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Thermobarometry, Sm/Nd Ages and Geophysical Evidence for the Location of the Suture Zone Between Cuyania and the Western Proto-Andean Margin of Gondwana

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Abstract

Basement rocks comprising ortho- and paragneisses and schists whose tectono-metamorphic evolution is poorly known, are exposed in the Sierras de Umango, Maz-Espinal and Las Ramaditas, in the northwest of the La Rioja Province, Argentina. These units were included in the Maz, El Taco, El Zaino complexes, as well as the Tambillos Metamorphics that would be part of the northern end of the Cuyania terrane, a microcontinent derived from Laurentia that collided with Western Gondwana during the early Paleozoic, or belong to the active margin of the continent. To recognize rocks belonging to each of these tectonic units and to understand the history and physical conditions of accretion were some of the main goals of the multidisciplinary investigation whose preliminary results are presented here. Geochemical studies, trace and REE elements and Sm-Nd model ages allowed the recognition of several episodes of crustal accretion in these rocks. The oldest one occurred at ca. 2.2 Ga in an arc/back-arc environment along the eastern segment of the Sierra de Maz, and was possibly coeval with development of a early Proterozoic continental crust that acted as source to sediments of Maz Complex. The following episode of crustal accretion that formed rocks in this region was at ca. 1.4 Ga and is registered by tonalites emplaced in an extensional environment cropping out in the western flank of the Sierra del Espinal.

In the Sierra de Umango, an arc/back-arc sequence registered an episode of crustal accretion during the Grenvillian Cycle (ca. 1.3 Ga). The last episode of crustal accretion detected in this area (800 Ma) is represented by an old alkaline volcanism in the Sierra de Umango. This episode could be representing the first stage of break-up of the Rodinia supercontinent during the Neoproterozoic.

The metamorphic grade reached by these rocks is mostly represented by fabrics with mineral assemblages of intermediate to high pressures and high temperatures, typical of collisional environments. The oldest rock-forming fabrics tectono-metamorphic episode recognized is of middle Proterozoic age (ca. 1.04 to 0.969 Ga, garnet-whole-rock Sm/Nd age) being registered by metapelites from Maz Complex that attained temperatures of 650°C–6.3 kbar. A younger metamorphic event (463 Ma, garnet – whole-rock Sm/Nd age) is verified in metatonalites intrusive in these metapelites. Another metamorphic event at ca. 301 Ma (garnet-WR Sm/Nd age) was recognized in metasediments from El Taco Complex. Peak metamorphic conditions of this event, probably registering the last major tectonic episode that affected rocks of this area was established in 868°C–9.8 kbar. It is impossible to distinguish fabrics belonging to totally different tectonic episodes based on structural or metamorphic data. Therefore, distinction between major tectono-thermal events of totally different ages such as the high-T middle Proterozoic deformation and with N–NWestwards tectonic transport direction registered in the Sierras de Maz-Espinal and Umango from the youngest one (ca. 301 Ma) that attained the highest-P/T conditions, recognized in the Sierra de Las Ramaditas, had to be done on the basis of Sm/Nd ages.

Geophysical evidence indicates the presence of extensive WNW-oriented lineaments that separate basements blocks of different magnetic and gravimetric signatures that are thought to represent ancient Grenvillian age suture zones. On the other hand, the northern segment of the Valle Fértil lineament that runs between Sierras de Umango and Maz-Espinal is at present interpreted as marking the eastern boundary of the Cuyania terrane. This is supported by isotopic data as well as the contrasting history of tectono-metamorphic events as determined for both of these segments of the NW Sierras Pampeanas.

Key words: Thermobarometry, Sm/Nd, geophysics, Cuyania, Gondwana.

Introduction

Accretion tectonics is the main process responsible for the evolution of cordilleran-type orogenic belts, such as the exposed along the circum-pacific region. In the case of the Andes, one of the classical and most studied examples of a cordilleran orogenic belt, this process is thought to have built approximately forty percent of continental growth since the end of the Neoproterozoic (Ramos, 2000a, b).

A mosaic of tectonic units forms cordilleran orogens with dimensions between few hundred and thousands square kilometers, known as displaced terranes. These are frequently of distant provenance; present structural and lithological features not directly related to subduction processes and were accreted to the continental margin during a long period of geological time (Coney et al., 1980; Sengör and Dewey, 1990; Sengör, 1991).

Recognition of terranes in southern South America has been based on their stratigraphic, magmatic, paleontological, geophysical and paleomagnetic characteristics, as well as their contrasting tectonic histories (e.g., Ramos et al., 1986; Ramos, 1988, 2000a, b, 2004; Astini et al., 1995, Vujovich and Kay, 1998; Pankhurst et al., 1998, 2000; Cañas, 1999; Quenardelle and Ramos, 1999; Benedetto et al., 1999; Coira et al., 1999; Rapalini et al., 1999; Cingolani and Varela, 1999; Sato et al., 2000; Chernicoff and Ramos, 2003; Chernicoff and Zappettini, 2003; Leal et al., 2003). However, despite the widespread application of concepts of terrane tectonics to diverse geological situations in several continents, there is no detail account of structural or metamorphic effects of accretion tectonics of a classical terrane, such as at the northern sector of Cuyania, reported in the literature.

The Cuyania composite terrane comprises the Precordillera and Pie de Palo terranes (Ramos et al., 1998) that crop out along the central-southern segment of the Andes in the NW of Argentina (Fig. 1). Cuyania has long been recognized as a microcontinent derived from Laurentia (Ramos et al., 1986, 1998; Dalla Salda et al., 1992a, b; Astini et al., 1995, 1996; Astini and Thomas, 1999; Pankhurst and Rapela 1998; Thomas et al., 2002; Thomas and Astini, 2003) although a Gondwanic origin for this terrane has been postulated more recently (Aceñolaza et al., 2002 an others therein). Due to its well-known geological characteristics, fossiliferous record and available palaeogeographic data (see Rapalini et al., 1999; Benedetto, 2004–this volume; Ramos, 2004–this volume, and others therein) the crystalline basement of Cuyania terrane have been elected as target of a multidisciplinary investigation to improve our understanding of the process of accretion tectonics.

In this paper we present the first results of a study where methods of metamorphic, isotopic and structural geology with the support of LANDSAT and ASTER satellite images, as well as geophysics, were used to investigate the history of tectonic evolution of the Cuyania terrane.

The main objective was to raise data in order to test second order hypothesis related to the accretional history of Cuyania, something that can translated in terms of the metamorphic, structural, isotopic and petrological signature left by the accretion process in rocks belonging to this terrane.

Due to the wide variety but small quantity of the data obtained so far only a short account of the structural, isotopic and geophysical characteristics of the main rock units of the NW Sierras Pampeanas (Maz-Espinal, Umango and Las Ramaditas) cropping out along the northern boundary of the Cuyania terrane is presented in this paper. This is followed by a brief discussion of their possible meaning in the context of the geological evolution of the southern-central segment of the Andes during the Paleozoic.

Despite the early stage of development of our study in, we shall present evidence enough to raise the possibility that some of the rocks sequences of NW Sierras Pampeanas, considered as belonging to the northern part of Cuyania terrane, might not be allochthonous, being, instead, part of the western margin of Gondwana.

Geological Setting

The study area is located in the northwest of La Rioja Province (Argentina). It is characterized by basement rocks cropping out in the Sierras de Las Ramaditas, Maz-Espinal and Umango (Fig. 2). These rocks were exposed by movement of reverse faults during the Cenozoic activated by shortening related to the shallow subduction of the Nazca Plate underneath South America (Ramos et al., 2002).

The location of the study area, between the Precordillera and the Ordovician magmatic arc exposed in the Famatina terrane (Fig. 1) is key to the understanding of the history of growth of this segment of continental crust. This is because it could belong to the northern tip of the Cuyania terrane that was accreted during the early Paleozoic (Ramos et al., 1998; Casquet et al., 2001a) or represent part of the western edge of the proto-Andean margin of Gondwana (Becchio and Lucassen, 2002; Aceñolaza et al., 2002).

Sierra de Las Ramaditas and Maz-Espinal

Three metamorphic complexes were recognized at the sierras de Las Ramaditas and Maz-Espinal: El Taco, Maz and El Zaino Metamorphic complexes (Fig. 2). Original distribution and the main rock types of these units are as proposed by Kilmurray and Dalla Salda (1971) incorporating changes by Vujovich et al. (2001).

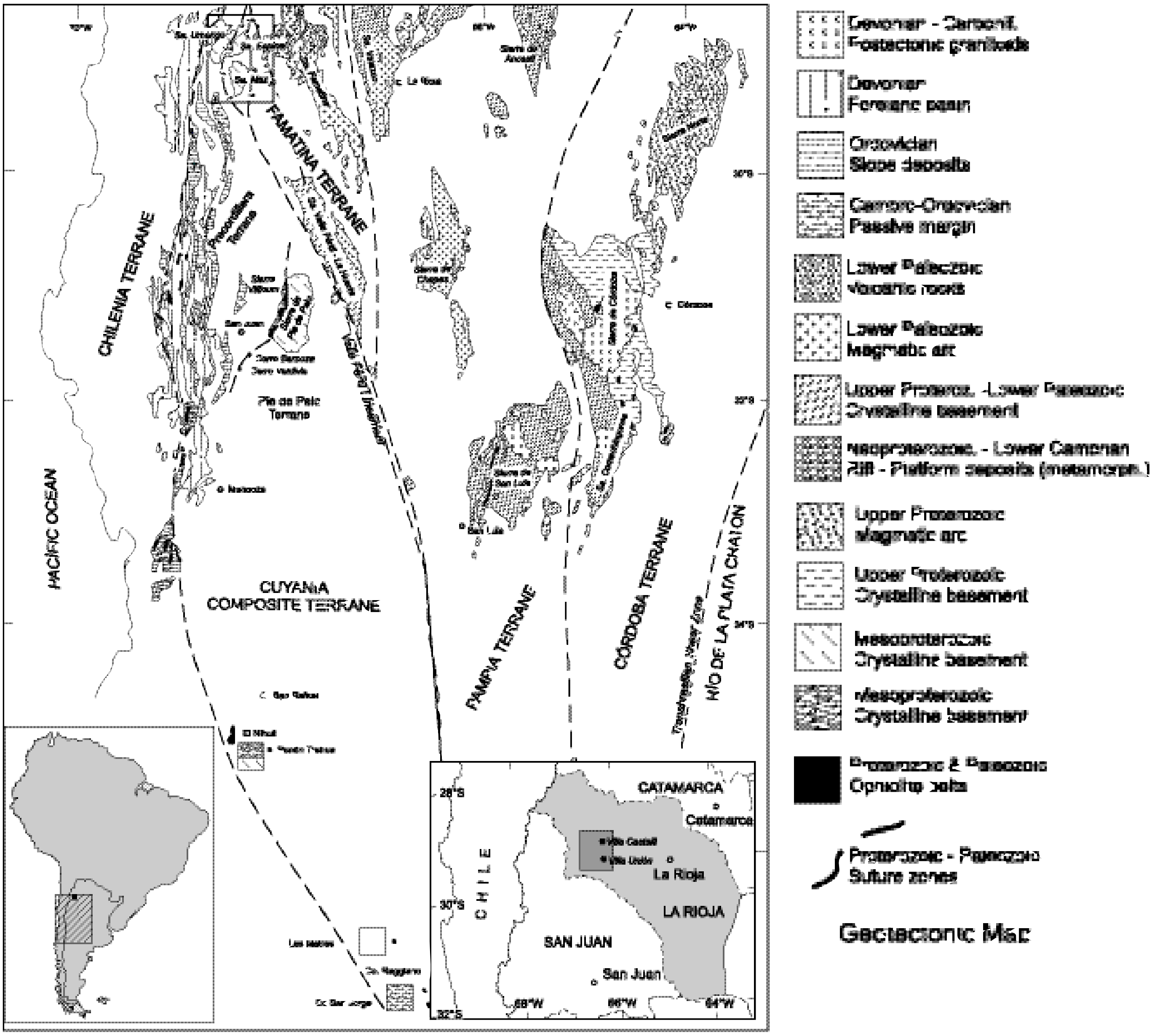

Fig. 1. Map of the central-western part of Argentina showing the main geotectonic units and location of the area of study (after Vujovich and Ramos 1999, partially modified after Leal et al., 2003).

El Taco Complex

Rocks ascribed to this complex crop out mainly in the Sierra Las Ramaditas and in southern part of Sierra de Maz. A sequence of marbles, calc-silicated rocks and quartz-mica schists, probably representing marls, impure sandstones and pelites, associated with amphibolites and an ultramafic rock are typical of this complex (Kilmurray and Dalla Salda, 1971). Interlayered with marbles, lenses of calc-silicate rocks and amphibolites with dimensions ranging from 1 to 10 meters are typical of the El Taco Complex. Protoliths of the amphibolites include impure sediments where associated with marbles as well as igneous rock characteristic of arc or back-arc tectonic settings, as demonstrated by Vujovich and Kay (1996). The ultramafic rocks occur as boudins interlayered with metasediments in Cerro Noqués, at the western part of Sierra de Maz (Lavandio, 1968; Kilmurray, 1969, 1970; Villar, 1985). These are represented by metamorphosed peridotites, in close spatial association with quartzites and garnet-biotite gneisses, and have geochemical affinity with a magmatic arc setting (Vujovich et al., 2004). An U-Pb titanite age of 428 Ma (Becchio and Lucassen, 2003) and an U/Pb SHRIMP zircon age of 452 Ma±6 Ma (Casquet et al., 2001b) were obtained for calc-silicate rocks from

El Taco Complex in the southwestern part of the Sierra de Maz. These were interpreted as age of metamorphic peak.

Maz Complex

Rocks ascribed to the Maz Complex crop out in the western and central area of Sierra de Maz, extending northwards to the Sierra del Espinal (Espinal Formation, Turner, 1964). This complex is characterized by metasediments (pelites and sandstones) associated with amphibolites, metagabbros and meta-tonalites (Kilmurray and Dalla Salda, 1971; Vujovich et al., 2001).

The metasediments occur as lenses with variable bulk-composition marked by muscovite-biotite and graphite schists interbanded with quartz-rich gneisses and quartzites.

Amphibolites, gabbros, diorites, leucogabbros and tonalites represent the igneous rocks of the Maz Complex. Despite showing intrusive relations with the metasediments they were affected by the same deformational and metamorphic events of the host rocks, as indicated by their compatible orientation and nature of structures and textures. Geochemical data presented by Vujovich et al. (2004) shows that these igneous rocks were formed in several tectonic settings, ranging from intraplate to magmatic arc.

The metagabbros and metadiorites occur as intrusions of variable bulk-composition, dimension and grain size observed at the northeastern sector of Sierra de Maz and at Filo del Aspero in Sierra del Espinal (Vujovich et al., 2001, 2004). Some metagabbros occur as intrusions with

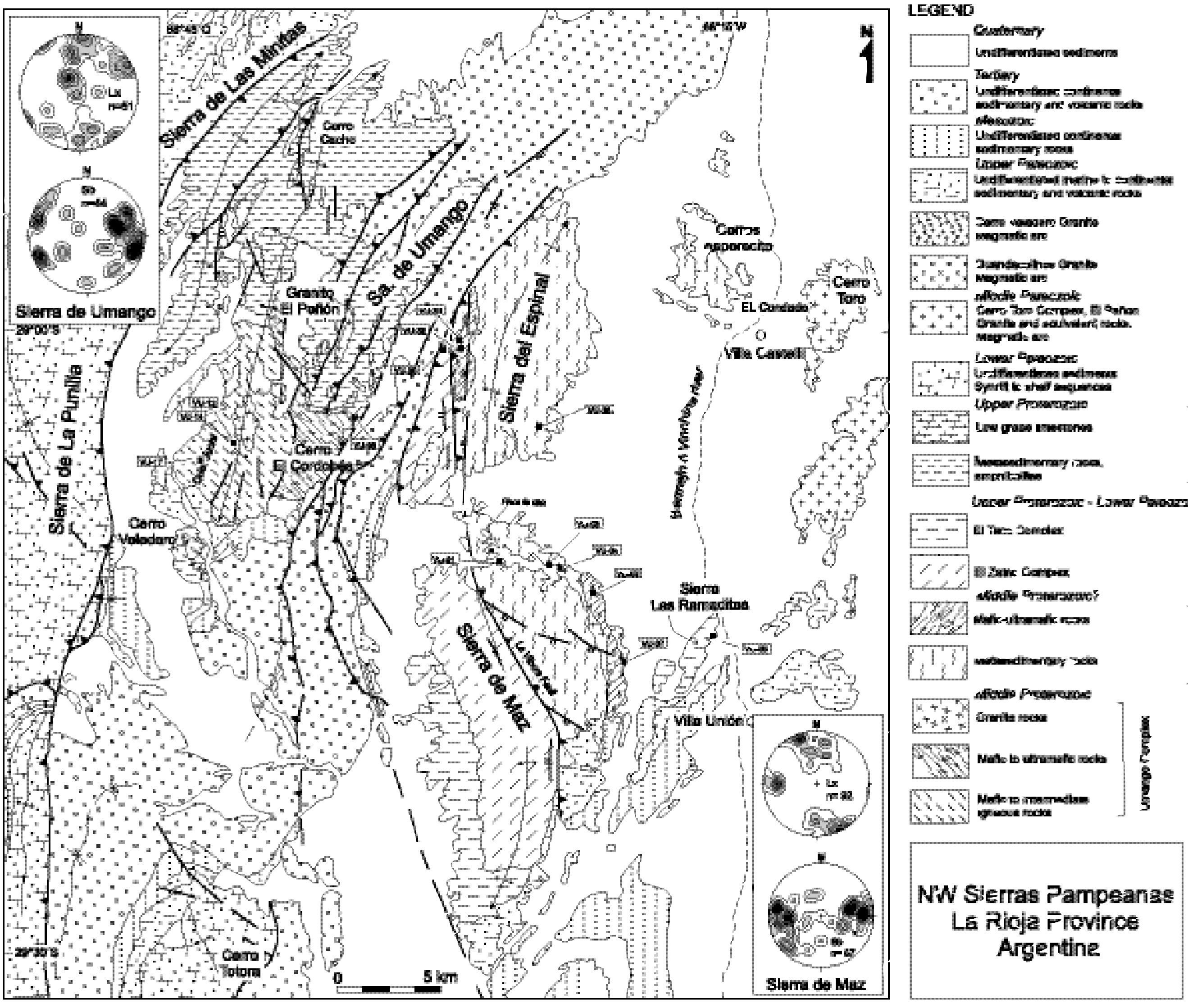

Fig. 2. Geological outline of the NW Sierras Pampeanas of La Rioja Province. Units were distinguished on the basis of field data, interpretation of Landsat and Aster satellite images and compilation from the literature (de Alba, 1954; Furque, 1972; Kilmurray and Dalla Salda, 1971; Fauqué, 2000; Varela et al., 2003). Stereonets show the attitude of the main planar and linear fabrics presented by these rocks.

mylonitic foliation along the rims and gabbroic pegmatites bands with internal deformation. In the northern sector of Sierra de Maz plagioclase-rich leucosomes are observed forming lenses parallel or oblique to the main foliation. These were interpreted as gabbroic cumulates and are probably associated with rocks belonging to a magmatic arc or back-arc tectonic setting (Vujovich and Kay, 1996; Vujovich et al., 2004).

Amphibolites interpreted as basaltic dykes and sills intrusions occur along the eastern flank of Sierra de Maz (Vujovich et al., 2001). These are similar to amphibolites mapped south- and northwards of this area (de Alba, 1954; Turner, 1964). Some of these rocks have been interpreted as basic dykes of tholeiitic composition, related to a magmatic arc or a back arc tectonic setting (Toselli et al., 1994; Vujovich and Kay, 1996). At the northern part of the Sierra de Maz tholeiitic intrusions with augen of plagioclase are marking the N–NW-trending stretching direction of the main middle Proterozoic deformation that affected these rocks (see below). U-Pb titanite ages of 535, 465 and 435 Ma were obtained for calc-silicate rocks of this sequence (Becchio and Lucassen, 2003) but these are interpreted as belonging to the Maz Complex, considering locations of samples (Vujovich et al., 2001).

Granitic aplites and pegmatites, represented by decimetric to decametric-thick veins and lenses are common in the Sierra de Las Ramaditas and the eastern part of the Sierra de Maz y Espinal. The granitic intrusions are both parallel and discordant to the main foliation. Similar rocks are described by Turner (1964) in the northern sector of Sierra del Espinal. Kilmurray and Dalla Salda (1971) interpreted these rocks as belonging to a lower Paleozoic granitic event associated to regional metamorphism and migmatization.

El Zaino Complex

A sequence of metasediments, represented by sandstones, pelites and calc-silicate rocks comprises most of the El Zaino Complex. These rocks crop out at the western sector of Sierra de Maz and extend until the Sierra del Espinal. The contact between the El Zaino and Maz Complex is tectonic, represented by a reverse fault (Kilmurray and Dalla Salda, 1971; Vujovich et al., 2001).

The metasediments are characterized by schists with a quite variable bulk composition and amphibolites, marbles and calc-silicate rocks interlayered. In the central area of the Sierra de Maz pure and impure marbles associated with amphibolites and schists crop out, an exposure that extends to the south, up to Cerros del Carrizal.

Amphibolite occurrences are rare being restricted to southwestern of Sierra del Espinal. These occur as lenses and tabular bodies with thickness between 0.5 and 1.0 m interlayered with metasediments. They were interpreted as basaltic dykes formed in an oceanic arc or as intrusions in continental crust of thin to normal thickness (Vujovich and Kay, 1996).

Poorly constrained U-Pb zircon dating of El Zaino rocks yielded middle Proterozoic and Pampean ages for garnet-mica schist of the southwestern area of Sierra del Espinal (Vujovich et al., 1996). The latter are consistent with metamorphic ages of 529+5 Ma obtained for a migmatite of the Espinal Formation near Villa Castelli (Rapela, 2000) and the 530 to 510 Ma concordant U/Pb ages in titanites interpreted as metamorphic episodes in the Maz Complex. (Becchio and Lucassen, 2003)

Sierra de Umango

Rock sequences cropping out in the Sierra de Umango contains two distinct units: (i) a metamorphosed igneous complex – the Juchi Orthogneiss (Varela et al., 1996) included into the Umango Complex (Vujovich et al., 2001) and (ii) a sequence of metasediments that in part corresponds to the Tambillos Metamorphics (Varela et al., 2003 a, b), in addition to intermediate to acidic intrusive bodies of Paleozoic ages (Cingolani et al., 1993; Varela et al.,1996, 2000, 2002, 2003a, b).

The Juchi Orthogneiss include tonalitic to granitic orthogneisses and associated mafic rocks (Varela et al., 1996). This unit corresponds to the metatonalites, granodiorites and mafic dykes of the Umango Complex that also includes the metagabbros of Cerro del Cordobés (Vujovich et al., 2001). The metagabbros are abundant, show a characteristic compositional banding and are intruded by basic dykes (homogeneous amphibolites); in some areas mixing zones between this units and quartz-feldspathic injections are observed. Similar rocks metamorphosed at granulite to eclogite facies were described at Quebrada de Juchi by Varela et al. (1996).

At the central zone of Sierra de Maz tonalitic-granodioritic to granitic gneisses interlayered with numerous amphibolite bodies (metagabbros/diorites) crop out. Contacts are transitional, marked mainly by different proportions of mafic (hornblende, biotite±garnet) and felsic minerals. At the central sector this sequence is intruded by aplitic to pegmatitic granitic veins.

Protholits of these gneisses are tonalites, diorites and granites intruded by mafic dykes that represent the roots of a magmatic arc (Vujovich et al., 2001). Geochemical data of tonalites and diorites indicate an affinity with arc/back-arc tectonic settings (Vujovich et al., 2004). Leucotonalitic bands that cut the main foliation suggest partial melting processes affecting the orthogneisses. The amphibolites of this sequence were originally interpreted as emplaced either in a magmatic arc or in a backarc on a thinned continental crust (Vujovich and Kay, 1996). However, recent data indicate that these rocks have geochemical signatures similar to intraplate alkaline basalts (Vujovich et al., 2004).

Conventional U-Pb zircon ages of 1090±30 Ma and 1216±19 Ma were obtained for the tonalitic orthogneiss and an age of 1108±12 Ma was obtained for a granitic orthogneisses (Varela et al., 2003 a, b). A Rb-Sr isochron age of 1030±30 Ma obtained from a low $^{87}Sr/^{86}Sr$ initial ratio granitic orthogneiss has been assigned to an amphibolite-granulite facies metamorphic event (Varela et al., 1996). Lower Paleozoic K-Ar hornblende ages (539±14 Ma and 442±15 Ma) in garnet-bearing orthoamphibolites were related to a post-intrusion metamorphic event (Varela et al., 2003a, b).

The Tambillos Metamorphics includes siliciclastic and carbonate bearing metasediments, amphibolites and few gneisses and pegmatites that crop out at the Sierras de Cacho, Umango Tambillito and La Bolsa. Based on carbonate and oxygen isotopic data this sequence was interpreted as representing shelf sediments deposited on a cratonic basement of middle Proterozoic age (Varela et al., 2001, 2003a, b). Amphibolite geochemical signature is consistent with intraplate alkaline magmatism (Vujovich et al., 2004).

The Tambillos Metamorphics also seems to correspond to the metasediments of the Umango Complex of our study and occupy most the central and northern area of Sierra de Umango and also along Quebrada del Cordobés, in the SE. According to Vujovich et al. (2001) and Varela et al. (2003a, b) the Tambillos Metamorphics shows tectonic relations with the Juchi Orthogneiss Complex. However, despite the fact that the gneisses seem to be occupying the core of a large-scale F3 fold the nature and kind of the boundary between both units before folding is still to be determined (cf. below).

Ages between 640 and 580 Ma for sedimentation of the carbonatic sequence were suggested by Varela et al. (2001) based on $^{87}Sr/^{86}Sr$ isotopic ratios. Rb-Sr ages of 379 Ma and 373 Ma (whole-rock and minerals isochron, respectively) were obtained for deformed pegmatites included into Tambillos Metamorphics, and have been interpreted as related to the last tectono-metamorphic event that affected rocks of this unit (Varela et al., 2002). A Sm-Nd isochron age of 392±50 Ma (whole-rock minerals) was obtained for an amphibolite of the Tambillos Metamorphics (Varela et al., 2003a, b). It was interpreted as representing a mid- to late-Devonian tectonothermal event. An amphibolite sample from the same sequence shows a 1804±37 Ma age with εNd = –3.16 (Varela et al., 2002).

U-Pb (zircon) conventional discordia ages of 1139±82 Ma (upper intercept) and of 447±36 (lower intercept) were obtained by Varela et al. (2003a, b) on a biotite-rich paragneiss. The former was interpreted as a inherited age while the latter age has been associated with a late Ordovician tectonic event. These authors also mention a U-Pb monazite age (^{238}U–^{206}Pb) of 452+6 Ma for this same tectono-metamorphic event, obtained from a mylonitic paragneiss. Becchio and Lucassen (2003) presented an U-Pb titanite 422–425 Ma ages for the calc-silicate rocks, possibly belonging to the Tambillos Metamorphics. This age have been interpreted by the authors as the metamorphic crystallization of titanite under temperatures of upper amphibolite facies.

Granitoids

The El Peñón Granite is a deformed granitic body intruded into low-grade metasediments and amphibolites of the Tambillos Metamorphics in the eastern sector of the Sierra de Umango. The granite is both homogeneous and banded (granitic orthogneisses), and includes granodioritic pegmatites and deformed granodiorites (Varela et al., 2000).

A conventional U-Pb zircon of 473+17 Ma age was obtained for this unit being interpreted as age of crystallization (Varela et al., 2003a, b). The Rb-Sr whole-rock isochron 469±9 Ma age ($^{87}Sr/^{86}Sr$ initial ratio = 0.7110±0.0002) obtained for this granite was interpreted as the age of the tectono-metamorphic event that affected the granitoids as well as the supracrustal rocks (Varela et al., 2000). These authors also mentioned a K-Ar muscovite 409–381 Ma age, interpreted as related to the last tectono-metamorphic event that affected these rocks.

The Guandacolinos Granite crops out at southern Sierra de Las Minitas, and comprises granodiorites and monzogranites with ductile deformation structures concordant with the supracrustal rocks of the Tambillos Metamorphics. A Rb-Sr isochron (whole-rock and minerals) indicate an age of 352±14 Ma ($^{87}Sr/^{86}Sr$–0.7039±0.0003) for the peak of deformation of this granitoid and it was interpreted as related to the Chanic phase (Devonian) of the Famatinian Cycle (Varela et al., 1996).

The Veladeros Granite corresponds to a small granitic stock that intrudes the low-grade metasediments in the west of Sierra de Umango. Its composition ranges from quartz-bearing monzonites and monzodiorites to granites and quartz-bearing syenites. A Rb-Sr whole-rock isochron of 311±15 Ma age, with low initial $^{87}Sr/^{86}Sr$ initial ratios (0.70455) was obtained for these rocks (Cingolani et al., 1993).

Geophysical Data

A geological-structural interpretation of the magnetic and gravimetric nature of the northern part of the Cuyania terrane (A, in Fig. 3a) was carried out; the geophysical signature of the surrounding region was also analysed for comparison. The aeromagnetic data were obtained from the Argentine Geological-Mining Survey, whereas the ground magnetic data were acquired during the present research; finally, the gravimetric data is derived from a subgrid of the gravimetric map of Argentina (Introcaso, in Lizuaín, 1994) since our ground data are still being processed.

The regional aeromagnetic data indicate the presence of first-order basement discontinuities, as evidenced by conspicuous breaks in the orientation and intensity of the magnetic and gravimetric anomalies; a preliminary interpretation of these major features is presented in this article. In addition, the magnetic data also allowed to recognize the presence of sub-regional scale structures (Fig. 3a).

Megastructures

Guandacol lineament (Lineament 1): It corresponds to a WNW structure accross which an abrupt change in magnetic intensity (ca.70 nT) takes place. A magnetic high is located to the south of the lineament (Block 1), where partly coincides with a positive residual Bouguer anomaly whose maximum intensity falls outside the project area, immediately to the south of 30°S (Fig. 3d); a magnetic low is located to the north of the lineament, in block 3 (integrated by the Sierras de Maz, Espinal and Umango). The eastern boundary of the Cuyania terrane is marked by Valle Fértil lineament (Lineament 3) which, in turn, is cut and possibly displaced by reactivation of the Guandacol lineament.

The Guandacol lineament (L1) extends for at least 230 km, from 29°09'S/69°36'W in the western end (Cordillera Frontal area, outside map boundaries of figure 3, possible continuation of the Cuyania terrane under the Cordillera Frontal-Chilenia terrane lithologic units?), up to at least 29°51'S/67°28'W, in its eastern end. This megastructure can be recognized in both the shallow and the deeper magnetic sources (Fig. 3b and c, respectively).

The prominent nature of this megastructure allows to regard it as a boundary between two basements of

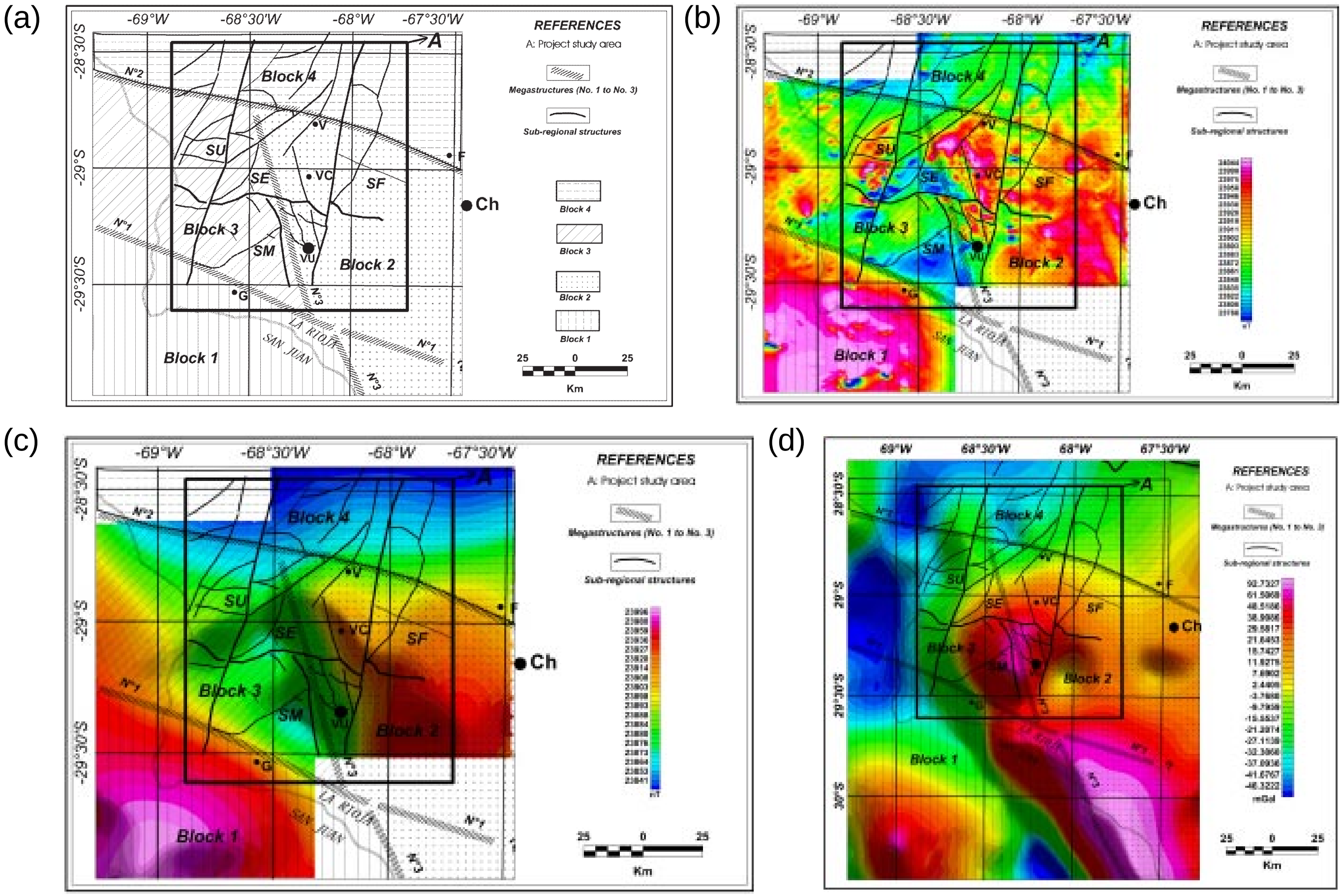

Fig. 3. (a) Preliminary structural interpretation of the geophysical surveys (magnetometry and gravimetry) of the study area and surrounding region (partial coverage). (b) Interpretation overlain on the aeromagnetic map (total magnetic field). (c) Interpretation overlain on the upward continuation (15 km) of aeromagnetic map. (d) Interpretation overlain on the residual Bouguer anomaly map (includes southern extension of study area). References: SU–Sierra de Umango, SE–Sierra de Espinal, SM– Sierra de Maz, SF–Sierra de Famatina, G–Guandacol, VC–Villa Castelli, V–Vinchina, Ch–Chilecito, T–Tinogasta.

contrasting geophysical properties, which could be compatible with an old suture zone. There is evidence of a reactivation of this suture zone, by late strike-slip displacement that offsets Valle Fértil lineament (L3).

The extension of Guandacol lineament (L1) both further west and further east of the Cuyania terrane boundaries could be explained as a result of the post-lower Paleozoic reactivation of this feature, as a wrench fault zone.

To the north of Guandacol lineament (L1) the geophysical surveys define two basement blocks (2 and 3, see below). These blocks are divided by a conspicuous NNW structure, which is the northern extension of the Valle Fértil lineament (L3); even further north, the latter megastructure is, in turn, truncated by the Vinchina lineament (L2).

Vinchina lineament (Lineament 2): It derives from another major geophysical discontinuity; it also trends WNW, i.e., parallel to Guandacol lineament (L1). Vinchina lineament (L2) is defined by an abrupt change in magnetic intensity (ca.50 nT). To the north of this feature the magnetic field reaches the lowest values of the region (Block 4).

The prominent nature of this megastructure is also evidenced by its length, of ca. 250 km, from 28°33'S/69°32'W in the west, to at least 29°00'S/67°32'W in the east, where it ends the aeromagnetic information. Similarly to Guandacol lineament, this megastructure also extends further to the west and east of the boundaries of the Cuyania terrane, which is interpreted as a result of its possible reactivation after the end of the Paleozoic. Vinchina lineament can also be identified both in the shallow and deeper magnetic sources (Fig. 3b and c, respectively).

The prominent nature of this megastructure also allows to regard it as a boundary between two basements of contrasting geophysical properties, which is interpreted as an old suture zone. As mentioned above, Lineament 2 truncates the Valle Fértil lineament (L3) at about 28°40'S, which points to a post-lower-Paleozoic reactivation of this structure, in accordance with the age previously assigned to the Valle Fértil lineament.

Valle Fértil lineament (Lineament 3): To the south of the study area this structure corresponds to the previously defined Valle Fértil lineament (or Desaguadero - Bermejo lineament), whereas in the study area proper its northern extension, is located to the north of Guandacol lineament (L1). The segment herein recognized shows NNW trends and has a length of at least 100 km (from 28°44'S/68°29'W to 29°37'S/68°12'W). This structure is conspicuously seen in both the aeromagnetic and gravimetric surveys of the region (to the south of the project area the Valle Fértil lineament where it shows the highest gravimetric values; see Fig. 3d). The Valle Fértil lineament has been considered as the boundary between the Cuyania and Pampia terranes (e.g., Giménez et al., 2000; Introcaso and Ruiz, 2001; Ruiz and Introcaso, 2001).

Structural Geology

Structural traverses in the sierras de Maz-Espinal, Umango and Las Ramaditas (Fig. 2) indicate that rock sequences exposed in these areas were affected by progressive deformation under high-grade metamorphic conditions.

The main deformational episode registered in these rocks gave rise to a flat-lying composite fabrics with well-developed NW-N trending stretching and mineral lineations. This fabrics and the few observed large scale shear zones ascribed to this deformation were affected by several sets of younger upright folds and faults that control their attitudes across the area.

Due to the difficulties of reconstructing the original attitude and orientation of the structures older than the F3 upright folds, and the problems to correlate structures (folds in particular) between different exposures due to variations of strain intensity, the nomenclature used for the group of folds ('F1s' and 'F2s') originated during the high temperature flow that gave rise to the main flat-lying fabrics is valid only for geometrical relationships within single or nearby exposures. Therefore, kinematic interpretation of the main deformation refers only to the ductile structures older than the upright folds ('F3s') that show N/NE trends in Sierras de Umango and Espinal and N-S in the Sierra de Maz. The latter are the major folds that control the outcrop pattern and seem to be affecting paleozoic and mesozoic sequences alike.

The composite banding, as recognized in most rock types of this area, includes the lithological succession, representing the original and a metamorphic segregation banding (Fig. 4a) or a schistosity (depending on the rock-type and metamorphic conditions), as well as two sets of tight to isoclinal folds (Fig. 4c). The composite banding was the only structure that could be correlated between exposures with some degree of confidence due to the complex geometry controlled by several sets of late folds and faults (Fernandes et al., 2002). The general geometry of this banding can be observed with some detailed in exposures at several scales, including the 15m resolution Aster images here hinge of isoclinal (F1 - F2 ?) folds can be observed in large cliffs. This fabrics shows, in addition to isoclinal folds (F1 + F2), boudins and pinch-and-swell structures in almost all observed rocks, particularly in calc-silicate rocks containing marbles and amphibolites, where the viscosity contrast is high as indicated by shape of boudins (Fig. 4a). Igneous rocks represented by bodies of several sizes and composition ranging from amphibolites, diorites to sienogranites intrude the composite banding. Despite showing various structural relations with respect to the main fabrics, most of these rocks where plastically deformed and present the same N-NW trending stretching lineation ubiquitous in deformed rocks of this area.

In the few high-strain zones recognized, structures such as foliation fish, shear bands, and lithoclasts are very common being typical of non-homogeneous ductile progressive deformation with a component of simple shear (Fig. 4b).

Microstructures and kinematic indicators observed in these rocks include asymmetric sigma-type recrystalization tails in feldspar porphyroclasts and prismatic subgrains in quartz (Fig. 4e, f), confirming the high-T conditions of the principal deformation, as determined by thermobarometric studies (see below). Foliation-fish and mica-fish are common in mylonites developed from marbles and metasediments (Fig. 4a).

Kinematic indicators show conflicting sense of movement (top-to-N and S). This might be controlled by tight folds and many other factors whose confirmation should be checked by detail geometric studies. However, in high-T major shear zones with relatively simple geometry, such as the one at Cerro Cacho (NW of Sierra de Umango), a top-to-north sense of movement parallel to the NW-N trending stretching lineation could be determined with confidence.

Linear structures include boudins, fold mullions, stretching and mineral lineations, usually marked by amphibole.

Two sets of folds older than the upright F3s are observed in most exposures. The F1 folds are generally small (cm to dm) and present high amplitude/wavelength ratios (~10). They are marked mainly by felsic bands in aluminous and quartz-feldspatic gneisses and mafic bands in the calc-silicatic sequences. The hinges are thickened and the limbs are often attenuated characterizing them as rootless intrafolial folds of class 2 and 1C geometry (Fig. 4c).

The F2 folds are isoclinal and tight with thickened hinges, developing 1C and 2 geometries and intermediary amplitude/wavelength ratios (~5). These folds are generally intrafolial (Fig. 4c) and are usually acylindrical showing wide variation of hinges within the composite banding. It is very hard to distinguish them from structures that were labeled as F1 folds in exposures where only one generation of folds is present.

The F3 folds are concentric, open normal (subvertical axial plane) to inclined double plunging folds with axial planes of N/NE direction. Their trends change from NE in Sierras de Umango and Espinal to NW in the Sierra de Maz, making up a pattern of an open "S" at the regional scale (Fig. 2). The axial plane foliation is marked by crenulation cleavages where features of pressure solution are common in more schistose rocks and a spaced cleavage in more siliceous units. Faults are commonly associated with these low-T folds (Fig. 4d).

The F4 folds present a more NE trends and are particularly well-developed in the SW limb of Sierra de Maz. Axial-planar cleavage in metapelites is a zonal crenulation. Despite being upright flexural folds and the other late major set of folds that control the 'egg-box' geometry, they differ from the F3s not only by trends but also for presenting smaller amplitudes and localized development. From observation of DTM models they seem to be better developed along the limbs of large F3s.

Analysis of orientation diagrams shows that stretching and mineral lineations of the main deformation present N-NW/S-SE trends and low plunges (cf. stereonets in Fig. 2). They were not strongly reoriented by the young NE-SW trending flexural folds in most of the area since the F3s present the same trends and the F4s are restricted to certain areas. The same happens with the main fabrics whose general attitude was sub-horizontal if the effects of late flexural folds is restored. This seems to be true for measurements taken from rocks of whole area, including Sierra de Las Ramaditas, where the highest temperature fabrics registered in the area yielded carboniferous ages (see below).

Metamorphism

Thermobarometry was used to constrain physical conditions of metamorphism, and, in combination with isotopic and structural analysis, to support interpretation of radiometric ages, improving our understanding of the history of burial and exhumation of a terrane with a sialic basement accreted to a continental margin.

The assemblages of samples studied, irrespective of their ages, are typical of Barrovian-type of metamorphism formed under middle to upper amphibolite facies conditions. Intermediate-pressure type of metamorphism is commonly found in collisional tectonic settings.

In the case of the studied rocks from Sierra de Maz, the ones presenting metamorphism of middle Proterozoic age, the higher temperature given by individual samples (such as VU-03D) might depend on local heat sources such as syntectonic intrusions. Despite proximity between samples, which would mean that they were positioned in similar structural levels if the effect of the late (F3s and F4s) folds is considered (Fig. 2) there is no evidence to support the existence of major discontinuities in metamorphic conditions within Sierra de Maz, or between these rocks and the ones from Sierra de Umango, where the location of the suture between Cuyania and Pampia has been placed (Ruiz and Introcaso, 2001). However,

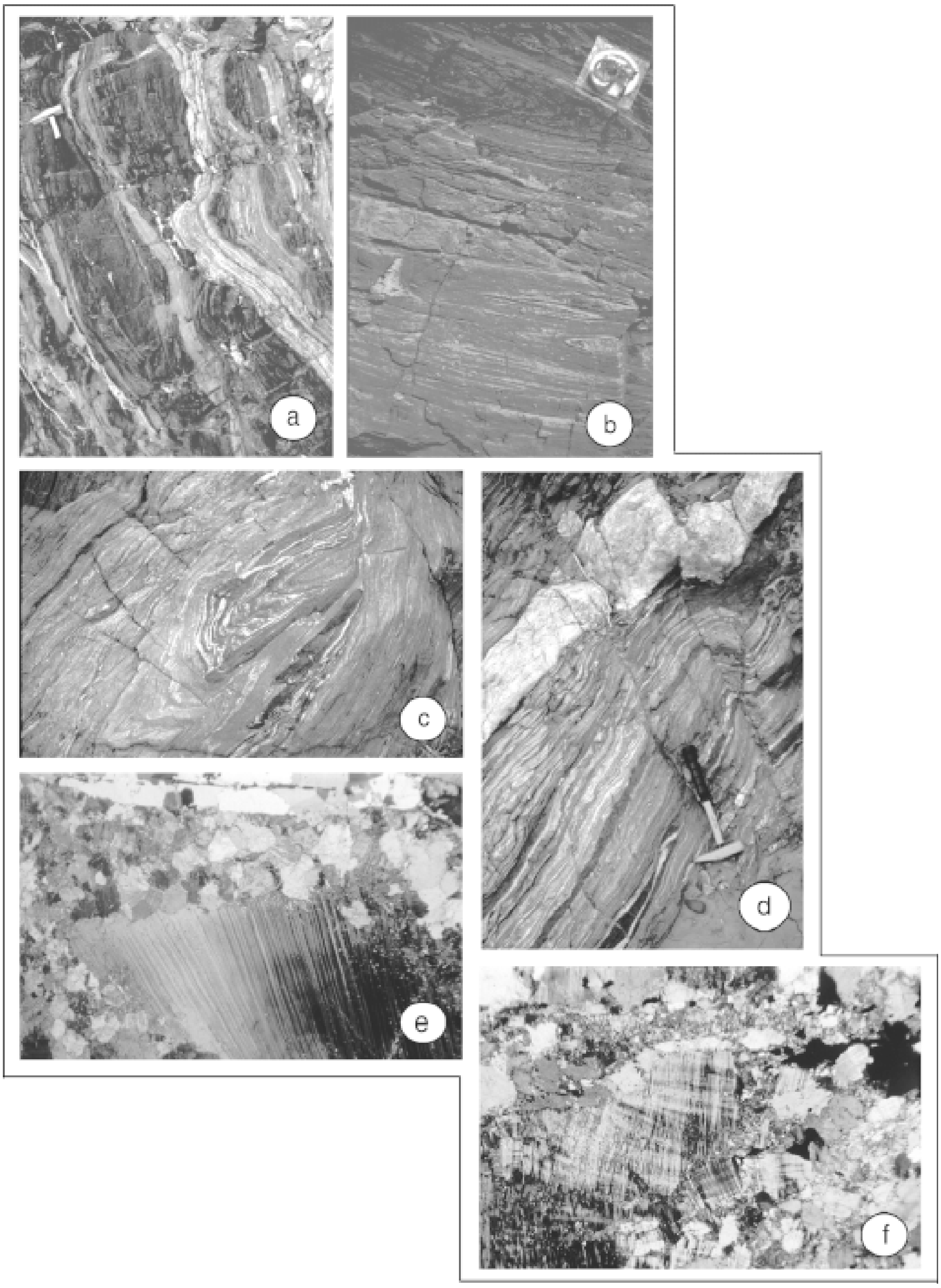

Fig. 4. Macrostructural features: (a) High viscosity contrast boudin in calc-silicate rocks (amphibolite) and marbles of El Taco Complex, Las Ramaditas. (b) Transposed rootless isoclinal folds and lithoclasts in mylonitic marbles of a high strain zone within Tambillos Metamorphics, Quebrada del Cordobés. (c) Mesoscopic scale intrafolial F2 folds affecting an early isoclinal (F1) fold in metasediments of Maz Complex, Finca de Maz. (d) F3 fold with genetically associated faults affecting metasediments of the Maz Complex, Finca de Maz. (e) Prismatic sub-grains in feldspar porphyroclast with deformation twins of quartz-feldspathic mylonite in Tambillos Metamorphics of Cerro Cacho. (f) Grain-size reduction of an asymmetrical d-type porphyroclast of a quartz-feldspathic mylonites in Tambillos Metamorphics of Cerro Cacho.

our isotopic data, although still in small number, indicate the possibility that rocks of Sierra de Umango belong to Cuyania while Maz-Espinal and Las Ramaditas are part of the active protomargin of West Gondwana (see discussion to follow).

On the other hand, the metamorphism of Carboniferous age recorded by rocks of the Cerro Noqués at the Sierra de Las Ramaditas shows relatively high pressures conditions. However, the meaning of this metamorphic episode needs to be discussed under the light of its tectonic setting since it affects rocks representing early Proterozoic crust (see below).

Following a short description of the methodology the main paragenesis of each sample is presented. Temperatures and pressures obtained are then commented in the context of the geometry and structural evolution of these rocks and their possible tectonic meaning. Although rather lengthy the way our data was presented was aimed at facilitating its retrieving and comparison as the geology of this region has been recently object of intense investigation.

Methodology

Thermobarometry and isotopic studies were performed in samples from El Taco, Maz and Umango complexes, cropping out in the Sierras de Las Ramaditas, Maz-Espinal and Umango, respectively. Whenever possible, samples for radiometric dating (Sm-Nd/WR-garnet) were collected from the same exposures. The intention behind the obvious determination of timing of high-T tectonometamorphic event was to check for the presence of chemical heterogeneities in garnets, as well as to check metamorphic temperatures determined from mineral assemblages. Mineral activity was determined with the help of the AX program (Holland and Powell, 2000) and THERMOCALC (v. 2.6 - Holland and Powell, 1998) was used for thermobarometric calculations.

Rocks belonging to the Maz Complex, the most suitable unit for thermobarometric determinations due to the wide occurrence of metapelites, had four samples studied in detail. Rocks from El Taco and Umango complexes had each only one sample investigated by thermobarometric studies. Samples studied are listed below (Table 1) being followed by a short description of their predominant textures and mineral compositions.

Maz Complex

Metapelites

Four samples of metapelites were analyzed in more detail to determine metamorphic conditions and age of development of the main fabrics. Thermobarometric data was obtained for all of them. Whole-rock Sm-Nd isotopic data was obtained for samples VU-3D (Fig. 5b), VU-30 A (Fig. 5c) and VU-21G (Fig. 5a) and Sm-Nd garnet while whole-rock were produced for samples VU-3D and VU-30A.

Sample VU-02A is from Quebrada Montosa, northern sector of Sierra de Maz. It has a main foliation marked by quartz lenses and feldspar-rich bands. Oriented biotite aggregates and sillimanite-rich lenses surrounding garnet porphyroblasts are common. The metamorphic assemblage is composed by garnet-sillimanite-biotite-quartz-plagioclase-K-feldspar-rutile.

Sample VU-03D is from Cerrito del Misterio, north of Sierra de Maz, while VU-30A was collected in Corral de Martínez, Sierra de Espinal. These samples show similar metamorphic assemblages. The first has a peak metamorphic assemblage composed by kyanite-garnet-plagioclase-biotite-quartz. This peak assemblage is strongly

Table 1. Analysed samples from each complex with kind of study undertaken. Tectonic setting is based on studies of geochemical affinity (Vujovich et al., 2004).

Unit	Sample	Rock type	PT	Sm-Nd T_{DM}	Sm-Nd Grt-WR	Tectonic setting*
El Taco Complex	VU-6-E	Qtz-fds gneiss	X	X	X	-
	VU-6-F	Qtz-fds gneiss	X	X		-
	VU-6-G	Qtz-fds gneiss	X	X		-
	VU-06J	Pyroxenite		X		Magmatic arc
	VU-02A	Metapelite	X			-
Maz Complex	VU-03-A	Metatonalite		X	X	Magmatic arc
	VU-03-D	Metapelite	X	X	X	-
	VU-04-E	metatonalite		X		Magmatic arc
	VU-07E	Metagabbro		X		Back-arc
	VU-21-G	Pelitic schist	X	X		-
	VU-30-A	Pelitic gneiss	X	X	X	-
	VU-32-A	Metatonalite/leucogabbro		X		Intraplate
	VU-33E	Metatonalite		X	X	Intraplate
	VU-36B	Amphibolite		X		Arc/back-arc
Umango Complex	VU-08A	Amphibolite		X		Intraplate alkaline
	VU-13-B	Metadiorite		X		Arc/backarc
	VU-13A	Amphibolite /metagabbro		X		Intraplate alkaline
	VU-14-H	Amphibolite	X	X		Intraplate alkaline
	VU-14-C	Metatonalite		X		Arc/back-arc
	VU-17C	Amphibolite		X		Intraplate alkaline

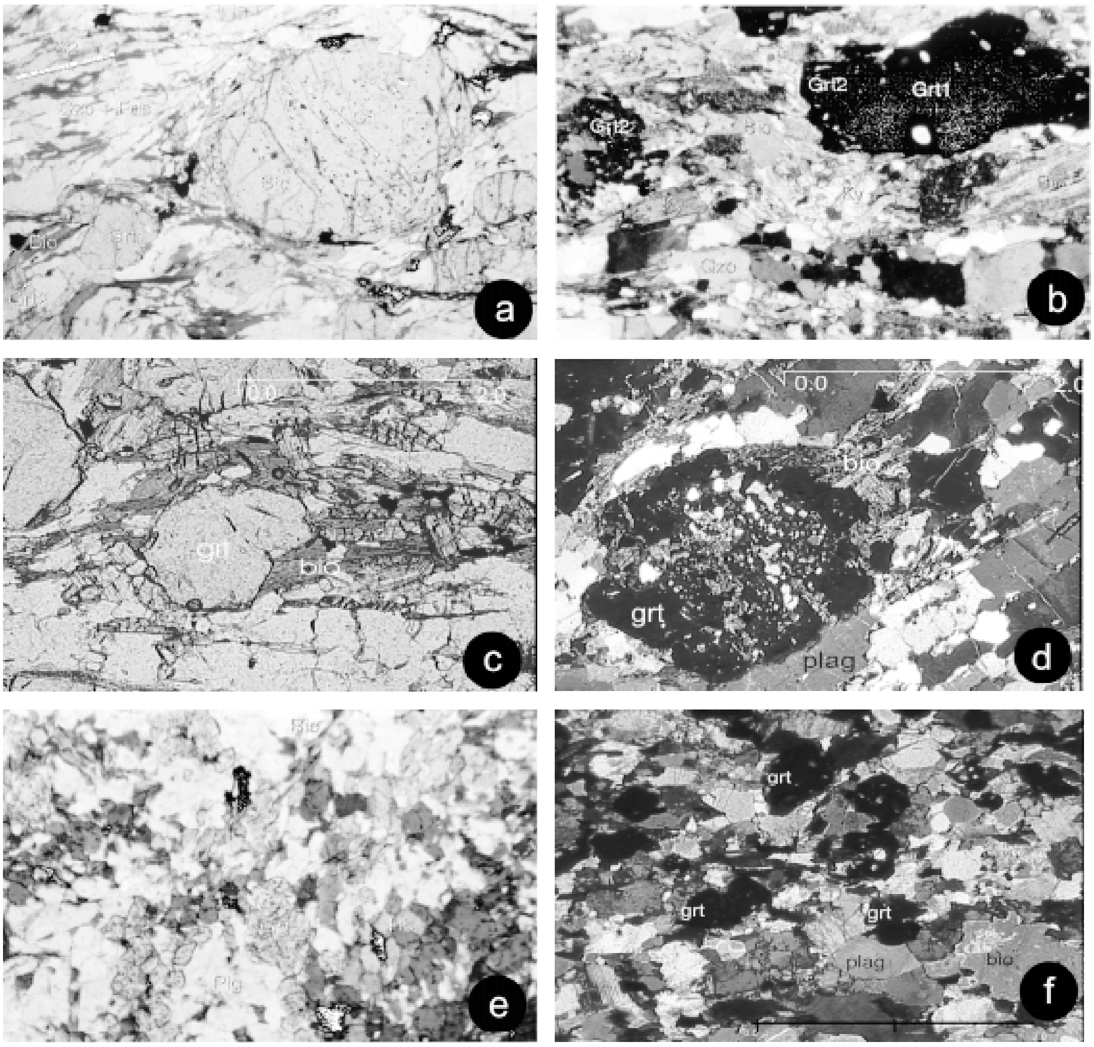

Fig. 5. Microstructural features and metamorphic paragenesis of the studied samples: (a) VU-21G: Metapelite with garnet, staurolite and biotite. (b) VU-03D: Metapelite with garnet, kyanite and biotite. (c) VU-30A: metapelite with garnet, kyanite, sillimanite, staurolite, biotite and plagioclase. (d) VU-02A: Metapelite with garnet, sillimanite, biotite, plagioclase and rutile. (e) VU-14 G: Amphibolite with garnet, plagioclase, biotite and hornblende. (f) VU-06E: Metapelite with garnet, biotite and plagioclase.

affected by high strain deformation, indicated mainly by strong sectorial extinction, development of subgrains in porphyroblasts of kyanite and porphyroblasts of garnet surrounded by the main foliation. These features indicate pre- to syndeformational crystallization conditions of the peak mineral assemblage.

Peak metamorphic conditions in sample VU-30A are recorded by the assemblage kyanite-sillimanite-staurolite-garnet-plagioclase-K-feldspar-muscovite-biotite-quartz. Textural evidences suggest intermediate strain conditions during metamorphic crystallization. Two textural types of garnet were identified. The first one is composed by large anhedral ellipsoidal porphyroblasts slightly surrounded by the main foliation. Cores of these garnets are rich of small inclusions of quartz while towards the rim they tend to be inclusion-free. The second type of garnet is characterized by subhedral small, inclusion-free porphyroblasts growing over the main foliation. This garnet type occurs in small modal proportions in the rock.

Sample VU-03D has a peak metamorphic assemblage composed by kyanite-garnet-plagioclase-K-feldspar-biotite-quartz. Textural evidences, as strongly deformed kyanite porphyroblasts, suggest intermediate to high strain conditions during metamorphic crystallization. As in sample VU-30A two textural types of garnet were recognized. One is composed by large anhedral ellipsoidal porphyroblasts, slightly surrounded by main foliation. The other type is characterized by small subhedral garnet porphyroblasts growing over the main foliation.

In sample VU-21G, peak metamorphic conditions are indicated by an assemblage composed by staurolite-garnet-biotite-plagioclase-K-feldspar-quartz (-muscovite). Textural features are typical of low strain conditions during crystallization of the peak metamorphic assemblage.

Thermobarometric data are consistent with these metamorphic conditions being presented below (Table 2).

Orthometamorphic rocks

Metamorphic rocks with igneous protoliths are observed in many outcrops of Maz Complex. In some case, they are the dominant rock type in the outcrop, while in others they occur as deformed veins or dykes in metasedimentary rocks. In either case these orthometamorphic rocks display fabrics parallel to the main foliation observed in the metasediments.

Metatonalite samples VU-03A and VU-04E came from bands intruded into metasediments of the Sierra de Maz. They show minerals with igneous features such as zoning in plagioclase. Geochemical signatures of these rocks indicate a magmatic arc tectonic setting (Vujovich et al., 2004). The other metatonalite samples (VU-33A and VU-33E) came from a large body from Sierra del Espinal and have a strong metamorphic fabrics that erased all evidence of its magmatic parentage. Geochemical data presented by Vujovich et al. (2004) indicate an intraplate setting for these samples. Garnet porphyroblasts occurs in all samples mostly growing over mafic aggregates and are not surrounded by foliation. This suggests that their crystallization occurred during a post-tectonic metamorphic episode. The metamorphic assemblages (and textures) of these rocks, although not the most appropriated to determine precise metamorphic conditions, are consistent with the medium to upper amphibolite metamorphic facies.

In amphibolites samples (VU-07E and VU-36B) metamorphic crystallization was extensive and produced a granoblastic texture indicative of low strain. Sample VU-07E is a metagabbro from a orthometamorphic sequence that probably corresponds to an intrusive multiple dyke complex (Vujovich et al., 2001). Geochemical data suggest an extensional magmatic arc/back-arc setting (Vujovich et al., 2004). A peak metamorphic condition of upper amphibolite facies is indicated by an assemblage composed by plagioclase-hornblende-garnet-quartz-sphene. Sample VU-36B, that occurs as an intrusive dike in a metasedimentary sequence shows geochemical affinity consistent with a arc/back-arc environment (Vujovich et al., 2004).

Table 2. Temperatures and pressures obtained for metamorphic rocks of the NW Sierras Pampeanas. Maz Complex (VU-02 A, VU-03 D, VU-21 G, VU-30 A), El Taco Complex (VU-06 E) and Umango Complex (VU-14H).

Sample	Mineral Paragenesis	GTB Results	Metodology
VU-02 A	Pl-Grt-Sil-Bt-Qtz-Ru	653°C – 6.2 kbar	Line Intersection
VU-03 D	Pl-Grt-Ky-Bt-Qtz	771°C – 6,3 kbar	Line Intersection
VU-21 G	St-Ms-Grt-Bt-Qtz-Pl	630 – 642°C (5 – 7 kbar)	Grt-Bt
VU-30 A	Pl-Grt-Ky-Bt-Qtz-St	624°C – 6,4 kbar	Line Intersection
VU-06 E	Pl-Ru-Grt-Qtz-Bt	868°C – 9.8 kbar	Line Intersection
VU-14 H	Hbl-Pl-Grt-Qtz	610 – 650°C (6.1 – 6.9 kbar)	Hbl-Pl

Umango Complex

With exception of a metatonalite sample (VU-14C), all studied samples from Umango Complex have basic to intermediate compositions and show a granoblastic texture indicating static metamorphic crystallization. The amphibolites samples VU-13A, VU-13B (metadiorite), VU-14H, VU14G (Fig. 5e) and VU-17C show mineral assemblages composed by hornblende, plagioclase and sphene. Quartz and garnet may be also present. Geochemical data indicate an arc/back-arc environment for samples VU-14C and VU-13B, while the other samples have geochemical signatures consistent with intraplate alkaline basaltic magmas (Vujovich et al., 2004).

Sample VU-08A has a distinctive assemblage, displaying a strong linear fabrics (L-tectonite) marked by prismatic cummingtonite. This rock shows geochemical affinity typical of an alkaline intraplate magmatic environment (Vujovich et al., 2004).

El Taco Complex

Metasediments

Metasedimentary rocks collected from El Taco Complex as VU-06E (Fig. 5f), VU-06F and VU-06G are all very similar. They present a granoblastic texture with little or no intracrystalline deformation, indicating static metamorphic crystallization of an assemblage composed typically by plagioclase - biotite - quartz - garnet. Rutile is only present in sample VU-06E. This assemblage suggests an impure sedimentary protolith.

Meta-ultramafic rock

The metapyroxenite studied of this sequence (VU-06J) is composed by clinopyroxene (diopside), orthopyroxene (hyperstene), olivine and spinel. The texture is granoblastic and partial serpentinization of olivine is observed along fractures. The geochemical signature of this rock is typical of magmatic arc (Vujovich et al., 2004).

Sm-Nd Ages

Isotopic work emphasized the application of the Sm/Nd method to determine crustal residence (T_{DM}) and metamorphic ages. T_{DM} ages indicate crustal residence of rocks allowing recognition of crustal segments of diverse origin so that they are essential for the purpose of our study. Whole-rock-garnet metamorphic ages were used to determine relationships between fabrics and tectonic events and to correlate them at the regional scale. Dating of tectonic events is as important as the age of protoliths to understand the history of accretion of the continental crust, but it is essential in the rocks of the area studied due to their polycyclic nature.

Samples for Sm/Nd geochronology were initially selected to establish the general isotopic pattern for the area, providing guidelines for more detailed work.

Sm-Nd T_{DM} ages were obtained for a relatively large number of samples (19) of different rocks types as an attempt to determine crustal accretion ages. Garnet ages were obtained for five samples, four from the Maz Complex and one from the El Taco Complex. We have no ages of metamorphism from Sierra de Umango rocks but several have been recently published (Varela et al., 2001, 2002, 2003a, b).

Analytical methods

Garnet concentrates were obtained using standard crushing, magnetic separation and heavy-liquid techniques. Clean garnet separates were obtained by carefully handpicking and only optically inclusion-free grains were selected for analysis. Garnet sample weighed 70–50 mg and whole-rock samples 100–50 mg, depending on rock composition. All samples were spiked before digestion. Samples (garnet separates and whole-rock powder) were dissolved in Teflon (Savillex) beakers using ultrapure HF, HNO_3 and HCl. T_{DM} ages were calculated following DePaolo (1981). Sm-Nd isochronic ages were determined by ISOPLOT/Ex rev.2.49-A (Ludwig, 1991), with decay constants of $^{147}Sm = 6,53974 \times 10^{-11}/y$ (Lungmair and Marti, 1978).

Implications of Sm-Nd Ages

To facilitate retrieving and comparing data presented here in this paper with the literature the meaning of T_{DM} model and garnet ages reported here will be discussed for each unit first and then considered together. Analytical results are presented in table 3 and ages and temporal Nd evolution are presented in figures 6 and 7.

Maz Complex

Metasediments of this unit present the oldest model and garnet age of the study area. T_{DM} ages from Maz metapelites are self-consistent and indicate important contribution of an old source of early Proterozoic or even older age. This would be the oldest record of continental crust in the entire region and accordingly to the literature more typical of the margin of the western margin of proto-Gondwana striking tectonic implications for our investigation.

T_{DM} ages for orthometamorphic rocks of this unit are more scattered and together with the lack of crystallization ages make their interpretation more debatable. The largest number of T_{DM} ages obtained from metatonalites that show intrusive field relations with metapelites are from 2.1 to 1.4 Ga. The samples with older ages (VU-03A and VU-04E) came from veins and show geochemical affinity of extensional magmatic arcs. The younger ages are from samples of a larger intrusive body (VU-32A and VU-33E) that show intraplate geochemical affinity. The evolution lines from the metatonalites with older ages in the Nd isotope evolution diagram are very similar to those of the metasediments (Fig. 7). This suggests crustal assimilation of sediments by the tonalitic magma, with the older metatonalite T_{DM} ages indicating a higher degree of assimilation and the younger ages indicating low or no assimilation. If that is the case, only the younger metatonalite T_{DM} ages define a second episode of crust formation that for rocks of the Maz Complex would have occurred in an extensional regime.

The T_{DM} age obtained from an orthoamphibolite (VU-36B) vein intrusive in metasediments is comparable to the younger metatonalite model ages and is considered to place this second crustal extraction age within the 1.4–1.2 Ga interval. However, since these rocks have geochemical affinity completely different from the younger metatonalites, we consider that this orthoamphibolite records a third accretional episode within an arc/back-arc tectonic setting.

T_{DM} age from sample VU-07E is the most difficult to interpret with confidence. This rock came from an orthometamorphic sequence with metagabbros, metadiorites and metatonalites, representing an intrusive complex with multiple injections. The T_{DM} age falls within the same range of the metapelites, but $Nd_{(0)}$ from the metagabbro (–15.32) is higher than that of metapelites (–17.92 to –23.87), what is inconsistent with a hypothetical assimilation of the metapelites. Also, since this metagabbro shows geochemical affinity with intraoceanic arc magmatism it can not be representing the source area for the metapelite sedimentation because that must be a developed continental crust. Therefore T_{DM} age presented by VU-07E sample must represent a crustal extraction episode, that although contemporaneous to crustal extraction of the source area for the Maz metapelites source area occurred in a different tectonic setting.

Two garnet - whole-rock Sm-Nd isochrons obtained for the metapelites (samples VU-03D and VU-30A) yielded age of ca. 1.0 Ga. This result is interpreted as indicating the age of the first metamorphism of the Maz Complex and, according to peak metamorphic conditions, to mark a middle Proterozoic collisional episode.

A garnet - whole-rock Sm-Nd isochron obtained for a metatonalite (VU-33E) gave an age of ca. 460 Ma that indicates the timing of the second most important metamorphic episode registered in the rocks of Maz Complex.

Umango Complex

The T_{DM} ages from orthometamorphic rocks from the Juchi Orthogneiss are dependent on protolith composition. The basic rocks represented by three samples of amphibolites (VU-13A, VU-14H and VU-17C) are consistently around 800 Ma. T_{DM} ages of more acidic (and differentiated) rocks (VU-13B and VU-14C), though, gave older values of ca. 1.2–1.3 Ga. Magmatic crystallization ages of ca. 1.1–1.2 Ga known from the metatonalitic gneiss (Varela et al., 2003 a, b) allowed the calculation of $Nd_{(t=1100)}$ at the time of crystallization for more acidic protoliths. Both rocks show positive values of $Nd_{(t=1100)}$, indicative of low or no crustal contamination. Therefore their T_{DM} ages indicate the first crustal extraction episode for this unit that occurred in an arc/back-arc environment. Nd results from the amphibolites gave younger T_{DM} ages. Although there is no magmatic crystallization ages for these samples, their $Nd_{(0)}$ values are positive, indicating a strong mantle contribution to this basic magmatism. Therefore, amphibolites T_{DM} ages mark a second crustal

Table 3. Sm/Nd isotopic data for garnet and whole rock. TM: Tambillos Metamorphics).

Unit	Samples	Material	Sm (ppm)	Nd (ppm)	Mesured ratios		S %	$\varepsilon Nd_{(0)}$	Age (Ma)	$\varepsilon Nd_{(t)}$	$T_{DM\ (Ma)}$	WR-garnet Age Sm-Nd (Ma)
					$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd^*$						
Maz Complex	VU-03D (metapelite)	WR	10.97	53.49	0.124001	0.511719	0.0019	–17.92			2241	
		Grt	7.03	4.51	0.941278	0.517296	0.0027	-	-	-	-	1039.9±3.1
	VU-21G (metapelite)	WR	7.23	37.95	0.115109	0.511677	0.0014	–18.75			2102	
	VU-30 A (metapelite)	WR	8.21	44.54	0.111459	0.511414	0.0012	–23.87			2422	
		Grt	1.45	2.89	0.303932	0.512638	0.0048	-	-	-	-	969±20
	VU-03 A (metatonalite)	WR	1.78	12.28	0.087755	0.511530	0.0009	–21.61			1821	
	VU-04 E (metatonalite)	WR	1.47	7.88	0.112880	0.511651	0.0011	–19.26			2095	
	VU-07 E (metagabbro)	WR	9.9	45.6	0.131407	0.511853	0.0013	–15.32			2196	
	VU-32 A (metatonalite)	WR	0.71	3.23	0.133788	0.512295	0.0011	–6.688			1417	
	VU-33 E (metatonalite)	WR	0.9	5.7	0.098660	0.511950	0.0013	–13.42			1440	
		Grt	0.4	0.6	0.372302	0.512780	0.0054	-	-	-	-	463±16
	VU-36B (amphibolite)	WR	3.4	13.2	0.156815	0.512587	0.0068	–1.00			1215	
TM	VU-08 A (amphibolite)	WR	3.3	13.3	0.149390	0.512575	0.0046	–1.23			1106	
Umango Complex	VU-13 A (amphibolite)	WR	2.9	11.0	0.160595	0.512770	0.0012	2.57			798	
	VU-13B (metadiorite)	WR	10.30	45.73	0.136213	0.512415	0.0020	–4.358	1100	4.17	1230	
	VU-14C (metatonalite)	WR	0.14	1.03	0.082031	0.511880	0.0034	–14.78	1100	1.38	1340	
	VU-14 H (amphibolite)	WR	7.68	31.31	0.148290	0.512713	0.0014	1.4548			782	
	VU-17C (amphibolite)	WR	8.3	36.3	0.138814	0.512651	0.0025	0.26			806	
El Taco Complex	VU-06 E (metapelite)	WR	5.91	26.47	0.135019	0.512399	0.0012	–4.672			1242	
		Grt	3.6	8.0	0.270487	0.512666	0.0025	-	-	-	-	301±16
	VU-06 F (metagreywake)	WR	3.50	15.70	0.134649	0.512261	0.0014	–7.36			1498	
	VU-06 G (metagreywake)	WR	3.68	17.49	0.127356	0.512250	0.0019	–7.577			1392	
	VU-06 J (pyroxenite)	WR	0.8	3.0	0.155133	0.512128	0.0016	–9.94			2378	

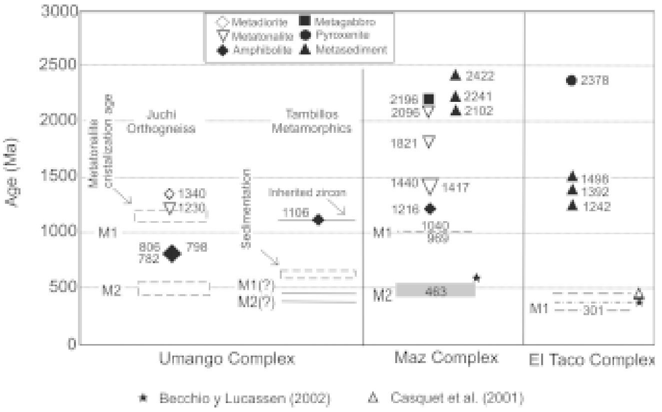

Fig. 6. Graphic displaying T_{DM} and metamorphic ages presented in this paper for rocks of Umango, Maz and El Taco complexes. Metamorphic ages are marked by dashed lines in Maz and El Taco complexes. In the Umango Complex ages of metamorphic crystallization, sedimentation and inheritated zircon came from Varela et al. (2003 a, b).

addition episode at ca. 800 Ma in the Juchi Orthogneiss that occurred in an extensional tectonic setting.

The only sample analyzed from the Tambillos Metamorphics came from an amphibolite interleaved with marbles in Quebrada del Cordobés (VU-08A). This amphibolite shows alkaline geochemical affinity, similar to amphibolites from Juchi Orthogneiss (Vujovich et al., 2004). However, since the $Nd_{(0)}$ for this sample has low negative values being compatible with a low or no crustal contamination, its T_{DM} age is interpreted as indicating another episode of crustal extraction within an extensional tectonic environment at ca. 1.1 Ga.

El Taco Complex

All isotopic data from this complex came from the same outcrop. So that although they give some information about nature and evolution of rocks of the El Taco Complex at the Sierra de Las Ramaditas, they might not reflect the nature of the entire complex. Three analyzed samples are from immature quartz-feldspathic metasediments and one is from a metapyroxenite interleaved with marbles within a metasedimentary sequence.

The metasedimentary samples gave T_{DM} ages between 1.2 and 1.5 Ga. Since these rocks appear to be very immature and $Nd_{(0)}$ are not very negative (considering the T_{DM} age), they might reflect a proximal sedimentation environment and their T_{DM} age could be interpreted as indicating a source area extracted from the mantle during the middle Proterozoic.

Interpretation of T_{DM} in the metapyroxenite is even more dubious, mainly because the origin of the protolith is not well-constrained. However, recent geochemical data indicate it might represent an igneous cumulate formed within an magmatic arc environment (Vujovich et al., 2004). If that is the case, T_{DM} age of this rock must be recording a crustal extraction episode of ca. 2.4 Ga in El Taco Complex.

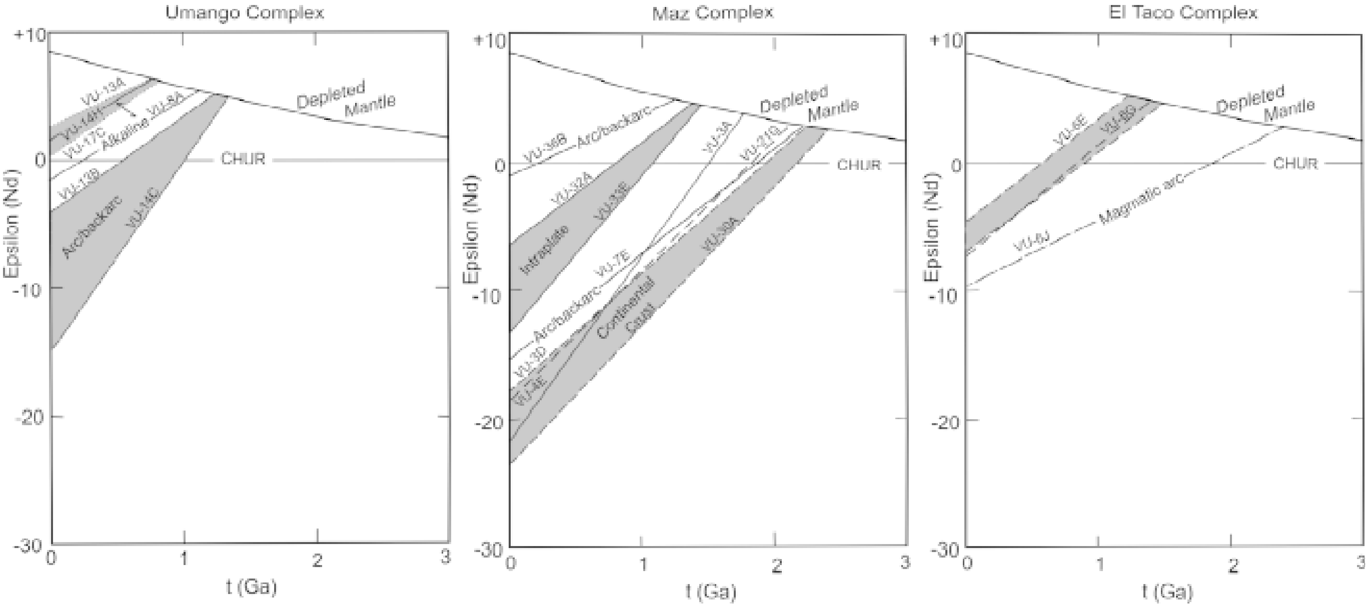

Fig. 7. Evolution εNd X time diagram in relation to the curve of evolution of the model of depleted mantle from DePaolo (1981) showing data from Umango, Maz and El Taco complexes. In diagram of the Umango Complex dashed lines represent samples of basic amphibolites and full lines represent metadiorite and metatonalite samples. In diagram of the Maz Complex dashed lines are from metapelites, gray full lines are from metatonalites and black full lines are from amphibolite (VU-36B) and metagabbro (VU-07E). In diagram of the El Taco Complex dashed lines are from metasediments and full line is from the pyroxenite. Accretion episodes are emphasized by heavy lines or painted gray area. Geochemical affinity of rock samples is based on Vujovich et al. (2004).

One garnet - whole-rock Sm-Nd isochron obtained for a metapelite of El Taco Complex (VU-06E) gave an age of ca. 300 Ma. This is interpreted as the age of peak metamorphism of the El Taco Complex. However, the possibility that it is indicating a post-metamorphic cooling can not be ruled out since closure temperatures for garnet are thought to be in the range between 800°C to 650°C.

Discussion and Conclusions

Interpretation of the structural evolution of the crystalline rocks of this area, although based on preliminary data, permitted the recognition of a very complex tectonic history involving several episodes of crustal accretion, metamorphism and deformation. These span from early Proterozoic to Carboniferous times.

Metasediments of the Maz Complex with T_{DM} ages ranging between 2.4 and 2.1 Ga comprise the oldest rocks in this area and indicate the presence of a source area with continental crust of similar age. This might have important implications in terms of the paleotectonic setting of rocks from Maz-Espinal and Las Ramaditas in the east as opposed to Umango's further to the west. A contemporaneous crustal accretion episode in an intraoceanic arc is recorded by gabbros and amphibolites in Sierra de Maz (at ca. 2.2 Ga) and, possibly, by metapyroxenite of the El Taco Complex in Sierra de Las Ramaditas (at ca. 2.4 Ga). This event is followed in the Sierra de Maz-Espinal by the accretion of metatonalites, possibly related to an intraplate extensional environment of Grenvillian age (ca. 1.4Ga).

In the Sierra de Umango, on the other hand, there are no events of early Proterozoic age recognized so far. The first crustal addition episode in this area is represented by 1.3 Ga old crystallization ages in metatonalite and amphibolites (1.2 Ga). These rocks include gabbros, tonalites and granodiorites that resembles supra-subduction complexes. They show tholeiitic affinity and were formed in a arc or back-arc tectonic environment, as indicated by analysis of the Th-Hf/3-Ta diagram (cf. Fig. 3 of Vujovich et al., 2004). Although T_{DM} age of this episode could belong to the same range of ages of a Grenvillian crustal extraction episode recognized in Sierra de Maz-Espinal, they occurred in diverse tectonic settings.

The last crust-forming episode (ca. 800 Ma) identified in the area is recorded only by rocks of Sierra de Umango. It is marked by intraplate alkaline basic dykes that might represent rifting of Rodinia during the Neoproterozoic (Vujovich et al., 2004). Therefore T_{DM} ages from Sierras de Maz-Espinal and Umango seems to indicate that until at least 800 Ma ago rocks of these two areas belonged to crustal segments with diverse evolution. From rocks of both of these regions were affected by several episodes of high-grade metamorphism and deformation, as discussed below.

The recognition that high-T fabrics-forming tectono-metamorphic episodes of early Cambrian (Pampean) age have affected these rocks (Becchio and Lucassen, 2003), seems to provide additional evidence that, in the case of rocks of the Sierra de Maz-Espinal, we might be dealing with rocks belonging to the active Gondwana margin. According to the literature tectonic events of Pampean age are not typical of the Grenville of the Ouachita embayment, the region of Laurentia where Cuyania terrane was supposed to have been derived from (c.f. Ramos, 2004 - this volume).

Metamorphic events of intermediate to high pressures and high temperatures, typical of collisional environments, were identified in Sierra de Maz-Espinal. The oldest rock-forming fabrics tectono-metamorphic episode recognized is of middle Proterozoic age (ca. 1.04 to 0.969 Ga, garnet - whole-rock Sm/Nd age) being recorded by metapelites from Maz Complex that attained temperatures of 650°C–6.3 kbar. Transport directions were to the north. A younger metamorphic event, (463 Ma, garnet - whole-rock Sm/Nd age) is verified in metatonalites intrusive in this metapelites. This age is similar to others obtained for rocks of Sierra de Maz-Espinal and Sierra de Umango, reported in the literature (e.g., Varela et al.2003 a, b; Becchio and Lucassen, 2003) and interpreted as accretion of the Cuyania Microcontinent (e.g., Ramos et al., 1998). Another metamorphic event at ca. 301 Ma (garnet-WR Sm/Nd age) was recognized in metasediments from El Taco Complex. Peak metamorphic conditions of this event, probably the last major tectonic episode that affected these rocks, have attained 868°C–9.8 kbar. It was impossible to distinguish fabrics belonging to totally different tectonic episodes based on structural or metamorphic data in these rocks. They all seem to show similar structural evolution and orientations probably as a result of undetected tectonic interleaving of different crustal segments during younger deformation. Therefore, Sm/Nd dating of fabrics is essential for our study and in this respect the role of the last high-T deformation event recorded in the El Taco rocks of Las Ramaditas should be investigated with priority.

Geophysical evidence indicates the presence of extensive WNW-trending lineaments that separate basements blocks of different magnetic and gravimetric signatures that might represent ancient Grenvillian age suture zones. In the northern portion of Cuyania there is geophysical evidence for the occurrence of two old (1000–1200 Ma?) WNW suture zones, corresponding to the Guandacol lineament and to the Vinchina lineament. The location of these old sutures is consistent with the presence of analogous structures in Laurentia, more specifically in the region of the Ouachita embayment, where they assemble pre-Grenvillian cratonic nuclei (cf. Mosher, 1998; Bickford et al., 2000). It is argued that the WNW transform faults pertaining to the Ouachita rift would have developed as a result of a reactivation of compressional structures (thrust belts) of identical orientation associated to the accretion of Grenvillian terranes. More specifically, the comparison of figures 1 and 2 of Thomas (1991) suggests that the Alabama-Oklahoma transcurrent fault is the result of reactivation of the Ouachita thrust belt that juxtaposed rock units of contrasting tectonic environments at the end of the Proterozoic and beginning of the Paleozoic. The Guandacol (L1) and the Vinchina (L2) Lineaments would be in physical continuity with analogous megastructures in the Ouachita embayment region and are interpreted here as discontinuities of middle Proterozoic age (cf. Nash, 1997; Chernicoff and Nash, 2001). From geophysical evidence the suture zone between Cuyania and the western margin of Gondwana would be located east of Sierra de Maz-Espinal, along the Valle Fértil lineament. However, the isotopic data indicate that the suture would be located between Sierras de Umango and Maz-Espinal in coincidence with a NNE trending lineament of regional extent restricted to shallow levels (Fig. 3b). A possible explanation for the latter structure is that it could represent a second-order suture. Ongoing geological and geophysical investigation will provide additional elements to locate the suture zone between the Cuyania terrane and the western margin of Gondwana.

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