Geodesy and Geodynamics 9 (2018) 77–92

Contents lists available at ScienceDirect

Geodesy and Geodynamics

journal homepages: www.keaipublishing.com/en/journals/geog; http://www.jgg09.com/jweb_ddcl_en/EN/volumn/home.shtml

Anomalously deep earthquakes related to the Ojo de Agua Lineament and its tectonic significance, Sierras Pampeanas of Córdoba, Central Argentina

Ana Caro Montero [a,*], Roberto D. Martino [a,b], Alina B. Guereschi [a,b]

[a] CICTERRA, Centro de Investigaciones en Ciencias de la Tierra (CONICET–UNC), Córdoba, Argentina

[b] Departamento de Geología Básica, Facultad de Ciencias Exactas, Físicas y Naturales (FCEFyN), Universidad Nacional de Córdoba (UNC) y CIGEA (FCEFyN–CNEA), Córdoba, Argentina

ARTICLE INFO

Article history:
Received 12 April 2017
Received in revised form
2 October 2017
Accepted 9 October 2017
Available online 6 December 2017

Keywords:
Brittle tectonics
Faulting
Seismotectonics
Deep earthquakes
Andean foreland

ABSTRACT

The Sierras de Córdoba are the easternmost uplifted ranges of the Sierras Pampeanas geological province of Argentina. They are composed of a Neoproterozoic–Paleozoic basement arranged in north–south aligned mountain ranges, limited by west-vergent reverse faults, reactivated or formed by compressive tectonics during the Andean orogeny. The ranges are also affected by oblique subvertical lineaments, probably related to pan-Gondwanan structures. The recorded seismicity shows anomalously deep earthquakes (up to 80 km depth) concentrated in the northwestern area. We attribute this seismicity to the current tectonic activity of the Ojo de Agua Lineament. This lineament is a N130º–135° strike, 70º–80° NE dip, macrostructure with more than 80 km depth and 160 km length. A sinistral trans-compressional kinematics (convergent oblique shear) is deduced by the focal mechanism of a deep earthquake, together with hydrological and geomorphological features strongly modified. The continental lithosphere under the Sierras de Córdoba would be colder and more rigid than in a normal subduction area, due to the retraction of the asthenospheric wedge to the foreland, causing seismicity to depths greater than 40 km, below the Mohorovičić discontinuity. Neogene volcanism would be closely related to this lineament, allowing the rapid ascent of melts from the mantle.

1. Introduction

The Sierras de Córdoba are the easternmost ranges of the Argentinean geological province of Sierras Pampeanas and are part of the Andean foreland. They are composed of Neoproterozoic–Paleozoic basement outcrops arranged in north–south aligned mountain ranges. West-vergent reverse faults, formed by compressive tectonics during the Andean orogeny, produced the uplifting of east-tilted asymmetric blocks and the present landscape of the sierras. Oblique to the mountains, older subvertical faults are also recognized, known as lineaments. Along geological time, several compressive and extensional events were superimposed, with reactivations of preexisting structures. In this geological framework, the oblique lineaments have been proposed as one of the main controls of the Andean tectonic deformation in the Eastern Sierras Pampeanas [1–3].

The seismicity recorded in the Sierras de Córdoba shows a diffuse epicentral distribution. Most of the hypocenters are located between 5 and 40 km depth, but a group of them are between 40 and 90 km depth. These deep earthquakes can not be attributed to the Nazca plate, which subducts below the South American plate to an estimated depth between 175 and 200 km below the sierras [4]. In addition, these earthquakes occurred at a depth greater than the Mohorovičić discontinuity in this area, established here between 35 and 38 km by Perarnau et al., [5]. Most of the anomalously depth earthquakes are found in the northwestern sector of the Sierras de Córdoba and could be related to one of the oblique lineaments, such

* Corresponding author. Av. Vélez Sársfield 1611, Córdoba X5016GCA Argentina.
E-mail address: acaromontero@gmail.com (A. Caro Montero).

Peer review under responsibility of Institute of Seismology, China Earthquake Administration.

Production and Hosting by Elsevier on behalf of KeAi

https://doi.org/10.1016/j.geog.2017.10.001

1674-9847/

as the Ojo de Agua lineament. The subduction of the horizontal Nazca plate causes the migration of the asthenospheric wedge to the foreland [6,7], displacing the isotherms and causing the cooling of the crust, and that particular geotectonic setting must be analyzed to explain the causes of deep seismicity.

Therefore, the main objectives of this work are: (1) to analyze the anomalously deep seismicity detected in the northwestern sector of the Sierras de Córdoba and its relationship with the recognized surface structures, particularly with the Ojo de Agua lineament; and (2) to explain the causes of the occurrence of seismicity below 40 km depth by means of a hypothetical model of the distribution of isotherms in the crust, based on previous studies at these latitudes.

2. Geological setting

2.1. Regional setting

The Sierras Pampeanas are a region of elongated mountain ranges of crystalline basement outcrops and intervening broad valleys. Their uplifting is conditioned by the effect of the present compressional tectonics on the Andean foreland, at around 1000 km from the Chilean trench, coinciding with a sector of low-angle subduction of the Nazca plate beneath the South American plate. The "flat-slab" geometry of the subducted Nazca plate and the deformation of the upper plate (South American plate) have been compared with the Laramide orogeny in North America and the external massifs of the Western Alps [8–12]. The foreland deformation is the result of the flat-slab subduction between 27° and 32° since 20 Ma to present [13,14]. In a review, Ramos & Folguera [15] constrained the flat-slab subduction geometry from 12 Ma to present. Basement deformation (thick-skinned tectonics) affected an area of about 800 × 600 km and the basement blocks were uplifted mainly by reverse faulting, locally folded.

The Sierras de Córdoba, the easternmost group of the Sierras Pampeanas, consists of a polydeformed metamorphic basement [16,17] of Neoproterozoic–early Paleozoic ages [18,19]. The metamorphic basement is predominantly composed of large anatectic migmatitic massifs, over 1000 km^2 as the San Carlos Massif and Yacanto Group (Fig. 1), with minor gneisses, amphibolites and marbles. The metamorphic basement was intruded by Paleozoic granitoids, as the Achala Batholith in the central area of the ranges (Fig. 1). In the northwestern area, an important group of Neogene trachyandesitic volcanic rocks and pyroclastic deposits (Pocho Volcanic Complex) are recognized. This magmatism is a product of the eastern migration of the Andean magmatic arc due to the "flat-slab" subduction of the Nazca plate (7.9–4.5 Ma [20,21]).

The metamorphic basement has a highly pervasive metamorphic foliation called S2 (Neoproterozoic–Cambrian age), which exerted a strong control on later deformations [1,2,16,22–25]. The basement was imbricated by contractional ductile shear zones (e.g., Ambul–Mussi Shear Zone, Fig. 2) during Cambrian, Ordovician–Silurian and Devonian times [26,27].

The Sierras de Córdoba are arranged in north–south mountain ranges formed by uplifted asymmetric blocks, limited by reverse faults generated or reactivated during the Andean orogeny. The mountain ranges are also affected by northwest–southeast subvertical lineaments, oblique to the main faults, as the Ojo de Agua Lineament, target of this study (Figs. 1 and 2). These were mentioned as faults the first time by Gross [28], who suggested they had a profuse pattern of internal fracturing. However, in most cases there is no visible deformation other than the linear geomorphological feature. Petrographically, retrograded biotite replaced by muscovite and chlorite is commonly observed in the affected rocks [29]. These lineaments would probably be related to pan-Gondwanan structures [30,31]. The role of the oblique lineaments has been considered as part of the nucleation and development of the Cenozoic faulting by Martino et al. [1–3].

According to Jordan & Allmendinger [10], the uplift of the basement blocks in the Sierras de Córdoba would have started about 10 Ma ago, but today there is evidence of raising as old as the Carboniferous period through K–Ar dating in fault gouge, and (U/Th)/He thermochronology in apatite and zircon show the same ages for cooling and probably exhumation [32–37]. Block uplift could be produced by: (1) low-angle reverse faults (basement thrusts [22,38]), locally modified to higher angles by stacking of the under-thrusting wedge [24]; and (2) reactivation by inversion of high-angle normal faults of the Cretaceous rift [39]. Other older faults, mentioned above as oblique lineaments, also have been reactivated [3].

The seismicity in the Sierras de Córdoba was studied by Richardson [40], Perarnau et al. [5] and Richardson et al. [36], with the aim of identifying the major discontinuities: the brittle–ductile transition in the crust and the Mohorovičić discontinuity. Richardson et al. [36] defined four clusters based on earthquakes recorded by seismic stations installed in the Sierras de Córdoba during their research between August 2008 and August 2009 (Fig. 3): (1) Sierra de Los Cóndores cluster, south of the Sierra Chica; (2) Cruz del Eje cluster, north of the Sierras, between the Sierra de Pocho and Sierra Chica faults; (3) Nono Valley cluster, near the nexus between the Sierra Grande and the Sierra de Comechingones; and (4) Merlo cluster, under the trace of the Sierra de Comechingones Fault. The earthquakes included in this clusters are shallow (mainly less than 30 km depth) and their magnitudes are less than 2.5 on the Richter scale.

2.2. Local structural setting

In the northwestern zone of the Sierras de Córdoba (Fig. 1), the Ojo de Agua Lineament is recognized as a straight, subvertical structure with 130–135° N trend. In this sector, it would be the nexus between the Ciénaga del Coro Fault and La Sierrita Fault (Fig. 4), forming a regional sigmoidal structure (Fig. 2 [2,3]). The lineament extends to the northwest, cutting the Sierra de Pocho Fault at the eastern foothill of the homonymous sierra, where it forms a deep gorge near the town of Guasapampa. Towards the southeast, it crosses the Achala Batholith up to their eastern metamorphic country rocks, where it would continue in the Soconcho Lineament. Thus, the Ojo de Agua Lineament longitude would be 160 km, crossing all the Sierras de Córdoba (Fig. 1). This study focuses in the present seismic zone of the lineament, with a length of 75 km, between the Sierra de Pocho and Sierra Grande (Fig. 2).

The Pocho Volcanic Complex (Fig. 1) has an elongated morphology, with WNW–ESE maximum axis. Arnosio et al. [21] found two main strikes trends of the dykes in the center of the complex: northwest–southeast and northeast–southwest (Fig. 2). These are described as conjugated fractures cutting the basement at regional scale and probably related to the compressive strain accommodated during the Andean cycle, with significant strike-slip movements. The Ambul–Mussi Shear Zone, located at the southeast of the volcanic complex and that would continue below it [26,41], could be related to the emplacement of the Cenozoic Pocho volcanism [21].

The Pocho Volcanic Complex could be associated with the hydrated mantle wedge above the subducted flat-slab Nazca plate [42] causing a trachyandesitic volcanism, located in the area, during two distinct magmatic cycles (whole rock, K–Ar radiometric data [43]). In the first cycle (7.0 ± 0.6 to 7.9 ± 0.6 Ma), four domes of K-rich calc-alkaline composition

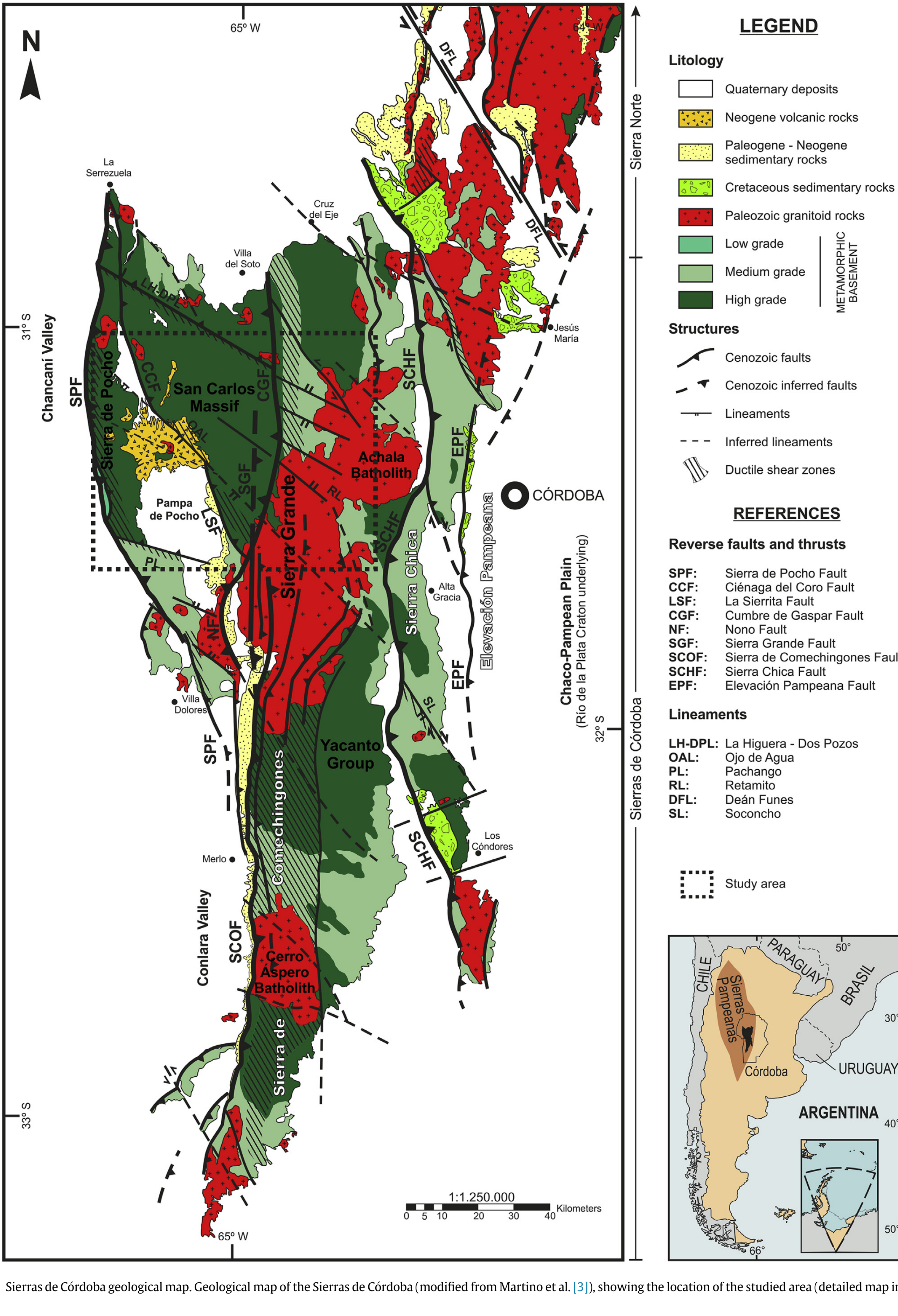

Fig. 1. Sierras de Córdoba geological map. Geological map of the Sierras de Córdoba (modified from Martino et al. [3]), showing the location of the studied area (detailed map in Fig. 2).

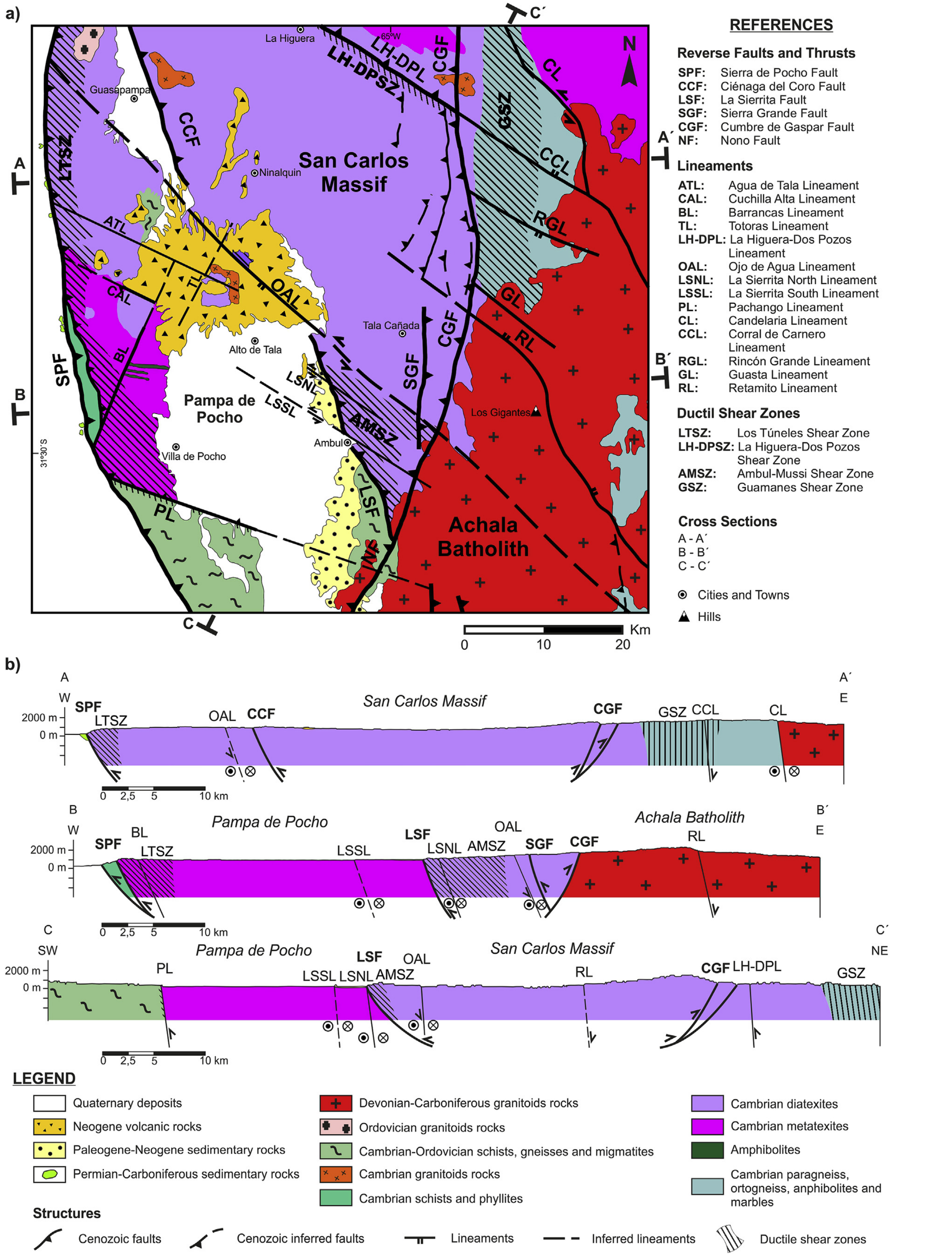

Fig. 2. Studied area geological map. a) Detailed geological map of the northwestern part of the Sierras de Córdoba (see Fig. 1 for location). b) Geological sections crossing the main brittle structures of the studied area: A–A′ and B–B′ sections are perpendicular to the main reverse faults, and C–C′ section is perpendicular to the lineaments. Dips are based on the available data [2,3].

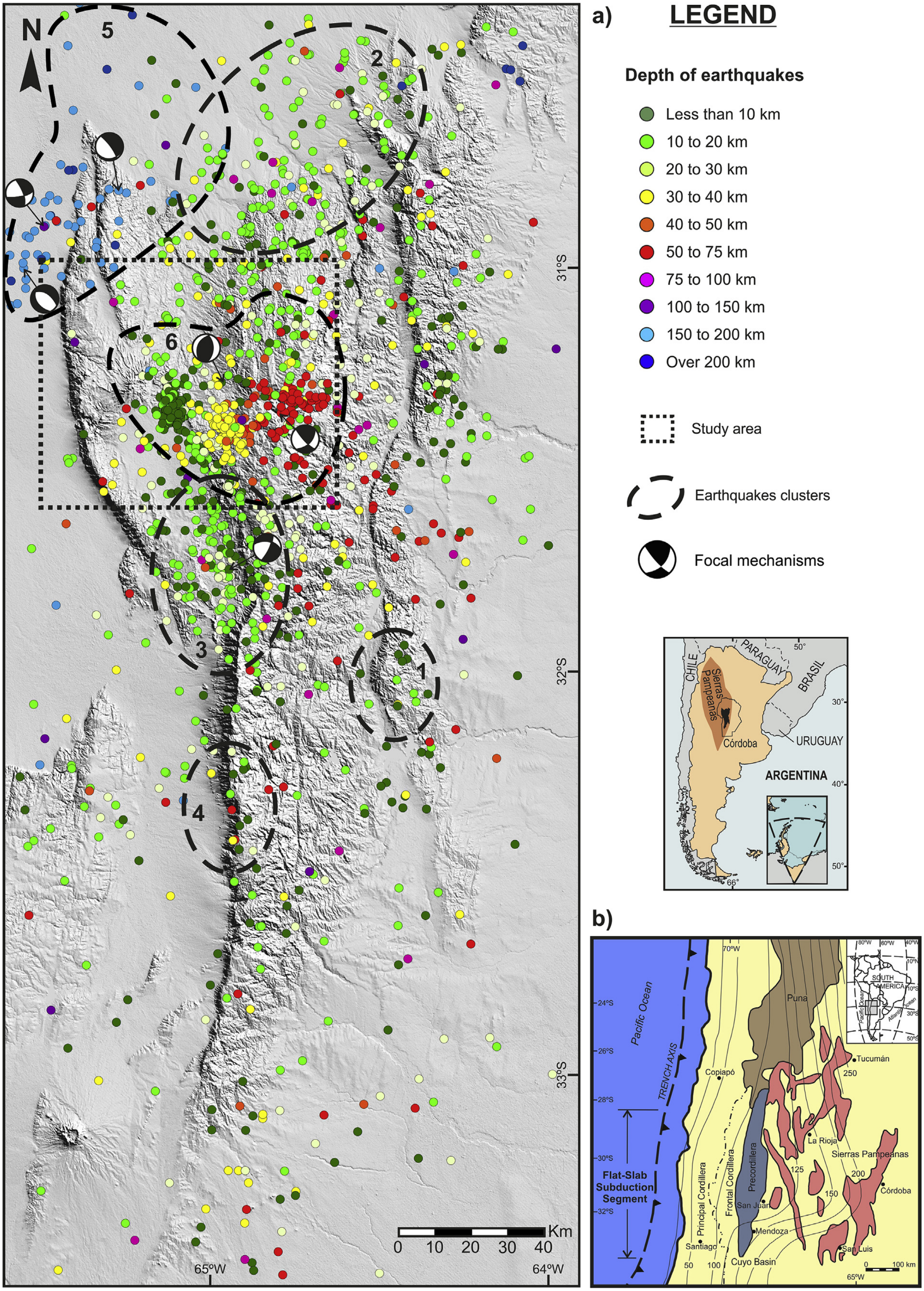

Fig. 3. Seismological distribution in Sierras de Córdoba. a) Seismic epicenters of the Sierras de Córdoba database used for this study (INPRES, USGS and Richardson [40]) projected on a digital terrain elevation model. See Appendix. b) Map of the central sector of Argentina showing the contours of the low angle subduction of the Nazca plate from Cahill & Isacks [4] at these latitudes (modified from Ramos & Folguera [15]).

Fig. 4. Panoramic view of the Ciénaga del Coro Fault scarp, Ojo de Agua Lineament, and La Sierrita and surroundings. a) Panoramic view to the southeast of the scarp of the Ciénaga del Coro fault. b) Panoramic view to the northeast showing the typical trace of the lineaments (indicated by the arrow) that affect the Pocho Volcanic Complex (in the background), and are partially covered by soils, as the Ojo de Agua lineament. In the foreground, outcrops of anatectic migmatites of the San Carlos Massif are exposed. c) Panoramic view to the ESE showing, in the foreground, the Pampa de Pocho; in the central part, La Sierrita fault that uplift the darkest small sierra composed of mylonites of the ductile Ambul–Mussi Shear Zone; and, in the background, the Sierra Grande. Note that the three scarps in the photographs are seen facing towards the observer.

were emplaced, from the northwestern metamorphic country rocks to the central zone of the present-day Pocho Volcanic Field [21]. The second magmatic cycle (6.0 ± 0.4 to 4.7 ± 0.3 Ma) embraces the final activity of the complex, when four new domic bodies were developed, three of them with a shoshonitic affinity and K-rich calc-alkaline the last one. Both series could be modeled as a continuous sequence of fractional crystallization with magma mixing in an open system [20].

3. Methodology

In order to analyze the anomalously deep seismicity, a seismic database for the Sierras de Córdoba was developed with the earthquakes recorded by the Instituto Nacional de Prevención Sísmica of Argentina (INPRES) (http://www.inpres.gov.ar/desktop/), the United States Geological Survey (USGS) (https://earthquake.usgs.gov/earthquakes/map/) and Richardson [40]. Database (originally projected on WGS 1984 geographic coordinates) was re-projected on Argentina POSGAR07 planar projection, zone 3. Focal mechanisms published by the International Seismological Center (ISC) were also included in order to characterize the structures and their kinematics (Fig. 2).

The location of the hypocenter of one of the earthquakes in the studied area, for which the focal mechanism has been calculated and published by the ISC (http://www.isc.ac.uk) (Nov. 8, 2012, see Appendix), differs by more than 40 km according to the INPRES and USGS databases. Based strictly on geological criteria, discussed below (see Results), it was decided to use the data provided by the USGS database. This is the only case in which both databases differ by more than 5 km in the location of an earthquake.

Others focal mechanisms published by Richardson [40] and Richardson et al. [44] have not been included in the database because many of them, calculated for the same earthquake, were different in both studies. This disagreement in the results is probably due to the few seismic stations available to define them. Thus, several valid solutions can be calculated for the same earthquake, and we can not know which focal mechanism defines the kinematics of the fault that generated it.

In order to assign the earthquakes recorded in the northwestern sector of the Sierras de Córdoba to the fault that generated them, all faults and lineaments in this area were accurately defined. DEM (different digital elevation models) of diverse resolution were used depending on the work scale and the objective to analyze: 90 m DEM (STRM, Shuttle Radar Topography Mission; CGIAR–CSI, Consultative Group on International Agricultural Research–Consortium for Spatial Information) (http://srtm.csi.cgiar.org/SELECTION/inputCoord.asp), 45 m DEM (Instituto Geográfico Nacional, Argentina) and 12 m DEM (Alaska Satellite Facility). All of the DEMs were re-projected on Argentina POSGAR07 planar projection, zone 3. From these DEMs, the slope map (in percentage), the water supplies and the principal watershed were calculated with the SAGA software (http://www.saga-gis.org/en/index.html) (Fig. 5). Slope and hydrological maps allow to delimit the brittle structures on surface, and to infer blind structures that would affect the drainage network and watershed limits.

The geological mapping was based in the Villa Dolores geological map [41] and the Sierras de Córdoba geological map published by Guereschi & Martino [45]. Three geological sections perpendicular to the main faults and lineaments were performed; on the basis of the available data [2,3], the apparent dips of the structures were calculated (Fig. 2).

In order to select earthquakes belonging to the Ojo de Agua Lineament, 15 perpendicular sections were performed. Earthquakes in a 5 km wide area for each section were represented showing the distance to the Ojo de Agua Lineament in relationship with depth (Fig. 6a and Fig. 7). A trend line was defined in sections with more data available (cross section 4 and 5 in Fig. 7), and extrapolated to the other cross sections.

The epicentral and hypocentral estimated errors are $\pm$8.44 and $\pm$ 8.39 km (see Appendix); therefore, all the earthquakes in an area less to 10 km radius around the trend line were assigned to the Ojo de Agua Lineament.

The hypocenters were recalculated for a topographic level of 0 km to represent the depth of the earthquakes in each structural section (Fig. 6b) and to develop a 3D model for the Ojo de Agua Lineament. Finally, the earthquakes belonging to the Ojo de Agua Lineament were selected and interpolated by the Natural Neighbor method in order to show a three-dimensional view (Fig. 8).

The brittle–ductile transition, between 20 and 25 km depth, and the Mohorovičić discontinuity, at 38 km depth calculated by Perarnau et al. [5] and confirmed by other satellite gravimetric studies and crustal thickness models for the South American continent [46,47] and for the Andes Cordillera [48,49], were also represented (Figs. 6b and 8).

The arrangement of epicenters and their depths would be enough to perform a reliable study because the seismotectonic interpretations require location errors smaller than the size of the seismogenic structures under study. Given the studied area and depth values recorded in the database, the estimated errors are acceptable and allow the adequate characterization of the Ojo de Agua Lineament.

4. Results

The seismic database for the Sierras de Córdoba developed in this study allow to confirm the four clusters defined by Richardson et al. [36] and to identify two new ones (Fig. 3): (5) Serrezuela cluster, north of the Sierras de Pocho and Guasapampa, and (6) Pocho cluster, between the Pampa de Pocho and the Sierra Grande. The Serrezuela cluster, with most of the earthquakes located more than 150 km depth, could be related to the flat-slab Nazca plate, between the structural contours of 150 and 200 km depth defined by Cahill & Isacks [4]. The Pocho cluster reflects the seismicity of the Ojo de Agua Lineament (Figs. 3 and 6).

Despite being seismically active, the Ojo de Agua Lineament does not show a well developed geomorphological escarpment (as the Retamito Lineament to the east, Fig. 5a), only clearly recognized on the Pocho Volcanic Complex (Fig. 4b). In addition, its trace is partially inferred by changes in the courses, in zig-zag or staggered, in the calculated drainage network (dashed arrows in Fig. 5b), and anomalies in the boundaries of the main watersheds (pointed squares). This kind of modifications in the watershed boundaries can also be observed, although less developed, in the La Higuera–Dos Pozos Lineament (north to the Ojo de Agua Lineament) and in the Pachango Lineament (to the south, Fig. 5b). On the Achala Batholith, the high plain (<10% slope), known as Pampa de Achala, has an irregular morphology, whose boundaries are affected by the Ojo de Agua Lineament (Fig. 5a).

Two minor lineaments displaced sinistrally the trace of the La Sierrita Fault in its central part. These lineaments are first identified here, and named LSNL (La Sierrita Norte Lineament) and LSSL (La Sierrita Sur Lineament), oriented N 125° and N 128° respectively (Fig. 2). They have lengths of 10–20 km, subparallel to the Ojo de Agua Lineament, and are probably satellite fractures. The Ambul–Mussi Shear Zone, which is located in the hangingwall of the La Sierrita Fault (to the northeast, Figs. 2 and 5a), has an "M" or zigzag shape on the map, probably conditioned by these three lineaments (Figs. 2 and 5a).

In total, 355 earthquakes were recorded in the studied area between 1974 and 2016, plus one historic earthquake in 1936. Of these, 94 occurred below the Mohorovičić discontinuity (Fig. 6), estimated at a depth of 38–40 km beneath the Sierras de Córdoba [5,46,47,49]. We must highlight that almost 20% of the earthquakes recorded in the area occurred at considerable depth, on top of the lithospheric mantle. Three of these earthquakes (obtained from the INPRES database) are very deep (>100 km) and scattered, outside the Serrezuela cluster (5), although a relation with the subducted Nazca plate is not excluded (Figs. 3 and 6a).

The sections perpendicular to the Ojo de Agua Lineament (15 in total), covering all its trace in the studied area, show a trend (marked with dashed line in Figs. 6b and 7) that represents a seismically active brittle structure. The deepest earthquakes were recorded in the southeast sector of the area, reaching about 80 $\pm$ 8.39 km; the recorded depth is lower in the northwest sector along the lineament.

There are two focal mechanism solutions available in the studied area (Fig. 6). The first one, with a 56 km depth (USGS database,

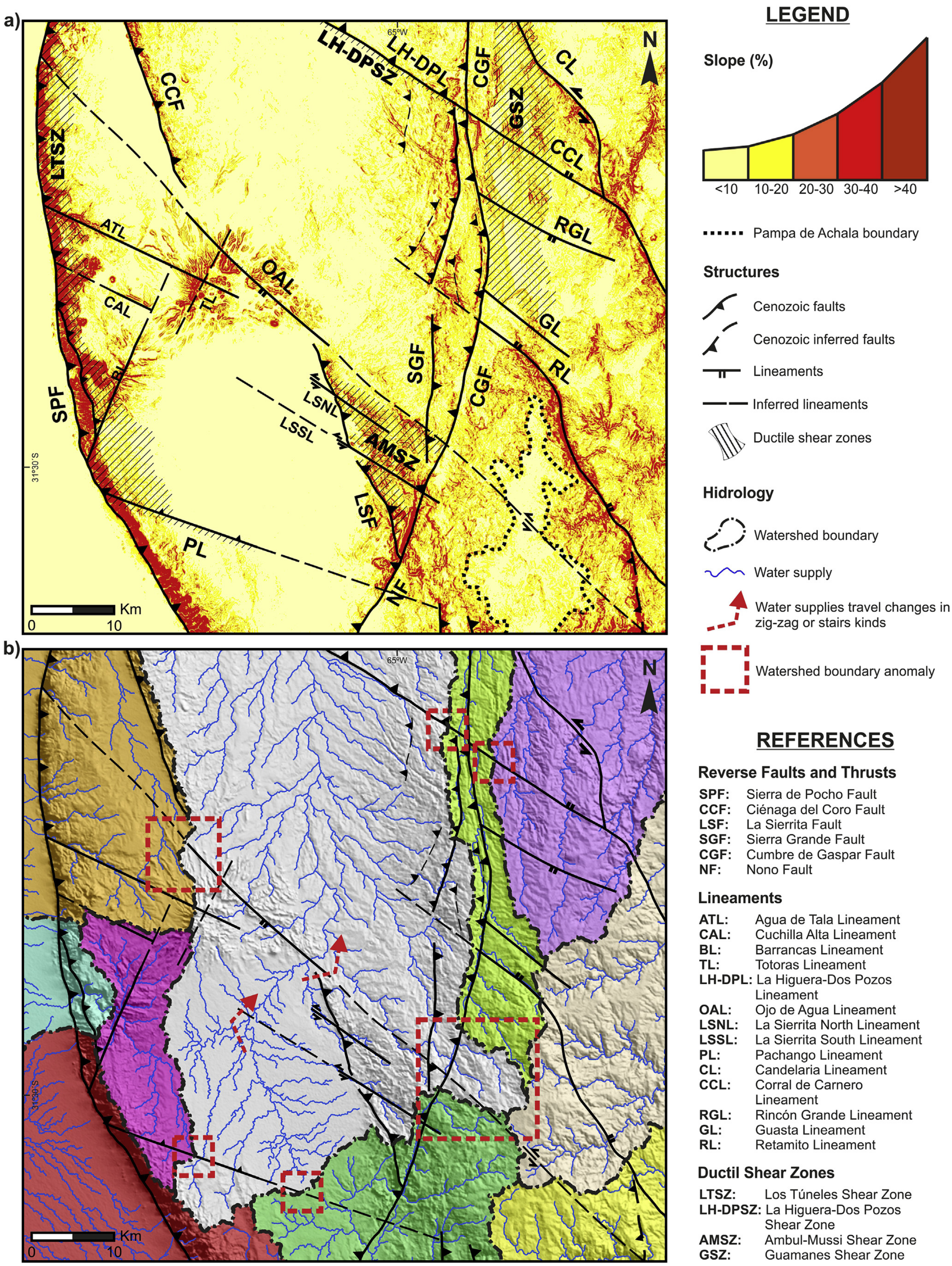

Fig. 5. Slope and hydrological maps of Sierras de Córdoba. a) Slope map of the study area showing the main brittle structures and their kinematics. b) Hydrological map showing the main drainage basins and the calculated hydrological network, along with the main structures of the study area. Both maps were generated with the SAGA program.

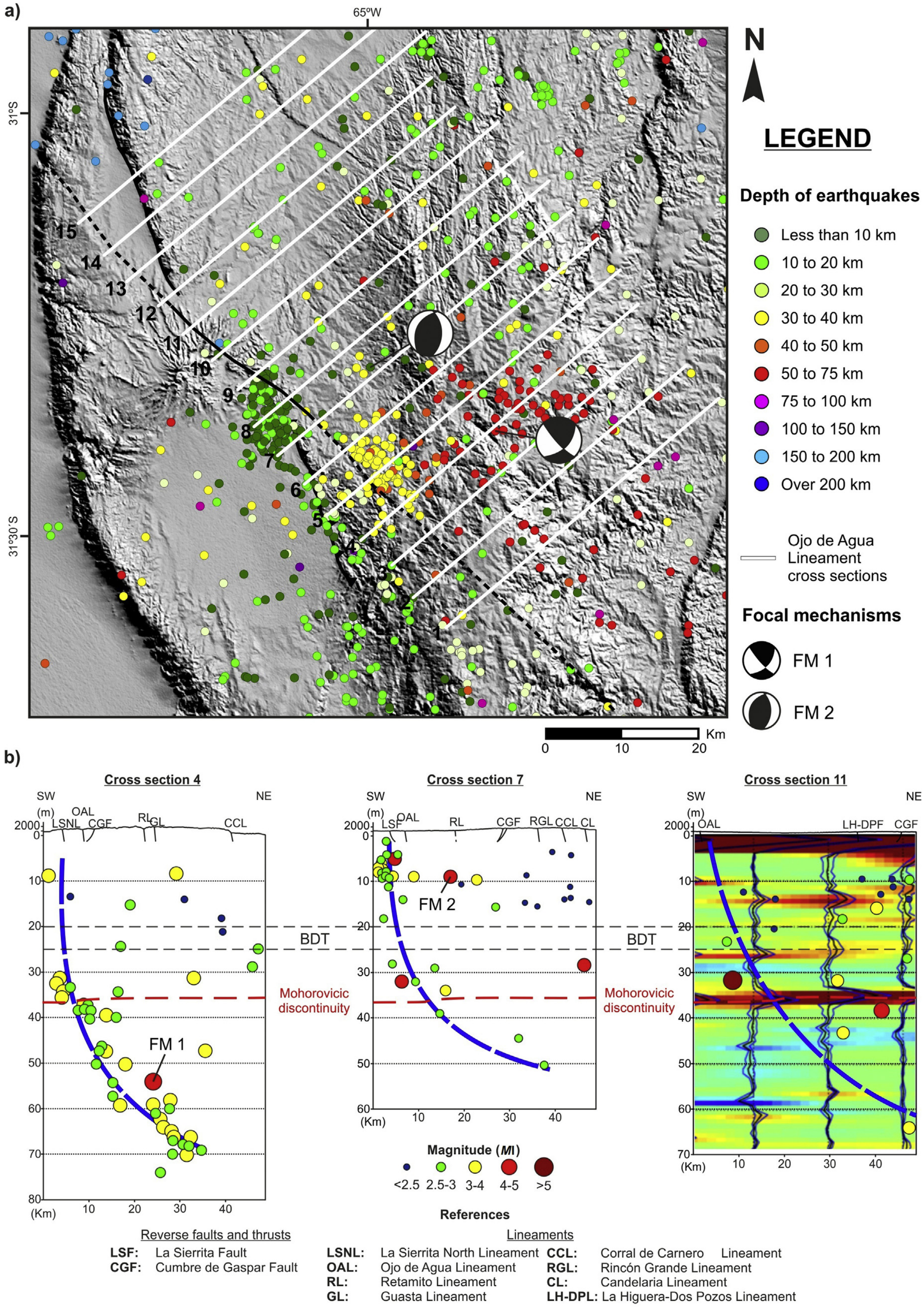

Fig. 6. Ojo de Agua Lineament cross sections. a) Digital terrain elevation model (45 m DEM, IGN) of the study area showing the epicenters of earthquakes ranked by depth, the available focal mechanisms, and the 15 cross sections made to study and model the Ojo de Agua Lineament. b) Cross sections 4, 7 and 11, representative of this study, showing the topographic profile, and the main faults and lineaments. The depths of the brittle–ductile transition zone (BDT) and the Mohorovičić discontinuity are from Perarnau et al. [5]. The calculated trend lines for earthquakes belonging to the Ojo de Agua Lineament are shown. Section 11 also includes the results of the receiver function analysis modified from Perarnau et al. [5] (2012, A–A′ section). See explanation in the text.

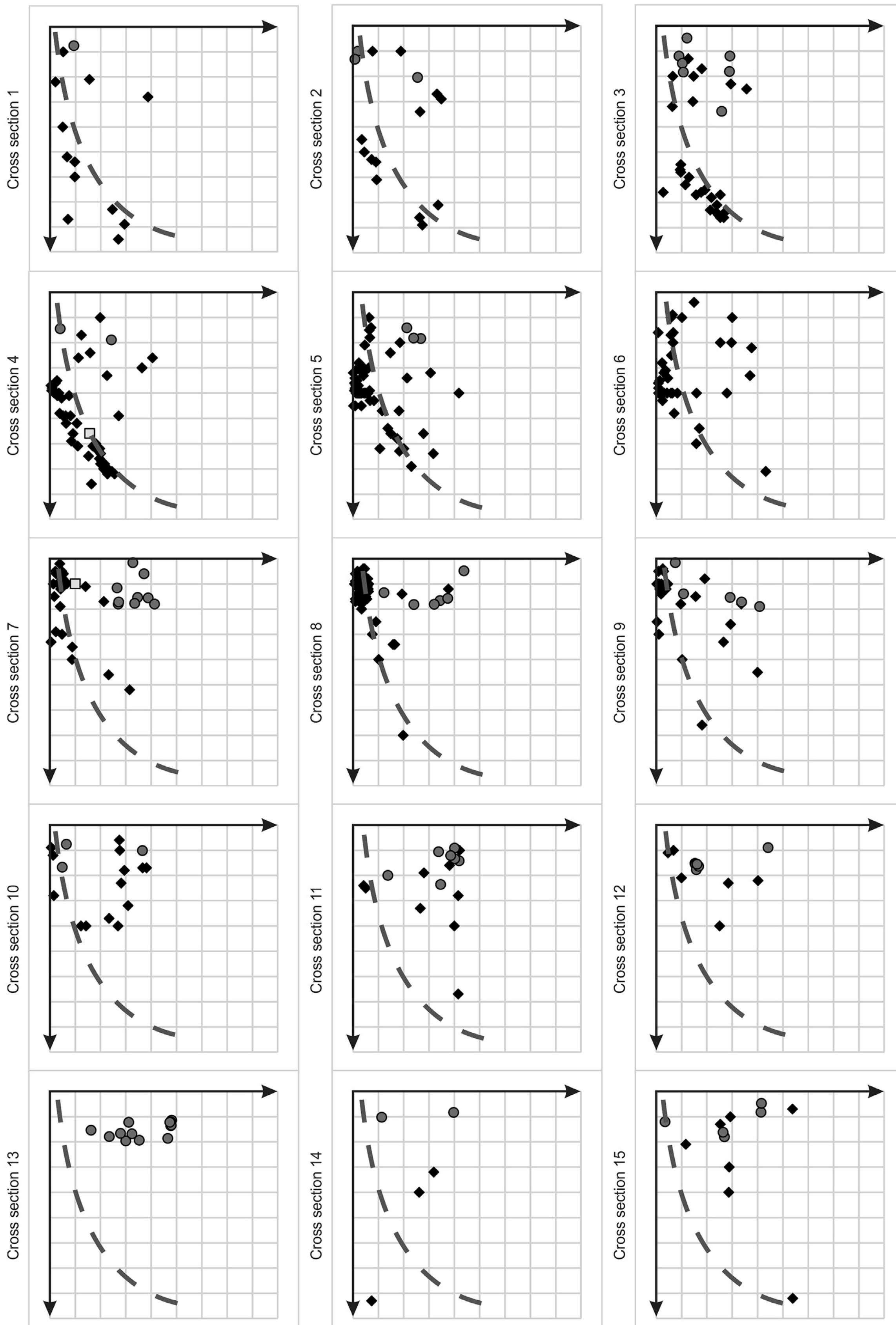

Fig. 7. Earthquakes projection distance to the Ojo de Agua Lineament vs. depth. Projection of earthquakes as a function of the distance to the Ojo de Agua Lineament (*X* axis) and depth (*Y* axis) for each section perpendicular to it (see location in Fig. 5 sections). The grid is 10 km on the side. Databases: black diamonds, INPRES; Gray circles, Richardson [40]; Squares light gray, USGS. The same gray dashed line, estimated in Sections 4 and 5, has been marked.

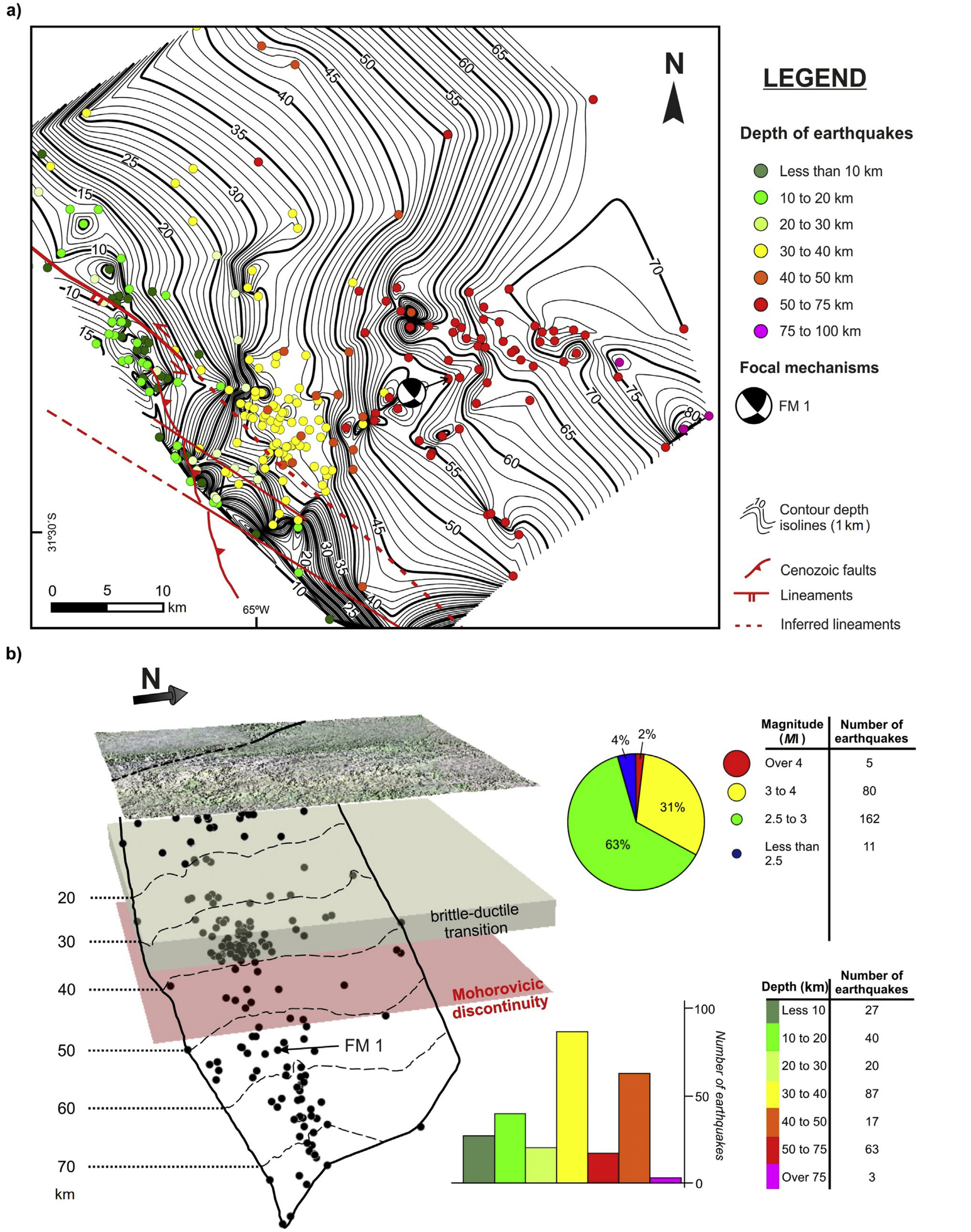

Fig. 8. Structural contours and 3D model of Ojo de Agua Lineament. a) Map of structural contours of the Ojo de Agua Lineament obtained by the interpolation of the related earthquakes. These earthquakes are ranked by depth, showing the fragile structures that are involved, and the calculated focal mechanism for one of them. b) 3D modeling of the Ojo de Agua Lineament from the earthquakes that define it. The brittle–ductile transition zone and the Mohorovičić discontinuity calculated by Perarnau et al. [5] are drawn. Statistical analysis of the depth and magnitude of earthquakes recorded in the area are also included. See explanation in the text.

and published in ISC), indicates an oblique dextral shear movement, whose calculated fault plane strikes N42.5° and 56.3ºNW dip. This fault plane does not correspond to any structure reported near the epicentral area. However, if we consider the other nodal plane strikes N132.5° and approximately 70° NE dip, it corresponds with the strike and dip of the Ojo de Agua Lineament as observed in surface and at depth (Fig. 6), and indicates a sinistral shear movement. Therefore, this focal mechanism can be reinterpreted and linked to this structure to describe its kinematics.

The second focal mechanism solution shows a slightly oblique reverse fault, with 10–12 km depth (USGS and INPRES database), in agreement with the behavior of the Cenozoic reverse faults of the study area in the upper crust. The fault plane calculated strikes N201.7° and 41.3ºW dip; this fault plane is consistent with the available data for the Cumbre de Gaspar Fault, located to the northeast of the Ojo de Agua Lineament (Fig. 2). Although the epicenter is more than 10 km away of the surface fault trace, throwing its hypocenter on the fault plane 41.3°W dip is within the margin of error assumed, and it would belong to the Cumbre de Gaspar Fault (Fig. 6). This is the only east-vergent fault of the Cenozoic reverse fault system in the Sierras de Córdoba.

The seismically active structure of the Ojo de Agua Lineament, detected through the perpendicular sections, is better defined in the southeastern area (Fig. 8). Five times more earthquakes (n) were detected there than in the northwest area ($n = 177$ in cross sections 1–7, $n = 36$ in cross sections 8–15), probably because the time window is not wide enough to fully characterize the lineament. In the cross section 7 (Fig. 6b), an earthquake cluster located near to the surface (<10 km depth), below the Pocho Volcanic Complex. In the cross section 11 (Fig. 6b), we show the trend lines calculated for earthquakes belonging to the Ojo de Agua Lineament projected on the results of the receiver function analysis performed by Perarnau et al. [5] (2012, A–A′ section). This allows us to infer, on the one hand, that the Mohorovičić discontinuity shows a slight inflection, decreasing its depth 1–2 km below the location of the Ojo de Agua Lineament. On the other hand, comparing with the other cross sections in this study, we found that the lineament dip also changes at this point.

The 3D modeling of the Ojo de Agua lineament from the recorded earthquakes shows a planar to listric geometry, 52 km in length (seismic segment) and up to 80 km in depth. A total of 257 earthquakes were modeled, 83 of them are located below 40 km depth, which implies that more than 30% occurred below the Mohorovičić discontinuity, in the lithospheric mantle (Figs. 6 and 8). Towards the southeast of the lineament trace, the fault plane deepens abruptly, presenting a dip angle of approximately 80° NE up to a depth of 40 km, then it becomes less steep and close to 70° NE. Towards the northwest, this change in the dip of the fault plane is not appreciable, but it steadily deepens with a dip angle of approximately 65°–70° NE (Fig. 6). We assume that this lateral variation is not a characteristic of the lineament, but of the available seismic data: the greater number of earthquakes recorded in the southeastern area reflects more accurately the structure in this sector.

5. Discussion

The occurrence of earthquakes at depths below the Mohorovičić discontinuity is not frequent. In a sector of central-western Argentina, in the Mendoza province, Lupari et al. [50] reported continuous seismicity from the crust up to 70 km in depth. The earthquakes located in the continental crust (<35 km depth) are related to the San Rafael Block and the Las Malvinas fault, located on its eastern boundary. The seismicity occurring in the lithosphere mantle is attributed to the dehydration of the stable minerals at these depths, favored by the presence of a shallow asthenospheric plume [51]. Deep earthquakes have also been detected in the Western Alps, where the hypocenters distribution is continuous between 20 and 70 km depth. Eva et al. [52] modeled them as a high-dipping structural plane (the Rivoli–Marene Fault) that could represent the boundary between two tectonic domains. In the same way, the Ojo de Agua Lineament has continuous seismicity from shallow levels to below the crust boundary, into the lithospheric mantle. However, this lineament would not be related to a tectonic boundary, but it is part of a similar lineaments family, currently under study, that affects the Sierras de Córdoba at these latitudes.

The Ojo de Agua Lineament is a brittle, almost vertical macrostructure, oriented N130º–135°, with a straight trace on the map and a seismic segment modeled here of 52 km in length and up to 80 km in depth. It is oblique to the main north-south reverse faults that uplifted the Sierras Pampeanas of Córdoba and its length can reach 160 km. It would be an ancient feature probably inherited from Pan-Gondwanan structures [30,31], with a protracted tectonic activity, which controlled the Phanerozoic deformation [3]. This structure would be reactivated by foreland shortening and compression during the Andean Orogeny, as a consequence of the flat-slab subduction of the Nazca plate.

The Ojo de Agua Lineament is not the unique macrostructure of this type recognized in the Sierras de Córdoba: the Deán Funes Lineament (DFL, Fig. 1), which acts as a boundary between this ranges and the Sierra Norte, is more than 200 km length, and extends to the Atlantic margin in the present Salado Basin, with a variable width of about one kilometer [53]. Its strike is N150° (similar to the Ojo de Agua Lineament) and can be recognized to depths over 40 km, displacing the Mohorovičić discontinuity. The current kinematics of both lineaments is sinistral (left-shear fault), based on available focal mechanisms and geomorphological features previously described [2,3]. The deduced sinistral shear movement is consistent with the present convergence direction (N78°) of the Nazca plate with the South American plate at these latitudes [54].

A critical feature in the Ojo de Agua Lineament study is that 30% of the modeled earthquakes occur in the lithospheric mantle (Figs. 6 and 8). The depth of the Mohorovičić discontinuity in the continental margin and in the Andean foreland varies according to the authors and methodology used (marked in Fig. 9c), specially below the Precordillera, where the values oscillate between approximately 60 to 70 km [48,55]. Under the Sierras de Córdoba, the Mohorovičić discontinuity is inferred at 40 km depth. Beneath Sierra Chica, Perarnau et al. [5] show a clear vertical step of approximately 3 km, attributed later to the Deán Funes Lineament movement by Martino et al. [3]. In this work, an inflection of approximately 1–2 km is found for the Ojo de Agua Lineament (Fig. 6b).

The brittle faulting associated with the uplift in basement blocks of the Sierras Pampeanas has been related to a very cold crust, due to the occurrence of earthquakes at its base. This thermal behavior of the crust is attributed to the fact that the present Nazca "flat-slab" subduction thermally insulates the South American plate lithosphere of the hot asthenosphere [56]. The Nazca plate "flat-slab" process causes both the asthenospheric wedge shift and the volcanic arc migration to the foreland [15,42,57]. Others consequences are the generation of a negative thermal anomaly in the continental lithosphere (cooling) and the increase of interplate coupling [6,7]. Therefore, the eastward shift of the asthenospheric wedge would be one of the main causes of the lithosphere cooling at these latitudes.

The lithosphere in the continental margin and Andean foreland, between 30° and 33° S latitude (Fig. 9a) is extremely heterogeneous, due to the long and complex geological history, with

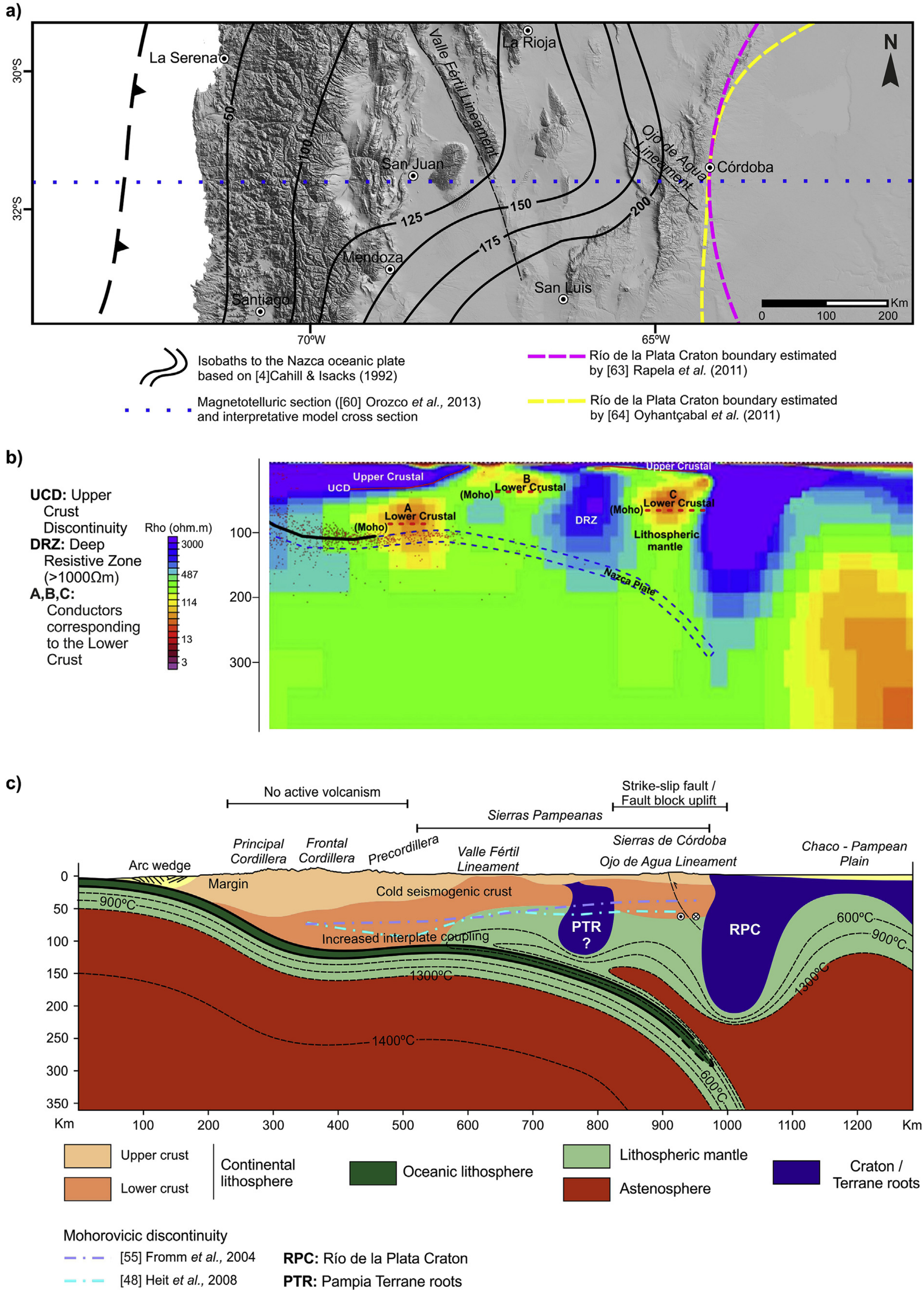

Fig. 9. Flat slab and magnetotelluric sections and thermal model hypothesis proposed. a) Digital terrain elevation model between the latitudes where the 'flat-slab' subduction of the Nazca plate occurs (90 m DEM, STRM, CGIAR–CSI). b) Magnetotelluric section modified from Orozco et al. [60]. c) Thermal model hypothesis proposed in this work, based on the studies of Gutscher [6] and Muñoz [7], and the magnetotelluric section from Orozco et al. [60,63,64].

numerous discontinuities produced by the accretion of terranes and basins development. Synthetically, this continental lithosphere, belonging Southwestern Gondwana, was assembled towards the end of the Proterozoic [32,58], by basement planar anisotropies that controlled the Phanerozoic basins development in Argentina. The accretion of terranes at the Pacific margin of Gondwana during the early Paleozoic reactivated these anisotropies and generated new ones, mainly during the Ocloyic orogeny (Ordovician–Silurian boundary). The Mesozoic basins were accommodated by northeast and northwest planar structural fabrics in the basement, both towards the Atlantic and towards the Pacific continental margins [1]. The Cenozoic Andean compression, at the Nazca "flat-slab" subduction begins, caused the Cretaceous basins inversion [39], blocks faulting and clockwise tilting (facing north), thus being configured the current landscape [3,16].

The crustal thickness is maximum in the Principal Cordillera and Precordillera (Fig. 9c), with values around 65 km, decreasing towards the east, with 45–60 km thickness in the Western Sierras Pampeanas. Following Gilbert et al. [49], this crustal thickening is due to the partial eclogitization of the lower crust, becoming denser than the middle crust and preventing it from rising isostatically. In the Eastern Sierras Pampeanas, located near 700 km away the Chilean trench, the crustal thickness reaches about 36 km [55,59].

The crustal thickening of the back-arc zone of the Andean orogen can also be detected by a magnetotelluric study [60]. A high resistivity zone was also detected (DRZ, 100 km thick in its central part, Fig. 9b) below the crystalline basement of the Sierra de Ulapes, between the Valle Fértil Lineament and the Sierras de Córdoba. The DRZ may be related to a part of the lithosphere, cold and rigid, whose upper boundary is separated from the upper crust by a thin high conductivity zone [60]. The high resistivity values of the DRZ zone are similar to those observed more to the east, attributed to the presence of the Río de la Plata Craton. This implies that it is a crust cooler and older than the adjacent ones, and could belong to the Pampia terrane (Fig. 9c), accreted during the Neoproterozoic–Cambrian Pampean orogeny to the western margin of the Río de la Plata Craton [61,62].

We proposed a thermal model hypothesis of the lithosphere at latitude 31° 36′ S, which includes the present Andean building, between the Chilean trench and the Chaco–Pampean plain. It is based on the theoretical thermal models of Gutscher et al. [6] and Muñoz [7], and the magnetotelluric section of Orozco et al. [60]. The asthenosphere wedge, shifted towards the Andean foreland, is partially squeezed between the Nazca flat-slab and the Pampia terrane and the Río de la Plata Craton, being extruded toward the east and generating a positive thermal anomaly below the Chaco–Pampean plain. This effect causes the continental crust and the lithospheric mantle located below the Sierras de Córdoba to be anomalously cold and rigid, enabling the occurrence of earthquakes to more than 40 km of depth, as in the case of the Ojo de Agua Lineament studied here (note that the lineament passes through the lithosphere mantle). A brittle–ductile transition zone has been inferred at a depth of 25–30 km under the Sierras de Córdoba [5]. However, this depth and geometry should be revised according to the results obtained in this work.

The arrangement of the Pocho Volcanic Complex on top of the Ojo de Agua Lineament, along with other minor lineaments and faults previously described in the area (Figs. 2 and 6), imply an important connection between them. The shallow earthquakes (<10 km depth) clustered below the central volcanic building (Fig. 6b, cross section 7) could be related with a residual magmatic chamber. It is noted that the volcanic domes were emplaced linearly, with northwest–southeast trend parallel to the Ojo de Agua Lineament and less than 5 km south of the trace. The Ojo de Agua Lineament, as seen above, is a very deep brittle structure that cut across the continental crust and upper mantle, being an area favorable for the ascent of magmas from the dehydration of the subducted Nazca plate. The K-rich calc-alkaline signature of the first domes [21] emplaced in the area implies that ascending asthenospheric magma is contaminated by the overlying sialic continental crust. This first cycle would correspond to the ascent and magmatic chamber development in the zone where the described lineaments and faults intersect orthogonally. Thus, the Ojo de Agua Lineament would have favored the rapid ascension of mantle material, leaving the magma chamber as an open system through which the magma can ascend from the mantle in different pulses [20](7.9–4.5 Ma).

The type of seismicity detected in the studied area would not be of the volcanic type, but of the tectonic type. As can be seen in Figs. 3 and 6, the area affected by seismicity has a planar distribution in depth according to a structure with a surface trace of tens of kilometers in length, which significantly exceeds the Pocho Volcanic Field. In addition, the last magmatic pulse is dated in 4.7 ± 0.3 Ma [20,21]. These features, together with the thermal model hypothesis proposed here, which indicates the shifting of the asthospheric wedge to the east, would not allow to assign the detected seismicity to a current magmatic activity in the Pocho Volcanic Field. Therefore, it is concluded that both the shallow and deep seismicity detected in the lithosphere mantle would have been produced by the tectonic activity of the Ojo de Agua Lineament. Other similar ancient oblique lineaments in the Sierras de Córdoba, even larger as the Deán Funes Lineament, would also have been reactivated during the Andean orogeny and show an analogous seismicity.

6. Conclusions

The seismicity recorded in the northwestern sector of the Sierras Pampeanas of Cordoba would be related to the tectonic activity of a northwest-southeast trending, subvertical macrostructure, named the Ojo de Agua Lineament. It is a seismically active, brittle fault with more than 80 km depth and 52 km in length (modeled seismic segment), but it extends up to 160 km length cutting obliquely to the main mountain ranges. A sinistral transcompressional kinematics (convergent oblique shear) is deduced by the focal mechanism of a deep earthquake, together with the observed geomorphological modifications and anomalies.

Over 40 km depth seismicity would be due to the continental lithosphere below the Sierras de Córdoba is colder and rigid than expected in a normal subduction area. This would be the result of the asthenospheric wedge shifting towards the Andean foreland, produced by the flat-slab subduction of the Nazca plate, which develop a thermal anomaly below the ranges. At these latitudes, the Río de la Plata Craton together with the sialic Pampia terrane, cold and older than adjacent crust, cause the asthenosphere to be squeezed between the Nazca plate and the craton boundaries, being partially extruded to the east.

The current seismicity would not be related to the volcanic activity of Pocho, except a small cluster of surface earthquakes bordering the volcanic field, which is interpreted as a residual magma chamber. During the Neogene, the Ojo de Agua Lineament would act as a channel of direct ascent of magmas.

The Ojo de Agua Lineament is an ancient feature, probably inherited from Pan-Gondwanan structures, with successive reactivations, that controlled the emplacement of magmas during the Neogene and is currently seismically active.

Acknowledgments

The CONICET (PIP 00628, PUE 2016–CICTERRA), FONCyT (PID–00013), SECyT–UNC (05/I641) and Institute of Aging are thanked for supporting our research. Formal revisions by three referees, two anonymous reviewers and A. Folguera, are highly appreciated for their contribution to significantly improve the manuscript. Special thanks to the Guest Editor Silvana Spagnotto.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.geog.2017.10.001.

References

[1] R.D. Martino, A.E. Toledo, A.B. Guereschi, Lineamientos transtensionales en el margen noroccidental del batolito de Achala y su relación con la exhumación de rocas de alto grado y la extensión cretácica en las Sierras de Córdoba. 15° Reunión de Tectónica, Libro de Resúmenes, San Juan, 2012, p. 90.
[2] R.D. Martino, A.B. Guereschi, A. Caro Montero, La estructura cenozoica (paleógena–neógena) de las Sierras de Córdoba, in: R.D. Martino, A.B. Guereschi (Eds.), Geología y Recursos Naturales de la Provincia de Córdoba. Relatorio del 19° Congreso Geológico Argentino, Asoc Geol Argent, Córdoba, 2014, pp. 649–671.
[3] R.D. Martino, A.B. Guereschi, A. Caro Montero, Reactivation, inversion and basement faulting and thrusting in the Sierras Pampeanas of Córdoba (Argentina) during Andean flat-slab deformation, Geol Mag 153 (2016) 962–991.
[4] T. Cahill, B.L. Isacks, Seismicity and shape of the subducted Nazca plate, J Geophys Res 97 (1992) 17503.
[5] M. Perarnau, H. Gilbert, P. Alvarado, R.D. Martino, M. Anderson, Crustal structure of the Eastern Sierras Pampeanas of Argentina using high frequency local receiver functions, Tectonophysics 580 (2012) 208–217.
[6] M.A. Gutscher, W. Spakman, H. Bijwaard, E.R. Engdahl, Geodynamics of flat subduction: seismicity and tomographic constraints from the Andean margin, Tectonics 19 (2000) 814–833.
[7] M. Muñoz, No flat Wadati–Benioff Zone in the central and southern central Andes, Tectonophysics 395 (2005) 41–65.
[8] T.E. Jordan, B.L. Isacks, R.W. Allmendinger, J.A. Brewer, V.A. Ramos, C.J. Ando, Andean tectonics related to geometry of subducted Nazca plate, Geol Soc Am Bull 94 (1983) 341.
[9] T.E. Jordan, B.L. Isacks, V.A. Ramos, R.W. Allmendinger, Mountain building in the central Andes, Episodes (1983) 20–26.
[10] T.E. Jordan, R.W. Allmendinger, The Sierras Pampeanas of Argentina; a modern analogue of Rocky Mountain foreland deformation, Am J Sci 286 (1986) 737–764.
[11] J. Rodgers, Chains of basement uplifts within cratons marginal to orogenic belts, Am J Sci 287 (1987) 661–692.
[12] S. Marshak, K. Karlstrom, J. Michael Timmons, Inversion of Proterozoic extensional faults: an explanation for the pattern of Laramide and Ancestral Rockies intracratonic deformation, United States, Geology 28 (2000) 735–738.
[13] G.A. Yáñez, C.R. Ranero, R. von Huene, J. Díaz, Magnetic anomaly interpretation across the southern central Andes (32°–34°S): the role of the Juan Fernández Ridge in the late Tertiary evolution of the margin, J Geophys Res Solid Earth 106 (2001) 6325–6345.
[14] V.A. Ramos, E.O. Cristallini, D.J. Pérez, The Pampean flat-slab of the central Andes, J S Am Earth Sci 15 (2002) 59–78.
[15] V.A. Ramos, A. Folguera, Andean flat-slab subduction through time vol. 327, Geol Soc, London, 2009, pp. 31–54. Special Publications.
[16] C.E. Gordillo, A.N. Lencinas, Sierras Pampeanas de Córdoba y San Luis, in: J.C. Turner (Ed.), 2° Simposio de Geología Regional Argentina, Academia Nacional de Ciencias, Córdoba, 1979, pp. 577–650.
[17] R.D. Martino, A.B. Guereschi, La estructura neoproterozoica–paleozoica inferior del complejo metamórfico de las Sierras de Córdoba, in: R.D. Martino, A.B. Guereschi (Eds.), Geología y Recursos Naturales de la Provincia de Córdoba. Relatorio del 19° Congreso Geológico Argentino, Asoc Geol Argent, Córdoba, 2014, pp. 95–128.
[18] C.W. Rapela, R.J. Pankhurst, C. Casquet, E. Baldo, J. Saavedra, C. Galindo, et al., The Pampean Orogeny of the southern proto-Andes: Cambrian continental collision in the Sierras de Córdoba, vol. 142, Geol Soc, London, 1998, pp. 181–217. Special Publications.
[19] S. Siegesmund, A. Steenken, R.D. Martino, K. Wemmer, M.G. López de Luchi, R. Frei, et al., Time constraints on the tectonic evolution of the eastern Sierras Pampeanas (central Argentina), Int J Earth Sci 99 (2010) 1199–1226.
[20] S.M. Kay, C.E. Gordillo, Pocho volcanic rocks and the melting of depleted continental lithosphere above a shallowly dipping subduction zone in the central Andes, Contrib Miner Petrol 117 (1994) 25–44.
[21] M. Arnosio, C. Popridkin, W. Báez, E. Bustos, El volcanismo terciario: complejo volcánico Pocho, in: R.D. Martino, A.B. Guereschi (Eds.), Geología y Recursos Naturales de la Provincia de Córdoba. Relatorio del 19° Congreso Geológico Argentino, Asoc Geol Argent, Córdoba, 2014, pp. 623–647.
[22] P. Kraemer, R.D. Martino, M. Giambastiani, J. Sfragulla, Análisis dinámico-cinemático preliminar de la Falla de Santa Rosa, Dpto. de Calamuchita, prov. de Córdoba, in: J.C. Turner (Ed.), 5° Reunión de Microtectónica, Actas, 1988, pp. 107–120. Córdoba.
[23] A. Massabie, C. Szlafsztein, Condiciones geomecánicas y edad del fallamiento neotectónico en las Sierras Pampeanas Orientales, Córdoba, Argentina, Asoc Argent Geol Apl la Ing Actas 6 (1991) 154–168.
[24] P. Kraemer, R.D. Martino, La falla de la Sierra Chica, cabalgamiento de basamento sobre una cuña sedimentaria imbricada, Cosquín, in: 9° Reunión sobre Microtectónica, Actas, 1993, pp. 13–14. Mendoza.
[25] C. Simpson, S.J. Whitmeyer, D.G. De Paor, L.P. Gromet, R. Miro, M.A. Krol, et al., Sequential ductile to brittle reactivation of major fault zones along the accretionary margin of Gondwana in Central Argentina, vol. 186, Geol Soc, London, 2001, pp. 233–255. Special Publications.
[26] R.D. Martino, Las fajas de deformación dúctil de las Sierras Pampeanas de Córdoba: una reseña general, Rev Asoc Geol Argent 58 (2003) 549–571.
[27] A. Steenken, K. Wemmer, R.D. Martino, M.G. López de Luchi, A.B. Guereschi, S. Siegesmund, Post-pampean cooling and the uplift of the Sierras Pampeanas in the West of Córdoba (central Argentina), Neues Jahrb Für Geol Und Paläontol – Abh 256 (2010) 235–255.
[28] W. Gross, Cuadro tectónico del valle de Punilla, Rev Asoc Geol Argent 3 (1948) 73–132.
[29] R.D. Martino, Geología y petrología del basamento metamórfico de la región situada al norte de Cuchilla Nevada, sierra Grande de Córdoba, Doctoral Thesis, Universidad Nacional de Córdoba, Córdoba, Argentina, 1988 [Inedit)].
[30] M.C. Daly, Crustal shear zones in Central Africa: a kinematic approach to Proterozoic tectonics, Episodes 11 (1988) 5–11.
[31] A.J. Tankard, M.A. Uliana, H.J. Welsink, V.A. Ramos, M. Turic, A.B. França, et al., Tectonic controls of basin evolution in southwestern Gondwana, in: A.J. Tankard, R. Suárez Soruco, H.J. Welsink (Eds.), Petroleum basins of south America, vol. 62, Am Association of Petroleum Geologists, Tulsa, 1995, pp. 5–52.
[32] V.A. Ramos, Late Proterozoic –early Paleozoic of south America – a collisional history, Episodes 11 (3) (1988) 168–174.
[33] T.E. Jordan, P. Zeitler, V. Ramos, A.J.W. Gleadow, Thermochronometric data on the development of the basement peneplain in the Sierras Pampeanas, Argentina, J S Am Earth Sci 2 (1989) 207–222.
[34] T.J. Coughlin, P.B. O'Sullivan, B.P. Kohn, R.J. Holcombe, Apatite fission-track thermochronology of the Sierras Pampeanas, central western Argentina: implications for the mechanism of plateau uplift in the Andes, Geology 26 (1998) 999.
[35] S. Löbens, F.A. Bense, K. Wemmer, I. Dunkl, C.H. Costa, P. Layer, et al., Exhumation and uplift of the Sierras Pampeanas: preliminary implications from K–Ar fault gouge dating and low-T thermochronology in the Sierra de Comechingones (Argentina), Int J Earth Sci 100 (2011) 671–694.
[36] T. Richardson, K.D. Ridgway, H. Gilbert, R. Martino, E. Enkelmann, M. Anderson, et al., Neogene and Quaternary tectonics of the Eastern Sierras Pampeanas, Argentina: active intraplate deformation inboard of flat-slab subduction, Tectonics 32 (2013) 780–796.
[37] F.A. Bense, K. Wemmer, S. Löbens, S. Siegesmund, Fault gouge analyses: K–Ar illite dating, clay mineralogy and tectonic significance—a study from the Sierras Pampeanas, Argentina, Int J Earth Sci 103 (2014) 189–218.
[38] P. Kraemer, M. Escayola, R.D. Martino, Hipótesis sobre la evolución tectónica neoproterozoica de las Sierras Pampeanas de Córdoba (30° 40_ LS – 32° 40_ LS), Rev Asoc Geol Argent 50 (1995) 47–59.
[39] C.J. Schmidt, R.A. Astini, C.H. Costa, C.E. Gardini, P.E. Kraemer, Cretaceous rifting, alluvial fan sedimentation, and neogene inversion, Southern Sierras Pampeanas, Argentina, in: A.J. Tankard, R.S. Suárez, H.J. Welsink (Eds.), Petroleum basins of south America, vol. 62, Am Association of Petroleum Geologists, Tulsa, 1995, pp. 341–358.
[40] T.J. Richardson, A geophysical and geologic analysis of the development, structure, and activity of the eastern Sierras Pampeanas, Argentina, Thesis, Faculty of Purdue University, West Lafayette, Indiana, 2011 [Inedit)].
[41] A.A. Bonalumi, R.D. Martino, E.D. Baldo, J. Zarco, J. Sfragulla, C. Carignano, et al., Hoja Geológica 3166-IV, Villa Dolores. provincias de Córdoba, La Rioja y San Luis, vol. 250, Instituto de Geología y Recursos Minerales, Servicio Geológico Minero Argentino, Buenos Aires, 1999, p. 123.
[42] S.M. Kay, C. Mpodozis, Magmatism as a probe to the Neogene shallowing of the Nazca plate beneath the modern Chilean flat-slab, J S Am Earth Sci 15 (2002) 39–57.
[43] C.E. Gordillo, E. Linares, Geocronología y petrografía de las vulcanitas terciarias del Departamento de Pocho. Provincia de Córdoba, Rev la Asoc Geol Arg 36 (4) (1981) 380–388.
[44] T. Richardson, H. Gilbert, M. Anderson, K.D. Ridgway, Seismicity within the actively deforming eastern sierras Pampeanas, Argentina, Geophys J Int 188 (2012) 408–420.
[45] A.B. Guereschi, R.D. Martino, Las migmatitas de las Sierras de Córdoba, in: R.D. Martino, A.B. Guereschi (Eds.), Geología y Recursos Naturales de la Provincia de Córdoba. Relatorio del 19° Congreso Geológico Argentino, Asoc Geol Argent, Córdoba, 2014, pp. 67–94.
[46] M. van der Meijde, J. Julià, M. Assumpção, Gravity derived moho for South America, Tectonophysics 609 (2013) 456–467.
[47] M. Assumpção, M. Feng, A. Tassara, J. Julià, Models of crustal thickness for South America from seismic refraction, receiver functions and surface wave tomography, Tectonophysics 609 (2013) 82–96.

[48] B. Heit, X. Yuan, M. Bianchi, F. Sodoudi, R. Kind, Crustal thickness estimation beneath the southern central Andes at 30°S and 36°S fromSwave receiver function analysis, Geophys J Int 174 (2008) 249–254.
[49] H. Gilbert, S. Beck, G. Zandt, Lithospheric and upper mantle structure of central Chile and Argentina, Geophys J Int 165 (2006) 383–398.
[50] M.N. Lupari, S.L. Spagnotto, S.V. Nacif, G. Yacante, H.A.G. García, F. Lince-Klinger, et al., Sismicidad localizada en la zona del Bloque San Rafael, Argentina, Rev Mex Ciencias Geol 32 (2) (2015) 190–202.
[51] A.I. Burd, J.R. Booker, R. Mackie, A. Favetto, M.C. Pomposiello, Three-dimensional electrical conductivity in the mantle beneath the Payún Matrú Volcanic Field in the Andean back-arc of Argentina near 36.5°S: decapitation of a mantle plume by resurgent upper mantle shear during slab steepening, Geophys J Int 198 (2) (2014) 812–827.
[52] E. Eva, M.G. Malusà, S. Solarino, A seismotectonic picture of the inner southern Western Alps based on the analysis of anomalously deep earthquakes, Tectonophysics 661 (2015) 190–199.
[53] R.D. Martino, A.B. Guereschi, C.A. Carignano, Control tectónico del Lineamiento Transbrasiliano sobre el magmatismo Cámbrico y Devónico de las Sierras Pampeanas Orientales, in: R.D. Martino, A.B. Guereschi (Eds.), Actas del 19° Congreso Geológico Argentino, Asoc Geol Argent, Córdoba, 2014, pp. 1478–1479.
[54] R. Somoza, M.E. Ghidella, Convergencia en el margen occidental de América del Sur durante el Cenozoico: subducción de las placas de Nazca, Farallón y Aluk, Rev la Asoc Geol Arg 60 (4) (2005) 797–809.
[55] R. Fromm, G. Zandt, S.L. Beck, Crustal thickness beneath the Andes and Sierras Pampeanas at 30°S inferred from Pn apparent phase velocities, Geophys Res Lett 31 (2004).
[56] P.M. Alvarado, S. Beck, G. Zandt, R. Fromm, M. Araujo, M. Bufaliza, et al., Deep crustal earthquakes in the sierras Pampeanas region of the south central Andean Backarc, Eos Trans AGU 84 (46) Fall Meet Suppl (2003), Abstract S41D-0124.
[57] V.D. Litvak, S. Poma, S.M. Kay, Paleogene and Neogene magmatism in the Valle del Cura region: new perspective on the evolution of the Pampean flat slab, San Juan province, Argentina, J South Am Earth Sci 24 (2007) 117–137.
[58] V.A. Ramos, M. Escayola, D.I. Mutti, G.I. Vujovich, Proterozoic-early Paleozoic ophiolites of the Andean basement of southern South America, in: Special Paper 349 Ophiolites and Oceanic Crust New Insights from Field Studies and the Ocean Drilling Program, 2000, pp. 331–349.
[59] R. Fromm, G. Zandt, S.L. Beck, Crustal thickness beneath the Andes and Sierras Pampeanas at 30ºS inferred from Pn apparent phase velocities, Eos Trans AGU 84 (46) Fall Meet Suppl (2003), Abstract S41D-0125.
[60] L.A. Orozco, A. Favetto, C. Pomposiello, E. Rossello, J. Booker, Crustal deformation of the Andean foreland at 31° 30′S (Argentina) constrained by magnetotelluric survey, Tectonophysics 582 (2013) 126–139.
[61] V.A. Ramos, R.D. Martino, J.E. Otamendi, M.P. Escayola, Evolución geotectónica de las Sierras Pampeanas Orientales, in: R.D. Martino, A.B. Guereschi (Eds.), Actas del 19° Congreso Geológico Argentino, Asoc Geol Argent, Córdoba, 2014, pp. 623–647.
[62] V.A. Ramos, M. Escayola, P. Leal, M.M. Pimentel, J.O.S. Santos, The late stages of the Pampean Orogeny, Córdoba (Argentina): evidence of postcollisional Early Cambrian slab break-off magmatism, J S Am Earth Sci 64 (2015) 351–364.
[63] C.W. Rapela, C.M. Fanning, C. Casquet, R.J. Pankhurst, L. Spalletti, D. Poiré, et al., The Rio de la Plata Craton and the adjoining Pan-African/brasiliano terranes: their origins and incorporation into south-west Gondwana, Gondwana Research 20 (2011) 673–690.
[64] P. Oyhantçabal, S. Siegesmund, K. Wemmer, The Río de la Plata Craton: a review of units, boundaries, ages and isotopic signature, Int J Earth Sci 100 (2011) 201–220.

Ana Caro Montero, Master in Environmental Geology and Geological Resources. Current position as a PhD student in Geological Sciences at the Facultad de Ciencias Exactas, Físicas y Naturales, Universidad Nacional de Córdoba (Argentina). Her current research is the study of structure, kinematics and evolution of Cenozoic faults in the Sierras Pampeanas of Córdoba, Central Argentina.