



Ordovician klippen structures of the Sierra de Umango: New insights on Tectonic evolution of the Western Sierras Pampeanas, Argentina

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ABSTRACT

The basement rock of the Pampean flat-slab (Sierras Pampeanas) in the Central Andes was uplifted and rotated in the Cenozoic era. The Western Sierras Pampeanas are characterised by meta-igneous rocks of Grenvillian Mesoproterozoic age and metasedimentary units metamorphosed in the Ordovician period. These rocks, known as the northern Cuyania composite terrane, were derived from Laurentia and accreted toward Western Gondwana during the Early Paleozoic. The Sierra de Umango is the westernmost range of the Western Sierras Pampeanas. This range is bounded by the Devonian sedimentary rocks of the Precordillera on the western side and Tertiary rocks from the Sierra de Maz and Sierra del Espinal on the eastern side and contains igneous and sedimentary rocks outcroppings from the Famatina System on the far eastern side.

The Sierra de Umango evolved during a period of polyphase tectonic activity, including an Ordovician collisional event, a Devonian compressional deformation, Late Paleozoic and Mesozoic extensional faulting and sedimentation (Paganzo and Ischigualasto basins) and compressional deformation of the Andean foreland during the Cenozoic.

A *Nappe* System and an important shear zone, La Puntilla–La Falda Shear Zone (PFSZ), characterise the Ordovician collisional event, which was related to the accretion of Cuyania Terrane to the proto-Andean margin of Gondwana. Three continuous deformational phases are recognised for this event: the D1 phase is distinguished by relics of S1 preserved as internal foliation within interkinematic staurolite porphyroblasts and likely represents the progressive metamorphic stage; the D2 phase exhibits P-T conditions close to the metamorphic peak that were recorded in an S2 position or a mylonitic foliation and determine the main structure of Umango; and the D3 phase is described as a set of tight to recumbent folds with S3 axial plane foliation, often related to thrust faults, indicating the retrogressive metamorphic stage. The *Nappe* System shows a top-to-the S/SW sense direction of movement, and the PFSZ served as a right lateral ramp in the exhumation process. This structural pattern is indicative of an oblique collision, with the Cuyania Terrane subducting under the proto-Andean margin of Gondwana in the NE direction. This continental subduction and exhumation lasted at least 30 million years, nearly the entire Ordovician period, and produced metamorphic conditions of upper amphibolite-to-granulite facies in medium- to high-pressure regimes.

At least two later events deformed the earlier structures: D4 and D5 deformational phases. The D4 deformational phase corresponds to upright folding, with wavelengths of approximately 10 km and a general N–S orientation. These folds modified the S2 surface in an approximately cylindrical manner and are associated with exposed, discrete shear zones in the Silurian Guandacolinis Granite. The cylindrical pattern and subhorizontal axis of the D4 folds indicates that the S2 surface was originally flat-lying. The D4 folds are responsible for preserving the basement unit Juchi Orthogneiss synformal *klippen*. This deformation corresponds to the Chanica Tectonic during the interval between the Devonian and Carboniferous periods. The D5 deformational phase comprehends cusped-lobate shaped open plunging folds with E–W high-angle axes (D5 folds) and sub-vertical spaced cleavage. The D5 folds and related spaced cleavage deformed the previous structures and could be associated with uplifting during the Andean Cycle.

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1. Introduction

The tectonic history of the basement of west-central Argentina is characterised by a Late Neoproterozoic–Early Cambrian Pampean orogenic cycle and an Ordovician Famatinian orogenic cycle. The latter is associated with the accretion of a Laurentian-derived microcontinent (Cuyania Terrane) to the southwestern proto-Andean margin of Gondwana (Ramos, 1988a; Ramos et al., 1998, and synthesis in Thomas and Astini, 2003, Ramos, 2004), and both events are recorded in the Sierras Pampeanas. The Sierras Pampeanas are made up of igneous and metamorphic rocks uplifted and rotated during the Cenozoic by the compressive foreland tectonics of the Pampean flat-slab (Ramos et al., 2002).

Rocks of Mesoproterozoic age have been recognised along an N–S trending belt (Fig. 1) that includes the Western Sierras Pampeanas (*sensu* Caminos, 1979) in the north and Las Matras block in the south (Sato et al., 2000). This belt is considered to be the basement of the Cuyania Terrane and includes the Toro Negro, Umango, Maz and Espinal Ranges in the north, the Pie de Palo range and surroundings in the central area, and the San Rafael and Las Matras blocks in the south (Sato et al., 2000, 2004 and references therein).

The Umango, Maz and Espinal Ranges, which are part of the Western Sierras Pampeanas, consist of meta-igneous and meta-sedimentary rocks, which are exposed between 28°45'–29°30'S latitude and 68°50'–68°15'W longitude in southwestern La Rioja

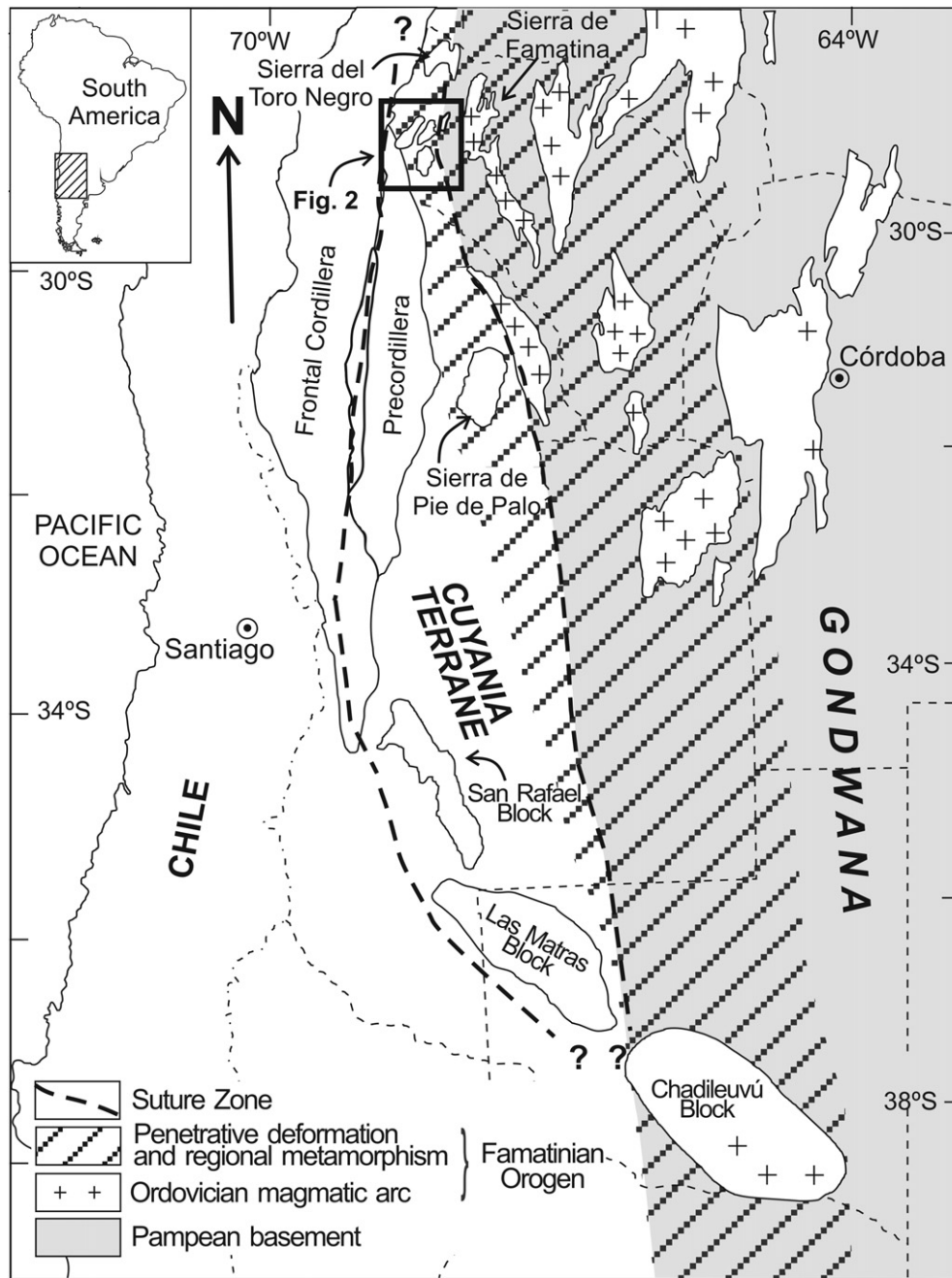


Fig. 1. Tectonic relationship between the proto-Andean margin of Gondwana (Pampean basement) and the accreted Cuyania Terrane (after Sato et al., 2004). Note the broad extension of the penetrative deformation and regional metamorphism associated with the Famatinian collisional event that overprinted both the Cuyania Terrane and the Gondwana border. The Ordovician magmatic arc intruded within the Pampean basement of the Gondwana margin.

Province, Argentina. These units are bounded by Devonian sedimentary rocks (Punilla Formation) of the Precordillera Occidental in the west and by granitic, volcanic and sedimentary rocks of the Famatina System in the east (Fig. 2).

Since Hausen's (1921) first descriptions, the diversity of lithotypes and the structural complexity of the basement of the Sierra de Umango have been described by Furque (1972); more recently, geochemistry, geochronology (Varela et al., 1996, 2000, 2001, 2003a,b, 2008) and thermo-tectonic evolution (Porcher et al., 2004 and references therein) have revealed the history of this

range. The geological units of the Sierra de Umango are summarised in Varela et al. (2008, 2011), but a more comprehensive overview of these units is required to improve the interpretations of available geochronological data. In fact, characterisations of deformational events, the metamorphic history and the relationships among geological units are essential to an improved understanding of the geodynamic history of the Famatinian orogenic belt.

The objectives of this contribution were to review the relationships between the geological units of the Sierra de Umango, to identify and describe their main structures and to explain the

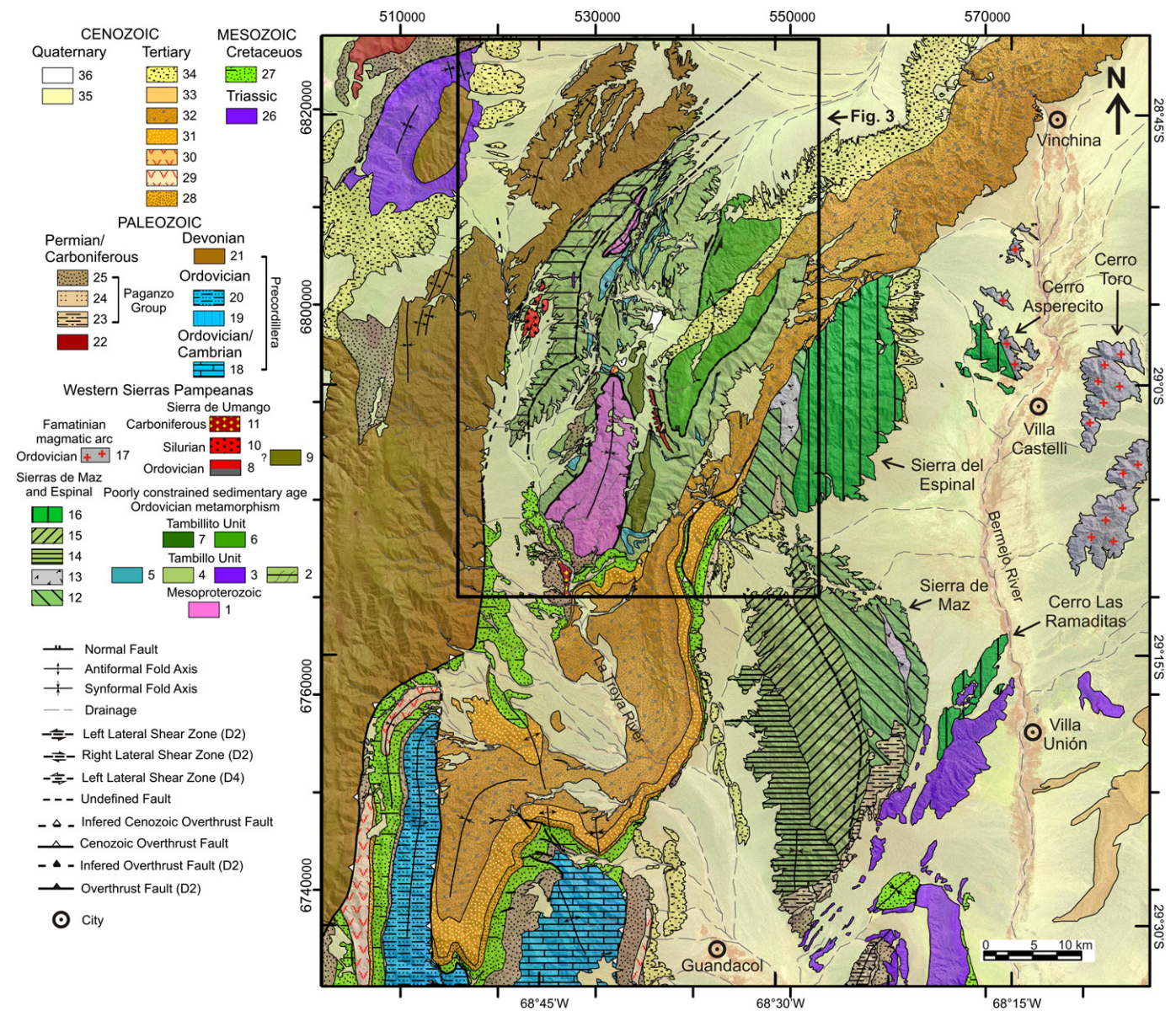


Fig. 2. Geological map of the Umango, Maz and Espinal ranges and surrounding area (compiled and adapted after Kilmurray and Dalla Salda, 1971; Casquet et al., 2008; Caminos and Fauqué, 1999; Fauqué et al., 2004 and Meira, 2010). For geographical location, see Fig. 1. Quaternary: 36 – “Barreal”; 35 – Undifferentiated Quaternary; Neogene: Tertiary basins – Late Pliocene: 34 – El Corral and Toro Negro Formations; Pliocene: 33 – Undifferentiated Pliocene; Early Pliocene: 32 – Zapallar Formation; Middle/Late Miocene: 31 – Vinchina Formation; 30 – Tertiary volcanic rocks; Middle Miocene: 29 – Cerro Morado Formation; Oligocene/Early Miocene: 28 – Puesto La Flecha Formation; Mesozoic: *Ischigualasto Basin* – Cretaceous: 27 – Ciénaga del Rio Huaco Formation; Triassic: 26 – Undifferentiated Triassic; Paleozoic: *Paganzo Basin* – Permian: 25 – Rio del Peñon, Patquia and Panacán Formations; Late Carboniferous: 24 – Tupe and Vólcan Formations; Early/Late Carboniferous: 23 – Guadacol Formation; Carboniferous: 22 – Undifferentiated Granitoids; *Precordillera* – Late Devonian/Early Carboniferous: 21 – Punilla Formation; Ordovician: 20 – Trapiche Group; 19 – La Troya Marble; Cambrian/Ordovician: 18 – Cerro Totora and San Juan Formations; *Famatinian Magmatic Arc* – Ordovician: 17 – Granitoids; *Sierras De Maz and Del Espinal* – 16 – Espinal Formation; 15 – El Zaino Group; 14 – El Taco Group; 13 – Anortosites; 12 – Maz Group; *Sierra de Umango* – Carboniferous: 11 – Cerro Veladero Granite (Post-Orogenic Granite); Silurian: 10 – Guadacolinos Granite (Late-Orogenic Granite); Ordovician/Silurian?: 9 – El Cordobés Unit (Metabasic rocks); Ordovician: 8 – El Peñon Granite (Pre- to Syn-Orogenic Granite); Poorly constrained sedimentary age and Ordovician Metamorphism: Tambillito Unit: 7 – Metagabbro; 6 – Metasedimentary Sequence; Tambillo Unit: 5 – Marbles; 4 – Metavolcanosedimentary Sequence; 3 – Garnet-bearing metagabbro; 2 – Mylonites PFSZ; Estenian Mesoproterozoic: 1 – Juchi Orthogneiss. A color version of this figure is available in the online edition.

relevant kinematic history. Geological mapping, petrography, and structural analysis were used to achieve these goals. Our new data (see below) suggest the development of a *Nappe System* (according to McClay and Price, 1981) with a top-to-the S/SW sense direction of movement and an important right lateral shear zone, La Puntilla–La Falda Shear Zone (PFSZ), that served as a lateral ramp in the shortening processes associated with the Ordovician oblique collisional event (Famatinian Orogeny) caused by accretion of the Cuyania Terrane with the proto-Andean margin of Gondwana (Meira, 2010 and Varela et al., 2011). The metamorphic conditions accompanying this event in this part of the Sierras Pampeanas fall up to the medium- to high-pressure regime of the upper amphibolite-to-granulite facies. Two post-collisional and diachronous events were identified: the Chanica Phase and the Andean Cycle in the Devonian–Carboniferous and Tertiary periods, respectively (Meira, 2010 and Varela et al., 2011).

2. Geological overview

Andean geological history has been extensively studied, and its complexity has been recognised, since the middle of the last century (e.g., Gansser, 1973; Coira et al., 1982; Ramos et al., 1986; Ramos, 1988a,b, 1999a,b; Ramos and Aleman, 2000). Morphological, structural and geological differences along the length of the Andes–Cordillera (8000-km long) led to the identification of three major sections: the Northern, Central and Southern Andes (Gansser, 1973).

Processes, such as accretion of “suspect” terrane, played an important geodynamic role in continental growth, and the principles of these processes were mainly described in the 1980s by Coney et al. (1980), Jones et al. (1983) and Howell (1989).

Paleozoic “suspect” terranes, which had docked along the western border of Gondwana in the Central Andes were first described by Ramos et al. (1984, 1986). Since then, many other geotectonic hypotheses involving accretion of “suspect” terranes have been suggested and their terrane boundaries have been outlined. Most of the proposed tectonic hypotheses involve an allochthonous (Laurentian) origin: 1. The Occidentalia Terrane was a large part of Laurentia and was left behind after continent–continent collision during the Neoproterozoic to Early/Middle Paleozoic eras (Dalla Salda et al., 1992a,b; Dalziel et al., 1994); 2. The Cuyania, or Precordillera, Terrane was an independent smaller continental block that rifted away from Laurentia prior to collision with Gondwana during the Middle Ordovician (synthesis in Thomas and Astini, 2003 and Ramos, 2004) or Silurian/Devonian period (e.g., Keller et al., 1998; Pankhurst and Rapela, 1998; Rapela et al., 1998); and 3. An adjacent plateau (Keller, 1999), the Texas Plateau (Dalziel, 1997), attached as a promontory to Laurentia, was left behind after a short collision with Gondwana. The Chilena Terrane was thought to be another smaller continental block that docked later during the Silurian or Devonian period (Ramos et al., 1998; Quernadelle and Ramos, 1999; Ramos, 1999b). In contrast to these exotic interpretations, Aceñolanza and Toselli (1988), Baldis et al. (1989), Aceñolanza et al. (2002) and Finney et al. (2003) proposed that the Cuyania Terrane had a para-autochthonous Gondwanan origin, situated in the same latitudinal belt as Laurentia to help explain the Precordillera carbonate platform and their palaeontology. These authors suggested that a strike-slip displacement moved the “SAFRAN” platform from the southern sector of Gondwana – between South America, Africa and Antarctica – to its present position. Although, the solely strike-slip accretion of the Cuyania Terrane is refuted by strong tectono-metamorphic evidences in the Sierra de Pie de Palo that the accretion involved subduction of the Iapetus Ocean (van Staal et al., 2011).

The most characteristic rocks of these terranes are Grenvillian-age basement rocks (Western Sierras Pampeanas, Precordillera basement and Frontal Cordillera, San Rafael and Las Matras blocks) and a unique Early Paleozoic sedimentary cover (Precordillera).

Sato et al. (2000) proposed the existence of an N–S trending belt of Grenvillian-age rocks along the Western Sierras Pampeanas to the Las Matras block and interpreted this structure as the basement of the Cuyania Terrane (Fig. 1). The geological history of this belt is heterogeneous along its strike (see synthesis in Rapela et al., 2010, Varela et al., 2011).

The northern part of the Grenvillian belt is widely exposed at the Toro Negro, Umango, Maz and Espinal Ranges and in the surrounding lands. Following pioneering lithological descriptions by Hausen (1921), De Alba (1954), Turner (1964) and Furque (1972) and detailed works by Kilmurray and Iñiguez Rodríguez (1968), Kilmurray (1969, 1970, 1971) and Kilmurray and Dalla Salda (1971), the basement units of the Umango, Maz and Espinal Ranges, as well as the surrounding areas, were interpreted recently using isotopic constraints and provenance analyses (e.g., Casquet et al., 2006; Porcher et al., 2004; Varela et al., 2011). Portions of the Maz and Espinal Ranges revealed a different geodynamic history in the Early to Middle Proterozoic era, showing isotopic affinities with the Mesoproterozoic Arequipa–Antofalla Craton that are compatible with an autochthonous or para-autochthonous proto-Gondwanan origin (Casquet et al., 2006, 2008; Ramos, 2008). However, the Mesoproterozoic rocks of the Sierra de Umango (Juchi Orthogneiss – Varela et al., 1996, 2003a, 2008) and its supracrustal units are more comparable with the Sierra de Pie de Palo basement, indicating a Laurentian origin in this segment, as part of the Cuyania Terrane (Vujovich and Kay, 1998; Vujovich et al., 2004; Porcher et al., 2004; Varela et al., 2008, 2011).

Overlying the Grenvillian basement, the Early Paleozoic sedimentary strata of the Precordillera are the key to understanding the evolution of the Central Andes. Its palaeontological content, stratigraphy and structural evolution are supporting a Laurentian origin of the Cuyania Terrane (Keller, 1999; Benedetto, 2004; Thomas and Astini, 2003 and references therein). The Precordillera corresponds to a high-level N–S trending fold-and-thrust belt formed during the Andean (Late Tertiary) Orogeny (Jordan et al., 1993) and purportedly related to shallow, eastward subduction of the Nazca Plate beneath the South America (Jordan et al., 1983). The Andean tectonics led to eastward thrusting above a buried basal *décollement* of the Cambrian to Late Tertiary sedimentary sequence (Baldis et al., 1984) and produced an overall crustal shortening by more than 50% (Allmendinger et al., 1990; von Gosen, 1992; Jordan et al., 1993). The Andean shortening was preceded by Early Paleozoic (Ordovician to Devonian) deformation, linked by dominant W-vergent folding and associated thrust faulting and a low-grade metamorphic overprint (up to greenschist facies), Carboniferous to post-Triassic normal faulting and Tertiary thin-skinned tectonic activity, that highlight the polyphase structural evolution of the Precordillera (von Gosen, 1992, 1995, 1997; von Gosen et al., 1995; Thomas and Astini, 2007).

South of the basement rocks of the Sierra de Umango, the Precordillera sedimentary rocks are represented by the Cerro Totorá Formation, an Early Cambrian syn-rift deposit comprising a succession of red beds and dolomites interlayered with evaporite (Thomas and Astini, 2003); the San Juan Formation, which is mostly composed of Ordovician shallow-marine carbonates that form the top of a passive-margin sequence (Thomas and Astini, 2003) and the Trapiche Group, which consists of Late Ordovician siliciclastic deposits in a syn-orogenic clastic wedge (Thomas and Astini, 2003). Devonian siliciclastic sedimentary rocks composed of sandstones, pelites, conglomerates and diamictites (Fauqué et al., 2004) in the Punilla Formation form the western boundary of the Umango basement rocks.

An extensive retroarc basin in this area, associated to the magmatic arc from the Gondwanic Tectonic Cycle (Pankhurst and Rapela, 1998), is characterised by the Paganzo Group, which was active during the Carboniferous to Permian periods (Limarino et al., 2002 and references therein). These sedimentary rocks are overlain unconformably above the Precordillera and the basement rocks. Mesozoic deposits (Triassic and Cretaceous rocks) are associated with extensional events on the Gondwana margin and the early rifting of the Atlantic Ocean (Ramos, 1988a).

Cenozoic deposits are mainly related to the Andean foreland basins. These rocks, mainly the Puesto La Flecha, Vinchina, Zapallar, El Corral and Toro Negro formations from the Oligocene to Miocene epochs, are frequently deformed (Caminos and Fauqué, 1999).

3. Geology of the Sierra de Umango

The crystalline rocks of the Sierra de Umango are composed of a Mesoproterozoic basement unit, called Juchi Orthogneiss; two supracrustal sequences of Ordovician-age metamorphism (Varela et al., 2011) and poorly constrained sedimentary age, named the Tambillo and Tambillito units; the El Cordobés metamafic sequence; the Ordovician pre- to syn-collisional El Peñon Granite (Varela et al., 2011) and the late- to post-collisional Guandacolinis and Cerro Veladero Granites. The La Troya Marble, Punilla Formation, Late Paleozoic sedimentary rocks, and Mesozoic and Cenozoic layers complete the geological units exposed at the Sierra de Umango (Fig. 3).

3.1. Juchi orthogneiss

The basement unit of the Sierra de Umango consists mainly of hornblende-biotite tonalitic gneisses, biotite granodioritic gneisses and migmatites. The migmatites are characterised by fine-grained trondhjemitic leucosome, biotite and hornblende-rich melanosome and paleosome with 20% mafic mineral content. Metabasic rocks are intercalated within the gneissic sequence in centimetres- to decimetres-thick bands that locally contain garnet and clinopyroxene. Boudins and metres-thick bands of retroeclogites/high-pressure mafic granulites were described in the northwestern area of the Sierra de Umango in the Agua La Falda region (González et al., 2005). Red-pinkish leucocratic decimetres- to metres-thick bands of biotite syenogranitic gneisses are common, often with mylonitic foliation. Syenogranitic veins have intruded into the gneissic package and are deformed with it.

The Juchi Orthogneiss occurs in synformal structures and overlies the Tambillo Unit, limited by ductile thrust faults. These structures have been interpreted as *klippen* (see description below), called Juchi Klippe and La Falda Klippe (Figs. 3, 4 and 8). Gneissic banding is the main structure in these rocks and represents the S2 foliation. Relics of S1 foliation have been preserved in D2 intrafolial folds and S2 often exhibits mylonitic and protomylonitic fabrics. Open-to-tight folds deform the S2 surface, essentially in the limbs of the synformal structure (Fig. 8). These folds could be related to the D3 or D4 folding phases (see synthesis of the tectono-metamorphic events in Table 1 and further reading below).

The mineralogical assemblages of the felsic gneisses generally comprises biotite, quartz, plagioclase, K-feldspar, hornblende, garnet, opaque minerals and occasionally clinopyroxene and epidote group minerals; the metamafic rocks contain garnet, clinopyroxene, quartz, plagioclase, hornblende, rutile, titanite and opaque minerals. These mineral assemblages suggest that these rocks were metamorphosed under medium- to high-pressure upper amphibolite-to-granulite facies conditions.

The ages of Juchi Orthogneiss range from 1216 ± 29 Ma (Varela et al., 2003b) to 1084 ± 7 Ma (Varela et al., 2008) and have been

interpreted as dating the time of crystallisation. New SHRIMP U/Pb zircon data indicate inherited Mesoproterozoic cores (in the same interval cited above) and Ordovician rims (474 ± 12 Ma; Varela et al., 2011), suggesting a metamorphic overprint associated with the Famatinian collisional event (Varela et al., 2011).

A detailed metamorphic study of this unit is required to better understand the tectono-metamorphic evolution of these rocks, especially with respect to their pre-Ordovician history.

3.2. Tambillo Unit

The Tambillo Unit is exposed in a major part of the Sierra de Umango including a thick shear zone along its western boundary (PFSZ) and displays important differences between the western and the eastern portions (Fig. 3).

In the western portion, marble beds occur in ten- to hundred-metre-thick layers interlayered within amphibolites, calcsilicate rocks and feldspatic schists (meta-greywackes). The eastern area is characterised by intercalations of biotite–muscovite schists, biotite–muscovite–quartz schists, quartzites, calcsilicate rocks, amphibolites and minor marbles.

The main structure is characterised by an S2 transposition foliation which is generally parallel to the compositional layering (S0) and is defined by mica-rich bands in micaceous schists, discontinuous kyanite–sillimanite and biotite-rich bands interleaved with granoblastic quartz and plagioclase-rich sub-millimetre-thick bands in feldspatic schists and alternating hornblende-rich/plagioclase-rich bands in amphibolites. D2 recumbent folds with relics of S1 foliation preserved in their hinges are also characteristic. These structures are well developed where the amphibolites are interlayered with marbles. D3 and D4 folds are defined by close-to-open asymmetric folds that deform the S2 foliation. E–W open folds outline the D5 deformational phase, often with a high-angle plunging axis.

A well-developed shear zone affects the Tambillo Unit along its western boundary. The NNE trending La Puntilla–La Falda Shear Zone (PFSZ) is approximately 4 km in width and more than 38 km in length. Alternating aluminous silicate–garnet–plagioclase–quartz–biotite mylonites, marble breccias and amphibolite boudins are the major lithologies, but minor porphyroclastic, grey mylonitic granites and dark-grey ultramylonites also occur. A tabular body of garnet-bearing metagabbro is exposed at Cerro Cacho (4000 m above sea level) (Figs. 3 and 4). The protomylonitic to mylonitic foliation is correlated to the main regional S2 foliation, which is typified by fine-grained biotite-rich bands, quartz ribbons and feldspar and garnet porphyroclasts. The mylonitic foliation was modified by upright, open D4 folds.

The mineralogical assemblages show that these rocks have undergone a metamorphism of upper amphibolite facies. According to our data, the metamorphic grade varies from muscovite-bearing rocks in the eastern portion to conditions beyond the muscovite-breakdown reaction, which produces K-feldspar in the presence of sillimanite and/or kyanite in the western region and the PFSZ (Meira, 2010).

Isotopic Sr–C–O studies on marbles of the Tambillo Unit suggest a Neoproterozoic (580–640 Ma) depositional age for the siliciclastic–carbonate sequence (Varela et al., 2001). This age is tentative because of the assumption that the rocks remained close system with respect to these isotopic systems during the medium- to high-grade metamorphism and that such rocks have preserved their original sedimentary isotopic compositions.

3.3. Tambillito Unit

The Tambillito Unit consists mainly of alternating staurolite and/or garnet-bearing mica schists, quartzites, minor amphibole

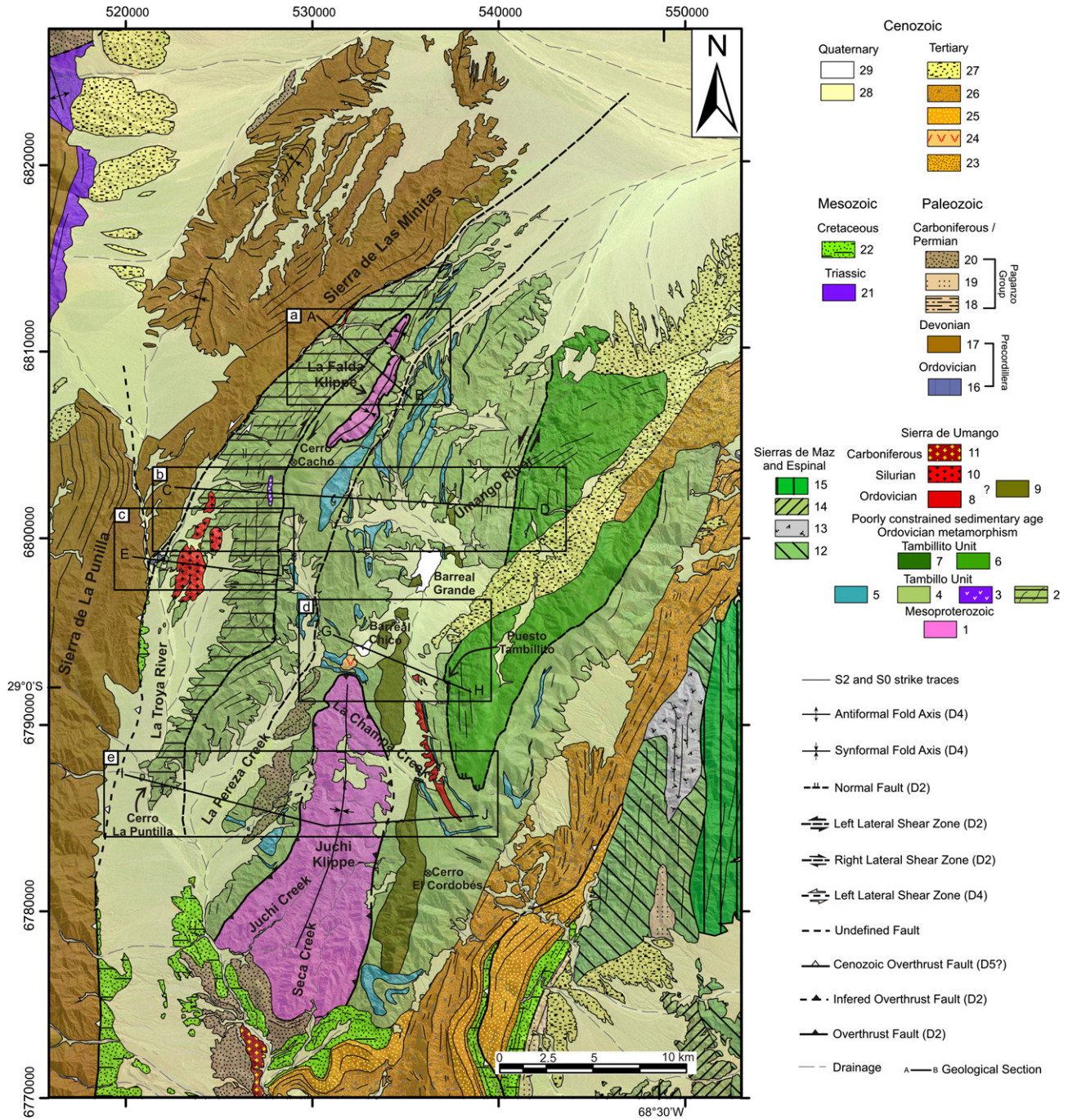


Fig. 3. Geological map of the Sierra de Umango (adapted after Meira, 2010). For geographical location, see Fig. 2. Detailed geological sections are marked by rectangles: a – Água La Falda Section; b – Cerro Cacho-Umango River Section; c – Los Guandacolinos Section; d – Barreal Chico-Puesto Tambillito Section; e – Puntilla-La Champa Creek Section. Quaternary: 29 – “Barreal”; 28 – Undifferentiated Quaternary; Neogene: Tertiary Basins – Late Pliocene: 27 – El Corral and Toro Negro Formations; Early Pliocene: 26 – Zapallar Formation; Middle/Late Miocene: 25 – Vinchina Formation; 24 – Tertiary volcanic rocks; Oligocene/Early Miocene: 23 – Puesto La Flecha Formation; Mesozoic: Ischigualasto Basin – Cretaceous: 22 – Ciénaga del Río Huaco Formation; Triassic: 21 – Undifferentiated Triassic; Paleozoic: Paganzo Basin – Permian: 20 – Río del Peñón, Patquia and Panacán Formations; Late Carboniferous: 19 – Tupe and Vólcan Formations; Early/Late Carboniferous: 18 – Guandacol Formation; Precordillera – Late Devonian/Early Carboniferous: 17 – Punilla Formation; Ordovician: 16 – La Troya Marble; Sierras De Maz and Del Espinal - 15 – Espinal Formation; 14 – El Zaino Group; 13 – Anortosites; 12 – Maz Group; Sierra de Umango – Carboniferous: 11 – Cerro Veladero Granite (Post-Orogenic Granite); Silurian: 10 – Guandacolinos Granite (Late-Orogenic Granite); Ordovician/Silurian?: 9 – El Cordobés Unit (Metabasic rocks); Ordovician: 8 – El Peñón Granite (Pre- to Syn-Orogenic Granite); Poorly constrained sedimentary age and Ordovician Metamorphism: Tambillito Unit: 7 – Metagabbro; 6 – Metasedimentary Sequence; Tambillo Unit: 5 – Marbles; 4 – Metavolcanosedimentary Sequence; 3 – Garnet-bearing metagabbro; 2 – Mylonites PFSZ; Estenian Mesoproterozoic: 1 – Juchi Orthogneiss. A color version of this figure is available in the online edition.

schists, amphibolites and calcsilicate rocks. A tabular to lenticular body of coarse-grained metagabbro is exposed in the contact between the Tambillo and Tambillito units (Figs. 3 and 6).

All the information about this unit comes from the area east of the Puesto Tambillito and the easternmost Umango River section. The southern and eastern limits were delineated with satellite images and need to be verified in the future.

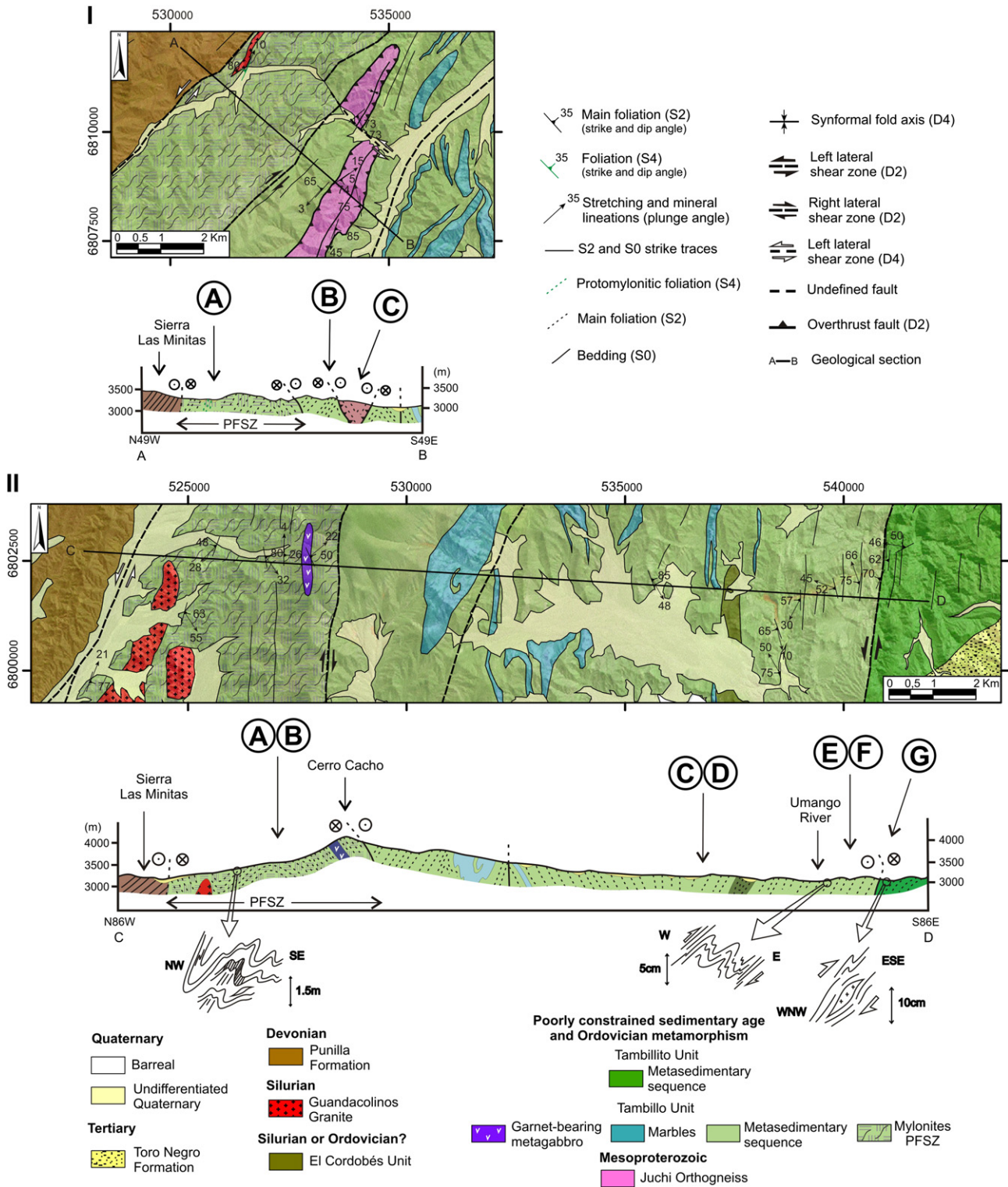


Fig. 4. Detailed geological sections. For geographical locations, see Fig. 3. (I) Ágüa La Falda section: the contact between the Punilla Formation and the PFSZ, the S4 protomylonitic foliation deforming the thin lens-shaped Guandacolinos Granite and the La Falda Klippe are highlighted in this section; (II) Cerro Cacho-Umango River section: a section cross-cutting the northern Sierra de Umango, showing mainly S2 foliation deformed by D3 close folds (sketch from the western portion) and D4 open upright folds. A color version of this figure is available in the online edition.

The observed contact between the Tambillo and Tambillito units is tectonic, characterized by abrupt change in the metamorphic grade of the metasedimentary rocks, and it is defined by a folded steeply dipping fault. The rocks of the Tambillo Unit indicate

metamorphic conditions up to upper amphibolite facies, reaching partial melting reactions, while the metapelitic rocks of Tambillito Unit show metamorphism with stability of garnet and staurolite in the lower amphibolite facies conditions. The small amount of

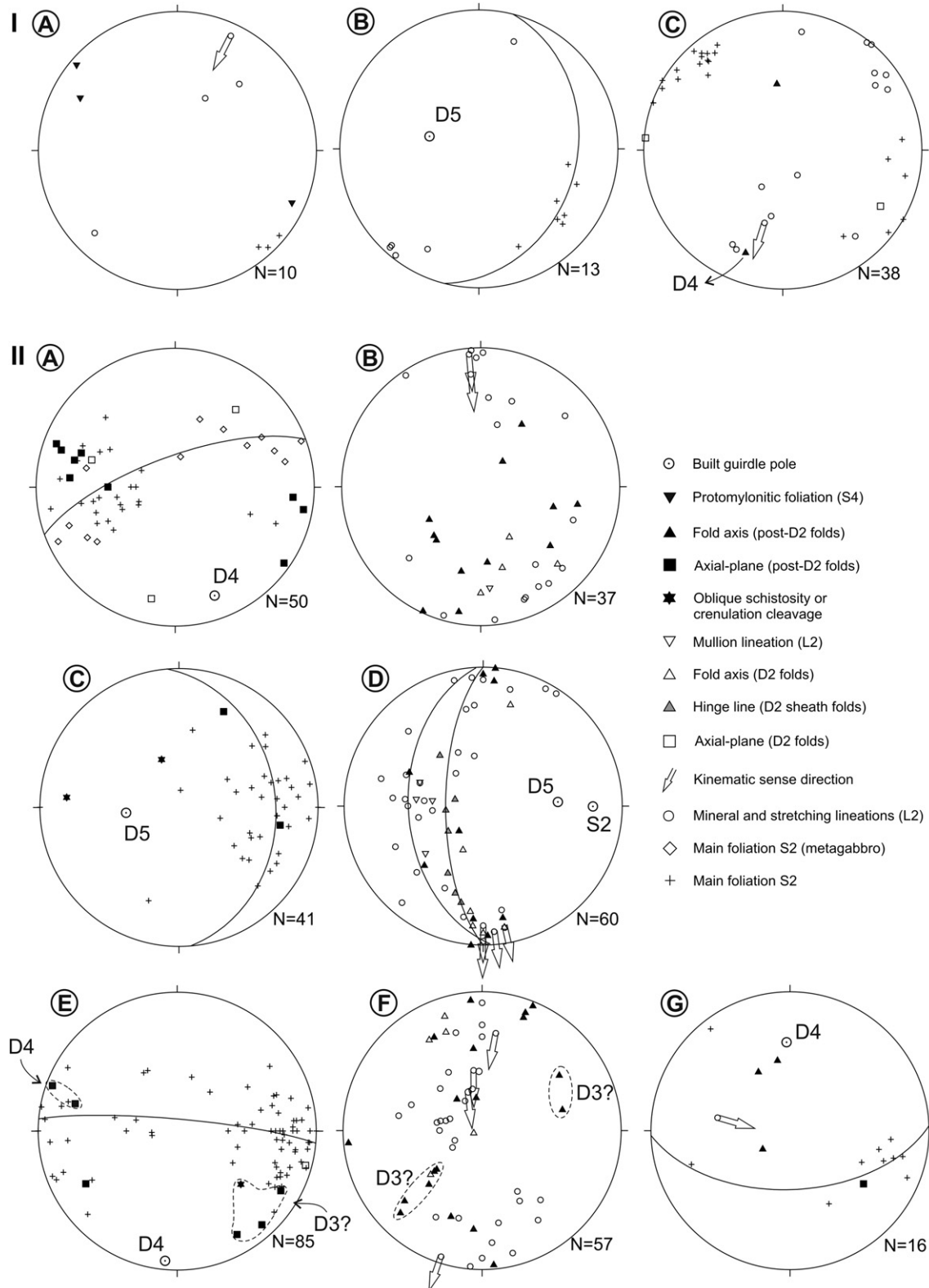


Fig. 5. Lower hemisphere equal area stereographic projections of fabric elements. (I) Águá La Falda section: stereogram A – structural data from thin lens-shaped Guandacolinos Granite and PFSZ; stereogram B – structural data from Tambillo Unit. Note the N–S dispersal pattern of the S2 foliation poles, associated to D5 folding; stereogram C – structural data from Juchi Orthogneiss (La Falda Klippe). This stereogram highlights the shear sense (top-to-the SSW) of the La Falda Klippe and the ~N–S trending upright synformal fold (D4 folds). (II) Cerro Cacho-Umango River section: stereograms A and B – planar and linear structural data, respectively, from Cerro Cacho surroundings. Note that the E–W dispersal pattern of the S2 foliation poles defines the D4 open upright folds; stereograms C and D – planar and linear structural data, respectively, from Barreal Grande area. These stereograms highlight the top-to-the S sense of movement related to the D2 deformational phase, the D2 sheath folds (see also Fig. 13) and the ~N–S dispersal pattern of the S2 foliation poles, associated to D5 folding; stereograms E and F – planar and linear structural data, respectively, from Umango River section (Tambillo Unit). The ~E–W dispersal pattern of the S2 foliation poles associated to the D4 upright folds also can be observed in these stereograms and the D3 deformational phase is associated to the folds with NE–SW plunging axes; stereogram G – structural data from Umango River section (Tambillo Unit).

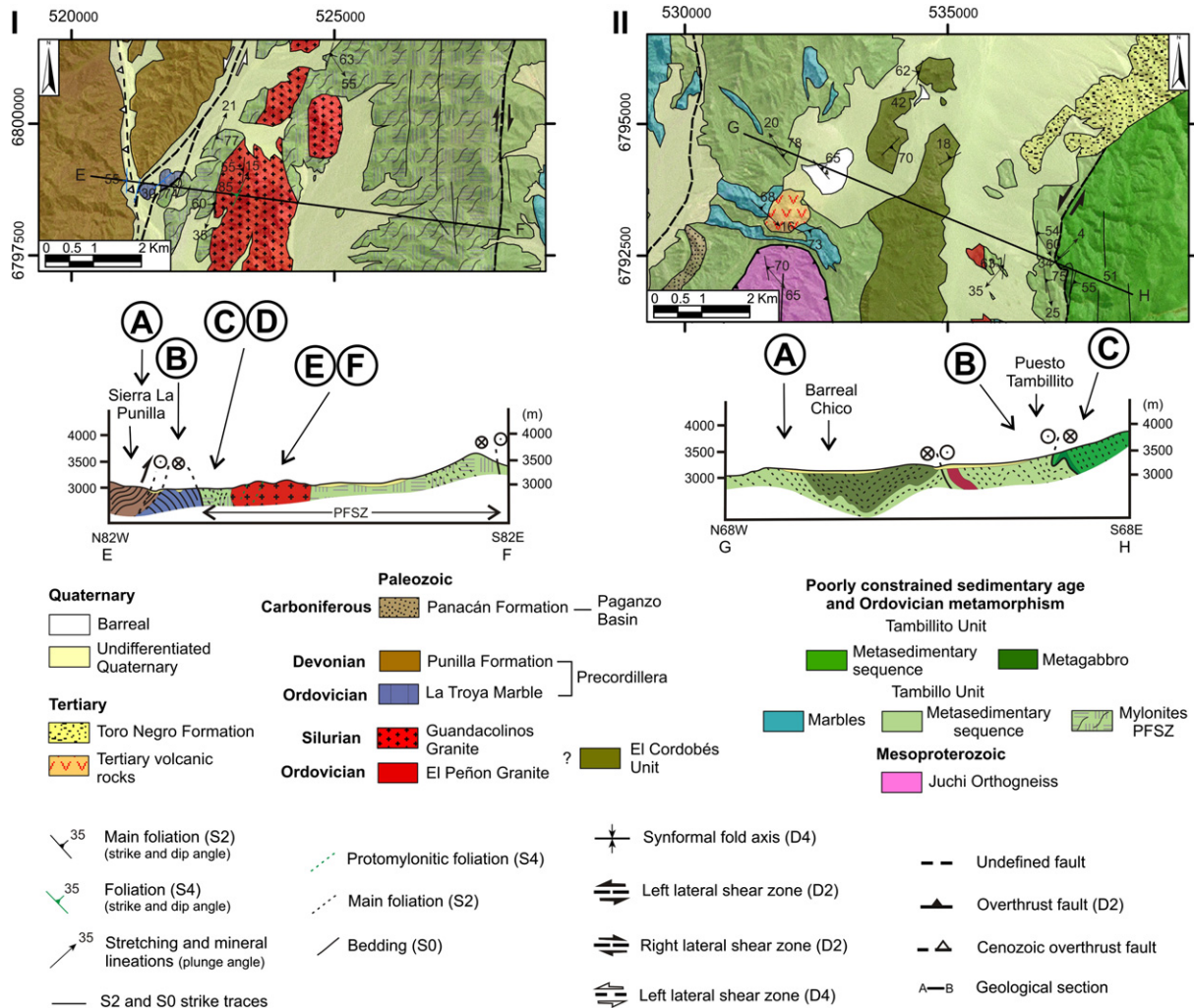


Fig. 6. Detailed geological sections. For geographical locations, see Fig. 3. (I) Los Guandacolinos section: this section includes the tectonic contacts from the Punilla Formation, the La Troya Marble and the PFSZ. Note also that the S4 protomylonitic foliation affects the Guandacolinos Granite; (II) Barreal Chico-Puesto Tambillito section: D4 open upright fold can be observed in the synformal fold of the El Cordobés unit and in the folds delineated by the S2 foliation in the Tambillo Unit. A color version of this figure is available in the online edition.

structural data and the geological interpretation based on satellite images suggest that the Tambillito Unit lies structurally over the Tambillo Unit in an upright-to-E-vergent synformal fold (interpreted as D4 fold, on basis of its geometry and orientation). Based on a limited number of kinematic indicators, the western boundary represents a sinistral shear zone folded in an overturned limb of a synformal fold with a half-wavelength of approximately 5 km. An interpreted normal sense direction at the hinge (southern limit) suggests movement of this metasedimentary unit in the E to NNE direction.

The main schistosity is interpreted as an S2 surface, defined mostly by mica-rich bands and biotite and sillimanite-rich bands interlayered within lenticular quartz-rich bands. In mafic rocks, S2 is characterised by alternating mafic and felsic bands formed by hornblende/epidote group minerals and quartz/plagioclase.

The metapelitic rocks record medium-grade metamorphism (intermediate pressure/amphibolite facies), varying from the staurolite zone in Puesto Tambillito to the sillimanite zone (sillimanite first isograd) in the eastern Umango River section. Mafic rocks show a mineral assemblage, composed of hornblende and epidote minerals indicative of medium to lower amphibolite facies. These estimated metamorphic conditions suggest a lower

metamorphic grade than those found in the underlying Tambillo Unit (Meira, 2010).

TIMS U/Pb zircon dating from an amphibolite of the Tambillito Unit yielded an upper intercept of 1108 ± 4 Ma and a lower intercept of 428 ± 12 Ma (Varela et al., 2008, 2011). The authors interpret the Mesoproterozoic age as representing the crystallisation timing of the mafic igneous protolith (as dykes or sills), while the Silurian age could correspond to a later thermal event associated with the Famatinian collisional event. Varela et al. (2008) did not discard the possibility of the dated zircon grains are xenocrysts collected from the host rocks.

3.4. El Cordobés Unit

The predominance of metabasic rocks in the Cerro El Cordobés was first documented by Hausen (1921). This unit corresponds to an N–S and NNE–SSW trending belt (Fig. 3) composed mostly of coarse-grained hornblende-bearing metagabbros, amphibolites and (garnet)–(biotite)–epidote–hornblende gneisses.

Near Barreal Grande and the surroundings of Barreal Chico (Fig. 3), coarse-grained hornblende-bearing metagabbros, minor amphibolite and mica–quartz schist are exposed. At La Champa Creek occurs

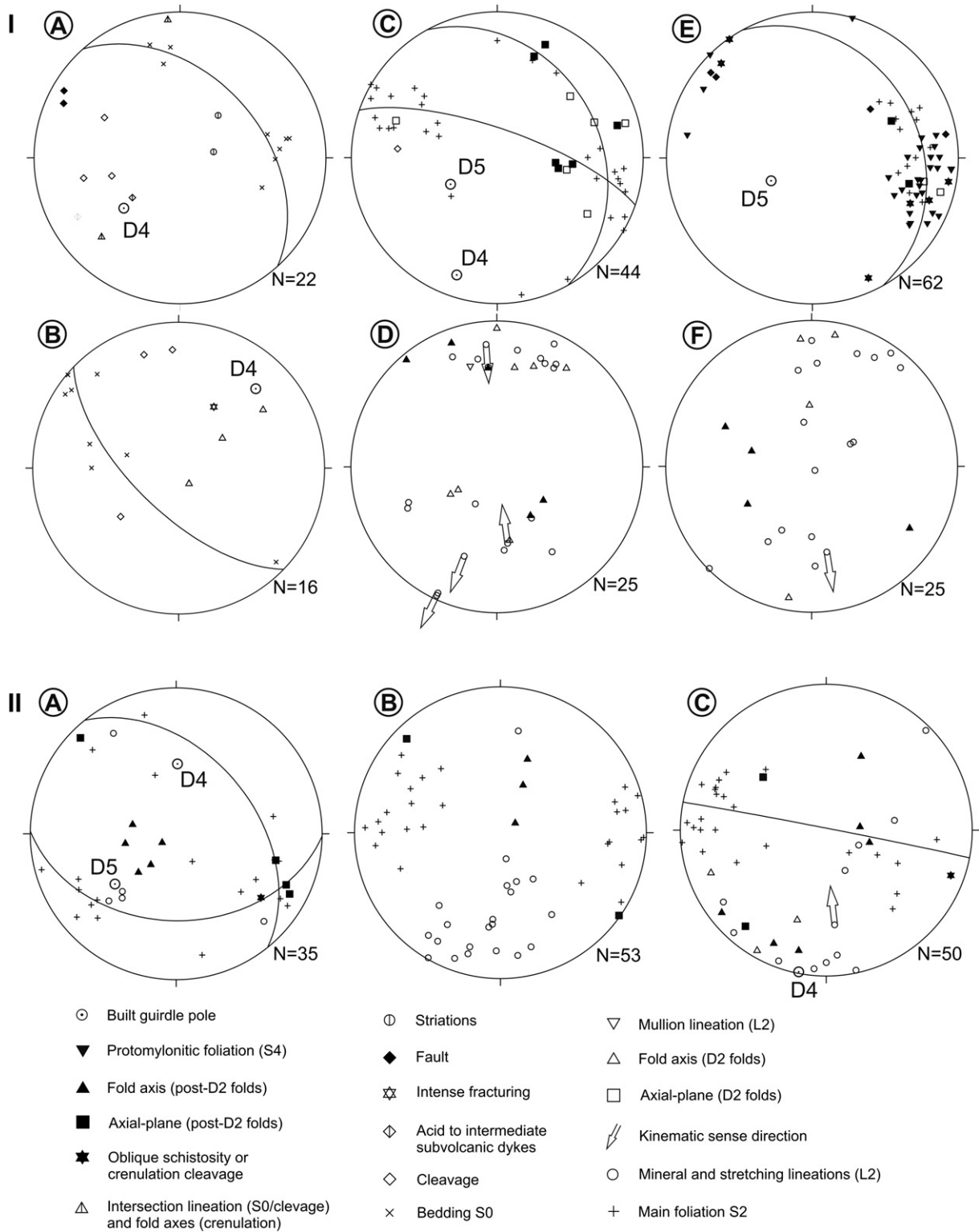


Fig. 7. Lower hemisphere equal area stereographic projections of fabric elements. (I) Los Guandacolinos section: stereogram A – structural data from Punilla Formation; stereogram B – structural data from La Troya Marble. The ~E–W dispersal pattern of the bedding in both A and B stereograms is well observed, associated to the D4 folding; stereograms C and D – planar and linear structural data, respectively, from PFSZ (west of Guandacolinos Granite). Note both ~E–W and ~N–S dispersal patterns of the S2 foliation poles and the top-to-the S/SW sense of movement associated to L2; stereograms E and F – planar and linear structural data, respectively, from Guandacolinos Granite. The main fabric elements in these stereograms are the S4 protomylonitic foliation with an average NE–SW-striking and dipping steeply toward NW. The ~N–S dispersal pattern of the S4 pole is also notable in the stereogram E. (II) Barreal Chico-Puesto Tambillito section: stereogram A – structural data from Barreal Chico surroundings. This stereogram shows both ~E–W and ~N–S dispersal pattern of the S2 foliation poles, associated to D4 and D5 folding, respectively; stereogram B – structural data from Tambillito Unit (Puesto Tambillito); stereogram C – structural data from Tambillito Unit (Puesto Tambillito). The main geological data from the Tambillito Unit was collected in this area. Note the ~E–W dispersal pattern of the S2 foliation poles and the top-to-the N sense of movement associated to L2.

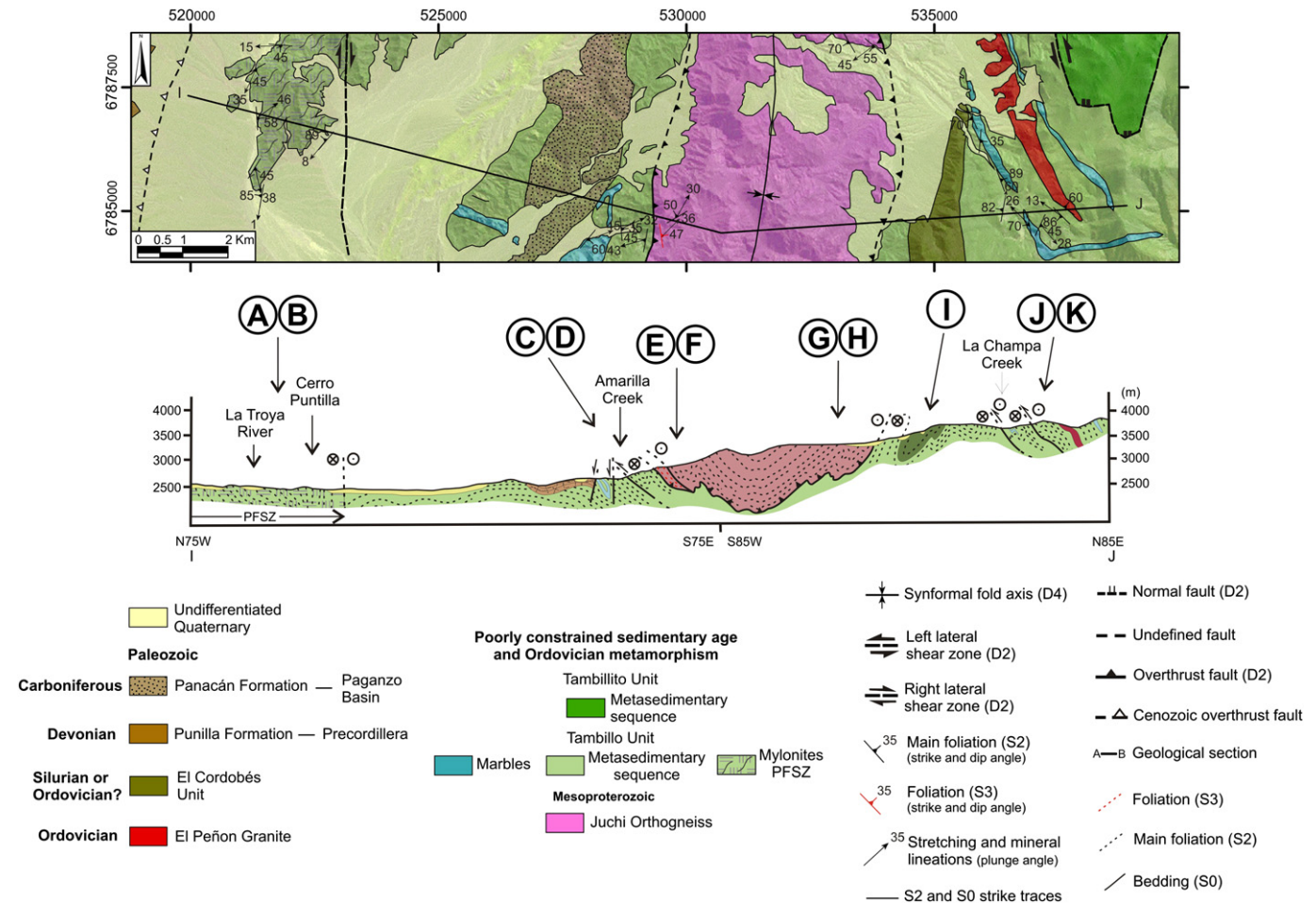


Fig. 8. Detailed geological section. For geographical locations, see Fig. 3. Puntilla-La Champa Creek section: a section cross-cutting the southern Sierra de Umango, highlighting the D4 synformal fold of the Juchi Klippe, W- to SW-vergent D3 folds and associated thrust to oblique faults. A color version of this figure is available in the online edition.

a sequence of mafic hornblende-bearing gneisses. The main foliation is concordant with the S2 foliation of the country rocks.

Structurally, the El Cordobés Unit lies above the Tambillo Unit in an interpreted, but not well defined, synformal structure.

A characteristic feature of the coarse-grained hornblende-bearing metagabbro is the presence of plagioclase-corona around opaque minerals that commonly define a stretching lineation.

Varela et al. (2008, 2011) presented a TIMS U/Pb zircon age from a metagabbro of 446 ± 3 Ma and interpreted this data as the magmatic crystallisation age of the El Cordobés Unit. Alternatively, this data could represent a metamorphic overprint age of an older (Mesoproterozoic?) mafic magmatism (Varela et al., 2011).

3.5. El Peñon Granite

A tabular, lens-shaped body of mylonitic granitoids is exposed in the southeastern area of the Sierra de Umango (Fig. 3). This body of granitoids corresponds to an NNW–SSE trending structure, 8.5 km long and 400 m wide, interlayered tectonically with the rocks of the Tambillo Unit and near the contact zone with Tambillito Unit (Figs. 3, 6 and 8). In this area, there are predominantly reddish mylonitic biotite granites, intensively foliated and lineated, intercalated with greyish mylonitic hornblende–biotite-bearing granodiorites, usually porphyroclastic and lineated. Deformed veins frequently occur in the Tambillo Unit, mainly in its eastern portion. Pegmatitic dykes occur discordantly and concordantly to the main foliation and are more abundant along the Umango River section. At the margin of the

Umango River, a small body of equigranular leucocratic coarse-grained biotite granite is exposed, with an exposure area with a diameter of approximately ten metres. These intrusive rocks are thought to correlate with the El Peñon Granite.

This rock has been interpreted as a syn-orogenic granite (TIMS U/Pb zircon ages of 487 ± 1 Ma – Varela et al., 2011) associated with the Ordovician collisional event (Varela et al., 2000, 2008, 2011).

3.6. Guandacolinós and Cerro Veladero Granites

Two granitic stocks were differentiated in the Sierra de Umango: Guandacolinós Granite (Varela et al., 1996) and Cerro Veladero Granite (Cingolani et al., 1993). In this study, the Guandacolinós Granite was studied in the field, and the lithological contacts of both stocks were interpreted based on satellite images (Fig. 3).

The Guandacolinós Granite is predominantly composed of porphyritic and hypidiomorphic pinkish to greyish medium- to coarse-grained biotite syenogranite, exposed along the western PFSZ (Fig. 6). This granite varies from hololeucocratic to leucocratic rocks, and local sub-parallel alignment of euhedral elongate feldspar crystals occurs, which suggests magmatic or submagmatic flow structures (according to Paterson et al., 1989). Mafic microgranular enclaves and xenoliths from country rocks are common. Discrete bands with protomylonitic foliations are well developed in some localities, indicating that a post-magmatic solid-state deformation affected these granitic rocks (following the assumptions of Paterson et al., 1989).

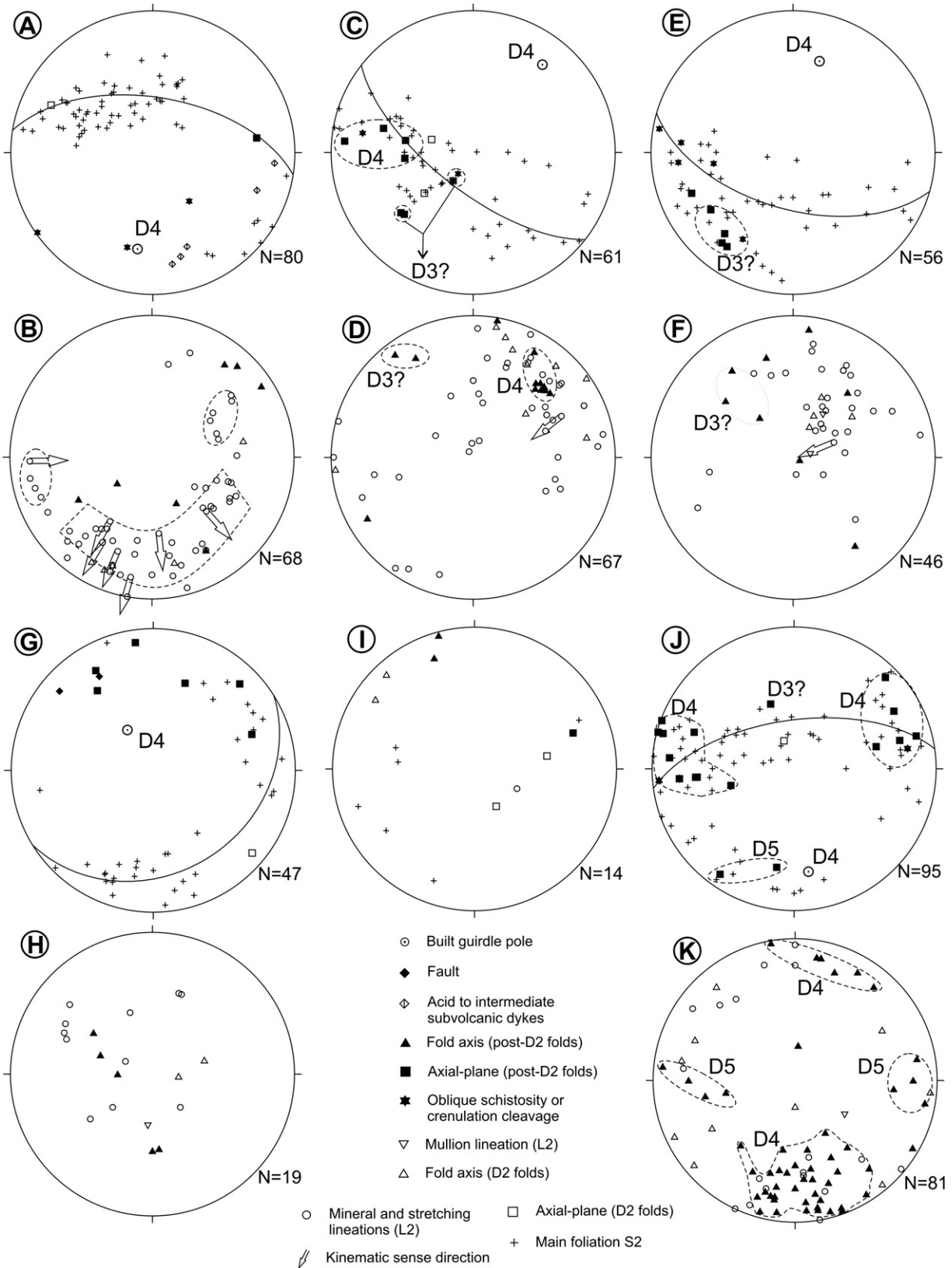


Fig. 9. Lower hemisphere equal area stereographic projections of fabric elements. Puntilla-La Champa Creek section: stereograms A and B – planar and linear structural data, respectively, from PFSZ (Cerro Puntilla). These stereograms show the ~E–W dispersal pattern of the S2 foliation poles, associated to the D4 folding and the major top-to-the S sense of movement associated to the L2. A group of NE–SW plunging L2 lineation shows top-to-the E sense of movement and could be associated to synchronously detachment shear zones; stereograms C and D – planar and linear structural data, respectively, from Tambillo Unit (Amarilla Creek). The D4 folding phase is shown in these stereograms with built girdle pole concordant with the NE plunging fold axes. The D3 folds are tentatively correlated to the NW plunging fold axes; stereograms E and F – planar and linear structural data, respectively, from Juchi Orthogneiss (Amarilla Creek). The ~E–W dispersal pattern of the S2 foliation poles is the major element in these stereograms. The D3 folding phase is associated to NW plunging fold axes and gently dipping axial planes toward NE; stereograms G and H – planar and linear structural data, respectively, from Juchi Orthogneiss (La Champa Creek). The D4 folding dispersal pattern is also notable in these stereograms; stereogram I – structural data from El Cordobés Unit (La Champa Creek); stereograms J and K – planar and linear structural data, respectively, from Tambillo Unit (La Champa Creek). These stereograms highlight both D4 and D5 folding, featuring mainly the D4 dispersal pattern.

Table 1
Sequence of tectonic events, deformational phases, structures, metamorphism and magmatism of the Sierra de Umango.

Tectonic event		Deformational phase	Structures	Metamorphism	Magmatism	Age
Famatinian Orogeny	Main orogenic Phase	D1	Relics of S1 folded by D2 folds and internal foliation within interkinematics porphyroblasts of staurolite and garnet	Prograde metamorphism from greenschist to amphibolite facies		
		D2	The main metamorphic structure defined by transposition or mylonitic S2 foliation. D2 intrafolial isoclinal tight folds, sheath folds and fishhook rootless folds	Peak P–T conditions from lower amphibolite-to-granulite facies	El Peñon Granite	Ordovician (480–450 Ma)
		D3	Close-to-tight asymmetric, inclined-to-recumbent folds. D3 folding is usually associated to disrupted limbs in thrust faults and axial plane schistosity or oblique schistosity (S3)	Retrograde metamorphism from lower amphibolite-to-greenschist facies	El Cordobés Unit (?)	
	Late- to Post-orogenic Phase - Chanica Tectonics	D4	Open-to-close, upright-to-east-vergent, N–S to NE–SW trending D4 folds. Discrete shear zones and S4 protomylonitic foliation	Greenschist facies	Guandacolinos Granite	Silurian (?) Devonian-Early Carboniferous (~375–345 Ma)
Gondwanic Orogeny					Cerro Veladero Granite	Late Carboniferous
Andean Orogeny		D5	Cuspate-lobate open D5 folds with E–W high-angle axis plunge			Late Tertiary

Dykes of metasedimentary xenolith-rich leucocratic granites and protomylonitic granite were described in the northwestern area of the Sierra de Umango. These rocks define thin lens-shaped granite within the PFSZ (Figs. 3 and 4) and could represent the deformed equivalent of the Guandacolinos Granite.

The Cerro Veladero Granite outcrops in the south of Juchi Klippe (Fig. 3) and is dominated by subhypidiomorphic equigranular medium-grained pinkish amphibole monzogranite that is rich in xenoliths and roof pendants of contact-metamorphosed sedimentary rocks.

3.7. La Troya Marble

This low-grade metasedimentary unit is tectonically juxtaposed between the PFSZ in the east and the Punilla Formation in the west (Figs. 3 and 6). The sequence corresponds to a tectonic slice composed of alternating light-brownish silicified meta-calcareous, slates and greyish to silvery phyllites. On the phyllitic planes, fan-shaped minerals can be observed, and most of these minerals are weathered to fine-grained white mica. Minor feldspathic meta-sandstones and meta-conglomerates also occur.

Varela et al. (2011) compared these rocks with the Early Paleozoic marbles and para-amphibolites of Las Damas Marble in the northwestern parts of Jague (Martina and Astini, 2009). Lithologically, this unit is comparable either to the Ordovician strata (San Juan Formation or Trapiche Group) or the Cambrian strata (Cerro Totorá Formation) of the Precordillera (Thomas and Astini, 2003) or to the Late Ediacaran to Cambrian rocks of Caucete Group in Sierra de Pie de Palo (Naipauer et al., 2010).

3.8. Precordillera sedimentary rocks

At the western limit of the Sierra de Umango units, a sedimentary sequence of the Western Precordillera, called the Punilla Formation, occurs (Fig. 3).

The Punilla Formation consists of continental and marine deposits from the Late Devonian to Early Carboniferous periods (Fauqué et al., 2004). This unit is folded on map-scale with a wavelength of synformal and antiformal folding of approximately 5 km. A Cenozoic thrust fault and a left-lateral shear zone delimit its contact with La Troya Marble and the basement rocks of the Sierra de Umango.

3.9. Sedimentary cover

The sedimentary cover of the Sierra de Umango is composed of Late Paleozoic to Mesozoic rift-related sedimentary sequences and Cenozoic syn-orogenic deposits (Fig. 3).

Carboniferous to Permian sedimentary rocks of the Paganzo Basin rest unconformably over the Late Devonian folded siliciclastic deposits in the northwestern-most Sierra de Las Minutas and the basement rocks of the Sierra de Umango (Tambillo Unit at La Perea Creek and southern limit of Juchi Orthogneiss). These sequences are represented by the Rio del Peñón and Panacán formations, respectively. The Panacán Formation at southern Juchi Creek consists of reddish to light feldspathic sandstones and dark conglomeratic sandstone. A reverse fault was observed deforming these psammite rocks.

Cretaceous rocks of the Ciénaga del Rio Huaco Formation are mostly composed of sandstones, conglomerates, pelites and evaporites and rest unconformably over the Panacán Formation (Fauqué et al., 2004).

A syn-orogenic Cenozoic sedimentary sequence separates the rocks of the Sierra de Umango from the basement rocks of the Sierra del Espinal and Sierra de Maz.

4. Structures of the Sierra de Umango

The polyphase structural evolution of the Sierra de Umango involved five deformational phases related to three diachronous

tectonic events (Table 1). These deformational phases were determined by fieldwork observations of the folds' characteristics and their interference patterns (Fig. 10 and descriptions below) and also by the interpretation of the stereograms (Figs. 5, 7 and 9).

The first three deformational phases (D1, D2 and D3) are interpreted to correspond to the main phase of the Famatinian Orogeny on basis of geochronological data reviewed by Varela et al. (2011) and are correlated with the development of a *Nappe System* associated with an oblique collisional event. The *Nappe System* concept in the Sierra de Umango follows the discussion published in McClay and Price (1981), which defined “a fold *nappe*” as “an allochthonous tectonic unit which exhibits large-scale stratigraphic inversion and may have initiated from large recumbent folds. The underlying limbs of these folds may be sheared out into thrust faults” and form *klippe* where these become isolated. The *klippen* of the Juchi Orthogneiss basement unit represent the large-scale stratigraphic inversion and its limit with the underlying Tambillo unit is characterized by a ductile thrust fault (Fig. 11a and b).

Two subsequent deformational events affected the Famatinian structures. The D4 deformational phase is correlated with the late-to post-orogenic phase of the Famatinian Orogeny (Chanica Phase) and was characterised by ~N–S open and closed upright folds and discrete sinistral protomylonitic shear zones (Fig. 11d). The D5 deformational phase was marked by E–W open, steeply plunging folds possibly associated with the Andean Orogeny (Fig. 11e).

In the following subsections, the structures that resulted from various events in the Sierra de Umango, from the Ordovician period to the Cenozoic era, are described in detail.

4.1. Ordovician structures

The main metamorphic structure of the Sierra de Umango basement rocks is defined by a transposition or mylonitic foliation, S2. This structure was formed in a collisional event that developed a *Nappe System* and an important shear zone (PFSZ) and it was dated in a range from 452 ± 11 to 474 ± 12 Ma (Varela et al., 2011). A continuous sequence of deformational phases (D1, D2 and D3) and accompanying metamorphism define this collisional event (Porcher et al., 2004; Meira, 2010; Varela et al., 2011). D1 likely corresponds to the prograde metamorphic stage; D2 exhibits P–T conditions close to the metamorphic peak; and D3 likely includes the retrograde metamorphic stage with growing of fine-grained muscovite and biotite in the S3. The metamorphism related to these deformations resulted in up to medium- to high-pressure granulite to upper amphibolite facies conditions, characterized by the paragenesis Ky/Sil–Grt–Kfs–Rt–Qtz in metapelites (Meira, 2010) and Grt–Di–Amp–Pl(oligoclase to andesine)–Ilm–Rt in metabasic rocks (González et al., 2005).

Previous studies (Fernandes et al., 2001, 2002; Porcher et al., 2004) have described four folding phases (F1, F2, F3 and F4) that

affected the rocks in the Maz, Espinal, Las Ramaditas and Umango ranges. The F1, F2 (isoclinal to tight folds) and composite banding were associated with the main event recorded in these rocks. These structures are correlated with D2 folds and S2 foliation of this work. The F3 and F4 phases likely represent younger deformations and will be discussed in the next sections.

The relic foliation, S1, is recognised mainly in the hinge zones of intrafolial and isoclinal D2 folds and is highlighted by intercalations of amphibolites and marbles (Fig. 12a and b). Asymmetric intrafolial folds delineated by quartz veinlets and, occasionally, by composite banding, also define the S1 foliation. The scarcity of these structures prevents spatial and geometric analyses. In thin sections, S1 appears as internal foliation within staurolite interkinematic porphyroblasts (Fig. 12c), suggesting continuous deformational and metamorphic patterns between S1 and S2.

The main foliation, S2, is associated with an originally flat-lying fabric, mostly defined by the orientation of micaceous minerals and amphibole, which are usually parallel to the composite banding and related to the axial planes of intrafolial folds (Fig. 12b and d). The isoclinal intrafolial folds (D2) can be observed in mesoscopic (outcrops) and macroscopic (satellite images – see Fig. 3) scales. Sheath folds (Fig. 13), boudins and pinch-and-swell structures are also linked to the D2 fabric. In the PFSZ, the main foliation corresponds to a mylonitic to protomylonitic foliation, mainly delineated by biotite-rich bands and quartz ribbons, which commonly contain pre- to syn-kinematic garnet porphyroblasts and porphyroclasts (Fig. 14a), as well as feldspar porphyroclasts (Fig. 14b). This structure is correlated with the D2 deformation. Stretching and mineral lineations lying in S2 predominantly have a trend between N–S or NW–SE and NE–SW. The L2 mullions and D2 axes are generally sub-parallel to the stretching lineations. The kinematic indicators include mesoscopic and microscopic porphyroclasts and suggest major movement with top-to-the S/SW, with minor top-to-the SE sense direction, parallel to the approximately N–S trending lineations (Fig. 14c and d).

At least three folding phases deformed the D2 structures and produced different interference and dispersal patterns. Two major pole dispersal patterns were recognised: an E–W pattern, associated with D4 folding, and an N–S pattern, related to D5 folding (Figs. 5, 7 and 9). These dispersal patterns are detailed in the next sections.

Close-to-tight asymmetric and inclined-to-recumbent folds were detected deforming the S2 foliation (Figs. 10 and 14e and f) and were associated to the D3 folds. These folds are generally associated with axial plane schistosity (S3) marked by aligned fine-grained mica (Fig. 14f) and thrust faults along the overturned limbs (Fig. 15a). The spatial control of D3 folds is poorly understood, but the available data suggest an axial plane trending in the NW–SE direction and dipping gently to steeply in the NE direction (Fig. 9C–F).

In general, the structure of the collisional event comprises the Juchi Orthogneiss *klippen*, which were overthrust onto the Tambillo Unit to the S–SW. In the west, the structure related to the collisional event is bounded by a right lateral shear zone (PFSZ) that acted as a lateral ramp. This collisional event was related to the accretion of the Cuyania Terrane to the proto-Andean margin of Gondwana during the Ordovician period. The available geochronological data (Varela et al., 2003a,b, 2008, 2011) indicate a range from 452 ± 11 to 487 ± 1 Ma for the collisional event (ages constrained by U/Pb in monazite from paragneisses in the PFSZ and TIMS U/Pb in zircon from biotite orthogneisses of the El Peñon Granite, respectively), in accordance with the data of Voldman et al. (2008), which provided evidences for metamorphism during the Early to Middle Ordovician in the Precordillera.

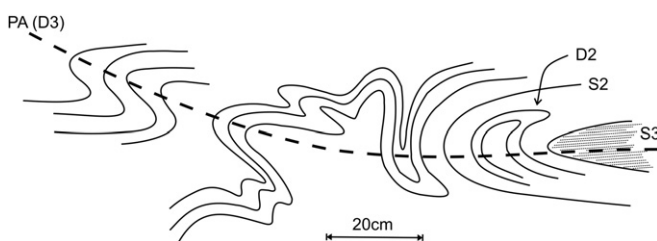


Fig. 10. Folding interference pattern observed on calcisilicate rocks from the Tambillo Unit. Note that the D2 folds are deformed by D3 recumbent to inclined asymmetric folds. The D3 axial plane is also deformed by a later open upright folding (D4 folds).

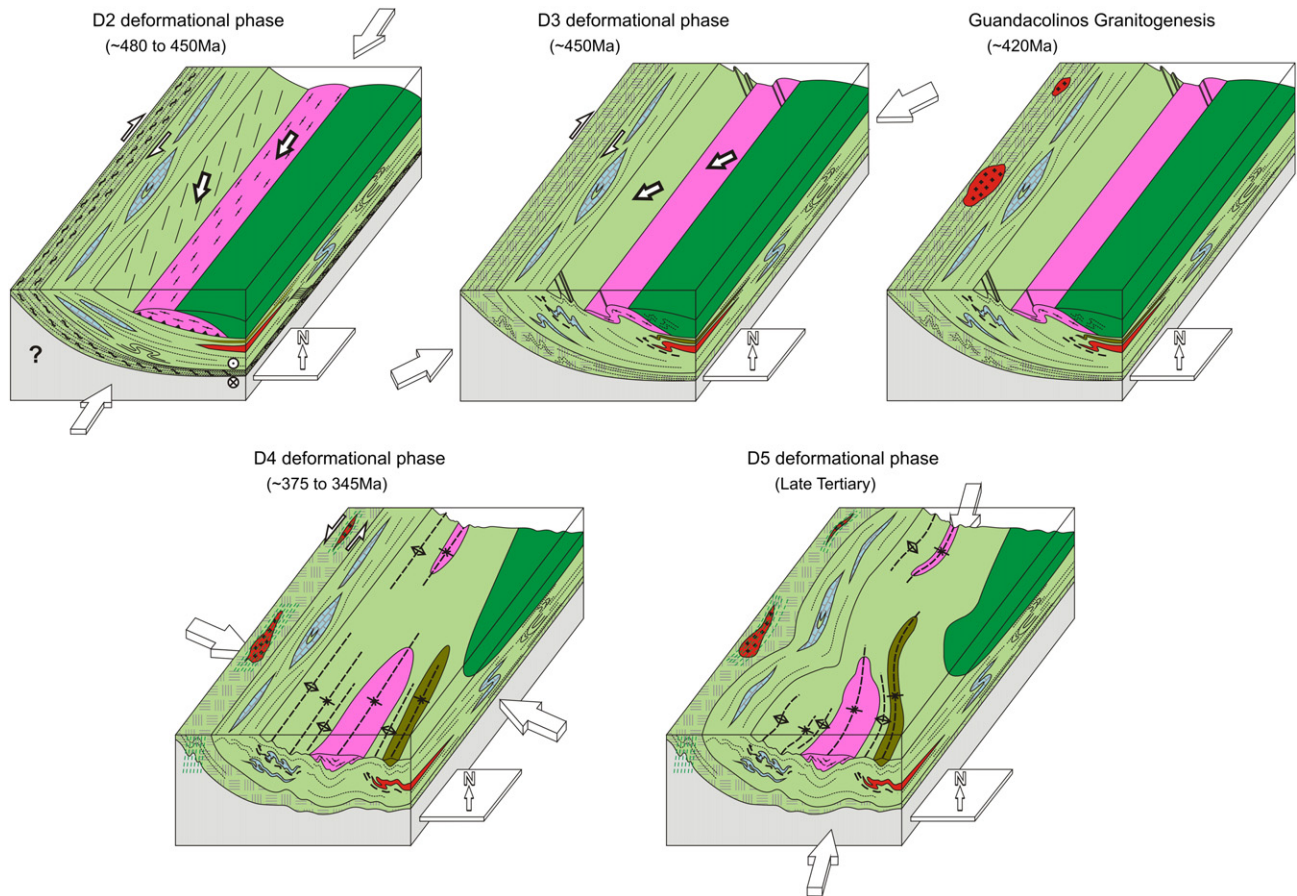


Fig. 11. Deformational evolution of the Sierra de Umango rocks. (a) Ordovician deformational phase associated to the development of *nappes* and the main foliation (S2), with top-to-the S/SW sense of movement; (b) The final stage associated to the main Ordovician metamorphic event, characterized by tight to close W- to SW-vergent folding; (c) Tectonic quiescence and the intrusion of the Guandacolinos Granite; (d) Tectonic reactivation during the Devonian–Carboniferous transition with ~E–W compression, associated to the Chilenia docking against the proto-Andean margin. Note the development of discrete shear zones and S4 protomylonitic foliation in the Guandacolinos Granite with sinistral shear sense; (e) Late tectonic reactivation with ~N–S compression associated to the Andean orogeny. For legends, see Fig. 3. A color version of this figure is available in the online edition.

4.2. Devonian structures

A subsequent deformation phase (D4) affected the Sierra de Umango basement rocks, the Guandacolinos Granite and the Punilla Formation. This deformation is attributed to the open-to-closed, upright-to-E-vergent folds (D4 folds) oriented in the N–S to NE–SW directions (Fig. 15b–d). This phase could be correlated with the F3 folds described by Fernandes et al. (2001), (2002) and Porcher et al. (2004). These folds are responsible for the E–W pole dispersal pattern of the main metamorphic foliation (S2) that controls the main orientation of the S2 surface in the Sierra de Umango. This dispersal pattern (Fig. 5-II A, B and E–G; Fig. 7-I A–C; Fig. 7-II A–C; Fig. 9A–K) indicates a nearly cylindrical geometry for the D4 folds and assumes that the S2 foliation was originally a shallowly-dipping surface. The D4 folding corresponds to a flexural fold with concentration of the deformation in the limbs, a wavelength varying from 5 to 10 km and an amplitude of approximately 1 km (Fig. 8). The map-scale folding defined by the outcrop pattern of the La Punilla Formation (Fig. 3 – Sierra de La Punilla and Sierra de Las Minitas) is thought to be related to these structures. Discrete shear zones, marked by protomylonitic foliation within the Guandacolinos Granite, trend sub-parallel to the axial plane of the D4 folds (Figs. 6-I and 7-I C–F) and were correlated with this deformational phase. A left-lateral (sinistral)

kinematic, determined at the protomylonitic shear zone, affected the lens-shaped granite in the northwestern region of the Sierra de Umango (Fig. 14e and f).

Two geological features reveal important clues about the timing of this deformation: 1) the discrete shear zones affected the Guandacolinos Granite and did not deform the Cerro Veladero Granite and 2) the deformation occurred after the deposition of the La Punilla Formation in Sierra de Las Minitas and before the deposition of the Rio del Peñon Formation in the northwestern-most region of Sierra de Las Minitas.

Distinct ages were obtained for the Guandacolinos Granite in the last fifteen years. The first radiometric data indicate a Late Devonian/Early Carboniferous age (Rb/Sr whole rock isochron – Varela et al., 1996), although newer Rb/Sr whole rock and U/Pb TIMS studies (Varela et al., 2005) pointed to the intrusion of Guandacolinos Granite during the Late Carboniferous period (Rb/Sr whole rock errochron of 324 ± 36 Ma and U/Pb TIMS in zircons of 314 ± 14 Ma). A recent SHRIMP U/Pb zircon aging study (unpublished data) revealed Silurian core ages and Devonian rim ages for zircon from the Guandacolinos Granite (Basei, personal communication). Cingolani et al. (1993) dated the Cerro Veladero Granite and determined an age of 311 ± 14 Ma for its crystallisation.

Based on palaeoflora, the depositional age of Punilla Formation is considered to be from the Late Devonian to Early Carboniferous

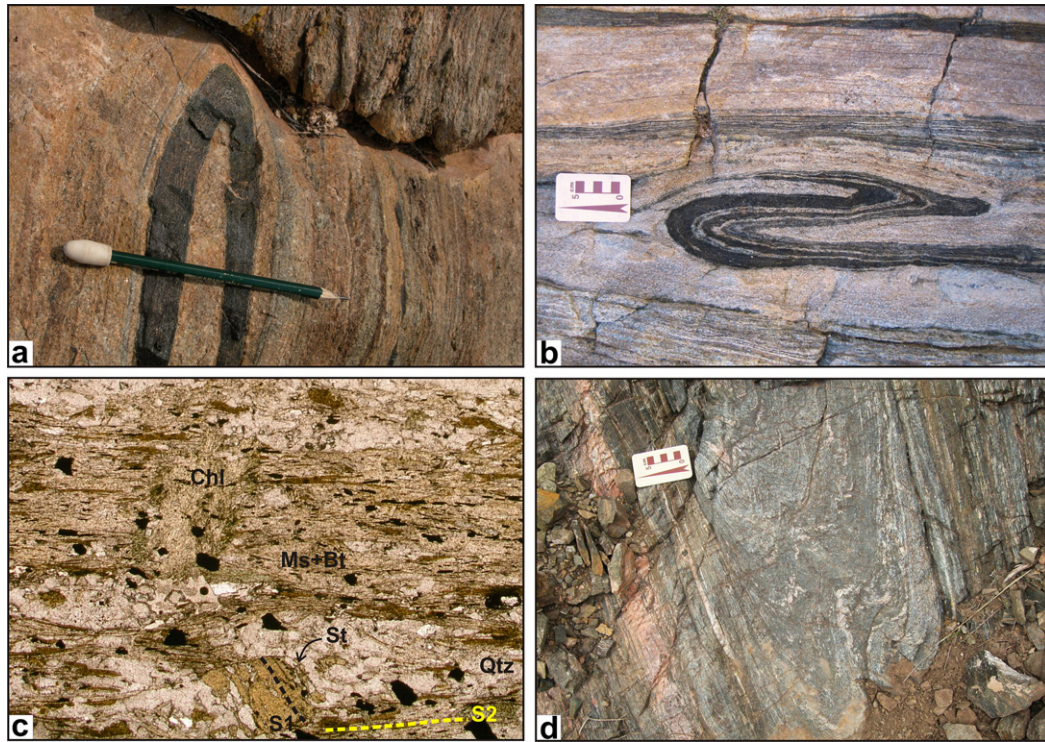


Fig. 12. Photographs of the S1 relics and the D2 isoclinal folds. (a) Intrafolial and isoclinal fold (D2), delineated by a 2 cm-thick amphibolite layer (Tambillo Unit – Barreal Grande area). Note that the internal foliation S1 is folded and transposed by the D2 fold and S2 foliation; (b) Rootless intrafolial and isoclinal fold (D2) defined by relics of S1 foliation within thin amphibolite and marble intercalations (Tambillo Unit – Umango River); (c) Photomicrography of biotite–opaque–muscovite schist with chlorite and staurolite porphyroblasts (Tambillito Unit). The staurolite porphyroblast attests the presence of an internal foliation (S1), suggesting an interkinematic growth (the long edge of the image is approximately 5 mm); (d) Intrafolial and isoclinal fold (D2) in banded biotite gneiss (Juchi Orthogneiss – La Falda *Klippe*).

periods (Caminos and Fauqué, 1999; Azcuy et al., 1999 and references therein). The Rio del Peñon Formation was deposited in the Late Carboniferous period (Caminos and Fauqué, 1999; Azcuy et al., 1999 and references therein) and overlain discordantly above

a Devonian sequence of folded sedimentary rocks (Carrizo, 1998; Carrizo and Azcuy, 1995, 1997). According to these data, the deformational phase (D4) occurred between the Devonian and Late Carboniferous periods.

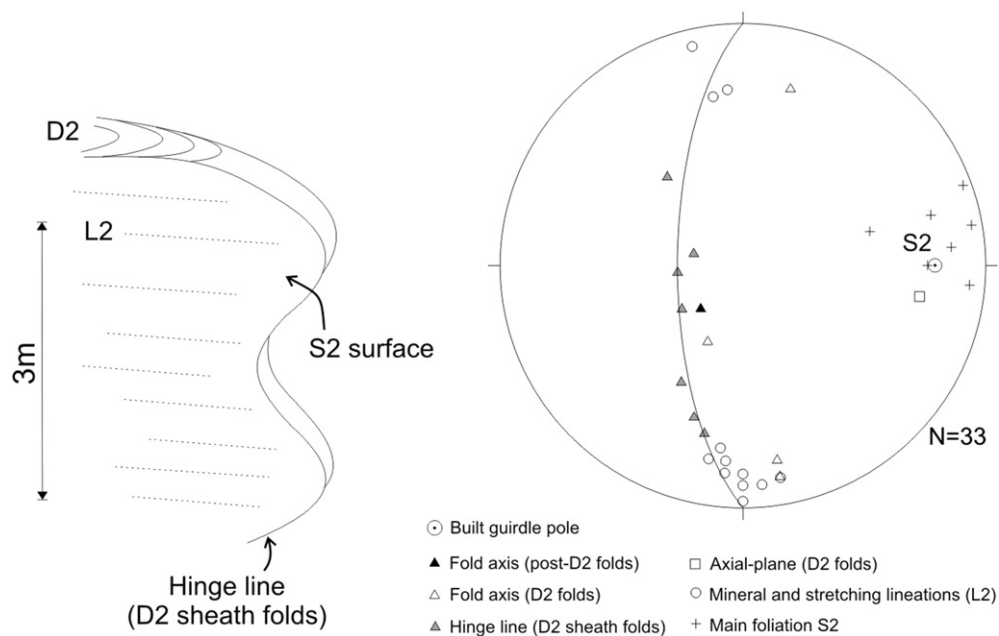


Fig. 13. Sketch of the sheath folds observed on metasedimentary rocks from the Tambillo Unit and the stereograms with the structural data collected in this outcrop. Note that the built girdle pole is coincident with the S2 foliation pole.

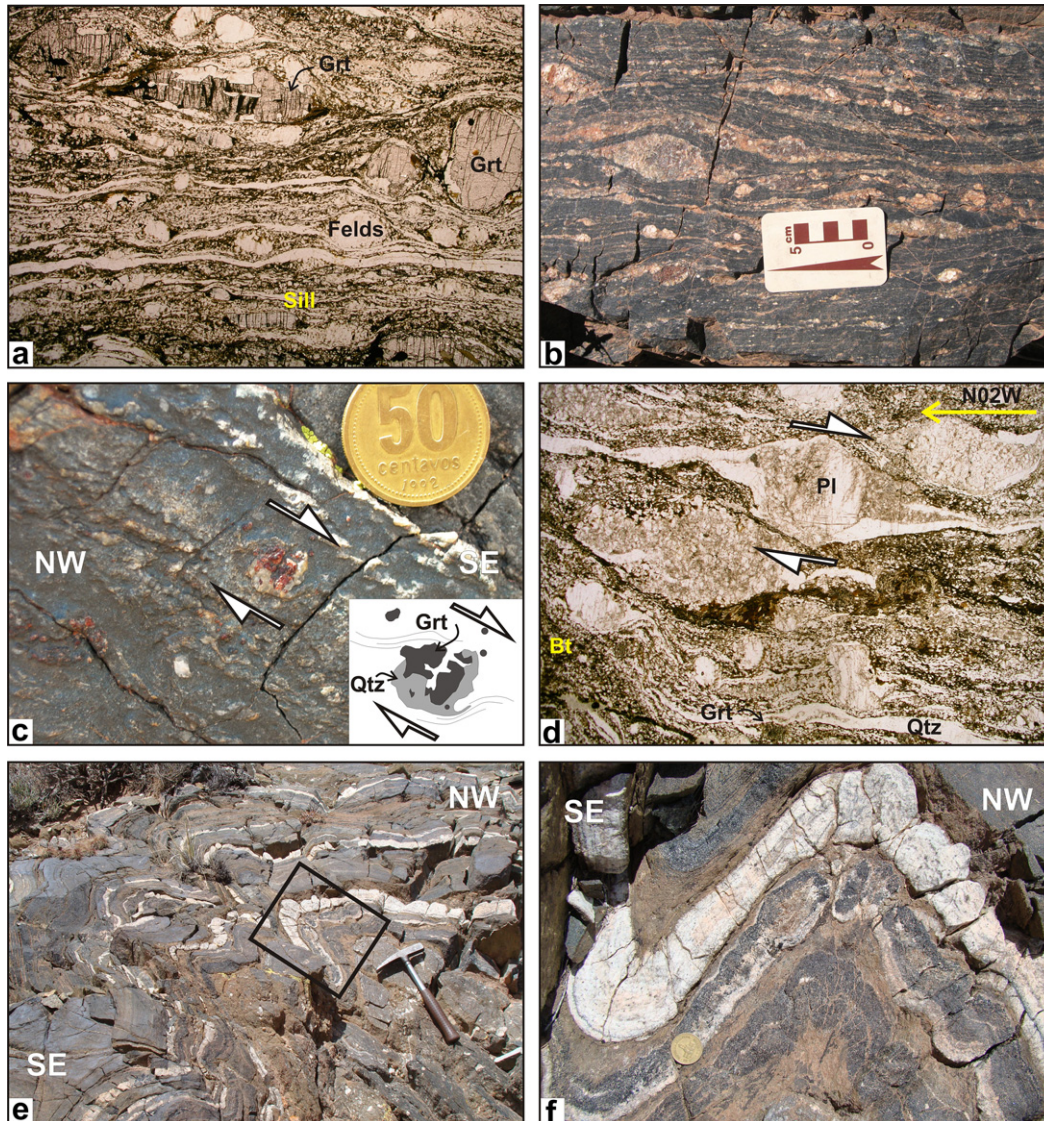


Fig. 14. Photographs of the S2 mylonitic foliation, porphyroclast kinematic indicators, D3 folds and S3 foliation in the metasedimentary protomylonites from the PFSZ (Cerro Puntilla): (a) Photomicrography (parallel nicols) of the general features of the mylonitic foliation (S2). Note that the garnet porphyroclasts are stretched parallel to the foliation, suggesting pre-kinematic growth and some garnet grains are rounded (right side of the photo), indicating pre- to syn-kinematic growth. The stretched garnet grains and the sillimanite porphyroblasts are strongly fractured orthogonally to the S2 foliation (the long edge of the image is approximately 10.2 mm); (b) general aspects of the mylonitic to protomylonitic foliation (S2); (c) δ -type kinematic indicator (garnet porphyroclast), suggesting top-to-the SE sense direction of movement; (d) Photomicrography (parallel nicols) of a δ -type kinematic indicator (plagioclase porphyroclast), suggesting top-to-the S sense direction of movement (the long edge of the image is approximately 10.2 mm); (e) D3 asymmetric folds deforming the S2 foliation; and (f) Detail from the later picture. The D3 folding deformed the boudinaged layers in the S2 mylonitic foliation and the S3 foliation can be observed in the metapelitic layers.

4.3. Late Tertiary structures

The last recognised deformational phase (D5) in the study area is related to cusped-lobate shaped open plunging folds with E–W high-angle axes (Fig. 15g). The sigmoidal contours of the mapped units, as shown in the PFSZ outline, seem to be associated with this folding phase. The stereograms and the N–S dispersal pattern of L2 lineation and S2 foliation poles (Figs. 5-I B, II C and D, 7-I C–E and F, II A and 9J and K) suggest the existence of the D5 deformation.

Fold- and thrust-deformed sedimentary rocks of foreland Tertiary basins are shown at the map-scale (Fig. 2). This deformation is attributed to the syn-orogenic deposits of the Andean tectonics during the Late Miocene to Pliocene epochs and was controlled by the uplifting of the Frontal Cordillera and Western Sierras Pampeanas in this region of Andean Cordillera (Ramos,

1999c and references therein). A Type 1 dome and basin interference pattern deformed the tertiary rocks (southwestern Fig. 2). This has been interpreted as two folding phases of Andean Orogeny; the earlier fold belongs to the D5 deformational phase, and the N–S trending folds and thrusts correspond to the later Andean Late Tertiary deformation.

5. Discussion and geotectonic implications

The polyphase structural evolution of the Western Sierras Pampeanas has been mentioned by Hausen (1921), De Alba (1954), Turner (1964), Furqu  (1972), and Kilmurray and Dalla Salda (1971), among others.

In the Western Sierras Pampeanas, the Ordovician deformation and metamorphism are attributed to the accretion of the Cuyania

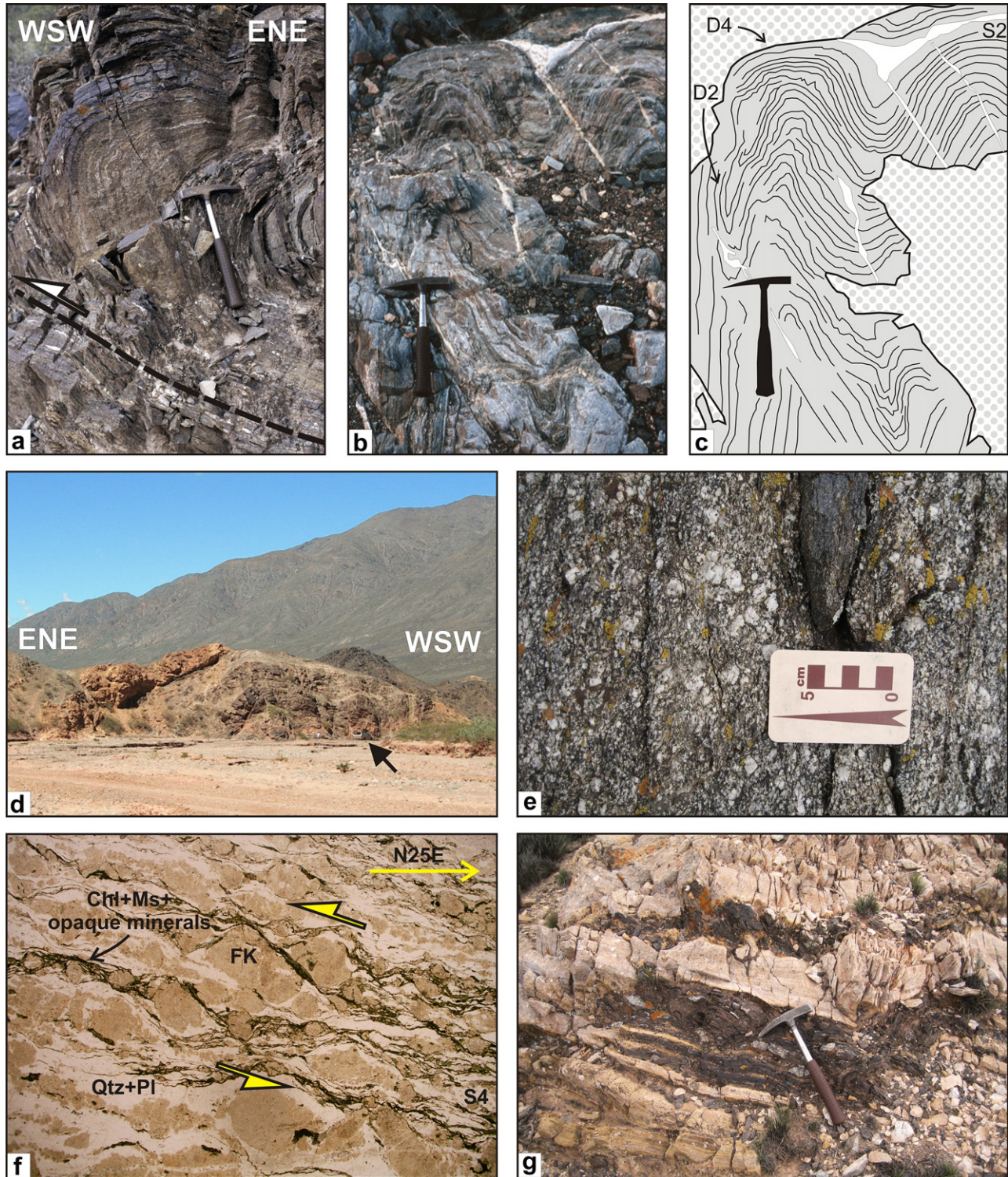


Fig. 15. Photographs of D3 and D4 folds, S4 protomylonitic foliation and D5 folds. (a) D3 recumbent folds with a disrupted limb verging to the W/SW direction and associated with thrust fault in brownish schist intercalated with thin quartz-rich ribbons (Tambillo Unit – Quebrada Amarilla); (b and c) Type 3 divergent-convergent folding interference pattern in greyish metamorphosed rocks intercalated with thin layers of brownish calcic pelitic rocks, showing S2 foliation and D2 tight folds deformed by D4 open upright folds (Tambillo Unit – Quebrada La Champa); (d) D4 open upright folds trending N–S in intercalations of light yellowish breccia marbles and dark pelitic mylonites (PFSZ – Cerro La Puntilla). The arrow indicates a truck as a graphic scale. In the foreground sets the La Troya River and the Sierra de La Punilla stands in the background; (e) Protomylonitic leucocratic coarse-grained granite showing the general character of S4 protomylonitic foliation (Guandacolinos Granite); (f) Photomicrograph (parallel nicols) of muscovite–chlorite protomylonitic granite (oriented thin section from the rock of the last photo), with S4 protomylonitic foliation defined by thin discontinuous lepidoblastic bands of chlorite, muscovite and opaque minerals, and feldspar porphyroclasts. Domino-type and σ -type kinematic indicators suggest left-lateral kinematic movement toward the discrete shear zones (D4 protomylonitic foliation); (g) Cuspate-lobate open D5 folds and sub-vertical spaced cleavage in intercalations of marble and amphibolite layers (Tambillo Unit – Barreal Chico surroundings).

Terrane onto the southwestern part of Gondwana (see synthesis in Ramos et al., 1998). At the Sierra de Umango, the main metamorphic structures are interpreted to belong to this collisional event, which is characterised by three continuous deformational phases (D1, D2 and D3). These deformational phases may record the prograde metamorphism (D1), the P-T conditions close to the metamorphic peak with thickened crust (D2) and the retrograde metamorphism with partial exhumation (D3). This event lasted at least 30 million years, nearly the entire Ordovician period (from ~480 to ~450 Ma – Varela et al., 2003a,b, 2008; Voldman et al., 2008). In the D2 deformational phase, the metamorphic conditions produced medium- to high-P granulite facies (Juchi Orthogneiss and PFSZ) (Porcher et al., 2004; González et al., 2005), medium-P amphibolite facies (Tambillo Unit) and medium-P lower amphibolite and greenschist facies (Tambillito Unit), consistent with collisional settings and continental wedge subduction (Meira, 2010). The extrusion of the subducted continental wedge occurred in a *Nappe* System and was facilitated by Lateral Shear Zones (e.g., PFSZ) until the development of conditions that produced lower amphibolite-to-greenschist facies (D3 phase).

In the Western Sierras Pampeanas, *Nappe* structures were also recognized and described in the Sierra de Pie de Palo by Ramos et al. (1996) and, more recently, by van Staal et al. (2011), Mulcahy et al. (2011) and references therein. These authors cited the Ordovician collisional history to explain the *nappen* structures (van Staal et al., 2011) and the composite middle to lower crustal section (Mulcahy et al., 2011).

Although it was once accepted as a scientific fact, discussions about the character and kinematic nature of this collision are ongoing. The results of this study suggest an oblique collision involving the northeastern subduction of the Cuyania Terrane under the proto-Andean margin of Gondwana. The subduction direction was inferred from the syn-metamorphic extrusion, registered on the *nappen* (top- to-S/SW) and on the PFSZ (right lateral shear zone), even so minor top-to-the N kinematic indicators occur in the surroundings of the Cerro Cacho (Fernandes et al., 2001, 2002; Porcher et al., 2004; Meira, 2010). Conversely, kinematic evidence from Puna, Sierra de Pie de Palo and Eastern Sierras Pampeanas is compatible with an E–W compression (top-to-the W sense) and an orthogonal collision in the Famatinian collisional event (e.g., Le Corre and Rossello, 1994; Martino, 2003; Simpson et al., 2003; van Staal et al., 2011).

Radiometric data from El Peñón Granite, interpreted as a pre- to syn-collisional granite, corroborate to the Early Ordovician magmatism associated to the evolution of the Famatinian Magmatic Arc (e.g., Dahlquist et al., 2007, 2008) and the Early to Middle Ordovician ductile deformation during the collisional event (Varela et al., 2000, 2008; Voldman et al., 2008). However, the crystallisation age of El Cordobés-related basic rocks is still debated. Sm/Nd data (whole rock, plagioclase and amphibole) from amphibolites of the Barreal Grande region reveal Devonian ages (392 ± 50 Ma – Varela et al., 2002), while zircon TIMS U/Pb data from the same area suggest older ages (446 ± 3 Ma – Varela et al., 2008). Varela et al. (2002, 2008) proposed that the El Cordobés Unit, together with the swarm pegmatites (well exposed in the Umango River section), represent the Chanica Tectonics effects at the Sierra de Umango, though Varela et al. (2011) did not discard the possibility that these ages correspond to metamorphic overprints of an older igneous unit (Mesoproterozoic-age basic rocks?).

Tectonic reactivation is marked by the D4 deformational phase, which includes ductile shear zones and the N–S to NE–SW trending open upright folds that affect the Punilla Formation, Guandacolinos Granite and Umango basement rocks. This deformation presumably occurred at a shallow crustal level with sinistral transpressional kinematic activity. As previously

mentioned, geological evidence has shown that D4 deformation would have occurred prior to the Late Carboniferous period (deposition of Rio del Peñón Formation). Varela et al. (2005) proposed that the Guandacolinos Granite deformation was of an intra-Carboniferous age (between 314 and 311 Ma). The authors agreed with the proposal of intra-Carboniferous tectonic movement in the Punilla Formation (Rio Blanco tectonic phase of Fauqué et al., 1999). Nonetheless, Azcuy et al. (1999) opposed the idea of the Rio Blanco tectonic phase, arguing that the sedimentary interval described by Fauqué et al. (1999) represents a transitional deposition in the Punilla Formation. Based on the SHRIMP U/Pb zircon age (Basei, personal communication) of the Silurian core (crystallisation age) and the Devonian rim (metamorphism?), the D4 deformational phase must have occurred during the Late Devonian period associated with the late- to post-orogenic phase of the Famatinian Orogeny (Chanica Phase), in agreement with Azcuy et al. (1999) and Varela et al. (2002). A Devonian sinistral transpressional event was also described in the Sierra de San Luis (von Gosen, 1998). This tectonic reactivation could be related with the collision of Chilenia Terrane onto the western margin of Gondwana (c.f. Ramos et al., 1998; Quernadelle and Ramos, 1999; Ramos, 1999b).

The uplifting of the basement outcrops at the Sierras Pampeanas occurred during the Late Cenozoic era in the Andean Orogeny and was likely reactivated by several pre-existent structures (Ramos et al., 2002). This deformation geometrically modified the Ordovician structures, which mainly resulted in the tilting of major blocks (c.f., Fig. 4b in Ramos et al., 2002). The D5 deformational phase described herein could be related to the Andean Orogeny.

6. Concluding remarks

A polyphase structural evolution process was identified at the Sierra de Umango. The Famatinian collisional event is defined by a *Nappe* System, the clearly delineated Mesoproterozoic Juchi Orthogneiss *klippen*, and an important shear zone (PFSZ) along the western boundary of the Sierra de Umango. The *Nappe* System revealed a top-to-the S/SW sense direction of movement and the PFSZ served as a right lateral ramp facilitating the exhumation process (Fig. 11a). An oblique collision is hypothesised, with the Cuyania Terrane subducting underneath the proto-Andean margin of Gondwana in the NE direction. The continental subduction and exhumation lasted at least 30 M.y., nearly the entire Ordovician period, and resulted in metamorphic conditions that produced upper amphibolite-to-granulite facies in medium- to high-pressure regimes. The El Peñón Granite exemplifies the pre- to syn-collisional granitoid intrusions. In the Silurian, a granitogenesis (Guandacolinos Granite intrusion – Fig. 11c) occurred that was possibly associated with the westward migration of the subduction. Compressive tectonic reactivation (Chanica tectonic phase), related to the Devonian accretion of the Chilenia Terrane along the Western margin of Gondwana, affected the previously deformed rocks, the Devonian sedimentary rocks of Precordillera (Punilla Formation) and the Guandacolinos Granite (Fig. 11d). The Chanica tectonic phase in the Sierra de Umango and the surroundings is characterised by the presence of open folds in the N–S direction and by sinistral discrete shear zones. Late Carboniferous post-collisional magmatism (Cerro Veladero Granite) intruded in the southern portion of the Umango basement rocks and is linked to the Gondwanic Tectonic Cycle. Extensional tectonics and deposition of Carboniferous/Permian sediments (e.g., Paganzo Basin) and Triassic deposits (Ischigualasto Basin) are also typical of the Gondwanic Cycle. Cretaceous extensional retroarc basins and Tertiary foreland basins are indicative of the Andean Orogeny. An approximately N–S

compressional regime (Fig. 11e) preceded the usual E–W shortening of the Andean tectonics.

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