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# The megascopic and mesoscopic structure of La Cocha ultramafic body, Sierra Chica of Córdoba, Argentina

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A B S T R A C T

The serpentinized ultramafic body of La Cocha is located in the Sierra Chica of Córdoba (31° 36′ 40″ South and 64° 32′ 40″ West). The body is a spinel harzburgite composed of olivine, enstatite and spinel, almost completely hydrated to associations of serpentine minerals. The rock is dark green, foliated, rich in serpentinized olivine and grains or aggregates of enstatite, partially to totally altered to bastite, with spinel as inclusions and a general porphyritic appearance. The $S_2$ metamorphic foliation was determined by a compositional layering defined by the lengthening and concentration of irregular pyroxene layers that alternate with olivine layers. This foliation is affected by $S_3$, composed of serpentine, which is parallel or cut sharply with low angles to $S_2$. The main structure of La Cocha ultramafic body is a low cylindrical recumbent fold interpreted as an "a"-type domal structure which is part of a major sheath fold, currently cut off by erosion. La Cocha ultramafic body is interpreted as an obducted slice of oceanic mantle, probably part of a basal tectonite of an ophiolitic complex. This slice, after its emplacement, was metamorphosed and deformed together with the country rocks.



## 1. Introduction

In between 27° and 33° South latitude there are a series of ophiolitic belts, in the region that includes the basement of the central Andes of Argentina, which were first described by Borrello (1969) and Villar (1975). These ophiolitic belts are zones interpreted as possible sutures of accreted terranes in the Gondwana margin during the Proterozoic to the early Palaeozoic. Nowadays, information about these belts at the regional level is quite irregular; in some cases they are only mentioned at recognition level (Villar, 1975, 1985). Recently, Ramos et al. (2000) have synthesized all the ophiolitic belts of the Palaeozoic and the early Proterozoic of the Andean basement and called attention to the incomplete general knowledge of the different belts that confirm the protomargin of Gondwana.

Two mafic and ultramafic belts denominated "Eastern Belt" and "Western Belt" (Kraemer et al., 1995) are identified, particularly for the Neoproterozoic-early Palaeozoic metamorphic basement of the Sierras Pampeanas of Córdoba, which is exposed in a series of N–S-oriented ranges uplifted during the Andean orogeny (Fig. 1). The lithology, the complex tectonic emplacement and the relationship with mylonitic rocks have allowed the interpretation of some of these belts as ophiolitic-type associations (Mutti, 1987; Escayola, 1994; Martino et al., 1995; Escayola et al., 1996). Kraemer et al. (1995) were the first workers who established the tectonic meaning of these belts in the evolution of the Sierras Pampeanas near Córdoba. These two belts have a strike of approximately N 340–350°, with high dipping between 50° and 70° E. The Eastern Belt separates the Pampia terrane from the Córdoba terrane, and the Western Belt separates the latter terrane from the Río de La Plata craton. Petrographical and geochemical characteristics allow us to deduce that these belts originated in different geotectonic environments and belong to different ophiolitic types.

The Western Belt is a harzburgite-type sequence and would represent systems of mid-ocean ridges. In this ophiolitic type, which is almost complete, it has been possible to recognize metamorphic peridotites with the transition zone, the cumulate gabbros and a section of pillow-lavas. Geophysical studies show high Bouguer anomalies that agree with the main axis of the Western Belt, explained as a zone of A-type subduction between two crustal blocks of different densities, separated by a very high dipping boundary. All the sequence was interpreted as a suture zone (Escayola et al., 1996).

The Eastern Belt is a lherzolitic-type sequence with minor associated websterites that could have probably originated in an ensialic back-arc setting. This belt extends from 31° to 32° South latitude (Fig. 1) in the Sierra Chica of Córdoba (Kraemer et al., 1995; Martino et al., 1995). The main outcrops along the Eastern

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Belt are Loma Negra, Bosque Alegre, Santa Cruz, Mina Ada, Cerro Sapo, La Cocha and other minor bodies studied by Mutti (1992a,b and references therein), Pugliese (1995) and Martino and Zapata (2002). The main outcrops of the Eastern Belt are exposed in the NW of the Alta Gracia city and in the central area of the Sierra Chica (Figs. 1 and 2); from south to north, they form the Cerro Santa Cruz, Cerro Negro, La Cocha, Sierra Chica Ultrabasic and Cerro San Bernardo bodies (Figs. 2 and 3). In general, these bodies are associated with marbles, amphibolites, gneisses and migmatites of medium- to high-grade in a minor belt, NNW oriented with intermediate dipping towards the NE. Main ultramafic varieties of these bodies are mostly lherzolites with subordinated harzburgites, abundant pyroxenites and gabbros, and leucocratic intrusives (Escayola et al., 1996 and references therein). Ramos et al. (2000) interpreted the Eastern Belt as an ophiolite remnant of a back-arc zone according to the geochemical characteristics.

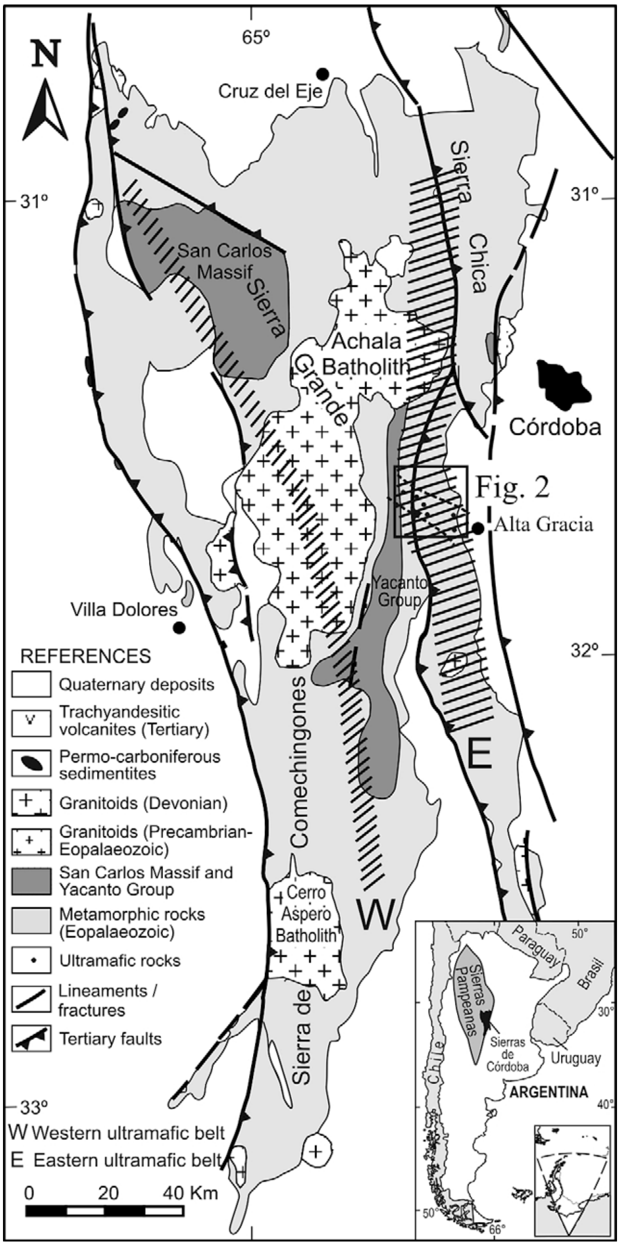


**Fig. 1.** Location of the Western and Eastern Ultramafic Belts in the Sierra de Córdoba of Argentina.

## 2. Geological setting of La Cocha ultramafic body

The serpentinized ultramafic body of La Cocha is located 2 km to the south of the Bosque Alegre Astronomic Observatory, in the Sierras de Córdoba (31° 36′ 40″ SL and 64° 32′ 40″ WL, 1250 m a.s.l). The La Cocha body is part of a group of ultramafic complexes disposed as an elongated and discontinuous minor belt, roughly oriented N 330° within the major Eastern Belt described above. Several bodies of this minor belt are exposed on top of the Sierra Chica (hanging wall) and others are distributed on the footwall, separated by the Sierra Chica main Tertiary fault (Fig. 2).

Maidana (1984) was the first to study the serpentinite body and its surroundings. Pugliese (1995) studied petrological and geochemical aspects of the serpentinite, interpreting it as an ophiolitic complex. Escayola et al. (1996) disagreed with this interpretation and suggested that serpentinites are a layered sequence, instead of an ophiolite sequence. Ramos et al. (2000) interpreted the Eastern Belt as an ophiolite from back-arc zone according to the geochemical characteristics. Pugliese and Villar (2001, 2002, 2004), using platinum group elements, proposed a mantelic origin and considered that serpentinites belong to tholeiitic geochemical series produced by a lithospheric rifting (Pugliese and Villar, 2002).

Following the mentioned authors, mainly Pugliese (1995), the La Cocha serpentinite body has a tabular shape with well-defined fault-bound contacts. The layering is sub-vertical and, based on the cumulate origin of this layering, it was deduced that the top of the sequence is in the east side of the body and the bottom is in the west (Pugliese, 1995; Pugliese and Villar, 2002, 2004). Pugliese (1995) interpreted the body as anticlinal.

In the present study, we describe the general (macroscopic scale, folding) and internal (mesoscopic scale, foliation and textural features) structure of the La Cocha body, adjusting the geometry and previous concepts about it, determining more precisely that its present shape conforms to a low cylindrical recumbent fold. The axis of this folded structure is sub-vertical, dipping with a high angle towards the north (N 20°/68°), and the axial plane has a NNE strike, dipping with a high angle towards the east (N 10°/85° E). This structure has important consequences on the polarity proposed by Pugliese (1995), and the petrography and general geometry of the La Cocha body allow us to propose that this body would be an obducted mantellic lens, probably part of a basal tectonite coming from an ophiolitic complex.

## 3. Field and laboratory methods

A map of the La Cocha ultramafic body and its metamorphic country rocks was made using standard aerial photographs and Landsat imagery. In the field, structural data and 70 oriented samples were collected, sectioned and examined petrographically and structurally. X-ray diffraction analyses in serpentinite were obtained with a scan range of 5–75°, step size of 0.02 and counting time of 1 s, using Phillips X Pert Pro equipment belonging to the Facultad de Ciencias Químicas of the Universidad Nacional de Córdoba (Argentina). Major element compositions in seven serpentinites and six amphibolites were determined by ICP–OES (inductively coupled plasma–optical emission spectrometry), at Activation Laboratories Ltd. (ACTLABS) in Canada.

## 4. Petrography

The serpentinite body, with its major axis oriented approximately N 20°, is located on the top of La Cocha hill and presents an elongated shape on the map, approximately 500 m wide and 200 m long, being wider in the south (Fig. 3). Decameter-long lenses of spinel piroxenites with chromite layers were recognized.

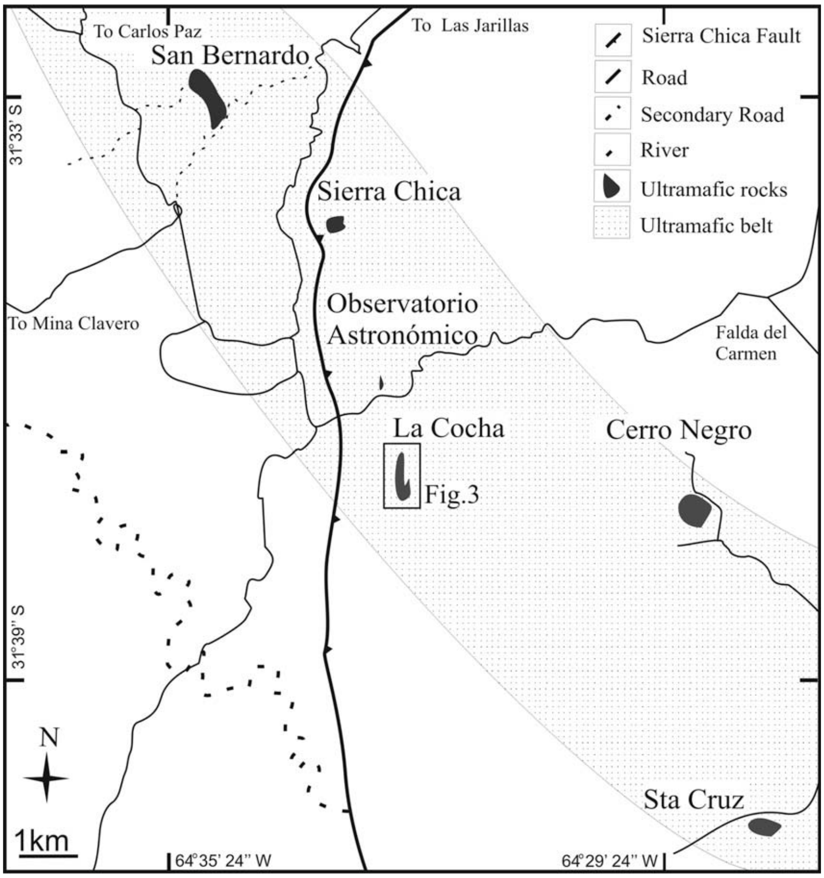


**Fig. 2.** Detailed map of the Eastern Ultramafic Belt and La Cocha ultramafic body.

Chromite was totally removed by mining. These lenses could be described as cumulates within the ultramafic rock. Some hornblendite lenses were also recognized. In an almost central position, a series of lens-like bodies (<200 m in length) of forsterite marbles, forsterite–tremolite marbles, hornblendites and amphibolites without pyroxene were recognized. Garnet–sillimanite gneisses and migmatites intercalated with pyroxene amphibolites and forsterite marbles are common country rocks. Finally, tabular and irregular leucocratic intrusives crosscut all rocks.

### 4.1. Serpentinite

The La Cocha body (Fig. 4) is mainly formed by dark green- to pale-colored, foliated serpentinites, dominantly composed of serpentinized olivine. Brown-colored, isolated crystals or aggregates of enstatitic piroxene crystals, which are partially to completely bastitized, give a general porphyritic look to the rock. The metamorphic foliation named here as $S_2$ and recognized in all of the body is given by a compositional layering defined by the elongation and irregular concentration of lens-like pyroxene layers that alternate with more regular olivine layers in the elongated granular aggregates along the $S_2$ foliation. This foliation is affected by another one, formed by a new fibrous serpentine and defined as $S_3$, which is arranged parallel or cutting with low angles to $S_2$.

In thin section serpentinite presents mesh and bastitic textures suggesting pseudomorphic textures (Gervilla, 1997). Olivine is partially to completely serpentinized from the edge to the core, displaying typical mesh textures leaving olivine relicts; when these relicts are also replaced, hourglass and window textures occur (Deer et al., 1992). In samples with the latter texture, it is represented by a lone green yellow tabular serpentine crystal in the middle of the replaced olivine crystal, oriented with (0 0 1) perpendicular to the $S_2$ foliation. Serpentinized olivine crystals have an opaque mineral rim that marks the old crystal contour (Fig. 4c).

Orthopyroxene, optically defined as enstatite, is partially to totally replaced by serpentine, forming centimeter-long bastites, showing opaque minerals in the fractures and edges. Sometimes, green spinel inclusions occur. Cleavage usually is parallel to $S_2$ foliation. Intrafolial microfolds of bastitized pyroxene aggregates have also been identified (Fig. 5c).

Spinel appears as inclusions in pyroxene, or as interstitial minerals present in isolated grains, or aggregates parallel to the visible $S_2$ foliation. The aggregates have grain boundaries with 120° triple points. Transitional variations from green spinel to chromite are observed.

X-ray powder diffraction was used to identify minerals that form pseudomorphic textures. The diffraction pattern from these minerals corresponds to lizardite 1*T*, brucite, magnetite and clinochlore (Fig 5a). This association indicates a retrograde serpentinization of peridotite by the reaction olivine = lizardite ± brucite ± magnetite (Wicks and O'Hanley, 1988). Prior to the serpentinization, clinochlore was probably formed by some $CO_2$ influence on olivine and spinel during pressure decrease. Supporting this interpretation, it is possible to recognize olivine associated with clinochlore and the serpentinization affecting both minerals, meshing the olivine and invading clinochlore through its (0 0 1) cleavage, respectively. Serpentine also occurs as non-pseudomorphic textures forming serrate veins along fractures with the fibers oriented perpendicularly to the walls that define the $S_3$ foliation (Fig. 4f). Serpentine serrate veins contain opaque minerals between the fibers or near the wall of the fractures. X-ray diffraction pattern analysis defines these minerals as lizardite 1*T*, antigorite, spinel

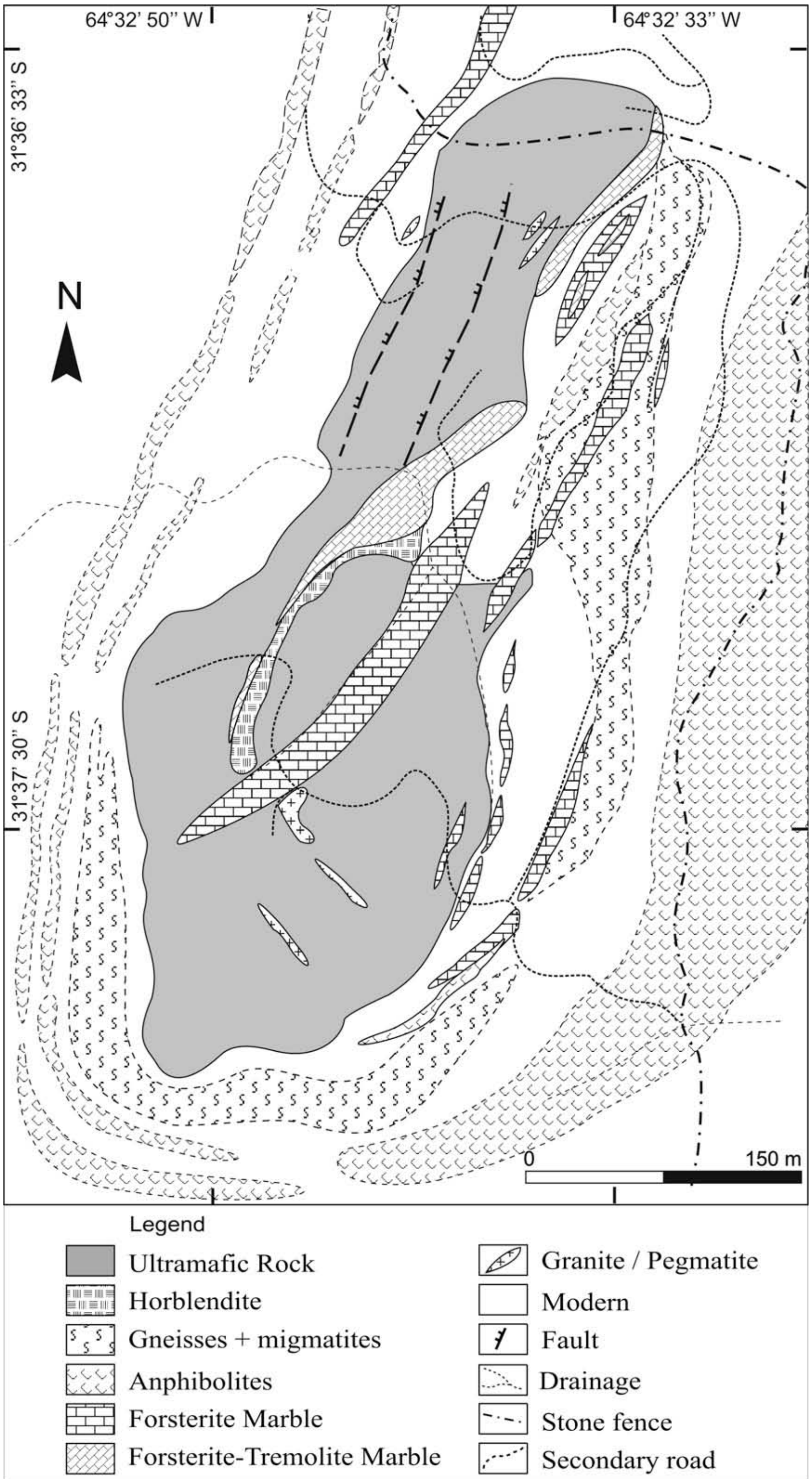


**Fig. 3.** Detailed geological map of La Cocha ultramafic body.

group Ni ($SiO_4$) and magnetite (Fig. 5b). Wicks and O'Hanley (1988) proposed that chrysotile veins are similar in form to lizardite 1*T* veins. The difference is that the veins of chrysotile are characterized by length-slow fibers oriented perpendicularly to the fracture; however, those of lizardite 1*T* are composed of length-fast fibers. Microscopic analysis of $S_3$ veins of La Cocha serpentinite determined length-fast fibers, which would be typical of lizardite 1*T* as determined by X-ray diffractometry.

The south area of the La Cocha body corresponds to the synformal hinge zone where axial plane cleavage develops. Coincident with this cleavage there are white to green centimetric veins and a patchy invasion of serpentine. Cutting irregularly or arranged parallel to $S_2$, prismatic tremolite (2 mm length), which is partially serpentinized around grains or across the cleavage, is recognized. Clinochlore in contact with amphibole has also been identified, commonly associated with opaque minerals.

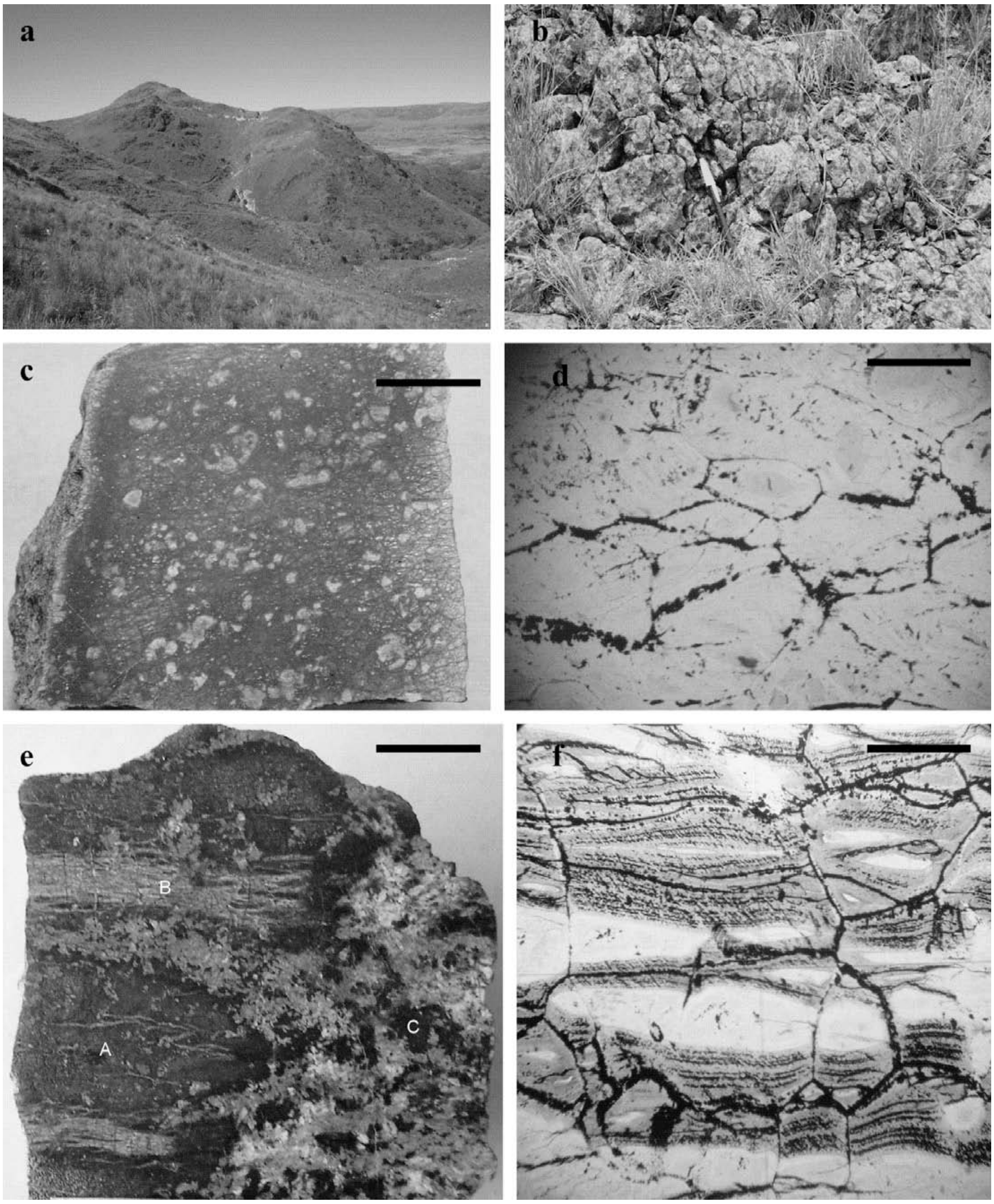


**Fig. 4.** (a) Panoramic view of La Cocha ultramafic body, structure of synformal folds. (b) Porphyritic look with the $S_2$ metamorphic foliation and the serpentine veins defined as $S_3$. (c) General porphyritic look and $S_2$ metamorphic foliation of dominant serpentinites in La Cocha ultramafic body (scale bar = 1 cm). (d) Photomicrographs illustrating serpentinite textures under plane-polarized light (scale bar = 0.5 mm). (e) Serpentinization events: $A = S_2$ serpentinite, $B = S_3$ serpentine veins, $C$ = patches and veins invasion of tremolite, serpentine and clinochlore (scale bar = 1 cm). (f) Detail of the non-pseudomorphic veins of lizardite 1*T* ($S_3$) (scale bar = 0.5 mm).

All the serpentinite rocks just described can be modally classified as spinel harzburgites. The average serpentinite geochemical composition is 38.75% of $SiO_2$, 7.19% of $Fe_2O_3(t)$ and 39.24% of MgO (Table 1).

In summary, the serpentinite from La Cocha is a metamorphic rock formed by the replacement of spinel harzburgites, with a $S_2$ foliation defined by olivine and pyroxene layers. It is intensely serpentinized, with pseudomorphic and non-pseudomorphic textures filling the fractures. According to the textural relations found in La Cocha serpentinite, three events of serpentinization can be established (Fig 4e): serpentinization of primary minerals, (b) development of serpentine veins forming $S_3$ foliation and (c) patchy and vein invasion of tremolite + serpentine + clinochlore.

### *4.2. Spinel pyroxenite lenses associated with chromite layers*

These lenses are several meters long and 0.2 m wide and are concordant with the $S_2$ foliation of the ultramafic body. They occur in a higher relief than the rest of the ultramafic rocks. They are black, plentiful of magnetic minerals, fine-grained, and contain millimetric lenses of opaque minerals and spinel in a matrix of partially serpentinized reddish pyroxene and olivine. Centimetric veins with abundant talc are also observed, giving a shining look to the rock.

Microscopically these lenses are composed of discrete opaque minerals, spinel in very small grains, orthopyroxene, olivine, tremolite, talc and serpentine.

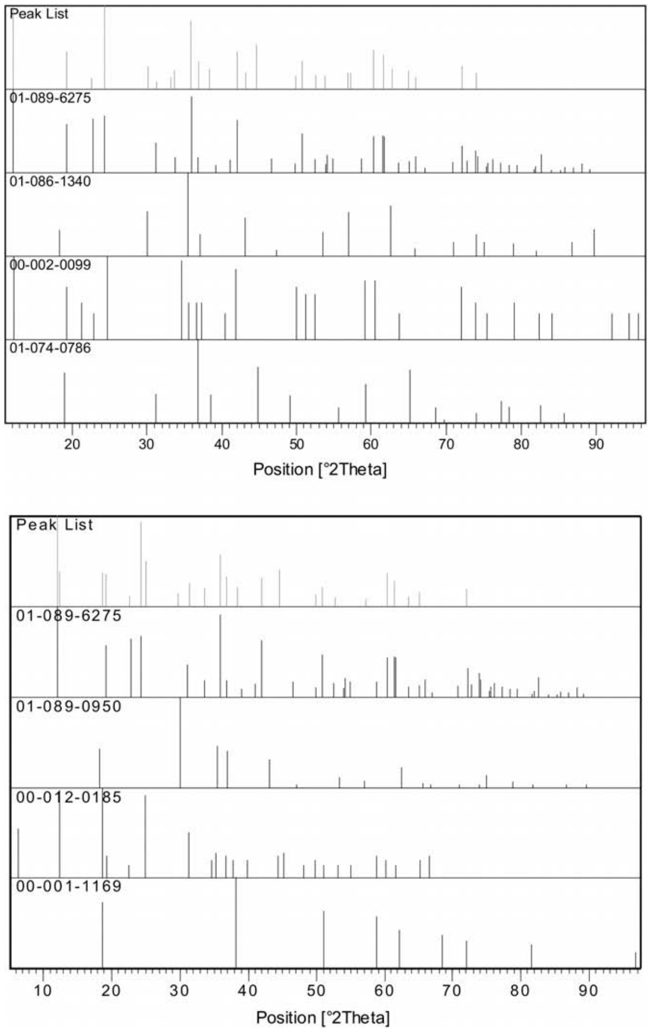


**Fig. 5.** X-ray diffraction of powdered rock sample and determined mineral patterns. (a) Serpentinite with pseudomorphic texture, (01-089-6275 lizardite 1*T*, 00-001-1169 = brucite, 01-089-0950 = magnetite and 00-012-0185 = clinochlore). (b) Serpentine with non-pseudomorphic texture (01-089-6275 = lizardite 1*T*, 00-001-1169 = brucite, 01-089-0950 = magnetite and 00-012-0185 = clinochlore)

**Table 1**
Average geochemical composition of serpentinite and amphibolite.

| | Serpentinite | Non-pyroxene amphibolite | Pyroxene amphibolite |
|---|---|---|---|
| $SiO_2$ | 38.75 | 48.02 | 43.57 |
| $Al_2O_3$ | 0.831 | 13.47 | 16.52 |
| $Fe_2O_3$ (*T*) | 7.193 | 10.48 | 13.17 |
| MnO | 0.101 | 0.21 | 0.257 |
| MgO | 39.24 | 8.94 | 9.38 |
| CaO | 0.264 | 15.07 | 11.76 |
| $Na_2O$ | 0.053 | 1.56 | 2.25 |
| $K_2O$ | 0.039 | 0.21 | 0.44 |
| $TiO_2$ | 0.02 | 0.75 | 0.277 |
| $P_2O_5$ | 0.007 | 0.09 | 0.02 |
| LOI | 13.3 | 1.07 | 1.93 |
| Total | 99.92 | 99.86 | 99.58 |

### 4.3. Hornblendite lenses

In the field, these rocks outcrop as concordant lenses parallel to the $S_2$ foliation within the ultramafic body. Outcrop dimensions vary from several meters long in the middle of the body to 1 m long lenses. They are coarse-grained, black rocks, with a weakly marked textural orientation. Microscopically they have an equigranular hypidiomorphic texture, mainly composed of green to brown centimeter-long hornblende. Opaque minerals and chloritized biotite occur as accessories. Iron oxide veins crosscutting through minerals and epidote veins are alteration products.

### 4.4. Amphibolites

Two varieties are recognized: non-pyroxene amphibolites and pyroxene amphibolites. Non-pyroxene amphibolite outcrops are wedged by folding and occur intercalated with the ultramafic rock in the body core. The rock texture is medium-grained (<4 mm) granonematoblastic. Grain size in non-pyroxene amphibolites is greater than that in pyroxene amphibolites. They are composed of hornblende and plagioclase, with remarkable amounts of opaque minerals and titanite. The average chemical composition is: $SiO_2$ 43.57%, $Al_2O_3$ 16.52%, $Fe_2O_3(t)$ 13.17%, MgO 9.38% and CaO 11.76% (Table 1).

Pyroxene amphibolites occur as tabular bodies of variable thickness, from ten meters in the west of the ultramafic body to hundreds of meters thick in the east. They are concordant with the country rocks foliation represented by garnet sillimanite gneisses. These amphibolites border the ultramafic body but are not in direct contact with it, separated by the gneisses. They are banded rocks, with alternating millimetric bands. Dark green-colored bands have a fine-grained nematoblastic texture and consist of hornblende and plagioclase. Pale green bands have a fine-grained granoblastic texture and are composed of pyroxene and plagioclase. Hornblende, plagioclase, orthopyroxene (En) and clinopyroxene (Di) are identified by microscopic analysis; accessories are opaque minerals. The average chemical composition of these amphibolites is: $SiO_2$ 48.02%, $Al_2O_3$ 13.47%, $Fe_2O_3(t)$ 10.48%, MgO 8.94% and CaO 15.07% (Table 1).

### 4.5. Marbles

They are intercalated with the ultramafic body and in the country rocks, as tabular and lens-like bodies concordant with the gneisses foliation. Two varieties are recognized: forsterite and forsterite–tremolite marbles. Forsterite marbles are coarse-grained rocks (10 mm), predominantly white in color, with yellowish green decimetric bands. They have a granoblastic texture and are composed of abundant dolomite and calcite, with forsterite, spinel, talc and opaque minerals as accessories concentrated in the bands. Forsterite is replaced by serpentine, giving the yellowish green color to the bands.

Forsterite–tremolite marbles are also in contact with the country rocks and the ultramafic rocks and are wedged by folding in the body core. They are fine-grained rocks (1 mm), with dark grey color generated by the abundance of accessories. Their composition is given by forsterite, tremolite–actinolite, calcite, dolomite and abundant opaque minerals. Clinochlore surrounding the opaque minerals and tremolite is recognized, the latter reaching 10 mm of length. Forsterite and tremolite-actinolite are totally to partially serpentinized.

### 4.6. Garnet sillimanite gneisses

These are the dominant varieties in the country rocks of the La Cocha body, in direct contact with ultramafic rocks. Metamorphic foliation is well developed in the N 20°/85° W direction, deflecting towards the E–W direction in the south area of the body. They are intensely deformed, with minor internal folding. Foliation is defined by alternation of bright and dark bands, with thicknesses varying between millimeters and centimeters. Leucocratic bands have a porphyroblastic texture formed by centimeter-sized garnet

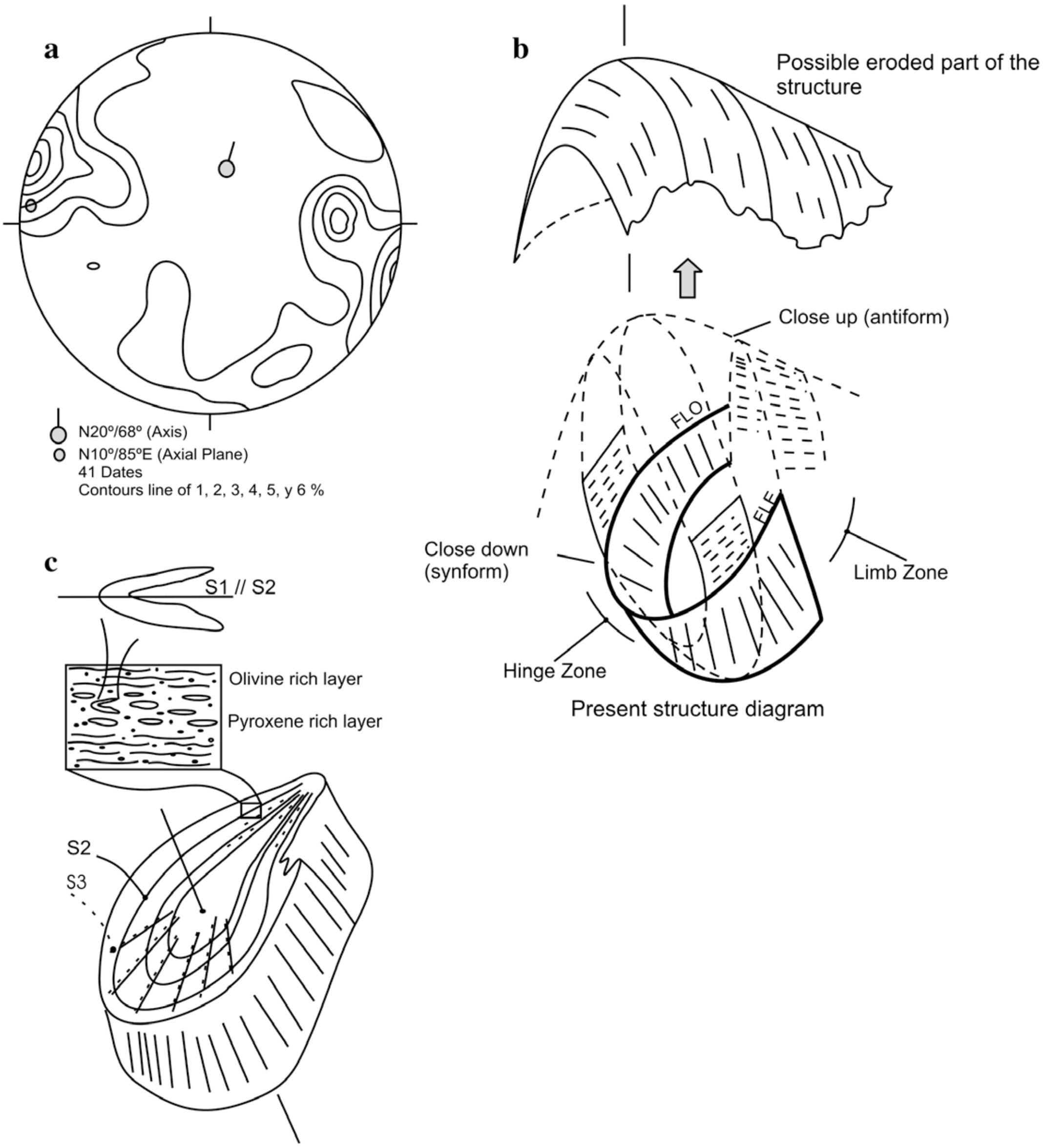


**Fig. 6.** Structure and interpretative diagram. See text for explanation.

in a fine-grained granoblastic matrix composed of quartz, plagioclase, potassium feldspar and minor biotite. In some bands, abundant fine-grained garnet also appears. Garnet porphyroblasts are often rimmed by biotite. Dark bands have lepidoblastic texture and are predominantly composed of biotite and sillimanite. The accessories are rutile associated to biotite, and minor zircon and scarce spinel included in garnet.

## 5. Structural description of foliation and folds

On a megascopic scale, a pervasive foliation is defined by the compositional bands described above and assigned to $S_2$. These compositional bands are materialized by the lengthening and concentration in the irregular layers of crystals or eye-shaped pyroxene aggregates. Sometimes, these aggregates form intrafolial microfolds probably defining a $S_1$ relict foliation. The described layers alternate with other more regular layers composed of elongated granular olivine aggregates parallel to the $S_2$ foliation (Fig. 4 c and d).

Distribution of the $S_2$ foliation is complex (Fig. 6a), defining a large low cylindrical reclined fold. The axis is sub-vertical, plunging with a high angle to the north (N 20°/68°); the axial plane strikes NNE, dipping with a high angle to the east (N 10°/85° E). This geometry is shown in Fig. 6b and will be used for a better description of this complex fold. The scheme shows the limbs zone, belonging to the north area of the La Cocha body, has an antiform geometry with the western limb dipping towards the west (FLO, Fig. 6b) and the eastern limb dipping towards the east (FLE, Fig. 6b). The hinge zone, integrated by the outcrops in the south area of the La Cocha body, displays a synformal geometry.

In the south area, associated with the hinge zone, a $S_3$ foliation is formed by serpentine veins cutting with low angles to $S_2$. In the limb zone, $S_3$ is parallel to $S_2$. These spacial relationships allow us to postulate $S_3$ as an axial plane foliation. Relationships of the three recognized foliations are shown in Fig. 6c.

In the forsterite–tremolite marbles, forsterite marbles, hornblendites and amphibolite lenses located in an almost central position in the serpentinite body, in the core of the reclined fold, the $S_2$

foliation refolded by $S_3$ is recognized, without a remarkable axial plane cleavage.

## 6. Discussion and interpretation

Several hypotheses were proposed to explain the genesis of ultramafic bodies in the Eastern Belt, and certain discrepancies about the lithologic types and their petrogenetic and tectonic significance still exist.

Villar (1985) proposed that ultrabasic rocks of the Sierras de Córdoba are of Alpine type. Mutti (1992a,b, 1994, cf. references in Mutti, 1997 too) carried out studies to establish the dominant ultrabasic types in the Sierras de Córdoba belts (including Eastern and Western Belts) and associated them as the basal sections of ophiolitic complexes indicating the presence of depleted mantle rocks generated in a back-arc and/or arc environment. Pugliese (1995) interpreted the La Cocha body as part of an ophiolitic complex, generated in the mantle, transported as oceanic crust towards the continental margin, subducted and emplaced by complex thermal tectonic mechanisms to the Sierra Chica of Córdoba. According to Pugliese (1995), this tectonic emplacement took place through old crust sutures that could have been in cold condition, supposed by the absence of thermal phenomena in the country rocks in contact with the ultramafic body. This author also suggested that the La Cocha body represents a minor part of the stratified ophiolitic complex, more specifically, the peridotite-gabbro transition zone. Escayola et al. (1996) interpreted the La Cocha body as a stratified type, similar to the Stillwater Complex. Mutti (1997) correlated petrologic, mineralogic, geochemical and structural data of ultramafic rocks and their metamorphic association in Sierra Chica and Sierra Grande of Córdoba and established the presence of a dismembered basal ophiolite section (mantle tectonite and transition zone) emplaced into upper crustal rocks (metapelites, metalavas, and carbonatic metasediments), proposing a tentative model applicable to the Proterozoic evolution of Sierras de Córdoba.

Ramos et al. (2000) interpreted the Eastern Belt as ophiolites formed in back-arc setting according to the geochemical characteristics. Pugliese and Villar (2002) postulated that the La Cocha body would not belong to an ophiolite; instead, it would be a gabbro generated in a rift zone as a product of crustal thinning. Subsequently, Pugliese and Villar (2004) assigned it to a stratified complex of Stillwater type, in spite of its reduced size, rich in magnetite and orthopyroxene and with tholeiitic geochemical signature.

The characteristics indicated by the serpentinite foliation in the La Cocha body, mainly the elongation and concentration of pyroxene and olivine layers along the $S_2$ foliation, suggest that this foliation had a metamorphic origin. This allows us to describe the La Cocha body as a tectonite in a broad sense. In addition to the foliation, the texture and mineralogical composition allows us to classify the dominant ultramafic rock as a spinel harzburgite, in which hornblendite lenses and spinel pyroxenite lenses associated with chromite layers are identified. All these characteristics allow us to postulate that La Cocha ultramafic body could be an obducted lens or a slice of oceanic mantle, probably a basal tectonite section of an ophiolite complex.

The geometry of $S_2$ foliation allows us to describe the serpentinite body fold as a low cylindrical reclined type. Combining the closings shown in Fig. 6b, these closings could belong to a domal "a"-type structure which would be part of a major sheath fold (Cobbold and Quinquis, 1980; Marshak and Mitra, 1988; Skjernaa, 1989), now partially eroded. Complementing Fig. 6b, this possible interpretation, indicated by the arrow, has been drawn separately.

These specific fold types have been recognized in other ultramafic bodies (Martino and Zapata, 2002) in Cerro Sapo, also in the Sierra Chica, 50 km to the north of the studied area. As discussed in Martino et al. (1999) and Martino and Zapata (2002), the presence of these structures would obey the $S_2$ foliation developed by a general shear as a result of thrusting tectonics, in high ductility conditions during the $M_2$–$D_2$ metamorphic peak (Guereschi and Martino, 2002) that generated $S_2$ in regional metamorphic rocks (see Fig. 7 in Martino et al., 1999). This event was produced by the collision of the Pampia terrane with the western margin of Gondwana during the end of the Pampean Orogeny at 530–520 Ma (Stuart-Smith et al., 1996; Rapela et al., 1998; Martino and Guereschi, 2006).

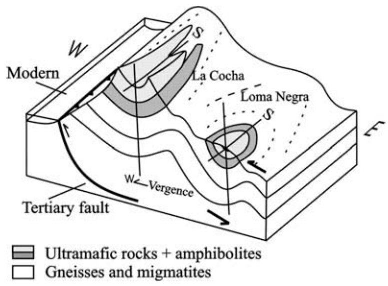


**Fig. 7.** Cross section of La Cocha and Loma Negra bodies showing the geomorphology.

On the basis of the structural studies carried out in the La Cocha body and the data collected from the Loma Negra ultramafic body, which is located towards the east of the studied area (Fig. 2), a schematic profile was made to determine the body's geometry (Fig. 7). It is possible to recognize a west-verging sequence of main asymmetric folds, which fold the $S_2$ metamorphic foliation generating the $S_3$ geometric foliation in the Loma Negra body. These main folds have axes N 340° and N 160°, with plunges 30° and 40°, respectively; axial plane is N 340°/75° E. The synformal structure of both ultramafic bodies, the relationships between lineation and hinge fold, the sheath fold geometry and the general vergence towards the west, associated with an asymmetric folding, establish that deformation would have developed in a simple shear regime, essentially post-metamorphic in time. This deformation would have affected the studied area of the Sierra Chica (hanging wall) and its footwall area too. La Cocha and Loma Negra ultramafic bodies are topographically arranged in high zones, corresponding to a typical inverted relief of hanging synformal (Martino and Anzil, 2006). This folding type is common in the Valley and Ridge Province in the Appalachians.

Finally, it is worth noting that Pugliese (1995) suggested that the La Cocha body represents a minor part of a stratified ophiolitic complex, specifically a peridotite-gabbro transition zone, with cumulate textures. These textures have not been found in this work, and considering the structure as a reclined fold, the bottom and the top of the serpentinite body would not be located to the west and east, respectively, as Pugliese (1995) proposed. Instead, the top would be in the central part of the ultramafic body, coincident with the core folds, whereas its bottom would be in both western and eastern margins in the fold limbs and in the hinge zone surrounding the body. Nevertheless, in this work, neither bottom nor top and no cumulates are identified, but the ultramafic sequence would correspond to an obducted lens or a slice of oceanic mantle, probably part of a basal tectonite of an ophiolitic complex. This slice, after emplacement, was metamorphosed and intensely deformed, along with the country rocks, during the main metamorphism $M_2$–$D_2$ that affected the Eastern Pampean Ranges at this latitude.

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