Chapter 5
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Circular Natural Geoforms, Sierras Pampeanas and Chacopampeana Plain, Argentina

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ABSTRACT

Structural geoforms often allow us to interpret the processes that gave rise to them. Circular geoforms are normally associated with meteorite falls, with the volcano caldera or the intrusion of igneous bodies, and elliptical geoforms with tectonic processes. We describe eight circular morphological features representing depressed areas based on visual interpretations from satellite and radar scans images. Three geoforms are located at the northern of the Sierras Pampeanas and the others five in Chacopampeana plain in Argentina. The La Ciénaga circular structure is 15 km in diameter, Las Cejas is 34 km in diameter and Schaqui is 21 km in diameter. The semicircular structures of the Chacopampeana plain (Las Víboras, El Fadeté, La Irma and Laguna de los Cisnes) are between 15 and 31.5 km in diameter. The elongated Campo del Cielo structure connected to the El Fadeté structure has an E-W strike, 12 km long and 4km wide, similar characteristics to those described in the literature. These studied structures have no associated volcanic rocks and no evidence of tectonic activity is observed. The La Ciénaga structure is a depression covered by quaternary sediments. The Schaqui structure is formed in an environment of intrusive rocks and its morphology is marked by the contact between them. In the Las Cejas structure, seismic profiles show the normal fault of one of its edges and the basin generated in its center. In Campo del Cielo several structures were found associated with the fall of meteorites; the structures described there seem to be formed by the impact of an object and contrast with the monotony of the rest of the area. Until now rings of these characteristics, magnitudes and diameters are unknown and unheard of in Argentina.

Keywords: Impact structures; meteorites; geoforms; pampean ranges; Chacopampeana plain.

1. INTRODUCTION

In nature, there are morphological features produced by processes or natural phenomena and whose geoforms, by themselves, allow to identify the process that generated them. For example, alluvial fans, glacier circuses, moraines, river basins, curved structures, elliptic structures, volcanic cones, volcanic caldera, impact structures, karst geoforms, etc. (e.g., [1,2,3,4,5,6,7]). The importance to study these geoforms lies in being able to understand the processes that formed them, abundance, geographical location, etc., in order to prevent and minimize natural risks.

Argentina has been alleged to have seventy-four meteorite impacts and seven other pseudo-meteorite impact sites [8,9,10]. In the strewn field of the Campo del Cielo meteorite in Chaco, 20 small craters are located within an area of 15km length [11,12], and the structures at Rio Cuarto (Cordoba) consist of elongated depressions that stretch over 40 km [13]. These meteorite impacts are arranged into five bands of NNE strike with a gap in the Santa Rosa region between 35° and 37°S and another in the Río Gallegos region (Fig. 1). We only know the age of 27 meteorite fall. The oldest are Luján in the province of Buenos Aires (50,000-20,000 years) and Campo del Cielo in the province of Chaco

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(4000±80 years, determined by radiocarbon) [14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29,30, [31,32,33,34,10,35]. The age of the other meteorite fall is between 1879 and 2008 (Table 1).

Fig. 1. Map of Argentina with the location of meteorite falls. With the dashed lines indicating that these sites lie in five bands with NNE strike. In the central and south area (Santa Rosa and Rio Gallegos) there are no records of meteorite falls

In the northern Sierras Pampeanas and in the Chacopampeana plain of Argentina we identified four areas with circulars natural geoforms for which we do not have any evidence to elucidate a process that gave rise to them (Fig. 2). The 15 km wide La Ciénaga geoform is east of the Sierra de Fiambalá in the province of Catamarca (27°25' S – 67°W), the 34km wide Las Cejas geoform is located to the north of Dorsal Mujer Muerta on the border between the provinces of Tucuman and Santiago del Estero (26°50' S – 64°45' W); to the southeast of the Otumpa hills, to the east and south of the meteorite impacts known as Campo del Cielo, five semicircular geoforms between 15 km and 31.5 km in diameter are identified (28° S - 62° W) and to the north-west of the Velazco Range is the Schaqui structure with 21km in diameter (28°30' S – 67°09' W).

Table 1. Age of meteorites fall in Argentina. WL: West latitude. SL: south latitude

WL	SL	Meteorite	Province	Location	Age (years)
-58° 20’	-31°55’	Berduc	Entre Ríos		2008
-68º 29'	-31°32'	Santa Lucía	San Juan	Villa Manuelita	2008
-68º 05'	-29°55'	Talampaya	La Rioja		1995
-65º 06'	-23°07'	Palca de Aparzo	Jujuy		1988
-58º 06'	-31°16'	La Criolla	Entre Ríos	La Criolla	1985
-64º 12'	-30°26'	Deán Funes	Córdoba	Deán Funes	1977
-65º 27'	-26°40'	Raco	Tucumán	Raco	1957
-60º 28'	-31°53'	Distrito Quebracho	Entre Ríos	Paraná	1957
-66º 00'	-33°00'	Árbol Solo	San Luis	Socoscora	1954
-67º 30'	-27°15'	Medanitos	Catamarca	Tinogasta	1953
-60º 40'	-31°25'	Arroyo Aguiar	Santa Fe		1950
-66° 09’	-44°07’	Uzcudún	Chubut	Ameghino	1948
-64º 52'	-32°20'	Belville	Córdoba	Unión	1937
-64º 33'	-30°53'	Capilla del Monte	Córdoba	Capilla del Monte	1934
-58º 03'	-30°47'	Chajarí	Entre Ríos	Federación	1933
-58º 37'	-33°00’	Gualeguaychú	Entre Ríos	La Constancia	1932
-63º 14'	-28°56'	Malotas	Santiago del Estero	Salavina	1931
-65º 14'	-31°36'	Aguada	Córdoba	Pocho	1930
-57º 57'	-31°11'	Isthilart	Entre Ríos	Federación	1928
-65º 17'	-32°45'	Renca	San Luís		1925
-61º 42'	-33°54'	Santa Isabel	Santa Fe		1924
-61º 32'	-37°20'	La Colina	Buenos Aires	General La Madrid	1924
-64º 57'	-33°10'	Achiras	Córdoba	Río cuarto	1902
-59º 50'	-32°22'	Nogoyá	Entre Ríos		1879
-60º 35'	-27°28'	Campo del Cielo	Chaco		4000±80
-59º 22'	-34°40'	Luján	Buenos Aires	Luján	50,000-20,000

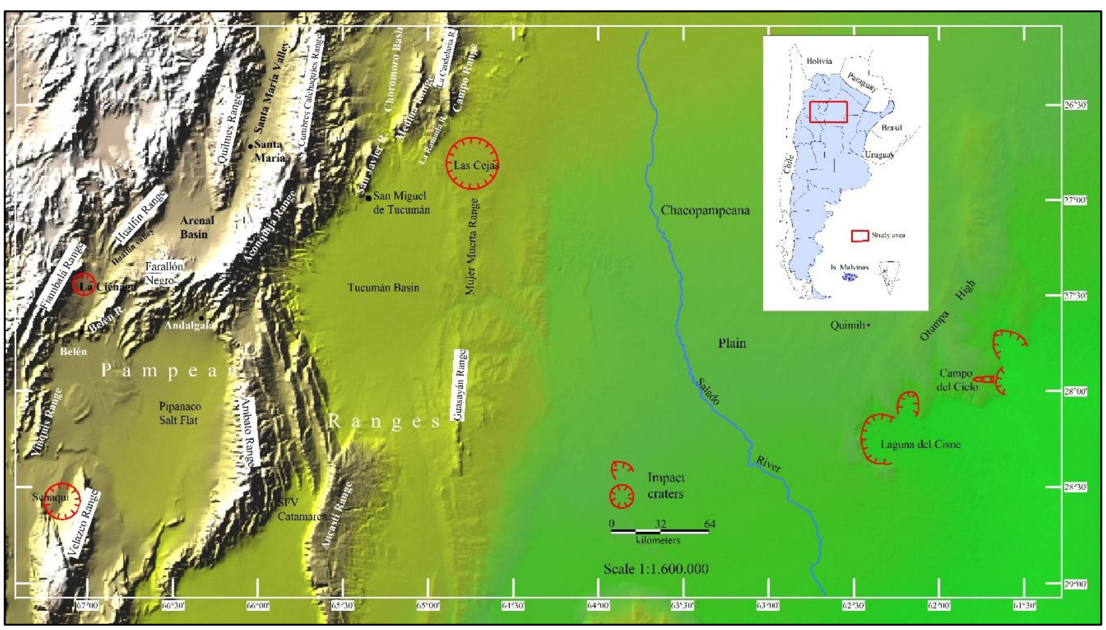

Fig. 2. Regional SRTM radar image showing the location of the La Ciénaga (15 km), Las Cejas (34 km), Campo del Cielo (31.5 km) and Schaqui (21 km) structural geoforms. It indicates the most important cities, the mountain ranges, and the largest basins

These structures are not associated with volcanic rocks, limestone, tectonic processes, glaciers, etc., with which we could link their origin; thus, it was thought that they could represent impact structures. Circular geoforms such as those studied in this work, are important not only for geomorphological analysis, because they could be associated with impact cratering, but also as a tool for analysis of the effects that the impact of large objects could produce and cause to our climate and biosphere in the affected area.

According to [36] an object of 750m width can generate a geoform of 15km diameter, which would be sufficient to produce an atmospheric explosion over the impact site, reducing solar radiation, causing temperature distortion and injecting of dust into the stratosphere, with a residence time of 1 Ma, and if the target composition was right, inject 5 times more sulphur than the current content in the atmosphere and thereby destroying the ozone layer. To generate a geological landform of 34km in diameter, it would require an object of 1700m width, causing a much greater impact, considering the impact of an object only 50m wide that produces a crater of 1km in diameter could obliterate an area of several hundred km2 around the impact site [37].

The impact structure Araguainha (Brazil) of 40km in diameter [38], was dated in 246 Ma (40Ar/39Ar) [39]. It is a complex crater that was eroded; its central part rises about 150m with respect to the surrounding surface, marked by rings of about 8km in diameter and an internal elliptical depression of about 3 to 4.5 km [39].

2. METHODOLOGY

La Ciénaga and Schaqui geoforms were identified from Landsat ETM and Sentinel2 images and the Las Cejas and Campo del Cielo in the Otumpa high geoforms on a Shuttle Radar Topographic Mission (SRTM) image. The following topographic maps were also used: 1:250,000 - 2766-II San Miguel de Tucuman and 2766-III Belen [40,41], 1:200,000 Hojas Geológicas, 12c Laguna Helada [42], 12d Capillitas [43], 1:250,000 - 2766-IV Concepción [44] and 1:250.000 – 2966-I Aimogasta [45]. We also use high-resolution digital elevation models (DEMs) with spatial resolutions of 12.5 m. These DEMs were generated from ALOS PALSAR data that we obtained from the Alaska satellite facilities (ASF DAAC, 2011). With the TopoToolbox program [46,47] we prepare slope maps and drainage network in order to identify anomalies in the drainage network that would allow us to infer neotectonic activity. The results obtained with this technique were not favorable. We also tried to get the originals of the seismic lines in the Las Cejas area and we did not succeed, so we use the diagrams published in the papers of [48,49]. We carried out observation campaigns in the areas of La Ciénaga, Las Cejas and Campo del Cielo but we did not obtain relevant data.

3. RESULTS

3.1 La Ciénaga Geoform (15km in Diameter)

The circular feature of La Ciénaga is located in the province of Catamarca, inside an intermountain depression situated between the Fiambalá Range to the west and the Belén Range to the east and south. To the north, a set of lower elevations separate the circular geoform from the Hualfín valley. This valley is limited to the NW by the Hualfín Range and to the SE by the Farallon Negro Volcanic Complex; toward the NE it is connected with the Campo del Arenal (Fig. 2).

La Ciénaga, situated southeast of the geoform, is the most important locality in the area. The Belén River flows to south along the eastern edge of the circular feature, it is the main collector of water in the area and the Loconte River and smaller channels flow down towards it from the mountains located to the west (Fig. 3).

We carried out a campaign to the La Ciénaga area that allowed us to recognize the regional geology, make measurements of structures, walk the side roads to the circular geoform, observe the gentle depression of the geoform and its sedimentary covers and appreciate the flat irons on the edge west of the Chango Real Formation. We did not find any superficial evidence that we could associate with meteorite impacts.

3.1.1 General geological characteristics

The oldest rocks are represented by metamorphic rocks of the Loma Corral Formation of Upper Precambrian - Lower Cambrian age that was intruded by granitic rocks of the Chango Real Formation in the Lower Palaeozoic [42]. These rocks form the core of the mountain that borders the geomorphic feature to the west, to the southeast there is a small outcrop of granitic rock that forms part of the Belén Range (Figs. 2 and 3).

The igneous-metamorphic rocks supporting continental sediments (El Cajón and El Morterito Formations) of Tertiary age belong to the El Bolsón Group. The volcanic rocks of the El Áspero Formation intrude the sequence of the El Morterito Formation and underlie the El Cajón Formation, which is also part of the El Bolsón Group [43,42]. The El Bolsón Group has its major development in the eastern sector of the area, close to the geomorphic feature; towards the northwest it overlies the igneous-metamorphic rocks (Fig. 3).

The geological sequence ends with three sedimentary levels of Quaternary alluvial fans and fluvioeolian deposits [42] (Fig. 3).

The igneous-metamorphic basement of the range that ends to the west of the geomorphic feature constitutes the core of a major anticlinal fold, striking NNE, which dips to the north (Fig. 3). The sedimentary sequence of the El Bolsón Group that forms part of the western flank of the fold dips westward. However, the eastern flank of the fold also consisting of the sequence of the El Bolsón Group is refolded, forming anticlines and synclines. Another outstanding feature of the eastern flank of the fold is that the sedimentary-volcanic sequence is not attached to the eastern flank of the igneous-metamorphic basement core. It is separated by the intermountain depression where the geomorphic circular feature is located. Only small outcrops are seen attached to the eastern edge of the mountain range (Fig. 3). All folds at the eastern edge of the intermountain depression strike NE and are cut by faults, eroded or covered by quaternary deposits (Fig. 3).

The metamorphic rocks of the Loma Corral Formation overlie the El Bolsón Group sequence because of a NE reverse fault that dips to the NW [42]. NW and NE regional lineaments parallel to the Loconte and Belén rivers are cutting folds in the northeast and southeast areas, respectively (Fig. 3). Here occur other minor lineaments that affect the entire geological sequence. In the intermountain depression, some lineaments are cutting the Quaternary deposits and Neogene sediments (Fig. 3).

3.1.2 Morphology of the circular feature

The circular geoform is a depressed area related to the rest of the intermountain region; the center of the depression is at 1800 ma.s.l. The western border is higher than the eastern with a 641m drop; the center is at 400m lower elevation compared to western side. The intermountain area is covered by Quaternary sediments that have formed as coalescing alluvial fans with a general slope to the southeast, distributed in three terraced levels. The depression of the circular geoform is evidence by the lowering sedimentary levels morphology. To the north, the second and third level deposits are truncated by the edge of the crater and the third level continually extends to the south. With greater development, but in the center of the depressed area, the third level can be seen only in the form of islands outcrops. After impact the depressed area was filled with deposits of the first level (Figs. 3 and 4).

The mountain range of NE strike, to the west of the study area, forms part of the Fiambalá Range (Fig. 2). The section that occupies the area is cut by three ESE striking lineaments. The lineament located between Azampay and Puesto Chistin marks a break in the range, to the north the range strike NE, and to the south in NS direction (Figs. 2 and 3). This break, coupled with the intense erosion of the eastern slope of the range has created an eastern concave shape, defining a semi-circular contour which forms the western edge of the crater (Figs. 3 and 4).

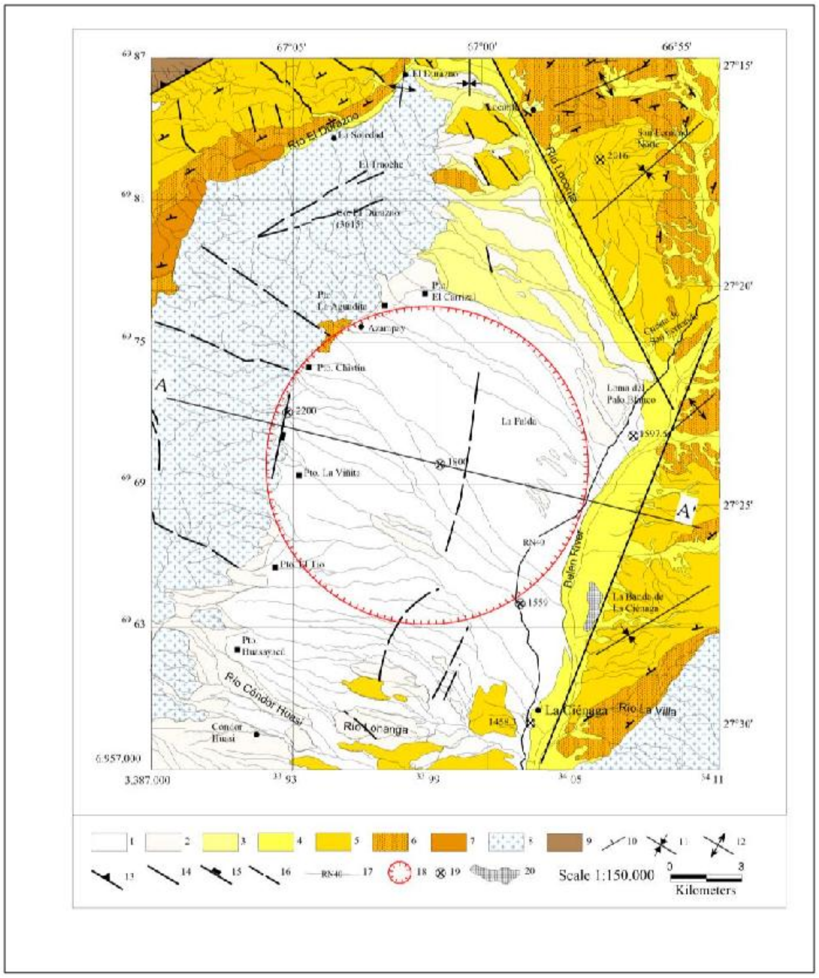

Fig. 3. Geological map of the La Ciénaga geoform. 1: Fluvial-eolian deposits (Q). 2, 3 and 4: Alluvial fans deposits (Q). 5: El Cajon Formation (El Bolson Group) (Ts). 6: El Áspero Formation (El Bolson Group) (Ts). 7: El Morterito Formation (El Bolson Group) (Ts). 8: Chango Real Formation (Pz). 9: Loma Corral Formation (Pc-C). 10: Stratification. 11: Syncline. 12: Anticline. 13: Reverse fault. 14: Lineament. 15: Normal fault. 16: Supposed fault. 17: National Route 40. 18: La Ciénaga geoform. 19: ma.s.l. 20: Acreage land area

The Neogene folded sequence of the El Bolsón Group is separated from the eastern flank of the range by the basin. Western reaches of these folds appear to have been cut, as if the sedimentary sequence had slipped into the depression, as the morphology presented alluvial fans in the northern sector (Figs. 3 and 4).

Northeast and northwest, outside the area, are the Farallón Negro and Vicuña Pampa volcanic complexes of Neogene age [50] (Fig. 2). The volcanic sequence of the El Cajón Formation (El Bolsón Group) originates from the Farallón Negro Volcanic Complex [43,42]; the circular feature appears to predate the sedimentary sequence of the El Bolson Group (Figs. 3 and 4). The E-W relief of the structure has a slope of 8% and the western edge is abrupt; in this slope, surficial drainage development and consequent erosion processes have occurred (Fig. 5). The eastern edge of the granitic rocks of the Chango Real Formation is marked by flat irons dipping to the east and constitute the edge of the circular geoform. These structures could have been modeled by normal faults (Figs. 3, 4, 5).

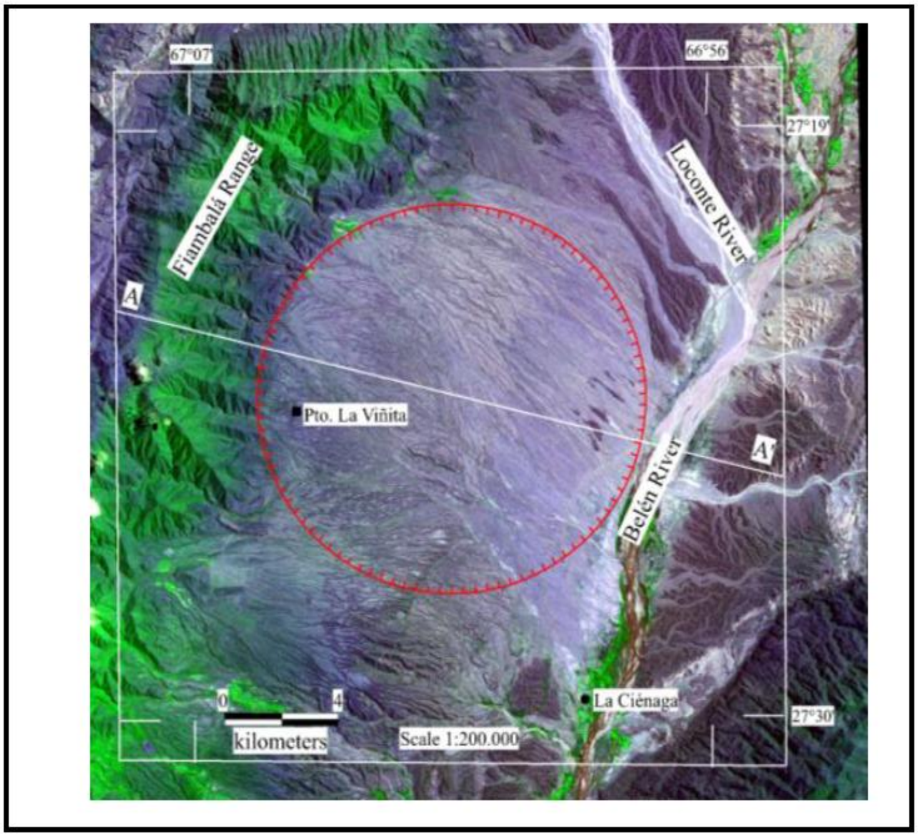

Fig. 4. Schematic location of the profile line and view of the regional morphology on a Sentinel image of the La Ciénaga circular structure

3.2 Las Cejas Geoform (34 km in Diameter)

Las Cejas geoform is located at the northernend of the Dorsal Mujer Muerta. This area forms part of a topographic high of sub-meridian strike that is 340 km long and 90 km wide and closes eastward of the Tucuman basin. To the north continue the foothills of the Campo Range, to the west border the La Ramada Range highlands, and to the east extend the Chacopampeana plains (Fig. 2). The locality of Las Cejas in the southern part of the depression is the most populated and important place around (Fig. 6).

We carried out a research campaign in the area of Las Cejas and the La Ramada Range. In the La Ramada Range we recognized the metamorphic basement and the sedimentary units that contain gypsum and limestone. In the circular geoform area, only the quaternary sedimentary cover, cultivated fields and some arid deposits are observed. From the edge of the circular structure it is possible to see the central depression of what is inferred may be an impact crater. Unfortunately, we do not find evidence in the outcrops of the area to corroborate this hypothesis.

3.2.1 General geological characteristics

The area is totally cultivated, so it is impossible to perform a visual interpretation of satellite images. The Dorsal Mujer Muerta is buried, covered by Neogene and Quaternary sediments. The rocks outcrop only in the Guasayán Range highlands (550 ma.s.l.). The natural drainage that flowed from the La Ramada Range was deactivated and replaced by artificial channels (Figs. 2, 6 and 7).

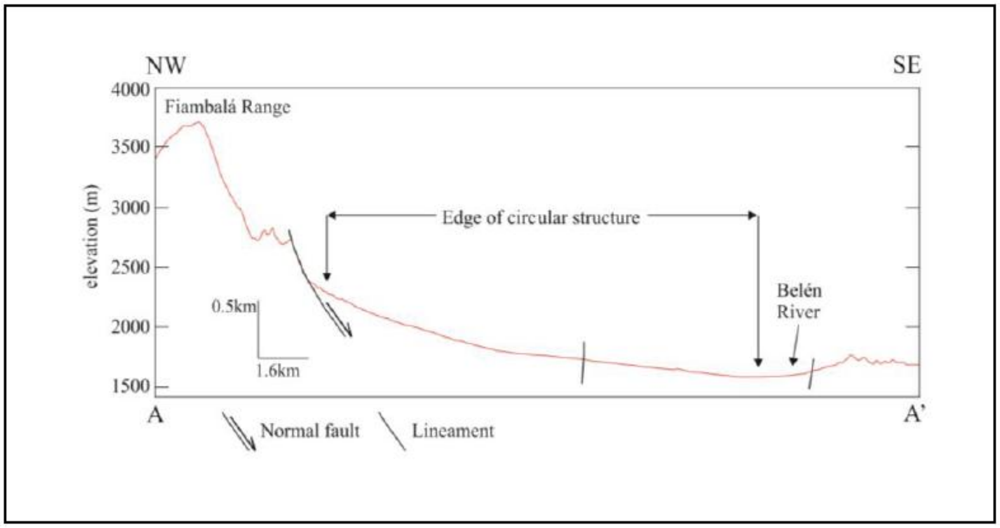

Fig. 5. Profile illustrating the general morphology of the La Ciénaga structure. The topographic difference in the eastern edge of the Fiambalá Range can be seen, which could be limited by a normal fault

In the de Guasayán Range outcrop metamorphic rocks of Upper Precambrian - Lower Cambrian age, intruded by granites, granodiorites and tonalities of Ordovician to Carboniferous age, which are covered by sedimentary rocks of Neogene and Quaternary age [44] (Fig. 2). To the west, in the ranges of La Ramada and Medina, there are outcrops of small bodies of Cretacic intrusive subvolcanic rocks [51].

A stratigraphic sequence represented by metamorphic basement, Middle Paleozoic, Cretaceous and Tertiary would be present in the subsoil of the Las Cejas circular structure [49] (Fig. 8a). A more detailed stratigraphic sequence was interpreted by [48] from seismic profiles 1567 and 2467, but they do not represent the Paleozoic horizon. Near the circular structure, we have not identified in satellite images or in the field any, rocks, or morphologies that could be thought typical of volcanic activity (Figs. 6 and 7).

3.2.2 Morphology of the circular feature

Las Cejas geoform is a semi-circular indentation of about 34km diameter that seems to have obliterated the northern tip of the Dorsal Mujer Muerta. In the radar image this feature is linked to a flat morphology elongated ESE (40km), a smooth surface that contrasts with the raised, truncated edges of the ridge to the west and south, and with others of lesser height to the north and east. Its minor axis is about 32km long. In topographic maps, it shows that the ground is not completely flat, with hills and depressions marking some 380m of topographic gradient (Figs. 6 and 7).

The center of the geoform is at 370 ma.s.l.; the western edge is higher than the eastern edge, with a vertical drop of 160m. The drop between the western edge and the central zone is 90m (Figs. 6 and 7).

In an N-S sequence of deep profiles (Figs. 7 and 8) interpreted from seismic lines, modified from [48] and [49], we can appreciate the internal structure of the Las Cejas geoform. The seismic line LS2463b (Figs. 7 and 8a) covers almost the entire circular feature, showing the stratigraphic sequence interpreted by [49] and the normal fault that marks the western edge of the circular structure. This normal fault does not affect the upper layers represented on the seismic line, but its superficial expression is marked by the edge of the circular structure (Figs. 7 and 8a). In the LS1567 seismic line (Figs. 7 and 8b) the Las Cejas circular structure is represented at the eastern end of the profile. The stratigraphic sequence interpreted by [48], folded, forming a syncline, is observed. Although the faults in this profile do not emerge, the normal faults at its eastern end coincide with the circular structure evidenced on the surface (Figs. 7 and 8b). The reverse fault of the western end of the profile (Fig. 8b) has a curved geometry, concave to the east, on which the stratigraphic sequences are stacked, forming the anticline; this fault does not outcrop either, but a surface expression is observed in the radar image (Fig. 7). The profile obtained with the LS2467 seismic line is located at the southern end of the circular structure; the stratigraphic sequence is observed discretely deformed by reverse and normal faults (Fig. 8c).

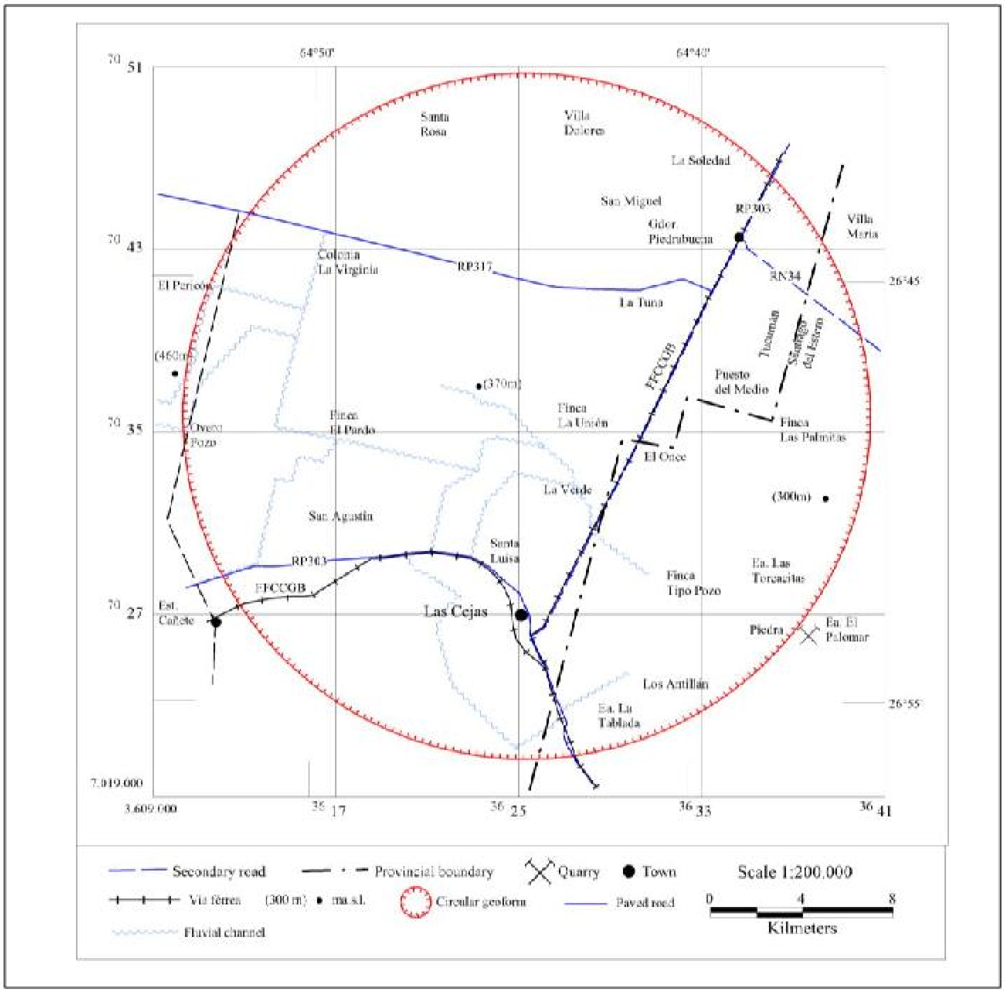

Fig. 6. Planialtimetric map of the Las Cejas geoform. It indicates localities, roads, artificial drainage and the interprovincial border

It is possible that the circular feature was formed prior to the deposition of Neogene sedimentary rocks.

3.3 Campo del Cielo Geoforms (31.5 km in Diameter)

In northern Argentina, the Campo del Cielo crater field consists of several meteorite impact craters, found in a band about 15 km long and 5 km wide trending approximately N60°E and formed at 4000 years ago; the largest meteorite discovered weighs 36t [11,52,53].

At east and southwest of the Campo del Cielo meteorite strewn field, at the southeastern edge of the Otumpa high, we identified in radar images the remains of four semi-circular and elliptical structures (Fig. 9). We can see in Fig. 9 the elongated elliptical depression E-W, formed by the impacts of Campo del Cielo meteorites. In this area, no volcanic manifestations were found which could be associated with these geoforms.

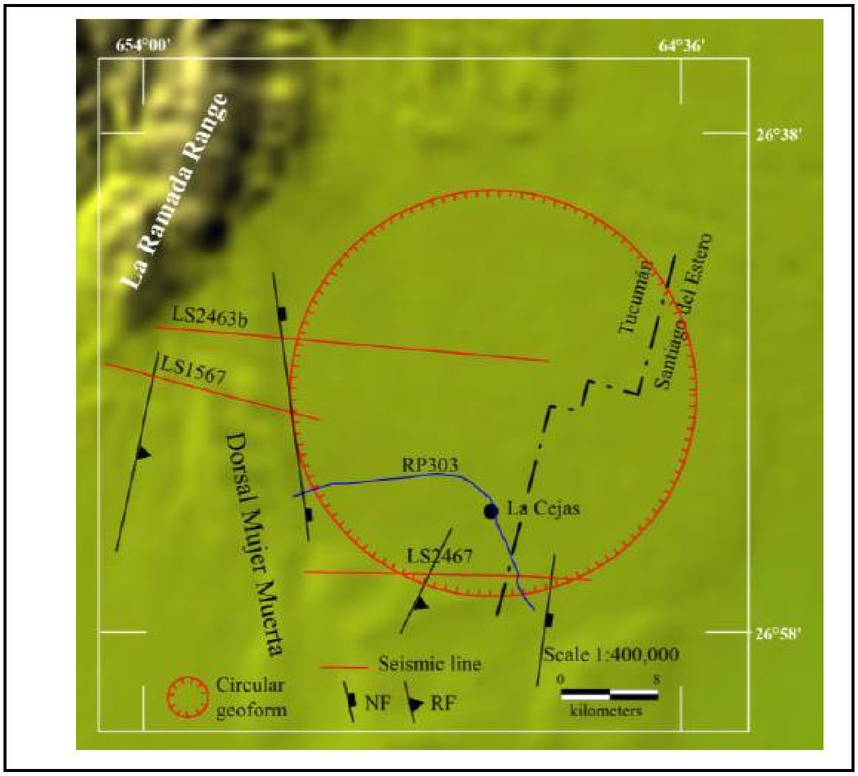

Fig. 7. Schematic location of the seismic lines (LS2463b, LS1567 and LS2467) and view of the regional morphology on a SRTM Radar image. Blind faults identified on seismic lines LS2463b and LS1567 are also drawn. The faults identified in the LS2467 seismic line have discrete surface expression

We carried out a research field trip in the Campo del Cielo area, visiting the excavated areas and taking photographs of the recovered meteorites. The area is forested, covered by Quaternary sediments, surface exploration is practically impossible with the naked eye and conventional remote sensing images, making it difficult to find evidence of the impacts without the help of underground research instruments.

3.3.1 General characteristics of the area

The Otumpa hills constitute a topographic high on the Chacopampeana plain and are represented by two elevations separated by the Árbol Blanco valley (Fig. 9). The Otumpa hills are very smooth topographic foothills whose relative heights with respect to the surrounding plain reach 100m [54]. The only rocky outcrops are represented by the Las Piedritas Formation correlated with the Ituzaingó Formation, of Pliocene age [55] and with the Tacuarembó Formation, of Jurassic-Cretaceous age [56]. The only outcrops of the quartzite sandstones of the Las Piedritas Formation are covered by loess and Quaternary river deposits [54]. The stratigraphic sequence of the area below the sedimentary cover would be represented by crystalline basement, Lower Paleozoic, Upper Paleozoic, Mesozoic and Cenozoic units [57]. These hillocks would have been formed by the tectonic activity of double vergent blind faults, reactivated during the Andean tectonics, causing the dissection of the quaternary floodplain [57]. The Salado river would have been antecedent to the Otumpa hills, later it migrated towards the west until finding its current NNW-SSE runoff, due to the quaternary growth of the relief [57]. The current channel of the Salado river is 109km west of Quimilí (Fig. 2).

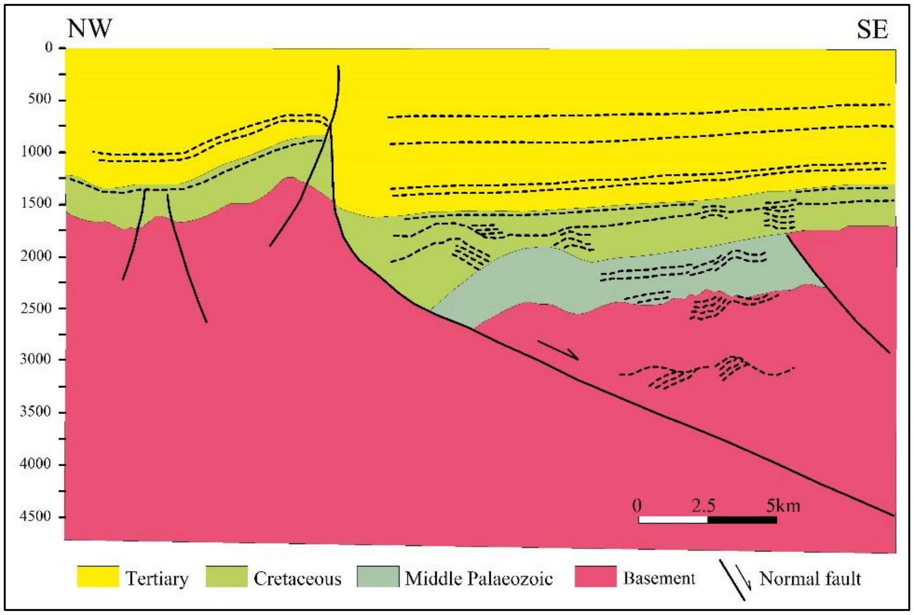

Fig. 8a. Profile obtained from the interpretation of seismic line LS2463b (YPF), modified from [49]. It shows much of the internal structure of the Las Cejas circular structure

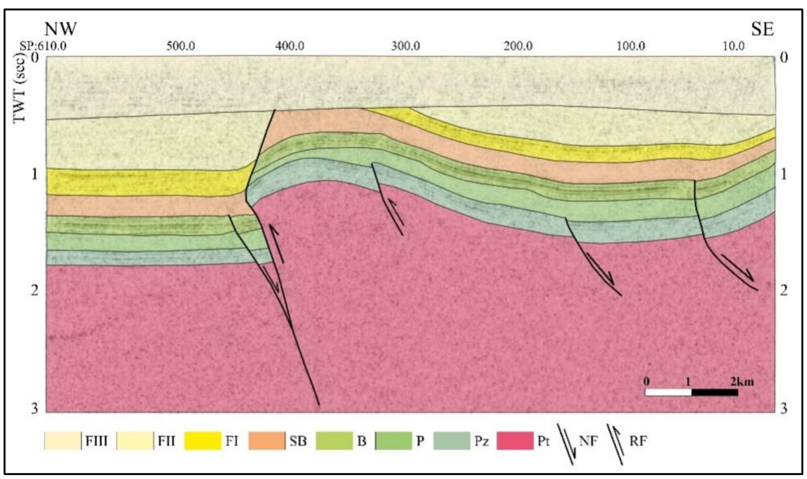

Fig. 8b. Profile obtained from the interpretation of seismic line LS1567 (YPF), modified from [48]. It shows part of the internal structure of the Las Cejas circular structure

3.3.2 Morphology of the semi-circular features

The figure 9 image shows the morphology of the raised relief on the Chacopampeana plain, known as Otumpa hills. They are two elevations separated by the Árbol Blanco valley; the Ochenta y seis high to the west and the Sachayoj and El Colorado topographic highs to the east. The Ochenta y seis high is approximately 151km long and the Sachayoj and El Colorado highs are 239km long. These elevations can only be seen on radar images due to the reduced unevenness (scarce 100m) existing with respect to the surrounding area. Both topographic highs have a break immediately south of the

Gancedo and Otumpa towns, to the north the direction of these elevations is N-S and to the south the direction is NE.

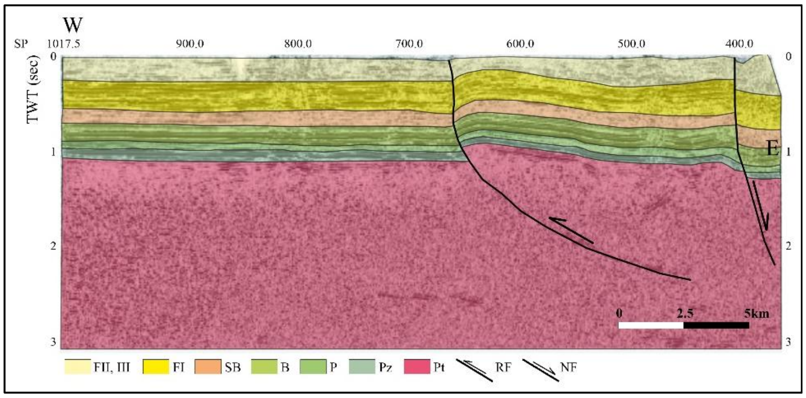

Fig. 8c. Profile obtained from the interpretation of seismic line LS2467 (YPF), modified from [49]. This profile is located on the southern edge of the circular structure

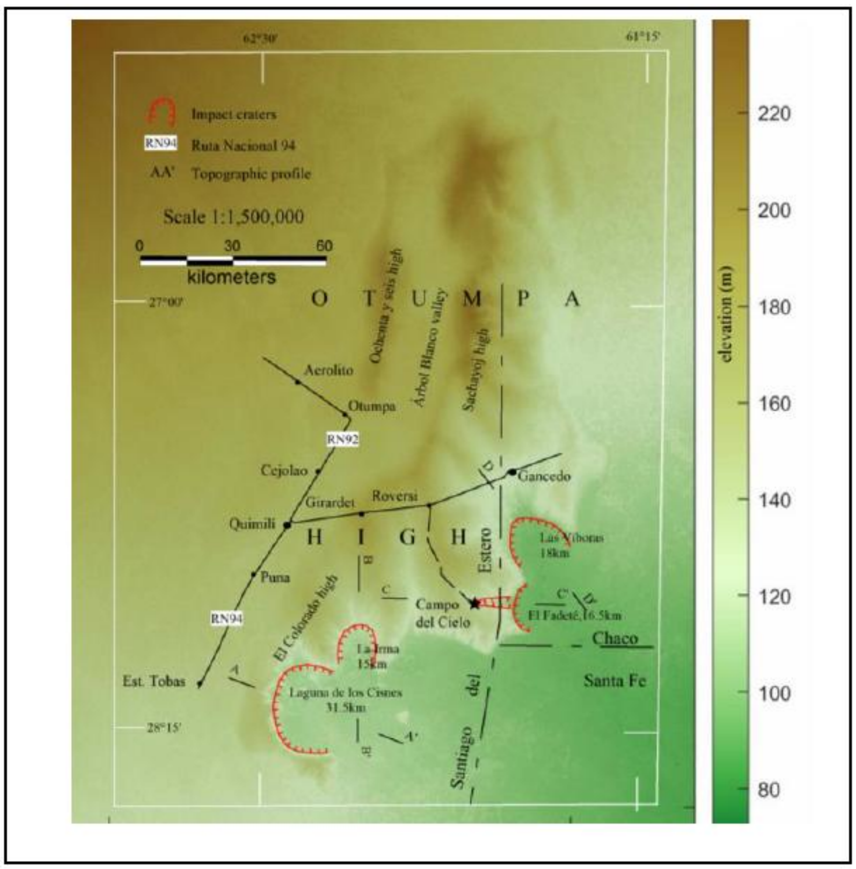

Fig. 9. DEMs generated from ALOS PALSAR from the Alaska satellite facilities. Topographic map showing four semicircular structures located in the Otumpa high area, east and southwest of the Campo del Cielo meteorite strewn field. These four structures represent lakes or small bodies of water. We also observe the E-W eliptical structure that represents the meteorite impacts known as Campo del Cielo as a whole

The eastern edge of the Otumpa hills is steeper and the counter-slope develops to the west, generally a slight erosion relief is observed. But that monotony breaks abruptly on the eastern edge of the El Colorado high, which contrasts with the rest of the area (Fig. 9). In the sector, intense differential erosion develops, with high-angle slope edges, generating semicircular geoforms oriented to the east and south (Figs. 9 and 10). We identified four outstanding semicircular structures: Las Víboras (18 km in diameter), El Fadeté (16.5km in diameter), La Irma (15km in diameter) and Laguna de Los Cisnes (31.5km in diameter). These structural depressions have now become lakes and occur as in showing the aftermath of an object's impact (Figs. 9 and 10). The El Fadeté and Laguna de los Cisnes structures, oriented east, have an abrupt western slope, 90m and 170m high, respectively (Fig. 10a and 10c). The slopes of the La Irma and Las Víboras structures oriented south and southeast are smooth, about 170m and 110m high, respectively (Fig. 10b and 10d).

The elliptical structure generated by the impact of meteorites known as Campo del Cielo [11,52,58] is identified immediately to the west of the semicircular structure El Fadeté (Figs. 9 and 10c). The Campo del Cielo structure is oriented E-W, is 12 km long and 4 km wide (Fig. 9). It is identified in the radar image by the different shades that reflect the relief (Fig. 9). The western slope is steep, the ground surface along the structure is uneven, with holes up to 25m deep and has a 70m ramp from the edge of the El Fadeté structure (Fig. 10c).

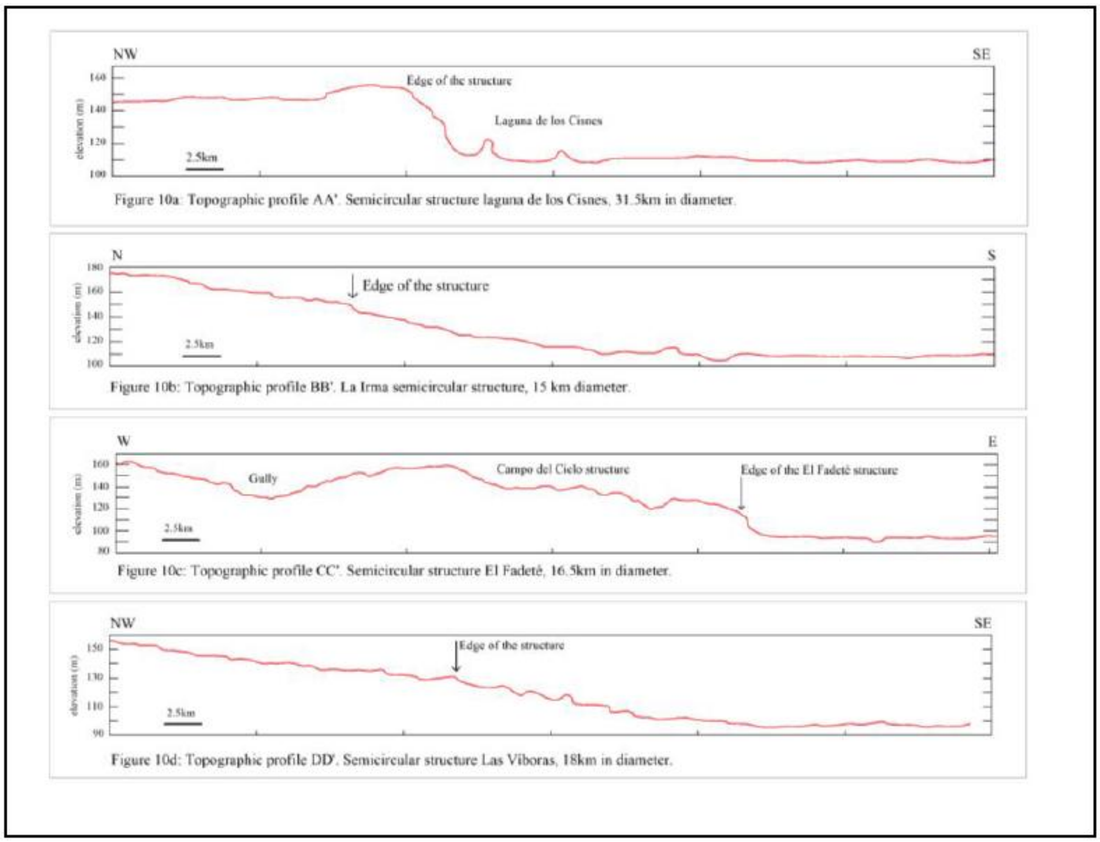

Fig. 10. Topographic profiles showing de surface relief of the semicircular structures in the Campo del Cielo area

3.4 Schaqui Geoform (21km in Diameter)

The Velazco Range is located in the northend of the La Rioja province, it is oriented N-S, has a triangular shape about 200 km long and its base in the north is about 33 km (Fig. 11).

At the northern end of the Velazco Range a circular structure about 21km in diameter is identified in satellite images (Fig. 11).

3.4.1 General geological characteristics

The igneous-metamorphic basement of the north Velazco Range is essentially made up of Paleozoic granitic rocks [59,60,61] (Fig. 11). The western edge is represented by the Ordovician Antinaco orthogneis. These intrusive rocks are affected by a mylonitic deformation belt (Mylonitic granitoides) with NW strike, of Ordovician age. On the eastern edge stands out the Asha granite, of Carbonic age. The Carbonic San Blas granite is in contact with the Asha granite. At the northern end of the Asha granite is a small intrusive, the Punta Negra porphyritic tonalite, of Ordovician age (Fig. 11).

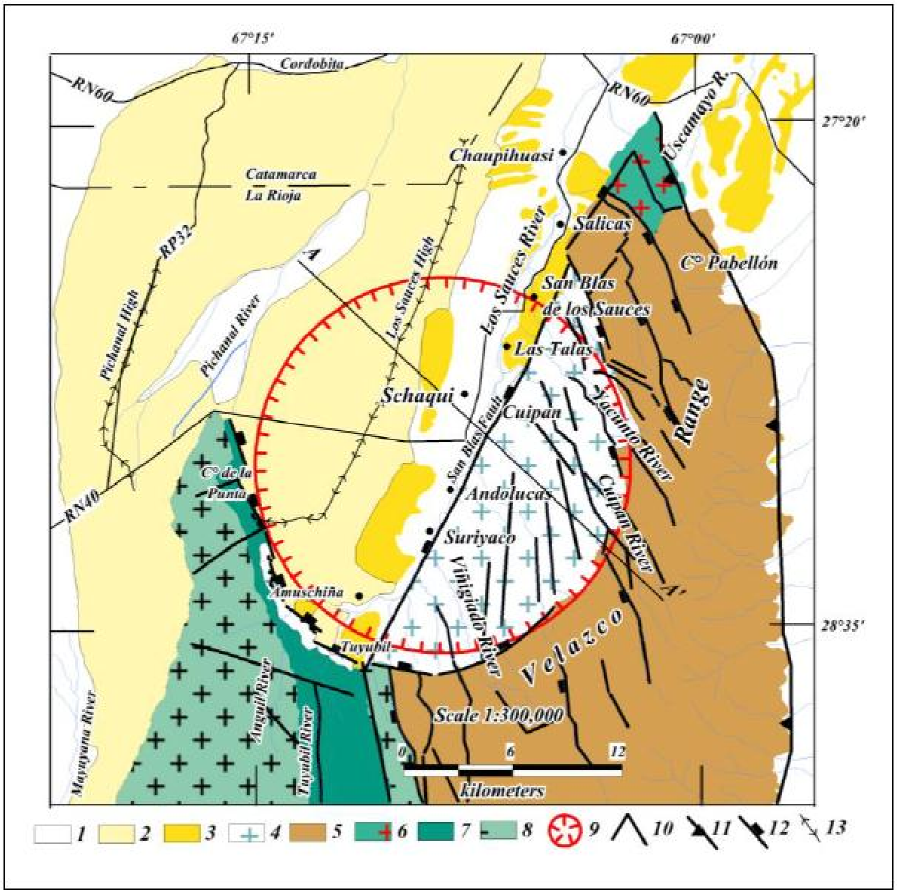

Fig. 11. Geological map of the northend Velazco Range. 1: Fluvio-aeolian deposits, gravels, sands (Quaternary). 2: Concepción Formation, conglomerates and coarse sandstones (Neogene). 3: Salicas Formation, sandstones, limolites and conglomerates (Neogene). 4: San Blas granite (Carbonic). 5: Asha granite (Carbonic). 6: Punta Negra tonalitic porphyry (Ordovician). 7: Mylonitic granitoids (Ordovician). 8: Antinaco orthogneis (Ordovician). 9: Circular structure. 10: Flat irons. 11: Reverse fault. 12: Normal fault. 13: Water divide

Towards the north-western sector and in contact with the intrusive rocks, sedimentary rocks are represented by the Salicas and Concepción formations of Neogene age (Fig. 11).

The eastern edge of the Velazco Range is raised and tilted to the west by a reverse fault. In the granitic rocks a parallel structural pattern with NW strike is observed (Fig. 11). The contact between the Asha granite and the Antinaco orthogneis is marked by a structure with NW strike, whose plane dips towards the NW, so it is interpreted as a normal fault (Fig. 11). The other structures that develop in the Asha granite are interpreted to be normal faults with inclination towards the SW (Fig. 11). The San Blas granite has a semicircular shape, whose diameter is marked by the San Blas normal fault, with NE strike and dip to the NW. The edge of this semicircle is a perfectly marked structure in contact with the Asha granite and the circular shape is completed by the edge of the Mylonitic granitoid and the Antinaco orthogneis, it is a normal structure that forms a depression towards the center of the circular geoform (Fig. 11). In the northeast wall of the Mylonitic granitoid and San Blas granitoid, flat irons are observed dipping towards the NE, showing the inclined plane of the normal fault (Fig. 11).

Towards the north-western sector of the map two discrete elevations are observed with NE strike, the topographic highs Los Sauces and Pichanal, which gently raise the strata of the Concepción Formation. These topographic elevations are separated by the Pichanal river valley (Fig. 11).

3.4.2 Morphology of the circular feature

In the image map of Fig. 12 it is possible to appreciate and distinguish the textures and the different morpho-structural features that characterize each of the intrusive units. The northwest corner of the Velazco Range is cut by the San Blas fault at the expense of which the Los Sauces river was formed, which discharges its waters to the NE (Figs. 11 and 12). The semicircle that forms the San Blas granite is sunk with respect to the intrusive Asha granite and Milonitic granitoids that surround it, limited by the Schaqui circular structure (Figs. 11 and 12). The Schaqui circular structure presents an internal depression highlighted by the San Blas fault and limited to the east by the intrusive San Blas and Asha and to the west by the Los Sauces topographic high (Figs. 12 and 13).

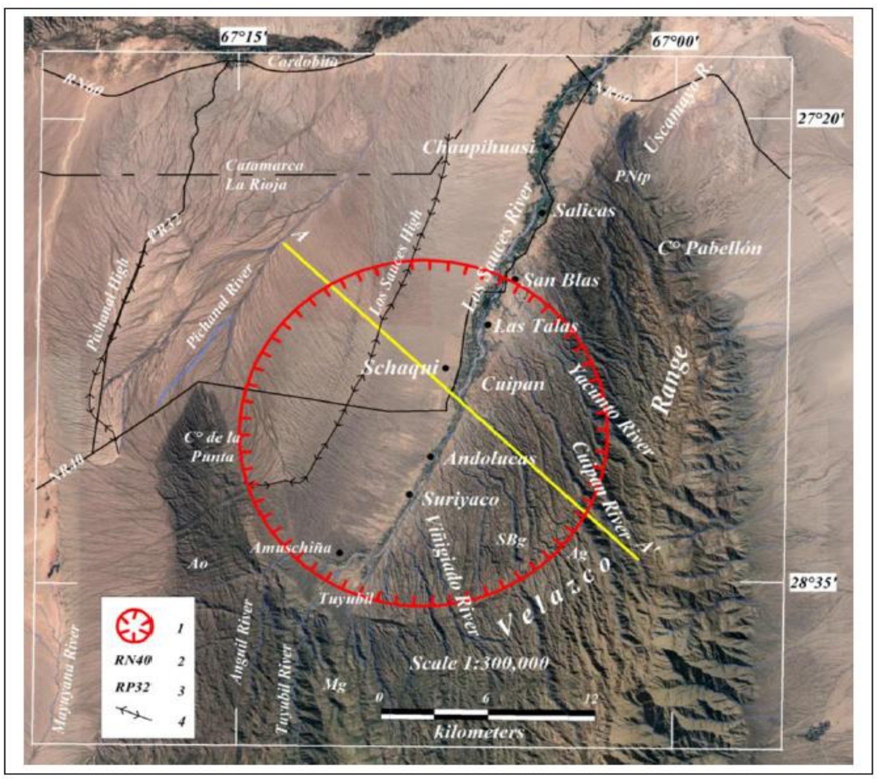

Fig. 12. Image map obtained from the visual interpretation of a Sentinel image. The morpho-structure of the intrusive igneous rocks and the landscape modeled in the sedimentary rocks can be seen. 1: Circular structure. 2: National Road N° 40. 3: Provincial Road N° 32. 4: Water divide. AA': Topographic profile. Ao: Antinaco orthogneis. SBg: San Blas Granite. Mg: Mylonitic granitoids. Ag: Asha granite. PNtp: Punta Negra porphyritic tonalite

4. DISCUSSION

No other circular structures of such diameters are known in Argentina. Of the seventy-four cases of meteorite falls and other seven pseudo-meteorites mentioned in the literature, only two are special cases of large meteorites (Campo del Cielo in Chaco and Río Cuarto in Córdoba). The meteorite falls in Argentina are aligned in a NNE strike, distributed from north to south, but in the central area (Santa Rosa) and to the south (Río Gallegos) there is no evidence of meteorite fall. The oldest meteorite falls (Lujan and Campo del Cielo) are dated between 50,000-20,000 years and 4000±80 years, respectively; the remaining meteorite falls age between the years 1879 and 2008 (Figs. 1 and 2; Table 1).

An impact structure can be simple or complex in its construction [62]. A simple crater on Earth is small, less than 4km in diameter, with a bowl-shaped geometry and a raised rim. A complex structure has diameters > to 4km and on Earth the largest known such structure was ca 250-300km wide, prior to erosion (Vredefort, South Africa) [63]. Except for very low-angle impact events, the resulting crater structures are invariably circular. According to impact magnitude and target composition, the interiors of complex impact structures will have a central peak (stratigraphic uplift), peak ring, or multiple ring structures.

La Ciénaga structure with a 15 km diameter, Las Cejas structure with a 34 km diameter and the Schaqui structure with a 21 km in diameter have circular shapes and in plan views on satellite images show a flat morphology with marked edges (Figs. 4, 7 and 12). Seen in a profile, these structures have a central depression (Figs. 5, 8a and 13).

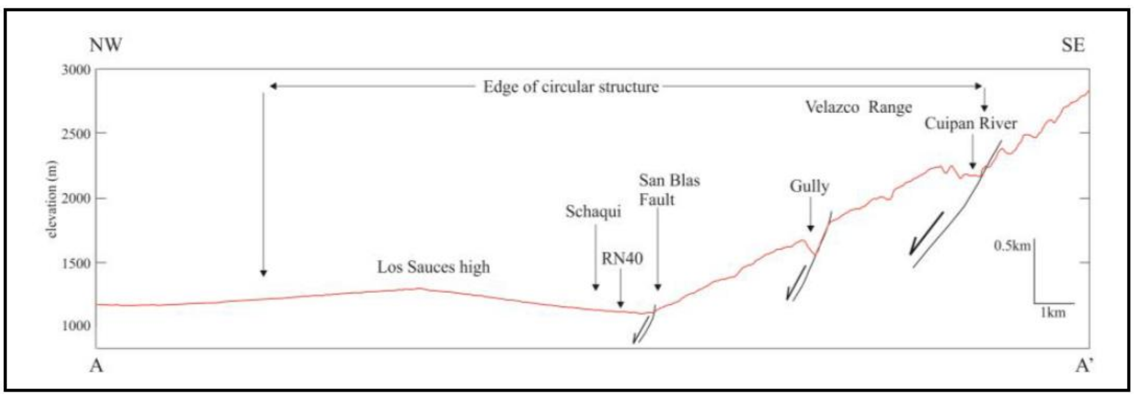

Fig. 13. Topographic profile of the sector interpreted as a Schaqui circular structure. The center of the depression and the normal faults of the eastern edge are observed

In Chaco, more than 20 impact craters are known from which numerous meteorite fragments were recovered; apart from Campo del Cielo other prominent craters are La Perdida, Rubin de Celiz, Gomez and Laguna Negra [9].

The crater generated by the fallen meteorites in the Campo del Cielo area is about 15km long and 5km wide and the trajectory of the objects would have had a N60°E strike, forming an elliptical structure; however, the trajectory of the object that generated crater 9 would have been N8°E [52]. The elliptical structure that we identified in the Campo del Cielo zone has an E-W strike, 12 km long and 4km wide, it was probably generated by the impact of meteorites fallen there. It is probable that the El Fadeté structure, which continues with the Campo del Cielo structure, was also formed by the impact of these meteorites.

Are Campo del Cielo geoforms (Las Víboras, El Fadeté, La Irma y laguna de los Cisnes) meteor impact structures related with meteorites fallen 4000±80 years ago? with other age meteorites? or are they natural erosional features?

In South America, the only known impact crater is Araguainha (Brazil) with 40 km in diameter [39]. La Ciénaga, Las Cejas and Schaqui structures do not have the morphology that characterizes Araguainha crater impact, perhaps because they are covered by Neogene and Quaternary sediments that bury those characteristic features. However, the erosion of these sediments marks the outer rings of structures, and can be observed in satellite images. They are not related to volcanic structures because there are no lava flows associated with them, nor have there been volcanic rocks identified near the structures, nor on satellite images nor during field work.

In Las Cejas structure, the seismic profiles show a normal fault on its western edge and the basin in the central area of the structure (Figs. 8a and 8b). The Schaqui structure is very well marked by the contact between the San Blas and Asha granites (Fig. 12). These intrusives were placed in a shallow environment, under a regime of extension and as a product of a shortlived coal-age magmatism [61]. The San Blas granite has a perfect semicircular morphology, its diameter marked by the San Blas fault, as if it were missing the other half, which could be buried, and the outcropping half is sunk with respect to the Asha granite (Fig. 12). Perhaps the Schaqui structure is simply the product of the igneous and tectonic processes that occurred in the Paleozoic.

La Ciénaga, Las Cejas, Schaqui and Campo del Cielo structures are geomorphic features that need to be investigated in more detail to elucidate their origin and age. A relation with meteorite impact or other natural events must be elucidated, considering that:

- They are circular, slightly elongated geoforms that are well defined.
- No impact structures have been yet identified in Argentina.
- The sediments that cover them appear to have slumped inward towards their rings and the erosion permits to see the circular morphology of the structures.
- Both structures La Ciénaga and Las Cejas appear to have been originated before deposition of the Neogene sediments.
- Nearby in the La Ciénaga area there are volcanic manifestations (Farallón Negro and Vicuña Pampa) but the circular structure does not seem to be related to a volcanic event.
- In the Las Cejas, Schaqui and Campo del Cielo area, no volcanic manifestations have been found that could be associated with these structures.
- The impact of large objects would produce catastrophic effects on the climate and biosphere. To generate an impact structure of 15km in diameter (La Ciénaga) it would require an object of 750m wide and to generate a structure of 34km (Las Cejas) an object of 1700m wide, at an average velocity of 25 km/s [63]. The impact of objects with these dimensions can produce an atmospheric explosion over the impact site, reducing solar radiation, temperature distortion and injection into the stratosphere, for periods of up to 1 Ma, five times more sulphur that the current content, destroying the ozone layer [36,37].

5. CONCLUSIONS

In none of the studied areas did volcanic events occur nor are there any karst soils with which circular and semicircular structures could be associated. The processes that could give rise to these structures would be tectonic, igneous, or meteorite impacts.

La Ciénaga structure has a central depression and its edges are discreetly insinuated under a cover of quaternary sediments. The Fiambalá range is curved and its eastern edge as modeled by a punch marks the western edge of the circular structure (Figs. 4 and 5).

Las Cejas structure has a surface expression only visible on radar images due to the differential erosion between the quaternary filling and its more resistant edges (Fig. 7). The geomorphological landscape presents a central depression on the surface and the seismic profiles show the normal fault of the western edge and the central basin modeled by some geological process. (Figs. 8a, 8b and 8c).

The morphology of the eastern edge of the El Colorado high, in the Otumpa hills, contrasts sharply with the erosion surfaces of the other elevated areas. They are semicircular structures with a steep slope as if they were modeled by the impact of an object, some of them are shallow lagoons, without rivers to feed them (Fig. 9). The elliptical structure Campo del Cielo, oriented E-W (Fig. 9), coincides with the description made by [11,52,53], and we consider that was produced by the impact of meteorites. The remaining structures (Las Víboras, El Fadeté, La Irma and Laguna de los Cisnes) could also have been formed by the impact of meteorites (Figs. 9 and 10).

The morphostructure of the Velazco Range evidences that its NW end is truncated by the San Blas fault (Figs. 11 and 12). The San Blas granite has a semicircular shape, it is sunk with respect to the Asha granite and the contact between these intrusives perfectly marks the Schaqui circular structure (Fig. 12). The Schaqui structure is also marked by the edge of the mylonitic rocks where flat irons are formed, also showing normal fault planes (Fig. 12). The center of the Schaqui structure is a depressed area, coinciding with the San Blas fault, to the east the Velazco Range rises and to the west the Los Sauces high (Figs. 12 and 13). Schaqui structure Perhaps is related to the igneous and tectonic processes that occurred in the Paleozoic.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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