Journal of Volcanology and Geothermal Research 201 (2011) 357–363

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

Deciphering lake and maar geometries from seismic refraction and reflection surveys in Laguna Potrok Aike (southern Patagonia, Argentina)

A.C. Gebhardt [a,*], M. De Batist [b], F. Niessen [a], F.S. Anselmetti [c], D. Ariztegui [d], T. Haberzettl [e], C. Kopsch [f], C. Ohlendorf [g], B. Zolitschka [g]

[a] *Alfred Wegener Institute for Polar and Marine Research, 27568 Bremerhaven, Germany*
[b] *Renard Centre of Marine Geology, University of Gent, 9000 Gent, Belgium*
[c] *Eawag, Swiss Federal Institute of Aquatic Science and Technology, Department of Surface Waters, 8600 Dübendorf, Switzerland*
[d] *Section of Earth & Environmental Sciences, University of Geneva, 1205 Geneva, Switzerland*
[e] *Institute of Geography, Friedrich-Schiller-University Jena, 07743 Jena, Germany*
[f] *Alfred Wegener Institute for Polar and Marine Research, 14473 Potsdam, Germany*
[g] *Institute of Geography, University of Bremen, 28359 Bremen, Germany*

ARTICLE INFO

Article history:
Received 15 August 2010
Accepted 28 December 2010
Available online 8 January 2011

Keywords:
explosive volcanism
maars
sedimentary basin processes
South America
PASADO project

ABSTRACT

Laguna Potrok Aike is a bowl-shaped maar lake in southern Patagonia, Argentina, with a present mean diameter of ~3.5 km and a maximum water depth of ~100 m. Seismic surveys were carried out between 2003 and 2005 in order to get a deeper knowledge on the lake sediments and the deeper basin geometries. A raytracing model of the Laguna Potrok Aike basin was calculated based on refraction data while sparker data were additionally used to identify the crater-wall discordance and thus the upper outer shape of the maar structure. The combined data sets show a rather steep funnel-shaped structure embedded in the surrounding Santa Cruz Formation that resembles other well-known maar structures. The infill consists of up to 370 m lacustrine sediments underlain by probably volcanoclastic sediments of unknown thickness. The lacustrine sediments show a subdivision into two sub-units: (a) the upper with seismic velocities between 1500 and 1800 m s^{-1}, interpreted as unconsolidated muds, and (b) the lower with higher seismic velocities of up to 2350 m s^{-1}, interpreted as lacustrine sediments intercalated with mass transport deposits of different lithology and/or coarser-grained sediments. The postulated volcanoclastic layer has acoustic velocities of >2400 m s^{-1}. The lake sediments were recently drilled within the PASADO project in the framework of the International Continental Scientific Drilling Program (ICDP). Cores penetrated through lacustrine unconsolidated sediments down to a depth of ~100 m below lake floor. This minimal thickness for the unconsolidated and low-velocity lithologies is in good agreement with our raytracing model.

1. Introduction

Southern South America is the only present-day landmass between 38°S and Antarctica. Investigation of its terrestrial environmental archives thus offers the unique opportunity to link climate archives of northern South America via Patagonia and the Antarctic Peninsula with those of Antarctica.

Laguna Potrok Aike, a hydrologically closed maar lake in southernmost Patagonia, is presently located at the boundary between the Southern Hemisphere Westerlies (SHW) and the Antarctic Polar Front, just north of the Strait of Magellan. The lake is extremely sensitive to hydrological and closely related climatological variations as reflected by subaerial and subaquatic terraces formed by lake level fluctuations (Haberzettl et al., 2005, 2008; Anselmetti et al., 2009). The lake has therefore been identified as a target of deep drilling within the International Continental Scientific Drilling Program (ICDP), and was finally drilled in austral spring 2008 within the "Potrok Aike Maar Lake Sediment Archive Drilling Project" (PASADO; Zolitschka et al., 2009a). Seven drill cores of two sites encountered lacustrine sediments to ~100 m below lake floor and retrieved an important record of the regional climate history for the past glacial stage. Core opening of the PASADO cores took place during summer/autumn 2009 and has shown that roughly 50% of the material is redeposited (Zolitschka et al., 2009b). Knowledge on the basin structure and geometries is in any case a prerequisite to understand the sedimentary record and subsequently to interpret the paleoclimate record that will derive from the PASADO cores. This knowledge should help to distinguish between specific sedimentation patterns related to this lake and background sedimentation related to regional environmental change.

On the basis of the lake's morphology, the presence of a phreatomagmatic tephra found on the leeward side of the lake and

---

* Corresponding author. Alfred Wegener Institute for Polar and Marine Research, Am Alten Hafen 26, 27568 Bremerhaven, Germany. Tel.: +49 471 48311946; fax: +49 471 48311926.
E-mail address: catalina.gebhardt@awi.de (A.C. Gebhardt).

0377-0273/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.jvolgeores.2010.12.019

due to its location within the Pali Aike Volcanic Field, the origin of Laguna Potrok Aike is thought to be related to maar eruptions (Zolitschka et al., 2006). Maar craters originate from the contact of rising magma with groundwater resulting in explosive, phreatomagmatic explosions. During these explosions, fragmented magma and bedrock is ejected from an explosion chamber to the surface. Multiphase explosions, back-fall breccia of ejected material, subsidence above the collapsed explosion chamber and dyke intrusions create the funnel-shaped part of a maar-diatreme volcano. These explosions cause a depression in the local groundwater level, and thus subsequent explosions take place at successively greater depths. Recent maars were shown to be formed by several successively deeper explosions in a time span of only a few days (small maars) to months (with up to several hundred explosions; large maars) (Lorenz, 1986; Lorenz, 2003, and references therein). Collapse of the surrounding bedrock fills the root zone with breccias after each single explosion. The collapse structure propagates to the surface and results in the initial maar crater. Lower layers of the collapse breccia are chaotic, unbedded, and characterized by a higher content of reworked material coming from surrounding bedrock, while upper layers are well-stratified and dominated by phreatomagmatic tephra beds (Lorenz, 2003). A tephra ring forms outside the crater during the phreatomagmatic activity of the maar-diatreme volcano and contains tephras related to the subsequent explosions in stratigraphic order. Once eruptions end, a lake is formed inside the crater up to the local groundwater level, and lacustrine sedimentation starts. Many of the older maars can be completely filled by post-eruptive sediments of any kind and have changed into dry maars, e.g., in the German Eifel region (e.g., Schaber and Sirocko, 2005).

Four extensive seismic surveys carried out from 2003 to 2005 unravel the deeper structure and geometries of the lake basin and confirm its presumed origin. This study summarizes the deeper structural information resulting from two seismic surveys in 2004 and 2005.

2. General settings of the investigated area

Laguna Potrok Aike is situated at 110 m a.s.l. in the Pliocene to late Quaternary Pali Aike Volcanic Field (Santa Cruz, southern Patagonia, Argentina) at about 52°S and 70°W, some 80 km north of the Strait of Magellan and about 90 km west of the city of Río Gallegos (Fig. 1a). The lake has a diameter of about 3.5 km. It is almost circular and bowl-shaped with a 100 m deep, flat plain in its central part (Fig. 1b). To date, lake level fluctuates interannually by at least 1 m. All measurements relative to the present lake level are therefore given with respect to the 2003 AD lake level. This closed lake basin contains a sub-saline water body and has only episodic inflows with discharge restricted to major snowmelt events with the most important inlet situated on the western shore.

Only two volcanic structures in the Pali Aike Volcanic Field contain permanent lakes, Laguna Potrok Aike and Laguna Azul (Haberzettl et al., 2005; Mayr et al., 2005; Zolitschka et al., 2006). Laguna Potrok Aike is the larger and deeper of these two lakes and located in the oldest, western part of the Pali Aike Volcanic Field which is a northwest–southeast-striking tectonovolcanic belt with a length of more than 150 km and a width of ~50 km. This backarc volcanic area is located in the Magellan Basin about 300 km east of the active Andean volcanic arc (Mazzarini and D'Orazio, 2003). The volcanism is characterized by plateau-like lava flows, scoria cones, and approximately 100 maars (500 to 4000 m in diameter, Zolitschka et al., 2006) of which all except of 2 are at least occasionally dry, dating from 0.01 Ma closer to the Atlantic Ocean to 3.8 Ma in its western part (Corbella et al., 2000; Corbella, 2002). Based on an Ar/Ar age determination, a phreatomagmatic tephra quite likely associated with the Laguna Potrok Aike eruption was formed around 770 ka (Zolitschka et al., 2006). The bedrock of the Pali Aike Volcanic Field consists of Oligocene marine sandstones and shales (Patagonia Formation) overlain by up to 1 km thick Miocene molasse-type fluvial sediments (Santa Cruz Formation) and Plio- to Pleistocene fluvioglacial sediments of the so-called Patagonian Plains related to the extended glacier advances that occurred between 3.5 and 1.0 Ma ago (Zolitschka et al., 2006).

3. Data acquisition and processing

Four seismic campaigns were carried out on the lake as site surveys in Laguna Potrok Aike prior to deep drilling in order to (a) gain a deeper insight into the sedimentary architecture of the lacustrine infill and (b) reveal the geometries and, subsequently, confirm the maar origin of the lake basin.

The first seismic survey was carried out in 2003 by the ETH Zurich (Switzerland) using a 3.5 kHz pinger system. This was followed by a second survey by the University of Geneva (Switzerland) in 2004 with two one cubic-inch airguns to get deeper sediment penetration (Anselmetti et al., 2009). Although both surveys imaged only the

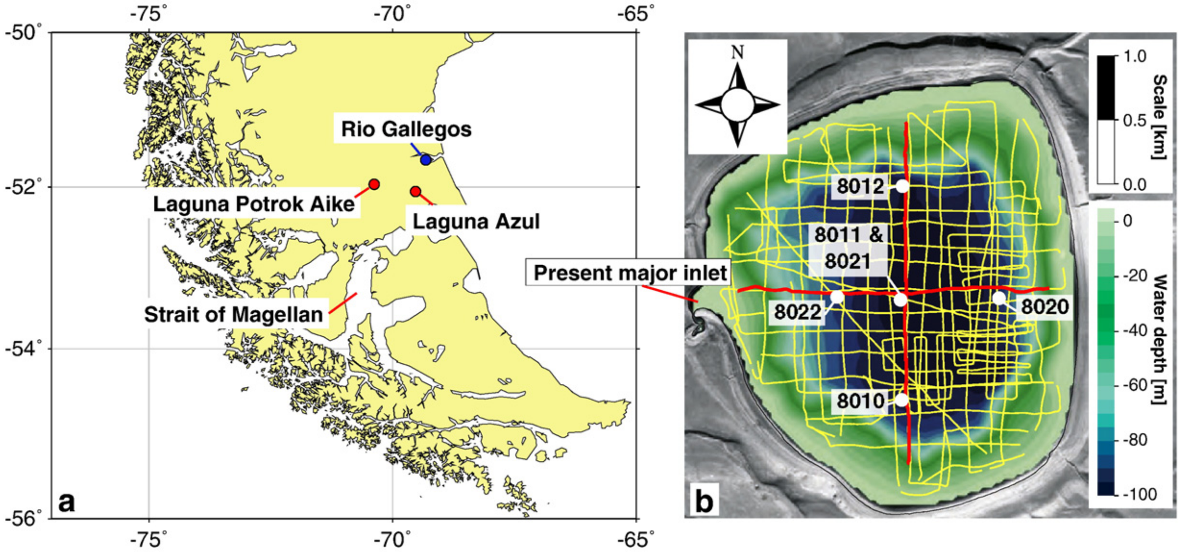

Fig. 1. General setting of Laguna Potrok Aike. a) Location of the lake in southern South America, b) Aerial photograph overlain by bathymetry. Yellow lines mark the sparker surveys, red lines the refraction profiles (S–N: AWI-20058010, W–E: AWI-20058020), and white circles the position of the sonobuoys. Note that the slope is inclined much more gently in the western part than in the remainder of the lake.

uppermost part of the sedimentary infill, they clearly show the high susceptibility of the basin to climatically induced changes as indicated by the presence of well-preserved sub-aquatic paleo-shorelines (Anselmetti et al., 2009) and a significant erosional horizon at ~33 m water depth interpreted as the lowest Late Glacial to Holocene lake level. However, due to the limited acoustic penetration, additional efforts were necessary to unravel the geometry of the proposed maar crater and the deeper structures of its lacustrine infill.

The seismic data used in this paper were acquired during two successive field campaigns that complemented the first two surveys. In 2004, a "Centipede" sparker survey was carried out by the Renard Centre of Marine Geology, University of Gent (Belgium). The in-house developed sparker source was operated at 300 J resulting in a broad-spectrum acoustic signal with a frequency range of 150 to 1500 Hz. A SIG (Société d'Instrumentation Géophysique, Toulon, France) single-channel high-resolution streamer with an active length of 2.7 m and 10 hydrophones with 0.3 m spacing was used as a receiver. The detected signal was pre-amplified in the streamer. Both source and receiver were towed at the water surface. A total of 74 sparker lines (approx. 110 km in total length) were recorded resulting in a high-density seismic grid covering the entire lake area (Fig. 1b). The sparker data were band-pass filtered (analog; 200–2300 Hz) prior to digital recording on a Delph-2 system (Triton-Elics, California, USA). GPS positioning data were directly captured by the Delph-2 system and recorded in each of the seismic trace headers. Data were post-processed by standard methods (i.e., frequency filtering, automatic gain control, spiking or predictive deconvolution) using the ProMAX (Landmark-Haliburton, Texas, USA) and/or KingdomSuite (Seismic Micro-Technology, Texas, USA) software packages.

In March 2005, the fourth seismic survey of Laguna Potrok Aike was carried out by the Alfred Wegener Institute (AWI) Bremerhaven (Germany). A 40 cubic-inches Mini-G gun (Sercel/Sodera, Nantes, France) was used as acoustic source. Two perpendicular seismic refraction lines were acquired (Fig. 1b) with three sonobuoys, each of them equipped with one single hydrophone below the buoy. Signals of two analogous sonobuoys were transmitted via radio to the platform, while the third sonobuoy was equipped with an internal digital storage device (construction by AWI Bremerhaven, details are given in Jokat et al., 2005; Niessen et al., 2005). Shot interval was set to 4 s, resulting in an average shot distance of 7 m. The seismic refraction data covered an offset range of up to 3 km (N–S profile) and 2.75 km (E–W profile) and were improved by standard processing (band-pass filtering 3–5–50–60 Hz, automatic gain control) to identify different reflection and refraction phases. Picking and modeling of the identified phases (Fig. 2a–d) was done using the "zplot" and "rayinvr" program packages (Zelt and Smith, 1992). A forward ray-tracing modeling technique was used to develop a model of layer thicknesses and velocities. An initial five-layer model was used to calculate synthetic seismic travel-times. It was iteratively modified until the calculated and observed travel-times were concordant (Fig. 2e and f). Modeling uncertainties were in the range of ±25 m.

4. Results and interpretation

Processing of the refraction data showed a funnel-like structure surrounded by higher-velocity rocks. The five-layer model includes a water layer and three layers of higher velocities inside the funnel (Fig. 2g and h). The surrounding structure (layer 5) is formed by the

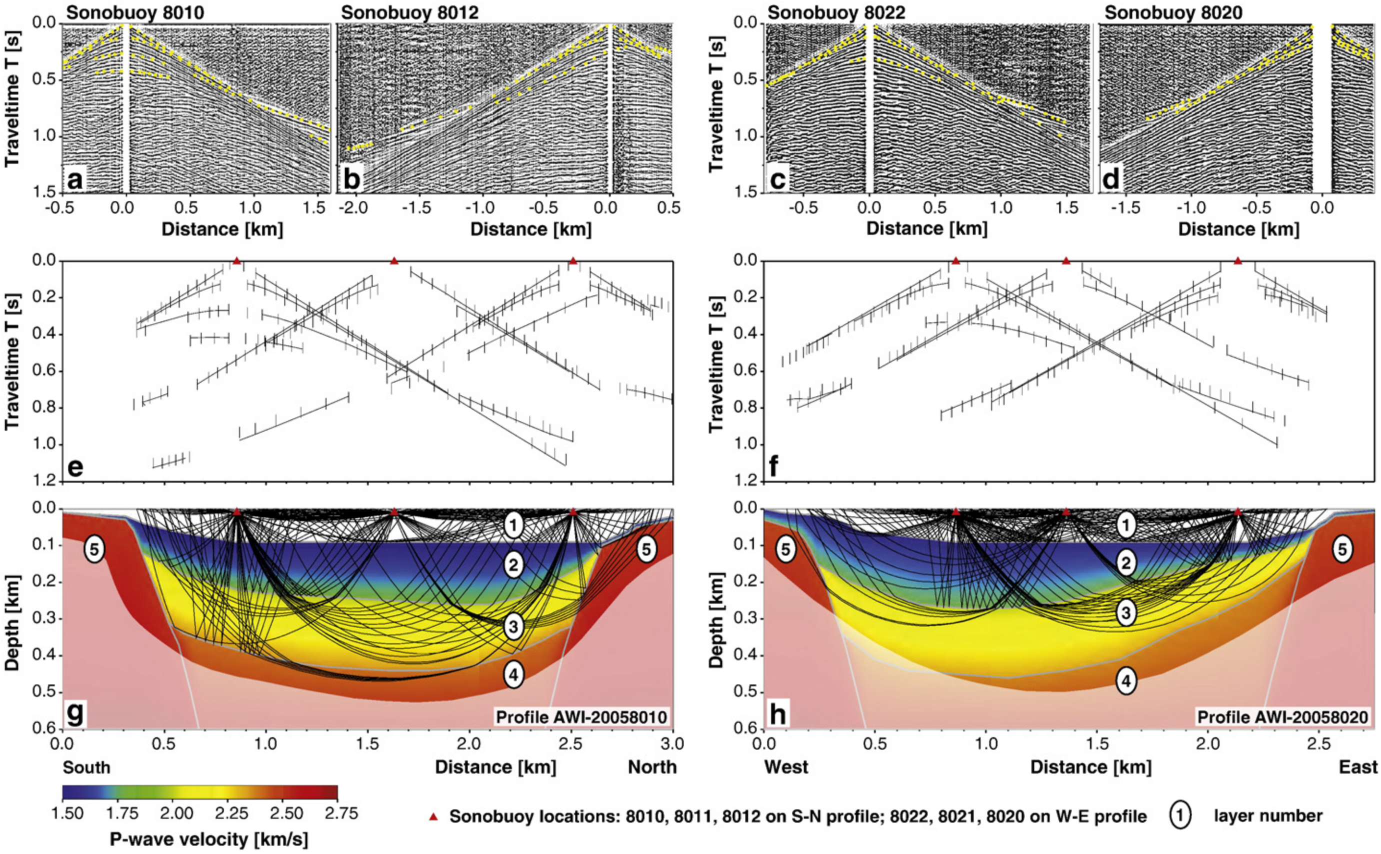

Fig. 2. Sonobuoy refraction data. Left: S–N profile AWI-20058010. Right: W–E profile AWI-20058020. Four seismic sections are shown in a) to d) with picked phases marked in yellow. Seismic data were band-pass filtered (3–5–50–60 Hz) and automatic gain control was set to 100 ms for illustration. Observed and calculated travel times are shown in e) and f). Error bars indicate picking uncertainties, and modeled synthetic rays are shown as lines. Additionally, the corresponding five-layer seismic velocity models are given in g) and h). For location of profiles and sonobuoys see Fig. 1. 1 = layer 1 (water layer), 2 = layer 2, 3 = layer 3, 4 = layer 4, 5 = layer 5 (surrounding bedrock).

sandstone bedrock of the Santa Cruz Formation outcropping in the lake's most proximal catchment. The funnel dips rather gently in its upper part, but shows steeper flanks further down. The uppermost layer (layer 1) inside the funnel corresponds to the water body of the lake. The layer below the water layer (i.e. layer 2) displays velocities of 1500 to 1800 m s^{-1} and a thickness of up to 180 m in the northern and western part. The layer below (layer 3) has velocities in the range of 2000 to 2350 m s^{-1} and a maximum thickness of 190 m. The lowermost layer (layer 4) has velocities of >2400 m s^{-1}; its thickness cannot be determined. All layers inside the funnel are bowl-shaped with flat basin floors and basin-ward dipping wedges along the basin rim. The angles of these marginal layers dipping basin-ward become gradually steeper at greater depths (Fig. 2g and h).

Following the stratigraphic numbering of Anselmetti et al. (2009), we use Unit I for lacustrine layers, Unit II for volcanoclastic layers and Unit III for the surrounding bedrock. Layer 2 with acoustic velocities of 1500 to 1800 m s^{-1} is interpreted to consist of unconsolidated lacustrine mud; this was further confirmed by the 100 m of lacustrine sediments drilled during austral spring 2008 (Zolitschka et al., 2009a). Layer 3 has higher velocities of up to 2350 m s^{-1} and is not symmetrically distributed in the basin. Its upper boundary is below the acoustic multiple in most areas (e.g. in the central part of the lake, the boundary is at 180 m sediment), but shallower in the eastern part of the lake (Fig. 2b and c). Layer 3 is interpreted to consist also of lacustrine muds, but probably with coarser grain size and quite likely contains a high number of mass transport deposits. These two layers together form Unit I; they are subdivided in Subunits Ia (layer 2) and Ib (layer 3). Layer 4 has even higher velocities of >2400 m s^{-1}, pointing towards a different character of this unit. Studies of other maars have shown a typical lithological succession with volcanoclastic rocks below lacustrine sediments (e.g., Pirrung et al., 2003). Thus it is quite likely that layer 4 consists of volcanoclastic sediments (Unit II). The rock surrounding the funnel (layer 5) holds acoustic velocities of ~2500 m s^{-1} (with some uncertainty as not many rays in the raytracing model penetrate this layer) and is interpreted to correspond to the sandstones of the Santa Cruz Formation outcropping around the lake (Unit III).

The refraction model allows the identification of the boundary between the sedimentary infill of the crater (Units I and II) and the sandstones of the surrounding Santa Cruz Formation (Unit III). This boundary is also well observable in the sparker data set and can be mapped down to about 200 m below lake level (i.e., down to the acoustic multiple) (Fig. 3). Sparker data show that the continuous seismic reflections of the lacustrine sediments clearly onlap onto the steep crater slopes (Fig. 4 gives an example from sparker profile pot52). For mapping, all sparker profiles (tracklines given in Fig. 1b) were considered. In some places, only a slight change in seismic facies is visible since the surrounding bedrock as well as the lacustrine infill are both well stratified with lakeward-dipping sediment layers. However, reflection spacing of the lacustrine sediments seems to be slightly closer in places. Furthermore, even if the bedding looks almost the same inside (lacustrine muds) and outside of the crater (bedrock), a distinct change in angle of the bedding marks the exact position of the boundary. This increase in bedding dip can be explained by the velocity contrast between the surrounding bedrock and the lacustrine infill, which results in a geometrical artifact in non-migrated sections. While this boundary is clearly visible and can be mapped in the northern, eastern, and southern areas of the lake, it is seismically masked by several tens of meters of acoustically transparent sediments in the western part of the basin close to the only sporadic inflow. The mapped crater slopes are funnel-shaped with gently dipping flanks in the upper part (6–8°) and steep slopes in the lower part (up to 60°). On the eastern shore, a distinct depression of the crater slope can be observed (Fig. 5).

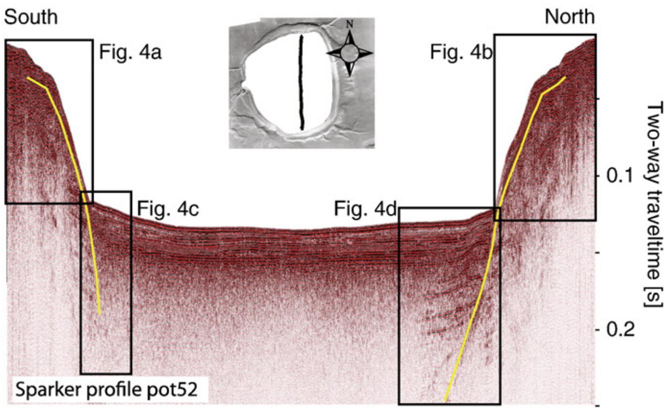

Fig. 3. Sparker profile with crater wall discordance. S–N sparker profile pot52 was used amongst all other sparker profiles to map the crater wall discordance marked in yellow. Detailed views are given in Fig. 4.

5. Discussion

Previous reflection seismic studies in other maar craters have already shown that the crater-wall discordance cannot always be easily detected, but often is marked only by a subtle facies change (Wiederhold, 2003; Schulz et al., 2005). Geophysical surveys at Messel and Baruth maars (Germany) were amongst the first attempts to investigate maar diatreme structures by high-resolution seismic methods (Wiederhold, 2003; Schulz et al., 2005; Buness et al., 2006). The Messel maar, a pit near Darmstadt, Germany, is an UNESCO World Heritage Site (since 1995) and mostly known for its fossil-rich oil shales, especially mammals and plants (e. g. Franzen, 1985). The rock is a very dark, organic-matter-rich and finely layered claystone. However, even though the Messel Pit attracted worldwide attention due to its fossils, its origin was unknown for a long time. Seismic investigations as well as a drilling program finally revealed that this basin was created by maar eruptions (Schulz et al., 2002; Buness et al., 2005, 2006). From these data a schematic model of the Messel maar was developed (Fig. 6c). The Baruth Maar is located in the Oberlausitz region (Saxony, Germany) and cannot be recognized from its surface structure as it is completely covered by about 50 m thick Miocene sediments. Its phreatomagmatic origin was supposed by Suhr and Goth (1996) based on a prominent negative gravity anomaly. A seismic survey, complemented by a drilling program and an electrical-resistivity survey, revealed a 1 km wide Oligocene maar structure correlated to the Paleogene volcanism in the Eger rift valley (Brunner et al., 1999; Goth and Suhr, 2000; Goth et al., 2003; Wiederhold, 2003).

The Laguna Potrok Aike structure is well comparable to other maars (Fig. 6). The crater wall discordance, recognized between the surrounding bedrock (Unit III) and the lacustrine sediments (Unit I) that were mapped using the sparker profiles, also shows up in the raytracing model and is comparable to the discordance identified in the Baruth Maar (Wiederhold, 2003). The observed funnel shape is typical of maar structures and thus confirms the phreatomagmatic origin of the Laguna Potrok Aike crater structure. This is further confirmed by different acoustic velocities inside and outside this discordance, as derived from the raytracing model.

Drill cores from the Messel and Baruth maars have low acoustic velocities for their lacustrine sediments in the upper part of the basin (Messel: 1600 m s^{-1}; Baruth: 1500 to 1600 m s^{-1}; Schulz et al., 2005). In the Baruth Maar, these sediments are underlain by a layer of slightly higher velocities (1800 to 2400 m s^{-1}), which was described as lacustrine sediments dominated by the irregular occurrence of turbidites. The same lithology was found in the Messel maar, but with a wider range of velocities (1600 m s^{-1} up to 3500 m s^{-1}; Felder and Harms, 2004; Schulz et al., 2005). The Baruth Maar formed in granodioritic bedrock, while the Messel Pit cut through granodiorites,

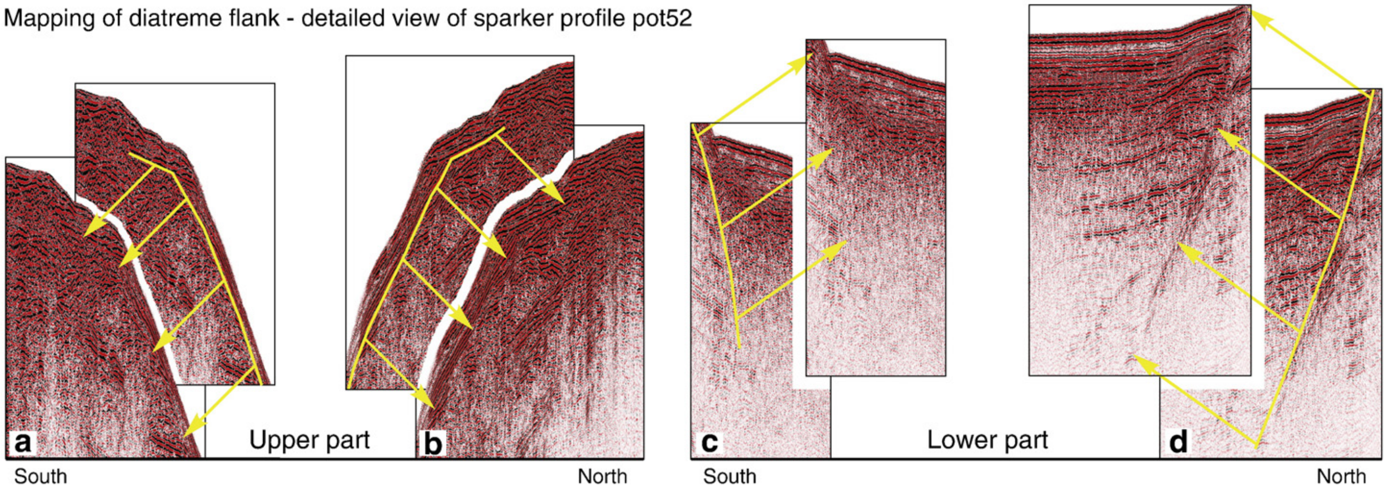

Fig. 4. Detailed view of crater wall discordance mapping. This figure shows detailed views of S–N sparker profile pot52. Positions of the details are given in Fig. 3. Note that the crater wall discordance (marked in yellow) is clearly visible in some places, whereas it can only be mapped tentatively in others.

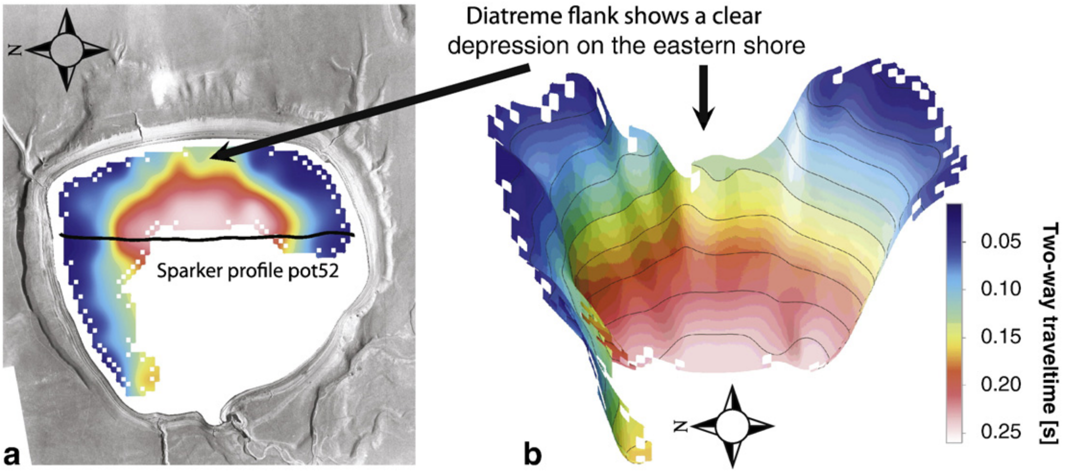

Fig. 5. Crater wall discordance of Laguna Potrok Aike. a) Plain view of the crater, b) Same data in 3D view. Depths are given in two-way travel times; 250 ms can be converted to ~170 m assuming an average acoustic velocity of 1500 m s^{-1}. Notice that a) and b) are oriented with north to the left for better illustration. The black line in a) marks the sparker line shown in Figs. 3 and 4.

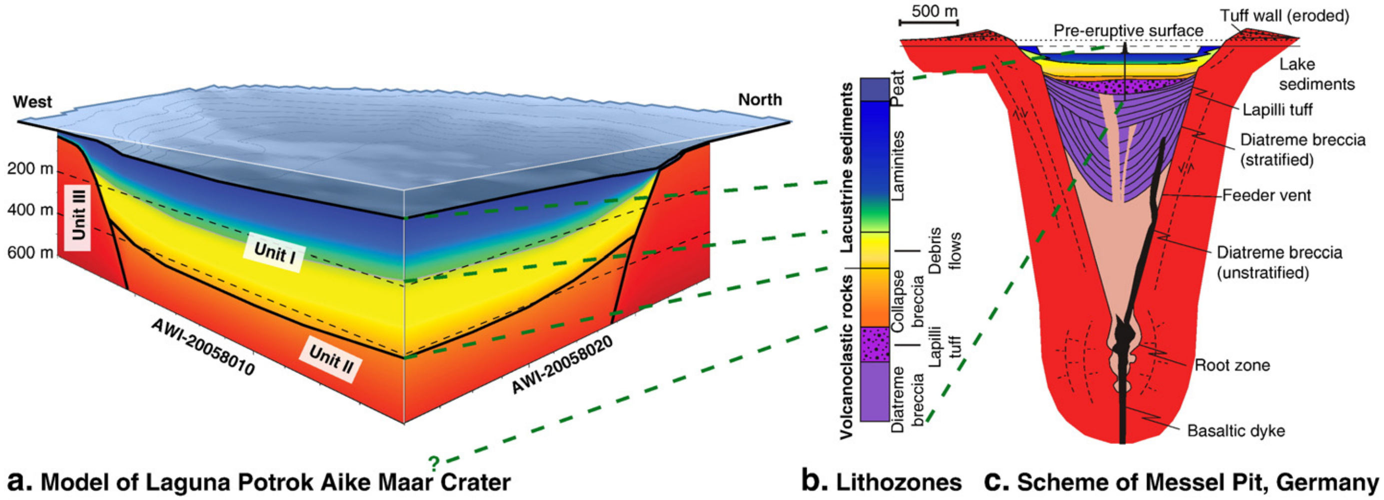

Fig. 6. Comparison of Laguna Potrok Aike with Messel, Germany. a) Refraction model of Laguna Potrok Aike (not to scale), b) Generalized lithofacies succession of filled maar craters (initially characterized by Pirrung et al., 2003), and c) Schematic structure of Messel (modified after Schulz et al., 2005).

amphibolites and Lower Permian sandstones (Schulz et al., 2005, and references therein).

As a comparison, seismic velocities of Laguna Potrok Aike are in the range of 1500 to 1800 m s^{-1} for the upper lacustrine Subunit Ia and show higher values of up to 2350 m s^{-1} in the lower lacustrine Subunit Ib. The third layer in the Laguna Potrok Aike model with seismic velocities of >2400 m s^{-1}, i.e. Unit II, resembles the findings at both Messel and Baruth (≥2000 and ≥2500 m s−1, respectively) (Schulz et al., 2005).

The fact that a tephra ring is only partially preserved around Laguna Potrok Aike points at high erosion rates in the upper part of the crater. Erosion of maar craters starts immediately after their formation, as documented by a study of the recent Ukinrek East Maar (Pirrung et al., 2008), and changes the initially steep into gently dipping flanks in the upper parts of the crater. Erosion is well documented for Laguna Potrok Aike with the lowest lake level at 33 m below the 2003 AD lake level that cuts deeply into previously deposited lacustrine sediments (Haberzettl et al., 2008; Anselmetti et al., 2009). Erosion of the relatively soft sandstones (Santa Cruz Formation) not only flattened the inner slope of the crater, but quite likely also changed an initially smaller diameter of the crater of ~2.2 km (extrapolated from the crater wall discordance visible in the seismic data) into the present shape with a diameter of 5 km at the highest subaerial terrace. This also explains why Laguna Potrok Aike seems to be well beyond the size of most known maars (less than 100 m to over 2 km in diameter; Lorenz, 2003). Only a few known maars are larger than Laguna Potrok Aike, but these were formed under permafrost conditions (Begét et al., 1996).

6. Conclusions

A model of the Laguna Potrok Aike basin calculated from the seismic refraction data results in a funnel-shaped structure of the surrounding Santa Cruz Formation sandstone filled by up to 370 m thick lacustrine sediments in its upper and probably volcanoclastic sediment (of unknown thickness) in its lower part. The lacustrine sediments are subdivided into two layers: an upper layer of unconsolidated mud with acoustic velocities in the range of 1500 to 1800 m s^{-1} and a lower layer with higher velocities of up to 2350 m s^{-1}, pointing quite likely at either coarser-grained sediments or intercalated mass movement deposits of different lithologies. The underlying potentially volcanoclastic sediments have higher velocities of >2400 m s^{-1}. The crater wall discordance can be mapped in the sparker data and shows the funnel-like maar structure in which the lake has formed. This sedimentary succession and subsurface structure is well comparable to other maars (e.g., Messel and Baruth maars, Germany) and confirms phreatomagmatic maar explosions as the origin of Laguna Potrok Aike.

Acknowledgements

We thank all expedition members in 2004 and 2005 for their excellent cooperation and support during field work at the lake, and especially François Charlet, Koen DeRycker, Hugo Corbella and Santiago Palamedi for their help with the acquisition of the sparker data as well as Hugo Corbella for logistical support. We are grateful to Capitan Jorge and Javier Moreteau and their crew who transported the Catamaran R/V Cardiel earlier on from far north to launch it on Laguna Potrok Aike, making these studies possible. We also thank the members of the INTA field station, in particular Guillermo Clifton, José Larrosa and Gabriel Oliva for providing the operational headquarters at the lake shore. Financial support by the Deutsche Forschungsgemeinschaft (DFG grants GE-1924/2-1 and ZO-102/5-1, 2, 3) is gratefully acknowledged.

References

Anselmetti, F.S., Ariztegui, D., De Batist, M., Gebhardt, A.C., Haberzettl, T., Niessen, F., Ohlendorf, C., Zolitschka, B., 2009. Environmental history of southern Patagonia unravelled by the seismic stratigraphy of Laguna Potrok Aike. Sedimentology 56, 873–892.

Begét, J.E., Hopkins, D.M., Charron, S.D., 1996. The largest known maars on Earth, Seward Peninsula, Northwest Alaska. Arctic 49 (1), 62–69.

Brunner, I., Friedel, S., Jacobs, F., Danckwardt, E., 1999. Investigation of a Tertiary maar structure using three-dimensional resistivity imaging. Geophys. J. Int. 136, 771–780.

Buness, H.A., Harms, F.-J., Nix, T., 2005. Seismische Erkundung eines eozänen Maars (Grube Messel). Cour. Forsch.-Inst. Senckenb. 255, 21–33.

Buness, H.A., Wiederhold, H., Wonik, T., 2006. Seismic reflection patterns of two Tertiary maars in Germany. Z. Dtsch Ges. Geowiss. 157 (3), 339–353.

Corbella, H., 2002. El campo volcano-tectónico de Pali Aike. In: Haller, M.J. (Ed.), Geología y Recursos Naturales de Santa Cruz. Asociacón Geológica Argentina, Buenos Aires, pp. 285–302.

Corbella, H., Borromei, A.M., Quattrocchio, M.E., 2000. Quaternary climate changes in southernmost South America inferred from lacustrine sediments preserved in volcanic maars. In: Smolka, P., Volkheimer, W. (Eds.), Southern hemisphere paleo- and neoclimates. Springer, Berlin, pp. 263–273.

Felder, M., Harms, F.-J., 2004. Lithologie und genetische Interpretation der vulkano-sedimentären Ablagerungen aus der Grube Messel anhand der Forschungsbohrung Messel 2001 und weiterer Bohrungen. Cour. Forsch.-Inst. Senckenb. 252, 151–203.

Franzen, J.L., 1985. Exceptional preservation of Eocene vertebrates in the lake deposit of Grube Messel (West Germany). Philos. Trans. R. Soc. Lond. B Biol. Sci. (1934-1990) 311 (1148), 181–186.

Goth, K., Suhr, P., 2000. Ein tertiäres Klimaarchiv in der Lausitz - Erste Ergebnisse der Forschungsbohrung Baruth. Z. Geol. Wiss. 28 (1), 229–236.

Goth, K., Suhr, P., Schulz, R., 2003. Zwei Forschungsbohrungen in das verdeckte Maar von Baruth (Sachsen). Z. Angew. Geol. 1 (2003), 9–17.

Haberzettl, T., Fey, M., Lücke, A., Maidana, N., Mayr, C., Ohlendorf, C., Schäbitz, F., Schleser, G.H., Wille, M., Zolitschka, B., 2005. Climatically induced lake level changes during the last two millennia as reflected in sediments of Laguna Potrok Aike, southern Patagonia (Santa Cruz, Argentina). J. Paleolimnol. 33, 283–302.

Haberzettl, T., Kück, B., Wulf, S., Anselmetti, F.S., Ariztegui, D., Corbella, H., Fey, M., Janssen, S., Lücke, A., Mayr, C., Ohlendorf, C., Schäbitz, F., Schleser, G.H., Wille, M., Zolitschka, B., 2008. Hydrological variability in southeastern Patagonia and explosive volcanic activity in the southern Andean Cordillera during Oxygen Isotope Stage 3 and the Holocene inferred from lake sediments of Laguna Potrok Aike, Argentina. Palaeogeogr. Palaeoclimatol. Palaeoecol. 259, 213–229.

Jokat, W., Schmidt-Aursch, M.C., Schroeder, M., Behr, Y., Birnstiel, H., Gebauer, A., Gebhardt, A.C., Goeßling, K., Guenther, D., Lensch, N., Martens, H., Raabe, W., Spengler, T., 2005. Marine Geophysics, Scientific Cruise Report of the Arctic Expedition ARK-XX/3 of RV "Polarstern" in 2004: Fram Strait, Yermak Plateau and East Greenland Continental Margin. Reports on Polar and Marine Research, pp. 27–40.

Lorenz, V., 1986. On the growth of maars and diatremes and its relevance to the formation of tuff rings. Bull. Volcanol. 48, 265–274.

Lorenz, V., 2003. Maar-diatreme volcanoes, their formation, and their setting in hard-rock or soft-rock environments. GeoLines 15, 72–83.

Mayr, C., Fey, M., Haberzettl, T., Janssen, S., Lücke, A., Maidana, N., Ohlendorf, C., Schäbitz, F., Schleser, G.H., Wille, M., Zolitschka, B., 2005. Palaeoenvironmental changes in southern Patagonia during the last millennium recorded in lake sediments from Laguna Azul (Argentina). Palaeogeogr. Palaeoclimatol. Palaeoecol. 228, 203–227.

Mazzarini, F., D'Orazio, M., 2003. Spatial distribution of cones and satellite-detected lineaments in the Pali Aike Volcanic Field (southernmost Patagonia): insights into the tectonic setting of a Neogene rift system. J. Volcanol. Geoth. Res. 125, 291–305.

Niessen, F., Gebhardt, A.C., Kopsch, C., 2005. Geophysical survey. In: Melles, M., Minyuk, P., Brigham-Grette, J., Juschus, O. (Eds.), The Expedition - El'gygytgyn Lake 2003 (Siberian Arctic): Reports on Polar and Marine Research, pp. 121–129.

Pirrung, M., Fischer, C., Büchel, G., Gaupp, R., Lutz, H., Neuffer, F.-O., 2003. Lithofacies succession of maar crater deposits in the Eifel area (Germany). Terra Nova 15, 125–132.

Pirrung, M., Büchel, G., Lorenz, V., Treutler, H.-C., 2008. Post-eruptive development of the Ukinrek East Maar since its eruption in 1977 A.D. in the periglacial area of south-west Alaska. Sedimentology 55, 305–334.

Schaber, K., Sirocko, F., 2005. Lithologie und Stratigraphie der spätpleistozänen Trockenmaare der Eifel. Mainz. Geowiss. Mitt. 33, 295–340.

Schulz, R., Harms, F.-J., Felder, M., 2002. Die Forschungsbohrung Messel 2001: Ein Beitrag zur Entschlüsselung der Genese einer Ölschieferlagerstätte. Z. Angew. Geol. 4 (2002), 9–17.

Schulz, R., Buness, H.A., Gabriel, G., Pucher, R., Rolf, C., Wiederhold, H., Wonik, T., 2005. Detailed investigation of preserved maar structures by combined gephysical surveys. Bull. Volcanol. 68, 95–106.

Suhr, P., Goth, K., 1996. Erster Nachweis tertiärer Maare in Sachsen. Zbl. Geol. Paläont. Teil I 1/2, 363–374.

Wiederhold, H., 2003. Das verdeckte Maar von Baruth im seismischen Bild. Z. Angew. Geol. 1, 26–35.

Zelt, C.A., Smith, R.B., 1992. Seismic traveltime inversion for 2-D crustal velocity structure. Geophys. J. Int. 108, 16–34.

Zolitschka, B., Schäbitz, F., Lücke, A., Corbella, H., Ercolano, B., Fey, M., Haberzettl, T., Janssen, S., Maidana, N., Mayr, C., Ohlendorf, C., Oliva, G., Paez, M.M., Schleser, G.H., Soto, J., Tiberi, P., Wille, M., 2006. Crater lakes of the Pali Aike Volcanic Field as key sites for paleoclimatic and paleoecological reconstructions in southern Patagonia, Argentina. J. S. Am. Earth Sci. 21, 294–309.

Zolitschka, B., Anselmetti, F., Ariztegui, D., Corbella, H., Francus, P., Ohlendorf, C., Schäbitz, F., Team, P.S.D., 2009a. The Laguna Potrok Aike Scientific Drilling Project PASADO (ICDP Expedition 5022). Sci. Drilling 8, 29–34.

Zolitschka, B., Anselmetti, F.S., Ariztegui, D., Corbella, H., Francus, P., Gebhardt, A.C., Hahn, A., Kliem, P., Lücke, A., Ohlendorf, C., Schäbitz, F., 2009b. Deep drilling at Laguna Potrok Aike, Argentina: recovery of a paleoclimate record for the Last Glacial from the Southern Hemisphere. Eos Trans. AGU 90 (52) Fall Meet. Suppl., Abstract PP14A-10.