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The Colônia structure, São Paulo, Brazil

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Abstract–The near-circular Colônia structure, located in the southern suburbs of the mega-city of São Paulo, Brazil, has attracted the attention of geoscientists for several decades due to its anomalous character and the complete absence of any plausible endogenous geologic explanation for its formation. Origin by impact cratering has been suggested repeatedly since the 1960s, but no direct evidence for this has been presented to date. New seismic data have been recently acquired at Colônia, providing new insights into the characteristics and possible layering of infill of the structure, as well as into the depth to the underlying basement. We review the current knowledge about the Colônia structure, present the new seismic data, and discuss the existing—as yet still indirect—evidence for a possible origin by an impact. The new data suggest the existence of a sedimentary fill of approximately 275 m thickness and also the presence of two intermediate zones between sediment and basement: an upper zone that is approximately 65 m thick and can be interpreted as a possible crater-fill breccia, whereas the other zone possibly represents fractured/brecciated basement, with a thickness of approximately 50 m. Although this depth to basement seems to be inconsistent with the expected geometry of a simple, bowl-shape impact structure of such diameter, there are a number of still unconstrained parameters that could explain this, such as projectile nature, size and velocity, impact angle, and particularly the current erosion depth.

INTRODUCTION

The Colônia structure is located at 23°52′ S and 46°42′20″ W in the southern suburbs of the city of São Paulo, Brazil, near the Atlantic mountain range (Fig. 1). This unusual, near-circular feature with a diameter of 3.6 km has attracted the attention of geoscientists for several decades, due to its anomalous character, near-perfectly circular geometry, and the absence of any plausible endogenous geologic explanation for its formation. For this reason, it has been suggested repeatedly since the early 1960s that Colônia was formed by impact of a large extraterrestrial body (Kollert et al. 1961; Crósta 1987; Riccomini et al. 1989, 1991, 1992; Riccomini and Turcq 2004). However, no direct evidence for the impact origin of Colônia has been presented to

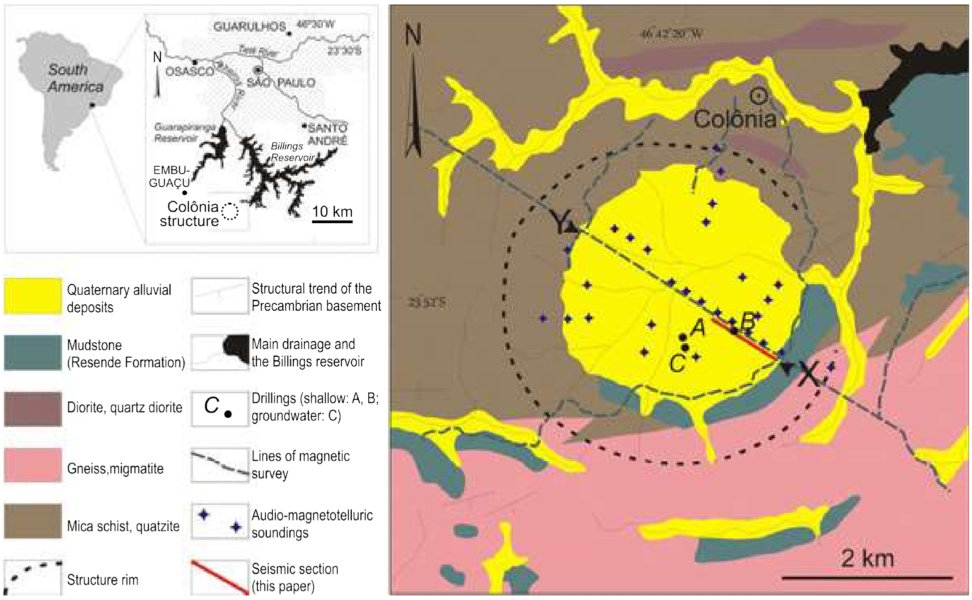

Fig. 1. Location (left) and geological map of the Colônia structure (modified from Coutinho 1980; Riccomini et al. 1991). X–Y indicate the location of the SE–NW section shown in Fig. 4.

date—due to the adverse local conditions, which prevent access to the actual crater floor, or to the lack of any impact-related material which might provide such evidence.

The structure comprises a prominent annular ring of hills reaching up to 125 m above the inner depression (Fig. 2). The structure is formed in crystalline basement rocks of Neoproterozoic (600–700 Ma) age. No direct radiometric age for the structure forming event is known yet. The depression is filled with organic-rich sediments of Quaternary age. The northern part has been urbanized in recent years, whereas the central part is presently a swamp, partially drained by the Vargem Grande stream, which exhibits a peculiar radial centripetal pattern with a single outlet through the eastern rim of the structure (Fig. 1).

The overall shape of the structure, the thickness of the sedimentary fill, and the depth of the sediment/basement interface have been analyzed using different geophysical methods by Masero and Fontes (1991, 1992), Motta and Flexor (1991), and Neves (1998). The Colônia structure and its sedimentary record have also become a reference site for tropical paleoenvironmental and paleoclimatic research in South America, after the discovery that the upper 8 m of sediments provide a detailed record of 130 ka paleoenvironmental history (Ledru et al. 2005, 2009). The results of sedimentological and palynological studies of this upper sequence of the sedimentary infill were reported by Riccomini et al. (1991) and Ledru et al. (2005, 2009) and were used to estimate the period of time necessary for the deposition of the complete infill of the depression, using

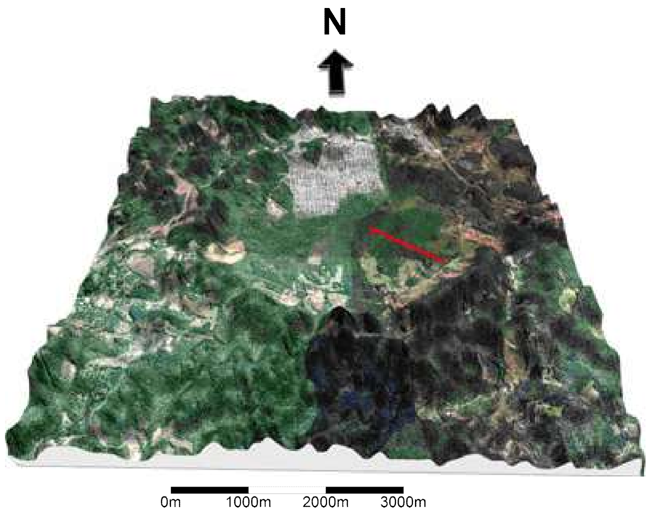

Fig. 2. Ikonos satellite image viewed in 3-D perspective projection. The elevation data were derived from the 1:50,000 topographic map (vertical exaggeration: 6.5×). The red line indicates the position of the seismic section shown in Fig. 6.

the depths obtained by geophysical methods. They suggested that this period could have been as long as 1.5–2.5 Ma. These studies have also provided important paleoenvironmental and paleoclimatic evidence of the conditions under which these top sediments were deposited.

We have recently acquired new seismic data at Colônia, which has provided new insights into the characteristics and possible layering of infill of the structure, as well as into the depth to the underlying basement. In this article, we review the current knowledge about the Colônia structure, present the new seismic data, and discuss the indirect evidence for a possible origin by impact. We also use the information gathered so far to stress the need and importance of obtaining direct data through drilling of the complete sedimentary record of the infill and into the underlying basement.

MORPHOLOGY AND GEOLOGIC SETTING OF THE COLÔNIA STRUCTURE

The Colônia structure is located at the southeastern edge of the Paulistano Plateau (Planalto Paulista; Almeida 1958), bounded to the south by the Atlantic Mountain Range. This plateau is a geomorphologic feature of probable Neogene age (Riccomini and Coimbra 1992), characterized by relatively low to moderate relief with rolling hills and some ridges with altitudes varying between 715 and 900 m. The region is within the domain of the Atlantic rain forest. Part of the interior of the structure contains remnants of the original forest, whereas the central part is a swamp possibly formed due to the near-closure of the depression. The northern part has been urbanized in recent years, forming the district of Vargem Grande. The name of the structure comes from the district of Colônia, located outside the northern rim (Fig. 1).

The interior of Colônia is drained by the Vargem Grande stream that exhibits a peculiar and well-defined radial centripetal drainage pattern typical of round depressed areas, with a single outlet flowing eastward through the eastern rim of the structure toward the Billings reservoir (Fig. 1). This drainage pattern is clearly visible over the Paulistano Plateau; the region around Colônia is dominated mostly by dendritic and/or structurally controlled rectilinear drainage patterns.

The structure was developed in Proterozoic crystalline rocks of the Ribeira Fold Belt (Hasui et al. 1975), which includes a network of EW to ENE-trending shear zones that remained active until the end of the Brasiliano–Pan African geotectonic cycle (0.5–0.7 Ga) (Sadowski and Campanha 2004). The main Proterozoic rock types of the basement comprise schist, quartzite, gneiss, migmatite, diorite, quartz-diorite, and mylonite after these lithologies (Fig. 1) (Sadowski 1974; Coutinho 1980). No carbonate rocks are known in this region, weathering of which could have induced the formation of collapsed sinkhole structures due to karstification. Paleogene mudstones related to the Eocene to Oligocene Resende Formation of the São Paulo Basin occur in the region of the structure (Riccomini et al. 2004). Pebble-mudstone of the Resende Formation occurs tectonically imbricated with gneiss of the basement along a WNW–ESE-oriented thrust-fault zone, dipping to NNE, about 1 km to the south of the structure. Riccomini et al. (1991) pointed out that this could represent part of the outer rim, composed of Precambrian rocks thrusted over Paleogene sedimentary rocks, but a possible relationship to regional Cenozoic tectonics should not be discarded.

Colônia is defined by a hilly circular outer rim, with elevations up to 125 m higher than the inner swampy alluvial plain. The comparatively higher hills are located in the southwestern part of the rim. The radial centripetal drainage pattern, together with the prominent circular outline of the structure, with its raised rim and depressed inner portion, makes Colônia an outstanding regional morphological anomaly.

Different episodes of convergent strike-slip faulting have favored uplift and denudation in the region since the beginning of the Neogene (Riccomini et al. 2004). Thermochronological data obtained from apatite fission-track analysis indicate that the entire Serra do Mar region has experienced high rates of uplift and exhumation since the Miocene (Franco-Magalhães et al. 2010; Hiruma et al. 2010). The formation of the Colônia structure would have occurred during this period of general uplift.

CHARACTERISTICS OF THE SEDIMENTARY INFILL OF THE COLÔNIA STRUCTURE

The limited current knowledge about the characteristics of the sedimentary infill of Colônia comes from two shallow (to 8.78 m depth) drillings by some of the authors (Riccomini et al. 1991; Ledru et al. 2005, 2009) near the center of the structure (Fig. 1, sites A and B). There is also some information from a groundwater borehole drilled in the southern part of the structure, which intersected 270 m of sediment but did not reach basement (Fig. 1, site C). However, core recovery from this borehole is very limited and discontinuous. The shallow drillings showed that the upper sediments comprise black, organic-rich, clayey sediment (peat), with quartz grains below 2.27 m and intercalations of fine sand with quartz and mica between this depth and 2.65 m (Riccomini et al. 1991, 2005). Analysis of the pollen record of one of the cores indicated the occurrence of subtropical forest-type vegetation in the sediments from 6 to 7.5 m, after which the sediments indicated changing of paleoconditions progressively upward to cooler and dryer climate conditions with a predominance of grassland-type vegetation, up to 2.73 m. ^{14}C age determinations provided ages between 28,050 and 18,180 yr BP for the interval between 2.73 and 0.50 m, respectively (Riccomini et al. 2005). The second core showed similar sedimentological characteristics, but with records from the Holocene in its upper portion, with ^{14}C ages between 4350 and 4565 yr BP for the interval between 0.51 to 0.53 m. Samples from depths around 1.80 m yielded ^{14}C ages in the range 33,150–36,700 yr BP (Ledru et al. 2005, 2009). A comparison of the Colônia record with data from cave speleothems from southern Brazil allowed us to estimate a time-interval of more than 100,000 yr for the deposition of the 7.80 m long core, providing for the first time a coverage of a complete interglacial/glacial cycle in a neotropical rainforest. According to Ledru et al. (2009) the floristic composition of the rainforest changed several times during each phase of expansion, twice during the interglacial, and three times during glacial episodes. The presence of the austral conifer Araucaria indicates the action of an extratropical precipitation regime until approximately 50,000 yr BP, when the first dry phase of the glacial was initiated. The biodiversity was high during both the interglacial and glacial episodes with small rainforest refugia during drier phases.

An extrapolation of the age record obtained from the two shallow drillings to the anticipated maximum depth of sediment infill of the Colônia structure (see the Possible Age of the Colônia Structure section) suggests a maximum age record for the sedimentary fill of 2.58 Ma. Information from the groundwater borehole (Fig. 1, site C) showed that the sedimentary column comprises essentially organic-rich clay, with minor intercalations of mudstones in the lower (70 m) part of the section (Fig. 3). Pebbly mud occurs below 257–258 m and may represent deposition of alluvial fans or breccia. The presence of Precambrian rock fragments in the mud suggests the lower section to be a fanglomeratic deposit derived from elevated parts of the inner rim, probably related to the initial filling of the depression (Riccomini et al. 2005), or to occurrence of a crater-fill breccia. The interface between the pebbly mud and the overlying sandy mud is clearly recognized in the seismic section (see Fig. 6). From 257 m upward the sediments are essentially composed of organic-rich silty mud with sandy intercalations at 242–174, 147–94, and 46–40 m. The organic-rich sediments are lacustrine in origin and were probably deposited under humid conditions. Sandy to conglomeratic intercalations are probably related to debris flows sourced from the inner slopes of the structure, under drier conditions, with a drop in the relative lake level and increasing erosion facilitated by the diminution of vegetation cover.

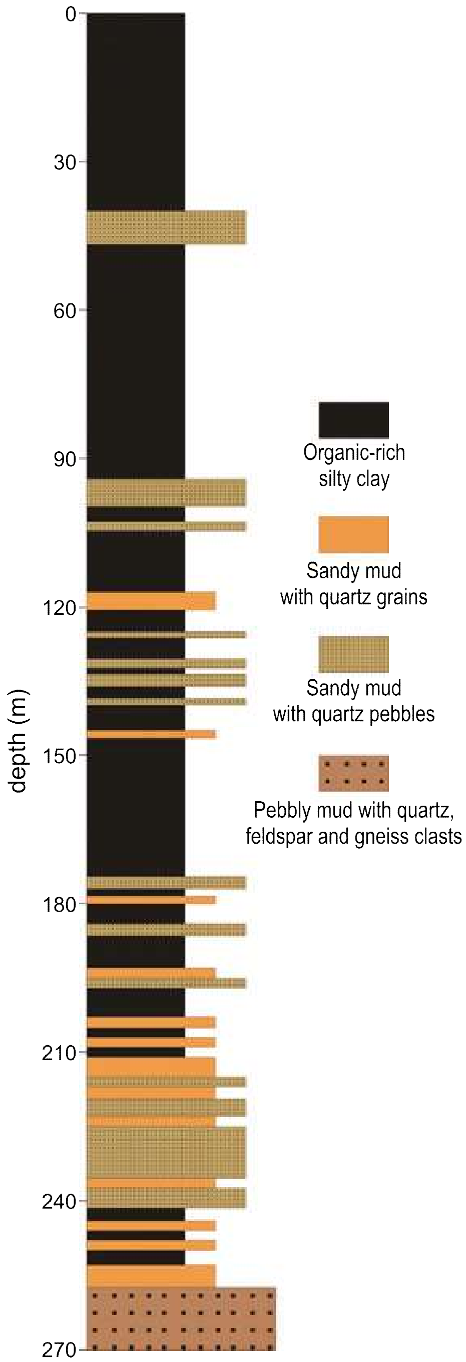

Fig. 3. Schematic section of the groundwater borehole (see Fig. 1, site A, for location).

GEOPHYSICAL DATA

In their initial gravimetric/electrical resistivity survey of Colônia, Kollert et al. (1961) observed the thick, deep-ranging nature of its sedimentary infill. The authors observed a circular gravimetric low coinciding with the structure. Kollert et al. (1961) estimated the depth of the basement at the center of the depression between 285 and 400 m. The estimation for the shallower depth was based on data from vertical electrical sounding, whereas the deeper value was derived from the gravimetric data.

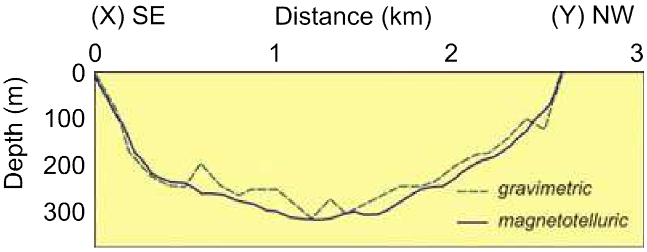

Fig. 4. SE–NW section of the Colônia structure (see Fig. 1 for location) based on gravimetric and audio-magnetotelluric data (Motta and Flexor 1991; Masero and Fontes 1991, 1992). For the audio-magnetotelluric section, an average between the maximum and the minimum depth values was used.

Based on these data, they attributed the origin of the Colônia structure to a meteoritic impact event.

Motta and Flexor (1991) conducted another gravimetric survey over Colônia and their results placed the depth of the sedimentary fill/basement into the range of 300–350 m, admitting a gravity contrast extrapolated to the ground surface of -1.4 g cm^{-3}. The Bouguer anomalies were characterized by negative values, decreasing from the rim toward the center of the structure (~−40 to −63 mgal).

Masero and Fontes (1991, 1992) performed a geoelectrical survey of the structure using the audio-magnetotelluric method, with the objective of estimating the sediment–basement interface. The method produces a maximum and a minimum estimation for the depth of the basement and the values obtained for the center of the structure are in the range of 200–440 m (Fig. 4). Most of the models obtained from the inversion showed a gradual increase of the resistivity with depth starting from approximately 10 ohm-m to more than 1000 ohm-m.

Neves (1998) employed seismic data acquired in sections in the southern part of the structure and estimated the sediment/basement interface to be in the depth range of 380–430 m. Neves (1998) also pointed out the occurrence of a low-seismic zone just at the top of basement, suggesting the presence of brecciated/deformed crystalline rocks.

To obtain a better estimate of the thickness of the sedimentary filling and the depth of the crystalline basement underneath the Colônia structure, as well as information on the characteristics of different layers within the structures, we acquired a seismic reflection section at Colônia in May 2010. Seismic data were acquired through a continuous common depth point (CDP) profile, 1 km in length, located in the southeastern part of the Colônia structure. It did not reach the structure's center due to the swampy conditions in this area. Acquisition parameters were defined based on previous walkaway tests executed near the center of the profile. Four 24-channel Geometrics-Geode seismographs were networked to simultaneously record 96 channels of data. Geophones of 14 Hz were placed at 2 m intervals and shots were done at every 4 m. During the acquisition, while the geophone array was kept fixed, the shot point was moved toward the first receiver until 12 shots had been recorded. With this setup, the minimum offset varied from 70 to 26 m.

The "mini-sosie" acquisition method (Barbier 1983) was employed, with two mechanical soil compactors as the source of energy. The energy is transferred to the ground over a period of 60 s. A reference trace, recorded by a 100 Hz geophone planted near the tampers (pilot trace) represents the signal that was introduced into the ground. The pilot trace is cross-correlated with the raw data. The two compactors operated simultaneously, with varying throttle, to achieve sufficient randomness in the sequence of impacts. The randomness of the signals is necessary to get the best results. Moreover, by using two compactors operating simultaneously more energy is transferred into the ground over a given length of time.

The data were processed using the Seismic Unix—SU package (Cohen and Stockwell 2010). The data processing flow involved geometry and trace editing, band pass and f-k filtering, deconvolution, sorting to CDP gathers, velocity analysis, normal move-out (NMO) correction, and stacking.

Velocity analysis was conducted using the velocity spectrum (semblance) plot and constant velocity stack (CVS) panel. They were displayed and analyzed simultaneously. The velocity analysis allows us to determine the stacking velocity functions that yield the optimum stack and it is done by interpolating between and extrapolating from these functions.

The analysis was performed at intervals of 50 CDPs along the entire section. In the CVS panel, 10 adjacent CDPs were NMO-corrected and stacked using a range of constant velocities (1000–2500 m s^{-1}) with intervals of 50 m s^{-1}. The velocity spectrum showed the coherence function value (semblance) for the same range of trial velocities. Figure 5 shows the panels (CVS and Semblance) and the stacking velocity function obtained for the CDP gathered at location 750. The interval velocities obtained for this CDP gathering (using the Dix equation) are presented in Fig. 5.

The velocities were extracted from semblance and CVS plots for the entire seismic data volume. The stacking velocity function in Fig. 5 shows a continuous increment of velocity with depth, starting from approximately 1500 to 2150 m s^{-1}, which is consistent with the expected increasing compaction of the saturated sediments with depth (the water table is very shallow within the Colônia structure). From the Dix equation, we derived the following distribution of interval

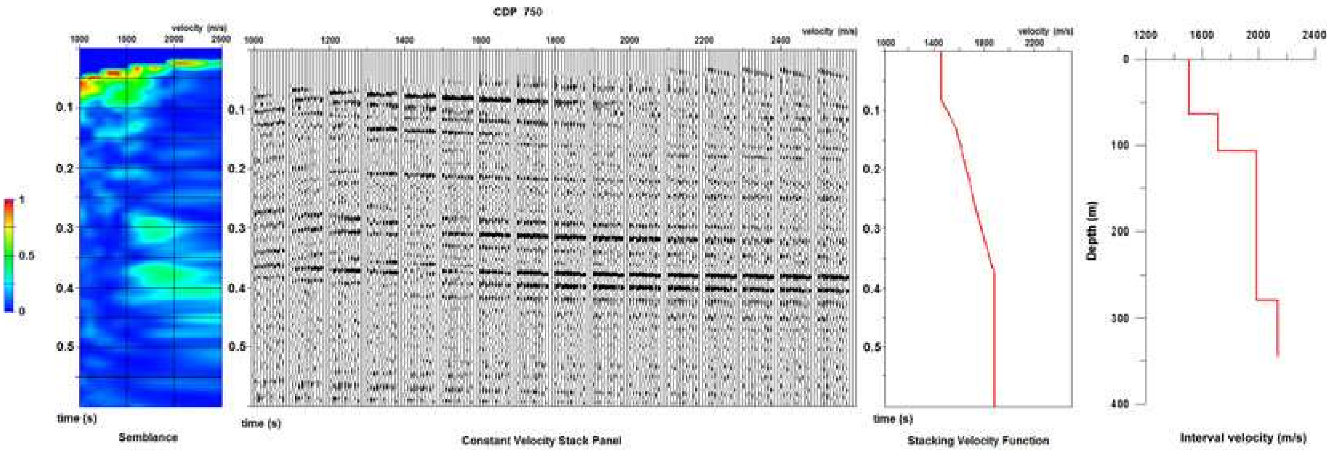

Fig. 5. From left to right are panels for Semblance, Constant Velocity Stacking, the Stacking Velocity Function from the velocity analysis of the common depth point (CDP) gather 750 and the Interval Velocity Profile also obtained from CDP gather 750 (all with the same time scale).

velocities (Fig 5): 1500 m s^{-1} until 0.08 s of two-way traveltime (TWT), 1700 m s^{-1} between 0.08 and 0.13 s TWT, 1980 m s^{-1} between 0.13 and 0.3 s TWT, and 2130 m s^{-1} between 0.3 and 0.36 s TWT.

The interpretation of the stack section and the interval velocity functions suggests the presence of three zones with distinct seismic signatures (Figs. 5 and 6). From top to bottom, the first zone (yellow) has a maximum thickness of 270–280 m near the center and is represented by the organic-rich clayey sediments and clastic material, as described by Riccomini et al. (2005) (Fig. 3), that can also be distinguished into different seismic units (Fig. 6). The second zone (in blue), with a maximum thickness of 65 m near the center, represents a transition between the sedimentary filling and the third, the lowermost part, might comprise brecciated/fragmented basement rocks. The reflectors in this zone exhibit a subtle subhorizontal pattern, possibly reflecting sedimentary reworking of the rock material from the inner slopes of the structure and/or deposition of breccia-type material. The third zone (in red), with a thickness of approximately 50 m, might be attributed—in the context of an impact model—to shocked/deformed basement rocks (schist and quartzite) in its upper part, grading to less shocked/less deformed basement rocks further below. The first and second layers thin out toward the rim of the structure, disappearing near the edge of the depression.

DISCUSSION

Hypotheses for the Origin of the Colônia Structure

Since the early studies of this structure (e.g., Kollert et al. 1961), the impact origin of the Colônia structure has been favored. Alternative hypotheses, such as (1) sinkhole formation, (2) a basin formed above a structural interference pattern, (3) presence of a magmatic intrusion, and (4) crypto-explosion (i.e., a phreato-magmatic structure related to a hypothesized igneous intrusion), among others, have been rejected because of (1) the absence of carbonate rocks in the region, (2) the persistence of the ENE structural trend in the regional basement, (3 and 4) the lack of such structures and/or minor intrusive bodies (dikes, sills, etc.) that could be associated with such intrusions, and the unusually large dimension of Colônia with respect to sizes of kimberlite pipes.

Nonetheless, no direct evidence for impact, such as shock deformation features (French 1998; French and Koeberl 2010), has been observed to date at this structure. In summary, available data on geomorphological aspects, geology, and geophysics of the Colônia structure, although possibly consistent, are not a priori conclusive of its origin and certainly not of an origin by meteorite impact—at present.

Possible Age of the Colônia Structure

An Eocene to Oligocene age for the mudstone of the Resende Formation in the São Paulo Basin was proposed by Riccomini et al. (2005). By extrapolating the sedimentation rate inferred for the upper 7.8 m of organic-rich clayey sediments (Ledru et al. 2005, 2009) and disregarding the effect of compaction and the existence of unconformities in the sedimentary succession, it was estimated that the filling of the crater-like structure was completed during at least 2.5 Ma (Riccomini et al. 2005). These authors also discussed empirical relations based on diameter preservation

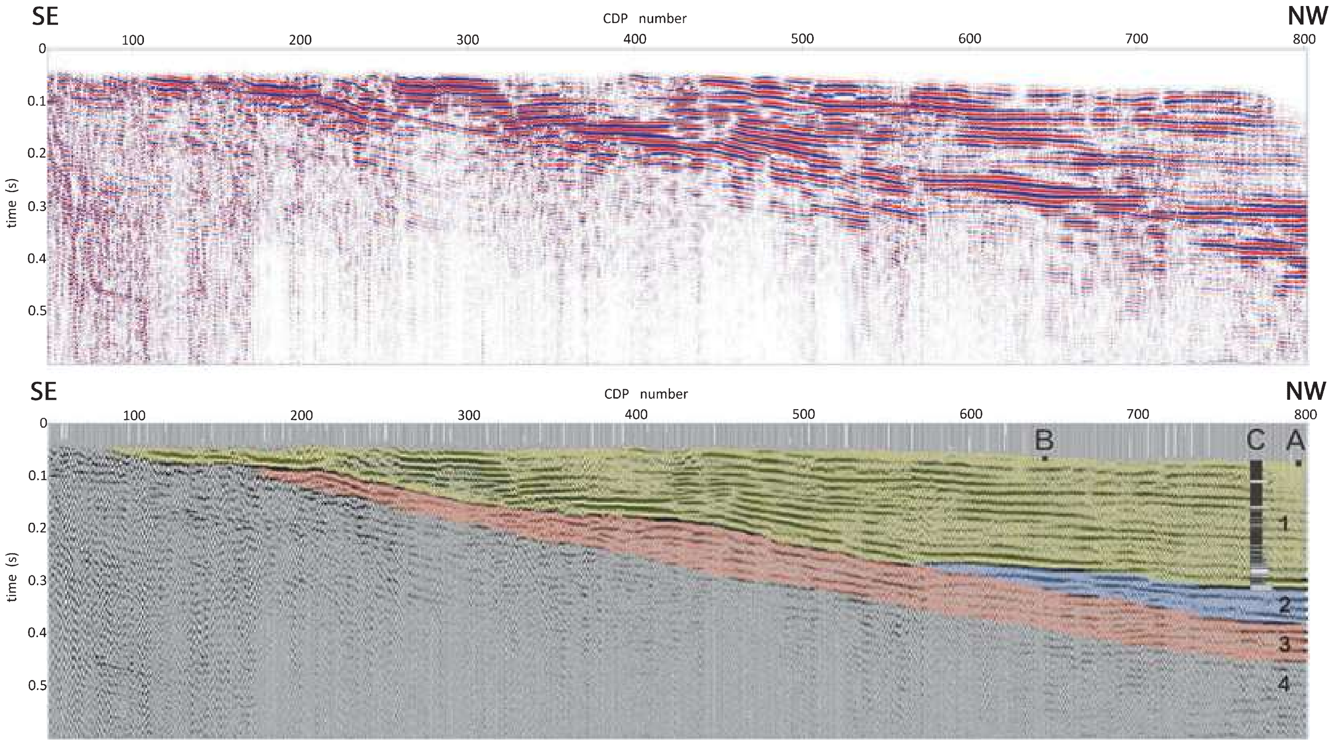

Fig. 6. Common depth point (CDP) seismic reflection SE–NW transect (1 km long) across Colônia (CDP trace distance = 2 m). 1. Sedimentary filling (~280 m); 2. Possible crater-fill breccia (~65 m); 3. Possible shocked crystalline basement (~50 m); 4. Unshocked crystalline basement. A, B, and C are the projections of the two shallow drillings and the groundwater borehole referred in text and in Fig. 1.

degree and known ages of impact craters (Grieve and Robertson 1979) that would suggest an interval between 36 and 5 Ma for the maximum age for a possible Colônia impact.

Therefore, the best approach of establishing, or even for better constraining, the age of the Colônia structure, is palynological analysis of the sedimentary column, and/or radiogenic isotope analysis of any melt if found at the sediment/basement interface of Colônia in the course of drilling.

Shape and Diameter Versus Depth Relationship

When regarded in plane view, the Colônia structure is visibly circular in shape. However, the gravimetric and audio-magnetotelluric data presented by Motta and Flexor (1991) and Masero and Fontes (1991, 1992) exhibit an asymmetry in the shape of the depression, with a slight elongation in the NW–SE direction suggested by the first study, and in the WNW–ESE direction by the second. At this stage, trying to interpret any possible causes for this asymmetry would be speculative, but eventual future modeling of the Colônia structure ought to take these aspects into consideration.

The gravimetric data presented by Kollert et al. (1961) and Motta and Flexor (1991) suggest that, if Colônia were an impact crater, it should be a simple, bowl-shape crater. The circular gravimetric low spatially coincident with the structure obtained by these authors would therefore match the expected gravimetric signature of simple craters as proposed to Grieve and Robertson (1979).

At 3.6 km diameter Colônia is a structure with a diameter close to the 4 km crossover value generally considered for the change from simple to complex (i.e., including central uplift features) impact structure geometries (e.g., Melosh 1989) for crystalline rock targets. Thus, a simple, bowl-shape geometry—in line with the findings of the geophysical investigations at Colônia—would not contradict the impact origin possibility.

A considerable number of impact structures of sizes comparable to that of Colônia (say, ~2.5–4 km) is known in the Earth impact record (e.g., Earth Impact Database, http://www.passc.net/EarthImpactDatabase/index.html; Kennedy and Coleman 2000). However, for only a few of these candidates either (1) good constraints on 3-D geometry (including maximum depth)—generally obtained by drilling, or at least (2) an indication for maximum depth from modeling of geophysical data or drilling are available. An example for case (1) would be Brent Crater (Ontario), a simple, bowl-shape impact structure of 3.8 km diameter formed entirely in Precambrian basement. An extensive drilling project (e.g., Grieve 1978, fig. 2) showed that the maximum depth at Brent would be around 850 m. A case (2) structure would be Roter Kamm, a 2.5 km diameter impact crater in Namibia (Reimold and Miller 1989; Miller 2010). Fudali (1973) modeled a strong negative gravity anomaly as indicating an approximately 300 m thick sand fill overlying some 500 m of impact breccia. This would suggest an approximate depth to basement of the crater floor of some 800 m. Grant et al. (1997) and Miller (2010) did not favor extensive degradation of this at <5 Ma relatively young impact structure. A second example for this case (2) would be the Kgagodi structure in Botswana, which at 3.4 km has a similar diameter as Colônia. Gravity modeling has suggested a maximum depth of 900 m (Brandt et al. 2002).

Comparisons can be made also between Colônia and the newly discovered Xiuyan crater in China (Chen et al. 2011). Although smaller in diameter, with only 1.8 km, the Xiuyan crater is geologically very similar to Colônia, having formed in equivalent Proterozoic metamorphic rocks and bearing a Quaternay lacustrine sedimentary filling. A drilling at the center of the Xiuyan crater revealed that the thickness of the crater-fill sediments was 200 m. In comparison with this figure, the thickness of the filling of Colônia, which has a diameter of 3.6 km, could be expected to be greater than the 250–350 m suggested by the geophysical data.

Consequently, the depths of 250–350 m currently suggested by various geophysical data sets for Colônia seem to be inconsistent with the expected geometry of a simple, bowl-shape impact structure. However, in the absence of another viable nonimpact alternative for the genesis of Colônia, one could draw on a suite of—collectively unconstrained—parameters, including projectile nature (asteroid of iron or stony type, or comet), projectile size and velocity, impact angle and—above all, a geological parameter, namely the current unconstrained erosion depth, in an attempt to justify the comparatively shallow depth of this crater structure. The Colônia impact would have occurred during the period of general uplift of the Serra do Mar region and, as a consequence, considerable erosion of a relatively old Colônia impact structure could have reduced the apparent depth of this structure to a degree where only a lowermost section (<350 m deep) is preserved. It is obvious that only drilling of Colônia could help to resolve this crater size versus depth issue.

CONCLUSIONS

The analysis of the available geophysical data for the Colônia structure, coupled with comparison with known impact craters of similar sizes and formed in crystalline rocks, point toward a simple, bowl-shape geometry.

New seismic data acquired for the Colônia structure suggest the existence of a sedimentary fill of approximately 280 m thick and also the presence of two intermediate zones in between the sediments and the basement. The uppermost of these two zones is approximately 65 m thick and, in the event that Colônia would be confirmed as an impact crater, could be interpreted as a possible crater-fill breccia, whereas the lower zone could represents the shocked basement, with a thickness of approximately 50 m.

The likelihood of finding any remains of ejecta outside the Colônia structure is significantly reduced by the fact that the entire Paulistano Plateau has been subject to deep weathering and intense erosion during the Neogene and the Quaternary periods. Therefore, the only likely location for eventual impact breccia/shocked target rocks would be below the sedimentary fill of the structure.

The depths of 250–350 m suggested by the seismic data for Colônia seem to be inconsistent with the expected geometry of a simple, bowl-shape impact structure. However, there are a number of still unconstrained parameters that could explain this depth, such as projectile nature, size and velocity, impact angle, and the current erosion depth.

Therefore, only drilling into the basement of the Colônia structure could provide the necessary information to unravel the true nature of the structure. In addition, Colônia could be remarkably important for providing key information about Earth's history in the Quaternary, as it can supply a new set of data on climatic changes in the Southern Hemisphere and evolution of a tropical rainforest.

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