentle, convex one. The valley shoulders of the Baikal and Malawi lakes reach similar elevations (about 1600 and 1700 m, respectively). These morpho-tectonic features were used to classify and identify the trench lakes in the Vostok–Dome C region (Tabacco *et al.* 2006).

The new RES data reveal the existence of a subglacial lake called ITL-28 (according to the Italian lake inventory) in the southern part of the Concordia Trench (76.1°S, 125°E) (Forieri *et al.* 2008).

Evidence for this lake comes from planar topography, the strength of the RES basal echo (10–20 dB stronger than those of the surrounding areas) and sharp edges similar to the margins of a catchment basin (Siegert 2000). This lake may well correspond to the previously identified SPRI-22 or SPRI-42–SPRI-43 of the Siegert inventory (Siegert *et al.* 2005).

This lake, clearly evident in the RES profiles with an apparent width of 7 km, is associated with an elongated, flat ice surface anomaly (refer to Fig. 1 in Tabacco *et al.* 2006), roughly N–S oriented, that indicates the possible elongated geometry of the lake itself. It is located in the topographic depression between the hangingwall and the footwall of the Concordia listric normal fault. This location accounts for the asymmetry of the lake depression, which is characterized by a steeper eastern slope and a gently rounded western one (see Fig. 8). The described morphological features allow the lake to be classified as a trench lake.

The straight, elongated shapes associated with the steep profiles of the trench lakes, such as Lake Vostok (Studinger *et al.* 2003) and the lake ITL-28, strongly resemble the morphology of tectonically controlled lakes on Earth. These considerations further support a tectonic origin for the trench lakes. A tectonic origin has also recently been proposed by Bell *et al.* (2006) for the Sovetskaya Lake and the 90° Lake. The detailed morphology of these last subglacial lakes is not well known due to the lack of available geophysical data. Satellite images have revealed their rectilinear and elongated shapes, similar to Lake Vostok, Lake Baikal and Lake Malawi. For this reason we expect them to be trench lakes, thus extending further west (to Ridge B) the subglacial lake classification proposed for the district between Lake Vostok and Dome C.

Concordia Lake is a typical basin lake, and occupies the bottom of a large depression characterized by smooth, gently dipping slopes all around. It is located at the northern termination of the Concordia Trench, in the deepest zone of the bedrock. The ice cover is over 4 km thick, thus making the expected pressure and temperature (P–T) conditions at the base of the ice compatible with the presence of accumulated water. Tikku *et al.* (2005) documented melting and freezing at the base of the ice atop Concordia Lake. It is possible that Concordia Lake may be fed by a N–S trending hydrological subglacial network, as predicted by Remy & Tabacco (2000) and Wingham *et al.* (2006). Moreover, the two opposed drainage

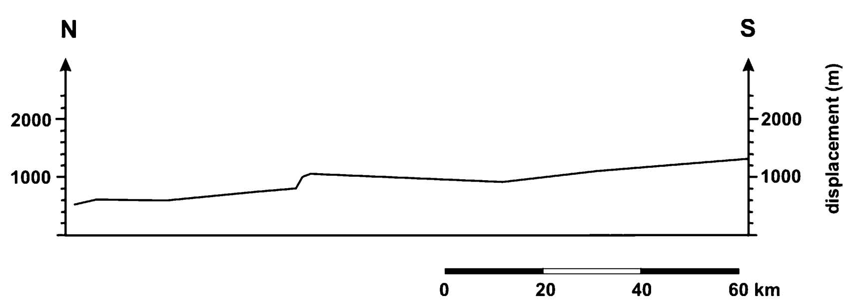

Figure 6. Along-strike displacement profile of the Concordia Fault. True displacement varies from 500 m in the north to 1300 m at the southern edge. Refer to Table 2 for computed values in each profile.

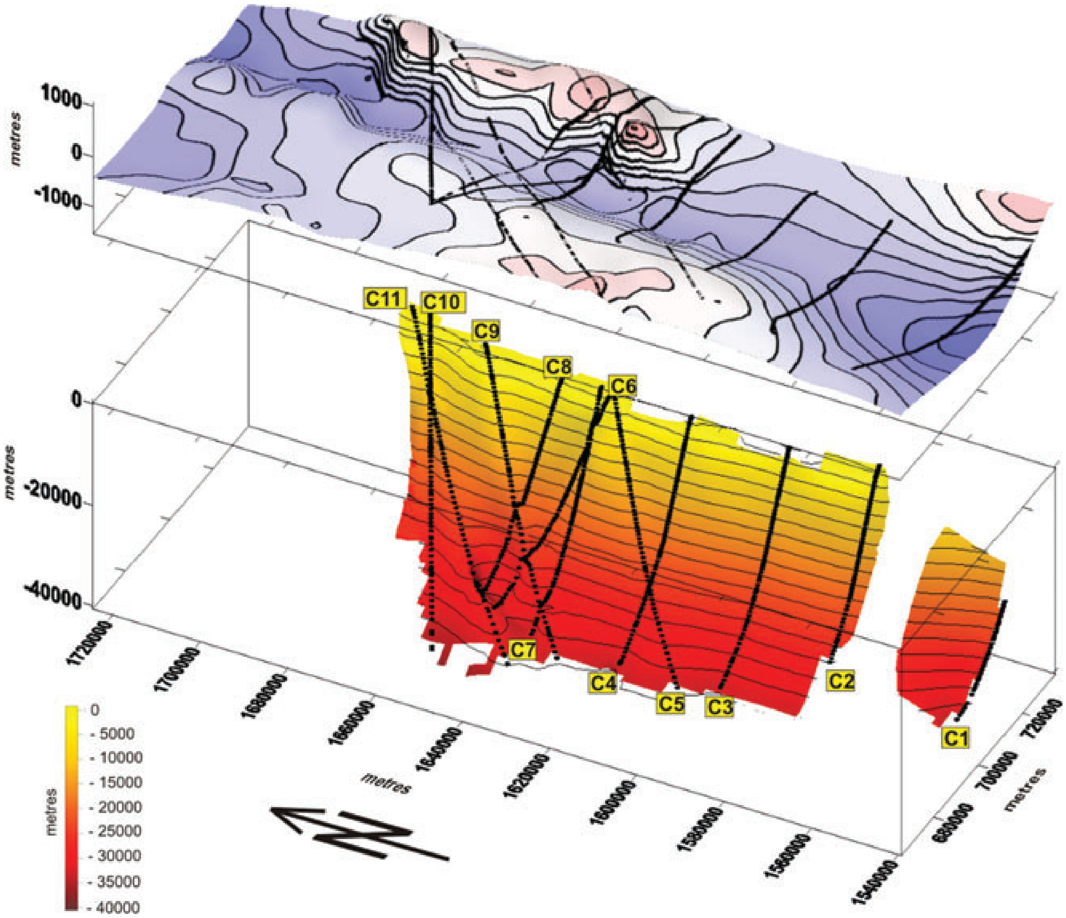

Figure 7. 3-D visualization of the Concordia Fault surface and the trace of the georeferenced, modelled fault profiles (black dots). The upper part of the figure shows the Concordia Trench bedrock morphology with a vertical exaggeration of 10 : 1. The small black crosses on it indicate the 11 RES profiles used for the bedrock numerical modelling.

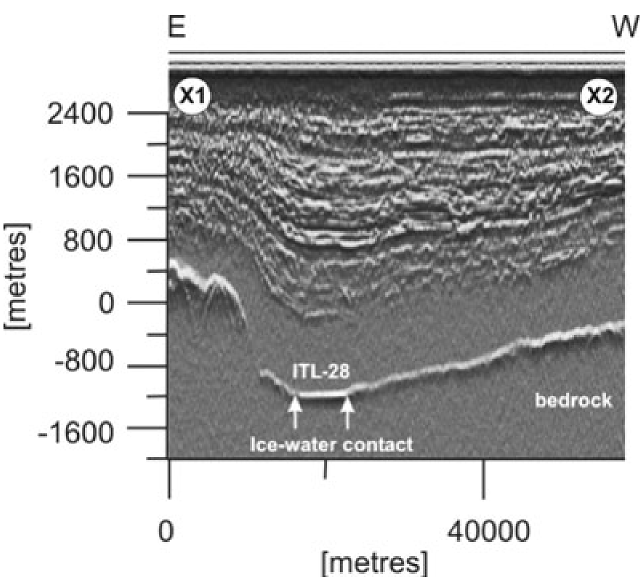

Figure 8. Subset of RES profile C1 showing the presence of Lake ITL-28 and its asymmetric depression lying between the hangingwall (right-hand panel) and the footwall (left-hand panel) of the Concordia listric normal fault. See Fig. 2 for location.

directions of the Concordia Trench are compatible with the existence of two subglacial lakes at both trench sides.

The morphological setting of Concordia Lake resembles the landscape of over-excavated glacial depressions, such as Lake Michigan and Lake Ontario (Dalziel 1998), which occupy depressions excavated by the Laurentide Ice Sheet during the late Cenozoic glaciation of North America. Concordia Lake is comparable in size to several northern hemisphere lakes with origins in glacial scour basins (e.g. Geneva Lake). The NNE–SSW elongation of Concordia Lake is aligned with the present ice flow from Dome C. Again, the Concordia Trench may exert a structural control on the ice flow pattern from Dome C, thus enhancing the Concordia Lake elongation.

The above considerations may apply to many basin lakes in the Vostok–Dome C district where the minor elongation in the lake basin morphology relates to the lake locations at the termination of a fault-controlled trough (e.g. Aurora Lake at the northern projection of the Aurora Trench, Tabacco *et al.* 2006).

Homogeneous steep slopes on all sides characterize relief lake physiography. These lakes are located in subglacial mountain zones at relatively high bedrock elevation and have a thinner ice cap cover than the basin and trench lakes.

We thus hypothesize that the existing *P–T* conditions necessary for compatibility with water rely on the presence of a higher geothermal flux rate. Relatively steep slopes and smaller dimensions are the main characteristics of relief lakes. In the Dome C region, relief lakes are concentrated in the Belgica Highlands. They develop in a bedrock landscape that shows similarities to recent volcanic regions. Their morphology strongly resembles the steep slopes of volcanic lakes, like Crater Lake in Oregon, USA, or Vico Lake in Italy. The extension of Relief Lake is comparable to the size of other volcanic lakes on Earth (tens of square kilometres).

CONCLUSIONS

Results from the PNRA Geophysical campaign of 2003 in the Concordia Trench-Lake system address a series of issues concerning the age and geological development of the region.

The previous description of the bed morphology has been improved, allowing geographical and geomorphological characterization not only of Concordia Lake but also of other previously identified lakes in the Dome C district. The new 3 km resolution map allows us to highlight the morphology of the Concordia Trench. This trench is characterized by two opposite drainage directions compatible with the existence of subglacial lakes located asymmetrically at both trough terminations.

Concordia Lake is located at the northern termination of the Concordia Trench, a tectonically controlled subglacial trough. Moreover, the new RES data revealed the existence of a second subglacial lake at the southern end of the Concordia Trench (ITL-28). The physiography and geological setting enabled us to classify it as a trench lake, thus bringing the total number of known trench lakes to six (including the Vostok, 90° and Sovetskaya Lakes).

The new data set provides better constraints on the along- and across-strike geometry of the Concordia Fault, confirming its importance at the regional scale. Modelling techniques based on the HCA numerical algorithm allowed us to reconstruct the 3-D geometry of this tectonic bedrock feature and to hypothesize a Cenozoic age for the subglacial trough/fault.

The newly identified N–S array of subglacial valleys cutting across the Belgica Subglacial Highlands may result from a network of N–S trending faults, the major one being the Concordia Fault.

Finally, morphological considerations discovered here strengthen the evidence for a tectonic origin for trench lakes, a glacial scour origin for the basin lakes and a volcanic origin for the relief lakes.

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